Microcontroller Programming
The Microchip PIC®
Microcontroller Programming
The Microchip PIC®

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There are two sides to the computer revolution: one is represented by the PC on your desktop and the second one by the device that remote-controls your TV, monitors and operates your car engine, and allows you to set up your answering machine and your microwave oven. At the core of the PC you find a microprocessor, while at the heart of a self-contained programmable device (also called an embedded system) is a microcontroller.

Microcontrollers are virtually everywhere in our modern society. They are found in automobiles, airplanes, toys, kitchen appliances, computers, TVs and VCRs, phones and answering machines, space telescopes, and practically every electronic digital device that furnishes an independent functionality to its user. In this sense a microcontroller is a self-contained computer system that includes a processor, memory, and some way of communicating with the outside world, all in a single chip that can be smaller than a postage stamp.

A microcontroller (sometimes called an MCU) is actually a computer on a chip. Essentially it is a control device and its design places emphasis on being self-sufficient and inexpensive. The typical microcontroller contains all the components and features necessary to perform its functions, such as a central processor, input/output facilities, timers, RAM memory for storing program data and executable code, and a clock or oscillator that provides a timing beat. In addition, some microcontrollers include a variety of additional modules and circuits. Some common ones are serial and parallel communications, analog-to-digital converters, realtime clocks, and flash memory.

Engineers, inventors, experimenters, students, and device designers in general deal with microcontrollers on an everyday basis. In fact, interest in microcontrollers is not limited to electrical, electronic, and computer engineers. Mechanical and automotive engineers, among many others, often design devices or components that contain microcontrollers. The system that controls the hatch of a ballistic missile silo and the one that operates the doglike toy that barks and rolls on its back, both contain microcontrollers.

The Microchip PIC

Microcontrollers include an enormous array of models and variations of general- and special-purpose devices. Discussing all of them in a single volume would have forced a superficial scope. Even the products of a single manufacturer can have a mind-bog-
gling variety, which sometimes include hundreds of different MCU models in a half-dozen families, all with very different applications and features.

For this reason we have focused the book on a single type of microcontroller: the Microchip PIC. Not only are the PIC the most used and best known microcontrollers, they are also the best supported. In fact, PIC system design and programming has become a powerful specialization with a large number of professional and amateur specialists. There are hundreds of WEB sites devoted to PIC-related topics. An entire cottage industry of PIC software and hardware has flourished around this technology.

For practical reasons we have limited the book's scope to 8-bit PICs. In fact, the book concentrates on a particular type of 8-bit PIC known as the mid-range family. We have chosen this approach partly because of space limitations and partly due to the fact that 16- and 32-bit microcontrollers (sometimes called external memory microcontrollers) are more related to microprocessor technology than to the topic at hand.

**The Book's Design**

The book is intended as a resource kit for PIC microcontroller programming. But programming microcontrollers is a different paradigm from microprocessor programming. PIC programming requires a set of skills and a knowledge base quite different from the one needed by a computer programmer. The reason is that the designer/programmer is responsible for the entire system. A typical embedded system has no DOS, Windows, or UNIX software to handle the operational and housekeeping chores. Thus, the PIC programmer provides all the functionality needed by the application with very little assistance from other programs. This makes the microcontroller programmer an application developer, a system's programmer, and an input/output specialist, all at the same time.

For these reasons, the microcontroller programmer must be familiar with a host of computer science topics, including low-level data representations, binary arithmetic, computer organization, input/output programming, concurrency and scheduling, memory management, timing operations, and system functions. At the same time, he or she must be quite conversant with digital electronics and circuit design since the object of the program is a hardware device.

In the first six chapters of the book we have attempted to provide the necessary background both in digital electronics and in computer science. Chapters 7, 8, and 9 are an overview of PIC architecture and programming tools. The remainder of the book deals with programming the various functions, modules, and devices. The appendices contain supplementary materials and expand the coding contained in the text. Readers familiar with electronics and circuit design can skip over Chapters 1, 5, and 6. Those well versed in computer science can do the same with Chapters 2, 3, and 4.

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June 28, 2006

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1.0 The Atom

Until the end of the nineteenth century it was assumed that matter was composed of small, indivisible particles called atoms. The work of J.J. Thompson, Daniel Rutheford, and Neils Bohr proved that atoms were complex structures that contained both positive and negative particles. The positive ones were called protons and the negative ones electrons.

Several models of the atom were proposed: the one by Thompson assumed that there were equal numbers of protons and electrons inside the atom and that these elements were scattered at random, as in the leftmost drawing in Figure 1-1. Later, in 1913, Daniel Rutheford’s experiments led him to believe that atoms contained a heavy central positive nucleus with the electrons scattered randomly. So he modified Thompson’s model as shown in the center drawing. Finally, Neils Bohr theorized that electrons had different energy levels, as if they moved around the nucleus in different orbits, like planets around a sun. The rightmost drawing represents this orbital model.

![Models of the Atom](image)

**Figure 1-1** Models of the Atom
Investigations also showed that the normal atom is electrically neutral. Protons (positively charged particles) have a mass of $1.673 \times 10^{-24}$ grams. Electrons (negatively charged particles) have a mass of $9.109 \times 10^{-28}$ grams. Furthermore, the orbital model of the atom is not actually valid since orbits have little meaning at the atomic level. A more accurate representation is based on concentric spherical shells about the nucleus. An active area of research deals with atomic and sub-atomic structures.

The number of protons in an atom determines its atomic number; for example, the hydrogen atom has a single proton and an atomic number of 1, helium has 2 protons, carbon has 6, and uranium has 92. But when we compare the ratio of mass to electrical charge in different atoms we find that the nucleus must be made up of more than protons. For example, the helium nucleus has twice the charge of the hydrogen nucleus, but four times the mass. The additional mass is explained by assuming that there is another particle in the nucleus, called a neutron, which has the same mass as the proton but no electrical charge. Figure 1-2 shows a model of the helium atom with two protons, two electrons, and two neutrons.

![Figure 1-2 Model of the Helium Atom](image)

### 1.1 Isotopes and Ions

But nature is not always consistent with such neat models. Whereas in a neutral atom, the number of protons in the atomic nucleus exactly matches the number of electrons, the number of protons need not match the number of neutrons. For example, most hydrogen atoms have a single proton, but no neutrons, while a small percentage have one neutron, and an even smaller one have two neutrons. In this sense, atoms of an element that contains different number of neutrons are isotopes of the element; for example water ($H_2O$) containing hydrogen atoms with two neutrons (deuterium) is called "heavy water."

An atom that is electrically charged due to an excess or deficiency of electrons is called an ion. When the dislodged elements are one or more electrons the atom takes a positive charge. In this case it is called a positive ion. When a stray electron combines with a normal atom the result is called a negative ion.
1.2 Static Electricity

Free electrons can travel through matter or remain at rest on a surface. When electrons are at rest, the surface is said to have a static electrical charge that can be positive or negative. When electrons are moving in a stream-like manner we call this movement an electrical current. Electrons can be removed from a surface by means of friction, heat, light, or a chemical reaction. In this case the surface becomes positively charged.

The ancient Greeks discovered that when amber was rubbed with wool the amber became electrically charged and would attract small pieces of material. In this case, the charge is a positive one. Friction can cause other materials, such as hard rubber or plastic, to become negatively charged. Observing objects that have positive and negative charges we note that like charges repel and unlike charges attract each other, as shown in Figure 1-3.

![Figure 1-3 Like and Unlike Charges](image)

Friction causes loosely-held electrons to be transferred from one surface to the other. This results in a net negative charge on the surface that has gained electrons, and a net positive charge on the surface that has lost electrons. If there is no path for the electrons to take to restore the balance of electrical charges, these charges remain until they gradually leak off. If the electrical charge continues building it eventually reaches the point where it can no longer be contained. In this case it discharges itself over any available path, as is the case with lightning.

Static electricity does not move from one place to another. While some interesting experiments can be performed with it, it does not serve the practical purpose of providing energy to do sustained work.

Static electricity certainly exists, and under certain circumstances we must allow for it and account for its possible presence, but it will not be the main theme of these pages.
1.3 Electrical Charge

Physicists often resort to models and theories to describe and represent some force that can be measured in the real world. But very often these models and representations are no more than concepts that fail to physically represent the object. In this sense, no one knows exactly what gravity is, or what is an electrical charge. Gravity, which can be felt and measured, is the force between masses.

By the same token, bodies in "certain electrical conditions" also exert measurable forces on one another. The term "electrical charge" was coined to explain these observations.

Three simple postulates or assumptions serve to explain all electrical phenomena:
1. Electrical charge exists and can be measured. Charge is measured in Coulombs, a unit named for the French scientist Charles Agustin Coulomb.
2. Charge can be positive or negative.
3. Charge can neither be created nor destroyed. If two objects with equal amounts of positive and negative charge are combined on some object, the resulting object will be electrically neutral and will have zero net charge.

1.3.1 Voltage

Objects with opposite charges attract, that is, they exert a force upon each other that pulls them together. In this case, the magnitude of the force is proportional to the product of the charge on each mass. Like gravity, electrical force depends inversely on the distance squared between the two bodies; the closer the bodies the greater the force. Consequently, it takes energy to pull apart objects that are positively and negatively charged, in the same manner that it takes energy to raise a big mass against the pull of gravity.

The potential that separate objects with opposite charges have for doing work is called voltage. Voltage is measured in units of volts (V). The unit is named for the Italian scientist Alessandro Volta.

The greater the charge and the greater the separation, the greater the stored energy, or voltage. By the same token, the greater the voltage, the greater the force that drives the charges together.

Voltage is always measured between two points that represent the positive and negative charges. In order to compare voltages of several charged bodies a common reference point is necessary. This point is usually called "ground."

1.3.2 Current

Electrical charge flows freely in certain materials, called conductors, but not in others, called insulators. Metals and a few other elements and compounds are good conductors, while air, glass, plastics, and rubber are insulators. In addition, there is a third category of materials called semiconductors; sometimes they seem to be good con-
ductors but much less so other times. Silicon and Germanium are two such semiconductors. We discuss semiconductors in the context of integrated circuits later in the book.

Figure 1-4 shows two connected, oppositely charged bodies. The force between them has the potential for work; therefore, there is voltage. If the two bodies are connected by a conductor, as in the illustration, the positive charge moves along the wire to the other sphere. On the other end, the negative charge flows out on the wire towards the positive side. In this case, positive and negative charges combine to neutralize each other until there are no charge differences between any points in the system.

Figure 1-4 Connected Opposite Charges

The flow of an electrical charge is called a current. Current is measured in amperes (a), also called amps, after Andre Ampere, a French mathematician and physicist. An ampere is defined as a flow of one Coulomb of charge in one second.

Electrical current is directional; therefore, a positive current is the flow current from a positive point A to a negative point B. However, most current results from the flow of negative-to-positive charges.

1.3.3 Power

Current flowing through a conductor produces heat. The heat is the result of the energy that comes from the charge traveling across the voltage difference. The work involved in producing this heat is electrical power. Power is measured in units of watts (W), named after the Englishman James Watt, who invented the steam engine.

1.3.4 Ohm’s Law

The relationship between voltage, current, and power is described by Ohm’s Law, named after the German physicist Georg Simon Ohm. Using equipment of his own creation, Ohm determined that the current that flows through a wire is proportional to its cross-sectional area and inversely proportional to its length. This allowed defining the relationship between voltage, current, and power, as expressed by the equation:

\[ P = V \times I \]
Where P represents the power in watts, V is the voltage in volts, and I is the current in amperes. Ohm's Law can also be formulated in terms of voltage, current, and resistance as shown later in this chapter.

1.4 Electrical Circuits

An electrical network is an interconnection of electrical elements. An electrical circuit is a network in a closed loop, giving a return path for the current. A network is a connection of two or more simple elements, and may not necessarily be a circuit.

Although there are several types of electrical circuits they all have some of the following elements:

1. A power source, which can be a battery, alternator, etc., produces an electrical potential.
2. Conductors, in the form of wires or circuit boards, provide a path for the current.
3. Loads, in the form of devices such as lamps, motors, etc., use the electrical energy to produce some form of work.
4. Control devices, such as potentiometers and switches, regulate the amount of current flow or turn it on and off.
5. Protection devices, such as fuses or circuit breakers, prevent damage to the system in case of overload.
6. A common ground.

Figure 1-5 shows a simple circuit that contains all of these elements.

![Figure 1-5 Simple Circuit](image)

1.4.1 Types of Circuits

There are three common types of circuits: series, parallel, and series-parallel. The circuit type is determined by how the components are connected. In other words, by how the circuit elements, power source, load, and control and protection devices are interconnected. The simplest circuit is one in which the components offer a single current path. In this case, although the loads may be different, the amount of current flowing through each one is the same. Figure 1.6 shows a series circuit with two light bulbs.
In the series circuit in Figure 1-6 if one of the light bulbs burn out, the circuit flow is interrupted and the other one will not light. Some Christmas lights are wired in this manner, and if a single bulb fails the whole string will not light.

In a parallel circuit there is more than one path for current flow. Figure 1-7 shows a circuit wired in parallel.

In the circuit of Figure 1-7, if one of the light bulbs burns out, the other one will still light. Also, if the load is the same in each circuit branch, so will be the current flow in that branch. By the same token, if the load in each branch is different, so will be the current flow in each branch.

The series-parallel circuit has some components wired in series and others in parallel. Therefore, the circuit shares the characteristics of both series and parallel circuits. Figure 1-8 shows the same parallel circuit to which a series rheostat (dimmer) has been added in series.
In the circuit of Figure 1-8 the two light bulbs are wired in parallel, so if one fails the other one will not. However, the rheostat (dimmer) is wired in series with the circuit, so its action affects both light bulbs.

1.5 Circuit Elements
So far we have represented circuits using a pictorial style. Circuit diagrams are more often used since they achieve the same purpose with much less artistic effort and are easier to read. Figure 1-9 is a diagrammatic representation of the circuit in Figure 1-8.

Certain components are commonly used in electrical circuits. These include power sources, resistors, capacitors, inductors, and several forms of semiconductor devices.
1.5.1 Resistors

If the current flow from, say, a battery is not controlled, a short-circuit takes place and the wires can melt or the battery may even explode. Resistors provide a way of controlling the flow of current from a source. A resistor is to current flow in an electrical circuit as a valve is to water flow: both elements "resist" flow. Resistors are typically made of materials that are poor conductors. The most common ones are made from powdered carbon and some sort of binder. Such carbon composition resistors usually have a dark-colored cylindrical body with a wire lead on each end. Color bands on the body of the resistor indicate its value, measured in ohms and represented by the Greek letter $\omega$. The color code for resistor bands can be found in Appendix A.

The potentiometer and the rheostat are variable resistors. When the knob of a potentiometer or rheostat is turned, a slider moves along the resistance element and reduces or increases the resistance. A potentiometer is used as a dimmer in the circuits of Figure 1-8 and Figure 1-9. The photoresistor or photocell is composed of a light sensitive material whose resistance decreases when exposed to light. Photoresistors can be used as light sensors.

1.5.2 Revisiting Ohm's Law

We have seen how Ohm's Law describes the relationship between voltage, current, and power. The law is reformulated in terms of resistance so as to express the relationship between voltage, current, and resistance, as follows:

$V = I \times R$

Note that the voltage value in Ohm's Law refers to the voltage across the resistor, in other words, the voltage between the two terminal wires. In this sense the voltage is actually produced by the resistor, since the resistor is restricting the flow of charge much as a valve or nozzle restricts the flow of water. It is the restriction created by the resistor that forms an excess of charge with respect to the other side of the circuit. The charge difference results in a voltage between the two points. Ohm's Law is used to calculate the voltage if we know the resistor value and the current flow.

$I = \frac{V}{R}$

$R = \frac{V}{I}$
A popular mnemonic for Ohm’s Law consists of drawing a pyramid with the voltage symbol at the top and current and resistance in the lower level. Then, it is easy to solve for each of the values by observing the position of the other two symbols in the pyramid, as shown in Figure 1-10.

1.5.3 Resistors in Series and Parallel

When resistors are in series the total resistance equals the sum of the individual resistances. The diagram in Figure 1-11 shows two resistors (R1 and R2) wired in series in a simple circuit.

In Figure 1-11 the total resistance (RT) is calculated by adding the resistance values of R1 and R2, thus, $RT = R1 + R2$.

In terms of water flow, a series of partially closed valves in a pipe add up to slow the flow of water.

Resistors can also be connected in parallel, as shown in Figure 1-12.
When resistors are placed in parallel, the combination has less resistance than any one of the resistors. If the resistors have different values, then more current flows through the path of least resistance. The total resistance in a parallel circuit is obtained by dividing the product of the individual resistors by their sum, as in the formula:

\[ RT = \frac{R_1 \times R_2}{R_1 + R_2} \]

If more than two resistors are connected in parallel, then the formula can be expressed as follows:

\[ RT = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots} \]

Also note that the diagram representation of resistors in parallel can have different appearances. For example, the circuit in Figure 1-13 is electrically identical to the one in Figure 1-12.
Figure 1-14 Resistors

Figure 1-14 shows several commercial resistors. The integrated circuit at the center of the image combines eight resistors of the same value. These devices are convenient when the circuit design calls for several identical resistors. The color-coded cylindrical resistors in the image are made of carbon.

Appendix A contains the color codes used in identifying resistors whose surface area does not allow printing its value.

1.5.4 Capacitors

An element often used in the control of the flow of an electrical charge is a capacitor. The name originated in the notion of a "capacity" to store charge. In that sense a capacitor functions as a small battery. Capacitors are made of two conducting surfaces separated by an insulator. A wire lead is usually connected to each surface. Two large metal plates separated by air would perform as a capacitor. More frequently capacitors are made of thin metal foils separated by a plastic film or another form of solid insulator. Figure 1-15 shows a circuit which contains both a capacitor and a resistor.

In Figure 1-15 charge flows from the battery terminals, along the conductor wire, onto the capacitor plates. Positive charges collect on one plate and negative charges on the other plate. The initial current is limited only by the resistance of the wires and by the resistor in the circuit. As charge builds up on the plates, charge repulsion resists the flow and the current is reduced. At some point the repulsive force from charge on the plates is strong enough to balance the force from charge on the battery, and the current stops.

Figure 1-15 Capacitor Circuit
The existence of charges on the capacitor plates means there must be a voltage between the plates. When the current stops this voltage is equal to the voltage in the battery. Since the points in the circuit are connected by conductors, then they have the same voltage, even if there is a resistor in the circuit. If the current is zero, there is no voltage across the resistor, according to Ohm's law.

The amount of charge on the plates of the capacitor is a measure of the value of the capacitor. This "capacitance" is measured in farads (f), named in honor of the English scientist Michael Faraday.

The relationship is expressed by the equation:

\[ C = \frac{Q}{V} \]

where \( C \) is the capacitance in farads, \( Q \) is the charge in Coulombs, and \( V \) is the voltage. Capacitors of one farad or more are rare. Generally capacitors are rated in microfarads (\( \mu f \)), one-millionth of a farad, or picofarads (\( pf \)), one-trillionth of a farad.

Consider the circuit of Figure 1-15 after the current has stabilized. If we now remove the capacitor from the circuit it still holds a charge on its plates. That is, there is a voltage between the capacitor terminals. In one sense, the charged capacitor appears somewhat like a battery. If we were to short-circuit the capacitor's terminals a current would flow as the positive and negative charges neutralize each other. But unlike a battery, the capacitor does not replace its charge. So the voltage drops, the current drops, and finally there is no net charge and no voltage difference anywhere in the circuit.

1.5.5 Capacitors in Series and in Parallel

Like resistors, capacitors can be joined together in series and in parallel. Connecting two capacitors in parallel results in a bigger capacitance value, since there is a larger plate area. Thus, the formula for total capacitance (\( CT \)) in a parallel circuit containing capacitors \( C_1 \) and \( C_2 \) is:

\[ CT = C_1 + C_2 \]

Note that the formula for calculating capacitance in parallel is similar to the one for calculating series resistance. By the same token, where several capacitors are connected in series the formula for calculating the total capacitance is:

\[ CT = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots} \]
Note that the total capacitance of a connection in series is lower than for any capacitor in the series, considering that for a given voltage across the entire group there is less charge on each plate.

There are several types of commercial capacitors, including mylar, ceramic, disk, and electrolytic. Figure 1-16 shows several commercial capacitors.

**1.5.6 Inductors**

Inductors are the third type of basic circuit components. An inductor is a coil of wire with many windings. The wire windings are often made around a core of a magnetic material, such as iron. The properties of inductors are derived from magnetic rather than electric forces.

When current flows through a coil it produces a magnetic field in the space outside the wire. This makes the coil behave just like a natural, permanent magnet. Moving a wire through a magnetic field generates a current in the wire, and this current will flow through the associated circuit. Since it takes mechanical energy to move the wire through the field, then it is the mechanical energy that is transformed into electrical energy. A generator is a device that converts mechanical to electrical energy by means of induction. An electric motor is the opposite of a generator. In the motor electrical energy is converted to mechanical energy by means of induction.

The current in an inductor is similar to the voltage across a capacitor. In both cases it takes time to change the voltage from an initially high current flow. Such induced voltages can be very high and can damage other circuit components, so it is common to connect a resistor or a capacitor across the inductor to provide a current path to absorb the induced voltage. In combination inductors behave just like resistors: inductance adds in series. By the same token, parallel connection reduces induction. Induction is measured in henrys (h), but more commonly in mh, and μh.
1.5.7 Transformers

The transformer is an induction device that changes voltage or current levels. The typical transformer has two or more windings wrapped around a core made of laminated iron sheets. One of the windings, called the primary, receives a fluctuating current. The other winding, called the secondary, produces a current induced by the primary. Figure 1-17 shows the schematics of a transformer.

The device in Figure 1-17 is a step-up transformer. This is determined by the number of windings in the primary and secondary coils. The ratio of the number of turns in each winding determines the voltage increase. A transformer with an equal number of turns in the primary and secondary transfers the current unaltered. This type of device is sometimes called an isolation transformer. A transformer with less turns in the secondary than in the primary is a step-down transformer and its effect is to reduce the primary voltage at the secondary.

Transformers require an alternating or fluctuating current since it is the fluctuations in the current flow in the primary that induce a current in the secondary. The ignition coil in an automobile is a transformer that converts the low-level battery voltage to the high voltage level necessary to produce a spark.

1.6 Semiconductors

The name semiconductor stems from the property of some materials that act either as a conductor or as an insulator depending on certain conditions. Several elements are classified as semiconductors including Silicon, Zinc, and Germanium. Silicon is the most widely used semiconductor material because it is easily obtained.

In the ultra-pure form of silicon the addition of minute amounts of certain impurities (called dopants) alters the atomic structure of the silicon. This determines whether the Silicon can then be made to act as a conductor or as a nonconductor, depending upon the polarity of an electrical charge applied to it.

In the early days of radio, receivers required a device called a rectifier to detect signals. Ferdinand Braun used the rectifying properties of the galena crystal, a semiconductor material composed of lead sulfide, to create a "cat's whisker" diode that served this purpose. This was the first semiconductor device.
1.6.1 Integrated Circuits

Until 1959, electronic components performed a single function; therefore, many of them had to be wired together to create a functional circuit. Transistors were individually packaged in small cans. Packaging and hand wiring the components into circuits was extremely inefficient.

In 1959, at Fairchild Semiconductor, Jean Hoerni and Robert Noyce developed a process which made it possible to diffuse various layers onto the surface of a silicon wafer, while leaving a layer of protective oxide on the junctions. By allowing the metal interconnections to be evaporated onto the flat transistor surface the process replaced hand wiring. By 1961, nearly 90% of all the components manufactured were integrated circuits.

1.6.2 Semiconductor Electronics

To understand the workings of semiconductor devices we need to re-consider the nature of the electrical charge. Electrons are one of the components of atoms, and atoms are the building blocks of all matter. Atoms bond with each other to form molecules. Molecules of just one type of atom are called elements. In this sense gold, oxygen, and plutonium are elements since they all consist of only one type of atom. When a molecule contains more than one atom it is known as a compound. Water, which has both hydrogen and oxygen atoms, is a compound. Figure 1-18 represents an orbital model of an atom with five protons and three electrons.

![Orbital Model of the Boron Atom with its Valence Electrons](image)

In Figure 1-18, protons carry positive charge and electrons carry negative charge. Neutrons, not represented in the illustration, are not electrically charged. Atoms that have the same number of protons and electrons have no net electrical charge.

Electrons that are far from the nucleus are relatively free to move around since the attraction from the positive charge in the nucleus is weak at large distances. In fact, it takes little force to completely remove an outer electron from an atom, leaving an ion with a net positive charge. A free electron can move at speeds approaching the speed of light (approximately 186,282 miles per second).

Electric current takes place in metal conductors due to the flow of free electrons. Because electrons have negative charge, the flow is in a direction opposite to the
positive current. Free electrons traveling through a conductor drift until they hit other electrons attached to atoms. These electrons are then dislodged from their orbits and replaced by the formerly free electrons. The newly freed electrons then start the process anew.

1.6.3 P-Type and N-Type Silicon

Semiconductor devices are made primarily of silicon. Pure silicon forms rigid crystals because of its four outermost electrons. Since it contains no free electrons it is not a conductor. But silicon can be made conductive by combining it with other elements (doping) such as boron and phosphorus. The boron atom has three outer valence electrons (Figure 1-18) and the phosphorus atom has five. When three silicon atoms and one phosphorus atom bind together, creating a structure of four atoms, there is an extra electron and a net negative charge.

The combination of silicon and phosphorous, with the extra phosphorus electron, is called an N-type silicon. In this case the N stands for the extra negative electron. The extra electron donated by the phosphorus atom can easily move through the crystal; therefore N-type silicon can carry an electrical current.

When a boron atom combines with a cluster of silicon atoms there is a deficiency of one electron in the resulting crystal. Silicon with a deficient electron is called P-type silicon (P stands for positive). The vacant electron position is sometimes called a "hole." An electron from another nearby atom can "fall" into this hole, thereby moving the hole to a new location. In this case, the hole can carry a current in the P-type silicon.

1.6.4 The Diode

Both P-type and N-type silicon conduct electricity. In either case, the conductivity is determined by the proportion of holes or the surplus of electrons. By forming some P-type silicon in a chip of N-type silicon it is possible to control electron flow so that it takes place in a single direction. This is the principle of the diode, and the p-n action is called a pn-junction.

A diode is said to have a forward bias if it has a positive voltage across it from the P- to N-type material. In this condition, the diode acts rather like a good conductor, and current can flow, as in Figure 1-19.

Figure 1-19 A Forward Biased Diode
If the polarity of the voltage applied to the silicon is reversed, then the diode is *reverse-biased* and appears nonconducting. This nonsymmetric behavior is due to the properties of the *pn-junction*. The fact that a diode acts like a one-way valve for current is a very useful characteristic. One application is to convert *alternating current* (AC) into *direct current* (DC). Diodes are so often used for this purpose that they are sometimes called rectifiers.
Number Systems

In order to perform more efficient digital operations on numeric data, mathematicians have devised systems and structures that differ from those used traditionally. This chapter presents the background material necessary for understanding and using the number systems and numeric data storage structures employed in digital devices.

2.0 Counting

The fundamental application of a number system is counting. A stone-age hunter uses his or her fingers to show other members of the tribe how many mammoths were spotted at the bottom of the ravine. In this manner the hunter is able to transmit a unique type of information that does not relate to the species, size, or color of the animals, but to their numbers. Our minds have the ability to capture this notion of "oneness" independently from other properties of objects.

The most primitive method of counting consists of using objects to represent degrees of oneness. The stone-age hunter uses fingers to represent individual mammoth. Alternatively, the hunter could have resorted to pebbles, sticks, lines on the ground, or scratches on the cave wall to show how many units there were of the object.

2.0.1 The Tally System

The tally system probably originated from notches on a stick or scratches on a cave wall. In its simplest form each scratch, notch, or line represents an object. The method is so simple and intuitive that we still resort to it occasionally. Tallying requires no knowledge of quantity and no elaborate symbols. Had there been 12 mammoth in the ravine the cave wall would have appeared as follows:

```
||| ||| ||
```

A logical evolution of the tally system consists of grouping the marks. Since we have five fingers in each hand, the 12 mammoth may have been grouped as follows:

```
||| |
```


Perhaps a primitive mathematical genius added one final sophistication to the tally system. By drawing one tally line diagonally the visualization is further improved, as in this familiar style:

\[ II \left/ \right. \]

### 2.0.2 Roman Numerals

Roman numerals show how a simple graphical tally system evolved into a symbolic numeric representation. The first five digits were encoded with the symbols:

\[ I, II, III, IIII, \text{ and } V \]

The Roman symbol V is conceivably a simplification of the tally encoding using a diagonal line to complete the grouping.

#### Table 2.1

*Symbols in the Roman Numeration System*

<table>
<thead>
<tr>
<th>ROMAN</th>
<th>DECIMAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
</tr>
<tr>
<td>V</td>
<td>5</td>
</tr>
<tr>
<td>X</td>
<td>10</td>
</tr>
<tr>
<td>L</td>
<td>50</td>
</tr>
<tr>
<td>C</td>
<td>100</td>
</tr>
<tr>
<td>D</td>
<td>500</td>
</tr>
<tr>
<td>M</td>
<td>1000</td>
</tr>
</tbody>
</table>

The Roman numeral system is based on an add-subtract rule whereby the elements of a number, read left-to-right, are either added or subtracted to the previous sum according to its value. Thereby the decimal number 1994 is represented in Roman numerals as follows:

\[
\text{MCMXCV} = 1000 + (1000 - 100) + (100 - 10) + (5 - 1)
\]

\[= 1994\]

The uncertainty in the positional value of each digit, the absence of a symbol for zero, and the fact that some numbers require either one or two symbols (I, IV, V, IX, and X) complicate the rules of arithmetic using Roman numerals.

### 2.1 The Origins of the Decimal System

The one element of our civilization which has transcended all cultural and social differences is our decimal system of numbers. While mankind is yet to agree on the most desirable political order, on generally acceptable rules of moral behavior, or on a universal language, the Hindu-Arabic numerals have been adopted by practically all the nations and cultures of the world.
By the 9th century A.D. the Arabs were using a ten-symbol positional system of numbers which included the special symbol for 0. The Latin title of the first book on the subject of "Indian numbers" is Liber Algorismi de Numero Indorum. The author is the Arab mathematician al-Khowarizmi.

In spite of the evident advantages of this number system its adoption in Europe took place only after considerable debate and controversy. Many scholars of the time still considered Roman numerals to be easier to learn and more convenient for operations on the abacus. The supporters of the Roman numeral system, called abacists, engaged in intellectual combat with the algorists, who were in favor of the Hindu-Arabic numerals as described by al-Khowarizmi. For several centuries abacists and algorists debated about the advantages of their systems, with the Catholic church often siding with the abacists. This controversy explains why the Hindu-Arabic numerals were not accepted into general use in Europe until the beginning of the 16th century.

It is sometimes said that the reason for there being ten symbols in the Hindu-Arabic numerals is related to the fact that we have ten fingers. However, if we make a one-to-one correlation between the Hindu-Arabic numerals and our fingers, we find that the last finger must be represented by a combination of two symbols, 10. Also, one Hindu-Arabic symbol, 0, cannot be matched to an individual finger. In fact, the decimal system of numbers, as used in a positional notation that includes a zero digit, is a refined and abstract scheme which should be considered one of the greatest achievements of human intelligence. We will never know for certain if the Hindu-Arabic numerals are related to the fact that we have ten fingers, but its profoundness and usefulness clearly transcends this biological fact.

The most significant feature of the Hindu-Arabic numerals is the presence of a special symbol, 0, which by itself represents no quantity. Nevertheless, the special symbol 0 is combined with the other ones. In this manner the nine other symbols are reused to represent larger quantities. Another characteristic of decimal numbers is that the value of each digit depends on its position in a digit string. This positional characteristic, in conjunction with the use of the special symbol 0 as a placeholder, allows the following representations:

- 1 = one
- 10 = ten
- 100 = hundred
- 1000 = thousand

The result is a counting scheme where the value of each symbol is determined by its column position. This positional feature requires the use of the special symbol, 0, which does not correspond to any unit-amount, but is used as a place-holder in multicolumn representations. We must marvel at the intelligence, capability for abstraction, and even the sense of humor of the mind that conceived a counting system that has a symbol that represents nothing. We must also wonder about the evolution of mathematics, science, and technology had this system not been invented. One intriguing question is whether a positional counting system that includes the zero symbol is a natural and predictable step in the evolution of our mathematical
thought, or whether its invention was a stroke of genius that could have been missed for the next two thousand years.

2.1.1 Number Systems for Digital-Electronics

The computers built in the United States during the early 1940s operated on decimal numbers. However, in 1946, von Neumann, Burks, and Goldstine published a trend-setting paper titled Preliminary Discussion of the Logical Design of an Electronic Computing Instrument, in which they state:

"In a discussion of the arithmetic organs of a computing machine one is naturally led to a consideration of the number system to be adopted. In spite of the long-standing tradition of building digital machines in the decimal system, we must feel strongly in favor of the binary system for our device."

In their paper, von Neumann, Burks, and Goldstine also consider the possibility of a computing device that uses binary-coded decimal numbers. However, the idea is discarded in favor of a pure binary encoding. The argument is that binary numbers are more compact than binary-coded decimals. Later in this book you will see that binary-coded decimal numbers (called BCD) are used today in some types of computer calculations.

In 1941, Konrad Zuse, a German who had done pioneering work in computing machines, released the first programmable computer designed to solve complex engineering equations. The machine, called the Z3, was controlled by perforated strips of discarded movie film and used the binary number system.

The use of the binary number system in digital calculators and computers was made possible by previous research on number systems and on numerical representations, starting with an article by G.W. Leibnitz published in Paris in 1703. Researchers concluded that it is possible to count and perform arithmetic operations using any set of symbols as long as the set contains at least two symbols, one of which must be zero.

In digital electronics the binary symbol 1 is equated with the electronic state ON, and the binary symbol 0 with the state OFF. The two symbols of the binary system can also represent conducting and nonconducting states, positive or negative, or any other bi-valued condition. It was the binary system that presented the Hindu-Arabic decimal number system with the first challenge in 800 years. In digital-electronics two steady states are easier to implement and more reliable than a ten-digit encoding.

2.1.2 Positional Characteristics

All modern number systems, including decimal, hexadecimal, and binary, are positional and include the digit zero. It is the positional feature that is used to determine the total value of a multi-digit representation. For example, the digits in the decimal number 4359 have the following positional weights:
The total value is obtained by adding the column weights of each unit:

\[
\begin{align*}
4000 & \quad 4 \text{ thousand units} \\
300 & \quad 3 \text{ hundred units} \\
+ 50 & \quad 5 \text{ ten units} \\
9 & \quad 9 \text{ unit} \\
\hline
4359
\end{align*}
\]

2.1.3 Radix or Base of a Number System

In any positional number system the weight of each column is determined by the total number of symbols in the set, including zero. This is called the base or radix of the system. The base of the decimal system is 10 and the base of the binary system is 2. The positional value or weight (P) of a digit in a multi-digit number is determined by the formula:

\[
P = d \times B^c
\]

where \(d\) is the digit, \(B\) is the base or radix, and \(c\) is the zero-based column number, starting from right to left. Note that the increase in column weight from right to left is purely conventional. You could construct a number system in which the column weights increase in the opposite direction. In fact, in the original Hindu notation the most significant digit was placed at the right.

In radix-positional terms a decimal number can be expressed as a sum of digits by the formula:

\[
\sum_{i=-m}^{n} d_i \times 10^i
\]

where \(i\) is the system’s range and \(n\) is its limit.

2.2 Types of Numbers

By the adoption of special representations for different types of numbers the usefulness of a positional number system can be extended beyond the simple counting function.
2.2.1 Whole Numbers

The digits of a number system, called the positive integers or natural numbers, are an ordered set of symbols. The notion of an ordered set means that the numerical symbols are assigned a predetermined sequence. A positional system of numbers also requires the special digit zero which, by itself, represents the absence of oneness, or nothing, and thus is not included in the set of natural numbers. However, 0 assumes a cardinal function when it is combined with other digits, for instance, 10 or 30. The whole numbers are the set of natural numbers, including the number zero.

2.2.2 Signed Numbers

A number system can also encode direction. We generally use the + and - signs to represent opposite numerical directions. The typical illustration for a set of signed numbers is as follows:

-9 -8 -7 -6 -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5 +6 +7 +8 +9

negative numbers <- zero -> positive numbers

The number zero, which separates the positive and the negative numbers, has no sign of its own, although in some binary encodings we can end up with a negative and a positive zero.

2.2.3 Rational, Irrational, and Imaginary Numbers

A number system also represents parts of a whole. For example, when a carpenter cuts one board into two boards of equal length we can represent the result with the fraction 1/2; the fraction 1/2 represents one of the two parts which make up the object. Rational numbers are those expressed as a ratio of two integers, for example, 1/2, 2/3, 5/248. Note that this use of the word rational is related to the mathematical concept of a ratio, and not to reason.

The denominator of a rational number expresses the number of potential parts. In this sense 2/5 indicates two of five possible parts. There is no reason why the number 1 cannot be used to indicate the number of potential parts, for example 2/1, 128/1. In this case the ratio x/1 indicates x elements of an undivided part. Therefore, it follows that x/1 = x. The implication is that the set of rational numbers includes the integers, since an integer can be expressed as a ratio by using a unit denominator.

But not all non-integer numbers can be written as an exact ratio of two integers. The discovery of the first irrational number is usually associated with the investigation of a right triangle by the Greek mathematician Pythagoras (approximately 600 BC). The Pythagorean Theorem states that in any right triangle the square of the longest side (hypotenuse) is equal to the sum of the squares of the other two sides.

\[
a = 1 \\
\text{c} \\
b = 1
\]
For this triangle, the Pythagorean theorem states that

\[ a^2 + b^2 = c^2 \]

\[ 2 = c^2 \]

\[ 2 = c \times c \]

\[ c = \sqrt{2} \]

Therefore, the length of the hypotenuse in a right triangle with unit sides is a number that, when multiplied by itself, gives 2. This number (approximately 1.414213562) cannot be expressed as the exact ratio of two integers. Other irrational numbers are the square roots of 3 and 5, as well as the mathematical constants \( \pi \) and \( e \).

The set of numbers that includes the natural numbers, the whole numbers, and the rational and irrational numbers is called the real numbers. Most common mathematical problems are solved using real numbers. However, during the investigation of squares and roots we notice that there can be no real number whose square is negative. Mathematicians of the 18th century extended the number system to include operations with roots of negative numbers. They did this by defining an imaginary unit as follows:

\[ i = \sqrt{-1} \]

The imaginary unit makes possible a new set of numbers, called complex numbers, that consist of a real part and an imaginary part. One of the uses of complex numbers is in finding the solution of a quadratic equation. Complex numbers are also useful in vector analysis, graphics, and in solving many engineering, scientific, and mathematical problems.

### 2.3 Radix Representations

The radix of a number system is the number of symbols in the set, including zero. Thus, the radix of the decimal system is 10, and the radix of the binary system is 2. Digital electronics is based on circuits that can be in one of two stable states. Therefore, a number system based on two symbols is better suited for work in digital electronics, since each state can be represented by a digit.

#### 2.3.1 Decimal versus Binary Numbers

The binary system of numbers uses two symbols, 1 and 0. It is the simplest possible set of symbols with which we can count and perform arithmetic. Most of the difficulties in learning and using the binary system arise from this simplicity. Figure 2.1 shows sixteen groups of four electronic cells each in all possible combinations of two states.
It is interesting to note that binary numbers match the physical state of each electronic cell. If we think of each cell as a miniature light bulb, then the binary number 1 can be used to represent the state of a charged cell (light ON) and the binary number 0 to represent the state of an uncharged cell (light OFF).

### 2.3.2 Hexadecimal and Octal

Binary numbers are convenient in digital electronics; however, one of their drawbacks is the number of symbols required to encode a large value. For example, the number 9134 is represented in four decimal digits. However, the binary equivalent 100011101110 requires fourteen digits. In addition, large binary numbers are difficult to remember.

One possible way of compensating for these limitations of binary numbers is to use individual symbols to represent groups of binary digits. For example, a group of three binary numbers allows eight possible combinations. In this case, we can use the decimal digits 0 to 7 to represent each possible combination of three binary digits. This grouping of three binary digits gives rise to the following table:

<table>
<thead>
<tr>
<th>Binary</th>
<th>Octal</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 0</td>
<td>0</td>
</tr>
<tr>
<td>0 0 1</td>
<td>1</td>
</tr>
<tr>
<td>0 1 0</td>
<td>2</td>
</tr>
<tr>
<td>0 1 1</td>
<td>3</td>
</tr>
<tr>
<td>1 0 0</td>
<td>4</td>
</tr>
<tr>
<td>1 0 1</td>
<td>5</td>
</tr>
<tr>
<td>1 1 0</td>
<td>6</td>
</tr>
<tr>
<td>1 1 1</td>
<td>7</td>
</tr>
</tbody>
</table>

**Figure 2-1 Electronic Cells and Binary Numbers**
The octal encoding serves as a shorthand representation for groups of 3-digit binary numbers.

Hexadecimal numbers (base 16) are used for representing values encoded in four binary digits. Since there are only ten decimal digits, the hexadecimal system borrows the first six letters of the alphabet (A, B, C, D, E, and F). The result is a set of sixteen symbols, as follows:

```
0 1 2 3 4 5 6 7 8 9 ABCDE
```

Most modern computers are designed with memory cells, registers, and data paths in multiples of four binary digits. Table 2.2 lists some common units of memory storage.

**Table 2.2**

<table>
<thead>
<tr>
<th>UNIT</th>
<th>BITS</th>
<th>HEX DIGITS</th>
<th>HEX RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nibble</td>
<td>4</td>
<td>1</td>
<td>0 to F</td>
</tr>
<tr>
<td>Byte</td>
<td>8</td>
<td>2</td>
<td>0 to FF</td>
</tr>
<tr>
<td>Word</td>
<td>16</td>
<td>4</td>
<td>0 to FFFF</td>
</tr>
<tr>
<td>Doubleword</td>
<td>32</td>
<td>8</td>
<td>0 to FFFFFFFF</td>
</tr>
</tbody>
</table>

In most digital-electronic devices memory addressing is organized in multiples of four binary digits. Here again, the hexadecimal number system provides a convenient way to represent addresses. Table 2.3 lists some common memory addressing units and their hexadecimal and decimal range.

**Table 2.3**

<table>
<thead>
<tr>
<th>UNIT</th>
<th>DATA PATH IN BITS</th>
<th>DECIMAL ADDRESS RANGE</th>
<th>HEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 paragraph</td>
<td>4</td>
<td>0 to 15</td>
<td>0-F</td>
</tr>
<tr>
<td>1 page</td>
<td>8</td>
<td>0 to 255</td>
<td>0-FF</td>
</tr>
<tr>
<td>1 kilobyte</td>
<td>16</td>
<td>0 to 65,535</td>
<td>0-FFFF</td>
</tr>
<tr>
<td>1 megabyte</td>
<td>20</td>
<td>0 to 1,048,575</td>
<td>0-FFFFF</td>
</tr>
<tr>
<td>4 gigabytes</td>
<td>32</td>
<td>0 to 4,294,967,295</td>
<td>0-FFFFFFFF</td>
</tr>
</tbody>
</table>

### 2.4 Number System Conversions

We use decimal numbers in our everyday life because they meaningfully represent common units used in the real world. To state that a certain historical event took place in the year 7C6 hexadecimal would convey little information to the average person. However, in computer systems based on two-state electronic cells binary representations are more convenient. Also note that hexadecimal and octal numbers are handy shorthand for representing groups of binary digits.

Numerical conversions between positional systems of different radices are based on the number of symbols in the respective sets and on the positional value (weight) of each column. But methods used for manual conversions are not always suitable for machine conversions, as we will see in the forthcoming sections.
2.4.1 Binary-to-ASCII-Decimal

To manually convert a binary number to its decimal equivalent we take into account the positional weight of each binary digit, as shown in Figure 2-2.

The positional weight table in Figure 2-2 lists the decimal value of each binary column. These weights are powers of the system’s base (2 in the binary system). In the digit value table, also in Figure 2-2, the decimal values of the binary columns holding a 1 digit are added. The sum of the weights of all the one-digits in the operand is the decimal equivalent of the binary number. In this case 10010101 binary = 149 decimal.

The method in Figure 2-2, although useful in manual conversions, is not an algorithm for computer conversions. Figure 2-3 is a flowchart of a low-level binary-to-decimal conversion routine.

Figure 2-2 Binary to ASCII Decimal Conversion Example

Figure 2-3 Flowchart for a Binary to ASCII Decimal Conversion
The algorithm for the processing in Figure 2-3 can be written as follows:

1. Set up and initialize a string storage area (sometimes called a buffer) to hold the ASCII decimal digits of the result. Set up the buffer pointer to the right-most digit position of the result.

2. Obtain the remainder of the value divided by 10.

3. Add 30H to remainder digit to convert to ASCII representation.

4. Store remainder digit in buffer and index the buffer pointer to the preceding digit.

5. Quotient of division by 10 becomes the new binary value.

6. End conversion routine if quotient is equal to 0. Otherwise, continue at step 2.

Note that the numerical digits are located from 30H to 39H in the ASCII table. This makes it easy to convert a binary digit to ASCII simply by adding 30H. Likewise, an ASCII digit is converted to binary by subtracting 30H.

2.4.2 Binary-to-Hexadecimal Conversion

The method described in Section 2.4.1 for a binary to ASCII decimal conversion can be adapted to other radices by representing the positional weight of each binary digit in the number system to which the conversion is to be made. In the case of a binary to ASCII hexadecimal conversion the positional weight of each binary digit is a hexadecimal value. Figure 2-4 shows the conversion of the binary value 10010101 into hexadecimal by using the corresponding positional weights.

![Figure 2-4](image)

The machine conversion binary to ASCII hexadecimal is similar to the binary to ASCII decimal algorithm described previously. In the case of the conversion into ASCII hexadecimal digits the buffer need only hold four ASCII characters, since a 16-bit binary cannot exceed the value FFFFH. In the case of binary to ASCII hex the divisor for obtaining the digits is 16 instead of 10.

2.4.3 Decimal-to-Binary Conversion

Longhand conversion of decimal into binary can be performed by using the positional weights to find the binary 1-digits and then subtracting this positional weight from the decimal value. The process is shown in Figure 2-5.
In the example of Figure 2-5 we start with the decimal value 149. Since the highest power of 2 smaller than 149 is 128, which corresponds to bit 7, we set bit 7 in the result and perform the subtraction:

\[ 149 - 128 = 21 \]

At this point the highest positional weight smaller than 21 is 16, which corresponds to bit 4. Therefore we set bit 4, and perform the subtraction:

\[ 21 - 16 = 5 \]

The remaining steps in the conversion can be seen in the illustration. The conversion is finished when the result of the subtraction is 0.

Suppose there is a numerical value in the form of a string of ASCII decimal, octal, or hexadecimal digits. In order for a processor to perform simple arithmetic operations on such data, the data must first be converted to binary. The binary value is then loaded into machine registers or memory cells. However, methods suited for manual conversion do not always make a good computer algorithm. Figure 2.6 shows two decimal-to-binary conversion algorithms that are suited for machine coding.

Using the first method of Figure 2-6, the individual decimal digits are multiplied by their corresponding positional values. The final result is obtained by adding all the partial products. Although this method is frequently used, it has the disadvantage that a different multiplier is used during each iteration (1, 10, 100, 1000). The second method in Figure 2-6 starts with the high-order ASCII-decimal digit. The calculations consist of multiplying an accumulated value by 10. Initially, this accumulated value is set to 0. After multiplication by 10, the value of the digit is added to the accumulated value. The following algorithm is based on the second method in Figure 2-6.
Figure 2-6 Machine Conversion of ASCII Decimal to Binary

1. Set up and initialize to binary zero a storage location for holding the value accumulated during conversion. Set up a pointer to the highest order ASCII digit in the source string.
2. Test the ASCII digit for a value in the range 0 to 9. End of routine if the ASCII digit is not in this range.
3. Subtract 30H from ASCII decimal digit.
5. Add digit to accumulated value.
6. Increment the pointer to the next digit and continue at step 2.

Figure 2-7 is a flowchart of the conversion algorithm.

Figure 2-7 Flowchart for ASCII to Machine Register Conversion
Chapter 3

Data Types and Data Storage

In this chapter we review the various encodings and formats used for representing character and numeric data in digital systems. The character formats are used for encoding the letters, symbols, and control codes of the various alphabets. The numeric formats allow representing binary numbers as signed and unsigned integers in several forms, binary floating-point numbers, and decimal floating-point numbers, usually called binary-coded decimals or BCD.

3.0  Electronic-Digital Machines

The mechanization of arithmetic is often traced back to the abacus, slide rule, mechanical calculators, and punch card machines. The work of John von Neumann at Princeton’s Institute for Advanced Study and Research marks the first highlight in the design and construction of a digital-electronic calculating machine. In von Neumann’s design, data and instructions are stored in a common memory area. An alternative approach, known as Harvard architecture, was discarded at first but has recently been re-validated and is in use in several microcontroller families.

The calculating power of the first computer was approximately 2000 operations per second, while previous electro-mechanical devices were capable of performing only 3 or 4 operations. Today’s digital machines can execute more than 1 billion instructions per second. Technological advances and miniaturization techniques have reduced the cost and size of computing machinery.

3.1  Character Representations

Over the years, data representation issues have often been determined by the various conventions used by the different hardware manufacturer. Machines have had different word lengths and different character sets and have used various schemes for storing character and data. Fortunately, in microprocessor and microcontroller design, the encoding of character data has not been subject to major disagreements.

Historically, the methods used to represent characters have varied widely, but the basic approach has always been to choose a fixed number of bits and then map the
various bit combinations to the various characters. Clearly, the number of bits of the storage format limits the total number of distinct characters that can be represented. In this manner, the 6-bit codes used on a number of earlier computing machines allow representing 64 characters. This range allows including the uppercase letters, the decimal digits, some special characters, but not the lowercase letters. Computer manufacturers that used the 6-bit format often argued that their customers had no need for lower-case letters. Nowadays 7- and 8-bit codes that allow representing the lower-case letters have been adopted almost universally.

Most of the world (except IBM) has standardized character representations by using the ISO (International Standards Organization) code. ISO exists in several national variants; the one used in the United States is called ASCII, which stands for American Standard Code for Information Interchange. All microcomputers and microcontrollers use ASCII as the code for character representation.

3.1.1 ASCII

ASCII is a character encoding based on the English alphabet. ASCII was first published as a standard in 1967 and was last updated in 1986. The first 33 codes, referred to as non-printing codes, are mostly obsolete control characters. The remaining 95 printable characters (starting with the space character) include the common characters found in a standard keyboard, the decimal digits, and the upper- and lower-case characters of the English alphabet. Table 3.1 lists the ASCII characters in decimal, hexadecimal, and binary.

Table 3.1

<table>
<thead>
<tr>
<th>DECIMAL</th>
<th>HEX</th>
<th>BINARY</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>00</td>
<td>0000000</td>
<td>annual (Null character)</td>
</tr>
<tr>
<td>001</td>
<td>00</td>
<td>0000001</td>
<td>SOH (Start of Header)</td>
</tr>
<tr>
<td>002</td>
<td>00</td>
<td>0000010</td>
<td>STX (Start of Text)</td>
</tr>
<tr>
<td>003</td>
<td>00</td>
<td>0000011</td>
<td>ETX (End of Text)</td>
</tr>
<tr>
<td>004</td>
<td>00</td>
<td>0000100</td>
<td>EOT (End of Transmission)</td>
</tr>
<tr>
<td>005</td>
<td>00</td>
<td>0000101</td>
<td>ENQ (Enquiry)</td>
</tr>
<tr>
<td>006</td>
<td>00</td>
<td>0000110</td>
<td>ACK (Acknowledgment)</td>
</tr>
<tr>
<td>007</td>
<td>00</td>
<td>0000111</td>
<td>BEL (Bell)</td>
</tr>
<tr>
<td>008</td>
<td>00</td>
<td>0001000</td>
<td>BS (Backspace)</td>
</tr>
<tr>
<td>009</td>
<td>00</td>
<td>0001001</td>
<td>HT (Horizontal Tab)</td>
</tr>
<tr>
<td>010</td>
<td>00</td>
<td>0001010</td>
<td>LF (Line Feed)</td>
</tr>
<tr>
<td>011</td>
<td>00</td>
<td>0001011</td>
<td>VT (Vertical Tab)</td>
</tr>
<tr>
<td>012</td>
<td>00</td>
<td>0001100</td>
<td>FF (Form Feed)</td>
</tr>
<tr>
<td>013</td>
<td>00</td>
<td>0001101</td>
<td>CR (Carriage Return)</td>
</tr>
<tr>
<td>014</td>
<td>00</td>
<td>0001110</td>
<td>SO (Shift Out)</td>
</tr>
<tr>
<td>015</td>
<td>00</td>
<td>0001111</td>
<td>SI (Shift In)</td>
</tr>
<tr>
<td>016</td>
<td>00</td>
<td>0010000</td>
<td>DLE (Data Link Escape)</td>
</tr>
<tr>
<td>017</td>
<td>00</td>
<td>0010001</td>
<td>DC1 (XON)(Device Control 1)</td>
</tr>
<tr>
<td>018</td>
<td>00</td>
<td>0010010</td>
<td>DC2 (Device Control 2)</td>
</tr>
<tr>
<td>019</td>
<td>00</td>
<td>0010011</td>
<td>DC3 (XOFF)(Device Control 3)</td>
</tr>
<tr>
<td>020</td>
<td>00</td>
<td>0010100</td>
<td>DC4 (Device Control 4)</td>
</tr>
<tr>
<td>021</td>
<td>00</td>
<td>0010101</td>
<td>NAK (- Acknowledge)</td>
</tr>
<tr>
<td>022</td>
<td>00</td>
<td>0010110</td>
<td>SYN (Synchronous Idle)</td>
</tr>
</tbody>
</table>

(continues)
### Table 3.1

**ASCII Character Representation (continued)**

<table>
<thead>
<tr>
<th>DECIMAL</th>
<th>HEX</th>
<th>BINARY</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>000</td>
<td>00000000</td>
<td>annual (Null character)</td>
</tr>
<tr>
<td>023</td>
<td>017</td>
<td>00010111</td>
<td>ETB (End of Trans. Block)</td>
</tr>
<tr>
<td>024</td>
<td>018</td>
<td>00011000</td>
<td>CAN (Cancel)</td>
</tr>
<tr>
<td>025</td>
<td>019</td>
<td>00011001</td>
<td>EM (End of Medium)</td>
</tr>
<tr>
<td>026</td>
<td>01A</td>
<td>00011010</td>
<td>SUB (Substitute)</td>
</tr>
<tr>
<td>027</td>
<td>01B</td>
<td>00011101</td>
<td>ESC (Escape)</td>
</tr>
<tr>
<td>028</td>
<td>01C</td>
<td>00011100</td>
<td>FS (File Separator)</td>
</tr>
<tr>
<td>029</td>
<td>01D</td>
<td>00011101</td>
<td>GS (Group Separator)</td>
</tr>
<tr>
<td>030</td>
<td>01E</td>
<td>00011110</td>
<td>RS (Request to Send)</td>
</tr>
<tr>
<td>031</td>
<td>01F</td>
<td>00011111</td>
<td>US (Unit Separator)</td>
</tr>
<tr>
<td>032</td>
<td>020</td>
<td>00100000</td>
<td>SP (Space)</td>
</tr>
<tr>
<td>033</td>
<td>021</td>
<td>00100001</td>
<td>! (exclamation mark)</td>
</tr>
<tr>
<td>034</td>
<td>022</td>
<td>00100010</td>
<td>&quot; (double quote)</td>
</tr>
<tr>
<td>035</td>
<td>023</td>
<td>00100011</td>
<td># (number sign)</td>
</tr>
<tr>
<td>036</td>
<td>024</td>
<td>00100100</td>
<td>$ (dollar sign)</td>
</tr>
<tr>
<td>037</td>
<td>025</td>
<td>00100101</td>
<td>% (percent)</td>
</tr>
<tr>
<td>038</td>
<td>026</td>
<td>00100110</td>
<td>&amp; (ampersand)</td>
</tr>
<tr>
<td>039</td>
<td>027</td>
<td>00100111</td>
<td>' (single quote)</td>
</tr>
<tr>
<td>040</td>
<td>028</td>
<td>00101000</td>
<td>( (left/opening parenthesis)</td>
</tr>
<tr>
<td>041</td>
<td>029</td>
<td>00101001</td>
<td>) (right/closing parenthesis)</td>
</tr>
<tr>
<td>042</td>
<td>02A</td>
<td>00101010</td>
<td>* (asterisk)</td>
</tr>
<tr>
<td>043</td>
<td>02B</td>
<td>00101011</td>
<td>+ (plus)</td>
</tr>
<tr>
<td>044</td>
<td>02C</td>
<td>00101100</td>
<td>, (comma)</td>
</tr>
<tr>
<td>045</td>
<td>02D</td>
<td>00101101</td>
<td>- (minus or dash)</td>
</tr>
<tr>
<td>046</td>
<td>02E</td>
<td>00101110</td>
<td>. (dot)</td>
</tr>
<tr>
<td>047</td>
<td>02F</td>
<td>00101111</td>
<td>/ (forward slash)</td>
</tr>
<tr>
<td>048</td>
<td>030</td>
<td>00110000</td>
<td>0 (decimal digits ...)</td>
</tr>
<tr>
<td>049</td>
<td>031</td>
<td>00110001</td>
<td>1</td>
</tr>
<tr>
<td>050</td>
<td>032</td>
<td>00110010</td>
<td>2</td>
</tr>
<tr>
<td>051</td>
<td>033</td>
<td>00110011</td>
<td>3</td>
</tr>
<tr>
<td>052</td>
<td>034</td>
<td>00110100</td>
<td>4</td>
</tr>
<tr>
<td>053</td>
<td>035</td>
<td>00110101</td>
<td>5</td>
</tr>
<tr>
<td>054</td>
<td>036</td>
<td>00110110</td>
<td>6</td>
</tr>
<tr>
<td>055</td>
<td>037</td>
<td>00110111</td>
<td>7</td>
</tr>
<tr>
<td>056</td>
<td>038</td>
<td>00111000</td>
<td>8</td>
</tr>
<tr>
<td>057</td>
<td>039</td>
<td>00111001</td>
<td>9</td>
</tr>
<tr>
<td>058</td>
<td>03A</td>
<td>00111010</td>
<td>: (colon)</td>
</tr>
<tr>
<td>059</td>
<td>03B</td>
<td>00111011</td>
<td>; (semi-colon)</td>
</tr>
<tr>
<td>060</td>
<td>03C</td>
<td>00111100</td>
<td>&lt; (less than)</td>
</tr>
<tr>
<td>061</td>
<td>03D</td>
<td>00111101</td>
<td>= (equal sign)</td>
</tr>
<tr>
<td>062</td>
<td>03E</td>
<td>00111110</td>
<td>&gt; (greater than)</td>
</tr>
<tr>
<td>063</td>
<td>03F</td>
<td>00111111</td>
<td>? (question mark)</td>
</tr>
<tr>
<td>064</td>
<td>040</td>
<td>01000000</td>
<td>@ (AT symbol)</td>
</tr>
<tr>
<td>065</td>
<td>041</td>
<td>01000001</td>
<td>A</td>
</tr>
<tr>
<td>066</td>
<td>042</td>
<td>01000010</td>
<td>B</td>
</tr>
<tr>
<td>067</td>
<td>043</td>
<td>01000011</td>
<td>C</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>090</td>
<td>05A</td>
<td>01011010</td>
<td>Z</td>
</tr>
<tr>
<td>091</td>
<td>05B</td>
<td>01011011</td>
<td>[ (left/opening bracket)</td>
</tr>
<tr>
<td>092</td>
<td>05C</td>
<td>01011100</td>
<td>\ (back slash)</td>
</tr>
<tr>
<td>093</td>
<td>05D</td>
<td>01011101</td>
<td>] (right/closing bracket)</td>
</tr>
</tbody>
</table>
Table 3.1
ASCII Character Representation (continued)

<table>
<thead>
<tr>
<th>DECIMAL</th>
<th>HEX</th>
<th>BINARY</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>094</td>
<td>05E</td>
<td>01011110</td>
<td>^</td>
</tr>
<tr>
<td>095</td>
<td>05F</td>
<td>01011111</td>
<td>_</td>
</tr>
<tr>
<td>096</td>
<td>060</td>
<td>01100000</td>
<td>a</td>
</tr>
<tr>
<td>097</td>
<td>061</td>
<td>01100001</td>
<td>b</td>
</tr>
<tr>
<td>098</td>
<td>062</td>
<td>01100010</td>
<td>c</td>
</tr>
<tr>
<td>122</td>
<td>07A</td>
<td>01111010</td>
<td>z</td>
</tr>
<tr>
<td>123</td>
<td>07B</td>
<td>01111101</td>
<td>{</td>
</tr>
<tr>
<td>124</td>
<td>07C</td>
<td>01111100</td>
<td>[</td>
</tr>
<tr>
<td>125</td>
<td>07D</td>
<td>01111101</td>
<td>}</td>
</tr>
<tr>
<td>126</td>
<td>07E</td>
<td>01111110</td>
<td>~</td>
</tr>
<tr>
<td>127</td>
<td>07F</td>
<td>01111111</td>
<td>DEL</td>
</tr>
</tbody>
</table>

3.1.2 EBCDIC and IBM

In spite of ASCII's general acceptance, IBM continues to use EBCDIC (Extended Binary Coded Decimal Interchange Code) for character encoding. IBM mainframes and midrange systems such as the AS/400 use a wholly incompatible character set primarily designed for punched cards.

EBCDIC uses the full eight bits available to it, so there is no place left to implement parity checking. On the other hand, EBCDIC has a wider range of control characters than ASCII.

EBCDIC character encoding is based on Binary Coded Decimal (BCD), which we discuss later in this chapter. There are four main blocks in the EBCDIC code page:

1. The range 0000 0000 to 0011 1111 is reserved for control characters.
2. The range 0100 0000 to 0111 1111 is for punctuation.
3. The range 1000 0000 to 1011 1111 is for lowercase characters.
4. The range 1100 0000 to 1111 1111 is for uppercase characters and numbers.

Actually, microprocessor and microcontroller design need not address how character data is encoded. Usually a set of instructions allows manipulating 8-bit quantities, but the processor need not be concerned with what the encodings represent. On the other hand, some mainframe processors do have instructions that manipulate character codes. For example, the EDIT instruction on the IBM 370 implements the kind of picture conversion that appears in COBOL programs.

3.1.3 Unicode

One of the limitations of the ASCII code is that eight bits are not enough for representing character sets in languages such as Japanese or Chinese which use large character sets. This has led to the development of encodings which allow representing large character sets. Unicode has been proposed as a universal character encoding standard that can be used for representation of text for computer processing.
Unicode attempts to provide a consistent way of encoding multilingual text and thus make it possible to exchange text files internationally. The design of Unicode is based on the ASCII code, but goes beyond the Latin alphabet to which ASCII is limited. The Unicode Standard provides the capacity to encode all of the characters used for the written languages of the world. Like ASCII, Unicode assigns each character a unique numeric value and name. Unicode uses three encoding forms that use a common repertoire of characters. These forms allow encoding as many as a million characters.

The three encoding forms of the Unicode Standard allow the same data to be transmitted in a byte, word, or double word format, that is, in 8-, 16- or 32-bits per character.

- **UTF-8** is a way of transforming all Unicode characters into a variable length encoding of bytes. In this format the Unicode characters corresponding to the familiar ASCII set have the same byte values as ASCII. By the same token, Unicode characters transformed into UTF-8 can be used with existing software.
- **UTF-16** is designed to balance efficient access to characters with economical use of storage. It is reasonably compact and all the heavily used characters fit into a single 16-bit code unit, while all other characters are accessible via pairs of 16-bit code units.
- **UTF-32** is used where memory space is no concern, but fixed width, single code unit access to characters is desired. In UTF-32 each Unicode character is represented by a single 32-bit code.

### 3.2 Storage and Encoding of Integers

The Indian mathematician Pingala first described binary numbers in the fifth century B.C. The modern system of binary numbers first appears in the work of Gottfried Leibniz during the seventeenth century. During the mid-nineteenth century the British logician George Boole described a logical system which used binary numbers to represent logical true and false. In 1937, Claude Shannon published his master's thesis that used Boolean algebra and binary arithmetic to implement electronic relays and switches. The thesis paper entitled *A Symbolic Analysis of Relay and Switching Circuits* is usually considered to be the origin of modern digital circuit design.

Also in 1937, George Stibitz completed a relay-based computer which could perform binary addition. The Bell Labs *Complex Number Computer*, also designed by Stibitz, was completed in January 1940. The system was demonstrated to the *American Mathematical Society* in September 1940. The attendants included John Von Neumann, John Mauchly, and Norbert Wiener. In 1945, von Neumann wrote a seminal paper in which he stated that binary numbers were the ideal computational format.

### 3.2.1 Signed and Unsigned Representations

For unsigned integers there is little doubt that the binary representation is ideal. Successive bits indicate powers of 2, with the most significant bit at the left and the least significant one on the right, as is customary in decimal representations. Figure 3-1 shows the digit weights and the conventional bit numbering in the binary encoding.
In order to perform arithmetic operations, the digital machine must be capable of storing and retrieving numerical data. Numerical data is stored in standard formats, designed to minimize space and optimize processing. Historically, numeric data was stored in data structures devised to fit the characteristics of a specific machine, or the preferences of its designers. It was in 1985 that the Institute of Electrical and Electronics Engineers (IEEE) and the American National Standards Institute (ANSI) formally approved mathematical standards for encoding and storing numerical data in digital devices.

The electronic and physical mechanisms used for storing data have evolved with technology. One common feature of many devices, from punched tape to integrated circuits, is that the encoding is represented in two possible states. In paper tape the two states are holes or no holes, while in electronic media they are usually the presence or absence of an electrical charge.

Data stored in processor registers, in magnetic media, in optical devices, or in punched tape is usually encoded in binary. Thus, the programmer and the operator can usually ignore the physical characteristics of the storage medium. In other words, the bit pattern 10010011 can be encoded as holes in a strip of paper tape, as magnetic charges on a mylar-coated disk, as positive voltages in an integrated circuit memory cell, or as minute craters on the surface of the CD. In all cases 10010011 represents the decimal number 147.

### 3.2.2 Word Size

In electronic digital devices the bistable states are represented by a *binary digit*, or *bit*. Circuit designers group several individual cells to form a unit of storage that holds
several bits. In a particular machine the basic unit of data storage is called the word size. Word size in computers often ranges from 8 to 128 bits, in powers of 2. Microcontrollers and other digital devices sometimes use word-sizes that are determined by their specific architectures. For example, some PIC microcontrollers use a 14-bit word size.

In most digital machines the smallest unit of storage individually addressable is eight bits (one *byte*). Individual bits are not directly addressable and must be manipulated as part of larger units of data storage.

### 3.2.3 Byte Ordering

The storage of a single-byte integer can be done according to the scheme in Figure 3-1. However, the maximum value that can be represented in eight bits is the decimal number 255. To represent larger binary integers requires additional storage area. Since memory is usually organized in byte-size units, any decimal number larger than 255 requires more than one byte of storage. In this case the encoding is padded with the necessary leading zeros. Figure 3-2 is a representation of the decimal number 21,141 stored in two consecutive data bytes.

```
<table>
<thead>
<tr>
<th>Machine Storage</th>
<th>Binary</th>
<th>Decimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>0101 0010 1001 0101</td>
<td>= 01010010 10010101</td>
<td>= 21,141</td>
</tr>
</tbody>
</table>
```

**Figure 3-2** Representation of an Unsigned Integer

One issue related to using multiple memory bytes to encode binary integers is the successive layout of the various byte-size units. In other words, does the representation store the most significant byte at the lowest numbered memory location, or vice versa? For example, when a 32-bit binary integer is stored in a 32-bit storage area we can follow the conventional pattern of placing the low-order bit on the right-hand side and the high-order bit on the left, as we did in Figure 3-1. However, if the 32-bit number is to be stored into four byte-size memory cells, then two possible storage schemes are possible, as shown in Figure 3-3.

**Figure 3-3** Byte Ordering Schemes
In the low-to-low storage scheme the low-order 8-bits of the operand are stored in the low-order memory byte, the next group of 8-bits are moved to the following memory byte in low-to-high order, and so on. Conceivably, this scheme can be described by saying that the “little end” of the operand is stored first, that is, in lowest memory. According to this notion, the storage scheme is described as the \textit{little-endian} format. If the “big-end” of the operand, that is, the highest valued bits, is stored in the low memory addresses then the byte ordering is said to be in \textit{big-endian} format. Some Intel processors (like those of 80x86 family) follow the little-endian format. Some Motorola processors (like those of the 68030 family) follow the big-endian format, while others (such as the MIPS 2000) can be configured to store data in either format.

In many situations the programmer needs to be aware of the byte-ordering scheme; for example, to retrieve memory data into processor registers so as to perform multi-byte arithmetic, or to convert data stored in one format to the other one. This last operation is a simple byte-swap. For example, if the hex value 01020304 is stored in four consecutive memory cells in low-to-high order (little-endian format) it appears in memory (low-to-high) as the values 04030201. Converting this data to the big-endian format consists of swapping the individual bytes so that they are stored in the order 01010304. Figure 3-4 is a diagram of a byte swap operation.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{byte_swap_diagram.png}
\caption{Data Format Conversion by Byte Swapping}
\end{figure}

### 3.2.4 Sign-Magnitude Representation

Representing signed numbers requires differentiating between positive and negative magnitudes. One possible scheme is to devote one bit to represent the sign. Typically the high-order bit is set (1) to denote negatives and reset (0) to denote positives. Using this convention the decimal numbers 93 and -93 are represented as follows:

\begin{verbatim}
01011101 binary = 93 decimal
11011101 binary = -93 decimal
\end{verbatim}

This way of designating negative numbers, called a \textit{sign-magnitude} representation, corresponds to the conventional way in which we write negative and positive numbers longhand, that is, we precede the number by its sign. Sign-magnitude representation has the following characteristics:
1. The absolute value of positive and negative numbers is the same.

2. Positive numbers can be distinguished from negative numbers by examining the high-order bit.

3. There are two possible representations for zero, one negative (10000000B) and one positive (00000000B).

But a major limitation of sign-magnitude representation is that the processing required to perform addition is different from that for subtraction. Complicated rules are required for the addition of signed numbers. For example, considering two operands labeled \(x\) and \(y\), the following rules must be observed for performing signed addition:

1. If \(x\) and \(y\) have the same sign, they are added directly and the result is given the common sign.
2. If \(x\) is larger than \(y\), then \(y\) is subtracted from \(x\) and the result is given the sign of \(x\).
3. If \(y\) is larger than \(x\) then \(x\) is subtracted from \(y\) and the result is given the sign of \(y\).
4. If either \(x\) or \(y\) is 0 or \(-0\) the result is the non-zero element.
5. If both \(x\) and \(y\) are \(-0\), then the sum is 0.

However, there are other numeric representations that avoid this situation. A consequence of sign-magnitude representation is that, in some cases, it is necessary to take into account the magnitude of the operands in order to determine the sign of the result. Also, the presence of an encoding for negative zero reduces the numerical range of the representation and is, for most practical uses, an unnecessary complication. An important limitation of using the high-order bit for representing the sign is the resulting halving of the numerical range.

### 3.2.5 Radix Complement Representation

The radix complement of a number is defined as the difference between the number and the next integer power of the base that is larger than the number. In decimal numbers the radix complement is called the ten's complement. In the binary system the radix complement is called the two's complement. For example, the radix complement of the decimal number 89 (ten's complement) is calculated as follows:

\[
\begin{align*}
100 & \quad \text{higher power of 10} \\
- & \quad 89 \\
\hline
11 & \quad \text{ten's complement of 89}
\end{align*}
\]

The use of radix complements to simplify machine subtraction operations can best be seen in an example. The operation \(x = a - b\) with the following values:

\[
\begin{align*}
a & = 602 \\
b & = 353
\end{align*}
\]

\[
\begin{align*}
602 & \\
-353 & \\
\hline
x & = 249
\end{align*}
\]
Note that in the process of performing longhand subtraction we had to perform two borrow operations. Now consider that the radix complement (ten's complement) of 353 is:

\[
1000 - 353 = 647
\]

Using complements we can reformulate subtraction as the addition of the ten's complement of the subtrahend, as follows:

\[
\begin{array}{c}
602 \\
+ 647 \\
\hline
1249 \\
\end{array}
\]

| discarded digit

The result is adjusted by discarding the digit that overflows the number of digits in the operands.

In performing longhand decimal arithmetic there is little advantage in replacing subtraction with ten's complement addition. The work of calculating the ten's complement cancels out any other possible benefit. However, in binary arithmetic the use of radix complements entails significant computational advantages because binary machines can calculate complements efficiently.

The two's complement of a binary number is obtained in the same manner as the ten's complement of a decimal number, that is, by subtracting the number from an integer power of the base that is larger than the number. For example, the two's complement of the binary number 101 is:

\[
\begin{array}{c}
1000B = 2^3 = 8 \text{ decimal (higher power of 2)} \\
- 101B = 5 \text{ decimal} \\
\hline
011B = 3 \text{ decimal}
\end{array}
\]

While the two's complement of 10110B is calculated as follows:

\[
\begin{array}{c}
100000B = 2^5 = 32 \text{ decimal (higher power of 2)} \\
- 10110B = 22 \text{ decimal} \\
\hline
01010B = 10 \text{ decimal}
\end{array}
\]

You can perform the binary subtraction of 11111B (31 decimal) minus 10110B (22 decimal) by finding the two's complement of the subtrahend, adding the two operands, and discarding any overflow digit, as follows:

\[
\begin{array}{c}
11111B = 31 \text{ decimal} \\
+ 01010B = 10 \text{ decimal (two’s complement of 22)} \\
\hline
101001B \\
\text{discard} \\
01001B = 9 \text{ decimal (31 minus 22 = 9)}
\end{array}
\]

In addition to the radix complement representation, there is a diminished radix representation that is often useful. This encoding, sometimes called the *radix-minus-one form*, is created by subtracting 1 from an integer power of the base that is larger than the number, then subtracting the operand from this value. In the decimal
system the diminished radix representation is sometimes called the *nine's complement*. This is due to the fact that an integer power of ten, minus one, results in one or more 9-digits. In the binary system the diminished radix representation is called the one's complement. The nine's complement of the decimal number 76 is calculated as follows:

\[
\begin{align*}
100 & \quad \text{next highest integer power of 10} \\
99 & \quad 100 \text{ minus 1} \\
-76 & \\
------ & \\
23 & \quad \text{nine’s complement of 89}
\end{align*}
\]

The one’s complement of a binary number is obtained by subtracting the number from an integer power of the base that is larger than the number, minus one. For example, the one’s complement of the binary number 101 (5 decimal) can be calculated as follows:

\[
\begin{align*}
1000B & \quad 2^3 = 8 \text{ decimal} \\
111B & \quad 1000B \text{ minus 1} = 7 \text{ decimal} \\
-101B & \quad 5 \text{ decimal} \\
------ & \\
010B & \quad 2 \text{ decimal}
\end{align*}
\]

An interesting feature of one’s complement is that it can be obtained changing every 1 binary digit to a 0 and every 0 binary digit to a 1. In this example 010B is the one’s complement of 101B. In this context the 0 binary digit is often said to be the complement of the 1 binary digit, and vice versa. Most modern computers contain an instruction that inverts all the digits of a value by changing all 1 digits into 0, and all 0 digits into 1. The operation is also known as *logical negation*.

Furthermore, the two’s complement can be obtained by adding 1 to the one’s complement of a number. Therefore, instead of calculating

\[
\begin{align*}
100000B & \\
-10110B & \\
------ & \\
01010B & \quad \text{two’s complement}
\end{align*}
\]

we can find the two’s complement of 10110B as follows:

\[
\begin{align*}
10110B & \quad \text{number} \\
01001B & \quad \text{change 0 to 1 and 1 to 0 (one’s complement)} \\
+1B & \quad \text{then add 1} \\
------ & \\
01010B & \quad \text{two’s complement}
\end{align*}
\]

This algorithm provides a convenient way of calculating the two’s complement in a machine equipped with a complement instruction. Finally, the two’s complement can be obtained by subtracting the operand from zero and discarding the overflow.

The radix complement of a number is the difference between the number and an integer power of the base that is larger than the number. Following this rule, we calculate the radix complement of the binary number 10110 as follows:

\[
\begin{align*}
100000B & \quad 2^5 = 32 \text{ decimal} \\
-10110B & \quad 22 \text{ decimal} \\
------ & \\
01010B & \quad 10 \text{ decimal}
\end{align*}
\]
However, the machine calculation of the two’s complement of the same value often produces a different result, for example:

\[
\begin{align*}
100000000B & \quad - 28 \quad 256 \text{ decimal} \\
- 00010110B & \quad - 22 \text{ decimal} \\
\hline
11101010B & \quad 234 \text{ decimal}
\end{align*}
\]

The difference is due to the fact that in the longhand method we have used the next higher integer power of the base compared to the value of the subtrahend (in this case 100000B) while the machine calculations use the next higher integer power of the base compared to the operand’s word size, which is normally either 8 or 16 bits. In this example the operand’s word size is eight bits and the next highest integer power of 2 is 100000000B. In either case, the results from two’s complement subtraction are valid as long as the minuend is an integer power of the base that is larger than the subtrahend.

For example, to perform the binary subtraction of 00011111B (31 decimal) minus 00010110B (22 decimal) we can find the two’s complement of the subtrahend and add, discarding any overflow digit, as follows:

\[
\begin{align*}
00011111B & \quad - 31 \text{ decimal} \\
+ 11101010B & \quad 234 \text{ decimal (two’s complement of 22)} \\
\hline
100001001B & \quad \text{discard (overflow)} \quad 00001001B \quad - 9 \text{ decimal (31 minus 22 = 9)}
\end{align*}
\]

In addition to the simplification of subtraction, two’s complement arithmetic has the advantage that there is no representation for negative 0. It can be argued that there are cases in which a negative zero notation could be useful, but in fact this is usually unnecessary. While both the two’s complement and the one’s complement schemes can be used to implement binary arithmetic, system designers usually prefer the two’s complement.

### 3.3 Encoding of Fractional Numbers

In any positional number system the weight of each integer digit is determined by the formula:

\[ P = d \times BC \]

where \( d \) is the digit, \( B \) is the base or radix, and \( C \) is the zero-based column number, starting from right to left. Therefore, the value of a multi-digit positive integer to \( n \) digits can be expressed as a sum of the digit values:

\[ d_nB^n + d_{n-1}B^{n-1} + d_{n-2}B^{n-2} + \ldots + d_0B^0 \]

where \( d \) is the value of the digit and \( B \) is the base or radix of the number system. This representation can be extended to represent fractional values. Recalling that we can
extend the sequence to the right of the radix point, as follows:

\[ x^{-n} = \frac{1}{x^n} \]

![Figure 3-5 Positional Weights in a Binary Fraction](image)

In the decimal system the value of each digit to the right of the decimal point is calculated as 1/10, 1/100, 1/1000, and so on. The value of each successive digit of a binary fraction is the reciprocal of a power of 2; therefore, the sequence is: 1/2, 1/4, 1/8, 1/16, ... Figure 3-5 shows the positional weight of the integer and fractional digits in a binary number.

In Chapter 2 we used the positional weights of the binary digits to convert a binary number to its decimal equivalent. A similar method can be used to convert the fractional part of a binary number. Using the decimal equivalents shown in Figure 3-5 we convert the binary fraction .10101 to a decimal fraction as follows

\[
\begin{align*}
.10101 & \quad = .65625 \\
.10101 & \quad \overset{.500}{=} .500 \\
.10101 & \quad \overset{.250}{=} .250 \\
.10101 & \quad \overset{.125}{=} .125 \\
.10101 & \quad \overset{.0625}{=} .0625 \\
.10101 & \quad \overset{.03125}{=} .03125 \\
.10101 & \quad \overset{.015625}{=} .015625 \\
.10101 & \quad \overset{.0078125}{=} .0078125 \\
.10101 & \quad \overset{.00390625}{=} .00390625 \\
\end{align*}
\]

**3.3.1 Fixed-Point Representations**

The encoding and storage of fractional numbers (also called real numbers) in binary form presents several difficulties. The first one is related to the representation of the *radix point*. Since there are only two symbols in the binary set, and both are used to represent the numerical value of the number, there is no other symbol available for the decimal point.
One possible solution is to predefine the digit field that represents the integer part and the one that represents the fractional part. For example, if a real number is to be encoded in two data bytes we can assign the high-order byte to encode the integer part and the low-order byte for the fractional part. In this case, the positive decimal number 58.125 could be encoded as shown in Figure 3-6.

In Figure 3-6 we assumed that the binary point is positioned between the eighth and the ninth digit of the encoding. Fixed-point representations assume that whatever distribution of digits is selected for the integer and the fractional part of the representation is maintained in all cases. This is the greatest limitation of the fixed-point formats.

Suppose we want to store the value 312.250. This number is represented in binary as follows:

\[
\begin{align*}
312 &= 100111000 \\
.250 &= .01
\end{align*}
\]

In this case, the total number of binary digits required for the binary encoding is 11. The number can be physically stored in a 16-digit structure (as the one in Figure 3-6) leaving five cells to spare. However, since the fixed-point format we have adopted assigns eight cells to the integer part of the number, 312.250 cannot be encoded because the integer part requires nine binary digits. In spite of this limitation, the fixed point format was the only one used in early computers.

### 3.3.2 Floating-Point Representations

An alternative to fixed-point is not to assume that the radix point has a fixed position in the encoding, but to allow it to float, hence the name floating-point. The idea of separately encoding the position of the radix point originated in scientific notation, where a number is written as a base greater than or equal to 1 and smaller than 10, multiplied by a power of 10. For example, the value 310.25 in scientific notation is written:

\[
3.1025 \times 10^2
\]

A number in scientific notation has a real part and an exponent part. Using the terminology of logarithms these two parts are sometimes called the mantissa and the characteristic. The following simplification of scientific notation is often used in computer work:

\[
3.1025 \ E2
\]
In the computer version of scientific notation the multiplication symbol and the base are implied. The letter $E$, which is used to signal the start of the exponent part of the representations, accounts for the name “exponential form.” Numbers smaller than 1 can be represented in scientific notation or in exponential form by using negative powers. For example, the number .0004256 can be written:

$$4.256 \times 10^{-4}$$

or as

$$4.256 \ E^{-4}$$

Floating-point representations provide a more efficient use of the machine’s storage space. For example, the numerical range of the fixed point encoding shown in Figure 3-6 is from 255.99609375 to 0.00390625. To improve this range we can re-assign the sixteen bits of storage so that four bits are used for encoding the exponent and twelve bits for the fractional part, called the significand. In this case the encoded number appears as follows:

```
0000 000000000000  +---+ +----------+
|__________ 12-bit fractional part     |
|___________________ 4-bit exponent part|
```

If we were to use the first bit of the exponent to indicate the sign of the exponent, then the range of the remaining three digits would be 0 to 7. Note that the sign of the exponent indicates the direction in which the decimal point is to be moved; this is unrelated to the sign of the number. In this example, the fractional part (or significand) could hold values in the range 1,048,575 to 1. The combined range of exponent and significand allows representing decimal numbers in the range 4095 to 0.00000001 that considerably exceeds the range in the same storage space in fixed-point format.

### 3.3.3 Standardized Floating-Point Representations

Both the significand and the exponent of a floating-point number can be stored as an integer, in sign-magnitude, or in radix complement form. The number of bits assigned to each field varies according to the range and the precision required. For example, the computers of the CDC 6000, 7000, and CYBER series used a 96-digit significand with an 11-digit exponent, while the PDP 11 series used 55-digit significands and 8-digit exponents in their extended precision formats.

Variations, incompatibilities, and inconsistencies in floating-point formats led to the development of a standard format. In March and July 1985, the Computer Society of the Institute of Electric and Electronic Engineers (IEEE) and the American National Standards Institute (ANSI) approved a standard for binary floating-point arithmetic (ANSI/IEEE Standard 754-1985). This standard establishes four formats for encoding binary floating-point numbers. Table 3.1 summarizes the characteristics of these formats.
Table 3.1

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SINGLE EXTENDED</th>
<th>DOUBLE EXTENDED</th>
</tr>
</thead>
<tbody>
<tr>
<td>total bits</td>
<td>32</td>
<td>64</td>
</tr>
<tr>
<td>significand bits</td>
<td>24</td>
<td>53</td>
</tr>
<tr>
<td>maximum exponent</td>
<td>+127</td>
<td>1023</td>
</tr>
<tr>
<td>minimum exponent</td>
<td>-126</td>
<td>-1022</td>
</tr>
<tr>
<td>exponent width</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>exponent bias</td>
<td>+127</td>
<td>+1023</td>
</tr>
</tbody>
</table>

3.3.4 IEEE 754 Single Format

Figure 3-7 shows the IEEE floating-point single format.

If a floating-point encoding is to allow the representation of signed numbers it must devote one binary digit to encode the number’s sign. In the IEEE 754 single format in Figure 3-7 the high-order bit represents the sign of the number. A value of 1 indicates a negative number.

The exponent of a binary floating-point number represents the integer power of the base with which the significand must be multiplied. The exponent can be stored in integer, sign magnitude, or radix complement representations. The IEEE 754 standard for floating-point arithmetic establishes that the exponent be stored in biased form, although the bias is not defined in all formats defined in the standard.

The word *bias*, in this context, means a constant that is added to the exponent in order to determine its final value. The term *excess-n notation* has also been used in this context. The constant is usually calculated to be approximately one-half the numerical range of the exponent field. For example, the IEEE single format devotes eight digits for the exponent field (see Figure 3-7). The numerical range of eight binary digits is 0 to 255 decimal and one-half of this range is approximately 127. Adding the constant 127 to all positive exponents places them in the range 127 to 255. The lower half of the range (1 to 126) is used for negative exponents. A 0-value in the exponent field is reserved to encode zero and *denormals*. Denormals are a special type of number discussed in the following paragraph. Table 3.2 shows the values of the exponent and the biased representation in the IEEE single format for floating-point numbers.
### Table 3.2
Interpretation of Exponent in the IEEE Single Format

<table>
<thead>
<tr>
<th>BIASED EXPONENT</th>
<th>SIGN OF NUMBER</th>
<th>TRUE EXPONENT</th>
<th>SIGNIFICAND</th>
<th>CLASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000 0000</td>
<td>+</td>
<td>-</td>
<td>00 ... 00</td>
<td>positive zero</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>00 ... 00</td>
<td>negative zero</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>11 ... 11</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>to</td>
<td>00 ... 01</td>
<td>denormals</td>
</tr>
<tr>
<td>0000 0001</td>
<td>-</td>
<td>-126</td>
<td>00 ... 00</td>
<td>normals</td>
</tr>
<tr>
<td>0111 1111</td>
<td>0</td>
<td>11 ... 11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000 0000</td>
<td>-</td>
<td>1</td>
<td>00 ... 00</td>
<td>normals</td>
</tr>
<tr>
<td></td>
<td></td>
<td>to</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1111 1110</td>
<td>+</td>
<td>127</td>
<td>11 ... 11</td>
<td></td>
</tr>
<tr>
<td>1111 1111</td>
<td>-</td>
<td>00 ... 00</td>
<td>+ infinity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>00 ... 00</td>
<td>- infinity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>10 ... 00</td>
<td>indefinite</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>00 ... 01</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>to</td>
<td>11 ... 11</td>
<td>not-a-number</td>
</tr>
</tbody>
</table>

Note in Table 3.2 that the exponent value 00000000B is used to represent zero and denormal numbers. Denormals, or denormalized numbers, occur when the exponent of the number is too small to represent in the corresponding floating-point format. On the other hand, the exponent 11111111B is used to encode numbers that are too large for the single format, or to represent error conditions. The exponent range 00000001B to 11111110B (decimal values 1 to 254) is used to represent normal numbers, that is, numbers that are within the range of the format.

In IEEE 754 floating-point formats the high bit of the exponent field does not encode the sign, as is the case in the sign-magnitude form. Instead, the bias 127 scheme, mentioned previously, is used to represent negative and positive exponents. Negative exponents are in the range 1 to 127 (see Table 3.2) and positive exponents are in the range 128 to 254. In contrast with fixed point conventions, the high bit of the exponent is set to indicate a positive exponent, and is zero to indicate negative exponent. The main advantage of a biased exponent is that the numbers can be compared bitwise, from left to right, to determine the larger one. The number’s true exponent is obtained by subtracting the bias.

The third field of the floating-point representation is known by several names: fractional part, mantissa, characteristic, and significand (see Figure 3-7). The word significand is the one most commonly used in the literature. Like the exponent, the significand can be stored as an integer, or in sign-magnitude or radix complement representations.

A floating-point binary number is said to be in normalized form when the first digit of its significand is 1. An un-normalized binary floating-point number can be normalized by successively shifting the digits of the significand to the left, while simultaneously subtracting one from the exponent. This process is continued until the
The high-order bit of the significand is a binary 1. The process does not change the value of the number, since shifting the significand bits to the left effectively multiplies the number by 2, while subtracting one from the exponent divides the number by 2. Clearly, the value of a number does not change if it is multiplied and divided by the same value. Also, note that normalization applies to the entire encoded number since it requires adjustments of both the exponent and the significand. Therefore, it is not correct to speak of a normalized significand or a normalized mantissa; we should refer to the significand of a normalized floating-point number.

One advantage of the normalized form is that the significand contains a maximum number of significant bits. However, addition and subtraction of floating-point numbers require that both operands have the same exponent. Therefore, before performing these operations it is often necessary to shift the significand digits to the right or to the left so that the exponents are equal.

The IEEE standard takes advantage of the fact that a normalized significand of a binary floating-point starts with a 1-digit. In the single- and double-precision formats this leading bit of the significand is assumed, in effect doubling the range of the representation. Not so in the extended formats, in which the digit must be explicitly coded. Note that this assumption is not valid if the exponent is all zeros. A zero exponent and a non-zero significand indicate a denormal, as shown in Table 3.2. Also, the use of an implicit bit makes necessary a special representation for zero (see Table 3.2). This special zero must be handled separately during arithmetic operations.

3.3.5 Encoding and Decoding Floating-Point Numbers

The formats in the IEEE 754 standard for binary floating-point arithmetic were designed to provide maximum storage capacity and processing efficiency. For example, the exponent in the IEEE single format, stored in biased form, takes up eight bits; however, these eight bits do not fall on a byte boundary. The exponent bits take up seven bit positions in the high-order byte, and one bit position in the next byte, as shown in Figure 3-7. In the same IEEE single encoding the significand takes up seven bits of the second byte as well as the third and fourth bytes. The sign of the number is the high-order bit of the high-order byte. Figure 3-8 shows the number 127.375 stored in the IEEE floating-point single format.

The encoding in Figure 3-8 is interpreted as follows:

- sign of number = 0 (positive)
- biased exponent = 10000101B = 133 decimal
- real exponent = 133 - bias = 133 - 127 = 6
- significand = 1.1111110 11000000 00000000 (adding explicit digit)
- significand is adjusted by moving the radix point six places to the right
- new significand = 111111.01100...00

The significand bits are interpreted as follows:

- integer part = 1111111 = 127
- fractional part = .01100..00 = .375
3.4 Binary-Coded Decimals (BCD)

Floating-point encodings are the most efficient format for storing numerical data in a digital device and binary arithmetic is the fastest way to perform numerical calculations. But other representations are also useful. BCD (binary-coded decimal) is a way of representing decimal digits in binary form. There are two common ways of encoding decimal digits in binary format. One is known as the packed BCD format and the other one as unpacked. In the unpacked format each BCD digit is stored in one byte. In packed form two BCD digits are encoded per byte. The unpacked BCD format does not use the four high-order bits of each byte, which is wasted storage space. On the other hand, the unpacked format facilitates conversions and arithmetic operations on some machines. Figure 3.9 shows the memory storage of a packed and unpacked BCD number.
3.4.1 Floating-Point BCD

Unlike the floating-point binary numbers, binary-coded decimal representations and BCD arithmetic have not been explicitly described in a formal standard. Each machine or software package stores and manipulates BCD numbers in a unique and often incompatible way. Some machines include packed decimal formats, which are sign-magnitude BCD representations. These integer formats are useful for conversions and input-output operations. For performing arithmetic calculations a floating-point BCD encoding is required. This approach provides all the advantages of floating-point as well as the accuracy of decimal encodings.

The BCD floating-point format which we call BCD12 is shown Figure 3-8.

Figure 3-10 Map of the BCD12 Format

BCD12 requires 12 bytes of storage and is described as follows:

1. The sign of the number (S) is encoded in the left-most packed BCD digit. Therefore, the first four bits are either 0000B (positive number) or 0001B (negative number).

2. The sign of the exponent is represented in the four low-order bits of the first byte. The sign of the exponent is also encoded in one packed BCD digit. As is the case with the sign of the number field, the sign of the exponent is either 0000B (positive exponent) or 0001B (negative exponent).

3. The following two bytes encode the exponent in four packed BCD digits. The decimal range of the exponent is 0000 to 9999.

4. The remaining nine bytes are devoted to the significand field, consisting of 18 packed BCD digits. Positive and negative numbers are represented with a significand normal-
ized to the range 1.00...00 to 9.00...99. The decimal point following the first significand
digit is implied. The special value 0 has an all-zero significand.

5. The special value FF hexadecimal in the number's sign byte indicates an invalid num-
ber.

The structure of the BCD12 format is described in Table 3.4.

**Table 3.4
Field Structure of the BCD12 Format**

<table>
<thead>
<tr>
<th>CODE</th>
<th>FIELD NAME</th>
<th>BITS WIDE</th>
<th>BCD DIGITS</th>
<th>RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>sign of number</td>
<td>4</td>
<td>1</td>
<td>0 - 1 (BCD)</td>
</tr>
<tr>
<td>S</td>
<td>sign of exponent</td>
<td>4</td>
<td>1</td>
<td>0 - 1 (BCD)</td>
</tr>
<tr>
<td>E</td>
<td>exponent</td>
<td>16</td>
<td>4</td>
<td>0 - 9999</td>
</tr>
<tr>
<td>M</td>
<td>significand</td>
<td>72</td>
<td>18</td>
<td>0 - 99..99 (18 digits)</td>
</tr>
</tbody>
</table>

**Notes:**
1. The significand is scaled (normalized) to a number in the range 1.00..00 to 9.99..99.
2. The encoding for the value zero (0.00..00) is a special case.
3. The special value FFH in the sign byte indicates an invalid number.

The BCD12 format, as is the case in all BCD encodings, does not make ideal use of the available storage space. In the first place, each packed BCD digit requires four bits, which in binary could serve to encode six additional combinations. At a byte level the wasted space is of 100 encodings (BCD 0 to 99) out of a possible 256 (0 to FFH). The sign field in the BCD12 format is wasteful since only one binary digit is actually required for storing the sign. Regarding efficient use of storage, BCD formats cannot compete with floating-point binary encodings. The advantages of BCD representations are a greater ease of conversion into decimal forms, and the possibility of using the processors' BCD arithmetic instructions.
Chapter 4

Digital Logic, Arithmetic, and Conversions

This chapter is about the fundamental arithmetic and logical operations of digital machines. It serves as a background for developing processing routines which involve decisions, data filtering and processing, and number crunching. Here we discuss logical and arithmetic operations in general, that is, without reference to any individual processor. There are so many different hardware versions of microcontrollers that it is not feasible to develop an actual routine for each device. On the other hand, once the logic is understood, the actual coding is a simple process of finding a way of implementing it in a specific instruction set. The chapter also includes material related to data type conversions since these operations are closely related to the other material in this chapter.

4.0 Microcontroller Logic and Arithmetic

All microcontrollers contain instructions to perform arithmetic and logic transformations on binary or decimal operands. These instructions can be classified into three groups:

1. Logical instructions. Sometimes these are called Boolean operators. The group includes instructions with mnemonics such as AND, NOT, OR, and XOR. They perform the logical functions that correspond to their names.

2. Arithmetic instructions. Typically this group of instructions performs integer addition and subtraction. Occasionally, the instruction set includes multiplication and division. The operands can be signed or unsigned binary and binary coded decimal numbers.

3. Auxiliary and bit manipulation instructions. This group includes instructions to shift and rotate bits, to compare operands, to test, set, and reset individual binary digits, and to perform various auxiliary operations.

4.0.1 CPU Flags

All microcontrollers are equipped with a special register that reflects the current processing status. This register, sometimes called the status register or the flags register, contains individual bits, usually called flags, that are meaningful during the execution of logic and arithmetic operations. The most common flags are:
1. The zero flag. This flag is set if a previous operation produces a value of zero.

2. The carry/overflow flag. This flag is set if there has been a carry or a borrow-out of the high-order bit of the operand.

3. The half-carry or digit-carry flag. This flag is set if there has been a carry or a borrow-out of the low-order nibble of the operand.

Not all instructions affect all the flags. For example, loading a zero constant into a register may be said to produce a zero value; however, such an instruction may or may not affect the zero flag, according to the implementation on each particular device. More powerful and sophisticated microcontrollers sometimes implement other flags, such as flags to indicate a negative operand, an arithmetic overflow, or an interrupt.

4.0.2 Word Size

The word-size of a computer or a digital device refers to the number of bits used in storing data and in moving data in and out of the various machine units. In other words, a machine's word-size is the native data unit for a particular architecture. In this manner we speak of the Pentium having a 32-bit word size or the PIC16x84 having an 8-bit word-size for data operations and 14-bit program words.

In the context of digital arithmetic and logic the data word-size determines the processing capabilities of each device. For example, a machine with an 8-bit word-size can perform unsigned addition of operands whose sum does not exceed the decimal value 255, since 255 is the largest unsigned integer that can be stored in eight bits. However, a machine with 16-bit words can perform unsigned additions up to a sum of 65,535 since it is the largest number that can be stored in 16 bits.

Therefore, the coding of numerical routines is determined by the word size of the machine or device. A device with 8-bit word-size requires multi-byte arithmetic to perform addition that exceeds a sum of 255, while a machine with a 16-bit word can do direct addition up to the sum 65,535. Considering that most popular microcontrollers have 8-bit word-sizes, we assume this limit in the arithmetic and logic algorithms and routines developed in this chapter.

4.1 Logical Instructions

The logical instructions include the Boolean operators, AND, OR, NOT, and XOR, as well as instructions to shift and rotate individual bits.

The logical instructions operate on a bit-by-bit basis; therefore, in the AND, OR, NOT, and XOR there is no interaction between bits. The action performed by the logical instructions is as follows:

1. AND, OR, and XOR logically combine each bit in the source operand with the corresponding bit in the destination operand. The result does not affect the neighboring bits.

2. The NOT operator inverts all bits in the destination operand.
These actions explain the term *bitwise operation* sometimes used to describe the instructions.

### 4.1.1 Logical AND

The AND instruction performs a bitwise logical AND of two operands. This determines that a bit in the result is set if and only if the corresponding bits are set in both operands. A frequent use of the AND operation is to clear one or more bits without affecting the remaining ones. This action is possible because ANDing with a 0 bit always clears the result bit and ANDing with a 1 bit preserves the original value of the first operand.

For example, if we have the binary coded decimal number 34 packed into a single byte, we can isolate the four low-order bits as follows:

<table>
<thead>
<tr>
<th>hexadecimal</th>
<th>binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>0011 0100</td>
</tr>
<tr>
<td>AND 0F</td>
<td>0000 1111 mask</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>04</td>
<td>0000 0100</td>
</tr>
</tbody>
</table>

The second operand, in this case 0FH, is called a *mask*. The AND operation preserves the 1-bits in the mask and clears the bits that are 0. Consequently, the mask 00000001B clears the seven high-order bits and preserves the original value of the low-order bit.

### 4.1.2 Logical OR

The OR operation performs the bitwise logical inclusive OR of two operands. After a logical OR, a bit in the result is set if one or both of the corresponding bits in the operands were set. A frequent use for the OR is to selectively set one or more bits. The action takes place because ORing with a 1-bit always sets the result bit, while ORing with a 0-bit preserves the original value in the first operand.

For example, to set the high-order bit (bit number 7) we can OR with a 1 bit, as follows:

<table>
<thead>
<tr>
<th>hexadecimal</th>
<th>binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>0011 0100</td>
</tr>
<tr>
<td>OR 80</td>
<td>1000 0000 mask</td>
</tr>
<tr>
<td>------------</td>
<td>-----------</td>
</tr>
<tr>
<td>B4</td>
<td>1011 0100</td>
</tr>
</tbody>
</table>

The OR operation sets the bits that are 1 in the mask and preserves the bits that are masked 0.

### 4.1.3 Logical XOR

The XOR operator performs the bitwise logical exclusive OR of the two operands. Therefore, a bit in the result is set if the corresponding bits in the operands have opposite values. For this reason, XORing a value with itself always generates a zero result since all bits necessarily have the same value. On the other hand, XORing with a 1-bit inverts the value of the other operand, since 0 XOR 1 is 1 and 1 XOR 1 is 0. This toggling action of XORing with a 1 bit generates identical bitwise results as the NOT operation,
but by selecting the XOR mask, the programmer can control which bits of the operand are inverted and which are preserved.

In this manner it is possible to invert the four high-order bits of an operand by XORing with a mask that has these bits set. If the four low-order bits of the mask are clear, then the original values of the bits in the other operand are preserved in the result. For example:

<table>
<thead>
<tr>
<th></th>
<th>hexadecimal</th>
<th>binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>0101 0101</td>
<td></td>
</tr>
<tr>
<td>XOR</td>
<td>F0 1111 0000 mask</td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>--------------</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>1010 0101</td>
<td></td>
</tr>
</tbody>
</table>

In the previous example, the XOR operation inverts the bits that are 1 in the mask and preserves the bits that are masked 0. Consequently, the XOR mask 11110000B inverts the four high-order bits.

### 4.1.4 Logical NOT

In contrast with the other logical operators which require two operands, the NOT instruction acts on a single value. Its action is consistent with a Boolean NOT function, which converts all 1-bits to 0 and all 0-bits to 1. Arithmetically, the result is the one's complement of the original value. This instruction can be useful in obtaining the two's complement representation by performing the logical NOT and then adding one to the results.

### 4.2 Microcontroller Arithmetic

Microcontrollers are not designed for intensive numeric processing; therefore, they are not equipped with many arithmetic operators usually found in microprocessors. A typical mid-range microcontroller has instructions to add and subtract integers and perhaps to increment and decrement. Hardware multiplication is rarely available and even more so is division. Likewise, there is usually no hardware support for decimal and floating-point arithmetic. For this reason the microcontroller programmer is often challenged to provide most arithmetic and data processing operations in software.

In this discussion we assume a mid-range microcontroller, such as the PIC 16f8x. These devices contain primitives for adding and subtracting integers, shifting and rotating bits, incrementing and decrementing machine registers, some support for decimal operations and conversions, as well as the basic logic primitives AND, OR, XOR, and NOT. Multiplication and division operators, as well as floating-point operators, are not available in the mid-range devices.

### 4.2.1 Unsigned and Two’s Complement Arithmetic

In Chapter 3 we discussed the various representations for signed and unsigned binary and decimal numbers. Arithmetic operations of unsigned operands are the simplest. In this case we assume that the encoding always represents a positive number and that all bits relate to the number’s magnitude.
Unsigned arithmetic can be binary or decimal. In a machine with 8-bit words binary arithmetic on unsigned numbers use the entire range of the format. This is true even when the primitive operations are valid in two’s complement form; in fact, it is one of the great advantages of two’s complement representation. Table 4.1 shows a 4-bit binary in several numeric formats.

**Table 4.1**
Interpretations of 4-bit Binary Numbers

<table>
<thead>
<tr>
<th>BINARY</th>
<th>1’S COMPLEMENT</th>
<th>DECIMAL VALUES</th>
<th>2’S COMPLEMENT</th>
<th>UNSIGNED</th>
</tr>
</thead>
<tbody>
<tr>
<td>0111</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>0110</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>0101</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>0100</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>0011</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>0010</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>0001</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>0000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1111</td>
<td>-0</td>
<td>-1</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>1110</td>
<td>-1</td>
<td>-2</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>1101</td>
<td>-2</td>
<td>-3</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>1100</td>
<td>-3</td>
<td>-4</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>1011</td>
<td>-4</td>
<td>-5</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>1010</td>
<td>-5</td>
<td>-6</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>1001</td>
<td>-6</td>
<td>-7</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>-7</td>
<td>-8</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

Assume a machine with a 4-bit word size and consider addition of two unsigned numbers:

<table>
<thead>
<tr>
<th>BINARY</th>
<th>DECIMAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0111</td>
<td>7</td>
</tr>
<tr>
<td>0110</td>
<td>6</td>
</tr>
<tr>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>1101</td>
<td>13</td>
</tr>
</tbody>
</table>

Note, in the previous example, that if the encoding were in two’s complement form, the addition of the positive values 6 plus 7 would produce a result that overflows the capacity of the representation. In 4-bit two’s complement representation there is no way of encoding the value 13.

The question that arises is: in a device that performs two’s complement addition, must we always assume that the operands are in two’s complement form? The answer is: no. Signed addition of two’s complement operands and the unsigned addition of integer operands can be performed with identical processing and by the same electronic circuitry. It is the software that must take into account the encoding of the operands in order to interpret the results. For example, in the 4-binary digit device previously considered, the two’s complement addition of the values 6 and 7 produce an overflow, which can be detected by observing the change in the high-order bit (the sign bit) of the result. Therefore, in this case, the result of the addition operation is invalid. However, if the same decimal values represent unsigned operands, then the addition of 7 plus 6 produce the valid result 13. In either case the binary values of the operands, as well as the result, are the same.
Microcontrollers usually support the fundamental operations of addition and subtraction on signed and unsigned integer operands with a single primitive operation. The addition and subtraction operators in low- and mid-range devices allow two operands. The more powerful microcontrollers support addition and subtraction of three operands, which is useful in implementing multi-digit routines. In either case, the software determines if the result is signed or unsigned by interpreting the changes in the high-order bit of the operands and by evaluating the status flags if these are available.

4.2.2 Operations on Decimal Numbers

Although microcontrollers are binary devices, the instruction set often includes operations for performing arithmetic on binary coded decimal numbers. In Chapter 3 we saw that BCD numbers can be stored in packed or unpacked form. In packed format two BCD digits are contained in each byte. The low-order BCD digit takes up bits 0 to 3 and the high-order BCD digit takes up bits 4 to 7. Unpacked BCD digits are stored one digit per byte; in this case the high-order nibble is unused. The packed and unpacked binary coded decimal formats can be seen in Figure 3-9.

Microcontroller designers usually adopt the packed BCD format for representing decimal operands. One advantage of packed BCDs is that the two decimal digits encoded in a single byte can be represented as hexadecimal digits. For example, the values H24 and H99 represent the packed BCD digits 24 and 99 respectively. Note that each hex digit is preceded by the letter H to indicate radix 16. In actual microcontroller programming other ways are often used for representing numbers in hexadecimal notation.

The addition and subtraction of decimal numbers represented in packed BCD can be performed with binary primitive operations, complemented with some additional adjustments. In some cases the addition of two BCD numbers in packed format may produce a valid result, for example:

\[
\begin{array}{c}
H23 \\
+ H12 \\
---- \\
H35
\end{array}
\begin{array}{c}
H31 \\
H38 \\
H69 \\
H78
\end{array}
\]

In the previous examples the results are valid because the sum of each digit does not exceed the range of the BCD format. However, the following additions do not produce valid BCD results:

\[
\begin{array}{c}
H33 \\
+ H27 \\
---- \\
H5A
\end{array}
\begin{array}{c}
H31 \\
H59 \\
H8A \\
H7D
\end{array}
\]

In the case of the first operation the valid BCD result would be: 33 + 27 = 60, in the second one 31 + 59 = 90, and in the third one 56 + 27 = 83. A simple adjustment corrects the error, as follows:
In all three cases adding 6 to the previous sum produces the expected result. The logic for deciding when the value 6 must be added is simple: if the sum of the low-order digit is greater than 9 or if the sum produced a carry out of the low-order nibble, then add 6 to the sum to perform the decimal adjustment. Some high-end microcontrollers contain a primitive instruction that executes the decimal adjustment automatically, that is, without having to test the sum. However, this instruction is not available in low- and mid-range devices.

Also note that the largest number that can be encoded in packed BCD format is the decimal 99. When adding two BCD digits the high-order digit of the sum cannot be greater than 9. If so, then the capacity of the format has been exceeded and the result cannot be adjusted by the simple addition of 6. Here again, a multi-byte processing routine can be developed in order to accommodate the result of BCD addition when the sum exceeds a single byte.

Many microcontrollers are equipped with a flag that indicates overflow from binary digit number 3. This flag, sometimes called the *digit carry* or the *half carry flag*, can be used to detect that a calculation has overflowed the storage capacity of four binary digits. The availability of this flag simplifies the logic necessary for adjusting binary addition of decimal operands since the value 6 must be added when the digit in the low-order nibble is larger than 9, or when there has been a carry to the next digit. The following flowchart shows this processing.

![Flowchart for Two-byte BCD Addition](image-url)
4.3 Bit Manipulations and Auxiliary Operations

In addition to basic logic and arithmetic, microcontrollers contain primitive operators to manipulate individual bits, to compare operands, to make decision based on the state of individual bits and flags, and to convert data to other formats. As always, presence or absence of some of these operations, as well as their degree of power and sophistication, varies with the individual microcontroller. In the following subsections we describe the most commonly available primitives.

4.3.1 Bit Shift and Rotate

The fundamental operators to shift and rotate are useful in developing BCD and binary arithmetic routines. One interesting use of bit shifting is in implementing binary multiplication and division routines.

*Shift operations* consist of transposing to the left or right all the bits in the operand. In microcontrollers the operand is usually a processor register. For example, after a right shift operation all the bits in the value 0110101B (75H) are moved one position to the right, resulting in the value 00111010B (3AH). Note that on a right shift the right-most bit disappears and a zero comes into the high-order bit. By the same token, in a left shift the high-order bit disappears and a zero comes into the low-order bit. Figure 4-2 shows the action of a left-shift operation.

![Figure 4-2 Left Shift Operation](image)

The rotate operation differs from the shift in that in the rotate the low-order bit is either a copy of the high-order bit or of the carry flag. In the first case the operation is a pure rotate, in the second case the rotate is referred to as *rotate-through-carry*. Figure 4-3 shows the action of a *left-rotate-through-carry* flag.

![Figure 4-3 Rotate-through-carry Left Operation](image)
Note in Figure 4-3 that the contents of the carry flag are first copied to the low-order bit of the destination operand, then the individual bits of the source (in gray in the illustration) are shifted left and moved to the destination. Finally the high-order bit of the source is copied to the carry flag.

There are several possible variations of the rotate operation. The Intel microprocessors distinguish between arithmetic and logic rotates. In the arithmetic rotation the high-order bit is preserved in order to maintain the sign of the operand. The rotate shown in Figure 4-3 is the one most common in microcontroller hardware. Clearing the carry flag before the rotate takes place makes the operation identical to a shift.

4.3.2 Comparison Operations

An interesting property of subtraction is its use in finding the relative size of two operands. This interesting action of subtraction is based on the following logic:

1. If the result of a subtraction is zero, then both operands were of the same size.
2. If the result of a subtraction is a positive number, then the subtrahend was smaller than the minuend.
3. If the result of a subtraction is a negative number, the subtrahend was larger than the minuend.

In a binary/digital device the result of a subtraction operation can be determined by observing the flags. If the zero flag is set, then the operands were the same (case 1, above). If the carry flag is set, then the subtrahend was larger than the minuend (case 3, above). If neither the carry nor the zero flag is set, then resulting subtrahend was smaller than the minuend (case 2, above). Since all microcontrollers offer some mechanism for re-directing execution according to the state of the flags, a program can use subtraction to make these decisions.

The one objection to the use of subtraction in comparing the size of two operands is that the process will change one of them. To use subtraction in comparison operations the programmer has to find some way of preserving the minuend. Alternatively, some devices contain a comparison operator that sets the flags as if a subtraction had taken place but without changing the operands. High-end microcontrollers are equipped with dedicated comparison operators, but the middle- and low-range devices usually are not.

4.3.3 Other Support Operations

Mid- and high-range microcontrollers contain other auxiliary bitwise, arithmetic, and logic operators that can be useful to the programmer. These include instructions to:

1. Increment and decrement operands
2. Clear registers or storage locations
3. Swap nibbles
4. Clear and set individual bits
5. Test individual bits
Usually instructions to increment and decrement and to test individual bits are also capable of redirecting execution according to the result. For example, a special decrement can be followed by a jump if decrementing sets the zero flag. Or a bit test instruction can include a jump that is taken if the tested bit is set or reset.

### 4.4 Unsigned Binary Arithmetic

Since microcontrollers are not used in data processing, microcontroller programming does not usually require the development of powerful or sophisticated numerical routines. At the same time, because microcontrollers often lack primitive support for even the most essential calculations, the programmer makes up for this deficiency. For example, mid-range PIC microcontrollers contain primitive instructions for signed and unsigned addition and subtraction of byte-size operands. Unsigned addition and subtraction operations that exceed one byte, as well as unsigned multiplication and division, must be provided in software.

In unsigned arithmetic all bits of the binary encoding are interpreted as magnitude bits and all numbers are positive. Addition of unsigned binary numbers is limited by the machine’s word size. For example, a mid-range PIC microcontroller performs unsigned addition on 8-bit operands. An overflow of the sum is reported by the carry flag set. In this case the carry flag clear indicates that the sum is within the storage capacity of the format. In unsigned arithmetic processing, routines for extending operations to multiple bytes are straightforward and relatively simple.

#### 4.4.1 Multi-byte Unsigned Addition

Many microcontrollers are one-byte machines, so operands and results for arithmetic operations must be contained within eight bits. The largest unsigned value that can be represented in a single byte is the decimal number 255. But often applications require adding operands that are larger than a single byte and storing results that exceed this limit. In these cases multi-byte routines become necessary.

The simplest case is the addition of two unsigned byte-size operands whose sum exceeds 255 decimal. This case requires storing the result in a two-byte area and detecting those cases in which there is a carry into the high-order byte. In this case the largest possible operands for byte addition are the hexadecimal numbers FF. Addition is as follows:

\[
\begin{array}{c}
\text{Binary:} \\
11111111 \\
+ 11111111 \\
\hline \\
11111110 \\
C <= \end{array}
\]

In this example the symbol $C <=$ represents a carry out of the high-order bit, the case when the sum exceeds the capacity of a single byte. In hexadecimal, the sum of HFF + HFF = H1FE. You can add two byte-size operands into a two-byte storage area by using byte addition to determine the low-order byte of the result and testing for a carry out of the high-order bit. If there is a carry, then the high-order byte of the result is 1; otherwise the high-order byte is 0.
The same logic can be generalized to add more than two byte-size operands as long as the storage area for the result exceeds the size of the operands by one byte. For example, two word-size operands (16 bits each) can be added into a 3-byte (24-bit) storage area, or two double-word operands (32 bits) into a 5-byte storage area. The general algorithm for multi-byte addition is shown in Figure 4-4.

The case shown in Figure 4-4 consists of adding two, 4-byte operands into a 5-byte sum. The addition of the first two operands assumes that there is no carry. In the remaining stages there can be a possible carry from the previous stage if the sum of the two byte-size operands, plus the previous carry, exceed the storage capacity of eight bits. The last byte of the result is determined solely by the possible carry from the previous stage.

In Figure 4-4 we see that multi-byte addition requires the sum of three values in all stages except the first and the last one. Some high-end microcontrollers have addition operators that accept a three-byte operand. Others have special addition opcodes that automatically add-in the carry flag. The latter operators are referred to as add-with-carry. However, in most low- and mid-range devices the software must take care of incrementing the sum if there is a carry from the previous stage. The actual multi-byte addition routines are developed in the context of programming the various microcontrollers, discussed later in this book.

4.4.2 Unsigned Multiplication

The case for multiplication cannot be generalized since high-end microcontrollers usually contain one or more multiplication operators; this is not the case in low- and mid-range devices. In the first case implementation is simply by using the correspond-
Arithmetically, multiplication is performed by repeated addition. The multiplier represents the number of times that the multiplicand must be added to itself. Therefore, 3 times 4 is the same as $3 + 3 + 3 + 3$. This fact allows implementing multiplication routines in software as long as the device contains an addition operator. The logic is based on using the multiplier as a counter. This counter is decremented each time that the multiplicand is added to itself. The routine ends when the counter is exhausted, as shown in the flowchart in Figure 4-5.

![Figure 4-5 Unsigned Multiplication Flowchart](image)

The beauty of the repeated addition algorithm is its simplicity and its main shortcoming is its slowness. An alternative way of performing multiplication is by shifting the bits of the operand. This method is based on the properties of a binary positional system, in which the value of each digit is a successive power of 2. Therefore, by shifting all digits to the left, the value 0001B (1 decimal) successively becomes 0010B (2 decimal), 0100B (4 decimal), 1000B (8 decimal), and so on.

Binary multiplication by means of bit shifting has the downside that the multiplier must be a power of 2. Otherwise, the software must shift by a power of 2 that is smaller than the multiplier and then add the multiplier as many times as necessary to complete the product. In this manner, to multiply by 5 we can shift left twice and add once the value of the multiplicand. To multiply by 7 we would shift left twice and then add three times the value of the multiplicand. As the multiplier gets larger and more distant from the smaller power of 2, the number of addition operations required is also larger, and the effectiveness of the algorithm diminishes.
A third approach is based on the manipulations performed during longhand multiplication. For example, the multiplication of 00101101B (45 decimal) by 01101101B (109 decimal) can be expressed as a series of products and shifts, in the following manner:

\[
\begin{array}{c}
00101101B = 45 \text{ decimal} \\
\times 01101101B = 109 \text{ decimal} \\
\hline
00101101 \\
00000000 \\
00101101 \\
00101101 \\
00000000 \\
00101101 \\
00101101 \\
00000000 \\
\hline
001001100101001B = 4905 \text{ decimal}
\end{array}
\]

The actual calculations in this method of binary multiplication are quite simple since the product by a 0 digit is zero and the product by a 1 digit is the multiplicand itself. Consequently, the multiplication routine simply tests each digit in the multiplier. If the digit is zero no action need be performed; if the digit is one, the multiplicand is shifted left and added into an accumulator.

The storage allocation to hold the product of a multiplication operation is not the same as that to hold the sum. In multi-byte addition one additional byte is required to hold the sum. In multiplication the storage allocation must be twice the size of the operands. For example, byte multiplication requires a two-byte storage, while multiplying two double-byte operands requires a four-byte storage allocation.

### 4.4.3 Unsigned Division

If multiplication can be reduced to repeated addition, then division can be conceptualized as repeated subtraction. In the case of division, the quotient (result) is the number of times the divisor must be subtracted from the dividend before zero or a negative value results from the subtraction. The flowchart in Figure 4-6 (in the following page) shows the logic steps in unsigned division.

In Figure 4-6 note that the logic tests for a zero divisor, since division by zero is mathematically undefined. Also, since the operation is unsigned, the result cannot be negative; therefore, the divisor must be larger than the dividend. Finally, the logic must consider the case in which subtracting the divisor from the reminder produces a negative value, in which case an adjustment is necessary to produce a valid quotient. This adjustment avoids the need for searching for a trial divisor, as in the case in the common longhand division algorithm. In machine code the negative result is detected as an overflow (carry flag set) from the subtraction.

### 4.5 Signed Binary Arithmetic

In two's complement and sign-magnitude representations the high-order bit represents the sign of the operand, while its magnitude is represented in the remaining bits. Therefore, in the case of signed numbers, a carry out of the high-order bit is meaning-
less since the high-order bit is not a magnitude bit. For example, consider the follow-
ing operation in an 8-bit device that performs unsigned and two’s complement addi-
tion:

\[
\begin{align*}
80 & = 0101 0000B \\
+ 90 & = 0101 1010B \\
\hline
170 & = 1010 1010B
\end{align*}
\]

If the operands are assumed to be in unsigned binary format the result is valid. However, if the operands (the decimal values 80 and 90) are assumed to be positive numbers in two’s complement form, then the result is invalid since the positive number 170 cannot be represented in an 8-bit two’s complement encoding.

Clearly, multi-byte operations on signed representations cannot be performed identically as with unsigned operands. Table 4.2 shows the unsigned and two’s complement representations of one-byte numbers.
Table 4.2
Signed and Unsigned Representations of One-Byte Numbers

<table>
<thead>
<tr>
<th>BINARY</th>
<th>2'S COMPLEMENT</th>
<th>UNSIGNED</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000 0000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0000 0001</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0000 0010</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>0000 0011</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>..</td>
<td>..</td>
<td>..</td>
</tr>
<tr>
<td>0111 1111</td>
<td>127</td>
<td>127</td>
</tr>
<tr>
<td>1000 0000</td>
<td>-128</td>
<td>128</td>
</tr>
<tr>
<td>1000 0001</td>
<td>-127</td>
<td>129</td>
</tr>
<tr>
<td>1000 0010</td>
<td>-126</td>
<td>130</td>
</tr>
<tr>
<td>1000 0011</td>
<td>-125</td>
<td>131</td>
</tr>
<tr>
<td>..</td>
<td>..</td>
<td>..</td>
</tr>
<tr>
<td>1111 1110</td>
<td>-2</td>
<td>254</td>
</tr>
<tr>
<td>1111 1111</td>
<td>-1</td>
<td>255</td>
</tr>
</tbody>
</table>

4.5.1 Overflow Detection in Signed Arithmetic

In unsigned addition the carry flag is magnitude-related. It is set when there is a carry out of the high-order bit of the destination operand, which takes place when its capacity has been exceeded. This is usually described as an overflow condition. However, a carry out of the high-order bit of the result is not always meaningful in signed arithmetic. For example, suppose the following two's complement addition:

Decimal  | binary  
----------|---------
127       | 0111 1111 
+ 127      | 0111 1111 
----       | -------- 
??        | 1111 1110

In this case the sum clearly exceeds the capacity of the format, since the largest positive value that can be represented in a two's complement 8-bit format is 127 (see Table 4-2). However, the operation did not generate a carry out of the high-order bit. Therefore, the carry flag could not have been used to detect the overflow error in this case.

Now consider the addition of two negative numbers in two's complement form:

Decimal  | binary  
----------|---------
-4        | 1111 1100 
* -5       | 1111 1011 
----       | -------- 
-9        | C <= 1111 0111

In this case the addition operation generated a carry out of the high-order bit; however, the sum is arithmetically correct. In fact, any addition of negative operands in two’s complement notation generates a carry out of the most significant bit.
These two examples show that the carry flag, by itself, cannot be used to detect an error or no-error condition in two’s complement arithmetic. Detecting an overflow condition in two’s complement representations requires observing the carry into the high-order bit of the encoding as well as the carry out. In both previous examples we note that there was a carry into the high-order bit of the result. However, in the first case there was no carry out. The general rule is: two’s complement overflow takes place when the carry into and the carry out of the high-order bit have opposite values. Figure 4-7 is a flowchart to detect overflow in signed arithmetic.

![Flowchart detecting overflow in two's complement arithmetic](image)

**Figure 4-7 Detecting Overflow in Two's Complement Arithmetic**

Most microprocessors and some high-end microcontrollers contain hardware facilities for detecting signed arithmetic overflow. In some cases the hardware support consists of a single overflow flag that is set whenever the result of an arithmetic operation exceeds the capacity of the format. In other cases, as in the PIC 18CXX2 family, the status register contains a negative bit flag that indicates a 1-bit in the sign bit position, as well as an overflow bit that is set whenever there is an overflow from the magnitude bits (0 to 6) into the sign bit (bit 7) of the destination operand. In this device, software can test one or both of these flags to detect two’s complement overflow.

In low- and mid-range devices, with no hardware support for signed arithmetic, detecting a two’s complement overflow is by no means simple. Without a hardware flag to report a carry condition into a particular bit position, software is confronted with several possible alternatives, but none is simple or straightforward.

**4.5.2 Sign Extension Operations**

Observing the carry into and the carry out of the most significant bit is a valid way of detecting overflow of a two’s complement arithmetic operation. In theory, the logic described in the flowchart of Figure 4-7 can be implemented in devices without hard-
ware support for signed overflow; however, the processing is complicated and therefore costly in execution time. An alternative approach is to ensure that the format has sufficient capacity to store the arithmetic result. The rule developed previously lets us determine that, for addition and subtraction, the destination format must have at least one more byte than the operands. In multiplication, the destination operand must be at least twice the size of the source operands.

A simple mechanism for extending the capacity of two's complement encoding is called sign extension. The process consists of copying the sign bit into the high-order bit positions of the extended encoding. For example, to extend a two's complement 8-bit number into 16 bits, copy the sign bit of the original value (bit number 7) into all the bits of the extended byte. The process is shown in Figure 4-8 for both positive and negative operands.

![Figure 4-8 Sign Extension of Two's Complement Numbers](image)

4.5.3 Multi-byte Signed Operations

Signed operations on two's complement numbers encoded in multiple bytes can be performed using the processor's arithmetic primitives. Consider the addition of the numbers -513 and -523, each one encoded in 16-bit two's complement form:

<table>
<thead>
<tr>
<th>decimal</th>
<th>binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>-513</td>
<td>1111 1101</td>
</tr>
<tr>
<td>-523</td>
<td>1111 1011</td>
</tr>
<tr>
<td>1036</td>
<td>1111 1010</td>
</tr>
</tbody>
</table>

In the preceding example, adding the low-order bytes produces the sum shown, plus a carry. Adding the high-order bytes plus the carry, and discarding the overflow, produces the sum of high-order bytes shown above. The result is the correct value in two's complement form. The fact that the result did not overflow the capacity of the 16-bit format can be ascertained by observing that there was a carry into the fif-
teenth digit but also a carry out. Carry in and carry out of the sign bit is one of the conditions for no overflow in the flowchart of Figure 4-7.

4.6 Data Format Conversions

Quite often code needs to convert data into and from different numeric formats; for example, to display ASCII digits in an output device, or to convert numeric keyboard input in ASCII into binary or BCD encodings for processing. In this section we consider the logic for the following cases:

1. BCD digits to ASCII decimal
2. Binary to string of ASCII decimal digits
3. String of ASCII decimal digits to binary
4. Binary to string of ASCII hexadecimal digits

As in the previous cases, implementation of these conversions is device-dependent and varies in the different hardware.

4.6.1 BCD Digits to ASCII Decimal

Packed BCD digits are encoded in one digit-per nibble, as shown in Section 4.2.2. Thus, each digit is a binary value in the range 0 to 9. Converting each digit to ASCII consists of isolating each nibble and then changing the binary into an ASCII representation. Note in Table 3.1 that the numeric ASCII digits start at 30H for the digit zero and extend to 39H for the digit 9. For this reason converting a numeric digit from binary into ASCII consists of adding 30H. By the same token, subtracting 30H converts a single ASCII digit to binary.

Assume four packed BCD digits in two consecutive memory bytes, labeled A and B, where A holds the two low-order digits; also, a four-digit storage buffer to which the variable P is a pointer. The conversion algorithm can be described as follows:

1. Initialize buffer pointer $P$ to the first storage location.
2. Copy digit $A$ to temporary digit $T$.
3. Mask out four high-order bits of $T$.
4. Add 30H to value in $T$ and store in buffer by pointer $P$.
5. Bump buffer pointer to next digit storage.
6. Copy digit $A$ to temporary digit $T$.
7. Mask out four low-order bits in $T$.
8. Shift four high-order bits to the right by 4 bits.
9. Add 30H to value in $T$ and store in buffer by pointer $P$.
11. Proceed with digit $B$ in the same manner.
4.6.2 Unsigned Binary to ASCII Decimal Digits

Often we hold an unsigned binary number in memory or a machine register and need to display its value to some ASCII-based output device. The process requires converting the binary value to a string of ASCII decimal digits. The number of decimal digits depends on the number of bits in the binary representation. A one-byte unsigned binary requires three ASCII decimal digits since the value ranges from 0 to 255. A two-byte unsigned binary requires a string of five ASCII decimal digits since the range of a two-byte representation is from 0 to 65,535, and so on. The storage area for the ASCII digits is sometimes referred to as a buffer.

The process of converting binary to ASCII decimal consists of dividing the binary by 10 to obtain each decimal digit, then adding 30H to the remainder in order to turn the digit into ASCII. The process continues until the original dividend is reduced to zero, as shown in the flowchart of Figure 4-9.

![Flowchart](https://example.com/flowchart.png)

**Figure 4-9** Unsigned Binary to ASCII Decimal String

4.6.3 ASCII Decimal String to Unsigned Binary

Another conversion operation frequently needed in software is the transformation of a string of ASCII decimal digits into binary. This type of conversion typically arises when the program needs to receive input which must later be processed by the device. For example, the user enters a numeric value from a keyboard and the application must process this data in binary form.

In designing the conversion routine we must first delimit the value range of the input data so as to allocate a sufficiently large binary format to store the result. For example, code can store in a single unsigned byte a binary in the range 0 to 255, but it requires two bytes to store one in the range 0 to 65,535. Once the binary storage size is determined, the conversion logic is based on converting each ASCII digit to binary, high-to-low, and adding its value to a previous sum multiplied by 10. The following flowchart describes the conversion logic.
The logic in the flowchart of Figure 4-10 assumes that there is some way of detecting the end of the string of ASCII digits. This could be a terminator character embedded in the string or a counter for the number of digits. Here again we use a buffer pointer that is initialized to the least significant digit in the ASCII string. The ASCII digit is converted to binary by subtracting 30H and then added to the previous sum, multiplied by 10. For example, assume the ASCII string of the decimal digits 564.

STRING = ‘564’

FIRST ITERATION:
STEP 1: B = 0
    P -> HIGH DIGIT IN STRING ‘564’
STEP 2: A = ‘5’
STEP 3: END OF STRING?
    NO
STEP 4: A = 4 (‘5’ – 30H = 5)
    B = (0 * 10) + A = 5
    P TO NEXT LOWER DIGIT

SECOND ITERATION:
STEP 2: A = ‘6’
STEP 3: END OF STRING?
    NO
STEP 4: A = 6 (‘6’ – 30H = 6)
    B = (5 * 10) + A = 56
    P TO NEXT LOWER DIGIT

THIRD ITERATION:
STEP 2: A = ‘4’
STEP 3: END OF STRING?
    NO
STEP 4: A = 4 (‘4’ – 30H = 4)
    B = (56 * 10) + A = 564

Figure 4-10 Decimal String to Unsigned Binary
P TO NEXT LOWER DIGIT

FOURTH ITERATION:
STEP 2: A = ??
STEP 3: END OF STRING?
YES
RESULT: B = 5 6 4

4.6.4 Unsigned Binary to ASCII Hexadecimal Digits

Converting a binary number to a string of ASCII hex digits is quite similar to converting from binary to an ASCII decimal string, as described in Section 4.6.2. Here again, the digit space to allocate for the ASCII string depends on the size of the binary operand. An 8-bit binary is represented in two ASCII hex digits, a 16-bit binary into four ASCII hex digits, and so on.

The process of converting binary to ASCII hexadecimal consists of dividing the binary by 16 to obtain each hex digit. If the remaining hexadecimal digit is in the range 0 to 9 we add 30H to turn it into the corresponding ASCII digit. If it is in the range A to F then we must add 40H to convert into ASCII. The process continues until the original dividend is reduced to zero, as shown in the flowchart of Figure 4-11.

![Figure 4-11 Unsigned Binary to ASCII Hexadecimal String](image-url)
4.6.6 Signed Numerical Conversions

Conversion routines that use signed operands are usually a variation of the unsigned ones described in previous sections. Although logic can be developed that directly encodes to and from two’s complement format, the more convenient approach is to determine the sign of the operand then use unsigned conversion for the digit values. For example, to convert a signed binary in two’s complement form into a string of ASCII decimal digits the logic first determines if the binary operand is negative or positive. If a positive number, then the unsigned conversion routine can be used directly. If the binary operand is a negative number, the minus sign is placed in the storage buffer. Then the two’s complement binary is converted to an unsigned number so that the ASCII digits can be obtained with the conversion routine described in Section 4.6.2.
Chapter 5

Circuits and Logic Gates

In Chapter 1 we covered basic electronics and elementary circuit components such as resistors, capacitors, inductors, transformers, and simple semiconductors. In this chapter we expand these topics and introduce new ones so as to provide a basic background in digital electronics and in the electronic circuits that are often used in microcontroller-based systems. The chapter also contains information on some of the simpler electronic devices often found in electronic circuit boards, such as diodes, LEDs, and logic gates. Chapter 6 covers other circuit components including switches, seven-segment displays, LCDs (liquid crystal displays), buzzers, motors, and flip-flops.

5.0 Digital Circuits

Digital circuits are the basic building blocks from which microprocessors, microcontrollers, computer systems, and virtually all digital electronic devices are constructed. These building blocks are essential and perform elementary functions. A single device can contain thousands of these primitive components. Knowing about these elementary building blocks is necessary if you are to design or program digital circuitry.

Understanding these components requires viewing them at the proper level of abstraction. To understand a simple digital device you must know how the simpler transistors that make up the device operate. To understand how a shift register works it is useful to visualize it in term of the logic gates from which it is built. Similarly, once you understand how counters and registers work it is easy to grasp how a complex large-scale integrated circuit, such as a serial port, operates.

Fortunately, at any given level of abstraction, it is not necessary to consider every single device of that class, because knowing about one or two representative devices is usually sufficient. For example, once you understand the operation of a few different logic gates you can assume that others work in a similar manner. So we start by explaining the basic facts about diodes and transistors, then we consider logic gates that are built from transistors, then the more complex circuits that are built from elementary logic gates, and so on.
5.1 The Diode Revisited

Chapter 1 concluded with a brief discussion of diodes and p-type and n-type silicon junctions. The diode acts as a very useful one-way valve for electrical current and is one of the most powerful developments in semiconductor physics.

But in order to use the diode it is not necessary to comprehend the physical and electrical principles that make it work. Rather, the diode can be treated as a device made from two pieces of silicon and it has the property of passing current in one direction.

When a voltage is applied to the diode that makes the n-type end more positive than its p-type end, electrons flow from the n to the p direction, but not from the p to n direction. In this manner the diode behaves as a one-way filter that allows electrons to flow in one direction but not in the other one. Figure 5-1 shows the p-n junction in a diode and its electrical symbol.

![Figure 5-1 Diode Construction and Symbol](image)

The general convention is that current flows from positive to negative, although in reality electrons flow from negative to positive. Benjamin Franklin is usually held responsible for this erroneous convention. Therefore, current in the diode in Figure 5-1 flows from the anode to the cathode, but not vice versa.

The electrical symbol for a diode, in Figure 5-1, resembles an arrow pointing in the direction of current flow. When the anode voltage of a diode exceeds the cathode voltage the diode is said to be forward-biased. A forward-biased diode acts like a short circuit. To prevent too much current from flowing a resistor is usually inserted in series with the diode, as in Figure 5-2.

![Figure 5-2 Diode and Resistor in a Circuit](image)
The diode’s behavior can be also be represented by a curve that shows current-versus-voltage, sometimes called an I/V curve. If the voltage is represented on the abscissa of the Cartesian coordinate plane (x-axis) and current on the ordinate (y-axis), then the plot resembles the one in Figure 5-3.

In Figure 5-3 the current is non-linear; that is, it becomes very large if a positive voltage difference across the diode exceeds about 0.6 volts. This point is called the forward breakover point. If the diode is reverse-biased and the voltage is progressively increased, a point is reached in which the junction suddenly begins to conduct. This is called the avalanche point. The effect is similar to an internal short and the diode can be destroyed. Note that the I-V plot of a resistor is quite different from that of a diode. Since the resistor obeys Ohm’s Law its I/V curve would be a straight line.

The typical diode, such as the ones used in logic and display circuits, can handle a current of 10 to 20 milliamps. For a 5-volt supply a 300-ohm series resistor limits the current through the diode to a reasonable value.

5.1.1 The Light-Emitting Diode (LED)

One of the most useful types of diodes is an LED (light emitting diode). The LED produces light when it is forward-biased. The most common LEDs have a distinctive red color, although they may be amber, green, blue, or white.

The LED is a semiconductor device that emits incoherent light when forward-biased. The color of the light depends on the chemical composition of the semiconducting material. The first practical LEDs were developed in 1962. LEDs are
used in many electronic devices to signal the presence of an electric current. Like any diode, the LED consists of a chip of semiconducting material impregnated with impurities to create a p-n junction. As is the case in all diodes, current flows easily from the p-side, or anode, to the n-side, or cathode, but not in reverse.

The first LEDs were made of gallium arsenide. Today LEDs are made of a variety of materials so as to produce light of different colors.

Advances in materials science have made possible the production of devices with ever shorter wavelengths, producing light in a variety of colors.

Because LEDs are diodes they light only with positive electrical polarity, that is, when forward-biased. When the polarity is reversed very little or no light is emitted by the LED. Figure 5-4 shows a typical LED.

![Figure 5-4 A Typical LED](image)

The correct polarity of a new LED can usually be determined by observing that the longest terminal is the anode. If the terminals have been altered, then it is risky to try to determine polarity by observing the LED’s internals. Although in most LEDs the larger internal tab is the cathode, there are others in which it is not. A more dependable clue to the LED’s polarity is the flat tab on the LED’s base, which indicates the cathode, as in Figure 5-4.

Ratings vary among the different sizes and types of LEDs. Most LEDs are rated to operate between 1.7 and 3.8 volts and at currents of 10 to 40 mA. The light-emitting capacity of an LED is measured in megacandela or mcd. Small commercial LEDs range from 10 to about 5000 mcd.

Once the LED’s ratings and circuit’s voltage are known it is necessary to calculate the value of the series resistor so that the current does not exceed the LED’s capacity. For example, the series resistor for wiring a commercial red LED rated at 2.6 VDC and 28 mA on a 5 volt circuit is calculated as follows:

**STEP 1:** Calculate the voltage across the resistor by subtracting the LED’s forward voltage from the supply voltage, in this case:

**STEP 2:** Apply Ohm’s Law to calculate the required resistor:

The electronic symbol for an LED is somewhat similar to that for a diode, as shown in Figure 5-5.
As a simple experiment, connect an LED in series with a 330-ohm resistor to a 5-volt power supply and see how light is emitted for one orientation of the diode and not emitted for the other. This little circuit makes a convenient probe for logic circuits. If the LED’s cathode is touched to some point in a circuit, the LED lights up if the voltage at that point is less than about one or two volts. The LED remains dark if the voltage is greater than this value. This is a 1-bit binary digital voltmeter.

In addition to LEDs, there are logic diodes such as the 1N4148 or its equivalent, the IN914. These are used simply to ensure that the current in some circuit can flow in only one direction. There are also much heftier diodes that are used to manufacture the DC power supplies needed for computers and other electronic equipment. They take the 110-volt AC that comes out of wall outlets and converts it to a unidirectional DC voltage.

5.2 The Transistor

The transistor is a solid state semiconductor device that is used for signal amplification, voltage stabilization, switching, signal modulation, and many other functions. It can be considered as a variable valve which controls the current it draws from a voltage source. Transistors are manufactured as individual components or as part of an integrated circuit. Transistors come in two basic varieties: bipolar and MOS.

5.2.1 Bipolar Transistor

The bipolar transistor was the first type of transistor to be commercially mass-produced. The terminals of a bipolar transistor are named emitter, base, and collector. Physically, the bipolar transistor consists of two n-type regions separated by a thin p-type region or, alternatively, by two p-type regions separated by a thin n-type. When a transistor has two n-type regions, the device is called an NPN transistor. One of the n-type regions is called the collector, the other the emitter, and the central p-type region the base. The NPN bipolar transistor is shown in Figure 5-6.
Simply, a bipolar transistor consists of two diodes connected back to back so that they share a common end. Since the central base region between the collector and emitter is very thin, the device has the unique property of serving as an amplifier. When the transistor's base-to-emitter p-n junction is forward-biased (this could be called the p-n diode) it creates a low resistance in the thin base region. This allows a much larger current to flow from the collector to the emitter. If the base-emitter current is turned off, then the collector-emitter current is also completely turned off. In this case the transistor is said to be cut off.

Over a given range, the collector-emitter current is directly proportional to the base-emitter current. In this manner the transistor amplifies small currents into larger ones, as in radios and other sound amplifying applications. For larger base currents the transistor acts as if there were nearly a short circuit between the collector and the emitter. In this case the transistor is said to be in saturation.

The effect is that a positive voltage on the base turns on the transistor and pulls the output low (to about 0.5 volts). When this voltage is removed, the transistor is turned off and the output is high (+5 volts). The action is that of a current controlled switch, as shown in Figure 5-7.

![Figure 5-7 NPN Transistor Used as a Switch](image.png)

The circuit in Figure 5-7 operates as follows: if the input voltage is held at zero volts, the p-n base-emitter junction has no current flowing through it and the output voltage is +5 volts. However, if the input voltage is raised to any value between +2 and +5 volts, a base-emitter current flows. This in turn allows a collector-emitter current to flow and the output voltage is pulled down to ground (typically between 0.5 and 1 V).

An alternative architecture for a bipolar transistor is called PNP. In this case the n-type silicon is sandwiched between two p-types, as shown in Figure 5-8.
The PNP transistor in Figure 5-8 works in the same way as the NPN transistor, except that in the PNP design the base has to have a negative voltage with respect to the emitter in order to turn on the transistor.

### 5.2.2 MOS Transistor

The second major type of transistor is the metal oxide semiconductor transistor, or MOS. It consists of two separate n-type regions embedded in p-type silicon. Alternatively, the MOS can consist of two p-type regions embedded in n-type silicon. In the first case the device is called an n-channel MOS (or NMOS) transistor; in the second case it is called a PMOS.

One of the two n-type regions is called the **source**, and the other is called the **drain**. An area between the source and the drain consists of a metal contact separated from the p-type body by a thin layer of non-conductive silicon dioxide. This area is called the **gate**. When a positive voltage is applied to the gate, the electric field attracts a thin layer of electrons into the p-type region underneath the gate. This provides a low resistance path between the two n-type regions. Figure 5-9 shows the construction of an NMOS transistor and the symbols for the NMOS and PMOS.
In construction of the MOS transistor the body is connected internally to the source. In the electrical symbols this is indicated by the central wire with an arrow. In the NMOS transistor the direction of the arrow indicates that electrons in the body are attracted to the gate when a positive voltage is applied. This same voltage repels electrons in the PMOS.

One of the most valuable features of the MOS transistors is that they require very small currents to turn on. This makes the MOS transistors behave like voltage-controlled switches in a digital circuit. Recall that the bipolar transistors operate as current-controlled switches.

5.3 Logic Gates

A logic gate is an electronic device that takes one or more binary signals as inputs and produces a binary output that is a logical function of the input or inputs. The basic logical operations of AND, OR, XOR, and NOT were covered in Section 4.1. Although logic gates can be made from electromagnetic relays, mechanical switches, or optical components, nowadays they are normally implemented using diodes and transistors.

Charles Babbage's Analytical Engine, developed around 1837, used mechanical logic gates based on gears. Electromagnetic relays were later used for logic gates, and these were eventually replaced by vacuum tubes, since Lee De Forest's modification of the Fleming valve can be used as an AND logic gate. In 1937, Claude E. Shannon wrote a thesis paper that introduced the use of Boolean algebra in the analysis and design of switching circuits. The first modern electronic gate was invented by Walther Bothe in 1924, for which he received part of the 1954 Nobel Prize in physics.

The primitive types of gate are AND, OR, and NOT; in addition, the XOR gate offers an alternative version of the OR. The other Boolean operations can be implemented by combining the three primitive types. However, for convenience, other combined types have been developed. These are called NAND (NOT plus AND), NOR (NOT plus OR), and XNOR (XOR plus NOT). The advantage of these secondary logic gates is that they require fewer circuit elements for a given function. In fact, the NAND gate is the simplest of all gates, except for the NOT gate. Also, a NAND can implement both a NOT and an OR function; therefore, it can replace AND, OR, and NOT. The NAND gate is the only type actually needed in a real system. Programmable logic arrays very often contain nothing but NAND gates. The symbols for logic gates are shown in Figure 5-10.

The notion of a binary signal is accomplished by allowing it to be in only one of two states. These states are designated as high and low. Conventionally, we represent a high signal with binary digit “1” and a low with a binary digit “0.” True and false and high and low are also associated with binary signals, binary 0 representing false or low and binary 1 representing true or high. In digital electronics, voltage is used to encode binary 0 and 1. A voltage of about 0.5 volts (actually 0 to 0.8 volts) is interpreted as logic 0 and a voltage of about 3.5 volts (actually 2.4 to 5.0 volts) is interpreted as logic 1. Voltages from 0.8 to 2.4 volts are not allowed. This voltage convention is referred to as TTL (transistor-transistor logic).
5.4 Transistor-Transistor Logic

Transistor-Transistor Logic is a class of digital circuits built from bipolar transistors and resistors. TTL is used in a popular family of integrated circuits originally developed by Texas Instruments in 1962. These are known as the 7400 series of ICs. Components of the 7400 family are used in computers, industrial controllers, music synthesizers, and electronic test and measurement instruments. TTL provided a low-cost digital option to the expensive analog methods of the day.

TTL integrated circuit are available to perform the following functions:

1. logic gates such as AND, OR, NAND, NOR, and XOR
2. flip-flops
3. latch elements
4. counters and adders
5. shift registers
6. timing circuits
7. data bus drivers and buffers
8. display drivers
9. multifunction logic
10. memory
11. programmable logic arrays
The TTL logic gates require a 5-volt DC power supply regulated to within 5% (5V ± 0.25V). They are available in a variety of packages. For prototyping and manually built applications the most-used package is the dual inline package (DIP). DIP integrated circuits have 14, 16, 20, 24, 28, or 40 pins arranged in a row along two sides of a rectangular plastic package containing the silicon chip. The ground pin is usually the last in the first row. For example, pin 7 of a 14-pin DIP. The 5-volt power pin is usually the highest numbered pin. For example, pin 14 on the 14-pin DIP. The pins in a DIP package are spaced 0.1" apart. DIP components are mounted on a printed circuit board by inserting the pins through a set of holes and then soldering the pins in place. Figure 5-11 shows two integrated circuits in a DIP package.

![Figure 5-11 Dual Inline Packaged (DIP) Integrated Circuits](image)

One objection to DIP packages is that they become too large if more than 40 pins are required. The pin grid array (PGA) is one solution to this problem. PGAs are square packages with an array of pins coming out of the bottom. Microprocessors are sometimes implemented in PGAs. Surface mount technologies are often used in commercial electronic boards, since they allow fitting more circuitry into a smaller space. The pins on surface mount packages are bent out horizontally and soldered to the top surface of the board. In surface mount ICs the pin spacing is .05 inch or less. But surface mount packages are difficult to handle outside of commercial production, since the smaller pins spacing require special soldering irons and inspection microscopes. For non-manufactured projects, such as the ones in this book, the DIP is the most suitable.

In the present context we discuss TTL logic gates furnished as integrated circuits constructed using semiconductor electronics. The part number of logic gate ICs is in the format 74XXX, where XXX refers to the specific gate implementation.

### 5.4.1 Inverter Gates

IC number 7404 is a hex inverter. Here the term hex refers to the six inverters included in the circuit. Figure 5-12 shows the schematics of the 7404 hex inverter.

![Figure 5-12 7404 TTL Hex Inverter IC](image)
The function of a given logic gate can be shown in a truth table, such as the one in Figure 5-12. The truth table lists the outputs (high or low) for the given inputs (also high or low).

5.4.2 The AND Gate

The 7408 is an AND gate that includes four individual gates per package. The 7408 AND gate and its truth table are shown in Figure 5-13.

![Figure 5-13 7408 Quad 2-input AND Gate](image)

The AND gate in Figure 5-13 is described as quad 2-input. Four individual AND gates are contained in the circuit and each one has two input lines. The gate logic corresponds to the Boolean AND: if both inputs are high, then the output is high, otherwise the output is low. If the input lines are designated as $A$ and $B$, and the output as $Y$, then the AND operation can be expressed in the equation:

$$Y = A \cdot B$$

In this case the dot operator represents the AND function, not arithmetic multiplication.

5.4.3 The NAND Gate

A variation of the AND gate is the 7400 NAND gate. In this case the AND operation is replaced with the inverted AND, or NAND. Thus, if both inputs are high, the output is low, otherwise the output is high. The 7400 NAND gate is shown in Figure 5-14.

![Figure 5-14 7400 Quad 2-input NAND Gate](image)
Note that in the NAND gate of Figure 5-14, the AND symbol has been replaced with the NAND symbol as in Figure 5-10. The logic equation for the NAND gate is the combination of the AND and NOT operations, as follows:

\[ Y = \overline{A \cdot B} \]

Here the vertical bar over the equation’s right-hand side indicates negation.

### 5.4.4 The OR Gate

The 7432 OR gate performs the Boolean OR of the two input lines. If either line \( A \) or line \( B \) is high, then line \( Y \) is high, otherwise line \( Y \) is low. Figure 5-15 is a diagram of the 7432 quad 2-input OR gate.

\[ Y = A + B \]

The plus sign in the previous equation indicates the Boolean OR operation, not arithmetic addition.

### 5.4.5 The NOR Gate

Another version of the OR gate is the 7402 NOR quad 2-input NOR gate. Here the Boolean OR is negated, as shown in Figure 5-16.
The equation for the NOR gate consists of negating the inputs of the OR gate, as follows:

\[ Y = \overline{A + B} \]

The gates shown in this section contain two input lines, labeled \( A \) and \( B \). Logic gates are also available that contain more than two inputs, for example, the 7410 is a three 3-input NAND gate. Other logic gates with 3, 4, and 8 inputs are available. For example, the 7410 is a three 3-input NAND gate, the 7420 a two 4-input NAND gate, and the 7430 is a single 8-input NAND gate.

5.4.6 Positive and Negative Logic

The gates discussed so far assume that logic high is regarded as true and logic low as false. This is called positive logic. If we were to invert these assumptions so that logic high is regarded as true and logic low as false we would have a system based on negative logic. In this case the AND and the OR functions would be exchanged in regards to positive logic.

Digital circuit designers can often reduce the number of required integrated circuits by switching between positive and negative logic. For example, if an extra AND gate is available but the circuit requires an OR gate, the AND gate can be used by assuming negative logic. Circuit diagrams can be shown to use positive or negative logic by the position of the inverting circles. By convention, a circle on the input lines indicates negative logic and positive logic if it is placed on the output line. Figure 5-17 shows the equivalent circuits for gates using positive and negative logic.

![Figure 5-17 Circuit Symbols for Positive and Negative Logic Gates](image)

The position of the inverting circles in the circuit diagrams is consistent with the notion that inverting the inputs changes the gate function. Thus, a negative logic AND gate functions as an OR gate and vice versa. In this manner a circle on the input line is read as the signal on that line being active low. An active low signal is asserted as true when it is electrically low. For example, the output of the 2-input NAND gates of Figure 5-14 is low when inputs A and B are both high, as shown in the
circuit truth table. But the NAND gate can also be interpreted as a negative logic OR gate as in Figure 5-17. The one logic operation that is the same in negative or positive logic is NOT, as also shown in Figure 5-17.

An alternative explanation of positive and negative logic can be based on the truth table for the Boolean OR, as follows:

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>T</td>
<td>F</td>
<td>T</td>
</tr>
<tr>
<td>F</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>

In binary form and positive logic the OR truth table is as follows:

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

If we now invert the binary values in the second table, the results are as follows:

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Note that the last truth table matches that of the AND function. Thus, by inverting the truth table for the logical OR we produced the truth table for logical AND, validating the previous assertion that a negative logic AND gate is equivalent to an OR gate.

### 5.4.7 The XOR Gate

The last elementary logic gate is called the XOR or exclusive OR gate. In the XOR function the output is high if the inputs have opposite values, otherwise the output is low. Figure 5-18 shows the 7486 quad 2-input XOR gate and the corresponding truth table.

![Figure 5-18 7486 Quad 2-input XOR gate](image-url)
Since an XOR gate’s output is high if the inputs are different it can serve as a difference detector for logic levels. The following equation expresses the XOR relationship for two inputs (labeled \( A \) and \( B \)) and one output (labeled \( Y \)).

\[ Y = A \oplus B \]

The logic symbol for XOR is the symbol for OR (\( + \)) enclosed in a circle. The XOR function can also be expressed in terms of Boolean OR and AND operations, as in the following equation:

\[ Y = (A \cdot \overline{B}) + (\overline{A} \cdot B) \]

Figure 5-19 is the circuit diagram for the XOR gate constructed from OR, AND, and NOR gates.

![Figure 5-19 XOR Gate Circuit Diagram](image)

Note in the XOR truth table in Figure 5-18 that if one of the inputs is forced high, then the gate functions as an inverter for the other input. Also, note in the truth table for the NOR gate (Figure 5-16) that if both inputs are low or high, then the circuit also functions as an inverter. If the inputs of a NOR gate are tied together the gate performs as an inverter. Often a circuit designer can take advantage of these identities in order to use an available gate for a function other than the one originally intended, thus saving having to use an additional IC.

### 5.4.8 Schmitt Trigger Inverter

Digital signals used in operating electronic devices consist of pulses. Conceptually, the pulses instantly fluctuate between a high and a low voltage level, ideally generating a square waveform. But signal noise in a circuit often contaminates the waveform into a non-rectangular shape. This noise can be the cause of circuit problems. For example, consider a plot of output voltage versus input voltage for a simple inverter, as shown in Figure 5-20.
In Figure 5-20 you notice that as the input voltage is raised from zero, the output voltage stays high. However, when the input voltage reaches about 1.4 volts (dashed line in Figure 5-20) the output switches sharply from high to low. Now suppose there is noise on the input line and that this noise causes the voltage to go above 1.4 volts and then below this value. In this case, the inverter’s output may also switch its logic state several times during the transition period following the voltage fluctuations.

One common solution to this problem is based on a property of physical systems called *hysteresis*. Although the term derives from a Greek work meaning deficiency, it can also be related to “history.” In this sense hysteresis refers to the property of an object that does not instantly follow the forces applied to it, but reacts “historically” to these forces. In other words, the new state depends on the object’s immediate history. Adding hysteresis to a circuit’s input makes it so that the point at which the output changes state depends on the current state of the output. For example, if output is high, it does not go low until the input voltage is raised above 1.7 volts. On the other hand, once the output goes low it will not change back to high until the input falls below 0.9 volt. This “lag” before changing to a new state makes the output much less susceptible to being inadvertently switched by noise. Figure 5-21 shows a plot of the input versus the output currents on a circuit with hysteresis.

![Figure 5-20 TTL Input and Output Voltage](image1)

**Figure 5-20** TTL Input and Output Voltage

In Figure 5-20 you notice that as the input voltage is raised from zero, the output voltage stays high. However, when the input voltage reaches about 1.4 volts (dashed line in Figure 5-20) the output switches sharply from high to low. Now suppose there is noise on the input line and that this noise causes the voltage to go above 1.4 volts and then below this value. In this case, the inverter’s output may also switch its logic state several times during the transition period following the voltage fluctuations.

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![Figure 5-21 Effect of Hysteresis in an Inverter Circuit](image2)

**Figure 5-21** Effect of Hysteresis in an Inverter Circuit
Logic gates whose input has hysteresis are often known as a Schmitt trigger. Figure 5-22 shows a 7414 hex Schmitt trigger inverter.

![7414 Hex Schmitt Trigger Inverter](image)

Figure 5-22 7414 Hex Schmitt Trigger Inverter

Note in Figure 5-22 that there is a small hysteresis curve inside each inverter symbol. This indicates that the inverters are the Schmitt triggers.

5.5 Other TTL Logic Families

In 1971 a major advance in TTL logic occurred with the introduction of TTL devices that incorporate Schottky diodes. They are based on the property of aluminum to act much like a p-type semiconductor when in contact with n-type silicon. The Schottky diode acts like an ordinary p-n diode except that it has a faster response time and the voltage drop is about 0.3 volts instead of 0.6 volts. When a Schottky diode is connected between the base and the collector of a bipolar transistor, the transistor is prevented from going into saturation. The Schottky diode/transistor combination, known as a Schottky transistor, has a significantly faster switching speed. Schottky TTL logic devices have part numbers 74SXXX and give three times the speed of standard TTL using only twice the power.

By increasing the resistor sizes, low-power Schottky TTL was developed giving the same speed as standard TTL, but using only 1/5 the power. These devices, whose part numbers are in the format 74L5XXX, were the standard TTL logic parts for many years. In 1980, more sophisticated Schottky-type logic circuits using smaller, higher performance transistors were developed by Texas Instruments. These are the advanced Schottky and advanced low-power Schottky logic families. Their part numbers are 74ASXXX and 74ALSXXX respectively.

5.6 CMOS Logic Gates

Around the same time that the original TTL circuits using bipolar transistors were introduced, a line of logic circuits using CMOS (complementary metal-oxide semiconductor) technology became available. A line of TTL-compatible CMOS ICs have part numbers 74XXX. TTL series pinouts are also available with part numbers 74CXXX.

CMOS logic circuits have two significant advantages over TTL. In the first place, CMOS circuits operate with very low power dissipation. A CMOS input requires virtually no current to remain at a given logic level. In fact, the entire circuit draws insignificant current when it is not switching between logic levels. In CMOS, power is
consumed only during switching, while bipolar logic power dissipation is only weakly dependent on the switching rate. At low switching rates, CMOS provides huge savings in power dissipation.

A second advantage of CMOS is the smaller size of the circuits. Since no resistors and only two simple types of transistors are needed, the resulting logic gates require less area on a silicon wafer than their bipolar counterparts. The combined advantages of less power consumption and less area make CMOS the choice for VLSI (very large scale integration) integrated circuits such as microprocessors.

However, there are also significant drawbacks to CMOS which have prevented it from completely replacing bipolar logic. One of them is that CMOS circuits have slower switching speeds and propagation delays compared to bipolar circuits. The original CMOS logic gates had switching speeds that were about five to ten times slower than the 74XXX bipolar logic gates. High-speed CMOS, introduced in 1980, have improved processing technology and smaller transistor sizes, resulting in higher switching speeds and improved output drive current capability.

The CMOS 74HCT parts are completely TTL-compatible and can be freely intermixed with bipolar TTL parts. The 74HC series, on the other hand, have a logic transition threshold of 2.5 V when using a 5-volt power supply, compared to the 1.4 volts TTL standard. Since CMOS outputs have 5-volt and 0-volt logic levels, a 2.5-volt threshold provides better noise immunity than TTL; however, 74HC series parts cannot be mixed with standard TTL parts. For this reason, in mixed circuits, it is preferable to use the 74HCT parts.

An advanced CMOS technology family was introduced in 1985 having part numbers 74ACXXX. The TTL-compatible versions have part numbers 74ACTXXX. These new ICs have about double the speed of HC and HCT with yet another increase in drive power. The result is that the propagation delays for 74ACT parts approach those of bipolar TTL, although they are not quite equal to the fastest TTL families. To further increase CMOS speeds manufacturers turned to a process known as BiCMOS, which uses a mixture of bipolar and MOS transistors on the same chip. By strategically placing bipolar transistors at critical points in the circuit, the switching speed can be improved with only a small increase in power dissipation. The most popular BiCMOS logic family is the 74FCTXXX (fast CMOS) series of logic ICs.

Still another drawback to CMOS logic is that the circuits are susceptible to static electricity. The static discharge of the human body in a dry environment can destroy a CMOS transistor. Although protective diodes on CMOS circuit inputs provide some protection to static breakdown, all CMOS circuits are susceptible. For this reason ICs and circuits boards should be stored in conductive pouches and not handled until you have discharged yourself by touching a good electrical ground.
Chapter 6

Circuit Components

This chapter covers the most common general-purpose circuit components often found in microcontroller boards. Some simpler circuit devices such as diodes, LEDs, and logic gates, were discussed in chapter 5. Here we mention other common components including power supplies, switches, clocks and timers, flip-flops, decoders, seven-segment displays, and liquid crystal displays (LCDs). Other components sometimes found in microcontroller-based digital circuits are not discussed either because of their simplicity (buzzers and relays), their passive nature (connectors, adapters, batteries, and wiring), or their specialized features (motors, digital-to-analog and analog-to-digital converters, and memory).

6.0 Power Supplies

Standard logic circuits usually require a power source of +5 VDC. One possible source of +5 VDC is in one or more batteries. A D-cell battery generates 1.5 volts, so three of them can be connected in series to produce 4.5 VDC. An alternative power source can be from the standard wall outlet. Household electrical service in the United States is in the form of 110 volt AC (alternating current) power. Actually, 110 volts is the root mean square value of a sine wave that oscillates 60 times per second from about +155 volts to about -155 volts. The circuitry required to convert 110 VAC into 5 VDC is known as a power supply.

To obtain +5 VDC from 110 VAC requires scaling down the voltage and converting alternating current to direct current. In addition, most power supplies include a voltage regulator component that ensures that the circuit voltage is exactly +5 volts. The circuit in Figure 6-1 (in the following page) is a regulated 5-VDC power supply. The transformer reduces the household voltage from 110 to about 12 VAC. The diodes rectify the input to an oscillating signal of about +12 VDC. The 100mF electrolytic capacitor smoothes out the oscillation producing a largely DC voltage with little ripple. The 7805 is a voltage regulator that accepts an input voltage from about 8 volts to about 35 volts and produces a constant 5V output. Voltage regulator ICs are Zener diodes with a precise, reverse-biased breakdown voltage.
The 7805 is usually mounted on a metal base with a drilled hole so that a heat sink can be attached to it. With a heat sink the 7805 can produce up to 1 amp output. Figure 6-2 shows a 7805 voltage regulator IC.

A flip-flop is an electronic circuit with two stable states, since its output is either 0 or +5 VDC. In this context we say that a flip-flop is set if it stores a binary 1 and reset otherwise. The RS designation refers to the Reset and Set stages. The flip-flop can also be said to have memory since its output remains set or reset until it is intentionally changed. When the flip-flop output is 0 VDC it can be regarded as storing a logic 0 and when its output is +5 VDC as storing a logic 1.
Flip-flops can be constructed using primary logic gates. One possibility is using two NAND gates, as in Figure 6-3.

![Figure 6-3 NOR Gate-based RS Flip-flop](image)

Recall from Chapter 5 that a NAND gate is equivalent to a negative logic OR gate; this makes the flip-flop easier to understand. Looking at Figure 6-3, first consider that the Set input is pulled low by flipping the switch counterclockwise and sending the input to ground. In this case the output of the upper gate (1) is forced high since the gate’s output goes high if either input 1 or input 2 is low. Since the Reset input to the lower gate is high (4), then neither input of the lower gate (3 or 4) is low and its output is low. Note that input 3 is low because the bubble on the lower OR gate inverts the value fed back from the upper OR gate. Now the feedback line from the lower gate (6) sends low to input 2 on the upper gate, which is inverted by the upper gate bubble. So both inputs to the upper gate are high, determining that the upper gate’s output remains high even when the Set input returns to a logic high, as would be the case if the switch were turned back to the neutral position. Thus, the Q output of the flip-flop stays high (and the inverted Q output remains low). When the flip-flop is in this state, it is set. The flip-flop is placed in the cleared state by momentarily pulling the Reset input low. This forces the lower gate’s output to be high and the upper gate’s to be low.

The action of the flip-flop in Figure 6-3 is consistent with the description of a device with two steady states, labeled Set and Reset, and controlled by two corresponding input lines. Once a device is in either state, it remains in that state until the opposite state is enabled, thus “remembering” its set or reset status. The rotary switch mechanism ensures that the device will have either two high input lines or one high and one low. The condition of two low input lines is not allowed in this flip-flop, as shown in the truth table.

<table>
<thead>
<tr>
<th>Set</th>
<th>Reset</th>
<th>Q</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>H</td>
<td>no change</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>H</td>
<td>H</td>
<td>L</td>
</tr>
<tr>
<td>H</td>
<td>L</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>L</td>
<td>L</td>
<td>disallowed</td>
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</tbody>
</table>

All mechanical switches used in electronic devices contain a spring of some sort. It is this spring that maintains the switch’s contact in either position, but it also makes the switch electrically “bounce” whenever it is activated. Although the bounce only takes a few milliseconds, the logic level can change between high and
low several times during this period. If an RS flip-flop is connected to the switch, the first contact switches the flip-flop and subsequent ones have no effect, thus effectively “debouncing” the switch.

6.1.2 Clock-ded RS Flip-flop

So far the circuits discussed are examples of *combinatorial* or *asynchronous logic*. If we ignore a few nanoseconds of propagation delay, in combinatorial circuits the outputs change as soon as the inputs change. Although in theory you can build complex logic circuits using combinatorial logic, it is more convenient to use clocked logic pulses to ensure high reliability and noise immunity. Circuits that use clocked impulses are said to use *synchronous logic*.

In synchronous circuits unconstrained changes in logic gate outputs are not allowed. Instead, the logic is designed so that logic level changes can progress through the circuitry one stage at a time under control of a clock. Between the clock pulses that cause changes to take place, the temporary state of the system is stored in memory elements or flip-flops.

In clocked or synchronous logic all the gates in the system change outputs at the same time. The output state of each gate depends only on the state of the gate inputs at the time of the clock pulse. In combinatorial circuits the gates may briefly “see” the wrong logic level and cause incorrect operation of the circuit. With clocked logic, the gate outputs “settle down” during the time between clock pulses so that only valid logic levels are present by the time the next clock pulse arrives.

The RS flip-flop in Figure 6-3 is not suitable for use in a clocked logic circuit because its output changes immediately whenever the Set or Reset inputs change. However, the circuit can be made into a clocked RS flip-flop by adding two NAND gates, as shown in Figure 6-4.

![Figure 6-4 Clock-ded RS Flip-flop](image-url)
In the clocked flip-flop of Figure 6-4 the Set and Reset inputs can change at any time, but those changes are ignored by the flip-flop except during the interval when the logic high of a clock pulse is present. During the clock pulse the state of the Set or Reset line is stored by the flip-flop.

6.1.3 The D Flip-flop

One of the objections to the flip-flops in Figures 6-3 and 6-4 is that there are two data input lines, labeled Set and Reset in the illustrations. One possible solution is to only use one of the inputs by connecting an inverter between the Set line and the Reset input. The circuits for a D Flip-flop are shown in Figure 6-5.

The name D (or data) flip-flop originates in the fact that it contains a single data line. The D flip-flop is also called a transparent latch, or a D latch. In the D flip-flop the state of the input line, called the D input, is stored in the flip-flop when a clock pulse occurs. An advantage of this design is that the disallowed state (see Figure 6-3), in which both Set and Reset are simultaneously low, cannot be reached accidentally.

A flip-flop can be used for storing binary data. To visualize how this can be done, imagine four D flip-flops driven by the same clock signal. When the clock goes high, input data is loaded into the flip-flops and appears at the output. When the clock goes low, the output retains the data. For example, consider four data inputs, as follows:

\[ D_0D_1D_2D_3 = 0101 \]

When the clock signal goes high, these four bits are loaded into the D latches, resulting in the output:

\[ Q_0Q_1Q_2Q_3 = 0101 \]

This operation is represented in Figure 6-6.
In the 4-bit D latch of Figure 6-6 the output data is stored as soon as the clock goes low. For as long as the clock is low, the D values can change without affecting the Q values. The 7475 IC contains four D flip-flops and is called a quad bistable latch. This circuit is well suited for handling 4-bit data bits simultaneously (one nibble).

**6.1.4 The Edge-triggered D Flip-flop**

The D flip-flop or transparent latch is available in several versions in addition to the 7475. Although the pure D flip-flop is a useful IC, for some applications it has the drawback that outputs follow the D input during the entire time that the clock line is high. In some circuits it would be ideal to have a flip-flop that stores data at a unique point in time. The edge-triggered D-type flip-flop approaches this behavior. In this device, the flip-flop stores the state of the data line at the instant the clock signal makes a transition from low to high and ignores it otherwise. Figure 6-7 shows an edge-triggered D flip-flop.

**Figure 6-7 Edge-Triggered D Latch**

The circuit in Figure 6-7 is sometimes called an RC differentiated clock input latch. In this case RC stands for the resistor/capacitor combination at the input of the D latch. By design, the RC time constant is made smaller than the clock's pulse width. This determines that the capacitor fully charges when the clock goes high,
producing a narrow positive voltage spike across the resistor. Later, the trailing edge of the pulse results in a narrow negative spike, enabling the AND gates for a brief period. The effect is to activate the AND gates only during the positive spike; the negative spike does nothing in this circuit. The result is equivalent to sampling the value of D for an instant. At this point in time, D and its complement hit the flip-flop inputs, forcing Q to set or reset (unless Q is already equal to D).

### 6.1.5 Preset and Clear Signals

The use of flip-flops in digital circuits usually requires some way of placing the signals in a known state. In this sense a *Preset* signal is used to make sure that the Set line is high, and a *Clear* signal to make sure that the Reset line is high. Alternatively, these signals are referred to as *Preset R* and *Preset S*. Figure 6-8 shows how the Preset and Clear functions can be implemented in an RS flip-flop.

#### Figure 6-8 Implementing Preset and Clear

The OR gates in the circuit of Figure 6-8 allow selectively setting the S or the R lines of the edge-triggered D flip-flop. The Preset and Clear signals are called *asynchronous inputs* since they activate the R or S lines of the flip-flop independently of the clock. The D input, on the other hand, is *synchronous* since it has an effect only when the clock edge signal is high. Figure 6-9 shows the electrical symbol for a positive edge-triggered flip-flop with active high Preset and Clear lines.

#### Figure 6-9 D-Type Edge-triggered Flip-flop Symbol
In the normal mode of operation, a D-type flip-flop has the Set and Clear inputs high (not active), so that a transition of the clock input from low to high (called a positive edge) clocks the value of D into Q and the inverse of D into not-Q. The clock transition is required; D can do anything it wants to, but nothing happens to Q and not-Q until a positive edge occurs on the clock line.

6.1.6 D Flip-flop Waveform Action

An easy way of understanding the interaction of the various signals in a clocked RS flip-flop is by means of a waveform diagram. The reference circuit is the one in Figure 6-8. This includes a clock signal, a data input line, Preset and Clear lines, Set and Reset input lines into the flip-flop, and Q and not-Q output lines. The signals are described as follows:

1. The clock signal (CLK) is a square wave that oscillates between a high and a low state. It provides a synchronized beat that coordinates the various digital devices present in the circuit.

2. The data signal is used as a single input line into the flip-flop. Setting the data signal high also sets high the flip-flop’s Set line. A low data signal makes the flip-flop Reset line high.

3. The Set signal or line is one of the two inputs into the flip-flop. The other one is the Reset line.

4. The Preset line is used to make the flip-flop set line active. The Clear signal has the effect of setting high the Reset line into the flip-flop.

5. The Q and not-Q lines provide the flip-flop output. Q is high if the Set line is high; otherwise the not-Q line is high.

Figure 6-10 is a waveform diagram for a clocked RS flip-flop.

*Figure 6-10  Waveform Diagram for Clocked RS Flip-flop*
In reference to Figure 6-10 note that the clock input (at the top of the illustration) provides the synchronization beat for the flip-flop inputs (R and S) and the outputs (Q and not-Q). However, the Preset and Clear signals are asynchronous, that is, they operate independently of the clock pulse. Therefore, when the Preset line is set high, the S input line into the flip-flop immediately follows. However, the Q output line must wait until the next rising clock pulse, which corresponds to the dot-dash line labeled Set in the illustration. Similarly, the Clear signal immediately sets the R line; however, the not-Q output is not set until the next rising clock pulse. Note that during clock pulse number 4 both the R and S lines are held low. This corresponds to the hold state and the output on lines Q and not-Q remains unchanged.

6.1.7 Flip-flop Applications

The D-type flip-flop finds many uses in digital technology. Perhaps the most obvious one is as a memory. The flip-flop stores the value clocked into it from the D line; said value can be read on the output lines Q and not-Q. A type of memory known as static RAM is implemented as a large array of flip-flops with address decoding circuitry that allows selecting which flip-flop is being accessed by a read or write operation. Processors and microcontrollers contain many flip-flops, usually in the form of registers, which are just a group of 8, 16, 32, or 64 flip-flops. Flags are also flip-flops that are set or cleared by the results of the CPU’s internal operations.

Digital devices interface with the outside world by means of input and output ports. These elements are implemented as flip-flops. For example, supporting the logic requires turning on a LED so as to signal that some event has occurred. To achieve this, a data line from the digital device can be connected to the D input of a flip-flop. Then a pulse is sent on another line to the clock input. When the clock pulse goes from low to high, the state of the data line at that instant is clocked into the flip-flop. This state remains on the Q output until a new value is clocked in. Another example is the 74374 IC, which contains 8 flip-flops in a single 20-pin DIP package. The chip is called an octal latch because data is latched into all eight flip-flops all at once by a single clock line.

D-type flip-flops are also used in implementing digital interfaces; for example, to have a digital device read in data from some external source, such as a switch. Each time new data is produced by the switch, a flip-flop is set and the output of this flip-flop is connected to an interrupt request line (IRQ) on the device. When the IRQ line goes high, the microcontroller saves its current state and branches off to an input routine that takes some action according to the state of the switch; for example, turns on a LED if the switch is high. To prevent the microcontroller from getting interrupted again by the same input, the same signal is also used to clear the flip-flop until the next data byte comes along.

6.2 Clocks

A clock signal consists of a sequence of regularly spaced pulses, typically in the form of a square wave. Digital devices use the rising or the falling edges of the square wave to run logic circuits. Clocks provide the heartbeat without which the system would cease to function.
6.2.1 Clock Waveforms

In a digital device, such as a microcontroller system, the clock provides a periodic waveform that is used as a synchronizing signal. Although the typical clock waveform is depicted as a square wave (as in Figure 6-10) it need not be perfectly symmetrical. In fact, a series of positive or negative waves could serve as a timing pulse in a digital circuit. The one requirement of a clock pulse is that it be perfectly periodic.

The basic timing interval for a digital circuit, which is equal to one full waveform period, is called the clock cycle. This determines that all logic elements in the circuit, including gates and flip-flops, complete their transitions in a complete clock cycle or less.

We can assume that the ideal clock produces a perfectly square waveform that is absolutely stable, as the one shown in Figure 6-11.

![Figure 6-11 Ideal Waveform](image)

A stable and uniform waveform reaches exactly the same voltage every time the clock is high; for example, +5 volts. By the same token, every time the clock signal goes low the voltage level must be the same, typically 0 volts. In addition, the clock signal must remain at the high and low levels for the same time and the time between each high and low cycle must be exactly the same. This last element is usually called the frequency stability of the clock. In Figure 6-11 the frequency stability refers to the time it takes for the signal to transition from point $a$ to point $c$ during each clock cycle. In practice, the stability and uniformity of the clock signal are more important than the absolute value. For example, it is usually acceptable that the high voltage level of the clock signal be 4.8 volts instead of 5 volts, as long as the 4.8 volts level is exactly reproduced at every clock cycle. Figure 6-11 shows an ideal waveform.

Another characteristic of the clock signal is the time required for clock levels to change from high to low and vice versa. Ideally this transition could be represented by a vertical line, as in Figure 6-11. This would mean that the transition is instantaneous, which is not achievable in actual circuits. In practice some time is required for the waveform to transition from low to high and vice versa. So the actual graph of the waveform, as can be seen in an oscilloscope, shows a slightly sloping side. Customarily, the actual measurement of the transition time is referred to as the 10 and 90 percent points. For example, in a 5 volt waveform, the rise time is the time it takes for the voltage to go from 0.5 to 4.5 volts, which are the 10 and 90 percent points for that waveform.
6.2.2 The TTL Clock

A much used TTL-compatible clock can be built around a 7404 hex inverter IC such as the one in Figure 5-12. The idea is to use two inverters to build a two-stage amplifier with an overall shift of 360 degrees. The output signal at one of the inverters is fed back, through a crystal, to the first inverter; this determines that the circuit oscillates at a frequency determined by the crystal. Thus, the frequency of this clock signal is determined by the crystal: values between 1 and 20 MHz are common. The TTL clock circuit is shown in Figure 6-12.

![TTL Clock Circuit](image)

**Figure 6-12 TTL Clock Circuit**

The crystal in the circuit of Figure 6-12 makes the frequency of oscillation very stable. The third inverter is used as an output buffer and allows driving the load simulated by the RC circuit.

The clocks used in digital systems need to be stable and uniform so that the frequency is the same and each pulse is the same as every other one. To achieve this, a narrow band frequency-selective filter whose center frequency does not change is required. Quartz crystals are a good choice since they provide a stable, precision oscillation. A quartz crystal is actually a thin piece of polished crystalline quartz with contacts plated on each surface and a lead attached to each contact. Quartz is a piezoelectric material, which means that there is one particular electrical frequency that excites the crystal’s resonance. It is this narrow resonant frequency that is used to build a frequency-selective filter whose center frequency changes very little as the components age or with changes in temperature. Crystal oscillators are available with frequencies that range from 10 KHz up to 600 MHz or more. They are typically housed in small metal cases with the frequency printed on the outside.
6.2.3 The 555 Timer

One of the most versatile timer ICs is the TTL-compatible 555 timer. This chip can be used to make many different kinds of oscillators, pulse generators, and timers. As an oscillator, the 555 can be made to produce square, sawtooth, or triangle waves, and its frequency can be modulated by an external input. Although the 555 is not a TTL part, its output is TTL-compatible when it is used with a 5-volt power supply.

The 555 timer has two distinct output levels that continuously switch back and forth between two unstable states. Because of this oscillation, the circuit output is a periodic, rectangular waveform. The fact that neither output is stable accounts for the circuit being astable or bistable. The frequency of oscillation as well as the duty cycle are accurately controlled by two external resistors and a single timing capacitor. Figure 6-13 shows the logic symbol for a 555 timer as well as the wiring to implement an asymmetric square wave generator.

![Figure 6-13 555 Timer as a Square Wave Generator.](image)

6.2.4 Microcontroller Clocks

Microcontrollers, like most digital components, require a synchronizing timing pulse provided by some form of clocking device.

There are five common ways of implementing a timer in a microcontroller:
1. Internal clock
2. RC network
3. Crystal oscillator
4. Ceramic resonator
5. External oscillator
The selection depends on the specific microcontroller, the circuit requirements, and the cost of each available option. The least expensive option is the resistor/capacitor oscillator circuit (RC network). The disadvantages are its slow speed and inherent inaccuracies. Some of the newer generations of microcontrollers come equipped with an internal RC oscillator that operate as a programmable timer. Typical speeds are 4 MHz with a 1.5 percent error. The actual use and implementation of microcontroller clocks is discussed in relation to each specific device.

6.3 Frequency Dividers and Counters

*Frequency dividers* and *counters* are actually the same circuitry used in different ways. Counters are one of the most useful and versatile digital devices. Counters can be used to count the number of clock cycles and as an instrument for measuring time and therefore period or frequency. The two different types of counters are synchronous and asynchronous.

6.3.1 Frequency Dividers

Circuit designers often needed to reduce the frequency of a wave clock signal. One easy way of doing it is to divide the frequency by two, which is done by feeding back the not-Q output of a D-type flip-flop to its data line. Figure 6-14 shows a divide-by-2 circuit and its effect on the resulting wave.

![Figure 6-14 A Divide-by-two Circuit](image)

In the circuit of Figure 6-14 the frequency division occurs because each input clock rising edge toggles the flip-flop’s output. When the Q output goes low, the not-Q line goes high and the high feedback signal is fed back to the data line, thus canceling out the next high wave of the f signal.

6.3.2 The JK Flip-flop Counter

One type of specialized flip-flop that we did not cover in Section 6.2 is the JK flip-flop. The JK flip-flop is an ideal component to build a circuit that keeps track of the number of positive or negative clock edges on the input clock. The name of this flip-flop relates to the two variables, J and K, that are used as inputs to the circuit. Figure 6-15 shows one possible circuit implementation for the JK flip-flop.
In Figure 6-15 the RC circuit converts the rectangular wave clock pulse into a narrow spike. The three-input AND gates make the circuit positive-edge-triggered. When J and K are low, both AND gates are disabled; therefore, clock pulses have no effect. This corresponds to the first entry in the truth table. When J is low and K is high (second entry in the truth table) the upper gate is disabled, so the flip-flop cannot be set; it must be reset. When Q is high, the lower gate passes a Reset trigger as soon as the next positive clock edge arrives. This forces Q to become low (the same second entry in the truth table). Therefore, J low and K high means that the next positive clock edge resets the flip-flop.

When J is high and K is low (third entry in the truth table) the lower gate is disabled, so it is impossible to reset the flip-flop. However, the flip-flop can be reset when Q is low because not-Q is high; therefore, the upper gate passes a Set trigger on the next positive clock edge. This drives Q into the high state (the third entry in the truth table). As you can see, J = 1 and K = 0 means that the next positive clock edge sets the flip-flop (unless Q is already high). When J and K are both high it is possible to set or reset the flip-flop. If Q is high, the lower gate passes a RESET trigger on the next positive clock edge. On the other hand, when Q is low, the upper gate passes a SET trigger on the next positive clock edge. Either way, Q changes to the complement of the last state (see last entry in the truth table). Therefore, when J = 1 and K = 1 the flip-flop will toggle on the next positive clock edge.

6.3.3 Ripple Counters

The simplest of all counters is called a ripple counter. A two-bit ripple counter can be constructed by wiring together two divide-by-two circuits, as in Figure 6-16.
Stringing together two divide-by-two circuits, as in Figure 6-16, produces a divide-by-four circuit. Stringing together three flip-flops produces a divide-by-eight circuit, four flip-flops create a divide-by-sixteen circuit, and so on. The counting action of the connected flip-flops is based on the fact that each flip-flop changes state before triggering the next one in line. Thus, each stage performs as a bit in a binary counter, the first stage being the LSB and the last stage the MSB. Since the preceding flip-flop acts as a clock for the next one in line, the flip-flop to the right toggles each time its neighbor to the left goes low. In Figure 6-15 the signal labeled \( Q_0 \) is the LSB of a two-bit counter, while the signal labeled \( Q_1 \) is the most significant bit.

In this design each flip-flop is triggered by the previous one; thus the count is said to “ripple” down the device. One objection to the ripple counter is that the change in each output is determined by the previous output in the flip-flop chain; this produces a few nanoseconds of time lag from output line to output line. This cumulative settling time is why these counters are called serial or asynchronous.

Note that the ripple counter of Figure 6-16 uses the not-Q line to drive the following flip-flop. If a ripple counter is wired so that the Q line drives each next stage, then the transitions take place not when the previous waveform goes low, but when it goes high. The result is that the counter counts down instead of up. In other words, in the down counter, the count is reduced by one during each clock transition. Commercial counters, such as the 74193, can be made to operate as up-counters or down-counters by selecting the corresponding input line.
6.3.4 Decoding Gates

A decoding gate is a way of connecting the output of a counter so that it signals a given state. For example, if four D-type flip-flops are wired so as to produce a four-bit ripple counter similar to the one in Figure 6-15, the counter represents binary digits 0000 to 1111. If we wanted to detect the value 1101 (16 decimal) the resulting circuit could be designed as in Figure 6-17.

![Figure 6-17 Decoding Gate](image)

The circuit of Figure 6-17 uses a NOR gate to invert the value of bit number 1. Then the AND gate serves to trigger the output when bits 0, 2, and 3 are high and bit 1 is low. This corresponds to the binary value 1011.

6.3.5 Synchronous Counters

Although the ripple counter is the simplest one, it has the previously mentioned disadvantage that each flip-flop has to wait for its neighbor to switch states. This means that in a ripple counter the delay times are additive, and also that the total “settling” time for the counter is approximately the delay multiplied by the total number of flip-flops. In addition, with ripple counters the resulting delay creates the possibility of glitches occurring at the output of decoding gates. These problems can be overcome by the use of a synchronous or parallel counter.

By observing how counting takes place in binary numbers, a counter in which each flip-flop is triggered at every clock beat can be built. Binary counting has the property that when a bit changes from high to low (1 to 0) it sends a toggle command to its neighbor to the left. So assuming that the low-order bit changes consecutively from one state to its complement, and starting from all bits initialized to 0, binary counting can be visualized as in Figure 6-18.
Figure 6-18 The Binary Counting Mechanism

Note in Figure 6-18 that the arrows indicate the transition from high to low, which is the command for the column to the left to change to its complement (toggle). Using this property of binary counting, it is possible to wire four JK flip-flops so that every high-to-low transition of a flip-flop triggers its higher-order neighbor to toggle its state. Figure 6-19 shows such a system.

Figure 6-19 Synchronous Four-Bit Up Counter
In Figure 6-19 note that the first flip-flop (the one with the Q\textsubscript{0} output) has a positive-edge triggered clock input. The lowest-order flip-flop toggles with each rising edge of the clock signal (not shown in the illustration). The second flip-flop to the right toggles with every falling edge of the signal from its neighbor to the left. And so on to the last flip-flop in the chain. The arrows in the waveform portion of Figure 6-19 show that each succeeding output bit is toggled by the transition from high to low of its lower-ordered neighbor. Also note the dashed line that marks the point where all found counters are transitioning from high-to-low. At this point all four counters wrap around to zero and a new count begins.

Observe that the not-Q output line transitions opposite to the Q output. That is, when the Q output line goes high, not-Q goes low, and viceversa. So if the pulse into each successive flip-flop originated in the not-Q line, instead of the Q line, then the resulting circuit would be a synchronous counter that transitions on the positive edge (low-to-high) instead of in the negative edge, as is the case with the counter in Figure 6-19. Furthermore, the not-Q line provides a set of negated outputs in reference to the Q lines; therefore, it is possible to come up with a circuit that serves both as an up- and down-counter according to the selected set of outputs. Such a circuit is shown in Figure 6-20.

![Figure 6-20 Synchronous 4-bit Up- and Down-counter](image)

In the counter of Figure 6-20 the Q outputs generate the up-count series while the not-Q outputs produce the down-count series.

### 6.3.6 Counter ICs

Counters are available as standard TTL components. The 7493 is an asynchronous 4-bit ripple counter that counts from 0 to 15. The 7490 is another version of the ripple counter, called a decade counter, since the count output is in the range 0 to 9. The 74193 is a 4-bit synchronous up/down counter in the range 0 to 15. Figure 6-21 is a pin diagram of the 74193.
The 74193 is a synchronous counter, so its output changes precisely at each clock pulse. This is convenient since it allows connecting its output to other logic gates and avoids the glitches associated with ripple counters. Note from Figure 6-21 that the 74194 has separate clock inputs for counting up and counting down. The count increases as the up clock input becomes high (on the rising-edge). The count decreases as the down clock input becomes high (on the rising-edge). In both cases the other clock input should be high. For normal operation the Preset input should be high and the Reset input low. When the Reset input is high it resets the count to zero, that is, lines QA to QD are low. The counter can be preset by placing any desired binary number on inputs A to D and making the Preset input low. These inputs may be left unconnected if not required.

Several 74193 counters can be chained by wiring a common Reset line, connecting the carry to the up clock line of the next counter and the borrow to the down line.

6.3.7 Shift Registers

In chapter 4 we discussed logical operations that shift and rotate the operand bits. These manipulations are useful in inspecting individual bits, in performing fast multiplications, in implementing time delays, and in converting parallel input to serial output, and vice versa. The hardware implementation of shift-and-rotate operations are called shift counters or shift registers.

Shift counters are often based on the D-type flip-flop. Actually, several D-type flip-flops can be chained together so that the D output of one goes into the D input of the next one. If all the flip-flops are driven by the same clock signal, then the effect would be to shift the bits from one flip-flop into the next one at each rising clock pulse.

A common implementation of a shift counter is called a parallel-in/serial-out shift register, as the one in Figure 6-22.
Figure 6-22 Four-Bit Parallel-In/Serial-Out Shift Counter

The circuit in Figure 6-22 shows four flip-flops connected so that the output of one feeds into the input of the next one. Also, a set of NAND gates allow parallel data input. When the load signal is set high the flip-flops in the shift register are loaded simultaneously with the logic values at the inputs A, B, C, and D. The 74165 IC is an 8-bit parallel-in/serial-out shift register with asynchronous parallel load and two OR-gated clock inputs. Figure 6-23 is a pin diagram of the 74165 IC.

Figure 6-23 Pin Diagram of IC 74165

The serial input line in the diagram of Figure 6-22 and in the 74165 IC in Figure 6-23 allows cascading multiple chips.

Parallel-in/serial-out shift registers find common use in the implementation of serial ports. In serial communications data is sent one bit at a time over a single wire.
In order to accomplish this, data is first loaded into a parallel-in/serial-out shift register. The individual bits are then shifted out one at a time. The frequency of the driving clock in this case corresponds to the baud rate being used. To receive the data on a serial communications line a second type of shift register is used. In this case the operation is serial-in/parallel-out. The circuit that accomplishes this is based on D-type flip-flops in which the Q outputs are connected to the D input lines.

The 74164 IC is one such device. In actual serial ports, the transmitting and receiving shift registers are contained in a single device called a UART (universal asynchronous receiver/transmitter).

### 6.4 Multiplexers and Demultiplexers

There are many situations in digital electronics where different signals must be sent out on a single output line, or several signals must be received in a single input line. The digital circuits that perform these operations are called multiplexers and demultiplexers. Multiplexers and demultiplexers are TTL analogs of the many-to-one and one-to-many mechanical switches.

#### 6.4.1 Multiplexers

**Multiplexing** (also called muxing) is a way of combining data of two or more input channels into a single output channel. The hardware multiplexer, also called a mux, combines several electrical signals into a single one. In other words, the multiplexer performs a many-into-one function while the demultiplexer performs one-into-many. Sometimes multiplexers and demultiplexers are combined into a single device, which is still referred to as a “multiplexer.” Figure 6-24 shows the schematics diagram of a multiplexer.

![Multiplexer Schematics](image)

The truth table in Figure 6-24 describes the multiplexer operation. The line labeled “sel” in the illustration is the selector line. If the selector is low (S = 0) then input line, B, is mirrored in the output line O. Otherwise, input line A is vectored to the output.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>S</th>
<th>O</th>
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</thead>
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<td>0</td>
<td>B (0)</td>
</tr>
<tr>
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<td>0</td>
<td>1</td>
<td>A (0)</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>B (1)</td>
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<td>0</td>
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<td>A (0)</td>
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<td>0</td>
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<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>A (1)</td>
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</tbody>
</table>

**Figure 6-24** Multiplexer Schematics

The truth table in Figure 6-24 describes the multiplexer operation. The line labeled “sel” in the illustration is the selector line. If the selector is low (S = 0) then input line, B, is mirrored in the output line O. Otherwise, input line A is vectored to the output.
The Boolean expression for the multiplexer in Figure 6-24 is:

\[ O = (A \land S) \lor (B \land \neg S) \]

Often, a multiplexer circuit is preceded by a decoder circuit so that input can be compressed into fewer lines. For example, a four-to-one multiplexer receives a binary value in the range 0 to 3 (00 to 11) on two input lines and sets high one of four output lines accordingly. Figure 6-25 shows the circuit diagram for such a device.

**Figure 6-25 Two-Bit to One-of-Four Multiplexer**

In the circuit of Figure 6-25 there are four input lines. Which one of these four lines is copied to the multiplexer output depends on the binary value in the two S lines at the top of the illustration. The 2-to-4 line decoder converts this value into one of four selector lines, which are in one of these four states:

\[ LLLL \quad LLHL \quad LHLL \quad HLLL \]

Whichever line is high from the decoder output selects the corresponding input line. By analogy to the circuit in Figure 6-25, an 8-input multiplexer has eight data inputs and three binary selection inputs, which are converted into one-of-eight selection lines by the decoder. By the same token, a 16-input multiplexer requires four binary digits in the decoder input, which are converted into one-of-sixteen selection lines.

Alternatively, the decoder circuit can be eliminated by using multiple AND gates and negating the input signals, as shown in Figure 6-26.

In Figure 6-26 assume that the input bits are both low, that is, \( S_1 = 0 \) and \( S_2 = 0 \). The first-level NOR gates change the L signals to H. The two high signals go into the first multiple AND gate, as shown by the solid lines in the illustration. This determines that the first input line \( I_0 \) is copied to the circuit output. In fact, the four inverters at the top of the illustration perform the function of the two-to-four decoder in the circuit of Figure 6-25.
6.4.2 Demultiplexers

A demultiplexer takes one data input and a number of selection inputs, and returns multiple outputs. So while the multiplexer performs a many-into-one operation, the demultiplexer performs a one-into-many. For example, a 4-output demultiplexer has one data input line, two selection inputs, and four data output lines. Figure 6-27 shows such a circuit.
Demultiplexers can be made to act as decoders by holding the input line high. For example, the circuit in Figure 6-27 performs as a binary to four-line decoder if the I line is held high. The binary bit patterns on the two input lines are converted into a single output in one of the four output lines. Thus, if there were four devices, each one connected to one of the output lines, the demultiplexer circuit would select which one is enabled according to the binary value of the input.

### 6.4.3 Multiplexer and Demultiplexer ICs

Several ICs are available that perform multiplexing and demultiplexing operations. For example, the 74138 is a 3-line to 8-line decoder and demultiplexer. With this IC any of eight inputs can be selected by placing the corresponding 3-bit number on the device’s three address lines. The 74151 is a 1-of-8 data selector/multiplexer. This device routes data from eight sources to a single output line. Here again, a 3-bit selector is used to determine which of the eight inputs is routed to the output.

An important use of the multiplexer ICs is to encode row and column addresses into the address lines of dynamic RAM, although more often tristate buffers such as the 74541 are used. Another important use of multiplexers is in implementing dual-port memories for video displays.

### 6.5 Input Devices

Electronic devices, including computers and microcontrollers, often receive the data and commands required for their operation. In computer technology the most common input device is the keyboard, which allows entering text data as well as keystroke orders. Alternate computer input devices are the mouse, trackballs, light pens, graphical tablets, scanners, speech recognition devices, optical character recognition devices, and many others. Although these devices are not excluded from use in microcontroller-based systems, a more typical case is that microcontroller input devices are much simpler and limited. In this section we discuss the two most commonly used devices for microcontrollers: the switch and the keypad. Keep in mind that specialized systems often use special input devices; for example, a radio receiver could be the input device for a radio-controller microcontroller system.

#### 6.5.1 Switches

The electrical switch is a device for changing current flow in a circuit. Although mechanical switches find use in fields such as railroads and fluid flow control, here we refer to switches used in controlling electrical power or electronic telecommunications.

In abstract terms the switch is often referred to as a “gate”, in the same sense as the logic gates discussed in Chapter 5. In this sense an electronic device can be viewed as a system of logic gates. The simplest electrical switch has two components, called contacts, that touch to make the circuit and separate to break the circuit. The terms make and break are commonly used in this context. The selection of material for the contacts is important since corrosion can form an insulating layer that prevents the switch from performing its function. One possible solution is plat- ing the contacts with noble metals, such as gold or silver.
In a switch, the actuator is the part that applies the operating force to the contacts. Common switch types are rocker, toggle, push-button, DIP, rotary, tactile, slide, keylock, snap-action, thumbwheel, and several others. Figure 6-28 shows several switches commonly found in microcontroller circuit boards.

![Electrical Switches](image)

Figure 6-28 Electrical Switches

In switches, contacts are “closed” when there is no space between them, thus allowing electricity to flow. When the contacts are separated by a space, they are “open.” In this case no electricity flows through the switch.

Switches are classified according to the various contact arrangements. In the normally open switch the contacts are separated until some force causes them to close. In the normally closed switch the contacts are held together until some force separates them. Some switches can be selected to operate as either normally open or normally closed. The term pole is used in reference to a single set of contacts on a switch. The term throw refers to the positions that a switch can adopt. Figure 6-29, on the following page, shows some common switch designs and their electrical symbols.

A multi-throw switch can have two possible transient behaviors as it transits from one position to the other one. One possibility is that the new contact is made before the old one is broken. This make-before-break action ensures that the line is never an open circuit. Alternatively, there is a break-before-make action, where the old contact is broken before the new one is made. This mode of switch operations ensures that the two fixed contacts are never shorted. Both designs are in common use.
A biased switch is one in which the actuator is automatically returned to a certain position, usually by the action of a spring. A push-button switch is a type of biased switch, of which the most common type is a push-to-make switch. In this case, the contact makes when the button is pressed and breaks when it is released. A push-to-break switch, on the other hand, breaks contact when the button is pressed. Many other special function switches are available; for example, tilt switches, such as the mercury switch, in which contact is made by a blob of mercury inside a glass bulb as the switch is tilted. Other specialized switches are activated by vibration, pressure, fluid level (as in the float switch), linear or rotary movement, the turning of a key, a radio signal, or a magnetic field.

### 6.5.2 Switch Contact Bounce

Switch contact bounce is a common problem of electrical switches. Switch contacts are metal surfaces that are forced into contact by an actuator. Due to momentum and elasticity, the striking action of the contacts causes a rapidly pulsating electrical current instead of a clean transition from zero to full current. Parasitic inductance and capacitance in the circuit can further modify the waveform resulting in a series of sinusoidal oscillations.

Switch bounce sometimes causes problems in logic circuits that are not designed to cope with oscillating voltages, particularly in sequential digital logic circuits. Sev-
eral methods of switch debouncing have been developed. These can be divided into
timing-based schemes and hysteresis-based schemes. Timing-based techniques are
based on adding sufficient delays so as to prevent the bounce from being detected.
The main advantage of using timing to control bouncing is that it does not require
any special switch design. Alternatively, it is possible to use hysteresis to separate
the positions where the make and break actions are detected. We discussed
hysteresis in the context of Schmitt trigger inverters, which are actually switches, in
Section 5.6.8.

The actual hardware circuits used in switch debouncing belong to three common
types: RS flip-flops, CMOS gate debouncers, and integrated RC circuit debouncers.
The debouncing action of the RS flip-flop is obvious from its operation, that is, when
the key is in a position in which neither contact is touched (key bouncing) the in-
puts are pulled low by the pull-down resistors. In this case, the key appears as being
pressed. Before being pressed, the key is touching the set input and appears as an
RS flip-flop, which was covered in Section 6.1.2.

Alternatively, switch debouncing can be accomplished by means of CMOS buffer
circuit with high input impedance. One such circuit is the 4050 hex buffer IC, with
eight input and eight output gates. When the switch is pressed, the input line of the
4050 chip is grounded, and output is forced low. The output voltage, by means of an
internal resistor, is also kept low when the switch is bouncing. The effect is that the
switch action is debounced.

Finally, switch debouncing can be implemented by means of a simple resis-
tor-capacitor circuit. The circuit action is based on the rate at which the capacitor
recharges once the ground connection is broken by the switch. As long as the capac-
itor voltage is below the threshold level of the logic zero value, the output signal
continues to appear as logic zero.

6.5.3 Keypads

In the context of microcontroller-based circuits, a keypad (also called a numeric key-
pad) is a set of pushbutton switches sometimes labeled with digits, mathematical sym-
bols, or letters of the alphabet. For example, a calculator keypad contains the decimal
(occasionally hexadecimal) digits, the decimal point, and keys for the mathematical
features of the calculator. Although in theory the computer keyboard is a keypad, the
keypad is usually limited to a smaller arrangement of buttons or to part of a computer
keyboard consisting mainly of numeric keys.

By convention, the keys on calculator-style keypads and keypads on computer
keyboards are arranged such that the keys 123 are on the bottom row. On the other
hand, telephone keypads have the 123 keys on the top row.

Keypads are usually implemented as pushbutton switches located in a row and
column matrix. The location of any key on the keypad can be based on two coordi-
nates: the row and column position for that key. Therefore only eight outputs are re-
quired from the keypad: one for each row and one for each column. Determining
which switch on a keypad has been activated can be done either by polling or by
means of an interrupt routine. In the polling approach the controller checks the sta-
tus of each switch in a loop. A more efficient approach is to implement and interrupt-driven routine that notifies the processor of a keystroke.

Keypads, like the switches that they incorporate, require debouncing. The three methods of switch debouncing described in Section 6.5.2 apply to keypads.

6.6 Output Devices

As is the case with input devices, electronic systems, including computers and microcontrollers, must provide data output in a human-readable form. Here again, computer technology uses many different types of output devices, including video displays, printers, plotters, film recorders, projectors, sound systems, and even holographic devices. Although these output devices cannot be excluded from use in microcontroller systems, they use simpler and limited output means. In this section we discuss two common output devices used in microcontroller-based circuits: the seven-segment LED and the liquid crystal display. Simple devices, such as LEDs and buzzers, are sometimes used as output devices. LEDs were covered in Chapter 5. Buzzers are such simple components that their operation does not require a detailed explanation.

6.6.1 Seven-segment LED

Digital devices often need to output a numeric value. Although individual LEDs can be combined to represent binary, decimal, or hexadecimal digits, a far more convenient device consists of seven built-in LEDs which can be combined to represent all ten decimal digits and even the six letters of the hex character set. Such a circuit is furnished in a single IC, called a seven-segment LED, that is common in clocks, watches, calculators, and household appliances.

Seven-segment displays have been in use since the first generation of calculators came to market. The scheme consists of placing lighted bars in a figure-eight pattern. By selecting which bars are lighted, all the digits and some letters of the alphabet can be represented. In addition, seven-segment LEDs are usually capable of displaying one or two decimal points. Figure 6-30 shows the layout of a seven-segment LED and the combinations to generate the decimal and hex digit sets.

Note in Figure 6-30 that two of the letters (b and d) of the hexadecimal set are displayed in lower-case while the others are in upper-case. This is a limitation of the seven-segment LED since an upper-case letter “D” would coincide with the digit “0”, and an upper-case letter “B” with the digit “8.”

Some seven-segment LED displays are slanted to make the digits appear in italics. It is used in clock displays where the two digits are inverted so that the decimal points appear like a colon between the digits. In addition seven-segment displays are packaged in several different ways. Sometimes several digits are combined in a single IC. Another packaging is in the form of a 14-pin DIP.
Seven-segment displays are also furnished using display technologies other than LEDs. Many line-powered devices and home appliances, such as clocks and microwave ovens, use fluorescent seven-segment displays. Battery-powered devices, such as watches and miniature digital instruments, use seven-segment liquid crystal displays. Liquid crystal technologies are covered in sections that follow.

The LEDs in a seven-segment display are interconnected. The two interconnection modes are to wire together the cathodes of all individual LEDs, or to do so with the anodes. In one case the device is said to have a common-cathode and in the other one a common-anode. This circuit scheme simplifies the wiring and reduces the number of connections, since only one line is necessary for controlling each LED. There is no intrinsic advantage to either system since each one is suited to different applications. Figure 6-31, on the following page, shows the pin diagram for a common-cathode seven-segment LED in a DIP package.
6.6.2 Liquid Crystal Displays

A liquid crystal display (LCD) is a pixilated output device capable of displaying ASCII characters and dot-based graphics. LCDs can be color or monochrome according to their construction. One of the advantages of LCD displays is their very small consumption of electrical power, making them suitable for battery-powered devices. In operation the liquid crystal display consists of two pieces of polarized glass with perpendicular axes of polarity. Sandwiched between the polarizers is a layer of nematic crystals, as shown schematically in Figure 6-32.

In the top image of Figure 6-32 light cannot pass through the system since the liquid crystal layer preserves the original angle of vibration of the light which cannot pass through the polarizer. In the lower image the various molecular layers of the liquid crystal are twisted approximately 90 degrees. This twisting of the liquid crystal also changes the light’s pane of vibration. So when light reaches the second polarized filter it vibrates at the same angle as the final molecule layer of the liquid crystal and can pass through the polarizer. Note that the electrical current applied to the crystals has the effect of straightening the various molecular layers. When the current is released, the various molecular layers resume their twisted form. By varying the amount of twist in the liquid crystals the amount of light that passes through can be controlled.
6.6.3 LCD Technologies

Depending on the positioning of the light source LCDs can be either transmissive or reflective. A transmissive LCD is illuminated from the back and viewed from the front. This type is common in applications that require high levels of illumination, as is the case with computer displays and television sets. Reflective LCDs, on the other hand, are illuminated by an external source. This type finds use in digital watches and calcu-
Reflective technology produces a darker black color than the transmissive type, since light is forced to pass twice through the liquid crystal layer. Since reflective LCDs do not require a light source they consume less power than the transmissive ones. A third type, called *transflective* LCDs, work as either transmissive or reflective LCDs, depending on the ambient light.

LCDs can be color or monochrome. In color systems each individual pixel consists of three cells, which are colored red, green, and blue. These cells, sometimes called *subpixels*, are controlled independently to yield thousands (or even millions) of possible colors for each pixel. Most LCDs used in microcontroller systems are monochrome.

According to display technology, LCDs are alphanumeric or dot-addressable. The alphanumeric type, most frequently used in microcontroller applications, uses a matrix composed of linear segments. Figure 6-33 shows several possible electrode configurations of LCDs.

The first two electrode configurations in Figure 6-33 are based on linear segments similar to the ones in seven-segment LEDs. Segmented electrodes are suitable for simple alphanumeric displays as are often required in small digital devices such as watches or calculators. To display entire character sets or graphics, a dot-addressable matrix of electrodes is necessary. This setup is shown in the rightmost image in Figure 6-34. However, such power comes at a price, since the more addressable elements in the display, the greater the number of connections and the more complex the driver logic required to operate the system. Note that the 5 x 7 matrix display in Figure 6-34 actually contains eight dot rows. The reason is that the lowest row is used for displaying the cursor. Most popular LCD displays for microcontroller circuits use the 5 x 7 matrix format.

![Electrode Configurations in LCD Displays](image-url)
One way of reducing the number of electrical connections in an LCD is by means of a method called passive matrix display. Here the pixels to be lighted are determined by the crossing points between the row and the column selector electrodes. For example, in the 5 x 7 matrix display in Figure 6-34, the pixel at the center of the character is selected by picking row number 4 and column number 3. The name passive matrix originates in the fact that each pixel must retain its state between refreshes. As the number of pixels to be refreshed increases so does the time required for the refresh cycle. As a consequence of their design, passive matrix displays usually have slow response times and poor contrast.

In high-resolution and color LCDs an active matrix display is used. In this design a grid of thin-film transistors is added to the polarizing and color filters. Each pixel contains its own dedicated transistor and each row line and column line is addressed individually. During the refresh cycle each pixel row is activated sequentially. Active matrix displays are brighter and sharper and have quicker response time than passive matrix. Active matrix displays are also known as thin-film-transistor or TFT displays.
Chapter 7

The Microchip PIC

A microcontroller is a type of microprocessor furnished in a single integrated circuit and needing a minimum of support chips. Its principal nature is self-sufficiency and low cost. It is not intended to be used as a computing device in the conventional sense; that is, a microcontroller is not designed to be a data processing machine, but rather an intelligent core for a specialized dedicated system.

Microcontrollers are embedded in many control, monitoring, and processing systems. Some are general-purpose devices but most microcontrollers are used in specialized systems such as washing machines, telephones, microwave ovens, automobiles, and weapons of many kinds. A microcontroller usually includes a central processor, input and output ports, memory for program and data storage, an internal clock, and one or more peripheral devices such as timers, counters, analog-to-digital converters, serial communication facilities, and watchdog circuits.

More than two dozen companies in the world manufacture and market microcontrollers. They range from 8- to 32-bit devices. Those at the low end are intended for very simple circuits and provide limited functions and program space, while those at the high end have many of the features associated with microprocessors. The most popular ones include several from Intel (such as the 8051), Zilog (derivatives of their famous Z-80 microprocessor), Motorola (such as the 68HC05), Atmel (the AVR), Parallax (the BASIC Stamp), and Microchip. Some of the latter ones are the main topic of this book.

7.0 The PICMicro Microcontroller

PIC is a family of microcontrollers made by Microchip Technology. The original one was the PIC1650 developed by General Instruments. This device was called PIC for “Programmable Intelligent Computer” although it is now associated with “Programmable Interface Controller.” Microchip does not use PIC as an acronym. Instead they prefer the brand name PICmicro. Popular wisdom relates that PIC is a registered brand in Germany and Microchip is unable to use it internationally.
The original PIC was built to be used with General Instruments' CP1600 processor, which had poor I/O performance. The PIC was designed to take over the I/O tasks for the CPU, thus improving performance. In 1985, the PIC was upgraded with EPROM to produce a programmable controller. Today, a huge variety of PICs are available with many different on-board peripherals and program memories ranging from a few hundred words to 32K.

PICs use an instruction set that varies in length from about 35 instructions for the low-end PICs to more than 70 for the high-end devices. The accumulator, which is known as the work register in PIC documentation, is part of many instructions since the PIC contains no other internal registers accessible to the programmer. The PICs are programmable in their native Assembly Language, which is straightforward and not difficult to learn. In addition, C language and BASIC compilers have been developed for the PIC. Open-source Pascal, JAL, and Forth compilers are also available for PIC programming.

One of the reasons for the success of the PIC is the support provided by Microchip. This includes a professional-quality development environment called MPLAB which can be downloaded free from the company's website. The MPLAB package includes an assembler, a linker, a debugger, and a simulator. Microchip also sells a low-cost in-circuit debugger called MPLAB ICD 2. Other development products intended for the professional market are available from Microchip. The Microchip website furnishes hundreds of free support documents, including data sheets, application notes, and sample code.

In addition to the documents and products in the Microchip website, the PIC microcontrollers have gained the support of many hobbyists, enthusiasts, and entrepreneurs who develop code and support products and publish their results on the Internet. This community of PIC users is a treasure trove of information and know-how easily accessible to the beginner and useful even to the professional. One such Internet resource is an open-source collection of PIC tools named GPUTILS, which is distributed under the GNU General Public License. GPUTILS includes an assembler and a linker. The software works on Linux, Mac OS, OS/2, and Windows. Another product named GPSIM is an Open Source simulator featuring PIC hardware modules.

7.0.1 Programming the PIC

Programming a PIC microcontroller requires the following tools and components:
1. An Assembler or high-level language compiler. The software package usually includes a debugger, simulator, and other support programs.
2. A computer (usually a PC) in which to run the development software.
3. A hardware device called a programmer that connects to the computer through the serial, parallel, or USB line. The PIC is inserted in the programmer and “blown” by downloading the executable code generated by the development system. The hardware programmer usually includes the support software.
4. A cable or connector for connecting the programmer to the computer.
5. A PIC microcontroller.
**PIC Programmers**

The development system (assembler or compiler) and the programmer driver are the software components. The computer, programmer, and connectors are the hardware elements. Figure 7-1 shows a commercial programmer that connects to the USB port of a PC. The one in the illustration is made by MicroPro.

Many other programmers are available on the market. Microchip offers several high-end models with *in circuit serial programming* (ICSP) and *low voltage programming* (LVP) capabilities. These devices allow the PIC to be programmed in the target circuit. Some PICs can write to their own program memory. This makes possible the use of so-called *bootloaders*, which are small resident programs that allow loading user software over the RS-232 or USB lines. Programmer/debugger combinations are also offered by Microchip and other vendors.

**Development Boards**

A *development board* is a demonstration circuit that usually contains an array of connected and connectable components. Their main purpose is as a learning and experimental tool. Like programmers, PIC development boards come in a wide range of prices and levels of complexity. Most boards target a specific PIC microcontroller or a PIC family of related devices. Lacking a development board the other option is to build the circuits oneself, a time-consuming but valuable experience. Figure 7-2 (in the following page) shows the LAB-X1 development board for the 16F87x PIC family.

The LAB-X1 board, as well as several other models, is a product of microEngineering Labs, Inc. Some of the sample programs developed for this book were tested on a LAB-X1 board. Development boards from Microchip and other vendors are also available.
7.0.2 Prototyping the PIC Circuit

Very few of us are satisfied with writing a PIC program and assuming that it works correctly. Testing software is a simple matter if there happens to be a development board at hand, if the board is compatible with the PIC, and if it provides the hardware that we need to test. But often one of these elements is missing and it becomes necessary to build the circuit for which the program was designed. Here again, there are several options. These range from having the circuit built for us by a professional engineering firm, to using a breadboard to prototype the circuit ourselves.

*Breadboarding* a prototype circuit is one of the options. A breadboard is a reusable, solderless device that allows building a prototype circuit, usually for temporary use. Breadboards have strips down one or both sides that are used as power rails. One strip carries the circuit’s positive voltage and the other one is wired to the ground of the power supply. Wire jumper kits provide connectors of different lengths and colors for making the circuit connections on the breadboard. For complex circuits several breadboards can be easily interconnected. Figure 7-3 shows two interconnected breadboards used to test one of the programs developed for this book.
Once a circuit and the software have been tested, there are several available technologies for building a more permanent prototype. These include wire wrap, stripboards, and several other circuit board building tools and techniques, including prototyping boards specially designed for PIC circuits.

Finally, one can build a semi-professional quality *printed circuit board* (called a *PCB*) and solder the components to it. A PCB is used to mechanically support the electronic components and provides conductive pathways, called *traces*, that implement the circuit. The components are soldered to the PCB board using either surface mount or through-the-board technology. The PCB board is made of a non-conductive material and the conductive pathways are etched out of copper sheets laminated on one or both sides of the board. Once the board has been populated with electronic components it becomes a *printed circuit assembly*, or PCA. Industrial quality PCB boards are suited to high-volume production. The circuits of the development board in Figure 7-2 are on a commercial PCB.

Building one’s own PCB is quite possible and requires few tools and resources. Appendix B describes one technique that has been used successfully. Figure 7-4, in the following page, shows a drawing of both sides of a simple PCB board.
Figure 7-4 Drawing for Etching a PCB Board

The PCB in Figure 7-4 is intended for a copper-plated single-sided blank. The left-side image shows the actual circuit that is etched on the copper side of the board. The text and diagrams on the right-hand image are engraved (usually by silk screening) on the back side of the board and serve as a guide for welding the components. Refer to Appendix B for details on designing and building PCBs at the amateur level.

Several firms on the Internet offer PCB prototyping services from the circuit diagrams. In some cases the advertised turnaround time is a couple of days. One of these companies furnishes software tools for drawing the PCB in a format that they can use directly in manufacturing the prototypes. Googling “PCB prototypes” produces many hits.

7.1 PIC Architecture

PIC controllers are roughly classified by Microchip into three groups: baseline, mid-range, and high-performance. Within each of the groups the PICs are classified based on the first two digits of the PIC’s family type. However, the subclassification is not very strict, since there is some overlap. For this reason we find PICs with 16X designations that belong to the baseline family and others that belong to the mid-range group. In the following subsections we describe the basic characteristics of the various subgroups of the three major PIC families with 8-bit architectures.

7.1.1 Baseline PIC Family

This group includes members of the PIC10, PIC12, and PIC16 families. The devices in the Baseline group have 12-bit program words and are supplied in 6- to 28-pin packages. The microcontrollers in the baseline group are described as being suited for battery-operated applications since they have low power requirements. The typical member of the Baseline group has a low pin count, flash program memory, and low power requirements. The following types are in the Baseline group.
**PIC10 Devices**

The PIC10 devices are low-cost, 8-bit, flash-based CMOS microcontrollers. They use 33 single-word, single-cycle instructions (except for program branches, which take two cycles). The instructions are 12-bits wide. The PIC10 devices feature power-on reset, an internal oscillator mode that saves having to use ports for an external oscillator. They have a power-saving SLEEP mode, a Watchdog Timer, and optional code protection.

The recommended applications of the PIC10 family range from personal care appliances and security systems to low-power remote transmitters and receivers. The PICs of this family have a small footprint and are manufactured in formats suitable for both through-hole and surface mount technologies. Table 7.1 summarizes the characteristics of PIC10 devices.

<table>
<thead>
<tr>
<th>Table 7.1</th>
<th>PIC10F Devices</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Clock:</strong></td>
<td></td>
</tr>
<tr>
<td>Maximum Frequency of Operation (MHz)</td>
<td>4</td>
</tr>
<tr>
<td><strong>Memory:</strong></td>
<td></td>
</tr>
<tr>
<td>Flash Program Memory</td>
<td>256</td>
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<tr>
<td>Data Memory (bytes)</td>
<td>16</td>
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<td><strong>Peripherals:</strong></td>
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<td>Timer Module(s)</td>
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<tr>
<td>Wake-up from Sleep</td>
<td>Yes</td>
</tr>
<tr>
<td>Comparators</td>
<td>0</td>
</tr>
<tr>
<td><strong>Features:</strong></td>
<td></td>
</tr>
<tr>
<td>I/O Pins</td>
<td>3</td>
</tr>
<tr>
<td>Input Only Pins</td>
<td>1</td>
</tr>
<tr>
<td>Internal Pull-ups</td>
<td>Yes</td>
</tr>
<tr>
<td>In-Circuit Serial Programming</td>
<td>Yes</td>
</tr>
<tr>
<td>Instructions</td>
<td>33</td>
</tr>
</tbody>
</table>

Two other PICs of this series are the 10F220 and the 10F222. These versions include four I/O pins and two analog-to-digital converter channels. Program memory is 256 words on the 10F220 and 512 in the 10F222. Data memory is 16 bytes on the F220 and 23 in the F222.

**PIC12 Devices**

The PIC12C5XX family are 8-bit, fully static, EEPROM/EPROM/ROM-based CMOS microcontrollers. They use RISC architecture and have 33 single-word, single-cycle instructions (except for program branches, which take two cycles). Like the PIC10 family, the PIC12C5XX chips have power-on reset, device reset, and internal timer. Four oscillator options can be selected, including a port-saving internal oscillator and
a low-power oscillator. These devices can operate in SLEEP mode and have Watchdog Timer and code-protection features.

### Table 7.2

**PIC 12Cxxx and 12CExxx Devices**

<table>
<thead>
<tr>
<th></th>
<th>12C508(A)</th>
<th>12C518</th>
<th>12CE519</th>
<th>12C671</th>
<th>12CE674</th>
</tr>
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<td>Clock:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum Frequency of Operation (MHz)</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Memory:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EPROM Program Memory</td>
<td>512/1024/1024</td>
<td>512x12</td>
<td>1024x12</td>
<td>1024/2048/2048x14</td>
</tr>
<tr>
<td></td>
<td>RAM Data Memory (Bytes)</td>
<td>25/41/41</td>
<td>25</td>
<td>41</td>
<td>128</td>
</tr>
<tr>
<td>Peripherals:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EEPROM Data Memory (Bytes)</td>
<td>—</td>
<td>16</td>
<td>16</td>
<td>0/0/16</td>
</tr>
<tr>
<td></td>
<td>Timer Module(s)</td>
<td>TMR0</td>
<td>TMR0</td>
<td>TMR0</td>
<td>TMR0</td>
</tr>
<tr>
<td></td>
<td>A/D Converter (8-bit) Channels</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>4</td>
</tr>
<tr>
<td>Features:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wake-up from SLEEP on pin change</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Interrupt Sources</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>I/O Pins</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Input Pins</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Internal Full-ups</td>
<td>Yes/Yes/No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>In-Circuit Serial Programming</td>
<td>Yes/No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Number of Instructions</td>
<td>33</td>
<td>33</td>
<td>33</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Packages</td>
<td>8-pin DIP SOIC</td>
<td>8-pin DIP JW, SOIC</td>
<td>8-pin DIP JW, SOIC</td>
<td>8-pin DIP SOIC</td>
</tr>
</tbody>
</table>

The PIC12C5XX devices are recommended for applications including personal care appliances, security systems, and low-power remote transmitters and receivers. The internal EEPROM memory makes possible the storage of user-defined codes and passwords as well as appliance setting and receiver frequencies. The various packages allow through-hole or surface mounting technologies. Table 7.2 lists the characteristics of some selected members of this PIC family.

Two other members of the PIC12 family are the 12F510 and the 16F506. In most respects these devices are similar to the other members of the PIC12 family previously described, except that the 12F510 and 16F506 both have flash program memory. Table 7.3 lists the most important features of these two PICs.
Two other members of the PIC12F are the 12F629 and 12F675. The only difference between these two devices is that the 12F675 has a 10-bit analog-to-digital converter while the 629 has no A/D converter. Table 7.4 lists some important features of both PICs.

<table>
<thead>
<tr>
<th></th>
<th>12F629</th>
<th>12F675</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Clock:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Frequency of Operation (MHz)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td><strong>Memory:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flash Program Memory</td>
<td>1024</td>
<td>1024</td>
</tr>
<tr>
<td>Data Memory (bytes)</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td><strong>Peripherals:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Timer Module(s)</td>
<td>TMR0</td>
<td>TMR0</td>
</tr>
<tr>
<td>Wake-up from Sleep on Pin Change</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Features:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/O Pins</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>Input Only Pin</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Internal Pull-ups</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>In-Circuit Serial Programming</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Number of Instructions</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Packages</td>
<td>14-pin PDIP, SOIC, TSSOP</td>
<td>8-pin PDIP, SOIC, MSOP</td>
</tr>
</tbody>
</table>

Table 7.4

**PIC12F629 and 12F675**

<table>
<thead>
<tr>
<th></th>
<th>12F629</th>
<th>12F675</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Clock:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Frequency of Operation (MHz)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td><strong>Memory:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flash Program Memory</td>
<td>1024</td>
<td>1024</td>
</tr>
<tr>
<td>Data Memory (SRAM bytes)</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td><strong>Peripherals:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Timers 8/16 bits</td>
<td>1/1</td>
<td>1/1</td>
</tr>
<tr>
<td>Wake-up from Sleep on Pin Change</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Features:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/O Pins</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Analog comparator module</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Analog-to-digital converter</td>
<td>No</td>
<td>10-bit</td>
</tr>
<tr>
<td>In-Circuit Serial Programming</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Enhanced Timer1 module</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Interrupt capability</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Number of Instructions</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Relative addressing</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Packages</td>
<td>8-pin PDIP, SOIC, DFN-S</td>
<td>8-pin PDIP, SOIC, DFN-S</td>
</tr>
</tbody>
</table>
Several members of the PIC12 family; the 12F635, 12F636, 12F639, and 12F683, are equipped with special power-management features (called nano-watt technology). These devices were especially designed for systems that require extended battery life.

**PIC14 Devices**

The single member of this family is the PIC14000. The 14000 is built with CMOS technology; this makes it fully static and gives the PIC an industrial temperature range. The 14000 is recommended for battery chargers, power supply controllers, power management system controllers, HVAC controllers, and for sensing and data acquisition applications. Table 7.5 lists the most important characteristics of this PIC.

### Table 7.5

<table>
<thead>
<tr>
<th>PIC14000</th>
</tr>
</thead>
</table>

| Clock: | Maximum Frequency of Operation (MHz) | 20 |
| Memory: | Flash Program Memory | 4096 |
| | Data Memory (SRAM bytes) | 192 |
| Peripherals: | Timers (16 bits with capture) | 1 |
| | Wake-up from Sleep on Pin Change | Yes |
| Features: | I/O Pins | 22 |
| | Analog-to-digital converter | 2 channels |
| | On-chip temperature sensor | 1 |
| | On-chip comparator modules | 2 |
| | In-Circuit Serial Programming | Yes |
| Interrupt capability: | Internal | 6 sources |
| | External | 5 sources |
| | I2C-compatible serial port | 1 |
| | Number of Instructions | 35 |
| | Relative addressing | Yes |
| | Packages | 22-pin PDIP, SOIC, SSOP, Windowed CERDIOP |

#### 7.1.2 Mid-range PIC Family

The mid-range PIC family includes members of the PIC12 and PIC16 groups. According to Microchip, the mid-range PICs all have 14-bit program words with either flash or OTP program memory. Those with flash program memory have EEPROM data memory and support interrupts. Some members of the mid-range group have USB, I2C, LCD, USART, and A/D converters. Implementations range from 8 to 64 pins. In the following subsections the basic characteristics of some mid-range PICs are listed.
**PIC16 Devices**

This is by far the most extensive PIC family. Currently, over 80 versions of the PIC16 are listed in production by Microchip. The remainder of this book is devoted to programming two of these PICs: the 16F84 and the 16F877. Here we listed a few of the most prominent members of the PIC16 family and their most important features. The Microchip website has more detailed information on these devices.

Table 7.6

<table>
<thead>
<tr>
<th>PIC16 Devices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Clock:</th>
<th>16C432</th>
<th>16C58</th>
<th>16C770</th>
<th>16F54</th>
<th>16F84A</th>
<th>16F946</th>
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<tbody>
<tr>
<td>Maximum Frequency MHz</td>
<td>20</td>
<td>40</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Program memory type</td>
<td>OTP</td>
<td>OTP</td>
<td>OTP</td>
<td>Flash</td>
<td>Flash</td>
<td>Flash</td>
</tr>
<tr>
<td>K-bytes</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>0.75</td>
<td>1.75</td>
<td>14</td>
</tr>
<tr>
<td>K-words</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.5</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Data EEPROM</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>64</td>
<td>256</td>
</tr>
<tr>
<td>I/O channels</td>
<td>12</td>
<td>12</td>
<td>16</td>
<td>12</td>
<td>13</td>
<td>53</td>
</tr>
<tr>
<td>ADC channels</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Timers</td>
<td>1/8-bit</td>
<td>1/8-bit</td>
<td>2/8-bit</td>
<td>1/8-bit</td>
<td>1/8-bit</td>
<td>2/8-bit</td>
</tr>
<tr>
<td>Watchdog timer</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ICSP</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ICD</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Pin count</td>
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<td>20</td>
<td>18</td>
<td>18</td>
<td>64</td>
</tr>
<tr>
<td>Communications</td>
<td>-</td>
<td>-</td>
<td>NFC/SPI</td>
<td>-</td>
<td>AUSART</td>
<td></td>
</tr>
<tr>
<td>Packages</td>
<td>20/CERDIP, 18/CERDIP</td>
<td>20/CERDIP</td>
<td>18/PDIP</td>
<td>18/PDIP</td>
<td>64/TQFP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20/SOIC</td>
<td>18/SOIC</td>
<td>20/SOIC</td>
<td>18/SOIC</td>
<td>300mil</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300mil</td>
<td>300mil</td>
<td>300mil</td>
<td>300mil</td>
<td>300mil</td>
<td></td>
</tr>
</tbody>
</table>

**7.1.3 High-Performance PIC Family**

The high-performance PICs belong to the PIC18 group. They have 16-bit program words, flash program memory, a linear memory space of up to two Mbytes, and protocol-based communications facilities. They all support internal and external interrupts and have a much larger instruction set than members of the baseline and mid-range families.

**PIC18 Devices**

The PIC18 family is also a large one, with over 70 different variations currently in production. The PIC18 family uses 16-bit program words and are furnished in 18 to 80 pin packages. Microchip describes the PICs in this family as high-performance with integrated A/D converters. They have 32-level stacks and support interrupts. The instruction set is much larger and starts at 79 instructions. The PICs in this family have flash program memory, a linear memory space of up to 2 Mbytes, 8-by-8 bit hardware multiplier, and communications peripherals and protocols. Table 7.7 lists some members of the PIC18 family.
Table 7.7

**PIC18 Devices**

<table>
<thead>
<tr>
<th></th>
<th>18F222</th>
<th>18F2455</th>
<th>18F2580</th>
<th>18F4580</th>
<th>18F8622</th>
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<td><strong>Clock:</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Frequency MHz</td>
<td>40</td>
<td>48</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td><strong>Memory:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Program memory type</td>
<td>flash</td>
<td>flash</td>
<td>flash</td>
<td>flash</td>
<td>flash</td>
</tr>
<tr>
<td>K-bytes</td>
<td>4</td>
<td>24</td>
<td>32</td>
<td>32</td>
<td>64</td>
</tr>
<tr>
<td>K-words</td>
<td>2</td>
<td>12</td>
<td>16</td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td>Data EEPROM</td>
<td>256</td>
<td>256</td>
<td>256</td>
<td>256</td>
<td>1024</td>
</tr>
<tr>
<td><strong>Peripherals:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/O channels</td>
<td>25</td>
<td>23</td>
<td>25</td>
<td>36</td>
<td>70</td>
</tr>
<tr>
<td>ADC channels</td>
<td>10</td>
<td>10</td>
<td>8</td>
<td>11</td>
<td>16</td>
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<tr>
<td>Comparators</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Timers</td>
<td>1/8-bit</td>
<td>1/8-bit</td>
<td>1/8-bit</td>
<td>1/8-bit</td>
<td>2/8-bit</td>
</tr>
<tr>
<td>Watchdog timer</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Features:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EUSART</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ICSP</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ICD</td>
<td>1</td>
<td>3</td>
<td>3</td>
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<td>3</td>
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<tr>
<td>Pin count</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>44</td>
<td>80</td>
</tr>
<tr>
<td>Communications</td>
<td>MPC/SPI</td>
<td>MPC/SPI/USB</td>
<td>MPC/SPI</td>
<td>MPC/SPI</td>
<td>2-MPC/SPI</td>
</tr>
<tr>
<td>Packages</td>
<td>28/PDIP, 28/QFN</td>
<td>40/PDIP</td>
<td>40/TQFP</td>
<td>44/QFN</td>
<td>44/TQFP</td>
</tr>
<tr>
<td></td>
<td>28/QFN</td>
<td>28/PDIP</td>
<td>28/PDIP</td>
<td>28/PDIP</td>
<td>28/PDIP</td>
</tr>
<tr>
<td></td>
<td>300mil</td>
<td>300mil</td>
<td>300mil</td>
<td>44/TQFP</td>
<td></td>
</tr>
</tbody>
</table>
In Chapter 7 we encountered the three major PIC families of 8-bit devices. In the remainder of this book we focus on the mid-range family. Our reason for concentrating our attention on this group is that it is the mid-range PICs that have achieved greater success and popularity.

In addition, as the PIC architecture increases in complexity and power, so does the size, intricacy, and cost of the devices. For many purposes an 80-pin PIC with 64Kbytes of program memory, 1K EERPOM, 70 I/O ports, 16 A/D channels, is more complex than necessary. In fact, some high-end PICs appear to be closer to microprocessors than to microcontrollers. Furthermore, the programming complexity of these high-end PICs is also much greater than their mid-range counterparts because their instruction set has double the number of instructions and the assembly language itself is more difficult to learn and follow. Finally, the circuits in which we typically find the high-end devices are more advanced and elaborate and their design requires greater engineering skills. For these reasons, and for the natural space limitations of a single volume, we do not discuss the high-performance family or 8-bit PICs nor any of the 16-bit products.

It can be argued that the baseline PICs do find extensive use and are quite practical for many applications. Although this is true, the baseline PICs are quite similar in architecture and programming to their mid-range relatives. In most cases the difference between a baseline and mid-range device is that the low-end one lacks some features or has less program space or storage. So someone familiar with the mid-range devices can easily port their knowledge to any of the simpler baseline products.

Our conclusion has been to limit the coverage to the mid-range family of PICs. Within this family we have concentrated our attention on the two most used, documented, and popular PICs: the 16F84 (also 16F84A) and the 16F877. The F84 sets the lower limit of complexity and sophistications and the F877 the higher limit.
8.0 Processor Architecture and Design

PIC microcontrollers are unique in many ways. We start by mentioning several general characteristics of the PIC: Harvard architecture, RISC processor design, single-word instructions, machine and data memory configuration, and characteristic instruction formats.

8.0.1 Harvard Architecture

The PIC microcontrollers do not use the conventional von Neumann architecture but a different hardware design often referred to as Harvard architecture. Originally, Harvard architecture referred to a computer design in which data and instruction used different signal paths and storage areas. In other words, data and instructions are not located in the same memory area but in separate ones. One consequence of the traditional von Neumann architecture is that the processor can either read or write instructions or data but cannot do both at the same time, since both instructions and data use the same signal lines. In a machine with a Harvard architecture, on the other hand, the processor can read and write instructions and data to and from memory at the same time. This results in a faster, albeit more complex, machine. Figure 8-1 shows the program and data memory space in a mid-range PIC.

**Figure 8-1 Mid-range PIC Memory (Harvard Architecture)**

The most recent arguments in favor of the Harvard architecture are based on the access speed to main memory. Making a CPU faster while memory accesses remain at the same speed represents little total gain, especially if many memory accesses are required. This situation is often referred to as the von Neumann bottleneck and machines that suffer from it are said to be memory bound.

Several generations of microcontrollers, including the Microchip PICs, have been based on the Harvard architecture. These processors have separate storage for program and data and a reduced instruction set. The midrange PICs, in particular, have
8-bit data words but either 12-, 14-, or 16-bit program instructions. Since the instruction size is much wider than the data size, an instruction can contain a full-size data constant.

8.0.2 RISC CPU Design

The CISC (Complete Instruction Set Computer) design is based on each low-level instruction performing several operations. For example, one Intel 80x86 opcode can decrement a counter register, determine the state of a processor flag, and execute a jump instruction if the flag is set or cleared. Another CISC instruction moves a number of bytes of data contained in a counter register from an area pointed at by a source register, into another area pointed at by a destination register. Any popular Intel CISC CPU contains about 120 primitive operations in its instruction set. The original design idea of the CISC architecture was to provide high-level instructions in order to facilitate the implementation of high-level languages. Supposedly, this would be achieved through complex instruction sets, multiple addressing modes, and primitive operations that performed multiple functions.

However, some argued that the CISC architecture did not result in better performance. Furthermore, the more complex the instruction set resulted in greater decoding time. At the same time, implementing large instruction sets required more silicon space and considerably more design effort. Some CISC processors developed in the 1960s and 70s are the IBM System/360, the PDP-11, the Motorola 68000 family, and Intel 80x86 CPUs.

In contrast, a RISC (Reduced Instruction Set Computer) machine contains fewer instructions and each instruction performs more elementary operations. Consequences of this are a smaller silicon area, faster execution, and reduced program size with fewer accesses to main memory. The PIC designers have followed the RISC route. Other CPUs with RISC design are the MIPS, the IBM Power PC, and the DEC Alpha.

8.0.3 Single-word Instructions

One of the consequences of the PIC’s Harvard architecture is that the instructions can be wider than the 8-bit data size. Since the device has separate buses for instructions and data, it is possible for instructions to be sized differently than data items. Being able to vary the number of bits in each instruction opcode makes possible the optimization of program memory and the use of single-word instructions that can be fetched in one bus cycle.

In the mid-range PICs each instruction is 14-bits wide and every fetch operation brings into the execution unit one complete operation code. Since each instruction takes up one 14-bit word, the number of words of program memory in a device exactly equals the number of program instructions that can be stored. In a von Neumann machine, instruction storage and fetching becomes a much more complicated issue. Since von Neumann instructions can span multiple bytes, there is no assurance that each program memory location contains the first opcode of a multi-byte instruction.
As in conventional processors, the PIC architecture has a two-stage instruction pipeline; however, since the fetch of the current instruction and the execution of the previous one can overlap in time, one complete instruction is fetched and executed at every machine cycle. This is known as *instruction pipelining*. Since each instruction is 14-bits wide and the program memory bus is also 14-bits wide, each instruction contains all the necessary information, so it can be executed without any additional fetching. The one exception is when an instruction modifies the contents of the Program Counter. In this case, a new instruction must be fetched, requiring an additional machine cycle.

The PIC clocking system is designed so that an instruction is fetched, decoded, and executed every four clock cycles. In this manner, a PIC equipped with a 4MHz oscillator clock beats at a rate of 0.25 µs. Since each instruction executes at every four clock cycles, each instruction takes 1 µs.

### 8.0.4 Instruction Format

All members of the mid-range family of PICs have 14-bit instructions and a set of 35 instructions. The format for the instructions follows three different patterns: byte-oriented, bit-oriented, and literal and control instructions. Figure 8-2 shows the bitmaps for the three types.

**Figure 8-2** Mid-Range Instruction Formats
Note that the opcode field has variable number of bits in the PIC instruction set. This scheme allows implementing 35 different instructions while using a minimum of the 14 available opcode bits. Also note that instructions that reference a file register do so in a 7-bit field. The numerical range of seven bits is 128 values. For this reason, the mid-range PICs that address more than 128 data memory locations must resort to banking techniques. In this case, a bit or bit field in the STATUS register serves to select the bank currently addressed.

A similar situation arises when addressing program memory with an 11-bit field. Eleven bits allow 2048 addresses, so if a PIC is to have more than 2K program memory it is necessary to adopt a paging scheme in which a special function register is used to select the memory page where the instruction is located. Paging is required only in devices that exceed the 2K program space limit that can be encoded in 11 bits.

8.0.5 Mid-Range Device Versions

The device names used by Microchip use different encodings to represent different versions of the various devices. For example, the first letter following the family affiliation designator represents the memory type of the device, as follows:

1. The letter C, as in PIC16Cxxx, refers to devices with EPROM type memory.
2. The letters CR, as in PIC16CRxxx, refer to devices with ROM type memory.
3. The letter F, as in PIC16Fxxx, refers to devices with flash memory.

The letter L immediately following the affiliation designator refers to devices with an extended voltage range. For example, the PIC16LFxxx designation corresponds to devices with extended voltage range.

8.1 The Mid-range Core Features

Core features refer to the device oscillator, reset mechanism, CPU architecture and operation, Arithmetic-Logic Unit, memory organization, interrupts, and instruction set. We have already referred to the architecture and general features of the CPU. Memory organization is discussed in a separate section later in this chapter. The remaining topics are covered in the following subsections.

8.1.1 Oscillator

Mid-range PICs require an external device to produce the clock cycles required for its operation. The PIC executes an instruction every four clock cycles, so the oscillator speed determines the device performance.

Mid-range PICs support up to eight different oscillator modes. For example, in the 16F877, any of the eight modes can be used, while in the 16F84 only four oscillator modes are available. The oscillator mode is selected at device programming time and cannot be changed at runtime. The configuration bits, which are non-volatile flags set during device programming, determine which oscillator mode is used by the program, among the following:
1. LP Low Frequency Crystal
2. XT Crystal Resonator
3. HS High Speed Crystal Resonator
4. RC External Resistor/Capacitor
5. EXTRC External Resistor/Capacitor
6. EXTRC External Resistor/Capacitor with CLKOUT
7. INTRC Internal 4 MHz Resistor/Capacitor
8. INTRC Internal 4 MHz Resistor/Capacitor with CLKOUT

The resistor/capacitor oscillator option is the least expensive to implement, but also the least accurate one. This option is used only in systems where clock accuracy and consistency are not issues. The low-power frequency crystal option is the one with lowest power consumption and can be used in systems where the power consumption element is important.

The first three oscillator modes (LP, XT, and HS) allow selecting different frequency ranges. The HS option has the highest frequency range and consumes the most power. The XT option is based on a standard crystal resonator and has a mid-range power consumption. The LP option has low gain and consumes the least power of the three crystal modes. The general rule is to use the oscillator with the lowest possible gain that still meets the circuit requirements. The RC mode with EXTRC and CLKOUT features has the same functionality as the straight RC oscillator option.

The XT option (crystal resonator) can be purchased in a ceramic package. This device, called a ceramic resonator, contains three pins. The ones on the extremes are connected to the corresponding oscillator input lines on the PIC, labeled OSC1 and OSC2. The center pin is connected to ground. Figure 8-3 shows the circuit diagram for an oscillator and a crystal resonator.

![Circuit Diagram for Oscillators](image-url)
Alternatively, the oscillator function is provided by an integrated circuit (such as the ICS502) that can generate several different clock frequencies. Some circuits, especially in PIC demonstration boards, contain jumper pins that allow selecting among several clock rates.

8.1.2 System Reset

The reset mechanism places the PIC in a known condition. The reset mechanism is used to gain control of a runaway or hung-up program, as a forced interrupt in program execution, or to make the device ready at program load time. The processor’s !MCLR pin produces the reset action when it reads logic zero. The exclamation sign preceding the pin’s name (or a line over it) indicates that the action is active-low. To prevent accidental resets the !MCLR pin must be connected to the positive voltage supply through a 5K or 10K resistor. When a resistor serves to place a logic one on a line it is called a pull-up resistor.

The mid-range PICs are capable of several reset actions:
1. Reset during power on (POR).
2. !MCLR reset during normal operation.
3. Reset during SLEEP mode.
4. Watchdog timer reset (WDT).
6. Parity error reset.

The first two reset sources in the preceding list are the most common. POR reset serves to bring all PIC registers to an initial state, including the program counter register. The second source of reset action takes place when the !MCLR line is intentionally brought down, usually by the action of a push-button reset switch. This switch is useful during program development since it provides a way of forcefully restarting execution. Figure 8-4 shows a typical wiring of the !MCLR line to provide a reset action.

![Figure 8-4 Typical Wiring of the Reset Switch](image-url)
The second one is a product of purposefully bringing-in a logical zero to the MCLR pin during normal operation of the microcontroller. This second one is often used in program development.

User RAM memory is not affected by a reset. The GPRs (general purpose register) are in an unknown state during power-up and are not changed by reset. SFR registers, on the other hand, are reset to an initial state. The initialization conditions for each of the SFRs are found in the device data sheet. The most important of these is the program count (PC) which is reset to zero. This action directs execution to the first instruction and effectively restarts the program.

During power-up the processor itself initiates a reset and the power supply voltage increases from 1.2 to 1.8V. Several bits in various registers are related to the reset action, but these are not available in all mid-range devices. For example, some high-end devices in the mid-range group, such as the 16F87x, contain two reset-related bits in the PCON register. One of them (named !POR) determines the power-on reset status. The other one (named !BOR) informs about the brown-out reset status. However, the PCON register does not exist in the 16F84 or 16F84A.

8.1.3 Interrupts

The interrupt mechanism provides a way of having the microcontroller respond to events as they occur, rather than having to poll devices in order to determine their state. Thus, the interrupt works like a “tap on the shoulder” on the microcontroller, calling its attention to an event that requires an action or device that needs servicing. After responding to or ignoring the interrupt, the CPU resumes processing where it left off.

In computer technologies the interrupt mechanism is a complicated hardware/software system that often includes programmable interrupt controller ICs. Processors and microprocessors usually support hardware and software interrupts and maskable and non-maskable interrupts; interrupts originate in practically any device connected to the system. In the PICs, the interrupt mechanism is much simpler and varies considerably even among members of the same PIC family.

All PICs of the mid-range family to some degree support interrupts. The interrupt source usually originates in one of the hardware modules, although some sources generate more than one interrupt. The following are interrupt sources in the mid-range family, although not all are supported by every PIC.

- INT Pin Interrupt (external interrupt)
- TMR0 Overflow Interrupt
- PORTB Change Interrupt
- Comparator Change Interrupt
- Parallel Slave Port Interrupt
- USART Interrupts
- Receive and Transmit Interrupt
• A/D Conversion Complete Interrupt
• LCD Interrupt
• Data EEPROM Write Complete Interrupt
• Timer Overflow Interrupt
• CCP Interrupt
• SSP Interrupt

Several SFRs are related to the interrupt systems. The INTCON register provides interrupt enabling and control and the PIE1, PIE2, PIR1, and PIR2 registers have specific device-related functions. Programming interrupts is discussed in the context of the corresponding operations later in this book.

8.2 Mid-Range CPU and Instruction Set

In a digital system, the central processing unit (CPU) is the component that executes the program instructions and processes data. It provides the fundamental functionality of a digital system and is responsible for its programmability. In the PIC architecture, the CPU is the part of the device which fetches and executes the instructions contained in a program.

The arithmetic-logic unit (ALU) is the CPU element that performs arithmetic, bitwise, and logical operations. It also controls the bits in the STATUS register as they are changed by the execution of the various program instructions. For example, if the result of executing an instruction is zero, the ALU sets the zero bit in the STATUS register.

8.2.1 Mid-Range Instruction Set

The mid-range PIC instruction set consists of 35 instructions, divided into three general groups:

1. Byte-oriented and byte-wise file register operations
2. Bit-oriented and bit-wise file register operations
3. Literal and control instructions

Table 8.1 lists and briefly describes each instruction in the mid-range set.

<table>
<thead>
<tr>
<th>MNEMONIC</th>
<th>OPERAND</th>
<th>DESCRIPTION</th>
<th>CYCLES</th>
<th>BITS AFFECTED</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADDWF</td>
<td>f,d</td>
<td>Add w and f</td>
<td>1</td>
<td>C, DC, Z</td>
</tr>
<tr>
<td>ANDWF</td>
<td>f,d</td>
<td>AND w with f</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>CLRF</td>
<td>f</td>
<td>Clear f</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>CLRWF</td>
<td>-</td>
<td>Clear w</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>COMF</td>
<td>f,d</td>
<td>Complement f</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>DECF</td>
<td>f,d</td>
<td>Decrement f</td>
<td>1</td>
<td>Z</td>
</tr>
</tbody>
</table>

(continues)
### Table 8.1

**Mid-range PIC Instruction Set (continued)**

<table>
<thead>
<tr>
<th>MNEMONIC</th>
<th>OPERAND</th>
<th>DESCRIPTION</th>
<th>CYCLES</th>
<th>BITS AFFECTED</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BYTE-ORIENTED OPERATIONS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DECFSZ</td>
<td>f,d</td>
<td>Decrement, skip if 0</td>
<td>1(2)</td>
<td>-</td>
</tr>
<tr>
<td>INCF</td>
<td>f,d</td>
<td>Increment f</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>INCFSZ</td>
<td>f,d</td>
<td>Increment, skip if 0</td>
<td>1(2)</td>
<td>-</td>
</tr>
<tr>
<td>IORWF</td>
<td>f,d</td>
<td>Inclusive OR w and f</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>MOVF</td>
<td>f,d</td>
<td>Move f</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>MOVWF</td>
<td>f</td>
<td>Move w to f</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>NOP</td>
<td>-</td>
<td>No operation</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>RLF</td>
<td>f,d</td>
<td>Rotate left through carry</td>
<td>1</td>
<td>C</td>
</tr>
<tr>
<td>RRF</td>
<td>f,d</td>
<td>Rotate right through carry</td>
<td>1</td>
<td>C</td>
</tr>
<tr>
<td>SUBWF</td>
<td>f,d</td>
<td>Subtract w from f</td>
<td>1</td>
<td>C,DC,Z</td>
</tr>
<tr>
<td>SWAPF</td>
<td>f,d</td>
<td>Swap nibbles in f</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>XORWF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>BIT-ORIENTED OPERATIONS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BCF</td>
<td>f,b</td>
<td>Bit clear in f</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>BSF</td>
<td>f,b</td>
<td>Bit set in f</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>BTFSC</td>
<td>f,b</td>
<td>Bit test, skip if clear</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>BTFSS</td>
<td>f,b</td>
<td>Bit test, skip if set</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td><strong>LITERAL AND CONTROL OPERATIONS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADDLW</td>
<td>k</td>
<td>Add literal and w</td>
<td>1</td>
<td>C,DC,Z</td>
</tr>
<tr>
<td>ANDLW</td>
<td>k</td>
<td>AND literal and w</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>CALL</td>
<td>k</td>
<td>Call procedure</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>CLRWD</td>
<td>-</td>
<td>Clear watchdog timer</td>
<td>1</td>
<td>TO,PD</td>
</tr>
<tr>
<td>GOTO</td>
<td>k</td>
<td>Go to address</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>IORLW</td>
<td>k</td>
<td>Inclusive OR literal with w</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>MOVIL</td>
<td>k</td>
<td>Move literal to w</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>RETFIE</td>
<td>-</td>
<td>Return from interrupt</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>RETLWk</td>
<td>-</td>
<td>Return literal in w</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>RETURN</td>
<td>-</td>
<td>Return from procedure</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>SLEEP</td>
<td>-</td>
<td>Go into SLEEP mode</td>
<td>1</td>
<td>TO,PD</td>
</tr>
<tr>
<td>SUBLW</td>
<td>k</td>
<td>Subtract literal and w</td>
<td>1</td>
<td>C,DC,Z</td>
</tr>
<tr>
<td>XORIL</td>
<td>k</td>
<td>Exclusive OR literal with w</td>
<td>1</td>
<td>Z</td>
</tr>
</tbody>
</table>

Legend:
- f = file register
- d = destination: 0 = w register, 1 = file register
- b = bit position
- k = 8-bit constant
8.2.2 STATUS and OPTION Registers

The STATUS register is one of the SFRs in the mid-range PICs. The bits in this register reflect the arithmetic status of the ALU, the RESET status, and the bits that select which memory bank is currently being accessed. Because the bank selection bits are in the STATUS register it must be present and at the same relative position in every bank. Figure 8-5 is a bitmap of the STATUS register.

<table>
<thead>
<tr>
<th>bits:</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RP-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RP-0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **bit 7 IRP**: Register Bank Select bit (used for indirect addressing)
  - 1 = Bank 2, 3 (0x100 - 0x1ff)
  - 0 = Bank 0, 1 (0x000 - 0xff)
  For devices with only Bank0 and Bank1 the IRP bit is reserved, always maintain this bit clear.

- **bit 6:5 RP1:RP0**: Register Bank Select bits (used for direct addressing)
  - 11 = Bank 3 (0x180 - 0x1ff)
  - 10 = Bank 2 (0x100 - 0xff)
  - 01 = Bank 1 (0x80 - 0xff)
  - 00 = Bank 0 (0x00 - 0x7f)
  Each bank is 128 bytes. For devices with only Bank0 and Bank1 the IRP bit is reserved, always maintain this bit clear.

- **bit 4 TO**: Time-out bit
  - 1 = After power-up, CLRWDT instruction, or SLEEP instruction
  - 0 = A WDT time-out occurred

- **bit 3 PD**: Power-down bit
  - 1 = After power-up or by the CLRWDT instruction
  - 0 = By execution of the SLEEP instruction

- **bit 2 Z**: Zero bit
  - 1 = The result of an operation is zero
  - 0 = The result of an operation is not zero

- **bit 1 DC**: Digit carry/borrow bit for ADDWF, ADDLW, SUBLW, and SUBWF instructions. For borrow the polarity is reversed.
  - 1 = A carry-out from the 4th bit of the result
  - 0 = No carry-out from the 4th bit of the result

- **bit 0 C**: Carry/borrow bit for ADDWF, ADDLW, SUBLW, and SUBWF instructions
  - 1 = A carry-out from the most significant bit
  - 0 = No carry-out from the most significant bit

Figure 8-5 STATUS Register Bitmap
The STATUS register can be the destination for any instruction. If it is, and the Z, DC, or C bits are affected, then the write operation to these bits is disabled. In addition, the TO and PD bits are not writable.

Some instructions may have an unexpected action on the STATUS register bits, for example, the instruction

```assembly
clr STATUS
```

clears the upper 3 bits, sets the Z bit, and leaves all other bits unchanged. For this reason, it is recommended that only instructions that do not change the Z, C, and DC bits be used to alter the STATUS register. The only ones that qualify are BCF, BSF, SWAPF, and MOVWF.

The OPTION register is actually named the OPTION_REG to avoid name clash with the option instruction. The OPTION_REG register contains several bits related to interrupts, the internal timers, and the watchdog timer. Figure 8-6 is a bitmap of the OPTION_REG register.

<table>
<thead>
<tr>
<th>bits:</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPBU</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INTEDG</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOCS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOSE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PSA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

bit 7 RPBU: PORTB Pull-up Enable bit
1 = PORTB pull-ups are disabled
0 = PORTB pull-ups are enabled by individual port latch values

bit 6 INTEDG: Interrupt Edge Select bit
1 = Interrupt on rising edge of INT pin
0 = Interrupt on falling edge of INT pin

bit 5 TOCS: TMR0 Clock Source Select bit
1 = Transition on T0CKI pin
0 = Internal instruction cycle clock (CLKOUT)

bit 4 TOSE: TMR0 Source Edge Select bit
1 = Increment on high-to-low transition on T0CKI pin
0 = Increment on low-to-high transition on T0CKI pin

bit 3 PSA: Prescaler Assignment bit
1 = Prescaler is assigned to the WDT
0 = Prescaler is assigned to the Timer0

bit 2-0 PS2:PS0: Prescaler Rate Select bits

Figure 8-6 Bitmap of the OPTION_REG Register
8.3 EEPROM Data Storage

EEPROM (pronounced double-e PROM or e-squared PROM) stands for electrically-erasable programmable read-only memory. EEPROM is used in computers and digital devices as non-volatile storage. EEPROM is not RAM, since RAM is volatile and EEPROM retains its data after power is removed. EEPROM is found in USB flash drives and in the non-volatile storage of several microcontrollers, including many PICs.

One advantage of EEPROM is that it can be erased and written electrically, without removing the chip. The predecessor technology, named EPROM, required that the chip be removed from the circuit and placed under ultraviolet light. EEPROM simplifies the erasing and re-writing process.

EEPROM data memory refers to both on-board EEPROM memory and to EEPROM memory ICs as separate circuit components. In general, EEPROM elements are classified according to their electrical interfaces into serial and parallel. Most EEPROM memories used in PICs are serial EEPROMs, also called SEEPROMs. The typical use of serial EEPROM on-board memory and EEPROM on ICs is in the storage of passwords, codes, configuration settings, and other information to be remembered after the system is turned off. For example, a PIC-based security system can use EEPROM memory to store the system password. Since EEPROM can be written, the user can change this password and the new one will also be remembered.

8.3.1 EEPROM in Mid-Range PICs

The mid-range PICs are equipped with EEPROM memory in three possible sizes: 64 bytes, 128 bytes, and 256 bytes. EEPROM memory allows read and write operations. This memory is not mapped into the processor’s data or program area, but in a separate block that is addressed through some SFRs. The registers related to EEPROM operations are:

1. EECON1
2. EECON2 (not a physically implemented register)
3. EEDATA
4. EEADR

EECON1 contains the control bits, and EECON2 is used to initiate the EEPROM read and write operations. The 8-bit data item to be written must first be stored in the EEDATA register, while the address of the location in EEPROM memory is stored in the EEADR register. The EEPROM address space always starts at 0x00 and extends linearly to maximum in the device.

When a write operation is performed, the contents of the EEPROM location are automatically erased. The EEPROM memory used in PICs is rated for high erase/write cycles. EEPROM programming is the topic of Chapter 15.
8.4 Data Memory Organization

The structure and organization of data memory in the PIC hardware also has some unique and interesting features. The programmer accustomed to the flat, addressable memory space of the von Neumann computer with its multiple machine registers may require some time in order to gain familiarity with the PIC's data formats.

8.4.1 The w Register

PICs have only one addressable register called the work register or the w register. The CISC programmer who is used to having multiple general purpose registers into which data can be moved and later retrieved has to become used to a single machine register that takes part in practically every instruction. Add to this the lack of an addressable stack into which data can be pushed and popped, and you see that PIC programming is a different paradigm.

8.4.2 The Data Registers

PIC’s data memory consists of registers, also called file registers. These behave more like conventional variables, and can be addressed directly and indirectly. All data registers are 8-bits. Data registers come in two types: general purpose registers (GPRs) and special function registers (SFRs).

Memory Banks

The PIC instruction format devotes seven bits to the address field (see Figure 8-2, Section 8.0.4). A 7-bit address allows access to only 128 memory locations. Since many PICs of the mid-range family have more than 128 bytes of data memory, an addressing scheme based on memory banks must be implemented. The memory banking mechanism adopted by the PICs is effective, although not very user-friendly.

The number of banks vary according to the amount of available RAM, always in multiples of 128-bytes. All mid-range PICs have banked memory. Banking is accomplished through the special bank-select bits in the STATUS register (see Figure 8-5). Not all banking bits are implemented in all devices. For example, the 16F84/16F84A contain two memory banks; therefore, bank shifting requires a single bank-select bit (RP0). In this case the RP1 bit is not implemented. In devices with more than two memory banks bank selection is as shown in Table 8.2.

Table 8.2

<table>
<thead>
<tr>
<th>BANK ACCESSED</th>
<th>STATUS REGISTER BITS (RP1:RP0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0 : 0</td>
</tr>
<tr>
<td>1</td>
<td>0 : 1</td>
</tr>
<tr>
<td>2</td>
<td>1 : 0</td>
</tr>
<tr>
<td>3</td>
<td>1 : 1</td>
</tr>
</tbody>
</table>

Figure 8-7 shows how banked memory is accessed in direct addressing. The illustration refers to a mid-range PIC with four banks, as is the case with the 16F87x.
The special function registers are defined by the device architecture and have reserved names. For example, the TMR0 register is part of the system timer, the STATUS register holds several processor flags, and the INTCON register is used in controlling interrupts. Some SFRs can be written and read and others are read-only. Some reserved and not-implemented SFR bits always read as zero. Two SFR registers, which are used in indirect addressing, have special characteristics: one of them (the indirect address register) is not a physical register, and the other one (the FSR register) is used to initialize the indirect pointer. The SFR are allocated starting at the lowest RAM address (address 0).

Figure 8-8 (in the following page) is a map of the register file in the 16F87x family. Note in Figure 8-8 that the general purpose registers do not start at the same address offset in each bank. However, there is a common area that extends from 0x70 to 0x7f that is accessible no matter which bank is selected. In applications that require frequent bank switching, this 16-byte area is very valuable real-estate since user variables created in it are accessible no matter which bank is currently selected. GPRs created outside this common area are only accessible when the corresponding bank is selected.
The registers in boldface in Figure 8-8 are accessible from any bank. These registers, such as STATUS and the indirect addressing registers FSR and INDF, are bank-independent. Also, some registers are mirrored in more than one bank. For example, the PORTB register is accessible in bank 0 and in bank 2, and the TRISB register in bank 1 and bank 3. The mirrored registers are designed to simplify data access and minimize bank changes in applications.

![Figure 8-8 16F87x File Register Map](image)

* Actual name is OPTION_REG
Other members of the mid-range PIC group, such as the 16F84 and 16F84A, have a different memory footprint. Figure 8-9 is a bitmap of the 16F84A.

<table>
<thead>
<tr>
<th>Bank 0</th>
<th>Bank 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>INDF 0x00</td>
<td>INDF 0x80</td>
</tr>
<tr>
<td>TMRO 0x01</td>
<td>OPTION* 0x81</td>
</tr>
<tr>
<td>PCL 0x02</td>
<td>PCL 0x82</td>
</tr>
<tr>
<td>STATUS 0x03</td>
<td>STATUS 0x83</td>
</tr>
<tr>
<td>FSR 0x04</td>
<td>FSR 0x84</td>
</tr>
<tr>
<td>PORTA 0x05</td>
<td>TRISA 0x85</td>
</tr>
<tr>
<td>PORTB 0x06</td>
<td>TRISB 0x86</td>
</tr>
<tr>
<td>EEDATA 0x07</td>
<td>0x87</td>
</tr>
<tr>
<td>EEADR 0x08</td>
<td>EECON1 0x88</td>
</tr>
<tr>
<td>PCLATH 0x09</td>
<td>EECON2 0x89</td>
</tr>
<tr>
<td>INTCON 0x0a</td>
<td>PCLATH 0x8a</td>
</tr>
<tr>
<td>0x0b</td>
<td>INTCON 0x8b</td>
</tr>
<tr>
<td>0x0c</td>
<td>0x8c</td>
</tr>
<tr>
<td>0x4f</td>
<td>0xcf</td>
</tr>
</tbody>
</table>

* Actual name is OPTION_REG

Figure 8-9 16F84A File Register Map

Here again, the general purpose registers do not start at the same address offset in each bank. Also note that all GPRs are mapped to bank 0. In the 16F84A, this means that user-defined registers created in bank 0 are accessible no matter which bank is currently selected.

The GPRs

General purpose registers are created and named by the programmer and must be allocated in the reserved memory space. In the 16F84A all GPRs are mapped to the same memory area, no matter in which bank they are defined. The GPR memory space actually extends from 0x0c to 0x4f (68 bytes). A different situation exists in the 16F87x PICs, in which only 16 bytes of GPR space is mirrored in all three banks. This is the memory referred to as the common area in Figure 8-8. In the 16F87x the total available GPR space is as follows:
8.4.3 Indirect Addressing

The instruction set of most processors, including the PICs, provides a mechanism for accessing memory operands indirectly. **Indirect addressing** is based on the following capabilities:

1. The address of a memory operand is loaded into a register. This register is called the **pointer**.

2. The **pointer register** is then used to indirectly access the memory location at the address it “points to.”

3. The value in the pointer register can be modified (usually incremented or decremented) so as to allow access to other memory operands.

In the PIC architecture indirect addressing is implemented using two registers: INDF and FSR. The **INDF register**, always located at memory address 0x00 and mirrored in all banks, is not a physical register, in the sense that it cannot be directly accessed by code. The **FSR register** is the pointer register that is initialized to the address of a memory operand. Once a memory address is placed in FSR, any action on the INDF register takes place at the memory location pointed at by FSR. For example, if the FSR register is initialized to memory address 0x20, then clearing the INDF register has the effect of clearing the memory location at address 0x20. In other words, the action on the INDF register actually takes place at the address contained in the FSR register. Now, if FSR (the pointer register) is incremented and INDF is again cleared, the memory location at address 0x21 is cleared. Indirect addressing is covered in detail in the programming chapters.

8.5 Mid-range I/O and Peripheral Modules

Mid-range devices contain special modules to implement peripheral and I/O functions. The more complex the device the more peripheral modules are likely to be present. For example, a simple mid-range PIC like the 16F84A contains few peripheral modules, specifically, EEPROM data memory, I/O ports, and a timer module. The 16F87x PICs, on the other hand, in addition to I/O ports, EEPROM, and three individual timers, have a parallel slave port, a WPM (capture and compare) module, an MSSP (master synchronous serial port) module, a USART (universal asynchronous/synchronous receiver and transmitter) module, and an A/D (analog-to-digital converter) module.

Other members of the mid-range family have additional or different peripheral and I/O modules. In the following sections, we briefly describe the architecture of the most common peripheral modules. The programming details are covered elsewhere in the book.
Implementation of many different functions in a device with a small footprint requires multiplexing many of the PIC’s access connections. Figure 8-10 shows the pinout of the 16F84A and the 16F877 and the multiple functions of most pins in both devices.

Figure 8-10  16F84A and 16F877 Pin Diagrams

8.5.1 I/O Ports

Ports provide PICs access to the outside world and are mapped to physical pins on the device. In some mid-range PICs (see Figure 8-10) some port pins for I/O ports are multiplexed with alternate functions of peripheral modules. When a peripheral module is enabled, that pin ceases to be a general purpose I/O.

Port pins can be configured either as input or output, that is, general ports are bidirectional. Each port has a corresponding TRIS register which determines if a port is designated as input or output. A value of 1 in the port’s TRIS register makes the port an input and a value of 0 makes the mapped port an output. Typically, input ports are used in communicating with input devices, such as switches, keypads, and input data lines from hardware devices. Output ports are used in communicating with output devices, such as LEDs, seven-segment displays, LCDs (liquid-crystal displays), and data output lines to hardware devices.
Although port pins are bitmapped, they are read and written as a unit. For example, the PORTA register holds the status of the eight pins possibly mapped to Port-A, while writing to PORTA writes to the port latches. Write operations to ports are actually read-modify-write operations. In other words, the port pins are first read, then the value is modified, and then written to the port’s data latch. Some of the port pins are multiplexed; for example, pin RA4 is multiplexed with the Timer0 module clock input; therefore, it is labeled RA4/T0CKI pin. Other PORTA pins are multiplexed with analog inputs and with other peripheral functions. The device data sheets contain information about the functions assigned to each device pin.

8.5.2 Timer Modules

Timer modules are available in all mid-range devices. The TIMER0 module is present in all PICs of this family. It has the following features:

1. 8-bit timer/counter
2. Readable and writable
3. 8-bit software programmable prescaler
4. Internal or external clock select
5. Interrupt on overflow from FFh to 00h
6. Edge select for external clock

Chapter 12 is devoted entirely to the architecture and programming of timers and counters.

8.5.3 Capture-and-Compare Module

Some mid-range devices contain one or more capture-and-compare modules, designated as Capture/Compare/PWM modules. In Figure 8-10 you can see that one of the functions multiplexed onto pin 17 of the 16F877 is labeled CCP1 (capture-and-compare module number 1). The CCP2 module is multiplexed onto pin number 16. The principal function of the capture-and-compare modules is to enhance timer operations. Each module contains the following elements:

- A 16-bit register which can operate as:
  - a 16-bit capture register or a 16-bit compare register
- A PWM Master/Slave Duty Cycle register

When more than one capture-and-compare module is implemented in a single device, they are all identical in operation. In the 16F877, the two available modules are designated as CCP1 and CCP2 respectively. In each module a Capture/Compare/PWM Register1 (CCPR1) is comprised of two 8-bit registers: CCPR1L (low byte) and CCPR1H (high byte). The CCPR1CON register controls the operation of CCP1.

The CCP modules find use in recording events, measuring time periods, counting, generating pulses and periodic waveforms, and voltage averaging, among others. However, since these applications are not commonly found in the simple PIC circuits covered in this book we make no further reference to this topic.
8.5.4 Master Synchronous Serial Port (MSSP) Module

Some mid-range PICs come equipped with hardware modules to implement serial protocols, including SPI and I2C. The module that provides these interfaces is named the Master Synchronous Serial Port, or MSSP. The MSSP module can operate in either the slave or the master mode, as well as in a free-bus mode, also called the multi-master function.

The MSSP module is useful for communicating with other peripheral or microcontroller devices. The peripheral devices can be serial EEPROMs, shift registers, display drivers, A/D converters, etc. The MSSP module is discussed in Chapter 8, in the context of EEPROM data memory programming.

8.5.5 USART Module

The Universal Synchronous Asynchronous Receiver Transmitter (USART) module in the 16F87x family is also known as a Serial Communications Interface, or SCI. The USART module is used in communicating with devices and systems that support RS-232 communications, including computers and terminals. It can be configured as an asynchronous full duplex device, as a synchronous half-duplex master, or as a synchronous half-duplex slave. In the synchronous mode, the USART is useful in communicating with analog-to-digital and digital-to-analog integrated circuits or for accessing serial EEPROMS. The USART is discussed extensively in Chapter 14 and, in the context of programming serial EEPROMS, in Chapter 15.

8.5.6 A/D Module

Until recently, A/D conversions required the use of dedicated devices, usually in the form of an integrated circuit component. Mid-range PICs now come with on-board A/D hardware. One of the advantages of using on-board A/D converters is saving interface lines. Interfacing with a hardware IC usually requires three to four lines. A similar function can be implemented with on-board A/C hardware with a single line. Since I/O lines are often needed in PIC circuits, the advantage of on board A/C hardware is significant.

Mid-range PICs equipped with A/D converters have either 8- or 10-bit resolution and can receive analog input in 2 to 16 different channels. For example, the 16F877 contains eight analog input channels at a 10-bit resolution. An A/D converter uses a sample-and-hold capacitor to store the analog charge and performs a successive approximation algorithm to produce the digital result. When the converter resolution is 10 bits these are stored in two 8-bit registers, one of them having only four significant bits.

The A/D module has high- and low-voltage reference inputs which are selected by software. The module can operate while the processor is in the SLEEP mode, but only if the A/D clock pulse is derived from its internal RC oscillator. The A/D converter module is discussed in detail in Chapter 16.
Chapter 9

PIC Programming: Tools and Techniques

PIC microcontrollers can be programmed in high-level languages or in their native machine language. Machine language programming is facilitated by the use of an assembler program, and thus becomes assembly language programming. Although assembly language is the most used and popular way of PIC programming, there is an ongoing debate regarding the use of high-level languages.

The major argument in favor of high-level languages is their ease of use and their faster learning curve. The advantages of assembly language, on the other hand, are better control and greater efficiency. It is true that arguments that favor high-level languages find some justification in the computer world, but these reasons are not as valid regarding PIC programming. In the first place, the PIC programmer cannot avoid complications and technical details by resorting to a high-level language, since PIC programs relate closely to hardware devices and to electronic circuits. These devices and circuits must be understood at their most essential level if they are to be controlled and operated by software. For example, consider a PIC program to provide some sort of thermostatic control. In this case, the programmer must become familiar with temperature sensors, analog-to-digital conversions, motor controls, and so on. This is true whether the program is written in a low- or a high-level language.

Another reason for using assembly language in PIC programming is that the language itself is quite simple. The mid-range PICs have 35 instructions in their instruction sets and many of them are quite similar; so learning assembly language for PIC programming takes no great effort. Additionally, assembly language development tools are free from Microchip, while most high-level languages must be purchased from their developers. For these reasons we have excluded all high-level languages from consideration in this book.

9.0 Microchip’s MPLAB

The PIC assembly language development system provided by Microchip is named MPLAB. The package is furnished as an IDE (integrated development environment) and can be downloaded from the company’s web site at www.microchip.com.
One limitation of the MPLAB package is that it is furnished only for the PC. If you are a Mac, UNIX, or Linux user you cannot use MPLAB. Development packages for other operating systems are available on the Web.

The MPLAB IDE is intended for software development of embedded systems. An embedded system is designed for a specific purpose, in contrast with a computer system which is a general purpose machine. The embedded system is designed to perform specific and predefined tasks; for example, control a microwave oven, control a TV receiver, or operate a model railroad. The software of a general-purpose computer can be easily changed. You may, at will, run a word processor, a web browser, or a database management system on your computer. The software in an embedded system is usually fixed and cannot be easily changed; for this reason it is called “firmware.”

9.0.1 Embedded Systems

At the heart of an embedded system is a microcontroller (such as a PIC), sometimes several of them. These devices are programmed to perform one, or at most a few, tasks. In the most typical case, an embedded system also includes one or more “peripheral” circuits which are operated by dedicated ICs or by functionality contained in the microcontroller itself. The term “embedded system” refers to the fact that the device is often found inside another one; for instance, the control circuit is embedded in a microwave oven. Furthermore, embedded systems do not have (in most cases) general purpose devices such as hard disk drives, video controllers, printers, and network cards.

A typical embedded system is a control for a microwave oven. In this case, the controller includes a timer to clock various operations, a temperature sensor to provide information about the oven’s operation, a motor to rotate the oven’s tray, a sensor to detect when the oven door is open, and a set of pushbutton switches to select the operational options. A program running on the embedded microcontroller reads the commands and parameters input through the keyboard, programs the timer and the rotating table, detects the state of the door, and turns the heating element on and off as required by the user’s selection. Many other daily devices including automobiles, digital cameras, cell phones, and home appliances use embedded systems and many of them are PIC-based.

The development process of an embedded system consists of the following steps:

1. Define the system specifications. This step includes listing the functions that the system is to perform and determining the tests that are to validate their operations.

2. Select the system components according to the specifications. This step includes locating the microcontroller that best suits the system as well as the other hardware components.

3. Design the system hardware. This step includes drawing the circuit diagrams.

4. Implement a prototype of the system hardware by means of breadboards, wire boards, or any other changeable implementation technology.
5. Develop, load, and test the software. Loading software into a PIC is referred to as “burning” or “blowing” the PIC.

6. Implement the final system and test hardware and software.

9.1 Integrated Development Environment

The MPLAB development system consists of a system of programs that run on a PC. This software package is designed to help develop, edit, test, and debug PIC code.

Installing the MPLAB package is straightforward and simple. The package includes the following components:

1. **MPLAB editor.** This tool allows creating and editing the assembly language source code. It behaves like any Windows editor and contains the standard editor functions, including cut-and-paste, search-and-replace, and undo and redo functions.

2. **MPLAB assembler.** The assembler reads the source file produced in the editor and generates either absolute or relocatable code. **Absolute code** executes directly in the PIC. **Relocatable code** can be linked with other separately assembled modules or with libraries.

3. **MPLAB linker.** This component combines modules generated by the assembler with libraries or other object files, into a single executable file in .hex format.

4. **MPLAB debuggers.** Several debuggers are compatible with the MPLAB development system. Debuggers are used to single-step through the code, breakpoint at critical places in the program, and watch variables and registers as the program executes. In addition to being a powerful tool for detecting and fixing program errors, debuggers provide an internal view of the processor; this is a valuable learning tool.

5. **MPLAB In-circuit emulators.** These are development tools that allow performing basic debugging functions while the processor is installed in the circuit.

Figure 9-1 (in the following page) is a screen image of the MPLAB program. The application on the editor window is one of the programs developed later in this book.

9.1.1 Installing MPLAB

In normal installation, the MPLAB executable is placed in the following path:

```
C:\Program Files\Microchip\MPASM Suite
```

Once the development environment is installed, the software is executed by clicking the MPLAB IDE icon. It is usually a good idea to drag and drop the icon onto the desktop so that the program can be easily activated.

With the MPLAB software installed, it may be a good idea to check that the applications were placed in the correct paths and folders. Failure to do so produces assembly-time failure errors with cryptic messages. To check the correct path for the software, open the Project menu and select the Select Language Toolsuite command. Figure 9-2 shows the command screen.
In the toolsuite window make sure that the file location coincides with the actual installation path for the software. If in doubt, use the <Browse> button to navigate through the installation directories until the executable program is located. In this case, `mpasmwin.exe`. Follow the same process for all the executables in the Toolsuite Contents window.

**Figure 9-2** MPLAB Select Language Toolsuite Screen
Figure 9-3  MPLAB Set Language Tools Locations Screen

A more detailed control over the location of the various individual tools is provided by the **Set Language Tools Location** command, also in the **Project** menu. This command allows setting the installation path not only to the major suites, but also to the individual tools. Figure 9-3 shows the display screen of this command.

### 9.1.2 Creating the Project

In MPLAB, a project is a group of files generated or recognized by the IDE. Figure 9-4 shows the structure of an assembly language project.

![MPLAB Project Files Diagram](image)

**Figure 9-4**  MPLAB Project Files
Figure 9-4 shows an assembly language source file (prog1.asm) and an optional processor-specific include file which are used by the assembler program (MPASAM) to produce an object file (prog1.o). Optionally, other sources and other include files may form part of the project. The resulting object file, as well as one or more optional libraries, and a device-specific script file (device.lkr) are then fed to the linker program (MPLINK). MPLINK generates a machine code file (prog1.hex) and several support files with listings, error reports, and map files. The .hex file is used to blow the PIC.

In addition to the files in Figure 9-4, others may also be produced by the development environment according to the selected tools and options. For example, the assembler or the linker can generate a file with the extension .cod that contains symbols and references used in debugging.

Projects can be created using the <New> command in the Project menu. The programmer then proceeds to configure the project manually and add to it the required files. An alternative option, much to be preferred when learning the environment, is using the <Project Wizard> command in the Project menu. The wizard prompts you for all the decisions and options that are required, as follows:
1. Device selection. Here the programmer selects the PIC hardware for the project, for example 16F84A.
2. Select language toolsuite. This screen is the same one shown in Figure 9-2. Its purpose is to make sure that the proper development tools and paths are active.
3. Next, the wizard prompts the user for a project name and directory. It is possible to create a new directory at this time.
4. In the next step, the user is given the option of adding existing files to the project and renaming these files if necessary. This can be a useful option, since most projects reuse a template, an include file, or other preexisting resources.
5. Finally, the wizard displays a summary of the project parameters. When the user clicks on the <Finish> button, the project is created and programming can begin.

![Figure 9-5 Final Screen of the Project Creation Wizard](image)

---

**Figure 9-5** Final Screen of the Project Creation Wizard
9.1.3 Project Build Options

The <Build Options: Project> command in the Project menu allows the user to customize the development environment. Of the tabs available on the Build Options screen, the MPASM Assembler is probably the most used. The screen is shown in Figure 9-6.

![MPASM Assembler Tab in the Build Options Screen](image)

The MPASM Assembler tab allows performing the following customizations:

1. Disable/enable case sensitivity. Normally the assembler is case-sensitive. Enabling this option turns all variables and labels to upper case.

2. Select the default radix. Numbers without formatting codes are assumed to be hex, decimal, or octal according to the selected option.

3. The Macro Definition window allows adding macro directives. Macros are discussed later in this chapter.

4. The Use Alternate Settings text box is provided for command line commands in non-GUI environments.

5. The Restore Defaults box turns off all custom configurations.

9.1.4 Building the Project

Once all the options have been selected, the installation checked, and the assembly language source file written or imported, the development environment builds the project. Building consists of calling the assembler, the linker, and any other support
program in order to generate the files shown in Figure 9-4 and any others that result from a particular project or IDE configuration.

The build process is initiated by selecting the <Build All> command in the Project menu. Once the building concludes, a screen labeled Output is displayed showing the results of the build operation. If the build succeeded, the last line of the Output screen shows this result. Figure 9-7 shows the output screen after a successful build.

Figure 9-7 Output Window showing the Build Command Result

9.2 Simulators and Debuggers

In the context of MPLAB documentation the term debugger is reserved for hardware debuggers while the software versions are called simulators. Although this distinction is not always enforceable, we will abide by this terminology (whenever possible) in order to avoid confusion. The reader should note that there are MPLAB functions in which the IDE considers a simulator as a debugger.

The MPLAB standard simulator is called MPLAB SIM. SIM is part of the Integrated Development Environment and can be selected at any time. The hardware debuggers currently offered by Microchip are named ICD 2, ICE 2000, and ICE 4000. A simulator, as the term implies, allows simulating the execution of a program one instruction at a time and viewing file registers and symbols defined in the code. Debuggers, on the other hand, allow executing a program one step at a time or to a predefined breakpoint while the PIC is installed in the target system. This makes
possible realtime viewing of the processor’s internals, and also the state of circuit components.

In the sections that follow we present an overview of PIC simulators and debuggers and their use.

### 9.2.1 MPLAB SIM

Microchip documentation describes the SIM program as a *discrete-event simulator*. SIM is part of the MPLAB IDE and is selected by clicking on the `<Select Tool>` command in the **Debugger** menu. The command offers several options, one of them being MPLAB SIM. Once the SIM program is selected, a special debug toolbar is displayed. The toolbar and its functions is shown in Figure 9-8.

**Figure 9-8** SIM Toolbar

In order for the simulator to work the program must first be successfully built. The most commonly used simulator methods are single-stepping through the code and breakpoints. A *breakpoint* is a mark at a program line at which the simulator stops and waits for user actions.

Breakpoints provide a way of inspecting program results at a particular place in the code. *Single-stepping* is executing the program one instruction at a time. The three buttons labeled `<Step...>` are used in single-stepping. The first one allows breaking out of a subroutine or procedure. The second one is for bypassing a procedure or subroutine while in step mode. The third one single steps into whatever line follows.

Breakpoints are set by double-clicking at the desired line while using the editor. The same action removes an existing breakpoint. Lines in which breakpoints have been placed are marked, on the left document margin, by a letter “B” enclosed in a red circle. Right-clicking while the cursor is on the program editor screen provides a context menu with several simulator-related commands. These include commands to set and clear breakpoints, to run to the cursor, and to set the program counter to the code location at the cursor.
The View menu contains several commands that provide useful features during program simulation and debugging. These include commands to program memory, file registers, EEPROM, and special function registers. One command in particular, named <Watch>, provides a way of inspecting the contents of FSRs and GPRs on the same screen. The <Watch> command displays a program window that contains references to all file registers used by the program. The user then selects which registers to view and these are shown in the Watch window. The Watch window is shown in Figure 9-9.

![Watch Window in MPLAB SIM](image)

**Figure 9-9** Use of Watch Window in MPLAB SIM

When the program is in the single-step mode or breakpoint modes, the contents of the various registers can be observed in the Watch window. Those that have changed since the last step or breakpoint are displayed in red. The user can click the corresponding arrows on the Watch window to display all the symbols or registers. The <Add Symbol> or <Add FSR> button is then used to display the item on the Watch screen. Four different Watch windows can be enabled, labeled Watch 1 to Watch 4 at the bottom of the screen in Figure 9-9.

Another valuable tool available from the View menu is the one labeled <Simulator Trace>. The Simulator Trace window provides a view of the machine instruction combined with a window that displays the source code. The Simulator Trace window is shown in Figure 9-10.

### 9.2.2 MPLAB Hardware Debuggers

A more powerful and versatile debugging tool is a hardware or in-circuit debugger. Hardware debuggers allow tracing, breakpointing, and single-stepping through code while the PIC is installed in the target circuit. The typical in-circuit debugger requires several hardware components, as shown in Figure 9-11.
Figure 9-10  MPLAB SIM Simulator Trace Window

Figure 9-11  Components of a Typical Hardware Debugger
The emulator pod with power supply and communications cable provides the basic communications and functionality of the debugger. The communications line between the PC and the debugger can be an RS-232, a USB, or a parallel port line. The processor module fits into a slot at the front of the pod module. The processor is device-specific and provides these functions to the debugger. A flex cable connects the processor module to an interchangeable device adapter that allows connecting to the several PICs supported by the system. The transition socket allows connecting the device adapter to the target hardware. A separate socket allows connecting logic probes to the debugger.

Microchip provides two models of their in-circuit hardware debuggers, which they call In-Circuit Emulators, or ICEs. The ICE 2000 is designed to work with most PICs of the mid-range and lower series, while the ICE 4000 is for the PIC18x high-end family of PICs. Recently Microchip has released an in-circuit debugger designated as ICD 2 that offers many of the features of their full-fledged in-circuit emulators at a much reduced price. One of the disadvantages of the ICD 2 system is that it requires the exclusive use of some hardware and software resources in the target. Furthermore, the ICD requires that the system be fully functional. The ICEs, on the other hand, provide memory and clocks so that the processor can run code even if it is not connected to the application board.

9.2.3 A “Quick-and-Dirty” Debugger

The functionality of an actual hardware debugger can be replaced with a little ingenuity and a few lines of code. Most PICs are equipped with EEPROM memory. Programmers (covered in the following section) have the ability to read all the data stored in the PIC, including EEPROM. These two facts can be combined to obtain run-time information without resorting to a hardware debugger.

Suppose a defective application is suspected of not finding the expected value in a PIC port. The developer can write a few lines of code to store the port value on an EEPROM memory cell. An endless loop following this operation ensures that the stored value is not changed. Now the PIC is inserted in the circuit and the application executed. When the endless loop is reached, the PIC is removed from the circuit and placed back in the programmer. The value stored in EEPROM can now be inspected so as to determine the run-time state of the machine. In many cases, this simple trick is less complicated and time consuming than setting up a hardware debugger, even if such a device is available.

9.3 Programmers

In the context of microcontroller technology, a programmer is a device that allows transferring the program onto the chip. The process is called “burning” a PIC, or more commonly “blowing” a PIC. Most programmers have three components:

1. A software package that runs on the PC
2. A cable connecting the PC to the programmer
3. A programmer device
Dozens of PIC programmers are available on the Internet. When Microchip released the programming specifications of the PIC to the public without requiring a nondisclosure agreement, they originated a cottage industry. The commercial programmers on the Internet range from a “no parts” PIC programmer that has been around since 1998, to sophisticated devices costing hundreds of dollars and providing many additional features and refinements. For the average new PIC user, a nice USB programmer with a ZIF (zero insertion-force) socket and the required software can be purchased for about $50.00. Build-it-yourself versions are available for about half this amount.

An alternative programmer is made possible by the fact that some of the newer flash-based PICs can write to their own program memory. This allows placing a small bootloader program in PIC memory which loads an application over the RS-232 or USB lines.

Figure 9-12 is a screen capture of the driver software for a popular programmer from MicroPro.

Figure 9-12 Control Program for the DIY MicroPro Programmer

9.4 Engineering PIC Software

The program developer’s main challenge is writing code that performs the task at hand. In this context this means writing a PIC assembly language program that assembles without errors (usually after some effort) and makes the circuit perform as intended. We have already reviewed the IDE (integrated development environment) and
the various hardware components and software tools. We now focus on the various elements that are used in developing the program itself.

### 9.4.1 Using Program Comments

One of the first realizations of beginning programmers is how quickly we forget the reasoning and logic that went into our code. It is common that a few weeks, even a few hours, after we coded a routine we find that what was obvious then is now undecipherable and that the ideas that were clear in our minds a short time ago now evade our understanding. The only solution is to write good program comments that explain, not the elementary, but the trains of thought behind our code.

In PIC assembly language, the comment symbol is the *semicolon* (;). The presence of a semicolon indicates to the assembler that everything that follows, to the end of the line, must be ignored. Using comments judiciously and with good taste is the mark of the expert software engineer. Programs with few, cryptic, or confusing comments fall into the category of “spaghetti code.” In programming lingo, “spaghetti code” refers to a coding style that cannot be deciphered or understood. One of the worst offenses that can be said about one’s programming style is that it is spaghetti code.

How we use comments to explain our code or even to embellish it is a matter of personal preference. However, there are certain common sense rules that should always be considered:

1. Do not use program comments to explain the programming language or reflect on the obvious.
2. Abstain from humor in comments. Comedy has a place in the world but it is not in programs. By the same token, stay away from vulgarity, racial or sexist remarks, and anything that could be offensive. You can never anticipate who will read your code.
3. Write short, clear, readable comments that explain how the program works. Decorate or embellish your code using comments according to your tastes.

### Program Header

Every program should have a commented header that contains the following information:

1. Program name
2. Programmer’s or software company’s name
3. Copyright notice, if pertinent
4. Target device or hardware
5. Development environment
6. Development dates
7. Program description
Some of these elements allow various levels of detail. For example, the target device can be a simple reference to the PIC for which the program is written, a more-or-less detailed description of the target system, or a reference to a circuit diagram or board drawing. The development environment can also be described briefly or in detail. The date element can be a single entry that lists the first or the last program change, or a detailed description of all program changes, tests, and updates. The program description can be a short sentence or a mini-manual on using the application. In any case, the level of detail and the contents of each category are determined by the programmer’s style and the complexity and purpose of the application.

The following lines show the header of one of the programs developed for this book:

; File name: RTC2LCD.asm
; Last Update: June 6, 2006
; Author: Julio Sanchez
; Processor: 16F84A
;
; Description:
; Program to demonstrate use of the NJU6355 Real Time Clock
; IC. Program uses LCD to display results in hours, minutes,
; and seconds, as follows:
;
; Top LCD line: H:xx M:yy S:zz
; Initialization values are in #define statements that start
; with i, such as iYear, iMonth, etc.
;
; For LCD display parameters see the LCDTest2 program.
;
; WARNING:
; Code assumes 4Mhz clock. Delay routines must be
; edited for faster clock

**Commented Banners**

Often, we need to scroll through the code in search of a particular line or routine. Having banners that signal critical places in the program facilitates this search. Banners are created using comments and a framing symbol, as in the following code fragment:

;=======================================
; first text string procedure
;=======================================
storeMS1:
; Procedure to store in PIC RAM buffer the message
; contained in the code area labeled msg1
; ON ENTRY:
;   variable pic_ad holds address of text buffer
;   in PIC RAM
;   w register hold offset into storage area
;   msg1 is routine that returns the string characters
;   and a zero terminator
;   index is local variable that hold offset into
;   text table. This variable is also used for
;   temporary storage of offset into buffer
Sometimes, the programmer needs to emphasize a program area with a large banner that extends from margin to margin, as follows:

```
;============================================================
;============================================================
; LOCAL PROCEDURES
;============================================================
;============================================================
;==========================
; init LCD for 4-bit mode
;==========================
initLCD:
; Initialization for Densitron LCD module as follows:
; 4-bit interface
; 2 display lines of 20 characters each
; cursor on
; left-to-right increment
; cursor shift right
; no display shift
```

**Commented Bitmaps**

It is also possible to use comments to signal the function of bit fields and individual bits of an operand, as in the following code fragment:

```
; OPTION_REG bitmap
;  7  6  5  4  3  2  1  0 <- OPTION bits
;  | | | | | | |___ PS2-PS0 (prescaler bits)
;  | | | | | | 000 = 1:2  001 = 1:4
;  | | | | | 010 = 1:8  011 = 1:16
;  | | | 100 = 1:32 101 = 1:64
;  | | 110 = 1:128 *111 = 1:256
;  | | |___________________ PSA (prescaler assign)
;  | | | 1 = to WDT
;  | | 0 = to Timer0
;  | | |___________________ TOSE (Timer0 edge select)
;  | | | 0 = increment on low-to-high
;  | | 1 = increment in high-to-low
;  | | |___________________ TOCS (TMR0 clock source)
;  | | | 0 = internal clock
;  | | 1 = RA4/TOCKI bit source
;  | |______________________ INTEDG (Edge select)
;  | 0 = falling edge
; 1 = rising edge
; * indicates options selected
movlw b'00001000' ; Value installed
movwf OPTION_REG
```

Clearly commented bitmaps, banners, and many other code embellishments do not add to the quality and functionality of the code. It is quite possible to write very sober and functional programs without using them. The decision of how to comment and embellish programs is one of style.
9.4.2 Defining Data Elements

Most programs require the use of general purpose file registers. These registers are allocated to memory addresses reserved for this purpose in the PIC architecture, as shown in Figure 8-8 and Figure 8-9. Since the areas at these memory locations are already reserved for use as GPRs, the program can access the location either by address or by assigning to that address a name. The equ (equate) directory performs this function, as follows:

```
var1 equ 0x0c ; Name var1 is assigned to location 0x0c
```

Actually, the name (in this case var1) becomes an alias for the memory address to which it is linked. From this point on, program code can access the memory cell at address 0x0c as follows:

```
movf var1,w ; Contents of var1 to w
```

or:

```
movf 0x0c,w ; Same variable to w
```

In addition to the equ directive, PIC assembly language recognizes the C-like define directive, so the name assignment could be done as follows:

```
#define var1 0x0c
```

Although most of the time-named variables are to be preferred to hard-coding addresses, there are times when we need to access an internal element of some multi-byte structure. In these cases, the hard-coded form could be convenient, although not absolutely necessary.

**The cblock Directive**

Another way of defining memory data is by using one of the data directives available in PIC assembly language. Although there are several of these, perhaps the most useful is the cblock directive. The block directive specifies an address for the first item and other items listed are allocated from this first address. The group ends with the endc directive. The following code fragment shows the use of the cblock/endc directives.

```
; Reserve 20 bytes for string buffer
  cblock 0x20
    strData
  endc

; Reserve three bytes for ASCII digits
  cblock 0x34
    asc100
    asc10
    asc1
  endc
```

In reality, the cblock directive defines a group of constants which are assigned consecutive addresses in RAM. In the previous code fragment the allocation of 20 bytes for the buffer named strData is illusory since no memory is actually reserved. The illusion works because the second cblock starts at address 0x34 which is 20 bytes after strData, and also because the programmer abstains from allocating other variables in the buffer space.
### 9.4.3 Banking Techniques

Having to deal with memory banks is one of the aggravations of PIC programming. Banks are numbered starting with bank 0. All PICs of the mid-range family have at least two banks, so bank shifting operations are virtually unavoidable. The issue is more how to switch bank designation since there are several possible techniques.

Bank selection is by means of bit RP0 and RP1 in the STATUS register. In mid-range PICs with four banks, the various combinations are as shown in Table 9.1.

<table>
<thead>
<tr>
<th>RP1</th>
<th>RP0</th>
<th>BANK</th>
<th>ADDRESS RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>*Bank 3</td>
<td>0x180 - 0x1ff</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>*Bank 2</td>
<td>0x100 - 0x17f</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>Bank 1</td>
<td>0x80 - 0xff</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>Bank 0</td>
<td>0x00 - 0x7f</td>
</tr>
</tbody>
</table>

* RP1 bit is not used in devices with two banks

The most direct way to select the current bank is by clearing or setting the corresponding bits in the STATUS register. For example, to select bank 2 in a 4-bank device you could code:

```assembly
bsf STATUS,6 ; Set bit 6 in STATUS register
bcf STATUS,5 ; Clear bit 5
```

### The banksel Directive

Alternatively the application can use the `banksel` directive which selects the bank in which a particular register is located. For example, to select the bank in which the ADCON1 register is located code could be as follows:

```assembly
banksel ADCON1
```

The `banksel` directive also works with registers defined by the user (GPRs).

### Bank Selection Macros

An alternative way of performing bank selection is by coding the corresponding bank select macros. A `macro` is an assembler structure that allows defining a series of instructions inserted in the code every time the macro is referenced. The PIC macro language defines the following format:

```assembly
label macro [arg1, arg2... argn]
  .
  .
  .
endm
```

The ellipses are placeholders for the PIC instructions, assembler directives, macro directives, and macro calls. Macros are usually defined at the beginning of the program since forward references to macros are not allowed. The optional arguments passed to the macro (`arg1, arg2, etc`) are assigned values when the macro is
invoked. For example, the following macros make the corresponding bank selections in a mid-range PIC with four banks.

```assembly
; Macros to select the register banks
Bank0 MACRO ; Select RAM bank 0
  bcf STATUS,RP0
  bcf STATUS,RP1
ENDM

Bank1 MACRO ; Select RAM bank 1
  bsf STATUS,RP0
  bcf STATUS,RP1
ENDM

Bank2 MACRO ; Select RAM bank 2
  bcf STATUS,RP0
  bsf STATUS,RP1
ENDM

Bank3 MACRO ; Select RAM bank 3
  bsf STATUS,RP0
  bsf STATUS,RP1
ENDM
```

Once the bank switching macros have been defined, the application can change banks simply by calling the macro name; for example, if we know that the `ADCON1` register is in bank 1 we can select the bank by calling:

```assembly
Bank1
```

At this point in the code the macro expansion inserts the corresponding operations to make the switch.

Which method to use when switching banks is a matter of personal preference and program constraints. Setting and clearing the RP1/RP0 bits is simple enough, but can be error-prone. Using the `banksel` directive is convenient since we do not need to know in which bank the item is located. The objection to using `banksel` is that some unnecessary bank changes may take place. For example, if the program is already in bank 1 and the `banksel` directive appears with a register file in that same bank, bank switching is generated.

The use of bank selection macros seems like a suitable method for most conditions. One advantage of the macro approach is that programs for different PICs can have their own banking macros. This way code can be easily ported to a different architecture.

**Deprecated Banking Instructions**

Several instructions in the mid-range instruction set have been deprecated and are no longer recommended by Microchip. These instructions are `tris` and `option`. Microchip's reason for not recommending these instructions is to maintain compatibility with future mid-range products. From a programmer's viewpoint, it is difficult to see why using these instructions may be undesirable. In the unlikely case that code using `tris` or `option` is ported to a future device that does not support them, it will be easy enough to modify.
The **tris** and **option** instructions are convenient since they allow loading the contents of the \( w \) register to the \( \text{OPTION} \), \( \text{TRISA} \), and \( \text{TRISB} \) registers directly, without bank concerns. For example, the following code fragment sets port line 1 to input and all others to output:

```assembly
movlw b'00000010' ; Line 1 is input
tris PORTA
```

We continue to use the deprecated instructions in programs in which there is no concern about future consequences. In programs in which portability is an issue, we use the banking macros discussed previously.

### 9.4.4 Processor and Configuration Controls

PIC programs must define the processor to be used by the development software. The **processor** directive in the **assembler** (and also the **list** directive) allows defining the PIC type. For example, a program for the 16F877 would contain the following line:

```assembly
processor 16f877
```

**Configuration Bits**

The PIC microcontrollers contain a special register called the **configuration register**. The bits in this register allow customizing certain processor features. These bits are mapped to program memory location 0x2007. This memory location can be accessed only during the programming mode, so the bits cannot be changed during normal program operation. The configuration bits cannot be read at runtime.

Microchip recommends that the configuration bits be set by means of the **__config** directive. The bits are mapped as follows:

<table>
<thead>
<tr>
<th>CP1:CP0: Code Protection bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>01</td>
</tr>
<tr>
<td>00</td>
</tr>
</tbody>
</table>

Some devices use different numbers of bits to determine the level of code protection. Some use a single bit. In this case, the encoding is as follows:

<table>
<thead>
<tr>
<th>DP: Data EEPROM Memory Code Protection bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BODEN: Brown-Out Reset Enable bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>
Enabling Brown-out Reset automatically enables PWRT (the Power-up Timer) regardless of the value of bit PWRTE. The Power-up Timer must be enabled any time that the Brown-out Reset is enabled.

PWRT: Power-up Timer Enable bit
1 = PWRT disabled
0 = PWRT enabled
See note about the BODEN bit.

MCLR: MCLR Pin Function Select bit
1 = Pin’s function is MCLR
0 = Pin’s function is as a digital I/O.
    MCLR is internally tied to VDD.

WDTE: Watchdog Timer Enable bit
1 = WDT enabled
0 = WDT disabled

FOSC1:FOSC0: Oscillator Selection bits
11 = RC oscillator
10 = HS oscillator
01 = XT oscillator
00 = LP oscillator

FOSC2:FOSC0: Oscillator Selection bits
111 = EXTRC oscillator, with CLKOUT
110 = EXTRC oscillator
101 = INTRC oscillator, with CLKOUT
100 = INTRC oscillator
011 = Reserved
010 = HS oscillator
001 = XT oscillator
000 = LP oscillator

The __config directive is used to embed configuration data in the source file. Alternatively, the configuration bits can be set at the time the PIC is blown. The following code fragment shows setting the configuration bits for a 16F877 PIC:

; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; _CP_OFF
; * _CP_OFF
; * _PWRTE_ON Power-up timer ON/OFF
; _PWRTE_OFF
; _BODEN_ON Brown-out reset enable ON/OFF
; * _BODEN_OFF
; * _PWRTE_ON Power-up timer enable ON/OFF
; _PWRTE_OFF
; _WDT_ON Watchdog timer ON/OFF
; * _WDT_OFF
; _LPV_ON Low voltage IC programming enable ON/OFF
; * _LPV_OFF
; _CPD_ON Data EE memory code protection ON/OFF
; * _CPD_OFF
; OSCILLATOR CONFIGURATIONS:
; _LP_OSC Low power crystal oscillator
; _XT_OSC External parallel resonator/crystal oscillator
; * _HS_OSC High speed crystal resonator
; _RC_OSC Resistor/capacitor oscillator
; | (simplest, 20% error)
; |***** * indicates setup values presently selected
; __CONFIG _CP_OFF & _NDT_OFF & _BODEN_OFF & _PWRTE_ON & _HS_OSC &
; _NDT_OFF & _LVP_OFF & _CPD_OFF
9.4.5 Naming Conventions

The programmer must decide on the conventions to be followed for program labels and variable (register) names. The MPLAB assembler is case sensitive by default, so PORTB and portb can refer to different registers.

Using the `equ` or `#define` directives, the programmer can define all of the registers (SFRs and GPRs) used by an application. A safer approach is to import an include file (.inc extension) furnished in the MPALB package for each different PIC. The include files have the names of all SFRs and bits used by a particular device. The following code fragment is a listing of the MPLAB include file for the 16f84a:

```asm
LIST
; P16F84A.INC Standard Header File, Version 2.00
; Microchip Technology, Inc.
NOLIST
; This header file defines configurations, registers, and other
; useful bits of information for the PIC16F84 microcontroller.
; These names are taken to match the data sheets as closely as
; possible.
; Note that the processor must be selected before this file is
; included. The processor is selected by using:
; 1. Command line switch:
; C:\MPASM MYFILE.ASM /PIC16F84A
; 2. LIST directive in the source file
; LIST P=PIC16F84A
; 3. Processor Type entry in the MPASM full-screen interface
;==================================================================
;
; Revision History
;
;==================================================================
;Rev: Date: Reason:
;1.00 2/15/99 Initial Release
;==================================================================
;
; Verify Processor
;
;==================================================================

IFNDEF __16F84A

MESSG "Processor-header file mismatch. Verify selected processor."

ENDIF

;==================================================================
;
; Register Definitions
;
;==================================================================

W EQU H'0000'
F EQU H'0001'

;-- Register Files---------------------
```
INDF EQU H'0000'
TMR0 EQU H'0001'
PCL EQU H'0002'
STATUS EQU H'0003'
FSR EQU H'0004'
PORTA EQU H'0005'
PORTB EQU H'0006'
EEDATA EQU H'0008'
EEADR EQU H'0009'
PCLATH EQU H'000A'
INTCON EQU H'000B'

OPTION_REG EQU H'0081'
TRISA EQU H'0085'
TRISB EQU H'0086'
EECON1 EQU H'0088'

GIE EQU H'0007'
EEIE EQU H'0006'
T0IE EQU H'0005'
INTIE EQU H'0004'
RBIE EQU H'0003'
T0IF EQU H'0002'
INTF EQU H'0001'
RBIF EQU H'0000'

OPTION_REG Bits

NOT_RBPU EQU H'0007'
INTEDG EQU H'0006'
T0CS EQU H'0005'
T0SE EQU H'0004'
PSA EQU H'0003'
PS2 EQU H'0002'
PS1 EQU H'0001'
PS0 EQU H'0000'

EECON1 Bits

EEIF EQU H'0004'
WRERR EQU H'0003'
WREN EQU H'0002'
WR EQU H'0001'
RD EQU H'0000'

RAM Definition

__MAXRAM H'CF'
__BADRAM H'07', H'50'–H'7F', H'87'
Names in the include file are defined in all-capital letters. It is probably a good idea to adhere to this style instead of creating alternate names in lower case. The C-like #include directive is used to refer the .inc files at assembly time, for example:

#include <p16f84a.inc>

9.4.6 Errorlevel Directive

This directive allows controlling the warning and error messages produced at assembly and link times. One particular type of warning can be disturbing: those that refer to bank changes. Applications often turn off bank change related warning with the following line:

errorlevel -302

9.5 Pseudo Instructions

Sometimes a code listing contains instructions that are not part of the standard set for the particular device. The reason this happens is that MPLAB includes a set of pseudo-instructions for 12- and 14-bit devices. Table 9.2 lists these pseudo-instructions and their standard equivalents:

<table>
<thead>
<tr>
<th>MNEMONIC</th>
<th>DESCRIPTION</th>
<th>EQUIVALENT OPERATION(S)</th>
<th>STATUS BIT CHANGED</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADDCF f,d</td>
<td>Add Carry to File Register</td>
<td>BTFSC 3,0</td>
<td>Z</td>
</tr>
<tr>
<td>ADDDCF f,d</td>
<td>Add Digit Carry to File Register</td>
<td>INCF f,d</td>
<td></td>
</tr>
<tr>
<td>B k</td>
<td>Branch</td>
<td>GOTO k</td>
<td></td>
</tr>
<tr>
<td>BC k</td>
<td>Branch on Carry</td>
<td>GOTO k</td>
<td></td>
</tr>
</tbody>
</table>

(continues)
Table 9.2
PIC Pseudo Instructions

<table>
<thead>
<tr>
<th>MNEMONIC</th>
<th>DESCRIPTION</th>
<th>EQUIVALENT OPERATION(S)</th>
<th>STATUS BIT CHANGED</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDC k</td>
<td>Branch on Digit Carry</td>
<td>BTFSC</td>
<td>3,1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GOTO k</td>
<td></td>
</tr>
<tr>
<td>BNC k</td>
<td>Branch on No Carry</td>
<td>BTFSS 3,0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>GOTO k</td>
<td></td>
</tr>
<tr>
<td>BNDC k</td>
<td>Branch on No Digit Carry</td>
<td>BTFSS</td>
<td>3,1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GOTO k</td>
<td></td>
</tr>
<tr>
<td>BNZ k</td>
<td>Branch on No Zero</td>
<td>BTFSS 3,2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>GOTO k, 2</td>
<td></td>
</tr>
<tr>
<td>BZ k</td>
<td>Branch on Zero</td>
<td>BTFSC 3,2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>GOTO k</td>
<td></td>
</tr>
<tr>
<td>CLRC</td>
<td>Clear Carry</td>
<td>BCF 3,0</td>
<td></td>
</tr>
<tr>
<td>CLRDC</td>
<td>Clear Digit Carry</td>
<td>BCF 3,1</td>
<td></td>
</tr>
<tr>
<td>CLRZ</td>
<td>Clear Zero</td>
<td>BCF 3,2</td>
<td></td>
</tr>
<tr>
<td>LCALL k</td>
<td>Long Call</td>
<td>BCF/BSF 0x0a,3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>BCF/BSF 0x0a,4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CALL k</td>
<td></td>
</tr>
<tr>
<td>LGOTO k</td>
<td>Long GOTO</td>
<td>BCF/BSF 0x0a,3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>BCF/BSF 0x0a,4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>GOTO k</td>
<td></td>
</tr>
<tr>
<td>MOVFW f</td>
<td>Move File to W</td>
<td>MOVF f,0</td>
<td>Z</td>
</tr>
<tr>
<td>NEGF f,d</td>
<td>Negate File</td>
<td>COMF f,1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>INCF f,d</td>
<td></td>
</tr>
<tr>
<td>SETC</td>
<td>Set Carry</td>
<td>BSF 3,0</td>
<td></td>
</tr>
<tr>
<td>SETDC</td>
<td>Set Digit Carry</td>
<td>BSF 3,1</td>
<td></td>
</tr>
<tr>
<td>SETZ</td>
<td>Set Zero</td>
<td>BSF 3,2</td>
<td></td>
</tr>
<tr>
<td>SKPC</td>
<td>Skip on Carry</td>
<td>BTFSS 3,0</td>
<td></td>
</tr>
<tr>
<td>SKPDC</td>
<td>Skip on Digit Carry</td>
<td>BTFSS 3,1</td>
<td></td>
</tr>
<tr>
<td>SKPNC</td>
<td>Skip on No Carry</td>
<td>BTFSC 3,0</td>
<td></td>
</tr>
<tr>
<td>SKPNDCC</td>
<td>Skip on No Digit Carry</td>
<td>BTFSC 3,1</td>
<td></td>
</tr>
<tr>
<td>SKPNZ</td>
<td>Skip on Non Zero</td>
<td>BTFSC 3,2</td>
<td></td>
</tr>
<tr>
<td>SKPZ</td>
<td>Skip on Zero</td>
<td>BTFSS 3,2</td>
<td></td>
</tr>
<tr>
<td>SUBCF f,d</td>
<td>Subtract Carry from File</td>
<td>BTFSC 3,0</td>
<td>Z</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DECF f,d</td>
<td></td>
</tr>
<tr>
<td>SUBDCF f,d</td>
<td>Subtract Digit Carry from File</td>
<td>BTFSC 3,1</td>
<td>Z</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DECF f,d</td>
<td></td>
</tr>
<tr>
<td>TSTF f</td>
<td>Test File</td>
<td>MOVF f,1</td>
<td>Z</td>
</tr>
</tbody>
</table>

We have listed the PIC pseudo-instructions to provide a reference. In our programming we prefer to stay away from using them since they tend to make code less readable. Microchip recommends not using the pseudo-instructions.
Programming Essentials: Input and Output

In this chapter, we discuss the simplest circuits and programming operations. Using a PIC to control an LED or read a switch is as elementary as it gets. However, neither of these operations is trivial, since there is more to it than a few lines of code. Other input/output devices that are also considered are seven-segment LED displays and multiple switches, sometimes called *toggle switches*. A bank of multiple LEDs can also function as a *binary output device*.

10.0 16F84A Programming Template

We have found that program development can be simplified considerably by using *code templates*. A code template is a program devoid of functionality that serves to implement the most common and typical features of an application. The template not only saves the effort of redoing the same tasks, but reminds the programmer of program elements that could otherwise be forgotten. A professional developer will have collected many different templates over the years for different types of applications on various processors. The following template is for the 16F84A PIC:

```plaintext
;==========================================================================
; File name:      
; Date:           
; Author:         
; Processor:      
; Reference circuit:   
;==========================================================================
; Copyright notice: 
;==========================================================================
; Program Description:  
;==========================================================================
; configuration switches 
;==========================================================================
; Switches used in __config directive:
```
; _CP_ON     Code protection ON/OFF
; * _CP_OFF
; * _PWRTE_ON Power-up timer ON/OFF
; _PWRTE_OFF
; _WDT_ON    Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC    Low power crystal oscillator
; * _XT_OSC  External parallel resonator
; _HS_OSC    High speed crystal resonator (8 to 10 MHz)
; _RC_OSC    Resistor/capacitor oscillator
;           (simplest, 20% error)
;           |
;           * indicates setup values

;=============
; setup and configuration
;=============
processor 16f84A
include  <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

;===============================
; constant definitions
;===============================
; PIC register equates
;===============================
; variables in PIC RAM
;===============================
cblock  0x0c
endc

;=================================
; program
;=================================
org     0 ; start at address
goto    main
; Space for interrupt handlers
org     0x08

main:

;=================================
end        ; END OF PROGRAM
;=================================
In addition to the template file the program developer should keep at hand the necessary include files. In this case, `p16f84a.inc`.

10.1 Introducing the 16F84A

The circuits and programs in this chapter use the 16F84A, probably the most popular of all mid-range PIC microcontrollers. Although we have discussed the mid-range architecture, we start with a review of this processor in order to establish a base for the material that follows.

10.1.1 Template Circuit for 16F84A

Like the programmer uses a programming template for developing 16F84A code, the circuit designer uses a template circuit. This circuit contains the components that most 16F84A boards require. The elements include a diagram of the PIC itself with the pin-out, as well as the wiring of the standard components, including the power source, ground, the reset pin (MCLR), and the most commonly used oscillator. Figure 10-1 shows a circuit template for the 16F84A.

![16F84A Circuit Template](image)

**Figure 10-1** 16F84A Circuit Template

The circuit template in Figure 10-1 does not suit every possible circuit. Even the simplest components must sometimes be configured differently; for example, the reset line could be wired to a pushbutton switch, or a different oscillator may be used. In any case, it is always easier to make modifications to an existing base than to start from scratch every time.

10.1.2 Power Supplies

Every PIC-based circuit board requires a +5V power source. A possible source of power is one or more batteries. There is an enormous selection of battery types, sizes, and qualities. The most common ones for use in experimental circuits are listed in Table 10.1.
Table 10.1
Common Dry Cell Alkaline Battery Types

<table>
<thead>
<tr>
<th>DESIGNATION</th>
<th>VOLTAGE</th>
<th>LENGTH</th>
<th>DIAMETER</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>1.5</td>
<td>61.5</td>
<td>34.2</td>
</tr>
<tr>
<td>C</td>
<td>1.5</td>
<td>50</td>
<td>26.2</td>
</tr>
<tr>
<td>AA</td>
<td>1.5</td>
<td>50</td>
<td>14.2</td>
</tr>
<tr>
<td>AAA</td>
<td>1.5</td>
<td>44.5</td>
<td>10.4</td>
</tr>
<tr>
<td>AAAA</td>
<td>1.5</td>
<td>42.5</td>
<td>8.3</td>
</tr>
</tbody>
</table>

All of the batteries in Table 10.1 produce 1.5V. A PIC with a supply voltage of 2 to 6 volts uses two to four batteries. Note that in selecting the battery power source for a PIC-based circuit, other elements beside the microcontroller itself must be considered, such as the oscillator. Holders for several interconnected batteries are available at electronic supply sources.

Alternatively, the power supply can be a transformer with 120VAC input and 3 to 12VDC called AC/DC adapters. The most useful type for the experimenter are the ones with an ON/OFF switch and several selectable output voltages. Color-coded alligator clips at the output wires are convenient.

**Voltage Regulator**

A useful device for a typical PIC-based power source is a voltage regulator IC. The 7805 voltage regulator is ubiquitous in most PIC-based boards with AC/DC adapter sources. The IC is a three-pin device whose purpose is to ensure a stable voltage source which does not exceed the device rating. The 7805 is rated for 5V and produces this output from any input source in the range 8 to 35V. Since the excess voltage is dissipated as heat the 7805 is equipped with a metallic plate intended for attaching a heat sink. The heat sink is not required in a typical PIC application but it is a good idea to maintain the supply voltage closer to the device minimum rather than its maximum.

The voltage regulator circuit requires two capacitors: one electrolytic and the other one not. Figure 10-2 shows a power source circuit using the 7805.

![Figure 10-2 Voltage Stabilizer Circuit](image-url)
10.1.3 Comparisons in PIC Programming

The power and usefulness of programs is due, in great measure, to their decision-making ability, and decisions are based on comparison. In a comparison code, it is able to make decisions based on the relative values of two operands. For example, compare the values \( a \) and \( b \). If \( a \) is greater than \( b \) execute a certain code routine. If \( b \) is greater than \( a \), execute another one. If both operands have the same value then proceed to a third code branch.

CISC and even some RISC microprocessors contain a *compare* operator in their instruction set. However, the compare can be substituted, with some inconvenience, by a *subtraction*. Since there is no compare operation in the PIC instruction set, we have to simulate the comparison by subtracting the \( w \) register from a literal value or from a file register. The `sublw` and `subwf` instructions can be used. After the subtraction takes place, code can make decisions based on the state of the zero and the carry flags. For example, the following code fragment compares the value in the two registers, labeled OP1 and OP2 respectively, and directs execution to three possible routines:

```assembly
; Declare variables at 2 memory locations
OP1  equ 0x0c ; First operand
OP2  equ 0x0d ; Second operand

main:
    movlw 0x30 ; First operand
    movwf OP1 ; to OP1 register
    movlw 0x50 ; Second operand
    movwf OP2 ; To OP2 register
    movf OP2,w ; OP2 to w register (not really necessary)
    subwf OP1,w ; Subtract w (OP2) from OP1
    btfsc STATUS,2 ; 2 is zero bit. Test zero flag.
    ; Skip next instruction if Z bit = 0, that is if both numbers are not the same
    goto ops_are_eq ; OP2 = w routine
    ; At this point the zero flag is not set. Therefore the two operands are not equal
    ; Now test the carry flag for OP1 < OP2, in this case C = 1
    btfss STATUS,0 ; 0 is carry bit. Test carry flag
    ; and skip next instruction if C bit = 1
    goto op2big ; OP2 > w routine
    ; Processing for the case OP1 > OP2
    nop
    goto done
```

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The Infamous PIC Carry Flag

In PIC programming, the effects on the carry flag are different in addition than in subtraction. During addition (`addwf` and `addlw`) the carry flag indicates a carry-out of the most significant bit of the result. In this case, $C = 1$ if there was a carry out, and $C = 0$ otherwise. However, in subtraction the carry flag is described in the Microchip documentation as behaving as an *inverted borrow*. This means that when two numbers are subtracted and the result is too big to fit in the destination operand, then the carry flag is clear. What this amounts to is that in PIC subtraction (`sublw` and `subwf` operations) the carry bit is set if there is no carry-out of the high-order bit. This unusual behavior is shown in the preceding code fragment.

10.2 Simple Circuits and Programs

In the following sections we describe very simple PIC-based circuits that can be assembled with few components on a breadboard. The corresponding programs exercise the circuit components. The beginner should not skip building these circuits and coding the programs since they demonstrate essential hardware and software elements.

As a learning experience, it is a good idea to *reverse engineer* the code in these sample programs. With the processor’s instruction set at hand, listed in Appendix C, proceed to follow the code one instruction at a time until you can understand every processing detail.

10.2.1 A Single LED Circuit

One of the simplest circuits consists of a single LED lamp wired to Port-B, line 0, of a 16F84A PIC, as shown in Figure 10-3.

The power source for the circuit in Figure 10-3 is not shown in the diagram. Typically, a battery source or an AC/DC converter and a voltage stabilizer circuit as in the one in Figure 10-2 are used.

A program to turn on the LED on Port-B, line 0, requires a few but essential processing operations. Code must perform the following operations:
1. Define and select processor (in this case 16F84A).
2. Link-in the corresponding include file (p16f84A.inc).
3. Select the oscillator type (here external resonator, _XT type).
4. Direct execution to the main label.
5. Initialize Port-B for output.
6. Set line 0 in Port-B high.

The entire program is as follows:

```asm
; File: LEDOn.asm
; Date: June 1, 2006
; Author: Julio Sanchez
; Processor: 16F84A
;
; Description:
; Turn on LED wired to Port-B, line 0
;
; switches
;
; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; _CP_OFF
; _PWRT_ON Power-up timer ON/OFF
; _PWRT_OFF
; _WDT_ON Watchdog timer ON/OFF
; _WDT_OFF
; _LP_OSC Low power crystal oscillator
; _XT_OSC External parallel resonator/crystal oscillator
; _HS_OSC High speed crystal resonator (8 to 10 MHz)
```
Resonator: Murate Erie CSA8.00MG = 8 MHz

RC OSC Resistor/capacitor oscillator

| indicates setup values

processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

variables in PIC RAM
None used
main program

org 0 ; start at address 0
goto main

; space for interrupt handler

org 0x04

main program

main:

Initialize all line in Port-B for output

movlw B'00000000' ; w = 00000000 binary
tris PORTB ; Set up Port-B for output

Turn on line 0 in Port-B. All others remain off

movlw B'00000001'

movwf PORTB

Endless loop intentionally hangs up program

wait:
goto wait

end

The preceding program, named LEDOn, can be found in the book's online software.

LED Flasher Program

A different program makes the LED in the circuit in Figure 10-3 flash on and off. All that is necessary is a delay loop using a file register counter. The logic turns on the LED and counts down to zero. Then it turns the LED off and counts down again.
The counter routine demonstrates the creation of a *procedure* in PIC programming. In fact, a procedure is nothing more than a routine called by a *label* at its entry point and terminated with a *return* statement. The procedure is executed by a *call* statement to its initial label, as follows:

```plaintext
call delay ; Call to procedure
.
.
; Elsewhere in the program
delay:
    ; procedure instructions go here
return ; End of procedure
```

The simplest delay loop consists of wasting processor time. Since each instruction takes four clock cycles, the delay can be calculated by multiplying the number of instructions in the loop by the device's clock speed divided by four. The details of delay loops are discussed in Chapter 12, on timers and counters. Here we just present a *double-counter loop* without entering into timing details.

The timer loop requires two counters, since the maximum value that can be stored in a register file is 255 and a delay of 255 machine cycles is very short. In this example, we get around this limitation by creating *double counters*: an inner loop counts down 200 cycles and an outer loop repeats the inner loop 200 times. The result is that the routine repeats 200 multiplied by 200 times, or 40,000 iterations, which is sufficient for the purpose at hand. Code is as follows:

```plaintext
delay:
    movlw .200 ; w = 200 decimal
    movwf j ; j = w
jloop:
    movwf k ; k = w
    decfsz k,f ; k = k-1, skip next if zero
goto kloop
decfsz j,f ; j = j-1, skip next if zero
goto jloop
return
```

Code assumes that two variables were created in the processor's GPR space, as follows:

```plaintext
; Declare variables at 2 memory locations
j equ 0x0c
k equ 0x0d
```

The listing for the entire LEDFlash program, contained in the book's online software, is as follows:
; Description:
; Turn on and off LED wired to Port-B, line 0
;===================================================== variables in PIC RAM
; Declare variables at 2 memory locations
j equ 0xc
k equ 0xd
;===================================================== main program
; org 0 ; start at address 0
goto main
; space for interrupt handler
; org 0x04
; main program
main:
; Initialize all line in Port-B for output
  movlw B'00000000' ; w = 00000000 binary
  tris PORTB ; Set up Port-B for output
;
; Program loop to turn LED on and off
LEDonoff:
; Turn on line 0 in Port-B. All others remain off
  movlw B'00000001' ; LED ON
  movwf PORTB
  call delay ; Local delay routine
; Turn off line 0 in Port-B.
  movlw B'00000000' ; LED OFF
  movwf PORTB
  call delay
  goto LEDonoff

================================
; delay subroutine
================================
delay:
  movlw .200 ; w = 200 decimal
  movwf j ; j = w
jloop:
  movwf k ; k = w
kloop:
  decfsz k,f ; k = k-1, skip next if zero
  goto kloop
  decfsz j,f ; j = j-1, skip next if zero
  goto jloop
  return
End

10.2.2 LED/Pushbutton Circuit

A slightly more complex circuit contains a pushbutton switch. In this case, the program monitors the state of the pushbutton and lights the LED accordingly. Figure 10-4 (in the following page) shows one possible wiring for the LED/pushbutton circuit.

If a switch reports a zero bit when active, it is described as active-low. A switch that reports a one-bit when pressed is said to be active-high. The pushbutton switch on the preceding figure is active-low. In the same manner, an output device can be wired so that it is turned on with a logic 0 and off with logic 1 on the port pin. A device turned on by the port current is said to be a source current device. When the device is turned on when the port reports logic 0 the line is said to sink the current. PICs and other CMOS devices operate better sinking than sourcing current. Table 10.2 shows the maximum sink and source currents for the 16F84 ports.
The 4.7K Ohm resistor in the circuit of Figure 10-4 keeps RA0 high until the switch is pressed. This switch action determines that RA0 reads binary one when the switch is released and binary zero (low) when the switch is pressed (active).

To test if the switch in the circuit of Figure 10-4 is closed, the application can read RA0. If the value in the port is 1, then the switch is open (released). If 0, then the switch is closed. The following program, named LEDandPb, exercises the circuit in Figure 10-4:

```
; File: LEDandPb.asm
; Date: June 2, 2006
; Author: Julio Sanchez
; Processor: 16F84A
;
; Description:
; Circuit with LED wired to RB0 and pushbutton switch, active low, wired to RA0. Pushbutton action turns LED OFF when pressed and ON when released.
```
;=========================================
; switches
;=========================================
; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; * _CP_OFF
; * _PWRTE_ON Power-up timer ON/OFF
; _PWRTE_OFF
; _WDT_ON Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC Low power crystal oscillator
; * _XT_OSC External parallel resonator/crystal oscillator
; _HS_OSC High speed crystal resonator (8 to 10 MHz)
; Resonator: Murate Erie CSA8.00M G=8 Mhz
; _RC_OSC Resistor/capacitor oscillator (simplest, 20% error)
; |
; |____ * indicates setup values

processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF
;=========================================
; variables in PIC RAM
;=========================================
; Not used in this program
;=========================================
; main program
;=========================================
org 0 ; start at address 0
goto main
;=========================================
; space for interrupt handler
;=========================================
org 0x04
;=========================================
; main program
;=========================================
main:
; Initialize all lines in Port-B for output
    movlw B'00000000' ; w = 00000000 binary
    tris PORTB ; Set up Port-B for output
; Initialize Port-A, line 0, for input
    movlw B'00000001' ; w = 00000001 binary
    tris PORTA ; Set up RA0 for input
; Program loop to test state of pushbutton switch
;=========================================
; read PB switch state
;=================================
LEDctrl:
; Push button switch on demo board is wired to Port-A bit 0
; Switch logic is active low
    btfss PORTA,0 ; Test. Skip next line if
                   ; bit is set
    goto turnOFF ; Turn LED off routine
; At this point Port-A bit 0 is not set
; Switch is pressed (active low action)
; Turn ON line 0 in Port-B
    bsf PORTB,0 ; RB0 high
    goto LEDctrl

turnOFF:
; Routine to turn OFF LED
    bcf PORTB,0 ; RB0 low
    goto LEDctrl

End

10.2.3 Multiple LED Circuit

The following circuit allows a few more programming complications since it contains a battery of eight LEDs, all wired to Port-B.

![Multiple LED Circuit Diagram]

**Figure 10-5** Multiple LED Circuit
The circuit in Figure 10-5 can be programmed to do different functions. For example, the eight LEDs can be visualized as representing an 8-bit binary number and the circuit can be programmed to count in binary from 0 to 255. Since the eight LEDs are all wired to Port-B, the binary count can be directly echoed on the port. The following program, named LEDCount, performs this operation:

```
; File: LEDCount.asm
; Date: June 3, 2006
; Author: Julio Sanchez
; Processor: 16F84A
; Description:
; Circuit with eight LEDs wired to RB0 to RB7.
; Program displays a binary count from 0 to 255 on
; LEDs.
;==================================================
; switches
;==================================================
; Switches used in __config directive:
; _CP_ON        Code protection ON/OFF
; * _CP_OFF
; * _PWRTE_ON   Power-up timer ON/OFF
; _PWRTE_OFF
; _WDT_ON       Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC       Low power crystal oscillator
; * _XT_OSC     External parallel resonator/crystal oscillator
; _HS_OSC       High speed crystal resonator (8 to 10 MHz)
; _RC_OSC       Resistor/capacitor oscillator
; |________ * indicates setup values
processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF
;==================================================
; variables in PIC RAM
;==================================================
; Declare variables at 2 memory locations
j equ 0x0c
k equ 0x0d
;==================================================
; main program
;==================================================
org 0       ; start at address 0
goto main
;===============================================
; space for interrupt handler
;===============================================
```
org 0x04

; main program

main:
    ; Initialize all lines in Port-B for output
    movlw B'00000000' ; w = 00000000 binary
    tris PORTB ; Set up Port-B for output

    ; Set Port-B bit 0 ON
    movlw B'00000000' ; w := 0 binary
    movwf PORTB ; Port-B itself := w

    ; Clear the carry bit
    bcf STATUS,C

mloop:
    incf PORTB,f ; Add 1 to register value
    call delay
    goto mloop

; delay sub-routine

delay:
    movlw .200 ; w = 200 decimal
    movwf j ; j = w

jloop:
    movwf k ; k = w

kloop:
    decfsz k,f ; k = k-1, skip next if zero
    goto kloop

    decfsz j,f ; j = j-1, skip next if zero
    goto jloop

return

end

10.3 Programming the Seven-segment LED

A 7-segment display can be connected to output ports on the PIC and used to display numbers and some digits. The circuit in Figure 10-6 shows one possible wiring scheme.

As the name indicates, the seven-segment display has seven linear LEDs that allow forming all the decimal and hex digits and some symbols and letters. Once the mapping of the individual bars of the display to the PIC ports has been established, digits and letters are shown by selecting which port lines are set and which are not. For example, in the seven-segment LED of Figure 10-5, the digit 2 is displayed by setting segments a, b, g, e, and d. In this particular wiring, these segments correspond to Port-B lines 0, 1, 6, 4, and 5.
As the name indicates, the seven-segment display has seven linear LEDs that allow forming all the decimal and hex digits and some symbols and letters. Once the mapping of the individual bars of the display to the PIC ports has been established, digits and letters are shown by selecting which port lines are set and which are not. For example, in the seven-segment LED of Figure 10-6, the digit 2 is displayed by setting segments a, b, g, e, and d. In this particular wiring, these segments correspond to Port-B lines 0, 1, 6, 4, and 5.

Conversion of the individual digits to port display codes is easily accomplished by means of a lookup table. The processing depends on three special features of PIC assembly language:

- The program counter file register (labeled PC and located at offset 0x02) holds the address in memory of the current instruction. Since each PIC instruction takes up a single byte (except for those that modify the PC), one can jump to consecutive entries in a table by adding an integer value to the program counter.

- The addwf instruction is used to add a value in the w register to the program counter.

- The retlw instruction returns to the caller a literal value stored in the w register. In the case of retlw the literal value is the instruction operand.

If the lookup table is located at a subroutine called getcode, then the processing can be implemented as follows:
getcode:
    addwf PC,f ; Add value in w register to program counter
    retlw 0x3f ; code for number 0
    retlw 0x06 ; code for number 1
    retlw 0x5b ; code for number 2
    ...
    retlw 0x6f ; code for number 9

The calling routine places in the w register the numeric value whose code is desired, and then calls the table lookup, as follows:

    movlw 0x03 ; Code for number 3 desired
    call getcode
    movwf PORTB ; Display 3 in 7-segment display

### 10.4 A Demonstration Board

A *demonstration board*, also known as a demo board, is a useful tool in mastering PIC programming. Many are available commercially; like programmers, there is a cottage industry of PIC demo boards on the internet. Constructing your own demo boards and circuits is not difficult. The components can be placed on a breadboard, or wire-wrapped onto a special circuit board, or a printed circuit board can be homemade, or ordered through the internet. These options have been previously discussed and Appendix B contains instructions on how to build your own PCBs.

Figure 10-7 shows a simple 16F84A-based demo board with a seven-segment LED, buzzer, pushbutton switch, and a bank of four toggle switches.

#### 10.4.1 PCB Images for Demo Board

Some PCBs contain circuit etchings on both sides. In this case two circuit board images are required. In addition, most boards contain a top-side image of the components, company logos, model numbers, and other information. Commercially, this image is silk-screened onto the board.

The homemade board (see Appendix B) usually contains a single etched image and a top-side image with informational text and graphics. Both images can be created with a conventional drawing program, such as Corel Draw, Adobe Illustrator, or Windows Paint, or with a specialized application, several of which are available free and for purchase on the Web. Figure 10-7 shows the images used for making the PCB for the circuit in Figure 10-8.

Note that the top-side (text) image has been mirrored on the horizontal plane. This is necessary so that the text and graphics coincide with the circuit etchings once the images are transferred to the board. The process for making your own PCBs is described in Appendix B.
Figure 10-7 PIC 16F87A Demo Board

Figure 10-8 Bottom- and Top-side images of a PCB.
10.4.2 TestDemo1 Program

The following program exercises some of the experiments that can be implemented on the demo boards in Figure 10-7:

; File: TestDemo1.asm
; Date: June 2, 2006
; Author: Julio Sanchez
; Processor: 16F84A
;
; Description:
; Program to exercise the demonstration circuit and board
; number 1
;==============================================
; switches
;==============================================
; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; * _CP_OFF
; * _PWRTE_ON Power-up timer ON/OFF
; _PWRTE_OFF
; _WDT_ON Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC Low power crystal oscillator
; * _XT_OSC External parallel resonator/crystal
; oscillator
; _HS_OSC High speed crystal resonator (8 to 10 MHz)
; Resonator: Murate Erie CSA8.00MG = 8 MHz
; _RC_OSC Resistor/capacitor oscillator
; |
; |____ * indicates setup values

processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF
;==============================================
; variables in PIC RAM
;==============================================
cblock 0x0c ; Start of block
count1 ; Counter # 1
j ; counter J
k ; counter K
endc
;==============================================
P R O G R A M
;==============================================
org 0 ; start at address 0
goto main
;
; Space for interrupt handlers
org 0x08

main:
; Port A (5 lob) for input
    movlw B’00011111’ ; w := 00001111 binary
    tris PORTA ; Port-A (lines 0 to 4) to input
; Port-Bit (8 lines) for output
    movlw B’00000000’ ; w := 00000000 binary
    tris PORTB ; Port-B to output

; Pushbutton switch processing

pbbutton:
; Push button switch on demo board is wired to RA4
; Switch logic is active low
    btfss PORTA,4 ; Test and skip if bit is set
    goto buzzit ; Buz if switch ON
; At this point Port-A bit 4 is set (switch is off)
    call buzzoff ; Buzzer off
    goto readdip ; Read DIP switches

buzzit:
    call buzzer ; Turn on buzzer
    goto pbbutton

; DIP switch processing

readdip:
; Read all bits of Port-A
    movf PORTA,w ; Port A bits to w
; If board uses active low then all switch bits must be negated
; This is done by XORing with 1-bits
    xorlw b’11111111’ ; Invert all bits in w
; Eliminate all 4 high order bits
    andlw b’00001111’ ; And with mask
; Get digit into w
    call segment ; get digit code
    movwf PORTB ; Display digit
    call delay ; Give time
; Update digit and loop counter
    goto pbbutton

; 7-segment table of hex codes

segment:
    addwf PCL,f ; PCL is program counter latch
    relw 0x3f ; 0 code
; Just in case all on
retlw 0x7f ; Just in case all on
;
; piezo buzzer ON
;******************************************************************************
; Routine to turn on piezo buzzer on Port-B bit 7
buzon:
bsf PORTB,7 ; Tune on bit 7, Port-B
return
;
; piezo buzzer OFF
;******************************************************************************
; Routine to turn off piezo buzzer on Port-B bit 7
buzoff:
bcf PORTB,7 ; Bit 7 Port-B clear
return
;
; delay subroutine
;******************************************************************************
delay:
movlw .200 ; w = 200 decimal
movwf j ; j = w
jloop:
    movwf k ; k = w
kloop:
    decfsz k,f ; k = k-1, skip next if zero
    goto kloop
    decfsz j,f ; j = j-1, skip next if zero
    goto jloop
return
end
Chapter 11

Interrupts

An interrupt is an asynchronous signal calling for processor attention. Interrupts can originate in hardware or in software. The interrupt mechanism is a way to avoid wasting processor time, since without interrupts code has to poll hardware devices in ineffective, closed loops. With interrupts, the processor can continue to do its work since the interrupt mechanism ensures that the CPU receives a signal whenever an event occurs that requires its attention. PIC microcontrollers provide varying levels of support for interrupts. We focus on interrupts on the 16F84.

11.0 Interrupts on the 16F84

Four different sources of interrupts are available in the 16F84. These are discussed in Section 11.1. One instruction (RETFIE for return-from-interrupt) is specifically related to interrupt processing. Its purpose is to return to the program counter the address of the instruction that follows the location in code where the interrupt took place. It does so by loading into the program counter register the 13-bit address saved at the top of the stack. In addition, RETFIE sets the Global Interrupt Enable bit in the INTCON register (discussed in Section 11.0.1) automatically re-enabling interrupts.

In addition to the RETFIE instruction, two PIC hardware elements relate directly to interrupts: the OPTION register and the INTCON register. Both registers are readable and writeable and contain bits that allow setting up, controlling, and detecting the various interrupts. INTCON records individual interrupt requests in flag bits. It also contains the individual and global interrupt enable bits. The OPTION register has several bits that must be accessed in order to initialize interrupts.

11.0.1 The Interrupt Control Register

INTCON (the Interrupt Control Register) is a readable and writeable register located at offset 0x08 in bank 0. The INTCON register contains two classes of bits: bits to enable and disable the various interrupt sources, and flag bits that allow detecting the occurrence of the various interrupts. The bits to enable and disable interrupts have names that end with the letter E, while the interrupt flag bit names end with the letter F. They are known collectively as the INTCON E and INTCON F bits. Figure 11-1 is a bitmap of the INTCON Register.
The OPTION Register

The OPTION Register is a readable and writeable register that contains controls for configuring the prescaler bits and assigning them to either TIMER0 or the Watchdog Timer, for selecting the increment mode on the RA4/TOCKI pin, the TIMER0 source clock, the rising or falling edge in the RB0 interrupt, and for enabling and disabling the internal Port-B’s pull-up resistors. The OPTION register is located in Bank1, at address 0x81. Although this register is not directly related to interrupts, several of its bits are related to the various interrupts. Figure 11-2 is a bitmap of the OPTION register.

<table>
<thead>
<tr>
<th>bit 7</th>
<th>bit 6</th>
<th>bit 5</th>
<th>bit 4</th>
<th>bit 3</th>
<th>bit 2</th>
<th>bit 1</th>
<th>bit 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>GIE</td>
<td>EEIE</td>
<td>TOIE</td>
<td>INTE</td>
<td>RBIE</td>
<td>TOIF</td>
<td>INTF</td>
<td>RBIF</td>
</tr>
</tbody>
</table>

- **bit 7 GIE**: Global Interrupt Enable bit
  - 1 = Enables all unmasked interrupts
  - 0 = Disables all interrupts

- **bit 6 EEIE**: EE Write Complete Interrupt Enable bit
  - 1 = Enables the EE Write Complete interrupts
  - 0 = Disables the EE Write Complete interrupt

- **bit 5 TOIE**: TMR0 Overflow Interrupt Enable bit
  - 1 = Enables the TMR0 interrupt
  - 0 = Disables the TMR0 interrupt

- **bit 4 INTE**: RB0 Interrupt Enable bit
  - 1 = Enables the RB0 external interrupt
  - 0 = Disables the RB0 external interrupt

- **bit 3 RBIE**: Port Change Interrupt Enable bit
  - 1 = Enables the RB port change interrupt
  - 0 = Disables the RB port change interrupt

- **bit 2 T0IF**: TIMER0 Overflow Interrupt Flag bit
  - 1 = TMR0 register has overflowed
  - 0 = TMR0 register did not overflow

- **bit 1 INTF**: RB0 External Interrupt Flag bit
  - 1 = The RB0/INT external interrupt occurred
  - 0 = The RB0/INT external interrupt did not occur

- **bit 0 RBIF**: RB0-RB3 Port Change Interrupt Flag bit
  - 1 = At least one of the RB7:RB4 pins changed state
  - 0 = None of the RB7:RB4 pins have changed state

Figure 11-1 INTCON Register Bitmap
Interrupts

11.1 Interrupt Sources

The 16F8X supports four different sources of interrupt:

1. External interrupt detected by line 0 of Port-B
2. Interrupts that originate in the timer (TMR0 overflow interrupt)
3. Interrupts that originate in changes of lines RB7 to RB4 in Port-B
4. EEPROM complete data write interrupt
11.1.1 Port-B External Interrupt

This external interrupt is triggered by either the rising or falling signal edge on port-B, line 0. Whether it is the rising or the falling edge of the signal depends on the setting of the INTEDG bit of the OPTION register.

The Port-B interrupt is useful in detecting and responding to external events; for example, in measuring the frequency of a signal or in responding with some PIC action to a change in the state of a hardware device. This interrupt can be disabled by clearing the corresponding bit in the INTCON register. If enabled, once the interrupt takes place, code must clear the corresponding flag bit before re-enabling the interrupt.

Suppose there is a circuit that contains an emergency switch that is activated by some critical event. One possible approach is to check the state of the switch by continuously polling the port to which it is wired. But in a complex program it may be difficult to ensure that the switch polling routine is called with sufficient frequency so that an emergency event is detected immediately. A more effective solution is to connect the emergency switch to line number 0 of Port-B and set up the Port-B external interrupt source. Now, whenever the emergency switch is activated, the program immediately responds via the interrupt mechanism. Furthermore, once the interrupt code has been developed and debugged it continues to function correctly no matter what changes are made to the rest of the program.

11.1.2 Timer0 Interrupt

The 16F84 is equipped with a special timer module, named Timer0, which serves both as a timer and as a counter. The Timer0 module, which is discussed in greater detail in Chapter 12, consists of an 8-bit readable register operated by an internal or external clock and attached to an 8-bit programmable prescaler. The prescaler is used to delay the timer by dividing the previous clock signal. The timer0 module can be set up to interrupt on overflow. In this case, an interrupt is generated whenever the counter goes from 0xff to 0x00.

The Timer0 counter interrupt can be used to measure events and to respond to elapsed periods. For example, the timer is used to measure events by determining the number of timer interrupts that have taken place since an event occurred. The timer of each interrupt is determined from the processor clock speed and the prescaler set up. The event time is calculated by multiplying the time of each interrupt by the number of interrupts that have occurred. In this case, the interrupt routine increments a counter register that is accessible to code anywhere in the program; so the actual count can be reset from inside or outside the service routine.

In responding to an elapsed period, the Timer0 interrupt service routine not only keeps track of the time elapsed since the event, but also tests for a certain counter value that represents the desired time limit. Once the timer counter reaches this pre-set limit, the service routine responds directly with the required action.
One powerful and common application of a Timer0 interrupt is in implementing serial communications. In this case, the timer interrupt is set up to take place at the baud rate at which the serial line is polled for data or at which individual data bits are sent. The sample program LapseTmrInt, developed in Chapter 12, demonstrates this use of the timer interrupt.

11.1.3 Port-B Line Change Interrupt

The third 16F84 interrupt source relates to a change in the values stored in Port-B lines 4 to 7. When this interrupt is enabled, any change in status in any of the four Port-B pins labeled RB7, RB6, RB5, and RB4 can trigger an interrupt. The interrupt is set up to take place when their status changes from logic one to logic zero, or vice versa. For this interrupt to take place, Port-B pins 4 to 7 must be defined as input. Otherwise, the interrupt does not take place.

The Port-B line-change interrupt provides a mechanism for monitoring up to four different interrupt sources, typically originating in hardware devices. When the interrupt is enabled, the current state of the Port-B lines is constantly compared to the old values. If there is a change in state in any of the four lines the interrupt is generated.

Implementation of the line change interrupt is not without complications. The characteristics of the external signal are necessary to develop code that correctly handles the various possible sources. Two pieces of information that are necessary in this case are:

1. The signal's rising and falling edges
2. The pulse width of the interrupt trigger

The signal's rising and falling edges determine the service routine's entry point. For example, if the device is an active-low pushbutton switch, an interrupt typically is desired on the signal's falling edge, that is, when it goes from high-to-low.

Knowledge about the signal's width determines the processing required by the service routine. This is due to the fact that both the rising and the falling edge of the signal can trigger the interrupt. So, if the triggering signal has a small pulse width compared to the time of execution of the interrupt handler, then the interrupt line has returned to the inactive state before the service routine completes and a possible false interrupt on the signal's falling edge is not possible. On the other hand, if the pulse width of the interrupt signal is large and the service routine completes before the signal returns to the inactive state, then the signal's falling edge can trigger a false interrupt. Figure 11-3 (in the following page) shows both situations.

In the context of Figure 11-3, the period between the edge that triggers the interrupt and the termination of the interrupt handler is called the mismatch period. The mismatch period terminates when the service routine completes and the corresponding interrupt is re-enabled. If this happens after the interrupt signal is reset, no possible false interrupt takes place and no special provision is required in the handler. In fact, the interrupt handler runs correctly as long as the service routine takes longer to execute than the interrupt frequency. However, if the handler termi-
nates before the signal returns to its original state, then the handler must make special provisions to handle a possible false interrupt. In order to do this, the handler must first determine if the interrupt took place on the rising or the falling signal edge, which can be done by examining the corresponding port-B line. For example, if the interrupt is to take place on the rising edge only, and the line is low, then it can be ignored since it takes place on the falling edge.

Figure 11-3 Signal Pulse Width and Interrupt Latency

When an interrupt can take place on either the rising or the falling edge of the triggering signal, the interrupt source must have a minimum pulse width in order to ensure that both edges are detected. In this case, the minimum pulse width is the maximum time from the edge that triggered the interrupt to the moment when the interrupt flag is cleared. Otherwise, the interrupt is lost since the interrupt mechanism is disabled at the time it takes place.

The preceding discussion leads directly to the possibility of an interrupt taking place while the service routine of a previous interrupt is still in progress. These are called reentrant or nested interrupts. Several things must happen to allow reentrant interrupts. One of them is that interrupts must be re-enabled before the handler terminates. In addition, the service routine must be able to create different instances of the variables in use, usually allocated in the stack. The lack of a program-accessible stack and the PIC interrupt mechanism itself forces the conclusion that reentrant interrupts should not be attempted in PIC programs.
Multiple External Interrupts

One of the practical applications of the port-B line-change interrupt is in handling several different interrupt sources; for example, a circuit containing four push-button switches that activate four different circuit responses. If the switches are wired to the corresponding pins in Port-B (RB4 to RB7) and the line-change interrupt is enabled, the interrupt takes place when any one of the four switches changes level, that is, when any one of the interrupt lines go from high to low or from low to high. The interrupt handler software can easily determine which of the switches changed state and if the change took place on the signal’s rising or falling edge. The corresponding software routines then handle each case.

Later in this chapter we develop a sample program that uses the Port-B line-change interrupt to respond to action on four pushbutton switches.

11.1.4 EEPROM Data Write Interrupt

The origin of this interrupt relates to the relative slowness of the EEPROM data write operation, which is of 10 ms. The interrupt serves no other function than to allow the microcontroller to continue execution while the data write operation is in progress. The interrupt service routine informs the microcontroller when writing has ended through the EEIF bit located in the EECON1 register. The use of this interrupt is considered in Chapter 15, in the context of EEPROM data memory access and programming.

11.2 Interrupt Handlers

The interrupt handler, also called the interrupt service routine or the ISR, is the code that receives control upon occurrence of the interrupt. Most of the programming that goes into the service routine is specific to the application; however, there are certain housekeeping operations that should be included. The following list describes the structure of an interrupt service routine for the mid-range PICs:

1. Preserve the value in the w register.
2. Preserve the value of the STATUS register.
3. Execute the application-specific operations.
4. Restore the value of the STATUS register at the time of the interrupt.
5. Restore the value of the w register at the time of the interrupt.
6. Issue the RETFIE instruction to end the interrupt handler.

In the PIC 16F84, the interrupt service routine must be located at offset 0x004 in code memory. A simple org directive takes care of ensuring this location, as in the following code fragment:

```
org 0x000 ; Beginning of code area
goto start ; Jump to program start
org 0x004 ; Start of Service routine
.
.
; SERVICE ROUTINE GOES HERE
```
Alternatively, code can place a jump at offset 0x004 and locate the Service Routine elsewhere in the code. In this case, it is important to remember not to call the Service Routine, but to access it with a goto instruction. The reason is that the call opcode places a return address in the stack, which then polls for the retfie instruction.

### 11.2.1 Context Saving Operations

The only value automatically preserved by the interrupt mechanism is PC (the Program Counter), which is stored in the stack. Applications often need to restore the processor to the same state as when the interrupt took place, so the first operation of most interrupt handlers is saving the processor's context. This usually includes the w and the STATUS registers and occasionally others used by the specific implementation.

#### Saving w and STATUS Registers

Saving the w and the STATUS registers requires using register variables, but the process requires special care. Saving the w register is simple enough: its value at the start of the Service Routine is stored in a local variable from which it is restored at termination. But saving the STATUS register cannot be done with the MOVF instruction, since this instruction changes the zero flag. The solution is to use the SWAPF instruction which does not affect any of the flags. Of course, SWAPF inverts the nibbles in the operand, so it must be repeated so as to restore the original state. The following code fragment assumes that file register variables named old_w and old_status were previously created.

```assembly
save_cntx:
    movwf old_w ; Save w register
    swapf STATUS,w ; STATUS to w
    movwf old_status ; Save STATUS

; Interrupt handler operations go here
;
    swapf old_status,w ; Saved status to w
    movfw STATUS ; To STATUS register
; At this point all operations that change the
; STATUS register must be avoided, but swapf does not.
    swapf old_w,f ; Swap file register in itself
    swapf old_w,w ; reswap back to w
retfie
```

### 11.3 Interrupt Programming

In the sections that follow, we discuss programming interrupts that originate in Port-B, line 0, and those that originate in changes of port-B lines RB4 to RB7. Interrupts that relate to the Timer0 overflow or to EEPROM data write operations are cov-
11.3.1 Programming the External Interrupt

Port-B, line 0, is referred to as the External Interrupt source. The name is not the most adequate since other interrupts can also have external sources. One of the important uses of this interrupt source is to wake the processor from the SLEEP mode. This allows developing applications that can run on a small power source (such as batteries) since the program uses almost no power until some action associated with the interrupt source wakes up the PIC. A sample program using the RB0 interrupt is developed later in this chapter. Our first sample program is a simple demonstration of the installation and action of the interrupt. The program is based on the circuit in Figure 11-4.

![Figure 11-4 Circuit for RB0 Interrupt Demonstration](image)

In the circuit of Figure 11-4, a pushbutton switch is wired to the RB0 port. It is this switch which produces the interrupt when pressed. A red LED is wired to port RB1 and a green LED to port RB2. The main program flashes the green LED on and off at a rate of approximately one-half second. The red LED is toggled on and off when the pushbutton switch is pressed. The switch contains a 4.7K Ohm resistor that keeps the port high until the contact is made and sent to ground. This makes the
switch active low and the interrupt is programmed on the falling edge of the signal, which takes place when the contact is made.

**RB0 Interrupt Initialization**

In order to initialize the RB0 interrupt, the following operations must take place:

1. Port-B, line 0, must be initialized for input.
2. The interrupt source must be set to take place either on the falling or the rising edge of the signal.
3. The external interrupt flag (INTF in the INTCON Register) must be initially cleared.
4. Global interrupts must be enabled by setting the GIE bit in the INTCON Register.
5. The External Interrupt on RB0 must be enabled by setting the INTE bit in the INTCON Register.

The following code fragment, from the program RB0Int in the book’s online software package, performs these operations:

```assembly
org 0x04
goto IntServ

main:
    ; Set up interrupt on falling edge
    ; by clearing OPTION register bit 6
    movlw b'10111111'
    option
    movlw b'11111111' ; Set Port-A for input
    tris porta ; (not necessary for this program)
    movlw b'00000001' ; Port-B bit 0 is input
    tris portb ; all others are output
    clrf portb ; All Port-B to 0
    ; Initially turn on LED
    bsf portb,0 ; Set line 0 bit

    ; Clear external interrupt flag (intf = bit 1)
    bcf INTCON,intf ; Clear flag
    ; Enable global interrupts (gie = bit 7)
    bsf INTCON,gie ; Enable global int (bit 7)
    bsf INTCON,inte ; Enable RB0 int (bit 4)
```

---

Chapter 11
Program flashes LED wired to Port-B, line 2 lights:

```
movlw b'00000010' ; Mask with bit 1 set
xorwf portb,f ; Complement bit 1
call long_delay ; Local delay routine
call long_delay
call long_delay
goto lights
```

**RB0 Interrupt Service Routine**

The Service Routine for the RB0 interrupt depends on the specific application. Nevertheless, the following processing steps should be considered:

1. Determine if the source is an RB0 interrupt.
2. Clear the RB0 interrupt flag (INTF bit) in the INTCON Register.
3. Save the context. Which registers and variables need to be saved depends on the specific application.
4. Perform the interrupt action.
5. Restore the context.
6. Return from the interrupt with the `retfie` instruction.

In addition, the interrupt handler may have to perform operations that are specific to the application. For example, debounce a switch or initialize local variables. The following Interrupt Service routine is from the program RB0Int in the book's online software:

```
;=======================================================================
; Interrupt Service Routine
;=======================================================================
; Service routine receives control when there is
; action on pushbutton switch wired to port-B, line 0
IntServ:
; First test if source is an RB0 interrupt
btfss INTCON,INTF ; INTF flag is RB0 interrupt
goto notRB0 ; Go if not RB0 origin
; Save context
movwf old_w ; Save w register
swapf STATUS,w ; STATUS to w
movwf old_status ; Save STATUS
;=======================================================================
; interrupt action
;=======================================================================
; Debounce switch
; Logic:
; Debounce algorithm consists in waiting until the
; same level is repeated on a number of samplings of the
; switch. At this point the RB0 line is clear since the
; interrupt takes place on the falling edge. The routine
; waits until the low value is read several times.
    movlw D'10' ; Number of repetitions
    movwf count2 ; To counter
wait:
    ; Check to see that port-B bit 0 is still 0
    ; If not, wait until it changes
    btfsc portb,0 ; Is bit set?
    goto exitISR ; Go if bit not 0
    ; At this point RB0 bit is clear
    decfsz count2,f ; Count this iteration
    goto wait ; Continue if not zero
    ; Interrupt action consists of toggling bit 2 of
    ; port-B to turn LED on and off
    movlw b'00000100'; Xoring with a 1-bit produces
    ; the complement
    xorwf portb,f ; Complement bit 2, port-B
    ;========================
    ; exit ISR
    ;========================
exitISR:
    ; Restore context
    swapf old_status,w ; Saved status to w
    movfw STATUS ; To STATUS register
    swapf old_w,f ; Swap file register in itself
    swapf old_w,w ; re-swap back to w
notRB0:
    ; Reset interrupt
    bcf INTCON,intf ; Clear INTCON bit 1
    retfie

Note that the interrupt handler listed previously contains a debouncing routine
that cleans the switch’s signal. In this particular implementation the detection of a
signal of the wrong value determines that the interrupt is aborted. For the particular
switch used in the test circuit this approach seemed to work better. Alternatively,
the routine can be designed so that if a wrong edge is detected, execution continues
in the wait loop. In any case, the entire complication of software debouncing can be
avoided by debouncing the switch in hardware.

11.3.2 Wakeup from SLEEP Using the RB0 Interrupt

The PIC microcontroller sleep mode provides a useful mechanism for saving power. It is particularly useful in battery-operated devices.

The sleep mode is activated by executing the SLEEP instruction; it suspends all
normal operations and switches of the clock oscillator.
The sleep mode is suitable for applications that are not required to run continuously. For example, a device that records temperature at daybreak can be designed so that a light-sensitive switch generates an interrupt that turns the device on each morning. Once the data is recorded, the device goes into the sleep mode until the next daybreak.

Several events can make the device wake up from the sleep mode:

1. A device reset on the !MCLR pin
2. Watchdog timer wake-up signal, if WDT is enabled
3. Interrupt on RB0 line
4. Port change interrupt on RB4 to RB7 lines
5. EEPROM write complete interrupt

In the sleep mode, the device is placed on a power-down state that generates the lowest power consumption. The system clock is turned off in the sleep mode so signals that depend on the clock cannot be used to terminate the sleep. If enabled, the Watchdog Timer is cleared by the sleep instruction but keeps running. The PD bit in the STATUS register is also cleared and the TO bit is set. The ports maintain the status they had before the SLEEP instruction was executed.

The TO and PD bits in the STATUS register can be used to determine the cause of wake-up, since the TO bit is cleared if a Watchdog Timer wake-up took place. The corresponding interrupt enable bit must be set for the device to wake-up up due to an interrupt. Wake-up takes place regardless of the state of the General Interrupt Enable (GIE) bit. If the bit is clear, the device continues execution at the instruction following SLEEP. Otherwise, the device executes the instruction after the SLEEP instruction and then branches to the interrupt address. If the execution of the instruction following SLEEP is undesirable, the program should contain a NOP instruction after the SLEEP instruction.

The SleepDemo Program

The program named SleepDemo in the book’s online software package is a trivial demonstration of using the RB0 interrupt to wake the processor from sleep mode. The program can be tested using the circuit in Figure 11-4. SleepDemo flashes the green LED at ½ second intervals during 20 iterations and then goes into sleep mode. Pressing the pushbutton switch on line RB0 generates an interrupt that wakes the processor from sleep mode. The following code fragment shows the coding of the main loop in the program:

```assembly
; ==============================================================
; flash LED 20 times
; ==============================================================
wakeUp:
; Program flashes LED wired to port-B, line 2
; 20 times before entering the sleep state
movlw D’20’ ; Number of iterations
movwf count2 ; To counter
```
In the SleepDemo program the Interrupt Service Routine does nothing. Its coding is as follows:

```asm
;=======================================================
; Interrupt Service Routine
;=======================================================
; The interrupt service routine performs no operation
IntServ:
       bcf INTCON,INTF ; Clear flag
       retfie
```

The initialization of the RB0 interrupt is identical to the one in the RB0Int program previously listed.

### 11.3.3 Port-B Bits 4-7 Status Change Interrupt

In the PIC 16F84 microcontroller, a change of input signal on Port-B, lines 4 to 7, generates an interrupt. This interrupt sets the RBIF bit in the INTCON Register to indicate that at least one of the ports have changed value. The port change takes place when the port’s previous value changes from logic one to logic zero or vice versa. In order for port pins to recognize this interrupt, they must have been defined as input. If any one of the port pins (4 to 7) is defined as output the interrupt takes place. The status change of the ports is in reference to the last time port-B was read.

The principal application of this interrupt source is in detecting several different interrupt sources. Its principal disadvantage is that it forces the declaration of four port-B lines as input, although during processing not all lines need be recognized as interrupt sources. The conclusion is that applications that only need a single external interrupt source should use the RB0 interrupt described in previous sections. Only applications that require more than one external interrupt should use the Port-B lines 4 to 7 interrupt on change source.
Since the interrupt takes place on any status change (high-to-low or low-to-high) the service routine executes on both signal edges. If interrupt processing is required on only one edge, that is, either when the port goes high or low, then the filtering must be performed in software. The circuit in Figure 11-5 allows testing the Port-B Status Change Interrupt.

**Figure 11-5 Circuit for Testing the Port-B Status Change Interrupt**

In the circuit of Figure 11-5, a pushbutton switch is wired to the RB7 port and another one to RB4. Both of these switches produce the interrupt when pressed. A red LED is wired to port RA1 and a green LED to port RA0. The red and green LEDs are toggled on and off when the corresponding pushbutton switches are pressed. The switches contain a 4.7K Ohm resistor that keeps the port high until the contact is made and sent to ground. This makes both switches active low and the interrupt is programmed on the falling edge of the signal.

**RB4-7 Interrupt Initialization**

In order to initialize the RB4-7 change interrupt the following operations must take place:

1. Port-B lines 4 to 7 must be initialized for input.
2. The interrupt source must be set to take place either on the falling or the rising edge of the signal.
3. The RB port change interrupt flag (RBIF in the INTCON Register) must be initially cleared.

4. Global interrupts must be enabled by setting the GIE bit in the INTCON Register.

5. The RB port change interrupt must be enabled by setting the RBIE bit in the INTCON Register.

6. Internal pull-ups on port-B should be disabled in the OPTION register.

The following code fragment from the program RB4to7Int in the book's online software package shows the required processing:

```plaintext
;=====================================================================
; main program
;=====================================================================
main:
 ; Disable port-B internal pull-ups
 ; Interrupts on falling edge of pushbutton action
   movlw b'10111111'
   option
 ; Wiring:
 ; 7 6 5 4 3 2 1 0 <= port-B
 ; | |_______________ red pushbutton
 ; |_______________ black pushbutton
 ;
 ; 7 6 5 4 3 2 1 0 <= Port-A
 ; | |_____ red LED
 ; |________ green LED
 ;
   movlw b'00000000'    ; Set Port-A for output
   tris porta
   movlw b'11110000'    ; Port-B bits 0-3 are output
                       ; bits 4-7 are input
   tris portb
   clrf portb           ; All others are output
   movlw b'00000000'    ; Zero to w
   movwf bitsB47        ; Store in local variable
 ; Initially turn on LEDs
   bsf porta,0          ; Set LEDs on line 0
   bsf porta,1          ; and on line 1
 ;=====================================================================
 ; setup interrupts
 ;=====================================================================
 ; Clear external interrupt flag (intf = bit 1)
   bcf INTCON,rbif      ; Clear flag
 ; Enable global interrupts (gie = bit 7)
 ; Enable RB0 interrupt (inte = bit 4)
   bsf INTCON,gie       ; Enable global int (bit 7)
   bsf INTCON,rbie      ; Enable RB0 int (bit 3)
```
RB4-7 Change Interrupt Service Routine

The Service Routine for the RB4-7 change interrupt depends on the specific application. Nevertheless, the following processing steps should be considered:

1. Determine if the source is an RB4-7 change interrupt.
2. Clear the RBIF interrupt flag in the INTCON Register.
3. Save the context. Which registers and variables need to be saved depends on the specific application.
4. Perform the interrupt action.
5. Restore the context.
6. Return from the interrupt with the retfie instruction.

In addition, the interrupt handler may have to perform operations that are specific to the application; for example, debounce a switch or initialize local variables. The following Interrupt Service routine is from the program RB4to7Int in the book’s online software:

```
;==============================================
; Interrupt Service Routine
;==============================================
;
; Service routine receives control whenever any of
; port-B lines 4 to 7 change state
IntServ:
;
; First test: make sure source is an RB4-7 interrupt
   btfss INTCON,rbif ; RBIF flag is interrupt
   goto notRBIF ; Go if not RBIF origin
;
; Save context
   movwf old_w ; Save w register
   swapf STATUS,w ; STATUS to w
   movwf old_status ; Save STATUS

;===============================================
; interrupt action
;===============================================
;
; The interrupt occurs when any of port-B bits 4 to 7
; have changed status.
   movf portb,w ; Read port-B bits
   movwf temp ; Save reading
   xorwf bitsB47,f ; Xor with old bits, result in f

; Test each meaningful bit (4 and 7 in this example)
   btfsc bitsB47,4 ; Test bit 4
   goto bit4Chng ; Routine for changed bit 4
;
; At this point bit 4 did not change
   btfsc bitsB47,7 ; Test bit 7
   goto bit7Chng ; Routine for changed bit 7
;
; Invalid port line change. Exit
   goto pbRelease
```
bit 4 change routine

Check for signal falling edge, ignore if not

bit4Chng:
  btsc portb,4 ; Is bit 4 high
  goto pbRelease ; Bit is high. Ignore

; Toggling bit 1 of Port-A turns LED on and off
  movlw b'00000010' ; Xoring with a 1-bit produces
                      ; the complement
  xorwf porta,f ; Complement bit 1, Port-A
  goto pbRelease

bit 7 change routine

Check for signal falling edge, ignore if not

bit7Chng:
  btsc portb,7 ; Is bit 7 high
  goto exitISR ; Bit is high. Ignore

; Toggling bit 0 of Port-A turns LED on and off
  movlw b'00000001' ; Xoring with a 1-bit produces
                      ; the complement
  xorwf porta,f ; Complement bit 1, Port-A

pbRelease:
  call delay ; Debounce switch
  movf portb,w ; Read port-B into w
  andlw b'10010000' ; Eliminate unused bits
  btsc STATUS,z ; Check for zero
  goto pbRelease ; Wait

; At this point all port-B pushbuttons are released

exit ISR

exitISR:
; Store new value of port-B
  movf temp,w ; This port-B value to w
  movwf bitsB47 ; Store

; Restore context
  swapf old_status,w ; Saved status to w
  movfw STATUS ; To STATUS register
  swapf old_w,f ; Swap file register in itself
  swapf old_w,w ; re-swap back to w

; Reset, interrupt

notRBIF:
  bcf INTCON,rbif ; Clear INTCON bit 0
  retfie
Processing by the interrupt service routine is straightforward. The code first determines which line caused the interrupt and takes the corresponding action in each case. In either case, the handler waits until all pushbuttons have been released before returning from the interrupt. This serves to debounce the switches.

11.4 Sample Programs

The following programs demonstrate the programming discussed in this chapter.

11.4.1 The RB0Int Program

; File: RB0Int.ASM
; Date: April 22, 2006
; Author: Julio Sanchez
; Processor: 16F84A
;
; Description:
; Program to test interrupt on port RB0
; A pushbutton switch is connected to port RB0.
; The pushbutton toggles a LED on port-B, line 2
; Another LED on port-B, line 1, flashes on and off
; at 1/2 second intervals
;======================================
; switches
;======================================
; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; * _CP_OFF
; * _PWRTE_ON Power-up timer ON/OFF
; _PWRTE_OFF
; _WDT_ON Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC Low power crystal oscillator
; * _XT_OSC External parallel resonator/crystal oscillator
;
; _HS_OSC High speed crystal resonator (8 to 10 MHz)
; Resonator: Murata Erie CSA8.00M G=8 M Hz
; _RC_OSC Resistor/capacitor oscillator (simplest, 20%
; error)
; |
; |____ * indicates setup values
;
;======================================
; setup and configuration
;======================================
processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF
;================================================================================
variables in PIC RAM

Local variables

cblock 0x0d ; Start of block
J ; counter J
K ; counter K
count1 ; Auxiliary counter
count2 ; ISR counter
old_w ; Context saving
old_STATUS ; Idem
endc

; main program

org 0 ; start at address 0
goto main

; interrupt handler

org 0x04
goto IntServ

main:
; Set up interrupt on falling edge
; by clearing OPTION register bit 6
movlw b’10111111’
option
movlw b’11111111’ ; Set port a for input
tris PORTA
movlw b’00000001’ ; Port-B bit 0 is input
tris PORTB ; all others are output
clr PORTB ; All port-B to 0
; Initially turn on LED
bsf PORTB,0 ; Set line 0 bit

; setup interrupts

; Clear external interrupt flag (INTF = bit 1)
bcf INTCON,INTF ; Clear flag
; Enable global interrupts (GIE = bit 7)
; Enable RB0 interrupt (INTE = bit 4)
bsf INTCON,GIE ; Enable global int (bit 7)
bsf INTCON,INTE ; Enable RB0 int (bit 4)
Program flashes LED wired to Port-B, line 2 lights:

```assembly
movlw b'00000010' ; Mask with bit 1 set
xorwf PORTB,f ; Complement bit 1
call long_delay
call long_delay
call long_delay
goto lights
```

Interrupt Service Routine

Service routine receives control when there is action on pushbutton switch wired to Port-B, line 0

```assembly
IntServ:
; First test if source is an RB0 interrupt
btfss INTCON,INTF ; INTF flag is RB0 interrupt
goto notRB0 ; Go if not RB0 origin

; Save context
movwf old_w ; Save w register
swapf STATUS,w ; STATUS to w
movwf old_STATUS ; Save STATUS

; Make sure that interrupt occurred on the falling edge of the signal. If not, abort handler
btfsc PORTB,0 ; Is bit set?
goto exitISR ; Go if bit not 0

; Debounce switch
; Logic:
; Debounce algorithm consists in waiting until the same level is repeated on a number of samplings of the switch. At this point the RB0 line is clear since the interrupt takes place on the falling edge. An initial short delay makes sure that spikes are ignored.

movlw D'10' ; Number of repetitions
movwf count2 ; To counter

wait:
; Check to see that port-B bit 0 is still 0
; If not, wait until it changes
btfsc PORTB,0 ; Is bit set?
goto exitISR ; Go if bit not 0

; At this point RB0 bit is clear
decfsz count2,f ; Count this iteration
goto wait ; Continue if not zero

Interrupt action consists of toggling bit 2 of
; port-B to turn LED on and off
movlw b'00000100' ; Xoring with a 1-bit produces
xorwf PORTB,f ; the complement
; Complement bit 2, port-B

; exit ISR

;=========================
; exit ISR:
;=========================

exitISR:
; Restore context
swapf old_STATUS,w ; Saved STATUS to w
movfw STATUS ; To STATUS register
swapf old_w,f ; Swap file register in itself
swapf old_w,w ; re-swap back to w

; Reset, interrupt
donRB0:

bcf INTCON,INTF ; Clear INTCON bit 1
retfie

; Procedure to delay
; 10 machine cycles
;========================
delay:
movlw D'4' ; Repeat 12 machine cycles
movwf count1 ; Store value in counter
repeat
decfsz count1,f ; Decrement counter
goto repeat ; Continue if not 0
return

; long delay sub-routine
; (for debugging)
;========================
long_delay
movlw D'200' ; w = 200 decimal
movwf J ; J = w
jloop: movwf K ; K = w
kloop: decfsz K,f ; K = K-1, skip next if zero
goto kloop
decfsz J,f ; J = J-1, skip next if zero
goto jloop
return
end

11.4.2 The SleepDemo Program

; File: SleepDemo
; Date: April 25, 2006
Interrupts

; Author: Julio Sanchez
; Processor: 16F84A
;
; Description:
; Program to use the External Interrupt on port RB0
; to terminate the power-down state caused by the
; SLEEP instruction. A pushbutton switch is connected to
; port RB0. The pushbutton generates the interrupt that
; ends the SLEEP conditions.
; Demonstration:
; A LED on port-B, line 1, flashes on and off at 1/2
; second intervals for 20 iterations. At that time the
; program enters the SLEEP condition. Pressing the
; pushbutton switch on line RB0 generates the interrupt
; that ends the SLEEP.

:=------------------------------------------------------------------------:=
;
; switches
;=========================================================================
; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; * _CP_OFF
; * _PWRTE_ON Power-up timer ON/OFF
; _PWRTE_OFF
; _WDT_ON Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC Low power crystal oscillator
; * _XT_OSC External parallel resonator/crystal oscillator
; _HS_OSC High speed crystal resonator (8 to 10 MHz)
; Resonator: Murate Erie CSA8.00M G=8 MHz
; _RC_OSC Resistor/capacitor oscillator (simplest, 20% error)
; * |----- * indicates setup values
;
;=========================================================================
;
; setup and configuration
;=========================================================================

processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

;=========================================================================
;
variables in PIC RAM
;=========================================================================

Local variables

cblock 0x0d ; Start of block
J ; counter J
K ; counter K
count1 ; Auxiliary counter
count2 ; Second auxiliary counter
old_w ; Context saving
old_STATUS ; Idem
endc

;========================================================
; main program
;========================================================
org 0 ; start at address 0
goto main

;=============================  
; interrupt handler
;=============================
org 0x04
goto IntServ

;=================================================================
; main program
;=================================================================
main:
; Set up interrupt on falling edge
; by clearing OPTION register bit 6
movlw b'10111111'
option
movlw b'11111111' ; Set port a for input
tris PORTA
movlw b'00000001' ; Port-B bit 0 is input
tris PORTB ; all others are output
clrf PORTB ; All port-B to 0

;=================================================================
; setup interrupts
;=================================================================
; Clear external interrupt flag (INTF = bit 1)
bcf INTCON,INTF ; Clear flag
; Enable global interrupts (GIE = bit 7)
bsf INTCON,GIE ; Enable global int (bit 7)
bsf INTCON,INTE ; Enable RB0 int (bit 4)

;=================================================================
; flash LED 20 times
;=================================================================
wakeUp:
; Program flashes LED wired to port-B, line 2
; 20 times before entering the sleep state
movlw D'20' ; Number of iterations
movwf count2 ; To counter
lights:
    movlw b'00000010' ; Mask with bit 1 set
    xorwf PORTB,f ; Complement bit 1
    call long_delay
    call long_delay
    call long_delay
    decfsz count2,f ; Decrement counter
    goto lights
; 20 iterations have taken place
    sleep
    nop ; Recommended!
    goto wakeUp ; Resume execution

;=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-
; Interrupt Service Routine
;=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-
; The interrupt service routine performs no operation
IntServ:
    bcf INTCON,INTF ; Clear flag
    retfie

;=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-
; long delay sub-routine
;=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-
long_delay
    movlw D'200' ; w = 200 decimal
    movwf J ; J = w
    jloop:
        movwf K ; K = w
    kloop:
        decfsz K,f ; K = K-1, skip next if zero
        goto kloop
    decfsz J,f ; J = J-1, skip next if zero
    goto jloop
    return

end

11.4.3 The RB4to7Int Program

; File: RB4to7Int.ASM
; Date: April 26, 2006
; Author: Julio Sanchez
; Processor: 16F84A
;
; Description:
; Program to test the port-B, bits 4 to 7, STATUS
; change interrupt. Pushbutton switches are connected
; to port-B lines 4 and 7. A red LED is wired to port
; RA1 and a green LED to port RA0. The pushbuttons
; generate interrupts that toggle a LEDs on and off.

; ================
; switches
; ================
; Switches used in __config directive:
; _CP_ON       Code protection ON/OFF
; _CP_OFF
; * _PWRTE_ON  Power-up timer ON/OFF
; _PWRTE_OFF  
; _WDT_ON      Watchdog timer ON/OFF
; * _WDT_OFF  
; _LP_OSC      Low power crystal oscillator
; * _XT_OSC    External parallel resonator/crystal oscillator
; _HS_OSC      High speed crystal resonator (8 to 10 MHz)
; Resonator: Murate Erie CSA8.00M G=8 MHz
; _RC_OSC      Resistor/capacitor oscillator (simplest, 20%
; error)
; |
; |_____ * indicates setup values

; ================
; set up and configuration
; ================

processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

; ================
; variables in PIC RAM
; ================

Local variables

cblock 0x0d ; Start of block
J ; counter J
K ; counter K
count1 ; Auxiliary counter
count2 ; ISR counter
old_w ; Context saving
old_STATUS ; Idem
bitsB47 ; Storage for previous value
            ; in port-B bits 4-7
temp ; Temporary storage
endc

; ================
; main program
org 0 ; start at address 0

; interrupt handler

org 0x04

goto IntServ

main:
; Disable port-B internal pullups
; Interrupts on falling edge of pushbutton action

movlw b'10111111'

option

; Wiring:
; 7 6 5 4 3 2 1 0 <= port-B
; | |__________ red pushbutton
; |____________________ black pushbutton
;
; 7 6 5 4 3 2 1 0 <= Port-A
; | |____ red LED
; |______ green LED
;
movlw b'00000000' ; Set Port-A for output

tris PORTA

movlw b'11110000' ; Port-B bit 0-3 are output

tris PORTB ; all others are output

clf PORTB ; All Port-B to 0

movlw b'00000000' ; Zero to w

movwf bitsB47 ; Store in local variable

; Initially turn on LEDs

bsf PORTA,0 ; Set LEDs on line 0

bsf PORTA,1 ; and on line 1

; set up interrupts

; Clear external interrupt flag (intf = bit 1)

bcf INTCON,RBIF ; Clear flag

; Enable global interrupts (GIE = bit 7)

; Enable RB0 interrupt (inte = bit 4)

bsf INTCON,GIE ; Enable global int (bit 7)

bsf INTCON,RBIE ; Enable RB0 int (bit 3)

; flash LED
Main program does nothing. All action takes place in Interrupt Service Routine.

```
nop
goto lights
```

Interrupt Service Routine

```
; Service routine receives control whenever any of port-B lines 4 to 7 change state
IntServ:

; First test: make sure source is an RB4-7 interrupt
btfss INTCON,RBIF ; RBIF flag is interrupt
    goto notRBIF ; Go if not RBIF origin

; Save context
movwf old_w ; Save w register
swapf STATUS, w ; STATUS to w
movwf old_STATUS ; Save STATUS

; interrupt action

; The interrupt occurs when any of Port-B bits 4 to 7 have changed STATUS.
    movf PORTB, w ; Read Port-B bits
    movwf temp ; Save reading
    xorwf bitsB47, f ; Xor with old bits, result in f

; Test each meaningful bit (4 and 7 in this example)
    btfsc bitsB47, 4 ; Test bit 4
        goto bit4Chng ; Routine for changed bit 4
    btfsc bitsB47, 7 ; Test bit 7
        goto bit7Chng ; Routine for changed bit 7

; Invalid port line change. Exit
    goto pbRelease

; bit 4 change routine

; Check for signal falling edge, ignore if not
bit4Chng:
    btfsc PORTB, 4 ; Is bit 4 high
        goto pbRelease ; Bit is high. Ignore
    movlw b’00000010’ ; Xoring with a 1-bit produces
        xorwf PORTA, f ; Complement bit 1, Port-A
    goto pbRelease
bit7Chng:
    btfsc PORTB,7 ; Is bit 7 high
    goto exitISR ; Bit is high. Ignore

; Toggling bit 0 of Port-A turns LED on and off
    movlw b'00000001'; Xoring with a 1-bit produces
    xorwf PORTA,f ; the complement

pbRelease:
    call delay ; Debounce switch
    movf PORTB,w ; Read port-B into w
    andlw b'10010000'; Eliminate unused bits
    btfsc STATUS,Z ; Check for zero
    goto pbRelease ; Wait

; At this point all port-B pushbuttons are released
exitISR:
; Store new value of port-B
    movf temp,w ; This port-B value to w
    movwf bitsB47 ; Store

; Restore context
    swapf old_STATUS,w ; Saved STATUS to w
    movfw STATUS ; To STATUS register
    swapf old_w,f ; Swap file register in itself
    swapf old_w,w ; re-swap back to w

; Reset,interrupt
notRBIF:
    bcf INTCON,RBIF ; Clear INTCON bit 0
    retfie

; Procedure to delay
; 10 machine cycles
delay:
    movlw D'6'; ; Repeat 18 machine cycles
    movwf count1 ; Store value in counter
repeat:
    decfsz count1,f ; Decrement counter
    goto repeat ; Continue if not 0
    return

;==============================================
; long delay sub-routine
; (for debugging)
;=================================
long_delay
    movlw D'200' ; w = 200 decimal
    movwf J ; J = w
jloop:
    movwf K ; K = w
kloop:
    decfsz K,f ; K = K-1, skip next if zero
    goto kloop
    decfsz J,f ; J = J-1, skip next if zero
    goto jloop
    return
end
Timers and Counters

This chapter is about using the built-in timing and counting circuits on the 16F84. It relates to Chapter 11 since timing and counting operations can be set up to generate interrupts. The material also serves as background for Chapter 14, on serial communications, since these require precise pulses that are usually obtained through the timers.

12.0  The 16F84 Timer0 Module

One of the timers on the 16F84 PIC is known as the Timer0 module, the free-running timer, the timer/counter, or as TMR0. Timer0 is an internal 8-bit register that increments automatically with every PIC instruction cycle until the count overflows timer capacity. This takes place when the timer count goes from 0xff to 0x00. At that time, the timer restarts the count. The timer has the following characteristics:

1. A timer register that is readable and writeable by software
2. Can be powered by an external or internal clock
3. Timing edge for external clock can be selected
4. 8-bit software programmable prescaler
5. Interrupt capability
6. Can be used as a timer or as a counter

12.0.1  Timer0 Operation

Timer operation can be assigned to the internal clock or to the PIC’s RA4/TOCKI pin. Bit 5 of the OPTION register (labeled TOCS) performs this selection. If TOCS is set, then the timer is linked to the RA4/TOCKI pin. In this mode, the timer is used as a counter. If TOCS is reset, then the timer uses the PIC’s instruction cycle clock signal. If an external source is selected by setting the TOCS bit, then bit 4 of the OPTION register (labeled TOSE) allows selecting whether the timer increments on the high-to-low or low-to-high transition of the signal on the RA4/TOCKI pin. As shown in Figure 12-1, bits 6 and 7 of the OPTION register are not used in configuring the Timer0 module.
When used as a timer, Timer0 can be visualized as a register that increments with every instruction cycle at \( \frac{1}{4} \) the clock rate, without using the prescaler. In a PIC equipped with a 4 Mhz oscillator the timer register increments at a rate of one pulse per millisecond. Since there are eight bits in the counter register, the value stored is in the range 0 to 255 decimal. When the counter overflows the register is reset. Figure 12-1 is a simplified block diagram of the Timer0 hardware.

**Timer0 Interrupt**

Software can read the timer register directly or set up the timer to generate an interrupt at every transition from 0xff to 0x00. The timer register can be accessed in bank 0, offset 0x01. The timer interrupt is enabled by setting bit 5 (labeled TOIE) of the INTCON register. In this case the Global Interrupt Enable bit (labeled GIE) of INTCON register must also be set. Once the timer interrupt is enabled, the Timer Interrupt Flag, assigned to bit 2 of the INTCON Register and labeled TOIF, is set on every overflow of the timer register. At that time an interrupt takes place. The TOIF bit (Timer0 flag) must be cleared by the interrupt handler so that the timer interrupt can take place again. Later in this chapter we develop a sample program that uses Timer0 as an interrupt source.

**Timer0 Prescaler**

The counter prescaler consists of the three low-order bits in the OPTION register. These bits allow selecting eight possible values that serve as a divisor for the counter rate. When the prescaler is disabled, the counter rate is one-fourth the processor’s clock speed. If the prescaler is set to the maximum value (255) then one of 255 clock signals actually reach the timer. Table 12-1 shows the prescaler settings and their action on the rate of the Timer0 module and the Watchdog Timer, covered later in this chapter.
Table 12.1  
Prescaled Bits Selected Rates

<table>
<thead>
<tr>
<th>BIT VALUE</th>
<th>TMR0 RATE</th>
<th>WDT RATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>1:2</td>
<td>1:1</td>
</tr>
<tr>
<td>001</td>
<td>1:4</td>
<td>1:2</td>
</tr>
<tr>
<td>010</td>
<td>1:8</td>
<td>1:4</td>
</tr>
<tr>
<td>011</td>
<td>1:16</td>
<td>1:8</td>
</tr>
<tr>
<td>100</td>
<td>1:32</td>
<td>1:16</td>
</tr>
<tr>
<td>101</td>
<td>1:64</td>
<td>1:32</td>
</tr>
<tr>
<td>110</td>
<td>1:128</td>
<td>1:64</td>
</tr>
<tr>
<td>111</td>
<td>1:256</td>
<td>1:128</td>
</tr>
</tbody>
</table>

The prescaler can be assigned to either Timer0 or the Watchdog Timer, but not to both. If bit 3 of the OPTION register is set, then the prescaler is assigned to the Watchdog Timer if it is clear it is assigned to the Timer0 module.

12.1 Delays Using Timer0

The simplest application of the Timer0 module is as an instruction cycle counter in implementing delay loops. Applications in which the Timer0 register is polled directly are said to use a free running timer. There are two advantages of using free running timers over conventional delay loops: the prescaler provides a way of slowing down the count, and the delay is independent of the number of machine cycles in the loop body. In most cases, it is easier to implement an accurate time delay using the Timer0 module than by counting instruction cycles.

Calculating the time taken by each counter iteration consists of dividing the clock speed by four. For example, a PIC running on a 4 Mhz oscillator clock increments the counter every 1 Mhz. If the prescaler is not used, the counter register is incremented at a rate of 1 µs; the timer beats at a rate of 1,000,000 times per second. If the prescaler is set to the maximum divisor value (256) then each increment of the timer takes place at a rate of 1,000,000/256 µs, which is approximately 3.906 ms. Since this is the slowest possible rate of the timer in a machine running at 4 Mhz, it is often necessary to employ supplementary counters in order to achieve larger delays.

The fact that the timer register (Tmr0) is both readable and writeable makes possible some interesting timing techniques. For example, an application can set the Timer register to an initial value and then count until a predetermined limit is reached. For example, if the difference between the limit and the initial value is 100, then the routine counts 100 times the timer rate per beat. In another example, if a routine allows the timer to start from zero and count unrestrictedly, then when the count reaches the maximum value (0xff) the routine would have introduced a delay of 256 times the timer beat rate, as is the case in the previous example, in which a maximum value was used in the prescaler and the timer ran at a rate of 1,000,000 beats per second. Applying the prescaler, each timer beat takes place at a rate of 1,000,000/256, or approximately 3,906 timer beats per second. If we develop a routine that delays execution until the maximum value has been reached in the counter register, then the delay can be calculated by dividing the number of beats per second
(3,906) by the number of counts in the delay loop. In this case, 3,906/256 results in a
delay of approximately 15.26 iterations of the delay routine per second.

A general formula for calculating the number of timer beats per second is as fol-

\[ T = \frac{C}{4PR} \]

where \( T \) is the number of clock beats per second, \( C \) is the system clock speed in Hz, \( P \) is
the value stored in the prescaler, and \( R \) is the number of iterations counted in the
TMR0 register. The range of both \( P \) and \( R \) in this formula is 1 to 256. Also, note that the
reciprocal of \( T \) \((1/T)\) gives the time delay, in seconds, per iteration of the delay routine.

12.1.1 Long Delay Loops

In the previous section we saw that even when using the largest possible prescaler and
counting the maximum number of timer beats, the longest possible timer delay in a 4
Mhz system is approximately 1/15th of a second. Also consider that applications must
sometimes devote the prescaler to the Watchdog Timer, which impedes its use in
Timer0. Without the prescaler, the maximum delay is of approximately 3,906 timer
beats per second. Applications that measure time in seconds or in minutes must find
ways for keeping count of large numbers of repetitions of the timer beat.

In implementing counters for larger delays we have to be careful not to introduce
round-off errors. For instance, in the previous example a timer cycles at the rate of
15.26 times per second. The closest integer to 15.26 is 15, so if we now set up a sec-

Considering that in the previous example each iteration of the timer contains 256
individual beats, there are 3,906.25 individual timer beats per second at the maxi-
mum prescaled rate. So if we were to implement a counter to keep track of individ-
ual prescaled beats, instead of timer iterations, the count would proceed from 0 to
3,906 instead of from 0 to 15. Approximating 3,906.25 to the closest integer, 3,906, in-
troduces a much smaller round-off error than approximating 15.26 with 15.

Finally, in this same example, we could eliminate the prescaler so that the timer
beats at the clock rate, that is, at 1,000,000 beats per second. In this option, a coun-
ter that counts from 0 to 1,000,000 would have no intrinsic error due to round off.

Which solution is more adequate depends on the accuracy required by the appli-
cation and the complexity tolerated. A timer counter in the range of 0 to 15 can be
implemented in a single 8-bit register. A counter in the range 0 to 3,906 requires two
bytes. One to count from 0 to 1,000,000 requires three bytes. Since arithmetic opera-
tions in the 16F84 are 8-bits, manipulating multiple-register counters requires more
complicated processing.
How Accurate the Delay?

The actual implementation of a delay routine based on multi-byte counters presents some difficulties. If the timer register (TMR0) is used to keep track of timer beats, then detecting the end of the count poses a subtle problem. Intuitively, our program could detect timer overflow by reading the TMR0 and testing the zero flag in the status register. Since the `movf` instruction affects the zero flag, one could be tempted to code:

```assembly
wait:
    movf tmr0,w ; Timer value into w
    btfss status,z ; Was it zero?
    goto wait
; If this point is reached TMR0 has overflowed
```

But there is a problem: the timer ticks as each instruction executes. Since the `goto` instruction takes two machine cycles, it is possible that the timer overflows while the `goto` instruction is in progress; therefore the overflow condition would not be detected. One possible solution found in the Microchip documentation is to check for less than a nominal value by testing the carry flag, as follows:

```assembly
wait1:
    movlw 0x03 ; 3 to w
    subwf tmr0,w ; Subtract w – TMR0
    btfsc status,c ; Test carry
    goto wait1
```

One adjustment that is sometimes necessary in free running timers arises from the fact that when the TMR0 register is written, the count is inhibited for the following two instruction cycles. Software compensates for the skip by writing an adjusted value to the timer register. If the prescaler is assigned to Timer0, then a write operation to the timer register determines that the timer does not increment for four clock cycles.

The Black-Ammerman Method

A more elegant and accurate solution has been described by Roman Black in a Web article titled Zero-Error One Second Timer. Black credits Bob Ammerman with the suggestion of using Bresenham’s algorithm for creating accurate PIC timer periods. In the Black-Ammerman method, the counter works in the background, either by being polled or interrupt-driven, so the program can continue executing while the counter runs. In both cases, the timer-count value is stored in a 3-byte register decremented by the software.

In their interrupt-driven version, TMR0 generates an interrupt whenever the counter register overflows, that is, every 256th timer beat (assuming no prescaler). The interrupt handler routine decrements the mid-order register that holds the 3-byte timer count. This is appropriate since every unit in the mid-order register represents 256 units of the low-order counter, which in this case is the TMR0 register. If the mid-order register underflows when decremented, then the high-order one is decremented. If the high-order one underflows, then the count has reached zero and
the delay ends. Since the counter is interrupt-driven, the processor continues to do other work in the foreground.

An even more ingenious option proposed by Black is a background counter that does not rely on interrupts. This is accomplished by introducing a 1:2 delay in the timer by means of the prescaler. Since now the timer beats at one-half the instruction rate, 128 timer cycles are required for one complete iteration at the full instruction rate. By testing the high-order bit of the timer counter, the routine detects when the count reaches 128. At that time the mid-range and high-range counter variables are updated (as in the non-interrupt version of the software described in the previous paragraph). The high-order bit of the timer is then cleared, but the low-order bits are not changed. This allows the timer counter not to lose step in the count, which remains valid until the next time the high-order bit is again set. During the period between the updating of the 3-byte counter and the next polling of the timer register, the program continues to perform other tasks.

Many of the details of the Black-Ammerman method are missing in our description. The reader should refer to the Internet article for a thorough coverage of this algorithm.

12.2 Timer0 as a Counter

In Section 12.0.1, we saw that Timer0 operation can be assigned to the PIC’s RA4/TOCKI pin by setting bit 5 of the OPTION register (labeled TOCS). This mode is referred to as the counter mode. When the timer is set up to work as a counter, then bit 4 of the OPTION register (labeled TOSE) allows selecting whether the counter increments on the high-to-low or low-to-high transition of the signal.

When an external clock input is present in the RA4/TOCKI pin, it must meet certain requirements. Used for Timer0, these requirements ensure that the external source can be synchronized with the internal phase clock. When no prescaler is used, the external clock input must be high and low for at least twice the internal clock rate. In addition, there must be a resistor-capacitor induced delay of 20 ns on both the high and the low cycles.

When a prescaler is used, the external clock input must be high and low for at least four times the rate of the internal clock rate. In addition, there must be a resistor-capacitor induced delay of 40 ns on both the high and the low cycles.

Once the counter mode is enabled, any pulse on pin RA4/TOCKI is automatically counted in the TMR0 register. The mechanism can be compared to an automatic interrupt since no program action is required to keep track of the number of pulses. The routine can be coded so that when the timer count overflows, an interrupt is generated. The interrupt handler then increments a supplementary counter so that events that exceed 256 pulses are recorded. The program named Tmr0Counter developed later in this chapter and contained in the book’s online software is an example of using the counter function of the Timer0 module.
12.3 Timer0 Programming

Software routines that use the Timer0 module range in complexity from simple approximate delay loops to configurable, interrupt-driven counters that must meet very high timing accuracy requirements. When the time period to be measured does not exceed the one obtained with the prescaler and the timer register count, then the coding is straightforward and the processing is uncomplicated. But often this is not the case. The following elements should be examined before attempting to design and code a Timer0-based routine:

1. What is the required accuracy of the timer delay?
2. Can the prescaler be used or is the prescaler devoted to the Watchdog Timer?
3. Does the program suspend execution while the delay is in progress, or does the application continue executing in the foreground?
4. Can the timer be interrupt-driven or must it be polled?
5. Will the delay be the same on all calls to the timer routine, or must the routine provide delays of different magnitude?
6. How long must the delay last?

In this section we explore several timer routines of different complexity and requirements. The first one uses the Timer0 module as a counter, as described in Section 12.2. Later, we develop a simple delay loop that uses the Timer0 register instead of an instruction count. We conclude with an interrupt-driven timer routine that can be changed to implement different delays.

12.3.1 Programming a Counter

The 16F84 can be programmed so that port RA4/TOCKI is used to count events or pulses by initializing the Timer0 module as a counter. Without interrupts, the process requires the following preparatory steps:

1. Port-A, line 4, (RA4/TOCKI) is defined for input.
2. The Timer0 register (TMR0) is cleared.
3. The Watchdog Timer internal register is cleared by means of the clrwdt instruction.
4. The OPTION register bits PSA and PSO:PS2 are initialized if the prescaler is to be used.
5. The OPTION register bit TOSE is set so as to increment the count on the high-to-low transition of the port pin if the port source is active low. Otherwise the bit is cleared.
6. The OPTION register bit TOCS is set to select action on the RA4/TOCKI pin.

Once the timer is set up as a counter, any pulse received on the RA4/TOCKI pin that meets the restrictions mentioned in Section 12.2 is counted in the TMR0 register. Software can read and write to the TMR0 register, located at address 0x01 in bank 0, in order to obtain or change the event count. If the timer interrupt is enabled when the timer is defined as a counter, the interrupt takes place every time the counter overflows, that is, when the count cycles from 0xff to 0x00.
A Timer/Counter Test Circuit

The circuit shown in Figure 12-2 contains a pushbutton switch wired to port RA4/TOCKI and a seven-segment LED display wired to Port-B lines 0 to 6.

The Tmr0Counter Program

The program named Tmr0Counter in the book's online software package uses the circuit in Figure 12-2 to demonstrate the programming of the Timer0 module in the counter mode. The program detects and counts action on the pushbutton switch wired to port RA4/TOCKI. The value of the count in hex digits ranging 0x00 to 0x0f is displayed in the seven-segment LED connected to Port-B.

The following code fragment shows the program's initialization routine to set up the ports and the timer:

```
main:
    ; Clear the Watchdog Timer and reset prescaler
    clrwdt
    ; Set up the OPTION register bit map
    movlw b'10111000'
    ; 7 6 5 4 3 2 1 0 <= OPTION bits
    ; || || || || || ||| |__|__|_____ PS2-PS0 (prescaler bits)
    ; || || || || | Values for Timer0
```
<table>
<thead>
<tr>
<th>Decimal Value</th>
<th>Binary Code</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>001</td>
<td>1:4</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
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<tr>
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<td>011</td>
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<tr>
<td>27</td>
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</tr>
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</table>

*000 = 1:2  
*001 = 1:4  
*010 = 1:8  
*011 = 1:16  
*100 = 1:32  
*101 = 1:64  
*110 = 1:128 
*111 = 1:256 

---

Once the hardware is initialized, program operation consists of reading the value stored in TMR0, scaling this value to the display range 0 to 15, and displaying it on the seven-segment LED. Processing is as follows:

```assembly
; Set up ports
movlw 0x00 ; Set Port-B to output
tris portb
clrf portb ; All Port-B to 0

; Port-A. Five low-order lines set for input
movlw B'00011111' ; w = 00011111 binary
tris porta ; Port-A (lines 0 to 4) to input
```

### Timer and Counter 2

After setting up the ports, we can proceed with the main processing:

```assembly
; Check value in TMR0 and display
; Every press of the pushbutton switch connected to line RA4/TOCKI adds one to the value in the TMR0 register.
; Loop checks this value, adjusts to the range 0 to 15
; and displays the result in the seven-segment LED on Port-B

; Port-A. Five low-order lines set for input
movlw B'00011111' ; w = 00011111 binary
tris porta ; Port-A (lines 0 to 4) to input

; Check value in TMR0
movf mr0, w ; Timer register to w

; Eliminate four high order bits
andlw b'00001111' ; Mask off high bits

; At this point the w register contains a 4-bit value
; in the range 0 to 0xf. Use this value (in w) to
; obtain seven-segment display code

; Call segment
```
The programming of seven-segment LEDs was discussed in Chapter 10.

12.3.2 Timer0 as a Simple Delay Timer

Perhaps the simplest use of the Timer0 module is to implement a delay loop. In this application, the Timer0 module is initialized to use the internal clock by setting the TOSE bit of the OPTION register. If the prescaler is to be used, as is most likely, the PSA bit is cleared and the desired prescaling is entered in bits PS2 to PS0 of the OPTION register. The circuit in Figure 12-3 allows testing several timer-related programs developed in this chapter.

The program named Timer0, in the book's online software package, uses a timer-based delay loop to flash in sequence eight LEDs that display the binary values from 0x00 to 0xff. The delay routine executes in the foreground, so that processing is suspended while the count is in progress. The initialization requires clearing the TOCS bit in the OPTION register to select the internal clock. The prescaler is assigned to Timer0 by clearing the PSA bit and bits PS2 to PS0 are set to assign a 1:256 prescale to the timer. The following code fragment shows the processing.
Figure 12-3  Circuit for Testing Several Timer Programs

main:
; Clear the Watchdog Timer and reset prescaler
clrwdt
; Set up the OPTION register
movlw \texttt{b'11010111'}
; 7 6 5 4 3 2 1 0 <= OPTION bits
; | | | | | | | | PS2-PS0 (prescaler bits)
; | | | | | | | | Values for Timer0
; | | | | | | | | 000 = 1:2   001 = 1:4
; | | | | | | | | 010 = 1:8   011 = 1:16
; | | | | | | | | 100 = 1:32  101 = 1:64
; | | | | | | | | 110 = 1:128 *111 = 1:256
; | | | | | | | | PSA (prescaler assign)
; | | | | | | | | 1 = to WDT
; | | | | | | | | *0 = to Timer0
; | | | | | | | | TOSE (Timer0 edge select)
; | | | | | | | | 0 = increment on low-to-high
; | | | | | | | | *1 = increment in high-to-low
; | | | | | | | | TOCS (TMR0 clock source)
; | | | | | | | | *0 = internal clock

Timers and Counters
option
; Set up ports
movlw 0x00 ; Set Port-B to output
tris portb
crfr portb ; All Port-B to 0
; Port-A is not used in this program
mloop:
incf portb,f ; Add 1 to register value
call TM0delay
goto mloop

The delay procedure named TM0delay provides the necessary time lapse between successive increments in the count displayed. The code is as follows:

;****************************
; delay sub-routine
; uses Timer0
;****************************
TM0delay:
; Initialize the timer register
crfr tmr0 ; Clear SFR for Timer0
; Routine tests the value in the TMR0 register by subtracting 0xff from the value in TMR0. The zero flag is set if TMR0 = 0xff
cycle:
movf tmr0,w ; Timer to w
; w has TMR0 register value
sublw 0xff ; Subtract max value
; Zero flag is set if value in TMR0 = 0xff
btfss status,z ; Test for zero
goto cycle ; Repeat
Return

12.3.3 Measured Time Lapse

A variable time-lapse routine that can be edited or adjusted to produce delays within a specific time range is a useful tool in any programmer’s library. In previous sections, we developed delay routines that do so by counting timer pulses. This same idea can be used to develop a routine that produces accurate delays within a range.
The routine can be implemented to varying degrees of sophistication. One extreme would be a procedure that receives the desired time lapse as a parameter. Another option would be a procedure that reads the desired time lapse from program constants. In the program named LapseTimer contained in the book’s online software we develop a procedure in which the calling code passes the desired time delay in three variables containing the number of machine cycles necessary for the desired wait period. By using machine cycles instead of time units (such as microseconds or milliseconds), the procedure becomes easily adaptable to devices running at different clock speeds. Since each instruction requires four clock cycles, the device’s clock speed in Hz is divided by four in order to determine the number of machine cycles per time unit.

For example, a processor equipped with an 8 MHz clock executes at a rate of 8,000,000/4 machine cycles per second; that is, 2,000,000 instruction cycles per second. To produce a one-quarter second delay requires a wait period of 2,000,000/4 or 500,000 instruction cycles. By the same token, the 16F84 running at 4 MHz executes 1,000,000 instructions per second. In this case a one-quarter second delay would require waiting 250,000 instruction cycles.

The program titled lapseTimer in the book’s online software package uses Timer0 to produce a variable-lapse delay. The delay is calculated based on the number of machine cycles necessary for the desired wait period, as described in the preceding paragraph. The program uses the Black-Ammerman methods, which require a prescaler of 1:2 so that each timer iteration takes place at one-half the clock rate. The program initializes the OPTION register and the ports as follows:

```
main:
; Clear the Watchdog Timer and reset prescaler
clrf tmr0
clrwdt
; Set up the OPTION register bit map
movlw b'11010000' ; 76543210 <= OPTION bits
; | | | | | |___|___|__ PS2-PS0 (prescaler bits)
; | | | | | | Values for Timer0
; | | | | | *000 = 1:2  001 = 1:4
; | | | | | 010 = 1:8  011 = 1:16
; | | | | 100 = 1:32  101 = 1:64
; | | | 110 = 1:128 *111 = 1:256
; | | | PSAs (prescaler assign)
; | | | 1 = to WDT
; | | | *0 = to Timer0
; | | | TOSE (Timer0 edge select)
; | | 0 = increment on low-to-high
; | *1 = increment in high-to-low
; | TOC5 (TMR0 clock source)
; | *0 = internal clock
; | 1 = RA4/TOCKI bit source
; | INTE (Edge select)
```
The LapseTimer program is designed to produce a one-half second delay on a 16F84 running at 4 Mhz; therefore, the delay requires 500,000 clock beats. The value is converted to hexadecimal and stored in a 3-byte counter, as follows:

\[
500,000 = 0x07a120
\]

The variables countL, countM, and countH are defined locally and initialized by a procedure named onehalfSec, as follows:

```assembly
; Procedure to initialize local variables for a
delay of one-half second on a 16F84 at 4 Mhz.
; Timer is set up for 500,000 clock beats as
; follows: 500,000 = 0x07 0xa1 0x20
; 500,000 = 0x07 0xa1 0x20
;      — — —
;        | | |___ countL)
;        | |________ countM
;        |_____________ countH
onehalfSec:
    movlw 0x07
    movwf countH
    movlw 0xa1
    movwf countM
    movlw 0x20
    movwf countL
    return
```

The delay routine uses the Timer0 register to provide the low-order level of the count. Since the counter counts up from zero to ensure that the initial low-level delay count is correct—the value 128 - (xx/2) must be calculated, where xx is the value in the original countL register. The program performs the division by 2 by shifting bits to the right by one position. The resulting value is subtracted from 128 and the result stored in TMR0, as follows:
First calculate \( xx/2 \) by bit shifting

\[
\text{bcf status,c ; Clear carry flag}
\]
\[
\text{rrf countL,f ; Divide by 2}
\]

; now subtract \( 128 - (xx/2) \)
\[
\text{movf countL,w ; w holds low-order byte}
\]
\[
\text{sublw d’128’}
\]
; Now \( w \) has adjusted result. Store in \( \text{TMR0} \)
\[
\text{movwf tmr0}
\]

The delay routine detects timer overflow by testing bit 7 of the \( \text{TMR0} \) register. If the bit is set, then 256 time cycles have elapsed and the mid-order counter register is decremented. If the mid-order register underflows when it is decremented, then the high-order register is decremented. If it underflows, the counter has gone to zero and the delay routine ends. Processing is as follows:

\[
\text{cycle:}
\]
\[
\text{btfss tmr0,7 ; Is bit 7 set?}
\]
\[
\text{goto cycle ; Wait if not set}
\]

; At this point \( \text{TMR0} \) bit 7 is set
; Clear the bit
\[
\text{bcf tmr0,7 ; All other bits are preserved}
\]
; Subtract 256 from beat counter by decrementing the
; mid-order byte
\[
\text{decfsz countM,f}
\]
\[
\text{goto cycle ; Continue if mid-byte not zero}
\]
; At this point the mid-order byte has overflowed.
; High-order byte must be decremented.
\[
\text{decfsz countH,f}
\]
\[
\text{goto cycle}
\]
; At this point the time cycle has elapsed
\[
\text{return}
\]

The circuit in Figure 12-3 can be used to test the \( \text{lapseTimer} \) program.

**Interrupt-driven Timer**

Interrupt-driven timers and counters have several advantages over polled routines: first, the time lapse counting takes place in the background so that the application can continue to do other work in the foreground. Another advantage of an interrupt-driven counter is that the prescaler is unnecessary and can be used for the Watchdog Timer. Developing a timer routine that is interrupt-driven presents no additional challenges over the conventional interrupt-driven examples covered in Chapter 11. The initialization consists of configuring the \( \text{OPTION} \) and the \( \text{INTCON} \) register bits for the task at hand. In the particular case of an interrupt-driven timer, the following are necessary:
1. The external interrupt flag (INTF in the INTCON Register) must be initially cleared.
2. Global interrupts must be enabled by setting the GIE bit in the INTCON Register.
3. The Timer0 overflow interrupt must be enabled by setting the TOIE bit in the INTCON register.

In this example program, named LapseTmrInt, the prescaler is not used with the timer, so the initialization code sets the PSA bit in the OPTION register and the prescaler is assigned to the Watchdog Timer. The following code fragment is from the LapseTmrInt program:

```
main:
    ; Clear the Watchdog Timer and reset prescaler
    clrf tmr0
    clrwdt
    ; Set up the OPTION register bit map
    movlw b'11011000'
    ; 7 6 5 4 3 2 1 0 <= OPTION bits
    ; | | | | | | __|__|_____ PS2-PS0 (prescaler bits)
    ; | | | | | Values for Timer0
    ; | | | | 000 = 1:2  001 = 1:4
    ; | | | | 010 = 1:8  011 = 1:16
    ; | | | 100 = 1:32  101 = 1:64
    ; | | 110 = 1:128 *111 = 1:256
    ; | __|___________ PSA (prescaler assign)
    ; | | | *1 = to WDT
    ; | | | 0 = to Timer0
    ; | | __|___________ TOSE (Timer0 edge select)
    ; | | 0 = increment on low-to-high
    ; | | *1 = increment in high-to-low
    ; | __|___________ TOCS (TMR0 clock source)
    ; | | *0 = internal clock
    ; | 1 = RA4/TOCKI bit source
    ; | _____________ INTEDG (Edge select)
    ; | *0 = falling edge
    ; _____________ RBPU (Pullup enable)
    ; 0 = enabled
    ; *1 = disabled

    option
    ; Set up ports
    movlw 0x00 ; Set Port-B to output
    tris portb
    clrf portb ; All Port-B to 0
    ; Port-A is not used in this program
    ;============================
    ; set up interrupts
    ;============================
    ; Clear external interrupt flag (intf = bit 1)
    bcf    INTCON,intf    ; Clear flag
```
As in the program LapseTimer, developed previously in this chapter, the timer operates by decrementing a 3-byte counter that holds the number of timer beats required for the programmed delay. In the case of the LapseTmrInt program, the routine that initializes the register variables for a one-half second delay also correctly adjusts the initial value loaded into the TMR0 register. The code is as follows:

```assembly
;==========================================
; set register variables for
; one-half second delay
;==========================================

; Procedure to initialize local variables for a delay of
; one-half second on a 16F84 at 4 Mhz. Timer is set up for a
; 500,000 clock beats as follows: 500,000 = 0x07 0xa1 0x20
; 500,000 = 0x07 0xa1 0x20
; — — — — — — — — — — — — — — — — — —
; | | |___ countL)
; | |________ countM
; |_____________ countH

onehalfSec:

movlw 0x07
movwf countH
movlw 0xa1
movwf countM
movlw 0x20
movwf countL

; The TMR0 register provides the low-order level of
; the count. Since the counter counts up from zero,
; in order to ensure that the initial low-level delay
; count is correct, the value 256 - xx must be calculated
; where xx is the value in the original countL variable.

movf countL,w ; w holds low-order byte
sublw d'256'

; Now w has adjusted result. Store in TMR0
movwf tmr0
return
```

The interrupt service routine in the LapseTmrInt program receives control when the TMR0 register underflows, that is, when the count goes from 0xff to 0x00. The service routine then proceeds to decrement the mid-range counter register and adjust, if necessary, the high-order counter. If the count goes to zero, the handler toggles the LED on Port-B, line 0, and re-initializes the counter variables by calling the onehalfSec procedure described previously. The interrupt handler is coded as follows:
Interrupt Service Routine

Service routine receives control when there the timer register TMR0 overflows, that is, when 256 timer beats have elapsed

IntServ:

First test if source is a Timer0 interrupt

```
btfss INTCON,toif ; TOIF is Timer0 interrupt
go to notTOIF ; Go if not RB0 origin
```

If so clear the timer interrupt flag so that count continues

```
bcf INTCON,toif ; Clear interrupt flag
```

Save context

```
movwf old_w ; Save w register
swapf STATUS,w ; STATUS to w
movwf old_status ; Save STATUS
```

Interrupt action

Subtract 256 from beat counter by decrementing the mid-order byte

```
decfsz countM,f
goto exitISR ; Continue if mid-byte not zero
```

At this point the mid-order byte has overflowed.

High-order byte must be decremented.

```
decfsz countH,f
goto exitISR
```

At this point count has expired so the programmed time has elapsed. Service routine turns the LED on line 0, Port-B on and off at every conclusion of the count.

This is done by XORing a mask with a one-bit at the Port-B line 0 position

```
movlw b’00000001’ ; XORing with a 1-bit produces the complement
xorwf portb,f ; Complement bit 2, Port-B
```

Reset one-half second counter

```
call onehalfSec
```

Exit ISR

```
exitISR:
```

Restore context

```
swapf old_status,w ; Saved status to w
movfw STATUS ; To STATUS register
swapf old_w,f ; Swap file register in itself
swapf old_w,w ; re-swap back to w
```

Return from interrupt
One of the initial operations of the service routine is to clear the TOIF bit in the INTCON register. This action re-enables the timer interrupt and prevents counting cycles to be lost. Since the interrupt is generated every 256 beats of the timer, there is no risk that by enabling the timer interrupt flag a re-entrant interrupt will take place.

The interrupt-based timer program named LapseTmrInt can be tested on the same circuit shown in Figure 12-3.

### 12.4 The Watchdog Timer

The 16F84 contains an independent timer with its own clock source called the Watchdog Timer, or WDT. The Watchdog Timer provides a way for the processor to recover from a software error that impedes program continuation, such as an endless loop. The Watchdog Timer is not designed to recover from hardware faults, such as a brown-out.

The Watchdog Timer hardware is independent of the PIC’s internal clock. Its time-out period lasts approximately 18ms to 2.3s, depending on whether the prescaler is used and on its setting. It is not very accurate due to its sensitivity to temperature. According to Microchip’s documentation, under worst-case conditions, its time-out period can take up to several seconds. The following program elements relate to Watchdog Timer operation:

1. Configuration bit 2, labeled WDTE, enables and disables the Watchdog Timer during system configuration. The WDT cannot be set or reset at runtime. It is enabled and disabled during programming.
2. The PSA bit in the OPTION register selects whether the prescaler is assigned to the Watchdog Timer or to the Timer0 module.
3. Bits PS2 to PS0 in the OPTION register allow assigning eight rates to the Watchdog Timer, from 1:1 to 1:128.
4. Bit 4 of the STATUS register, named the TO bit, is cleared when a time-out condition occurred that originated in the WDT.
5. The power-down bit (PD) in the STATUS register is set after the execution of the clrwdt instruction.
6. The clrwdt instruction clears the Watchdog Timer. It also clears the prescaler count (if the prescaler is assigned to the Watchdog Timer) and sets STATUS bits TO and PD.

The WDT provides a recovery mechanism for software errors. When the WDT times-out, the TO flag in the STATUS register is cleared and the program counter is reset to 0000 so that the program restarts. Applications can prevent the reset by issuing the clrwdt instruction before the time-out period ends. When clrwdt executes the WDT time-out period restarts.
12.4.1 Watchdog Timer Programming

Not much information is available regarding the details of operation of the Watchdog Timer in the 16F84. Using the WDT in applications is not just a simple matter of restarting the counter with the `clrwdt` instruction. The timer is designed to detect software errors that can hang up a program, but how it detects these errors and which conditions trigger the WDT operation are not clear from the information provided by Microchip. For example, an application that contains a long delay loop may find that the Watchdog Timer forces an untimely break out of the loop. The Watchdog Timer provides a powerful error-recovery mechanism, but its use requires careful consideration of program conditions that could make the timer malfunction.

12.5 Sample Programs

The following programs demonstrate the programming discussed in this chapter.

12.5.1 The Tmr0Counter program

```assembly
; File name: Tmr0Counter.asm
; Date: April 30, 2006
; Author: Julio Sanchez
; Processor: 16F84A
;
; Test program for the Timer0 counter. The program counts
; the number of presses of the pushbutton switch on port
; RA4/TOCKI and displays the count on a seven segment LED.
; Switch is wired active low.
;
; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; * _CP_OFF
; * _PWRT_ON Power-up timer ON/OFF
; _PWRT_OFF
; _WDT_ON Watchdog Timer ON/OFF
; * _WDT_OFF
; _LP_OSC Low power crystal oscillator
; * _XT_OSC External parallel resonator/crystal oscillator
; _HS_OSC High speed crystal resonator (8 to 10 MHz)
; Resonator: Murata Erie CSA8.00M G=8 MHz
; _RC_OSC Resistor/capacitor oscillator
;
; |__________ * indicates set up values
;
; set up and configuration
;=========================
; set up and configuration
;=========================```
processor 16f84A
include p16f84A.inc
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

;=====================================================
; constant definitions
; (per circuit wiring diagram)
;=====================================================
define Pb_sw 4 ; Port-A line 4 to push button switch

;=================================
; local variables
;=================================
cblock 0x0c ; Start of block
J ; counter J
K ; counter K
dnc

;=================================
; program
;=================================
org 0 ; start at address 0
goto main

;=================================
; Space for interrupt handlers
;=================================
org 0x08

main:
; Clear the timer and the watchdog
clrf TMR0
clrwdt
; Set up the OPTION register bit map
movlw b’10111000’
; 7 6 5 4 3 2 1 0 <= OPTION bits
; 7 6 5 4 3 2 1 0 = 1:2 001 = 1:4
; 010 = 1:8 011 = 1:16
; 100 = 1:32 101 = 1:64
; 110 = 1:128 *111 = 1:256
; 000 = 1:4 001 = 1:8
; *1 = to WDT
; 0 = to Timer0
; 0 = increment on low-to-high
; *1 = increment in high-to-low
; 0 = internal clock
; *1 = RA4/TOCKI bit source
option

Set up ports
    movlw 0x00 ; Set Port-B to output
    tris PORTB
    clrf PORTB ; All Port-B to 0

; Port-A. Five low-order lines set for for input
    movlw B’00011111’ ; w = 00011111 binary
    tris PORTA ; Port-A (lines 0 to 4) to
               ; input

;=================================
; Check value in TMR0 and display
;=================================

    checkTmr0:
    movf TMR0,w ; Timer register to w
    ; Eliminate four high order bits
    andlw b’00001111’ ; Mask off high bits
    ; At this point the w register contains a 4-bit value
    ; in the range 0 to 0xf. Use this value (in w) to
    ; obtain seven-segment display code
    call segment
    movwf PORTB ; Display switch bits
    goto checkTmr0 ; Endless loop

;================================
; routine to returns 7-segment
; codes
;================================

segment:

    addwf PCL,f ; PCL is program counter latch
    retlw 0x3f ; 0 code
    retlw 0x06 ; 1
    retlw 0x5b ; 2
    retlw 0x4f ; 3
    retlw 0x66 ; 4
    retlw 0x6d ; 5
    retlw 0x7d ; 6
    retlw 0x07 ; 7
    retlw 0x7f ; 8
12.5.2 The Timer0 Program

; File: Timer0.ASM
; Date: April 27, 2006
; Author: Julio Sanchez
; Processor: a6F84A
;
; Description:
; Program to demonstrate programming of the 16F84A
; TIMER0 module. Program flashes eight LEDs in sequence
; counting from 0 to 0xff. Timer0 is used to delay
; the count.
;===================================================== switches
;===================================================== variables in PIC RAM
;===================================================== Timers and Counters 263

retnw 0x6f ; 9
retnw 0x77 ; A
retnw 0x7c ; B
retnw 0x39 ; C
retnw 0x5b ; D
retnw 0x79 ; E
retnw 0x71 ; F
retnw 0x7f ; Just in case all on
end

processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF
;===================================================== variables in PIC RAM
;=====================================================
org 0 ; start at address 0
main:
    ; Clear the Watchdog Timer and reset prescaler
    clrwdt
    ; Set up the OPTION register bit map
    movlw b'11010111'
    option
    ; Set up ports
    movlw 0x00 ; Set Port-B to output
    tris PORTB
    clrf PORTB ; All Port-B to 0
    ; Port-A is not used in this program
mloop:
incf PORTB,f ; Add 1 to register value
call TM0delay
goto mloop

;****************************
; delay sub-routine
; uses Timer0
;****************************

TM0delay:
; Initialize the timer register
clrf TMR0 ; Clear SFR for Timer0

; Routine tests the value in the TMR0 register by
; subtracting 0xff from the value in TMR0. The zero flag
; is set if TMR0 = 0xff

    cycle:
    movf TMR0,w ; Timer to w
    ; w has TMR0 register value
    sublw 0xff ; Subtract max value
    ; Zero flag is set if value in TMR0 = 0xff
    btfss STATUS,Z ; Test for zero
    goto cycle ; Repeat

    return

end

12.5.3 The LapseTimer Program

; File: LapseTimer.ASM
; Date: May 1, 2006
; Author: Julio Sanchez
; Processor: 16F84A

; Description:
; Using Timer0 to produce a variable-lapse delay.
; The delay is calculated based on the number of machine
; cycles necessary for the desired wait period. For
; example, a machine running at a 4 Mhz clock rate
; executes 1,000,000 instructions per second. In this
; case a 1/2 second delay requires 500,000 instructions.
; The wait period is passed to the delay routine in three
; program registers which hold the high-, middle-, and
; low-order bytes of the counter.

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; switches
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; _CP_OFF
; _PWRTE_ON Power-up timer ON/OFF
; __PWRTE_OFF
; __WDT_ON Watchdog Timer ON/OFF
; * __WDT_OFF
; __LP_OSC Low power crystal oscillator
; * __XT_OSC External parallel resonator/crystal oscillator
; __HS_OSC High speed crystal resonator (8 to 10 MHz)
; Resonator: Murate Erie CSA8.00MG = 8 MHz
; __RC_OSC Resistor/capacitor oscillator

; * indicates set up values

processor 16f84A
include <p16f84A.inc>
__config __XT_OSC & __WDT_OFF & __PWRTE_ON & __CP_OFF

;==========================================
; variables in PIC RAM
;==========================================
; Local variables
  cblock 0x0d ; Start of block
          ; 3-byte auxiliary counter for delay.
    countH ; High-order byte
    countM ; Medium-order byte
    countL ; Low-order byte
endc

;==========================================
; main program
;==========================================
org 0    ; start at address 0
goto main

;==========================================
; interrupt handler
;==========================================
org 0x04
; goto IntServ
;==========================================
; main program
;==========================================
main:
; Clear the Watchdog Timer and reset prescaler
    clrf TMR0
    clrwdt
; Set up the OPTION register bit map
    movlw b’11101000’
; 7 6 5 4 3 2 1 0 <= OPTION bits
; || || || || || __|__|____ PS2-PS0 (prescaler bits)
; || || || || || Values for Timer0
; | | | | | *000 = 1:2  001 = 1:4
; | | | | | 010 = 1:8  011 = 1:16
; | | | | | 100 = 1:32  101 = 1:64
; | | | | | 110 = 1:128  *111 = 1:256
; | | | | ___________ PSA (prescaler assign)
; | | | | 1 = to WDT
; | | | | *0 = to Timer0
; | | | ____________ TOSE (Timer0 edge select)
; | | | 0 = increment on low-to-high
; | | | *1 = increment in high-to-low
; | | ____________ TOCS (TMR0 clock source)
; | | *0 = internal clock
; | ____________ 1 = RA4/TOCKI bit source
; | ____________ INTEDG (Edge select)
; | *0 = falling edge
; _____________ RBPU (Pullup enable)
; | 0 = enabled
; | *1 = disabled

option
; Set up ports
movlw 0x00 ; Set Port-B to output
tris PORTB
clrf PORTB ; All Port-B to 0
; Port-A is not used in this program
;==========================
display loop
;==========================
mloop:
; Turn on LED
bsf PORTB,0
; Initialize counters and delay
call onehalfSec
call TM0delay
; Turn off LED
bcf PORTB,0
; Re-initialize counter and delay
call onehalfSec
call TM0delay
goto mloop
;=================================
; variable-lapse delay procedure
; using Timer0
;=================================
; ON ENTRY:
; Variables countL, countM, and countH hold
; the low-, middle-, and high-order bytes
; of the delay period, in timer units
; Routine logic:
The prescaler is assigned to Timer0 and set up so that the timer runs at 1:2 rate. This means that every time the counter reaches 128 (0x80) a total of 256 machine cycles have elapsed. The value 0x80 is detected by testing bit 7 of the counter register.

Note:

The Timer0 register provides the low-order level of the count. Since the counter counts up from zero, in order to ensure that the initial low-level delay count is correct the value 128 - (xx/2) must be calculated where xx is the value in the original countL register.

First calculate xx/2 by bit shifting

```
TM0delay:
    bcf STATUS,C ; Clear carry flag
    rrf countL,f ; Divide by 2
    ; now subtract 128 - (xx/2)
    movf countL,w ; w holds low-order byte
    sublw d'128'
    ; Now w has adjusted result. Store in TMR0
    movwf TMR0
    ; Routine tests timer overflow by testing bit 7 of the TMR0 register.
    cycle:
    btfss TMR0,7 ; Is bit 7 set?
    goto cycle ; Wait if not set
    ; At this point TMR0 bit 7 is set
    ; Clear the bit
    bcf TMR0,7 ; All other bits are preserved
    ; Subtract 256 from beat counter by decrementing the mid-order byte
    decfsz countM,f
    goto cycle ; Continue if mid-byte not zero
    ; At this point the mid-order byte has overflowed.
    ; High-order byte must be decremented.
    decfsz countH,f
    goto cycle
    ; At this point the time cycle has elapsed
    return
```

Procedure to initialize local variables for one-half second delay

```
; set register variables for one-half second delay
```

Procedure to initialize local variables for a delay of one-half second on a 16F84 at 4 Mhz. Timer is set up for 500,000 clock beats as follows: 500,000 = 0x07 0xa1 0x20
12.5.4 The LapseTmrInt Program

; File: LapseTmrInt.ASM
; Date: May 1, 2006
; Author: Julio Sanchez
; Processor: 16F84A
;
; Description:
; Interrupt-driven version of the LapseTimer program.
; Using Timer0 to produce a variable-lapse delay.
; The delay is calculated based on the number of machine
; cycles necessary for the desired wait period. For
; example, a machine running at a 4 Mhz clock rate
; executes 1,000,000 instructions per second. In this
; case a 1/2 second delay requires 500,000 instructions.
; The wait period is passed to the delay routine in three
; register variables which hold the high-, middle-, and
; low-order bytes of the counter.
;===========================
; switches
;===========================
; Switches used in __config directive:
;  _CP_ON      Code protection ON/OFF
;  _CP_OFF
;  _PWRT_ON    Power-up timer ON/OFF
;  _PWRT_OFF
;  _WDT_ON     Watchdog Timer ON/OFF
;  _WDT_OFF
;  _LP_OSC     Low power crystal oscillator
;  _XT_OSC     External parallel resonator/crystal oscillator
;  _HS_OSC     High speed crystal resonator (8 to 10 MHz)

; 500,000 = 0x07 0xa1 0x20
;        ___ ___ ___
;        | | |___ countL)
;        | |________ countM
;        |_____________ countH
onehalfSec:
    movlw 0x07
    movwf countH
    movlw 0xa1
    movwf countM
    movlw 0x20
    movwf countL
    return
end
processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

;===================================================
; variables in PIC RAM
;===================================================
; Local variables

cblock 0x0d ; Start of block
; 3-byte auxiliary counter for delay.
countH ; High-order byte
countM ; Medium-order byte
countL ; Low-order byte
och_w ; Context saving
old_STATUS ; Idem

;===================================================
; main program
;===================================================
org 0 ; start at address 0
goto main

; interrupt handler
;================================================================================
org 0x04
goto IntServ
;==============================================================================
; main program
;==============================================================================
main:
; Clear the Watchdog Timer and reset prescaler
clr TMR0
clrwdt
; Set up the OPTION register bit map
movlw b’11011000’
; 7 6 5 4 3 2 1 0 <= OPTION bits
; | | | | | | | __|__|______ PS2-PS0 (prescaler bits)
; | | | | | | | Values for Timer0
; | | | | | | | 000 = 1:2 001 = 1:4
; | | | | | | | 010 = 1:8 011 = 1:16
; | | | | | | | 100 = 1:32 101 = 1:64
; | | | | | | | 110 = 1:128 *111 = 1:256
; | | | | | |___________ PSA (prescaler assign)
; | | | | | | 1 = to WDT
; | | | | | | 0 = to Timer0
; | | | | | |___________ TOSE (Timer0 edge select)
; | | | | | | 0 = increment on low-to-high
; | | | | | | 1 = increment in high-to-low
; | | | | | |___________ TOCS (TMR0 clock source)
; | | | | | | 0 = internal clock
; | | | | | | 1 = RA4/TOCKI bit source
; | | | | | |___________ INTEDG (Edge select)
; | | | | | | 0 = falling edge
; | | | | | | 1 = enabled
; | | | | | | 1 = disabled

; Set up ports
movlw 0x00 ; Set Port-B to output
tris PORTB
clrf PORTB ; All Port-B to 0

; Port-A is not used in this program
;================================================================================
; set up interrupts
;================================================================================
; Clear external interrupt flag (INTF = bit 1)
bcf INTCON,INTF ; Clear flag
; Enable global interrupts (GIE = bit 7)
bsf INTCON,GIE ; Enable global int (bit 7)
bsf INTCON,T0IE ; Enable TMR0 overflow ; interrupt

; Init count
call onehalfSec
;================================================================================
; do-nothing loop
;================================================================================
; All work is performed by the interrupt handler
mloop:
goto mloop
;================================================================================
; set register variables for
; one-half second delay
;================================================================================
; Procedure to initialize local variables for a
delay of one-half second on a 16F84 at 4 Mhz.
; Timer is set up for 500,000 clock beats as
; follows: 500,000 = 0x07 0xa1 0x20
; 500,000 = 0x07 0xa1 0x20
;
onehalfSec:
    movlw 0x07
    movwf countH
    movlw 0xa1
    movwf countM
    movlw 0x20
    movwf countL

; The Timer0 register provides the low-order level
; of the count. Since the counter counts up from zero,
; in order to ensure that the initial low-level delay
; count is correct the value 256 - xx must be calculated
; where xx is the value in the original countL register.
    movf countL,w ; w holds low-order byte
    sublw d'255'
; Now w has adjusted result. Store in TMR0
    movwf TMR0
    return

;==================================================================
; Interrupt Service Routine
;==================================================================
; Service routine receives control when the timer
; register TMR0 overflows, that is, when 256 timer beats
; have elapsed
IntServ:
; First test if source is a Timer0 interrupt
    btfss INTCON,T0IF ; T0IF is Timer0 interrupt
    goto notTOIF ; Go if not RB0 origin
; If so clear the timer interrupt flag so that count continues
    bcf INTCON,T0IF ; Clear interrupt flag
; Save context
    movwf old_w ; Save w register
    swapf STATUS,w ; STATUS to w
    movwf old_STATUS ; Save STATUS

;======================================
; interrupt action
;======================================
; Subtract 256 from beat counter by decrementing the
; mid-order byte
    decfsz countM,f
    goto exitISR ; Continue if mid-byte not
zero
; At this point the mid-order byte has overflowed.
; High-order byte must be decremented.
    decfsz countH,f
    goto exitISR
At this point count has expired so the programmed time has elapsed. Service routine turns the LED on line 0, Port-B on and off at every conclusion of the count. This is done by xoring a mask with a one-bit at the Port-B line 0 position.

```assembly
movlw b'00000001' ; Xoring with a 1-bit produces the complement
xorwf PORTB,f ; Complement bit 2, Port-B
movlw b'00000001' ; Xoring with a 1-bit produces the complement
xorwf PORTB,f ; Complement bit 2, Port-B
```

Reset one-half second counter

```assembly
call onehalfSec
```

Exit ISR

```assembly
exitISR:
```

Restore context

```assembly
notTOIF:
```

Reset interrupt

```assembly
end
```
This chapter is about programming liquid crystal displays and interfacing the LCD with the PIC 16f84 microcontroller. LCDs are one of the most used devices for alphanumeric output in microcontroller-based circuits. Their advantages are their reduced size and cost and the convenience of mounting the LCD directly on the circuit board.

LCDs are classified according to their interface into serial and parallel. Serial LCDs require less I/O resources but execute slower than their parallel counterparts. In addition, they are considerably more expensive. In this chapter we discuss parallel-driven LCD devices based on the Hitachi HD44780 character-based controller, which is by far the most popular controller for PIC-driven LCDs. Serial interface with LCD devices is discussed in Chapter 13.

13.0 LCD Features and Architecture

The HD44780 is a dot-matrix liquid crystal display controller and driver. The device displays ASCII alphanumeric characters, Japanese kana characters, and some symbols. A single HD44780 can display up to two 28-character lines. An available extension diver makes possible addressing up to 80 characters.

The HD44780U contains a 9,920 bit character-generator ROM that produces a total of 240 characters: 208 characters with a 5 × 8 dot resolution and 32 characters at a 5 × 10 dot resolution. The device is capable of storing 64 x 8-bit character data in its character generator RAM. This corresponds to eight custom characters in 5 x 8-dot resolution or four characters in 5 x 10-dot resolution.

The controller is programmable to three different dy cycles: 1/8 for one line of 5 × 8 dots with cursor, 1/11 for one line of 5 × 10 dots with cursor, and 1/16 for two lines of 5 × 8 dots with cursor. The built-in commands include clearing the display, homing the cursor, turning the display on and off, turning the cursor on and off, setting display characters to blink, shifting the cursor and the display left-to-right or right-to-left, and reading and writing data to the character generator and to display data ROM.
13.0.1 LCD Functions and Components

The following hardware elements form part of the HD44780 controller: two internal registers labeled the data register and the instruction register, a busy flag, an address counter, a RAM area of display data (DDRAM), a character generator ROM, a character generator RAM, a timing generation circuit, a liquid crystal display driver circuit, and a cursor and blink control circuit. The controller itself is often referred to as the MPU in the Hitachi literature.

**Internal Registers**

The HD44780 contains an IR (*instruction register*) and a DR (*data register*). The IR is used to store instruction codes, such as those to clear the display, define an address, or store a bit-map in character generator RAM. The IR is written only from the controller.

The *data register*, DR, is used to temporarily store data to be written into DDRAM or CGRAM as well as temporarily store data read from DDRAM or CGRAM. Data placed in the data register is automatically written into DDRAM or CGRAM by an internal operation.

**Busy Flag**

When BF (the busy flag) is 1, the HD44780U is in the internal operation mode, and the next instruction not accepted. The busy flag is mapped to data bit 7. Software must ensure that the busy flag is reset (BF = 0) before the next instruction is entered.

**Address Counter**

AC (the address counter) stores the current address used in operations that access DDRAM or CGRAM. When an instruction contains address information, the address is stored in the address counter. The RAM area accessed—DDRAM or CGRAM—is also determined by the instruction that stores the address in the AC.

The AC is automatically incremented or decremented after each instruction that writes or reads DDRAM or CGRAM data. The variations and options in operations that change the AC are described later in this chapter.

**Display Data RAM (DDRAM)**

DDRAM (the display data RAM area) is used to store the 8-bit bitmaps that represent the display characters and graphics. Display data is represented in 8-bit character codes. When equipped with the extension, its capacity is 80 x 8 bits, or 80 characters. The area not used for storing display character can be used by software for storing any other 8-bit data. The mapping of DDRAM locations to the LCD display is discussed in Section 13.1.4.

**Character Generator ROM (CGROM)**

The character generator is a ROM that has the bitmaps for 208 characters in 5 x 8 dot resolution or 32 characters in 5 x 10 dot resolution. Figure 13-1 shows the standard character set in the HD44780.
With a few exceptions, the characters in the range 0x20 to 0x7f correspond to those of the ASCII character set. The remaining characters are Japanese kana characters and special symbols. The characters in the range 0x0 to 0x1f, ASCII control characters, do not function as such in the HD44780. Sending a backspace (0x08), a bell (0x07), or a carriage return (0x0d) code to the controller has no effect.

**Character Generator RAM (CGRAM)**

CGRAM (the character generator RAM) allows the creation of customized characters by defining the corresponding 5 x 8 bitmaps. Eight custom characters can be stored in the 5 x 8 dot resolution and four in the 5 x 10 resolution. The creation and use of custom characters is addressed later in this chapter.

**Timing Generation Circuit**

This circuit produces the timing signals for the operation of internal components circuits such as DDRAM, CGROM, and CGRAM. The timing generation circuit is not accessible to the program.
**Liquid Crystal Display Driver Circuit**

The liquid crystal display driver circuit consists of 16 common signal drivers and 40 segment signal drivers. The circuit responds to the number of lines and the character font selected. Once this is done, the circuit performs automatically and is not otherwise accessible to the program.

**Cursor/Blink Control Circuit**

The cursor and blink control circuit generates both the cursor and the character blinking. The cursor or the character blinking is applied to the character located in the data RAM address referenced in the address counter (AC).

**13.0.2 Connectivity and Pin-Out**

LCDs are powerful yet complex devices. Fortunately, the programmer does not have to deal with all the complexities of LCD displays since these devices are usually furnished in a module that includes the LCD controller. Furthermore, most LCDs used in microcontroller circuits are equipped with the same controller, the Hitachi HD44780. This controller provides a relatively simple interface between a microcontroller and the LCD.

But the fact that the HD44780 has become almost ubiquitous in LCD controller technology does not mean that these devices are without complications. The first difficulty confronted by the circuit designer is selecting the most appropriate LCD for the application among dozens (perhaps hundreds) of available configurations, each one with its own resolution, interface technology, size, graphics options, pin patterns, and other individual features. In this sense, it may be better to experiment with a simple LCD in a breadboard circuit before attempting a final circuit with hardware.

Two common connectors used with the 44780-based LCDs have either 14 pins in a single row, each pin spaced 0.100" apart, or two rows of eight pins each, also spaced 0.100" apart. In both cases, the pins are labeled in the LCD board. The two common connectors are shown in Figure 13-2.

![Figure 13-2 Typical HD44780 Connector Pin-Outs](image-url)
In LCDs with a backlight option sometimes the connectors have two extra pins, usually numbered 15 and 16. Pin number 15 is connected to a 5V source for the backlight and pin number 16 to ground. Typical LCD wiring is shown in Table 13.1.

Table 13.1
Hitachi HD44780 LCD Controller Pin-Out (80 characters or less)

<table>
<thead>
<tr>
<th>PIN NUMBER</th>
<th>SYMBOL</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vss</td>
<td>Ground</td>
</tr>
<tr>
<td>2</td>
<td>Vcc</td>
<td>Vcc (Power supply +5V)</td>
</tr>
<tr>
<td>3</td>
<td>Vee</td>
<td>Contrast control</td>
</tr>
<tr>
<td>4</td>
<td>RS</td>
<td>Set/reset</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 = instruction input</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 = data input</td>
</tr>
<tr>
<td>5</td>
<td>R/W</td>
<td>R/W (read/write select)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 = write to LCD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 = read LCD data</td>
</tr>
<tr>
<td>6</td>
<td>E</td>
<td>Enable. Clock signal to initiate data transfer</td>
</tr>
<tr>
<td>7</td>
<td>DB0</td>
<td>Data bus line 0</td>
</tr>
<tr>
<td>8</td>
<td>DB1</td>
<td>Data bus line 1</td>
</tr>
<tr>
<td>9</td>
<td>DB2</td>
<td>Data bus line 2</td>
</tr>
<tr>
<td>10</td>
<td>DB3</td>
<td>Data bus line 3</td>
</tr>
<tr>
<td>11</td>
<td>DB4</td>
<td>Data bus line 4</td>
</tr>
<tr>
<td>12</td>
<td>DB5</td>
<td>Data bus line 5</td>
</tr>
<tr>
<td>13</td>
<td>DB6</td>
<td>Data bus line 6</td>
</tr>
<tr>
<td>14</td>
<td>DB7</td>
<td>Data bus line 7</td>
</tr>
</tbody>
</table>

The pin-out in Table 13.1 refers to controllers that address no more than 80 characters. In addition, some LCDs with LED backlighting contain two additional pins, usually numbered 15 and 16. In these cases, pin number 15 is a +5 VDC source for the backlight and pin 16 is the backlight ground.

From the pin-out in Table 13.1, it is evident that the interface to the LCD uses eight parallel lines (lines 7 to 14). However, it is also possible to drive the LCD using just four lines, saving connections on limited circuits.

The reader should beware that LCDs are often furnished in custom boards that may or may not have other auxiliary components. These boards are often wired differently from the examples shown in Figure 13-2. In all cases, the device’s documentation and the corresponding data sheets should provide the appropriate wiring information.

13.1 Interfacing with the HD44780

The Hitachi 44780 controller allows parallel interfacing using 4- or 8-bit data paths. In the 4-bit mode, each data byte must be divided into a high-order and a low-order nibble and are transmitted sequentially, the high-nibble first. In the 8-bit parallel mode, each data byte is transmitted from the PIC to the controller as a unit. The advantage of using the 4-bit mode is greater economy of I/O lines on the PIC side. The disadvantages are slightly more complicated programming and minimally slower execution speed. Our first example and circuit uses the 8-bit data mode so as to avoid complications. Once
the main processing routines are developed, make the necessary modifications so as to make possible the 4-bit data mode.

In addition to the data transmission mode, there are other circuit options to be considered. Two control lines between the microcontroller and the HD44780-driven LCD are necessary in all cases: one to the RS line to select between data and instruction input modes, and another one to the E line to provide the pulse that initiates the data transfer. The R/W control line, which selects between the read and the write mode of the LCD controller, can be connected or grounded. If the R/W line is not connected to a microcontroller port, then the HD44780 operates only in the write data mode and all read operations are unavailable.

13.1.1 Busy Flag or Timed Delay Options

Since many applications do not read text data from controller memory, the write-only mode is often an attractive option, especially considering that microcontroller I/O ports are often in short supply and that this option saves one port for other duties. However, there is a less apparent drawback to not being able to read LCD data, which is that the application is not able to monitor the busy flag. This flag, which indicates that the controller has concluded its operation, is mapped to bit 7. Since testing the BF requires reading this bit, not connecting the R/W line has the effect that applications cannot use the busy flag and must rely on timing routines to ensure that each operation completes before the next one begins. The timing requirements for each instruction are listed in the rightmost column in Table 13.3. The subjects of timing and delay routines are discussed in detail later in this chapter.

For the circuit designer, to read or not to read controller data is a decision with several tradeoffs. Using time delay routines to ensure that each controller operation has concluded is a viable option that saves one interface line. On the other hand, code that relies on timing routines is externally dependent on the clocks and timer hardware. If code that relies on timing routines is ported to another circuit with a different microcontroller, clocks, or timer hardware, the delays may change and the routines could fail. Furthermore, the use of delay routines often is not efficient, since controller operations can terminate before the timed delay has expired.

On the other hand, code that reads the busy flag to determine the termination of a controller operation is not without dangers. If the controller or the circuit fails, then the program can hang up in an endless loop, waiting for the busy flag to clear. To be absolutely safe, the code would have to contain an external wait loop when testing the busy flag, so that if the external loop expires, then the processing can assume that there is a hardware problem and break out of the flag test loop. The programmer must decide whether this safety mechanism for reading the busy flag is necessary since its implementation requires a somewhat complicated exception response.

In the code samples developed in this chapter, we implement both ways of ensuring operation completion. The code also furnishes a software switch that allows selecting the preferred option.
13.1.2 Contrast Control

In addition to the control lines that require processor interface, the HD44780 contains other control lines. One such line is used for the LCD contrast. The *contrast control line* (usually labeled *Vee*) is connected to pin number 3 (see Table 13.1). The actual implementation of the contrast control function varies according to the manufacturer. In general, for an LCD with a normal temperature range, the contrast control line is wired as shown in Figure 13-3.

![Figure 13-3 Typical Contrast Adjustment Circuit](image)

13.1.3 Display Backlight

Some LCDs are equipped with a LED backlight so as to make the displayed characters more visible. In different LCDs, backlight is implemented in different ways. Some manufacturers wire the backlight directly to the LCD power supply, while others provide additional pins that allow turning the backlight on or off independently of the LCD display. Backlit displays with 14 pins belong to the first type, while those with 16 pins have independent backlight control. If the backlight pins are adjacent to the other display pins, then they are numbered 15 and 16. In this case pin number 15 is wired, through a current limiting resistor, to the +5V source and pin 16 to ground. Sometimes the current-limiting resistor is built into the display. This information is available in the device’s data sheet.

Note that some 4-line displays use pins 15 and 16 for other purposes. In these systems, backlight control, if available, is provided by separate pins.

13.1.4 Display Memory Mapping

The Hitachi HD44780 is a memory-mapped system in which characters are displayed by storing their ASCII codes in the corresponding memory address associated with each digit-display area. The area of controller RAM mapped to character-display memory has a capacity of 80 characters. This area is known as *display data RAM* or *DDRAM*. 
In order to save circuitry, the common lines of the controller outputs to the liquid crystal display hardware are multiplexed. In this context, the duty ratio of a system is the number of multiplexed common lines. The most common duty ratio is 1/16, although 1/8 and 1/11 are found in some systems. Since the duty ratio measures the number of multiplexed lines, it also determines the display mapping. For example, in a single-line-by-16 character display with a 1/16 duty ratio the first eight characters are mapped to one set of consecutive memory addresses and the second eight characters to another set of addresses. The reason is that in every display line, sixteen common access lines are multiplexed, instead of eight. By the same token, a two-line-by-sixteen character display with a 1/16 duty ratio requires 16 common lines. In this case, the address of the second lines is not a continuation of the address of the first line, but is in another address set not contiguous to the first one.

For example, in a typical two-line-by-sixteen character display, the addresses of the 16 characters in the first line are from 0x00 to 0x0F, while the addresses of the characters in the second line are from 0x40 to 0x4F. Since there are 80 memory locations in the controller’s DDRAM, each line contains storage for a total of 40 characters. The range of the entire first line is from 0x00 to 0x27 (40 characters total) but of these, only 16 are actually displayed. The same applies to the second line of 16 characters. In this case, the storage area is in the range 0x28 to 0x4f, but only 16 characters are displayed. In the single-line-by-sixteen character display mentioned first the addresses of the first eight characters would be a set from 0x00 to 0x07 and the addresses of the second eight characters in the line are from 0x40 to 0x47. Table 13.2 lists the memory address mapping of some common LCD configurations.

Table 13.2
7-bit DDRAM Address Mapping for Common LCDs

<table>
<thead>
<tr>
<th>CHARACTERS/LINE</th>
<th>LINE NUMBER</th>
<th>CHARACTER NUMBER</th>
<th>FIRST IN GROUP</th>
<th>NEXT IN GROUP</th>
<th>LAST IN GROUP</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/1</td>
<td>1</td>
<td>1</td>
<td>0x00</td>
<td>0x01</td>
<td>0x07</td>
</tr>
<tr>
<td>8/2</td>
<td>1</td>
<td>1</td>
<td>0x00</td>
<td>0x01</td>
<td>0x07</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>0x40</td>
<td>0x41</td>
<td>0x47</td>
</tr>
<tr>
<td>16/1</td>
<td>1</td>
<td>1</td>
<td>0x00</td>
<td>0x01</td>
<td>0x07</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>9</td>
<td>0x40</td>
<td>0x41</td>
<td>0x47</td>
</tr>
<tr>
<td>16/2</td>
<td>1</td>
<td>1</td>
<td>0x00</td>
<td>0x01</td>
<td>0x0f</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>0x40</td>
<td>0x41</td>
<td>0x4f</td>
</tr>
<tr>
<td>20/2</td>
<td>1</td>
<td>1</td>
<td>0x00</td>
<td>0x01</td>
<td>0x13</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>0x40</td>
<td>0x41</td>
<td>0x53</td>
</tr>
<tr>
<td>24/2</td>
<td>1</td>
<td>1</td>
<td>0x00</td>
<td>0x01</td>
<td>0x17</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>0x40</td>
<td>0x41</td>
<td>0x57</td>
</tr>
<tr>
<td>16/4</td>
<td>1</td>
<td>1</td>
<td>0x00</td>
<td>0x01</td>
<td>0x0f</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>0x40</td>
<td>0x41</td>
<td>0x4f</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1</td>
<td>0x10</td>
<td>0x11</td>
<td>0x1f</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1</td>
<td>0x50</td>
<td>0x51</td>
<td>0x5f</td>
</tr>
<tr>
<td>20/4</td>
<td>1</td>
<td>1</td>
<td>0x00</td>
<td>0x01</td>
<td>0x13</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>0x40</td>
<td>0x41</td>
<td>0x53</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1</td>
<td>0x14</td>
<td>0x15</td>
<td>0x27</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1</td>
<td>0x54</td>
<td>0x55</td>
<td>0x67</td>
</tr>
</tbody>
</table>
Note that systems that exceed a total of 80 characters require two or more HD44780 controllers. Although the information provided in Table 13.3 corresponds to the mapping in most LCDs, it is a good idea to consult the data sheet of the specific hardware in order to corroborate the address mapping in a particular device.

Table 13.3 contains the seven low-order bits of DDRAM addresses. HD44780 commands to set the DDRAM address for read or write operations require that the high-order bit (bit number 7) be set. Therefore, to write to DDRAM memory address 0x07, code uses the value 0x87, and to write to DDRAM address 0x43, code uses 0xc3 as the instruction operand.

13.2 HD44780 Instruction Set

The HD44780 instruction set includes operators to initialize the system and set operational modes, clear the display, manipulate the cursor, set, reset, and control automatic display address shift, set and reset the interface parameters, poll the busy flag, read and write to CGRAM and DDRAM memory.

13.2.1 Instruction Set Overview

Pin number 4 in Table 13.1 selects two modes of operation on the HD44780 controller: instruction and data input. When the instruction mode is enabled (RS pin is set low) the controller receives commands that set up the hardware and determine its configuration and mode of operation. These commands are part of the HD44780 instruction set shown in Table 13.3.

Table 13.3

<table>
<thead>
<tr>
<th>Instruction</th>
<th>RS</th>
<th>R/W</th>
<th>B7</th>
<th>B6</th>
<th>B5</th>
<th>B4</th>
<th>B3</th>
<th>B2</th>
<th>B1</th>
<th>B0</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Display</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1.64</td>
</tr>
<tr>
<td>Return home</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1.64</td>
</tr>
<tr>
<td>Entry mode set</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>I/D</td>
<td>S</td>
</tr>
<tr>
<td>Display/Cursor ON/OFF</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>D</td>
<td>C</td>
<td>37</td>
</tr>
<tr>
<td>Cursor/display shift</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>S/C</td>
<td>R/L</td>
<td>#</td>
<td>#</td>
<td>37</td>
</tr>
<tr>
<td>Function set</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>DL</td>
<td>N</td>
<td>F</td>
<td>#</td>
<td>#</td>
<td>37</td>
</tr>
<tr>
<td>Set CGRAM address</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>------------</td>
<td>address</td>
<td>37</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set DDRAM address</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>------------</td>
<td>address</td>
<td>37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Read busy flag and Address register</td>
<td>0</td>
<td>1</td>
<td>BF</td>
<td>------------</td>
<td>address</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Write data</td>
<td>1</td>
<td>0</td>
<td>------------</td>
<td>data</td>
<td>37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Read data</td>
<td>0</td>
<td>1</td>
<td>------------</td>
<td>data</td>
<td>37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Bits labeled # have no effect.

Clearing the Display

Clearing the display clears the display with blanks by writing the code 0x20 into all DDRAM addresses. It also returns the cursor to the home position (top-left display corner) and sets address 0 in the DDRAM address counter. After this command executes, the display disappears and the cursor goes to the left edge of the display.
Return home

Return home returns the cursor to home position at the upper left position of the first character line. It sets DDRAM address 0 in the address counter and sets the display to its default status if it was shifted. DDRAM contents remain unchanged.

Entry mode set

Entry mode set sets the direction of cursor movement and the display shift mode. If B1 (I/D) bit is set, cursor handling is set to the increment mode, that is, left-to-right. If this bit is clear, then cursor movement is set to the decrement mode, that is, right-to-left.

If B0 (S) bit is set, display shift is enabled. In the display shift mode, it appears as if the display moves instead of the cursor; otherwise display shift is disabled. Operations that read or write to CGRAM and operations that read DDRAM do not shift the display.

Display and Cursor ON/OFF

If B2 (D) bit is set, display is turned on. Otherwise, it is turned off. When the display is turned off data in DDRAM is not changed.

If B1 (C) bit is set, the cursor is turned on. Otherwise, it is turned off. Operations that change the current address in the DDRAM Address register, like those to automatically increment or decrement the address, are not affected by turning off the cursor. The cursor is displayed at the eighth line in the 5 x 8 character matrix.

If B0 (B) bit is set, the character at the current cursor position blinks. Otherwise, the character does not blink. Note that character blinking and cursor are independent operations and that both can be set to work simultaneously.

Cursor/display shift

Cursor/display shift moves the cursor or shifts the display according to the selected mode. The operation does not change the DDRAM content. Since the cursor position always coincides with the value in the Address register, the instruction provides software with a mechanism for making DDRAM corrections or to retrieve display data at specific DDRAM locations. Table 13.4 lists the four available options:

Table 13.4

<table>
<thead>
<tr>
<th>S/C</th>
<th>BITS</th>
<th>R/L</th>
<th>OPERATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Cursor position is shifted left. Address counter is decremented by one.</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td></td>
<td>Cursor position is shifted right. Address counter is incremented by one.</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td></td>
<td>Cursor and display are shifted left.</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td></td>
<td>Cursor and display are shifted right.</td>
</tr>
</tbody>
</table>
Function set

Function set sets the parallel interface data length, the number of display lines, and the character font. If B4 (DL) bit is set, then the interface is set to eight bits. Otherwise it is set to four bits. If B3 (N) bit is zero, the display is initialized for 1/8 or 1/11 duty cycle. When the N bit is set, the display is set to 1/16 duty cycle. Displays with multiple lines typically use the 1/16 duty cycle. The 1/16 duty cycle on a one-line display appears as if it were a two-line display, that is, the line consists of two separate address groups (see Table 13.2).

If B2 (F) bit is set then the display resolution is 5 x 10 pixels. Otherwise the resolution is 5 x 8 pixels. This bit is not significant when the 1/16 duty cycle is selected; that is, when the N bit is set.

The function set instruction should be issued during controller initialization. No other instruction can be executed before this one, except for changing the interface data length.

Set CGRAM address

Set CGRAM address sets the CGRAM (character generator RAM) address to which data is sent or received after this operation. The CGRAM address is a six-bit field in the range 0 to 64 decimal. Once a value is entered in the CGRAM Address register, data can be read or written from CGRAM.

Set DDRAM address

Set DDRAM address sets the DDRAM (display data RAM) address to which data is sent or received after this operation. The DDRAM address is a seven-bit field in the range 0 to 127 decimal. Once a value is entered in the DDRAM Address register, data can be read or written from CGRAM. DDRAM address mapping is discussed in Section 13.1.4.

Read busy flag and Address register

Read busy flag and Address register reads the busy flag to determine if an internal operation is in progress and reads the address counter content. The value in the Address register is reported in bits 0 to 6. Bit 7 (BF) is the busy flag bit. This bit is read only. The address counter is incremented or decremented by 1 (according to the mode set) after the execution of a data write or read instruction.

Write data

Write data writes eight data bits to CGRAM or DDRAM. Before data is written to either controller RAM area, software must first issue a set DDRAM address or set CGRAM address instruction (described previously). These two instructions not only set the next valid address in the Address register, but also select either CGRAM or DDRAM for writing operations. What other actions take place as data is written to the controller depends on the settings selected by the entry mode set instruction. If the direction of cursor movement or data shift is in the increment mode, then the data write operation adds one to the value in the Address register. If the cursor movement is enabled, then the cursor is moved accordingly after data write takes place. If the display shift mode is active, then the displayed characters are shifted either right or left.
**Read data**

Read data reads eight data bits to CGRAM or DDRAM. Before data is read from either controller RAM area, software must first issue a set DDRAM address or set CGRAM address instruction. These instructions not only set the next valid address in the Address register, but also select either CGRAM or DDRAM for writing operations. Failing to set the corresponding RAM area results in reading invalid data.

What other actions take place as data is read from the controller RAM depends on the settings selected by the entry mode set instruction. If the direction of cursor movement or data shift is in the increment mode, then the data read operation adds one to the value in the Address register. However, display is no shifted by a read operation even if the display shift is active.

The cursor shift instruction has the effect of changing the content of the Address register. So if a cursor shift precedes a data read instruction, there is not need to reset the address by means of an address set command.

### 13.2.2 A 16F84 8-bit Data Mode Circuit

The first circuit presented in this chapter is experimental. Its purpose is to exercises LCD display functions in the simplest forms. Therefore, the circuit uses 8-bit parallel data transmission interfacing with a 16F84 microcontroller. The circuit is shown in Figure 13-4.

**Figure 13-4** 16F84 to LCD 8-bit Mode Circuit
In the circuit of Figure 13-4, three control lines are wired between the microcontroller and the LCD. The line designations are shown inside ovals. The R/W line is not necessary, since it is possible to devise a system that does not read LCD data. In spite of this, the R/W line is not included since it allows reading the busy flag in synchronizing operations. Table 13.5 shows the control and data connections for the circuit in Figure 13-4.

<table>
<thead>
<tr>
<th>PIN</th>
<th>16F84 PORTBIT</th>
<th>LCD PIN</th>
<th>LINE NAME</th>
<th>FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A2</td>
<td>4</td>
<td>RS</td>
<td>Select instruction/ data register</td>
</tr>
<tr>
<td>2</td>
<td>A3</td>
<td>5</td>
<td>R/W</td>
<td>Read/write select</td>
</tr>
<tr>
<td>18</td>
<td>A1</td>
<td>6</td>
<td>E</td>
<td>Enable signal</td>
</tr>
<tr>
<td>13</td>
<td>B7</td>
<td>14</td>
<td>before</td>
<td>Busy flag.</td>
</tr>
<tr>
<td>6-13</td>
<td>B0-B7</td>
<td>7-14</td>
<td>Data</td>
<td>Data lines</td>
</tr>
</tbody>
</table>

13.3 LCD Programming

LCD programming is usually device-specific. Before attempting to write code, the programmer should become familiar with the circuit wiring diagram, the set up parameters, and the specific hardware requirements. It is risky to make assumptions that a specific device conforms exactly to the HD44780 interface since often a style sheet contains specifications that are not in strict conformance with the standard. In addition to the PIC set up and initialization functions, code to display a simple text message on the LCD screen consists of the following display-related functions:

1. Define the required constants, variables, and buffers.
2. Set up and initialize ports used by the LCD.
3. Initialize the LCD to circuit and software specifications.
4. Store text in PIC text buffer.
5. Select DDRAM start address on LCD.
6. Display text by transferring characters in PIC text buffer to LCD DDRAM.

If the LCD display consists of multiple lines, then the previous steps 4, 5, and 6 are repeated for each line. LCD initialization and display operations vary according to whether the interface is 4- or 8-bits and whether the code uses delay loops or busy flag monitoring to synchronize operations. All of these variations are considered in the examples in this chapter.

13.3.1 Defining Constants and Variables

In any program, defining and documenting constants and fixed parameters should be done centrally, rather than hard-coded through the code. Centralizing the elements that are variable under different circumstances makes it possible to adapt code to circuit and hardware changes.
Two common ways are available for defining constants: the C-like \texttt{#define} directive and the \texttt{equ} (equate) directive. In most cases, it is a matter of personal preference which is used, but a general guideline is to use the \texttt{#define} statement to create literal constants; that is, constants that are not associated with program registers or variables. The \texttt{equ} directive is then used to define registers, flags, and local variables.

According to this scheme, an LCD display driver program could use \texttt{#define} statements to create literals that are related to the wiring diagram or the specific LCD values obtained from the data sheet, such as the DDRAM addresses for each display line, as in the following code fragment:

\begin{verbatim}
；=====================================================
； constant definitions
； for PIC-to-LCD pin wiring and LCD line addresses
；=====================================================
#define E_line 1 ;| #define RS_line 2 ;| — from wiring diagram
#define RW_line 3 ;| #define LCD_1 0x80 ; First LCD line constant
#define LCD_2 0xc0 ; Second LCD line constant

；=====================================================
； PIC register equates
；=====================================================
porta equ 0x05
portb equ 0x06
fsr equ 0x04
status equ 0x03
indf equ 0x00
z equ 2
\end{verbatim}

By the same token, the values associated with PIC register addresses and bit flags are defined using \texttt{equ}, as follows:

\begin{verbatim}
；=====================================================
； constant definitions
； for PIC-to-LCD pin wiring and LCD line addresses
；=====================================================
#define E_line 1 ;| #define RS_line 2 ;| — from wiring diagram
#define RW_line 3 ;| #define LCD_1 0x80 ; First LCD line constant
#define LCD_2 0xc0 ; Second LCD line constant

；=====================================================
； PIC register equates
；=====================================================
porta equ 0x05
portb equ 0x06
fsr equ 0x04
status equ 0x03
indf equ 0x00
z equ 2
\end{verbatim}

One advantage of this scheme is that constants are easier to locate, since they are grouped by device. Those for the LCD are in \texttt{#define} directives area and those for the PIC hardware in an area of \texttt{equ} directives.

There are also drawbacks to this approach, since symbols created in \texttt{#define} directive are not available for viewing in the MPLAB debuggers. However, if the use of the \texttt{#define} directive is restricted to literal constants, then their viewing during a debugging session is not essential.

MPLAB also supports the \texttt{constant} directive for creating a constant symbol. Its use is identical to the \texttt{equ} directive but the latter is more commonly found in code.
Using MPLAB Data Directives

Often a program needs to define a block of sequential symbols and assign to each one a corresponding name. In the PIC 16F84, the address space allocated to general purpose registers allocated by the user is of 68 bytes, starting at address 0x0c. One possible way of allocating user-defined registers is to use the equ directive to assign addresses in the PIC SRAM space:

```
Var1 equ 0x0c
Var2 equ 0x0d
Var3 equ 0x0e
Buf1 equ 0x0f ; 10-byte buffer space
Var4 equ 0x19 ; Next variable
```

Although this method is functional, it depends on the programmer calculating the location of each variable in the PIC’s available SRAM space. Alternatively, MPLAB provides a cblock directive that allows defining a group of consecutive sequential symbols while referring only to the address of the first element in the group. If no address is entered in cblock, then the assembler assigns the address. This address is one higher than the final address in the previous cblock. Each cblock ends with the endc directive. The following code fragment showing the use of the cblock directive is from one of the sample programs for this chapter.

```
;=====================================================; variables in PIC RAM;=====================================================
; Reserve 16 bytes for string buffer
 cblock 0x0c
   strData
 endc
; Leave 16 bytes and continue with local variables
 cblock 0x1d ; Start of block
 count1 ; Counter # 1
 count2 ; Counter # 2
 count3 ; Counter # 3
 pic_ad ; Storage for start of text area
          ; (labeled strData) in PIC RAM
 J ; counter J
 K ; counter K
 index ; Index into text table
 endc
```

Note in the preceding code fragment, the allocation for the 16-byte buffer space named strData is ensured by entering the corresponding start address in the second cblock. The PIC microcontrollers do not contain a directive for reserving memory areas inside cblock, although the res directive can be used to reserve memory for individual variables.
13.3.2 LCD Initialization

LCD initialization depends on the specific hardware in use and on the circuit wiring. Information about the specific LCD can be obtained from the device’s data sheet. Sometimes, the data sheet includes examples of initialization values for different conditions and even code listings. The information is usually sufficient to ensure correct initialization.

A word of warning: the popular LCD literature available online often contains initialization “myths” for specific components requiring that a certain mystery code be used for no documented reason, or that a certain function be repeated a given number of times. The programmer should make sure that the code is rational and that every operation is actually required and documented.

Before the LCD initialization commands are used it is necessary to set the communications lines correctly. The E line should be low, the RS line should be low for command, and the R/W line (if connected) should be low for write mode. After the lines are set accordingly, there should be a 125ms delay. Note that at this point, the LCD busy flag is not yet reliable. The following code fragment shows the processing:

```
bcf porta,E_line ; E line low
bcf porta,RS_line ; RS line low for command
bcf porta,RW_line ; Write mode
call delay_125 ; delay 125 microseconds
```

The procedure delay_125 in the previous code fragment is described later in this chapter.

**Function Set Command**

Function set is the first initialization command sent to the LCD. The command determines whether the display font consists of 5x10 or 5x7 pixels. The latter is by far the more common. It determines the duty cycle, which is typically 1/8 or 1/11 for single-line displays and 1/16 for multiple lines. The interface width is also determined in the Function Set command. It is 4-bits or 8-bits. The following code fragment shows the commented code for the Function Set command:

```
;*******************************
; Function Set                
;*******************************
movlw 0x38 ; 00111000 (FUNCTION SET)
            ; | | | |__ font select:
            ; | | | 1 = 5x10 in 1/8 or 1/11
            ; | | | 0 = 1/16 dc
            ; | | |__ Duty cycle select
            ; | | 0 = 1/8 or 1/11
            ; | | 1 = 1/16 (multiple lines)
            ; |__ Interface width
            ; | 0 = 4 bits
            ; | 1 = 8 bits
            ; |__ FUNCTION SET COMMAND
```
movwf portb
call pulseE ; pulse E line to force LCD command

In the preceding code fragment, the LCD is initialized to multiple lines, 5 x 7 font, and 8-bit interface, as in the program LCDTest1 found in the book's online software package.

The procedure named pulseE sets the E line bit off and on to force command recognition by the LCD. The procedure is listed and described later in the chapter.

**Display Off**

Some initialization routines in LCD documentation and data sheets require that the display be turned off following the Function Set command. If so, the Display Off command is executed as follows:

```assembly
;***********************
; Display Off
;***********************
movlw 0x08 ; 00001000 (DISPLAY ON/OFF)
; | | | |___ Blink character at
; | | | | Cursor
; | | | 1 = on, 0 = off
; | | | Cursor on/off
; | | 1 = on, 0 = off
; | ___ Display on/off
; | 1 = on, 0 = off
; |___ COMMAND BIT
```  
movwf portb
call pulseE ; pulse E line to force LCD command

**Display and Cursor On**

Whether or not the display is turned off, it must be turned on first. Also code must select if the cursor is on or off, and whether the character at the cursor position is to blink. The following command sets the cursor and the display on and the character blink off:

```assembly
;***********************
; Display and Cursor On
;***********************
movlw 0x0e ; 00001110 (DISPLAY ON/OFF)
; | | | |___ Blink character at
; | | | | Cursor
; | | | 1 = on, 0 = off
; | | | Cursor on/off
; | | 1 = on, 0 = off
; | ___ Display on/off
; | 1 = on, 0 = off
; |___ COMMAND BIT
```  
movwf portb
call pulseE ; pulse E line to force LCD command
Set Entry Mode

The Entry Mode Command sets the direction of cursor movement or display shift mode. Normally, the display is set to the increment mode when writing in the Western European languages. The Entry Mode command controls display shift. If enabled, the displayed characters appear to scroll. This mode is used to simulate an electronic billboard effect by storing more than one line of characters in DDRAM and then scrolling the characters left-to-right. The following code sets entry mode to increment mode and no shift:

```assembly
movlw 0x06 ; 00000110 (ENTRY MODE SET)
```

Operations that read or write to CGRAM and operations that read DDRAM do not shift the display.

Cursor and Display Shift

These commands determine whether the cursor or the display shift according to the selected mode. Shifting the cursor or the display provides a software mechanism for making DDRAM corrections or for retrieving display data at specific DDRAM locations. The four available options appear in Table 13.4 previously in this chapter. The following instructions set the cursor to shift right and disable display shift:

```assembly
movlw 0x14 ; 00010100 (CURSOR/DISPLAY SHIFT)
```
Clear Display

The final initialization command is usually one to clear the display. It is entered as follows:

```
movlw 0x01 ; 0 0 0 0 0 0 0 0 0 0 0 1 (CLEAR DISPLAY)
            ; ___ COMMAND BIT
movwf portb ; 0 0 0 0 0 0 0 0 0 0 0 1
call pulseE
```

Note that the last command is followed by a 5ms delay. The delay procedure delay_5 is listed and described later in this chapter.

13.3.3 Auxiliary Operations

Several support routines are required for effective text display in LCD devices. These include time delay routines for timed access, a routine to pulse the E line in order to force the LCD to execute a command or to read or write text data, routines to read the busy flag when this is the method used for processor/LCD synchronization, and routines to merge data with port bits so as to preserve the status of port lines not being addressed by code.

Time Delay Routine

There are several ways of producing time delays in PIC microcontroller. The Bibliography lists a title by David Benson devoted almost entirely to timing and counting routines. The present concern is quite simple: to develop a software routine that ensures the time delay that must take place in LCD programming, as shown in Table 13.3.

One mechanism for producing time delays in PIC programming is by means of the TIMER0 module, a built-in 8-bit timer counter. Once enabled, Port-A pin 4, labeled the TOCKI bit and associated with file register 01 (TMR0), is used to time processor operations. In the particular case of LCD timing routines, using the TIMER0 module seems somewhat of an overkill, in addition to the fact that it requires the use of a Port-A line which is often required for other purposes.

Alternatively, timing routines that serve the purpose at hand can be developed using simple delay loops. In this case, no port line is sacrificed and coding is considerably simplified. These routines are generically labeled software timers, in contrast with the hardware timers that depend on the PIC timer/counter device described previously. Software timers provide the necessary delay by means of program loops;
that is, by wasting time. The length of delay provided by the routine depends on the execution time of each instruction and on the number of repeated instructions.

Instructions on the PIC 16F84 consume four clock cycles. If the processor clock is running at 4 MHz, then one fourth of 4 MHz is the execution time for each instruction, which is 1 µs. So if each instructions requires 1 µs, repeating 1000 instructions produces a delay of 1 ms. The following routines provide convenient delays for LCD interfacing:

```
; Procedure to delay 125 microseconds
movlw D'42' ; Repeat 42 machine cycles
movwf count1 ; Store value in counter
repeat:
    decfsz count1,f ; Decrement counter (1 cycle)
    goto repeat ; Continue if not 0 (2 cycles)
return

; Procedure to delay 5 milliseconds
movlw D'41' ; Counter = 41
movwf count2 ; Store in variable
delay:
    call delay_125mics ; Delay 41 microseconds
    decfsz count2,f ; 41 times 125 = 5125 ms.
    goto delay ; or approximately 5 ms
return
```

Actually, the delay loop of the procedure named delay_5ms is not exactly the product of 41 iterations times 125 µs, since the instruction to decrement the counter and the goto to the label delay are also inside the loop. Three instruction cycles must be added to those consumed by the delay_125mics procedure. This results in a total of 41 * 3 or 123 instruction cycles that must be added to the 5,125 consumed by delay_125mics. In fact, there are several other minor delays by the instructions to initialize the counters that are not included in the calculation. In reality, the delay loops required for LCD interfacing need not be exact, as long as they are not shorter than the recommended minimums.

For calculating software delays in the 16F84, the instruction execution time is determined by an external clock either in the form of an oscillator crystal, a resonator, or an RC oscillator furnished in the circuit. The PIC 16F84A is available in various processor speeds, from 4MHz to 20MHz. These speeds describe the maximum ca-
Pulsing the E Line

The LCD hardware does not recognize data as it is placed in the input lines. When the various control and data pins of the LCD are connected to ports in the PIC and data is placed in the port bits, no action takes place in the LCD controller. In order for the controller to respond to commands or to perform read or write operations, it must be activated by pulsating (or strobing) the E line. The pulsing or strobing mechanism requires that the E line be kept low and then raised momentarily. The LCD checks the state of its lines on the raising edge of the E line. Once the command has completed, the E line is brought low again. The following code fragment pulses the E line in the manner described.

```assembly
;========================
; pulse E line
;========================
pulseE
   bsf porta,E_line ; pulse E line
   bcf porta,E_line
   call delay_125mics ; delay 125 microseconds
   return
```

Note that the listed routine includes a 125µs delay following the pulsing operation. This delay is not part of the pulse function but is required by most LCD hardware. Some pulse functions in the popular PIC literature include a no operation opcode (nop) between the commands to set and clear the E line. In most cases this short delay does not hurt, but some LCDs require a minimum time lapse during the pulse and will not function correctly if the nop is inserted in the code.

Reading the Busy Flag

Synchronization between LCD commands and between data access operations is based on time delay loops or on reading the LCD busy flag. The busy flag, which is in the same pin as the bit 7 data line, is read clear when the LCD is ready to receive the next command, read, or write operation and is set if the device is not ready. By reading the state of the busy flag, code can accomplish more effective synchronization than with time delay loops. The sample program named LCDTest2, in the book’s online software package, performs LCD display using the busy flag method. The following procedure shows busy flag synchronization:

```assembly
;========================
; busy flag test routine
;========================
; Procedure to test the HD44780 busy flag
; Execution returns when flag is clear
busyTest:
   movlw b'11111111' ; All lines to input
   tris portb       ; in port B
   bcf porta,RS_line ; RS line low for control
```
bsf  porta,RW_line ; Read mode
bsf  porta,E_line  ; E line high
movf  portb,w ; Read port B into W
bcf  portb,E_line ; Port B bit 7 is busy flag
andlw 0x80 ; Test bit 7, high is busy
btfss status,z ; Test zero bit in STATUS
goto  busyTest ; Repeat if set

; At this point busy flag is clear
; Reset R/W line and port B to output
bcf  porta,RW_line ; Clear R/W line
movlw  b'00000000' ; All lines to output
tris  portb ; in port B
return

Note that testing the busy flag requires setting the LCD in read mode, which in turn requires implementing a connection between a PIC port and the R/W line. Also that the listed procedure contains no safety mechanism for detecting a hardware error condition in which the busy flag never clears. If such were the case, the program would hang in a forever loop. To detect and recover from this error the routine would have to include an external timing loop or some other means of recovering a possible hardware error.

**Bit Merging Operations**

Often, PIC/LCD circuits do not use all of the lines in an individual port. In this case the routines that manipulate PIC/LCD port access should not change the settings of other port bits. This situation is not exclusive to LCD interfacing; the discussion that follows has many other applications in PIC programming.

A processing routine can change one or more port lines without affecting the remaining ones. For example, an application that uses a 4-bit interface between the PIC and the LCD typically leaves four unused lines in the access port, or uses some of these lines for interface connections. In this case, the programming problem can be described as merging bits of the data byte to be written to the port and some existing port bits. One operand is the access port value and the other one is the new value to write to this port. If the operation at hand uses the four high-order port bits, then its four low-order bits must be preserved. The logic required is simple: AND the corresponding operands with masks that clear the unneeded bits and preserve the significant ones, then OR the two operands. The following procedure shows the required processing:

```
;=================
; merge bits
;=================
; Routine to merge the 4 high-order bits of the 
; value to send with the contents of port B 
; so as to preserve the 4 low-bits in port B 
; Logic:
; AND value with 1111 0000 mask```
AND port B with 0000 1111 mask

At this point low nibble in value and high nibble in port B are all 0 bits:

value = vvvv 0000
port B = 0000 bbbb

OR value and port B resulting in:

vvvv bbbb

ON ENTRY:

w contain value bits

ON EXIT:

w contains merged bits

merge4:

; ANDing with 0 clears the bit. ANDing with 1 preserves the original value
andlw b'11110000'

; Save result in variable
movwf store2

; port B to w register
movf portb,w

; Clear high nibble in port b and preserve low nibble
andlw b'00001111'

; OR two operands in w
iorwf store2,w
return

Note that this particular example refers to merging two operand nibbles. The code can be adapted to merge other size bit-fields by modifying the corresponding masks. For example, the following routine merges the high-order bit of one operand with the seven low-order bits of the second one:

; Routine to merge the high-order bit of the first operand with the seven low-order bits of the second operand

; ON ENTRY:

; w contains value bits of first operand
port b is the second operand

merge1:

; ANDing with 0 clears the bit. ANDing with 1 preserves the original value
andlw b'10000000'

; Save result in variable
movwf store2

; port B to w register
movf portb,w

; Clear high-order bit in port b and preserve the seven low order bits
andlw b'01111111'

; OR two operands in w
iorwf store2,w
return

Popular PIC literature describes routines to merge bit fields by assuming certain conditions in the destination operand, then testing the first operand bit to determine if the assumed condition should be preserved or changed. This type of operation is sometimes called “bit flipping,” for example:
flipBit7:
; Code fragment to test the high-order bit in the variable named
; oprnd1 and preserve its status in the register variable portb
  bcf    portb,7  ; Assume oprnd1 bit is reset
  btfs    oprnd1,7 ; Test operand bit and skip if
                   ; clear (assumption valid)
  bsf    portb,7  ; Set bit if necessary
  return

The logic in bit-flipping routines contains one critical flaw: if the assumed condition is false then the second operand is changed improperly, even if for only a few microseconds. However, the incorrect value can produce errors in execution if it is used by another device during this period. Since there is no such objection to the merge routines based on masking, the programmer should always prefer them.

13.3.4 Text Data Storage and Display

Text display operations require some way of generating the ASCII characters that are to be stored in DDRAM memory. Although the PIC Assembler contains several operators to generate ASCII data in program memory, there is no convenient way of storing a string in the General Purpose register area. Even if this was possible, SRAM is typically in short supply and text strings gobble up considerable data space.

Several possible approaches are available. The most suitable one depends on the total string length to be generated or stored, whether the strings are reused in the code, and other program-related circumstances. In this sense, short text-strings can be produced character-by-character and sent sequentially to DDRAM memory by placing the characters in the corresponding port and pulsing the E line.

The following code fragment consecutively displays the characters in the word “Hello.” Code assumes that the command to set the Address register has been entered previously:

; Generate characters and send directly to DDRAM
  movlw    'H'    ; ASCII for H in w
  movwf    portb  ; Store code in port B
  call    pulseE  ; Pulse E line
  movlw    'e'
  movwf    portb
  call    pulseE
  movlw    'l'
  movwf    portb
  call    pulseE
  movlw    'l'
  movwf    portb
  call    pulseE
  movlw    'o'
  movwf    portb
  call    pulseE
  movlw    'o'
  movwf    portb
  call    pulseE
  call    delay_5
Note in the preceding fragment, the code assumes that the LCD has been initialized to automatically increment the Address register left-to-right. For this reason, the Address register is bumped to the next address with each port access.

**Generating and Storing a Text String**

An alternative approach suitable for generating and displaying longer strings consists of storing the string data in a local variable (sometimes called a *buffer*) and then transferring the characters, one by one, from the buffer to DDRAM. This kind of processing has the advantage of allowing the reuse of the same string and the disadvantage of using up scarce data memory. The logic for one possible routine consists of first generating and storing in PIC RAM the character string, then retrieving the characters from the PIC RAM buffer and displaying them. The character generation and storage logic is shown in Figure 13-5.

![Flowchart for String Generation Logic](image)

**Figure 13-5** Flowchart for String Generation Logic

The processing is demonstrated in the following procedure.

```plaintext
;=============================================;
; first text string procedure
;=============================================

storeMN:
; Procedure to store in PIC RAM buffer the message
; contained in the code area labeled msg1
; ON ENTRY:
; variable pic_ad holds address of text buffer
; in PIC RAM
```
w register hold offset into storage area
msg1 is routine that returns the string characters
and a zero terminator
index is local variable that hold offset into
text table. This variable is also used for
temporary storage of offset into buffer
ON EXIT:
Text message stored in buffer
Store offset into text buffer (passed in the w register)
in temporary variable
movwf index ; Store w in index
Store base address of text buffer in fsr
movf pic_ad,w ; first display RAM address to W
addwf index,w ; Add offset to address
movwf fsr ; W to FSR
Initialize index for text string access
movlw 0 ; Start at 0
movwf index ; Store index in variable
w still = 0
get_msg_char:
call msg1 ; Get character from table
Test for zero terminator
andlw 0x0ff
btfsc status,z ; Test zero flag
goto endstr1 ; End of string
; ASSERT: valid string character in w
; store character in text buffer (by fsr)
movwf indf ; store in buffer by fsr
incf fsr,f ; increment buffer pointer
; Restore table character counter from variable
movf index,w ; Get value into w
addlw 1 ; Bump to next character
movwf index ; Store table index in variable
goto get_msg_char ; Continue
endstr1:
return
; Routine for returning message stored in program area
msg1:
addwf PCL,f ; Access table
retlw 'M'
retlw 'i'
retlw 'n'
retlw 'e'
retlw 's'
retlw 'o'
retlw 't'
retlw 'a'
retlw 0 ; terminator character

The auxiliary procedure named msg1, listed in the preceding code fragment, performs the character-generator function by producing each of the ASCII characters in the message string. Since a `retlw` instruction is necessary for each character, one instruction space in program memory is used for each character generated, plus a final binary zero for the string terminator.

**Displaying the Text String**

Once the string is stored in a local buffer, it is displayed by moving each ASCII code from the buffer into LCD DDRAM. Here again, we assume that the LCD has previously been set to the auto increment DDRAM mode and that the Address register has been properly initialized with the corresponding DDRAM address. The following procedure demonstrates initialization of the DDRAM Address register to the value defined in the constant named LCD_1:

```assembly
;========================
; Set Address register
; to LCD line 1
;========================
;
; ON ENTRY:
;
; Address of LCD line 1 in constant LCD_1

line1:
    bcf porta,E_line ; E line low
    bcf porta,RS_line ; RS line low, set up for control
    call delay_125 ; delay 125 microseconds

; Set to second display line
movlw LCD_1 ; Address and command bit
movwf portb
    call pulseE ; Pulse and delay

; Set RS line for data
    bsf porta,RS_line ; Set up for data
    call delay_125mics ; Delay

return
```

Once the Address register has been set up, the display operation consists of transferring characters from the PIC RAM buffer into LCD DDRAM. The following procedure can be used for this:

```assembly
;=============================
; LCD display procedure
;=============================
;
; Sends 16 characters from PIC buffer, with address stored in variable pic_ad, to LCD line previously selected

display16:

; Set up for data
    bcf porta,E_line ; E line low
bsf porta,RS_line ; RS line low for control
call delay_125 ; Delay
;set up counter for 16 characters
movlw D’16’ ; Counter = 16
movwf count3
; get display address from local variable pic_ad
movf pic_ad,w ; First display RAM address to W
movwf fsr ; W to FSR
getchar:
movf indf,w ; get character from display RAM
; location pointed to by file select
; register
movwf portb
call pulseE ; send data to display
; test for 16 characters displayed
decfsz count3,f ; Decrement counter
goto nextchar ; Skipped if done
return
nextchar:
incf fsr,f ; Bump pointer
goto getchar

Note the procedure display16, previously listed, assumes that the address of the
local buffer is stored in a variable name pic_ad. This allows reusing the procedure to
display text stored at other locations in PIC RAM.

The previously listed procedures demonstrate just one of many possible vari-
ations on this technique. Another approach is to store the characters directly in
DDRAM memory as they are produced by the message-returning routine, thus avoid-
ing the display procedure entirely. In this last case, the programming saves some
data memory space at the expense of having to generate the message characters
each time they are needed. Which approach is the most suitable one depends on the
application.

13.3.5 Data Compression Techniques

Circuits based on the parallel data transfer of eight data bits require eight devoted port
lines. Assuming that three other lines are required for LCD commands and interfacing
(RS, E, and R/W lines), then 11 PIC-to-LCD lines are needed, leaving two free port lines
at the most, on an 16f84 microcontroller. Not many useful devices can make do with
just two port lines. Several possible solutions allow compressing the data transfer
function. The most obvious one is to use the 4-bit data transfer mode to free four port
lines. Other solutions are based on dedicating logic components to the LCD function.

4-bit Data Transfer Mode

One possible solution is to use the capability of the Hitachi 44780 controller that al-
lows a parallel interface using just four data paths instead of eight. The objections are
that programming in 4-bit mode is slightly more convoluted and there is a very minor
performance penalty. In 4-bit mode, data must be sent one nibble at a time, so execu-
tion is slower. Since the delay is required only after the second nibble, the execution time penalty for 4-bit transfers is not very large.

Many of the previously developed routines for 8-bit data mode can be reused without modification in the 4-bit mode. Others require minor changes, and there is one specific display procedure that must be developed ad hoc. The first required change is in the LCD initialization since bit 4 in the Function Set command must be clear for a 4-bit interface. The remaining initialization commands should require no further change, although it is a good idea to consult the data sheet for the LCD hardware in use.

Displaying data using a 4-bit interface consists of sending the high-order nibble followed by the low-order nibble, through the LCD 4-high-order data lines, usually labeled DB5 to DB7. The pulsing of line E follows the last nibble sent. It is usually the case in the 16f84 PIC that circuit wiring in the 4-bit mode uses four of five lines in Port-A, or four of eight lines in port B. Software must provide a way of reading and writing to the appropriate port lines, the ones used in the data transfer, without altering the value stored in the port bits dedicated to other uses. Bit merging routines, discussed in Section 13.3, are quite suitable for the purpose at hand.

The following procedures are designed to send the two nibbles of a data byte through the four high-order lines in port B. The auxiliary procedure named merge4 performs the bit-merging operation while the procedure named send8 does the actual write operation:

```assembly
;========================
; Procedure to send two 4-bit values to port B lines
; 7, 6, 5, and 4. High-order nibble is sent first
; ON ENTRY:
; w register holds 8-bit value to send
send8:
    movwf store1 ; Save original value
    call merge4 ; Merge with port B
    movwf portb ; w to port B
    call pulseE ; Send data to LCD
    movf store1,w ; Recover byte into w
    swapf store1,w ; Swap nibbles in w
    call merge4
    movwf portb
    call pulseE ; Send data to LCD
    call delay_125
    return
;========================
; Procedure to send two 4-bit values to port B lines
; 7, 6, 5, and 4. High-order nibble is sent first
; ON ENTRY:
; w register holds 8-bit value to send
send8:
    movwf store1 ; Save original value
    call merge4 ; Merge with port B
    movwf portb ; w to port B
    call pulseE ; Send data to LCD
    movf store1,w ; Recover byte into w
    swapf store1,w ; Swap nibbles in w
    call merge4
    movwf portb
    call pulseE ; Send data to LCD
    call delay_125
    return
;merge bits
```
Routine to merge the 4 high-order bits of the value to send with the contents of port B so as to preserve the 4 low-bits in port B

Logic:

AND value with 1111 0000 mask
AND port B with 0000 1111 mask
Now low nibble in value and high nibble in port B are all 0 bits:
value = vvvv 0000
port B = 0000 bbbb
OR value and port B resulting in:
vvvv bbbb

ON ENTRY:
w contain value bits
ON EXIT:
w contains merged bits

merge4:
andlw b'11110000' ; ANDing with 0 clears the bit. ANDing with 1 preserves the original value
movwf store2 ; Save result in variable
movf portb,w ; port B to w register
andlw b'00001111' ; Clear high nibble in port b and preserve low nibble
iorwf store2,w ; OR two operands in w
return

The program named LCDTest3 in the book's online software package is a demonstration using the 4-bit interface mode. Figure 13-6 shows a PIC/LCD circuit that is wired for the 4-bit data transfer mode.

Note in the circuit of Figure 13-6 that a total of six port lines remain unused. Two of these lines are in Port-A and four in Port-B.

Master/Slave Systems

To this point we have assumed that driving the LCD is one of the functions performed by the PIC microcontroller, which also executes the other circuit functions. In practice, such a scheme is rarely viable for two reasons: the number of interface lines required and the amount of PIC code space used up by the LCD driver routines. A more efficient approach is to dedicate a PIC exclusively to controlling the LCD hardware, while one or more other microcontrollers perform the main circuit functions. In this scheme, the PIC devoted to the LCD function is referred to as a slave while the one that sends the display commands is called the master.
When sufficient numbers of interface lines are available, the connection between master and slave can be simplified by using a parallel interface. For example, if four port lines are used to interconnect the two PICs, then 16 different command codes can be sent to the slave. The slave reads the communications lines much like it would read a multiple toggle switch. A simple protocol can be devised so that the slave uses these same interface lines to provide feedback to the master. For example, the slave sets all four lines low to indicate that it is ready for the next command, and sets them high to indicate that command execution is in progress and that no new commands can be received. The master, in turn, reads the communications lines to determine when it can send another command to the slave.

But using parallel communications between master and slave can be a self-defeating proposition, since it requires at least seven interface lines to be able
to send ASCII characters. Since the scarcity of port lines is the original reason for using a master/slave set up, parallel communications may not be a good solution in many cases. On the other hand, communications between master and slave can take place serially, using a single interface line. The discussion of using serial interface between a master and an LCD slave driver PIC is left for the chapter on serial communications.

13.4 Sample Programs

The following section lists the sample programs discussed in this chapter.

13.4.1 LCDTest1

; File name: LCDTest1.asm
; Date: April 13, 2006
; Author: Julio Sanchez
; Processor: 16F84A
;
; Description:
; Program to exercise 8-bit PIC-to-LCD interface.
; Code assumes that LCD is driven by Hitachi HD44780
; controller and that the display supports two lines
; each one with 16 characters. The wiring and base
; address of each display line is stored in #define
; statements. These statements can be edited to
; accommodate a different set-up.
; Program uses delay loops for interface timing.
; WARNING:
; Code assumes 4Mhz clock. Delay routines must be
; edited for faster clock

; Displays: Minnesota State, Mankato
;
;====================================
; switches
;====================================
; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; * _CP_OFF
; * _PWRT_ON Power-up timer ON/OFF
; _PWRT_OFF
; _WDT_ON Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC Low power crystal oscillator
; * _XT_OSC External parallel resonator/crystal oscillator
; _HS_OSC
; Resonator: Murate Erie CSA8.00MG = 8 MHz
Resistor/capacitor oscillator (simplest, 20% error)

* indicates set up values

set up and configuration

processor 16f84A
  include <p16f84A.inc>
  __config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

constant definitions
for PIC-to-LCD pin wiring and LCD line addresses

#define E_line 1 ;
#define RS_line 2 ;! - from wiring diagram
#define RW_line 3 ;!

; LCD line addresses (from LCD data sheet)
#define LCD_1 0x80 ; First LCD line constant
#define LCD_2 0xc0 ; Second LCD line constant

; Note: The constants that define the LCD display line addresses have the high-order bit set in
; order to facilitate the controller command

variables in PIC RAM

Reserve 16 bytes for string buffer

cblock 0x0c
strData
dnc

; Leave 16 bytes and Continue with local variables

cblock 0x1d ; Start of block
count1 ; Counter # 1
count2 ; Counter # 2
count3 ; Counter # 3
pic_ad ; Storage for start of text area
  ; (labeled strData) in PIC RAM
J ; counter J
K ; counter K
index ; Index into text table (also used
  ; for auxiliary storage)

dnc

program
org 0 ; start at address
goto main
; Space for interrupt handlers
org 0x08

main:
    movlw b'00000000' ; All lines to output
    tris PORTA ; in Port-A
    tris PORTB ; and port B
    movlw b'00000000' ; All outputs ports low
    movwf PORTA
    movwf PORTB
; Wait and initialize HD44780
    call delay_5ms ; Allow LCD time to initialize
                        ; itself
    call initLCD ; Then do forced
                        ; initialization
    call delay_5ms ; Wait.
; Store base address of text buffer in PIC RAM
    movlw 0x0c ; Start address of text buffer
    movwf pic_ad ; to local variable

;=======================================
; first LCD line
;=======================================
; Store 16 blanks in PIC RAM, starting at address stored
; in variable pic_ad
    call blank16
; Call procedure to store ASCII characters for message
; in text buffer
    movlw d'3'; ; Offset into buffer
    call storeMN
; Set DDRAM address to start of first line
    call line1
; Call procedure to display 16 characters in LCD
    call display16

;=======================================
; second LCD line
;=======================================
    call delay_125mcs ; Wait for termination
    call blank16 ; Blank buffer
; Call procedure to store ASCII characters for message
; in text buffer
    movlw d'1'; ; Offset into buffer
    call storeUniv
    call line2 ; DDRAM address of LCD line 2
    call display16

;======================================
; done!
;==============
loopHere:
    goto loopHere ;done

;*****************************************************************************
; INITIALIZE LCD PROCEDURE
;*****************************************************************************
initLCD
; Initialization for Densitron LCD module as follows:
; 8-bit interface
; 2 display lines of 16 characters each
; cursor on
; left-to-right increment
; cursor shift right
; no display shift
;*************************
; COMMAND MODE
;*************************
    bcf PORTA,E_line ; E line low
    bcf PORTA,RS_line ; RS line low for command
    bcf PORTA,RW_line ; Write mode
    call delay_125mcs ;delay 125 microseconds
;*************************
; FUNCTION SET
;*************************
    movlw 0x38 ;00111000 (FUNCTION SET)
    ; | | | |__ font select:
    ; | | | 1 = 5x10 in 1/8 or 1/11
    ; | | | 0 = 1/16 dc
    ; | | |___ Duty cycle select
    ; | | 0 = 1/8 or 1/11
    ; | | 1 = 1/16
    ; |___ Interface width
    ; | 0 = 4 bits
    ; | 1 = 8 bits
    ; |___ FUNCTION SET COMMAND
    movwf PORTB ;0011 1000
    call pulseE ;pulseE and delay

;*************************
; DISPLAY OFF
;*************************
    movlw 0x08 ; 0 0 0 0 1 0 0 0 (DISPLAY ON/OFF)
    ; | | | |___ Blink character
    ; | | | 1 = on, 0 = off
    ; | | |___ Cursor on/off
movwf PORTB
call pulseE ;pulseE and delay

;********************
; DISPLAY AND CURSOR ON
;*********************
movlw 0x0e ; 0 0 0 0 1 1 1 0 (DISPLAY ON/OFF)
; | | | | | | | | Blink character
; | | | | 1 = on, 0 = off
; | | | | Cursor on/off
; | | 1 = on, 0 = off
; | | | Display on/off
; | 1 = on, 0 = off
; | | | | | | | | COMMAND BIT
movwf PORTB
call pulseE ;pulseE and delay

;********************
; ENTRY MODE SET
;******************
movlw 0x06 ; 0 0 0 0 0 1 1 0 (ENTRY MODE SET)
; | | | | | display shift
; | | | 1 = shift
; | | 0 = no shift
; | | increment mode
; | 1 = left-to-right
; | 0 = right-to-left
; | | | | | | | | COMMAND BIT
movwf PORTB ; 00000110
call pulseE

;********************
; CURSOR/DISPLAY SHIFT
;**********************
movlw 0x14 ; 0 0 0 1 0 1 0 0 (CURSOR/DISPLAY
; | | | | | | | | SHIFT)
; | | | | | | | | don’t care
; | | | | cursor/display shift
; | | | 00 = cursor shift left
; | | 01 = cursor shift right
; | | 10 = cursor and display
; | | | shifted left
; | | 11 = cursor and display
;  |  shifted right
;  |  ___ COMMAND BIT
movwf PORTB ;0001 1111
call pulseE

;***********************|
|  CLEAR DISPLAY      |
;***********************|
movlw 0x01 ;0 0 0 0 0 0 0 1 (CLEAR DISPLAY)
        |  ___ COMMAND BIT
movwf PORTB ;0000 0001

;        call pulseE
call delay_5ms ;delay 5 milliseconds after init
        return

;******************************************************
|  DELAY AND PULSE PROCEDURES
;******************************************************
;==============
|  Procedure to delay
|  42 microseconds
;==============
delay_125mcs
        movlw D’42’ ; Repeat 42 machine cycles
        movwf count1 ; Store value in counter
repeat
        decfsz count1,f ; Decrement counter
goto repeat ; Continue if not 0
        return ; End of delay

;==============
|  Procedure to delay
|  5 milliseconds
;==============
delay_5ms
        movlw D’41’ ; Counter = 41
        movwf count2 ; Store in variable
delay
        call delay_125mcs ; Delay
        decfsz count2,f ; 40 times = 5 milliseconds
goto delay
        return ; End of delay

;=================
|  pulse E line
;=================
pulseE
        bsf PORTA,E_line ;pulse E line
        bcf PORTA,E_line
call delay_125mcs ; delay 125 microseconds
return

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; long delay sub-routine
; (for debugging)
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
long_delay
movlw D'200' ; w = 200 decimal
movwf J ; J = w
jloop:
    movwf K ; K = w
kloop:
    decfsz K,f ; K = K-1, skip next if zero
goto kloop
    decfsz J,f ; J = J-1, skip next if zero
goto jloop
return
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; LCD display procedure
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Sends 16 characters from PIC buffer with address stored in variable pic_ad to LCD line previously selected
display16:
; Set up for data
    bcf PORTA,E_line ; E line low
    bsf PORTA,RS_line ; RS line low for control
    call delay_125mcs ; Delay
; Set up counter for 16 characters
    movlw D'16' ; Counter = 16
    movwf count3
; Get display address from local variable pic_ad
    movf pic_ad,w ; First display RAM address to W
    movwf FSR ; W to FSR
getchar:
    movf INDF,w ; get character from display RAM
    ; location pointed to by file select register
    movwf PORTB
    call pulseE ; send data to display
; Test for 16 characters displayed
    decfsz count3,f ; Decrement counter
    goto nextchar ; Skipped if done
return
nextchar:
    incf FSR,f ; Bump pointer
goto getchar
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; blank buffer
;=================================
; Procedure to store 16 blank characters in PIC RAM
; buffer starting at address stored in the variable
; pic_ad
blank16:
    movlw D'16' ; Set up counter
    movwf count1
    movf pic_ad,w ; First PIC RAM address
    movwf FSR ; Indexed addressing
    movlw 0x20 ; ASCII space character
    storeit:
        movwf INDF ; Store blank character in PIC
        RAM
        storeit
    decfsz count1,f ; Done?
    goto incfsr ; no
    return ; yes
    incfsr:
        incf FSR,f ; Bump FSR to next buffer
    space
        goto storeit

;=================================
; Set Address register
; to LCD line 1
;=================================
; ON ENTRY:
; Address of LCD line 1 in constant LCD_1
line1:
    bcf PORTA,E_line ; E line low
    bcf PORTA,RS_line ; RS line low, set up for
    control
    call delay_125mcs ; delay 125 microseconds
    ; Set to second display line
    movlw LCD_1 ; Address and command bit
    movwf PORTB ; Pulse and delay
    ; Set RS line for data
    bsf PORTA,RS_line ; Set up for data
    call delay_125mcs ; Delay
    return

;=================================
; Set Address register
; to LCD line 2
;=================================
; ON ENTRY:
; Address of LCD line 2 in constant LCD_2
line2:

    bcf   PORTA,E_line ; E line low
    bcf   PORTA,RS_line ; RS line low, set up for
                       ; control
    call   delay_125mcs ; delay
    ; Set to second display line
    movlw LCD_2 ; Address with high-bit set
    movwf   PORTB
    call   pulseE ; Pulse and delay
    ; Set RS line for data
    bsf   PORTA,RS_line ; RS = 1 for data
    call   delay_125mcs ; delay
    return

;=================================
; first text string procedure
;=================================
storeMN:
; Procedure to store in PIC RAM buffer the message
; contained in the code area labeled msg1
; ON ENTRY:
;    variable pic_ad holds address of text buffer
;    in PIC RAM
;    w register hold offset into storage area
;    msg1 is routine that returns the string characters
;    and a zero terminator
;    index is local variable that hold offset into
;    text table. This variable is also used for
;    temporary storage of offset into buffer
; ON EXIT:
;    Text message stored in buffer
;
; Store offset into text buffer (passed in the w register)
; in temporary variable
    movwf   index ; Store w in index
; Store base address of text buffer in FSR
    movf    pic_ad,w ; first display RAM address to W
    addwf   index,w ; Add offset to address
    movwf   FSR ; W to FSR
; Initialize index for text string access
    movlw 0 ; Start at 0
    movwf   index ; Store index in variable
; w still = 0
get_msg_char:
    call   msg1 ; Get character from table
; Test for zero terminator
    andlw 0x0ff
    btfsc STATUS,Z ; Test zero flag
goto endstr1 ; End of string

; ASSERT: valid string character in w
; store character in text buffer (by FSR)
movwf INDF ; store in buffer by FSR
incf FSR,f ; increment buffer pointer

; Restore table character counter from variable
movf index,w ; Get value into w
addlw 1 ; Bump to next character
movwf index ; Store table index in variable
goto get_msg_char ; Continue

endstr1:
return

; Routine for returning message stored in program area
msg1:
addwf PCL,f ; Access table
retlw 'M'
retlw 'i'
retlw 'n'
retlw 'n'
retlw 'e'
retlw 's'
retlw 'o'
retlw 't'
retlw 'a'
retlw 0

;=================================
; second text string procedure
;=================================
storeUniv:
; Processing identical to procedure StoreMSU
movwf index ; Store w in index

; Store base address of text buffer in FSR
movf pic_ad,0 ; first display RAM address to W
addwf index,0 ; Add offset to address
movwf FSR ; W to FSR

; Initialize index for text string access
movlw 0 ; Start at 0
movwf index ; Store index in variable

; w still = 0
get_msg_char2:
call msg2 ; Get character from table

; Test for zero terminator
andlw 0x0ff
btfsc STATUS,Z ; Test zero flag
g goto endstr2 ; End of string
; ASSERT: valid string character in w
; store character in text buffer (by FSR)
movf INDF ; Store in buffer by FSR
incf FSR,f ; Increment buffer pointer
; Restore table character counter from variable
movf index,w ; Get value into w
addlw 1 ; Bump to next character
movwf index ; Store table index in variable
goto get_msg_char2 ; Continue
endstr2:
return

; Routine for returning message stored in program area
msg2:
addwf PCL,f ; Access table
retlw 'S'
retlw 't'
retlw 'a'
retlw 't'
retlw 'e'
retlw ','
retlw 0x20
retlw 'M'
retlw 'a'
retlw 'n'
retlw 'k'
retlw 'a'
retlw 't'
retlw 'o'
retlw 0

end

13.4.2 LCDTest2 Program

; File name: LCDTest2.asm
; Date: April 16, 2006
; Author: Julio Sanchez
; Processor: 16F84A
;
; Description:
; Program to exercises 8-bit PIC-to-LCD interface.
; Code assumes that LCD is driven by Hitachi HD44780
; controller and that the display supports two lines
; each one with 16 characters. The wiring and base
address of each display line is stored in #define statements. These statements can be edited to accommodate a different set-up.
Program uses the busy flag to synchronize processor access, although delay loops are still required in some cases.
Displays: Minnesota State, Mankato
WARNING:
Code assumes 4Mhz clock. Delay routines must be edited for faster clock
Displays: Minnesota State, Mankato

Switches
Switches used in __config directive:
_CP_ON Code protection ON/OFF
* _CP_OFF
* _PWRTE_ON Power-up timer ON/OFF
* _PWRTE_OFF
_WDT_ON Watchdog timer ON/OFF
* _WDT_OFF
_LP_OSC Low power crystal oscillator
* _XT_OSC External parallel oscillator/crystal oscillator
_HS_OSC High speed crystal resonator (8 to 10 MHz)
_RC_OSC Resistor/capacitor oscillator
(simplest, 20% error)

* indicates set up values presently selected

processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

constant definitions
for PIC-to-LCD pin wiring and LCD line addresses

#define E_line 1 ;
#define RS_line 2 ; — from wiring diagram
#define RW_line 3 ;
LCD line addresses (from LCD data sheet)
#define LCD_1 0x80  ; First LCD line constant
#define LCD_2 0xc0  ; Second LCD line constant
; Note: The constants that define the LCD display line
; addresses have the high-order bit set in
; order to facilitate the controller command
;
;=================================================================
; variables in PIC RAM
;=================================================================
; Reserve 16 bytes for string buffer
cblock 0x0c
strData
endc
; Leave 16 bytes and Continue with local variables
cblock 0x1d  ; Start of block
count1  ; Counter # 1
count2  ; Counter # 2
count3  ; Counter # 3
pic_ad  ; Storage for start of text area
        ; (labeled strData) in PIC RAM
J       ; counter J
K       ; counter K
index   ; Index into text table (also used
        ; for auxiliary storage)
endc

;=================================================================
; program
;=================================================================
org 0  ; start at address
goto main
; Space for interrupt handlers
org 0x08

main:
  movlw b'00000000'  ; All lines to output
  tris PORTA  ; in Port-A
  tris PORTB  ; and port B
  movlw b'00000000'  ; All outputs ports low
  movwf PORTA
  movwf PORTB
; Wait and initialize HD44780
  call delay_5  ; Allow LCD time to initialize
                 ; itself
  call initLCD  ; Then do forced
initialization
; Store base address of text buffer in PIC RAM
  movlw 0x0c  ; Start address for buffer
movwf pic_ad ; to local variable
;======================
; first LCD line
;======================
; Store 16 blanks in PIC RAM, starting at address stored in variable pic_ad
; call blank16
; Call procedure to store ASCII characters for message in text buffer
movlw d'3' ; Offset into buffer
call storeMSU
; Set DDRAM address to start of first line
; call line1
; Call procedure to display 16 characters in LCD
; call display16
;========================
; second LCD line
;========================
call busyTest ; Wait for termination
call blank16 ; Blank buffer
; Call procedure to store ASCII characters for message in text buffer
movlw d'1' ; Offset into buffer
call storeUniv
call line2 ; DDRAM address of LCD line 2
call display16
;=======================
; done!
;=======================
loopHere:
goto loopHere ; done

;**********************************************************************
; INITIALIZE LCD PROCEDURE
;**********************************************************************
initLCD:
;***************************| COMMAND MODE |
;***************************
bcf PORTA,E_line ; E line low
call delay_125 ; delay 125 microseconds
bcf PORTA,RS_line ; RS line low
call delay_125 ; delay 125 microseconds
;***************************| FUNCTION SET |
;***************************
movlw 0x38 ; 0 0 1 1 1 0 0 0 (FUNCTION SET)
; | | | |__ font select:
; 1 = 5x10 in 1/8 or 1/11
; 0 = 1/16 dc
; Duty cycle select
; 1 = 1/8 or 1/11
; 0 = 1/16
; Interface width
; 0 = 4 bits
; 1 = 8 bits

movwf PORTB ;0011 1000

; *** FUNCTION SET COMMAND ***

; DISPLAY OFF
movlw 0x08 ;00001000 (DISPLAY ON/OFF)
; Blink character
; 1 = on, 0 = off
; Cursor on/off
; 1 = on, 0 = off
; Display on/off
; 1 = on, 0 = off

movwf PORTB
call pulseE ;pulseE and delay

; DISPLAY AND CURSOR ON
movlw 0x0e ;00001110 (DISPLAY ON/OFF)
; Blink character
; 1 = on, 0 = off
; Cursor on/off
; 1 = on, 0 = off
; Display on/off
; 1 = on, 0 = off

movwf PORTB
call pulseE ;pulseE and delay

; ENTRY MODE SET
movlw 0x06 ;00000110 (ENTRY MODE SET)
; display shift
; 1 = shift
; 0 = no shift
; increment mode

movwf PORTB
call pulseE ;pulseE and delay
```assembly
; 1 = left-to-right
; 0 = right-to-left
; ___ COMMAND BIT
movwf PORTB ;00000110
call pulseE

; CURSOR/DISPLAY SHIFT
;***********************|
movlw 0x14 ;00010100 (CURSOR/DISPLAY
; |||___ don’t care
; |___ cursor/display shift
; | 00 = cursor shift left
; | 01 = cursor shift right
; | 10 = cursor and display
; | shifted left
; | 11 = cursor and display
; | shifted right
; |___ COMMAND BIT
movwf PORTB ;0001 1111
call pulseE

; CLEAR DISPLAY
;***********************|
movlw 0x01 ;0 0 0 0 0 0 0 0 1 (CLEAR DISPLAY)
; |___ COMMAND BIT
movwf PORTB ;0000 0001

call pulseE
call busyTest ; Test for busy
return

;=====
; busy flag test routine
;=====
; Procedure to test the HD44780 busy flag
; Execution returns when flag is clear
busyTest:
  movlw b’11111111’ ; All lines to input
  tris PORTB ; in port B
  bcf PORTA,RS_line ; RS line low for control
  bsf PORTA,RW_line ; Read mode
  bsf PORTA,E_line ; E line high
  movf PORTB,w ; Read port B into W
  ; Port B bit 7 is busy flag
  bcf PORTA,E_line ; E line low
```
andlw 0x80
btfss STATUS,Z
goto busyTest
; At this point busy flag is clear
; Reset R/W line and port B to output
bcf PORTA,RW_line
movlw b'00000000'
tris PORTB
return

; Procedure to delay
; 42 microseconds
;=======================
delay_125:
    movlw D'42'
    movwf count1
    repeat:
        decfsz count1,f
        goto repeat
    return

; Procedure to delay
; 5 milliseconds
;=======================
delay_5:
    movlw D'41'
    movwf count2
delay:
    call delay_125
    decfsz count2,f
    goto delay
    return

; Pulse E line
;==============
pulseE
    bsf PORTA,E_line
    nop
    bcf PORTA,E_line
    call delay_5
    return

; Long delay sub-routine
; (for debugging)
;========================
long_delay
    movlw D'200' ; w = 200 decimal
    movwf J ; J = w
jloop:
    movwf K ; K = w
kloop:
    decfsz K,f ; K = K-1, skip next if zero
    goto kloop
    decfsz J,f ; J = J-1, skip next if zero
    goto jloop
    return

;=====================================
; LCD display procedure
;=====================================
; Sends 16 characters from PIC buffer with address stored
; in variable pic_ad to LCD line previously selected
display16
    call busyTest ; Make sure not busy
    ; Set up for data
    bcf PORTA,E_line ; E line low
    bsf PORTA,RS_line ; RS line high for data
    ; Set up counter for 16 characters
    movlw D'16' ; Counter = 16
    movwf count3
    ; Get display address from local variable pic_ad
    movf pic_ad,w ; First display RAM address to W
    movwf FSR ; W to FSR
    getchar
    movf INDF,w ; get character from display RAM
    ; location pointed to by file select
    ; register
    movwf PORTB
    call pulseE ;send data to display
    ; Test for 16 characters displayed
    decfsz count3,f ; Decrement counter
    goto nextchar ; Skipped if done
    return
    nextchar:
    incf FSR,f ; Bump pointer
    goto getchar

;=====================================
; blank buffer
;=====================================
; Procedure to store 16 blank characters in PIC RAM
; buffer starting at address stored in the variable
; pic_ad
blank16:
    movlw D'16' ; Set up counter
movwf count1
movf pic_ad,w ; First PIC RAM address
movwf FSR ; Indexed addressing
movlw 0x20 ; ASCII space character

storeit:
movwf INDF ; Store blank character in PIC RAM

decsz count1,f ; Done?
goto incfsr ; no
return ; yes
incfsr
incf FSR,f ; Bump FSR to next buffer ; space

goto storeit

;========================
; Set Address register
; to LCD line 1
;========================
; ON ENTRY:
; Address of LCD line 1 in constant LCD_1
linel:
bcf PORTA,E_line ; E line low
bcf PORTA,RS_line ; RS line low, set up for control
call busyTest ; busy?

; Set to second display line
movlw LCD_1 ; Address and command bit
movwf PORTB
call pulseE ; Pulse and delay

; Set RS line for data
bsf PORTA,RS_line ; Set up for data
call busyTest ; Busy?
return

;========================
; Set Address register
; to LCD line 2
;========================
; ON ENTRY:
; Address of LCD line 2 in constant LCD_2
line2:
bcf PORTA,E_line ; E line low
bcf PORTA,RS_line ; RS line low, set up for control
call busyTest ; Busy?

; Set to second display line
movlw LCD_2 ; Address with high-bit set
movwf PORTB
call pulseE ; Pulse and delay

; Set RS line for data
bsf PORTA,RS_line ; RS = 1 for data
call busyTest ; Busy?
return

;==================================================================
; first text string procedure
;==================================================================
storeMSU:
; Procedure to store in PIC RAM buffer the message
; contained in the code area labeled msg1
; ON ENTRY:
;
; variable pic_ad holds address of text buffer
; in PIC RAM
; w register hold offset into storage area
; msg1 is routine that returns the string characters
; and a zero terminator
; index is local variable that hold offset into
; text table. This variable is also used for
; temporary storage of offset into buffer
; ON EXIT:
;
; Text message stored in buffer
;
; Store offset into text buffer (passed in the w register)
; in temporary variable
movwf index ; Store w in index

; Store base address of text buffer in FSR
movf pic_ad,w ; first display RAM address to W
addwf index,w ; Add offset to address
movwf FSR ; W to FSR

; Initialize index for text string access
movlw 0 ; Start at 0
movwf index ; Store index in variable

; w still = 0
get_msg_char:
call msg1 ; Get character from table

; Test for zero terminator
andlw 0x0ff
btfsc STATUS,Z ; Test zero flag
goto endstr1 ; End of string

; ASSERT: valid string character in w
; store character in text buffer (by FSR)
movwf INDF ; store in buffer by FSR
incf FSR,f ; increment buffer pointer

; Restore table character counter from variable
movf index,w ; Get value into w
addlw 1 ; Bump to next character
movwf index ; Store table index in variable

goto get_msg_char ; Continue

endstr1:

return

; Routine for returning message stored in program area msg1:

addwf PCL,f ; Access table
retlw 'M'
retlw 'i'
retlw 'n'
retlw 'n'
retlw 'e'
retlw 's'
retlw 'o'
retlw 't'
retlw 'a'
retlw 0

;=================================
; second text string procedure
;=================================

storeUniv:

; Processing identical to procedure StoreMSU
movwf index ; Store w in index

; Store base address of text buffer in FSR
movf pic_ad,0 ; first display RAM address to W
addwf index,0 ; Add offset to address
movwf FSR ; W to FSR

; Initialize index for text string access
movlw 0 ; Start at 0
movwf index ; Store index in variable

; w still = 0

get_msg_char2:

call msg2 ; Get character from table

; Test for zero terminator

andlw 0x0ff

btfsc STATUS,Z ; Test zero flag

goto endstr2 ; End of string

; ASSERT: valid string character in w

; store character in text buffer (by FSR)

movwf INDF ; Store in buffer by FSR

incf FSR,f ; Increment buffer pointer

; Restore table character counter from variable

movf index,w ; Get value into w

addlw 1 ; Bump to next character

movwf index ; Store table index in
13.4.3 LCDTest3 Program

; File name: LCDTest3.asm
; Date: April 16, 2006
; Author: Julio Sanchez
; Processor: 16F84A
;
; Description:
; Program to exercise 4-bit PIC-to-LCD interface.
; Code assumes that LCD is driven by Hitachi HD44780
; controller and that the display supports two lines
; each one with 16 characters. The wiring and base
; address of each display line is stored in #define
; statements. These statements can be edited to
; accommodate a different set-up.
; Program uses delay loops for interface timing.
; WARNING:
; Code assumes 4Mhz clock. Delay routines must be
; edited for faster clock
;
; Displays: Minnesota State, Mankato
Switches used in __config directive:

- _CP_ON  Code protection ON/OFF
- _CP_OFF
- _PWRTE_ON  Power-up timer ON/OFF
- _PWRTE_OFF
- _WDT_ON  Watchdog timer ON/OFF
- _WDT_OFF
- _LP_OSC  Low power crystal oscillator
- _XT_OSC  External parallel resonator/crystal oscillator
- _HS_OSC  High speed crystal resonator (8 to 10 MHz)
- Resonator: Murate Erie CSA8.00M G=8MHz
- _RC_OSC  Resistor/capacitor oscillator
  (simplest, 20% error)

* indicates set up values presently selected

Set up and configuration

processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

For PIC-to-LCD pin wiring and LCD line addresses

#define E_line 1  
#define RS_line 2  
#define RW_line 3  

LCD line addresses (from LCD data sheet)
#define LCD_1 0x80  
#define LCD_2 0xc0  

Note: The constants that define the LCD display line
addresses have the high-order bit set in
order to facilitate the controller command

Reserve 16 bytes for string buffer
  cblock 0x0c
  strData
  endc
; Leave 16 bytes and Continue with local variables
cblock 0x1d ; Start of block
count1 ; Counter # 1
count2 ; Counter # 2
count3 ; Counter # 3
pic_ad ; Storage for start of text area
        ; (labeled strData) in PIC RAM
J ; counter J
K ; counter K
index ; Index into text table (also used
        ; for auxiliary storage)
store1 ; Local temporary storage
store2 ; Storage # 2
endc

;=========================================================
; program
;=========================================================
org 0 ; start at address
goto main

; Space for interrupt handlers
org 0x08

main:
    movlw b'00000000' ; All lines to output
    tris PORTA ; in Port-A
    tris PORTB ; and port B
    movlw b'00000000' ; All outputs ports low
    movwf PORTA
    movwf PORTB

; Wait and initialize HD44780
    call delay_5 ; Allow LCD time to initialize
        ; itself
    call delay_5
    call initLCD ; Then do forced initialization
    call delay_5 ; Wait again

; Store base address of text buffer in PIC RAM
    movlw 0x0c ; Start address for buffer
    movwf pic_ad ; to local variable

;===============
; first LCD line
;===============
; Store 16 blanks in PIC RAM, starting at address stored
; in variable pic_ad
    call blank16

; Call procedure to store ASCII characters for message
; in text buffer
movlw d'3' ; Offset into buffer
call storeMSU
; Set DDRAM address to start of first line
call line1
; Call procedure to display 16 characters in LCD
call display16

;========================================
; second LCD line
;========================================
call delay_5 ; Wait for termination
call blank16 ; Blank buffer
; Call procedure to store ASCII characters for message
; in text buffer
movlw d'1' ; Offset into buffer
call storeUniv
call line2 ; DDRAM address of LCD line 2
call display16

;========================================
; done!
;========================================
loopHere:
goto loopHere ; done

;=========================================
; initialize LCD for 4-bit mode
;=========================================
initLCD:
; Initialization for Densitron LCD module as follows:
; 4-bit interface
; 2 display lines of 16 characters each
; cursor on
; left-to-right increment
; cursor shift right
; no display shift
;=========================================
; set command mode
;=========================================

bcf PORTA,E_line ; E line low
bcf PORTA,RS_line ; RS line low
bcf PORTA,RW_line ; Write mode
call delay_125 ; delay 125 microseconds

;*******************************
; FUNCTION SET
;*******************************
movlw 0x28 ; 0 0 1 0 1 0 0 0 (FUNCTION SET)
; | | | | __ font select:
; | | | 1 = 5x10 in 1/8 or 1/11
;  |  |  | 0 = 1/16 dc
;  |  |  |___ Duty cycle select
;  |  |  | 0 = 1/8 or 1/11
;  |  |  | 1 = 1/16
;  |  |___ Interface width
;  |  | 0 = 4 bits
;  |  | 1 = 8 bits
;  |___ FUNCTION SET COMMAND

call send8 ; 4-bit send routine
; Set 4-bit mode command must be repeated
movlw 0x28
call send8

;******************************|
; DISPLAY AND CURSOR ON |
;******************************|
movlw 0x0e ; 0 0 0 0 1 1 1 0 (DISPLAY ON/OFF)
;  |  |  |___ Blink character
;  |  |  | 1 = on, 0 = off
;  |  |  |___ Cursor on/off
;  |  |  | 1 = on, 0 = off
;  |  |___ Display on/off
;  |  | 1 = on, 0 = off
;  |___ COMMAND BIT

call send8

;******************************|
; set entry mode |
;******************************|
movlw 0x06 ; 0 0 0 0 0 1 1 0 (ENTRY MODE SET)
;  |  |  |___ display shift
;  |  |  | 1 = shift
;  |  |  | 0 = no shift
;  |  |___ increment mode
;  |  | 1 = left-to-right
;  |  | 0 = right-to-left
;  |___ COMMAND BIT

call send8

;******************************|
; cursor/display shift |
;******************************|
movlw 0x14 ; 0 0 0 1 0 1 0 0 (CURSOR/DISPLAY
;  |  |  |___ SHIFT)
;  |  |  |___ don’t care
;  |  |___ cursor/display shift
;  |  | 00 = cursor shift left
;  |  | 01 = cursor shift right
;  |  | 10 = cursor and display
call send0
; Per documentation
call delay_5 ; Test for busy
return

; Procedure to delay
; 42 microseconds
;-------------------------
delay_125
movlw D'42' ; Repeat 42 machine cycles
movwf count1 ; Store value in counter
repeat
decfsz count1,f ; Decrement counter
goto repeat ; Continue if not 0
return ; End of delay

; Procedure to delay
; 5 milliseconds
;-------------------------
delay_5:
movlw D'41' ; Counter = 41
movwf count2 ; Store in variable
delay:
call delay_125 ; Delay
decfsz count2,f ; 40 times = 5 milliseconds
goto delay
return ; End of delay

; pulse E line
;-------------------------
pulseE
bsf PORTA,E_line ; Pulse E line
nop
bcf PORTA,E_line
return
;=============================  
; long delay sub-routine  
; (for debugging)  
;=============================  
long_delay:  
    movlw D'200' ; w = 200 decimal  
    movwf J ; J = w  
jloop:  
    movwf K ; K = w  
kloop:  
    decfsz K,f ; K = K-1, skip next if zero  
goto kloop  
    decfsz J,f ; J = J-1, skip next if zero  
goto jloop  
return

;=============================  
; LCD display procedure  
;=============================  
; Sends 16 characters from PIC buffer with address stored  
in variable pic_ad to LCD line previously selected  
display16  
    call delay_5 ; Make sure not busy  
    ; Set up for data  
    bcf PORTA,E_line ; E line low  
baf PORTA,RS_line ; RS line high for data  
    ; Set up counter for 16 characters  
    movlw D'16' ; Counter = 16  
movwf count3  
    ; Get display address from local variable pic_ad  
movf pic_ad,w ; First display RAM address to W  
movwf FSR ; W to FSR  
getchar:  
    movf INDF,w ; get character from display RAM  
    ; location pointed to by file select register  
    call send8 ; 4-bit interface routine  
    ; Test for 16 characters displayed  
    decfsz count3,f ; Decrement counter  
goto nextchar ; Skipped if done  
return  
nextchar:  
    incf FSR,f ; Bump pointer  
goto getchar

;=============================  
; send 2 nibbles in  
; 4-bit mode  
;=============================
; Procedure to send two 4-bit values to port B lines
; 7, 6, 5, and 4. High-order nibble is sent first
; ON ENTRY:
; w register holds 8-bit value to send
send8:
   movwf store1 ; Save original value
   call merge4 ; Merge with port B
; Now w has merged byte
   movwf PORTB ; w to port B
   call pulseE ; Send data to LCD
; High nibble is sent
   movf store1,w ; Recover byte into w
   swapf store1,w ; Swap nibbles in w
   call merge4
   movwf PORTB
   call pulseE ; Send data to LCD
   call delay_125
   return
;=================
; merge bits
;=================
; Routine to merge the 4 high-order bits of the
; value to send with the contents of port B
; so as to preserve the 4 low-bits in port B
; Logic:
; AND value with 1111 0000 mask
; AND port B with 0000 1111 mask
; Now low nibble in value and high nibble in
; port B are all 0 bits:
; value = vvvv 0000
; port B = 0000 bbbb
; OR value and port B resulting in:
; vvvv bbbb
; ON ENTRY:
; w contain value bits
; ON EXIT:
; w contains merged bits
merge4:
   andlw b'11110000' ; ANDing with 0 clears the
   ; bit. ANDing with 1 preserves
   ; the original value
   movwf store2
   movf PORTB,w ; port B to w register
   andlw b'00001111' ; Clear high nibble in port b
   ; and preserve low nibble
   iorwf store2,w ; OR two operands in w
   return
; blank buffer
;
; Procedure to store 16 blank characters in PIC RAM
; buffer starting at address stored in the variable
; pic_ad

Blank16

movlw D'16' ; Set up counter
movwf count1
movf pic_ad,w ; First PIC RAM address
movwf FSR ; Indexed addressing
movlw 0x20 ; ASCII space character
storeit

movwf INDF ; Store blank character in PIC RAM
; buffer using FSR register

decfsz count1,f ; Done?
goto return ; no
incf FSR,f ; Bump FSR to next buffer space
goto storeit

; Set Address register
; to LCD line 1
;
; ON ENTRY:
; Address of LCD line 1 in constant LCD_1
line1:

bcf PORTA,E_line ; E line low
bcf PORTA,RS_line ; RS line low, set up for control

call delay_5 ; busy?
movlw LCD_1 ; Address and command bit
call send8 ; 4-bit routine

; Set RS line for data
bsf PORTA,RS_line ; Set up for data
call delay_5 ; Busy?
return

; Set Address register
; to LCD line 2
;
; ON ENTRY:
; Address of LCD line 2 in constant LCD_2
line2:

bcf PORTA,E_line ; E line low
bcf PORTA,RS_line ; RS line low, set up for
; control
    call delay_5 ; Busy?
; Set to second display line
movlw LCD_2 ; Address with high-bit set
    call send8
; Set RS line for data
bsf PORTA,RS_line ; RS = 1 for data
    call delay_5 ; Busy?
return

;===============================
; first text string procedure
;===============================
storeMSU:
; Procedure to store in PIC RAM buffer the message
; contained in the code area labeled msg1
; ON ENTRY:
; variable pic_ad holds address of text buffer
; in PIC RAM
; w register hold offset into storage area
; msg1 is routine that returns the string characters
; andiy a zero terminator
; index is local variable that hold offset into
; text table. This variable is also used for
; temporary storage of offset into buffer
; ON EXIT:
; Text message stored in buffer
;
; Store offset into text buffer (passed in the w register)
; in temporary variable
movwf index  ; Store w in index
; Store base address of text buffer in FSR
movf pic_ad,w ; first display RAM address to W
addwf index,w  ; Add offset to address
movwf FSR  ; W to FSR
; Initialize index for text string access
movlw 0  ; Start at 0
movwf index  ; Store index in variable
; w still = 0
get_msg_char:
call msg1  ; Get character from table
; Test for zero terminator
andlw 0x0ff
btfs STATUS,Z ; Test zero flag
goto endstr1  ; End of string
; ASSERT: valid string character in w
; store character in text buffer (by FSR)
movwf  INDF ; store in buffer by FSR
incf  FSR,f ; increment buffer pointer
; Restore table character counter from variable
movf  index,w ; Get value into w
addlw 1 ; Bump to next character
movwf  index ; Store table index in
variable
goto  get_msg_char ; Continue
endstr1:
    return
; Routine for returning message stored in program area
msg1:
    addwf  PCL,f ; Access table
    retlw 'M'
    retlw 'i'
    retlw 'n'
    retlw 'n'
    retlw 'e'
    retlw 's'
    retlw 'o'
    retlw 't'
    retlw 'a'
    retlw 0

;=================================
; second text string procedure
;=================================
storeUniv:
; Processing identical to procedure StoreMSU
movwf  index ; Store w in index
; Store base address of text buffer in FSR
movf  pic_ad,0 ; first display RAM address to W
addwf  index,0 ; Add offset to address
movwf  FSR ; W to FSR
; Initialize index for text string access
movlw 0 ; Start at 0
movwf  index ; Store index in variable
; w still = 0
get_msg_char2:
    call  msg2 ; Get character from table
; Test for zero terminator
andlw 0x0ff
btfsc  STATUS,Z ; Test zero flag
goto  endstr2 ; End of string
; ASSERT: valid string character in w
; store character in text buffer (by FSR)
movwf  INDF ; Store in buffer by FSR
incf  FSR,f ; Increment buffer pointer
movf index, w ; Get value into w
addlw 1 ; Bump to next character
movwf index ; Store table index in
            ; variable
                    goto get_msg_char2 ; Continue
endstr2:
    return

; Routine for returning message stored in program area
msg2:
addwf PCL, f ; Access table
retlw 'S'
retlw 't'
retlw 'a'
retlw 't'
retlw 'e'
retlw ','
retlw 'M'
retlw 'a'
retlw 'n'
retlw 'k'
retlw 'a'
retlw 't'
retlw 'o'
retlw 0

end
Chapter 14

Communications

In this chapter we focus on digital communications techniques used in PIC interfacing with I/O devices, integrated circuits, and with other forms of programmable logic. Communications, in general, refers to the exchange of information following rules, sometimes called a protocol. Digital and computer communications come in two flavors: serial and parallel. Serial communications take place when the data is sent one bit at a time over the communications channel. In parallel communications all the bits that compose a single symbol or character are sent simultaneously.

Common wisdom regards serial communications as slower than parallel communications but with modern-day technologies this is often not the case, since serial techniques often match or even excel parallel methods in speed and performance. Computer networks such as Ethernet and fiber optic links are able to achieve high performance even though they use serial bit streams. The preference for serial over parallel communications is often more related to hardware, since parallel transmissions require more communication lines than serial transmissions.

14.0 PIC Communications Overview

Many communications standards were created with other interface and hardware requirements in mind and are not ideally suited for PIC applications. For example, RS-232-C, a serial protocol developed over 35 years ago, originated in an age of teletypewriters and modems. The voltage levels and circuit requirements of RS-232-C are not suited for PIC hardware. The more modern USB standard is more suited to PIC interfacing, but adopting a standard; RS-232-C, EIA-485, USB, or any other conventions, requires adhering to special configurations in hardware and the use of ad hoc software protocols. This compliance with a standard comes at a price of added hardware components and increased software complexity.

When PIC-based circuits must interface with other systems or devices that follow these standards, then there is no alternative but to design circuits and write programs that comply with the standards. On the other hand, when the communications take place in dedicated circuits, which do not interface with devices or systems that
follow standard communications protocols, then pure PIC communications techniques and hardware are often simpler and more effective. In other words, adhering to a communications protocol usually implies an additional cost in software and hardware complexity. Here are two examples: a PIC-based circuit that interfaces with a PC through the RS-232-C port would be a case where compliance with RS-232-C is required. Another case would be a PIC-based circuit that sends serial data to an onboard LCD display. In this case, the circuit and the software need not comply with any communications standards or protocols. Programmers often refer to techniques that use serial communications without the presence of specialized hardware, such as UART or USART chips, as *bit-banging*.

In the following sections, we discuss serial and parallel communications at their most essential level. In the general literature, communications concerns often focus on transmission speeds, system performance, and minimum processing time. Typically, PIC applications do not transfer large data files or communicate interactively on the Internet or in networks. In a typical PIC application, communication functions are used to upload stored data to a PC, sometimes called *data-logging*, or to receive small data sets or commands from a host machine. In this context there are no major concerns regarding super-fast transmission rates or maximum performance.

### 14.1 Serial Data Transmission

Serial communications take place by transmitting and receiving data in a stream of consecutive electrical pulses that represent data bits and control codes. The *Electronic Industries Association (EIA)* has sponsored the development of several standards for serial communications, such as RS-232-C, RS-422, RS-423, RS 449, EIA232E, and EIA232F, among others. In this designation the characters RS stand for the words *Recommended Standard*. The oldest, simplest to implement, and most-used serial communications standard is the *RS-232-C voltage level convention*. In the following sections we present the essential concepts of the RS-232-C standard. Most of the material also applies to the various updates of the standard. Later in the chapter we briefly discuss the EIA485 Standard.

#### 14.1.1 Asynchronous Serial Transmission

The information in a serial bit stream is contained in a time-dependent waveform, that is, each bit code (data, control, or error) is transmitted for a fixed time period, known as the *baud period*. The word baud was chosen to honor the French scientist and inventor *Jean Maurice Emile Baudot* who studied various serial encodings in the late 19th century.

The serial bit streams used in data transmission follow a very simple encoding: one bit is transmitted during each baud period. A binary 1 bit is represented with a negative voltage level and a binary 0 bit by a positive voltage. The line condition during the logic 1 transmission is called a *marking state*, and the one for a logic 0 a *spacing state*. The baud rate is equal to the number of bits per second being transmitted or received. Note that the voltage levels that represent a one and a zero bit in RS232 are somewhat counter-intuitive, since one would expect a logic 1 to be represented with a positive voltage, and not a negative one.
One possible approach to sending information bit-by-bit is based on the transmitter and receiver clocks being synchronized at the same frequency. That is, both receiver and transmitter operate at the same baud rate. Note that the expression “synchronized at the same frequency” implies not only that their clocks have the same speed, but that the high and the low portions of the waveform coincide.

In typical asynchronous serial communications bits are transmitted as separate groups, usually 7 to 10 bits long. Each group is called a character. The name character relates to the fact that in alphanumeric transmissions each bit group represents one numeric or alphabetic symbol. In reality, the term “character” is also applied to control codes, error codes, and other non-alphanumeric encodings.

Each character is sent in a frame consisting of a start bit, followed by a set of character bits, followed (optionally) by a parity bit, and finalized by one or more stop bits. The serial line is normally held marking, that is, at a logic 1 state. The change from logic high to logic low, signaled by the start bit, tells the receiver that a frame follows. The receiver reads the number of character bits expected according to the adopted protocol until a logic high, represented by one or more stop bits, marks the end of the frame.

Figure 14-1 shows the different elements in a serial communications bit stream. The term asynchronous reflects the fact that the time period separating characters is variable. The transmitter holds the line to logic high (marking state) until it is ready to send. The start bit (spacing state) is used to signal the start of a new character. The start bit is also used by the receiver to synchronize with the transmitter. The logic high and low regions of the signal wave occur at the same time. This compensates for drifts and small errors in the baud rate.

![Figure 14-1 Serial Communications Bit Stream](image-url)
This form of transmitting serial data is called *asynchronous* because the receiver resynchronizes itself to the transmitter using the start bit of each frame. The lack of synchronization does not refer to the bits within each frame, which must be in fact “synchronized,” but to the fact that characters need not come at a fixed time interval.

### 14.1.2 Synchronous Serial Transmission

An alternative approach to asynchronous serial data transmission is one in which the characters are sent in blocks with no framing bits surrounding them. In asynchronous communications, each character is framed by a start and a stop signal so that the receiver can know exactly where the character bits are located. In *synchronous communications*, the sender and receiver are synchronized with a clock or a signal that is part of the data stream.

In theory, synchronous communications implies that characters are sent out at a constant rate, in step with a clock signal. This scheme assumes that a separate line (or wire) is used for the clock signal, although, in some variations, the clock signal is contained in the transmitted characters. Alternatively, a clock line can be used to synchronize the moment in time at which the receiver reads the data line. In either case, it is this contained clock or command signal that identifies a synchronous transmission.

Most legacy PC communications systems are asynchronous, although the EIA232F standard supports both synchronous and asynchronous methods. The most common chip used in PC communications is the *UART* (*Universal Asynchronous Receiver and Transmitter*). An alternative chip called the USRT is used for synchronous communications and the USART (*Universal Synchronous/Asynchronous Receiver and Transmitter*) supports both.

Synchronous communications can be block- or bit-based. The block-based modes are also called character-based. In this mode, characters are grouped in blocks with each block having a starting flag, similar to the start bit used in asynchronous communications. Once the receiver and the transmitter are synchronized, the transmitter inserts two or more control characters known as *synchronous idle characters*, or SYNs. Then the block is sent and the receiver places the data in a memory storage area for later processing. Bit-oriented methods, on the other hand, are used for the transmission of binary data that is not tied to any particular character set.

### 14.1.3 PIC Serial Communications

Serial communications are often used in PIC programming, mostly due to the scarcity of available port lines. For example, an application in which a 16F84 PIC needs to read data in parallel from eight DIP switches and display the result, also in parallel, in eight LEDs, requires a total of 16 available port lines. But the 16F84 only has 13 lines, 8 in Port-B and 5 in Port-A; therefore, the application would not be feasible.

One possible solution is to find some way of reading the DIP switches serially; this requires three lines at most. Alternatively, the output data to the LEDs could be
transmitted serially, thus reducing the total lines required from 16 for parallel transmission, to six, or even less for serial transmission.

PIC communications can be designed both asynchronously and synchronously. Asynchronous modes are used when the same or compatible clock signals are available to both receiver and transmitter. For example, two PICs both running at the same clock rate can transmit and receive data using a single communications line, plus a common ground. PIC-to-PIC asynchronous data transmission mode is demonstrated later in this chapter with both circuit and code.

Asynchronous communications can be implemented by incorporating a dedicated IC, such as a UART or USART chip, in the circuit. PCs usually have one of these ICs, or functionally equivalent ones, in their implementation of the serial port. Some PICs include one or more serial circuits, which sometimes include a USART module. For example, the 16F877 PIC has two serial communication modules. One of them is the Master Asynchronous Serial Port, or MSSP. The other one is a USART. Later in this chapter we present serial communications programming examples using the USART module in the 16F877 PIC. Programs using the MSSP module are found in the chapter on EEPROM programming.

When communications take place between a PIC and a device that does not contain a clock, or whose clock runs at a different speed than the PIC’s, then synchronous communications is used. For example, a circuit can be designed using a shift register IC, such as the 74HC164, that performs an 8-bit serial-in, parallel-out function. In the previous example, it is possible to reduce the number of transmission lines by connecting the eight LEDs to the output ports of the 74HC164. But the 74HC164 contains no internal clock that runs at the speed of the 16F84. Thus, communications between the PIC and the shift register IC (74HC164 in this case) requires a clock or command signal transmitted through a separate line; that is, a synchronous serial transmission. In this chapter we present circuits and sample code showing synchronous communications between a PIC and one or more shift register ICs.

14.1.4 The RS-232-C Standard

RS-232-C was developed jointly by the Electronic Industries Association (EIA), the Bell Telephone System, and modem and computer manufacturers. The standard has achieved such widespread acceptance that its name is often used as a synonym for the serial port. EIA232F, published in 1997, is the latest update of RS-232-C. Today, RS-232-C is gradually being replaced by USB for local communications. USB is faster, has lower voltage levels, and uses smaller connectors that are easier to wire. USB has software support in most PC operating systems. On the other hand, USB is a more complex standard, requiring more complex software. Furthermore, serial ports are used to directly control hardware devices, such as relays and lamps, since the RS-232-C control lines can be easily manipulated by software. This is not feasible with USB.

In the following sections we describe the essential terminology and communications principles of RS-232-C.
Essential Concepts

The RS-232-C convention specifies that, with respect to ground, a voltage more negative than -3 V is interpreted as a 1 bit and a voltage more positive than +3 V as a 0 bit. Serial communications, according to RS-232-C, require that transmitter and receiver agree on a communications protocol. The following terminology refers to the RS-232-C communications protocol:

- **Baud period**: The rate of transmission measured in bits per second, also called the baud rate. In serial protocols, the transmitter and the receiver clocks must be synchronized to the same baud period.

- **Marking state**: The time period during which no data is transmitted. During the marking period, the transmitter holds the line at a steady high voltage, indicating logic 0.

- **Spacing state**: The time period during which data is transmitted. During the spacing period, the transmitter holds the line at a steady low voltage, indicating logic 1.

- **Start bit**: The transition that indicates that data transmission is about to start. The voltage low state that occurs during the start bit is called the spacing state.

- **Character bits**: The data stream composed of 5, 6, 7, or 8 bits that encode the character transmitted. The least significant bit is the first one transmitted.

- **Parity bit**: An optional bit, transmitted following the character bits, used in checking for transmission errors. If even parity is chosen, the transmitter sets or clears the parity bit so as to make the sum of the character’s 1 bits and the parity bit an even number. In odd parity, the sum of 1 bits is an odd number. If parity is not correct, the receiver sets an error flag in a special register.

- **Stop bits**: One or more logic high bits inserted in the stream following the character bits or the parity bit, if there is one. The stop bit or bits ensure that the receiver has enough time to get ready for the next character.

- **DTE (Data Terminal Equipment)**: The device at the far end of the connection. It is usually a computer or terminal. The DTE uses a male DB-25 connector, and utilizes 22 of the 25 available pins. DB-9 connectors with 9 pins are also used.

- **DCE (Data Circuit-terminating Equipment)**: Refers to the modem or other terminal of the telephone line interface. DCE has a female DB-25 connector, and utilizes the same 22 pins as the DTE for signals and ground. DB-9 connectors are also used.

- **Half-duplex**: A system that allows serial communications in both directions, but only one direction at a time. Half-duplex communications are reminiscent of radio communications where one user says the word “Over” to indicate the end of transmission. In other words, half-duplex is similar to a one-lane road in which traffic controllers at each end can direct flow in either direction, but only in one direction at a time.

- **Full-duplex**: A full-duplex system allows communication in both directions simultaneously. A full-duplex system is reminiscent of a two-lane highway in which traffic can flow in both directions at once.

The Serial Bit Stream

In the RS-232-C protocol, the transmission/reception parameters are selected from a range of standard values. The following are the most common ones:
Baud rate: 50, 110, 300, 600, 1200, 2400, 4800, 9600, and 19200

Data bits: 5, 6, 7, or 8.

Parity bit: Odd, even, or no parity.

Stop bits: 1, 1.5, or 2.

RS-232-C defines DTE (Data Terminal Equipment) and DCE (Data Circuit-terminating Equipment), sometimes called Data Communications Equipment. According to the standard, the DTE designation includes both terminals and computers and DCE refers to modems, transducers, and other devices. The serial port in a computer is defined as a DTE device.

**Parity Testing**

In RS-232 communications, a bit called a parity bit may optionally be transmitted along with the data. A parity bit provides a simple, but not too reliable, error test to detect data corruption that takes place during transmission. Parity can be even, odd, or none. Even or odd parity refers to the number of 1-bits in each data byte. The parity bit immediately follows the data bits.

If even parity is selected, the parity bit is transmitted with a value of 0 if the number of high bits is even. For example, the binary value:

```
0110 0011
```

contains a total of 4 one-bits; therefore, the parity bit is 0. By the same token, if even parity is selected, then the binary value

```
0101 0001
```

requires that the parity bit be 1. One way of describing the parity bit is to say that the bit is set to indicate a parity error; therefore, it serves as a parity error detector. Another description is that the parity coincides with the number of one-bits in the data, plus the parity bit. Thus, when even parity is selected the parity bit is added to the number of one-bits in the data to produce an even number.

Odd parity is the opposite of even parity. If odd parity were selected then the parity bit in the last example would be 0. Given odd or even parity, the sender counts the number of 1-bits and sets or clears the parity bit accordingly. The receiver, knowing that the parity is odd or even, can do likewise to determine if the number of 1-bits received matches the required parity setting.

Parity error checking is very primitive. In the first place, the parity error does not identify the bit or bits that cause the error. Furthermore, if an even number of bits are incorrect, then the parity bit would not show the error. On the other hand, over a long transmission, the parity check is likely to detect garbled data.

**Connectors and Wiring**

The RS-232-C standard requires specific hardware connectors with either 25 or 9 pins. The 25-pin connector is called a *D-shell connector*, or DB-25. The connector with 9 pins is called the *9-pin D-shell connector* or DB-9. In addition, the RJ-45 connector (the
name stands for Registered-Jack 45) is used for twisted-pair cables. RJ-45 use in RS-232-C serial interface is regulated by the EIA/TIA-561 standard. A common application of RJ-45 connectors is in Ethernet cables. Figure 14-2 shows the male DB-25, DB-9, and the female RJ-45 connectors.

![Figure 14-2 DB-25, DB-9, and RJ-45 Connectors](image)

The function assigned to each pin varies in the common connectors. Table 14.1 lists the assignment of the RS-232-C lines in the different hardware. The cable linking DTE and DCE devices is a parallel straight-through cable with no cross-over or self-connects.

### Table 14.1

<table>
<thead>
<tr>
<th>CONNECTOR CODE</th>
<th>CONNECTOR</th>
<th>CONNECTOR</th>
<th>FUNCTION</th>
<th>CODE NAME</th>
<th>DIRECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DB-25</td>
<td>DB-9</td>
<td>Ground</td>
<td>G</td>
<td>Output</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>Transmit data</td>
<td>TXD</td>
<td>Output</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>Receive data</td>
<td>RXD</td>
<td>Input</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>Request to send</td>
<td>RTS</td>
<td>Output</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>Clear to send</td>
<td>CTS</td>
<td>Input</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td>Data set ready</td>
<td>DSR</td>
<td>Input</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td>Chassis ground</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>Carrier detect</td>
<td>CD</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td>Data terminal ready</td>
<td>DTR</td>
<td>Output</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td>Ring indicator</td>
<td>RI</td>
<td>Input</td>
</tr>
</tbody>
</table>

The Null Modem

The RS-232-C standards describe the way a computer communicates with a peripheral device, such as a modem. In this case, the DTE and DCE lines serve as a communications control. In this context, DTE means data terminal equipment, such as a computer, and DCE is the abbreviation of data communication equipment, such as modems. Often, communications must take place in an environment that does not include a modem; for example, computers communicating with each other or with other devices such as a PIC-based board. In these cases, the use of the DTE/DCE communication lines in flow control is not well defined. The common RS-232-C control and data signals appear in Table 14.2.
Table 14.2

Definition of Common RS-232-C Lines

<table>
<thead>
<tr>
<th>SIGNAL NAME</th>
<th>DIRECTION</th>
<th>PURPOSE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CONTROL SIGNALS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Request to Send</td>
<td>DTE -&gt; DCE</td>
<td>DTE wishes to send</td>
</tr>
<tr>
<td>Clear to Send</td>
<td>DTE &lt;- DCE</td>
<td>Response to Request to Send</td>
</tr>
<tr>
<td>Data Set Ready</td>
<td>DTE &lt;- DCE</td>
<td>DCE ready to operate</td>
</tr>
<tr>
<td>Data Terminal Ready</td>
<td>DTE -&gt; DCE</td>
<td>DTE ready to operate</td>
</tr>
<tr>
<td>Ring Indicator</td>
<td>DTE &lt;- DCE</td>
<td>DTE receiving telephone ringing signal</td>
</tr>
<tr>
<td>Carrier Detect</td>
<td>DTE &lt;- DCE</td>
<td>DTE receiving a carrier signal</td>
</tr>
<tr>
<td><strong>DATA SIGNALS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmitted Data</td>
<td>DTE -&gt; DCE</td>
<td>Data generated by DTE</td>
</tr>
<tr>
<td>Received Data</td>
<td>DTE &lt;- DCE</td>
<td>Data generated by DCE</td>
</tr>
</tbody>
</table>

The term *null modem* refers to situations in which serial communications take place without the presence of a modem. In this case, the connection between the communicating devices, usually a cable, is wired in such a way so as to allow data transmission without a modem.

In Table 14.1 two pins are used in flow control: *RTS* *(request to send)* and *CTS* *(clear to send)*. In conventional RS232 communication (as is the case when a computer communicates with a modem), the RTS signal is an output and DCE an input. Before a character is sent, the sender sets the RTS line high to ask the DTE’s permission. Until the DTE grants permission, no data is sent. The DTE grants its permission by setting the CTS line high. If the DCE cannot receive new data it keeps the CTS signal low. This interface, which provides a simple mechanism for flow control in a single direction, is called a *handshake*.

In full duplex transmission the handshake must take place in both directions, that is, both devices must be able to signal their status. The *DTR* *(data terminal ready)* and *DSR* *(data set ready)* signals can be used for a second level of flow control. Finally, the *CD* *(carrier detect)* signal serves as an indication of the state of a modem.

**The Null Modem Cable**

Implementing handshaking without a modem requires that we take into account that two communicating devices can expect to find certain signals on given lines. For example, a device checks the CTS signal for a high value before sending data. If the CTS signal never goes high, transmission does not take place. When a cable is wired so that two devices can communicate without one of them being a modem, the cable is said to be a *null modem*.

One simple approach is to completely eliminate handshaking. In this case, cable wiring interconnects the transmit and the receive lines and the ground wire. The remaining pins are left unconnected, as shown in the null modem cable in Figure 14-3 (in the following page).
Null Modem with No Handshaking

The three-wire null modem cable can be used to interface devices that do not use modem control signals. However, if one of the devices checks one of the handshake lines, such as RTS/CTS, then the three-wire modem cable fails. To solve this problem, a modem cable can be designed so that the handshake signals are interconnected. For example, DTS to DSR and vice versa. Not knowing which handshake signals are to be used, manufacturers of standard modem cables usually interconnect all handshake lines, as shown in Figure 14-4.

Null Model With Full Handshaking

Some variations of the full-handshake null modem connect the DTR to the CD line at each end. Pin number 1 (CD) in both male and female connectors is dummied-out to pin number 4 (CDR).
A conventional, straight-through serial cable can be converted to null modem by means of a commercial null modem adapter that crosses over the corresponding signal lines. A continuity test is used to determine whether a serial cable is wired as null modem or not. If it is null modem, pin number 2 on one end would show continuity with number 3 pin on the other end.

A circuit tester is used to diagnose serial cables. The tester, which is plugged into the port connector, contains a LED for each of the communications lines. When the corresponding LED lights up the line is active. LED colors indicate positive or negative voltages, with green usually indicating positive and red negative. The light pattern is used to identify different handshakes. Figure 14-5 shows a DB-25 mini tester.

**Figure 14-5 DB-25 RS232 Line Tester**

### 14.1.5 The EIA-485 Standard

EIA-485 provides a two-wire, half-duplex serial connection standard, also known as RS-485. This convention provides a multipoint connection with differential signaling. The connection can be made full-duplex by using four wires. In this standard, data is conveyed by voltage differences. One polarity represents logic 1 and the reverse one logic 0. The standard requires that the difference of potential be at least 0.2 volts, but any voltage between +12 and -7 volts allows correct operation.

EIA-485 does not specify a data transmission protocol, making possible the implementation of simple, inexpensive local networks and communications links. Its data transmission speeds can reach 35 Mbits/s at distances of up to 10 m, and 100 kbit/s at distances up to 1200 m. The use of a twisted wire pair and the differential balanced line allows spanning distances of up to 4000 ft.

EIA-485 is often used with common UARTs and USARTs to implement low-speed data communications that require minimal hardware. It is also found in programmable logic controllers that are used with proprietary data communications systems. In factories and other electrically charged environments, the differential feature of EIA-485 makes it resistant to electromagnetic interference from motors and other
equipment. The standard also finds use in large sound systems, such as those found in theaters and music events. EIA-485 does not specify any connector.

**EIA-485 in PIC-based Systems**

In PIC-based systems, EIA-485 is often used to provide strong serial signals that can travel up to 4000 ft at high baud rates in noisy electrical environments. Only two wires are needed to carry the EIA-485 signals. These are usually labeled the A and B lines. Once the A/B data line is established, up to 32 devices can be connected to it. The system is referred to as an EIA-485 network.

Implementing the EIA-485 network requires some way of converting the 485 signal levels to the TTL-levels in the PIC circuit. This is accomplished by means of a dedicated IC, such as the Texas Instruments Differential Bus Transceiver chip named the SN75176. The chip actually converts 485 signals to RS-232-C TTL-level signals. This allows devices that traditionally communicate over RS-232-C serial connections to communicate over a two-wire EIA-485 network. Figure 14-6 shows the pin diagram of the SN75176.

![SN75176 PINOUT](pinout.jpg)

**Figure 14-6** Pin Out of the SN75176 IC

In addition to the SN75176, an EIA-485 circuit requires a 485 chip such as the MAX485. In PIC-based systems, the EIA-485 is sometimes used to communicate with multiple devices in a chain. It uses the same 8-bit asynchronous serial communications format as was described previously for RS-232-C.

### 14.2 Parallel Data Transmission

Parallel communications is the process of sending several bits of data simultaneously over individual data lines. In the computer environment, parallel communications are often associated with a popular printer interface developed by Centronics and sometimes called the Centronics or printer interface. Originally, the Centronics interface was designed for one-way communications. Later, it was made bi-directional, allowing its use in high-speed data transfers. The Centronics or parallel printer interface is now considered a legacy port.
In PIC-based systems, parallel communications often refer to the general principle rather than to the specific Centronics implementation. For example, wiring an 8-line toggle switch to the eight pins of the 16F85 Port-B line provides parallel communications between the switch and the PIC.

PIC circuits that use parallel data transfers offer many advantages. In the first place, parallel transmission is fast and the software is simple to develop. The hardware implementation is straightforward and does not require many additional components. Examples are connecting a multiple toggle switch to each of the lines of a PIC input port, or each of the pins of a seven-segment LED to the various pins of a PIC output port. The disadvantages of parallel systems are the distance limitations and the cost in system resources. Furthermore, parallel data transfers do not work well for data transmission over long distances. Many of the circuits and programs covered in previous chapters use parallel data transmission techniques. Since PIC-based systems rarely communicate with parallel printers or use the Centronics standard for data transfer, no further discussion of the Centronics standard is justifiable in this context.

14.2.1 PIC Parallel Slave Port (PSP)

Some PICs are equipped with an 8-bit Parallel Slave Port module (PSP). At present, the PSP is multiplexed onto Port D and is found in PICs of the mid-range family, such as the 16F877. The PSP is also called the microprocessor port.

The PSP module provides an interface mechanism with one or more microprocessors. The parallel slave port has an operating speed of 200 ns with a clock rate of 20 MHz, as well as several on-chip peripheral functions for implementing real world interfaces.

In PICs equipped with the PSP, the parallel slave port functions are assigned to Port D, with some Port E bits providing control signals. To initialize PSP mode, data direction bits in the TRISE register that correspond to RD, WR, and CS (TRISE<2:0>) are configured as inputs and the control bit PSPMODE (TRISE) is set. When the PSP mode is active, Port D is asynchronously readable and writable through the chip Select (RE2/CS), Read (RE0/RD), and Write (RE1/WR) control inputs.

At this time, not many general-purpose applications for the PSP port have been documented, outside of its use as a multi-microprocessor interface. For this reason we have excluded PSP programming from this context.

14.3 PIC “Free-style” Serial Programming

This section is about PIC serial programming and circuit design that does not follow any specific communications protocol. In this sense, we have used the expression “free-style” as opposed to circuits and programs constrained by the requirements of a standard or convention. Many self-contained PIC circuits that do not interface with standardized components can benefit from not having to follow any specific standard. Later in this chapter, and in other chapters in the book, we present examples of PIC circuits and programs that follow established communications protocols. The titles of
the corresponding sections refer to the specific standards or protocols; for example, the section titled *PIC RS-232-C Serial Programming* found in this chapter.

The advantages of so-called “free-style” circuit design and programming are greater in ease in development and the use of fewer hardware components. When designer and programmer are not constrained by the specifications of a standard, the circuit can be implemented with a minimal number of hardware components. By the same token, software is simpler and easier to develop.

The following examples of free-style communications systems are presented in the sections that follow:

1. A PIC to PIC communications circuit and program. Two programs are required: one for the receiver PIC and one for the sender.
2. Serial-to-parallel and parallel-to-serial circuit and program. Circuit uses 74HC164 and 74HC165 ICs.

### 14.3.1 PIC-to-PIC Serial Communications

Perhaps the most obvious and straightforward mode of PIC serial communications is one that takes place between two PICs. In this case, one PIC acts as a sender, or master, and the other one as a receiver or slave, although it is also possible for sender and receiver to exchange roles. Consider a circuit in which one PIC polls the state of a bank of switches and then sends the result serially to a second PIC that controls a bank of LEDs to be lighted according to the switch settings. The reason for this circuit is that some PICs may not have a sufficient number of ports to monitor eight switches and control eight LEDs.

#### PIC-to-PIC Serial Communications Circuits

Actually, the system required for one PIC reading data and serially sending the result to another PIC that outputs the data can be visualized as two separate circuits. One circuit is used to read the state of the eight DIP switches and to send the data serially to another PIC circuit that displays the results. Figure 14-7 shows the two PIC-based circuits.

Structurally, the circuits in Figure 14-7 are quite similar to ones described previously in this book. The bottom circuit contains eight DIP switches wired to ports RB0 to RB7. A pushbutton switch is wired to port RA2 and a LED to port RA3. The serial output is through port RA1. The circuit at the top of Figure 14-7 has eight LEDs wired to ports RB0 to RB7. There is a pushbutton on port RA2 and a LED on port RA3. Input into the circuit is through port RA0. In the remainder of this description we refer to the bottom circuit as the **sender circuit and PIC** and the one on the top as the **receiver circuit and PIC**.

The pushbuttons are necessary so that sender and receiver are synchronized. In operation, the receiver circuit is first activated by pressing the switch labeled “receive ready.” The LED on the top circuit lights to indicate the ready state. The sender circuit has a LED labeled “ready” that indicates its state. The user presses the switch labeled “send ready” in the sender circuit. At that time, the program in the sender reads the state of the DIP switches and sends the data out, one bit at a time, through the line labeled “serial out” in the diagram. The receiver reads the eight bits in its “serial in” line and lights the LEDs accordingly.
Figure 14-7  PIC-to-PIC Serial Communications Circuits
**PIC-to-PIC Serial Communications Programs**

The software consists of two different programs, one to run in the sender PIC and one in the receiver PIC. Asynchronous communications require that sender and receiver operate at the same data speed. Both devices need not run at the same clock speed, but both must synchronize data transmission and reception at the same clock rate. Since the easiest way to accomplish this is to have both PICs use the same oscillator at the same speed, we make this assumption in the programs that follow.

The instruction time and clock rate of a PIC are one-fourth of its clock speed. Thus, a PIC with a 4Mhz clock runs at 1,000,000 cycles per second, and the default timer speed is:

\[
\frac{1,000,000}{256} = 3,906.25 \mu s \text{ per bit}
\]

approximately 3,906µs per clock cycle. Although 3,906µs is not a standard baud rate, the present application is self-contained, therefore there is no need to conform to RS232-C or any other protocol.

Since it seems more intuitive to associate a high voltage with a logic 1 and a low voltage with a logic 0, we will adopt this convention in the present application. Nevertheless, we will borrow the character structure from the RS-232-C convention, that is, information will contain a start bit, a series of eight data bits, and a stop bit. No parity is implemented. Figure 14-8 shows the bit structure for one character in our application.

![Figure 14-8 Data Structure for PIC-to-PIC Application](image-url)
The sender program, named SerialSnd, performs the following initialization operations:

1. Line RA2 is initialized for input since the pushbutton switch is located on this line. Lines RB0 to RB7 are also input, since they are connected to the DIP switch array.

2. The prescaler is assigned to the Watchdog Timer so that channel TMR0 runs at full processor speed.

3. Interrupts are disabled.

Initialization code is as follows:

```assembly
; Port-A, bit 2 is input. All others are output
movlw b'00000100' ; Port-A bit 2 is input
               ; all others are output
tris porta
; Port-B is all input
movlw b'11111111'
tris portb
bsf porta,1       ;Marking bit
; Prepare to set prescaler
clrf tmr0
clrwdt
; Setup OPTION register for full timer speed
movlw b'11011000'
; 1 1 0 1 1 0 0 0 <= OPTION bits
; | | | | | ___|___PS2-PS0 (prescaler bits)
; | | | | | *000 = 1:2 001 = 1:4
; | | | | | 010 = 1:8 011 = 1:16
; | | | | | 100 = 1:32 101 = 1:64
; | | | | | 110 = 1:128 111 = 1:256
; | | | | |__________ PSA (prescaler assign)
; | | | | *1 = to WDT
; | | | 0 = to Timer0
; | | |__________ TOSE (Timer0 edge select)
; | | 0 = increment on low-to-high
; | | *1 = increment in high-to-low
; | |__________ TOCS (TMR0 clock source)
; | *0 = internal clock
; | 1 = RA4/TOCKI bit source
; |__________ INTEDG (Edge select)
; 0 = falling edge
; *1 = raising edge
; __________ RBPU pullups
; 0 = enabled
; *1 = disabled
option
; Disable interrupts
bcf intcon,5      ; Timer0 overflow disabled
```
Once initialized, the program performs the following functions:

1. The SEND READY LED is turned on.
2. Code monitors the SEND pushbutton switch.
3. Once the switch is pressed, the program turns off the SEND READY LED.
4. The state of the DIP switches is obtained by reading RB0 to RB7.
5. The byte from Port-B is sent through the serial line.

The following code fragment shows the procedure to send serial data.

```
bcf    intcon,7    ; Global interrupts disabled

;============================================================
; procedure to send serial data
;============================================================
; ON ENTRY:
;   local variable dataReg holds 8-bit value to be
;   transmitted through port labeled serialLN
; OPERATION:
;   1. The timer at register TMR0 is set to run at
;      maximum clock speed, that is, 256 clock beats.
;      The timer overflow flag in the INTCON register
;      is set when the timer cycles from 0xff to 0x00.
;   2. Each bit (start, data, and stop bits) is sent
;      at a rate of 256 timer beats. That is, each bit is
;      held high or low for one full timer cycle (256
;      clock beats).
;   3. The procedure tests the timer overflow flag
;      (tmrOVF) to determine when the timer cycle has
;      ended, that is when 256 clock beats have passed.
;
sendData:
    movlw 0x08    ; Setup shift counter
    movwf bitCount

;=============
; send START bit
;=============
; Set line low then hold for 256 timer clock beats.
    bcf    PORTA,serialLN    ; Send start bit
    clrf    TMR0            ; Reset timer counter
    bcf    INTCON,tmrOVF    ; Reset TMR0 overflow flag
    ; Wait for 256 timer clock beats
    startBit:
    btfss    INTCON,tmrOVF   ; timer overflow?
    goto    startBit        ; Wait until set

; At this point timer has cycled. Start bit has ended
    bcf    INTCON,tmrOVF    ; Clear overflow flag
```
Eight data bits are sent through the serial line starting with the high-order bit. The data byte is stored in the register named dataReg. The bits are rotated left to the carry flag. Code assumes the bit is zero and sets the serial line low. Then the carry flag is tested. If the carry is set the serial line is changed to high. The line is kept low or high for 256 timer beats.

```
send8:
  rlf dataReg,f ; Bit into carry flag
  bcf PORTA,serialLN ; 0 to serial line
  ; Code can assume the bit is a zero and set the line low since, if low is the wrong state, it will only remain for two timer beats. The receiver will not check the line for data until 128 timer beats have elapsed, so the error will be harmless. In any case, there is no assurance that the previous line state is the correct one, so leaving the line in its previous state could also be wrong.
  btfsc STATUS,c ; Test carry flag
  bsf PORTA,serialLN ; Bit is set. Fix error.

bitWait:
  btfss INTCON,tmrOVF ; Timer cycled?
  goto bitWait ; Not yet
  ; At this point timer has cycled.
  ; Test for end of byte, if not, send next bit
  bcf INTCON,tmrOVF ; Clear overflow flag
  decfsz bitCount,f ; Last bit?
  goto send8 ; not yet

;---------------------------
; hold MARKING state
;---------------------------
; All 8 data bits have been sent. The serial line must now be held high (MARKING) for one clock cycle
  bsf PORTA,serialLN ; Marking state

markWait:
  btfss INTCON,tmrOVF ; Done?
  goto markWait ; not yet

;---------------------------
; end of transmission
;---------------------------

return
The code comments explain the routine’s operation.

The receiving program, named SerialRcv, runs in the receiver PIC. In this case, the serial line is RA0. Input from the sender program is received through this line. The program performs the following initialization operations:

1. Lines RA0 and RA2 are initialized for input since the pushbutton switch is located on RA2 and RA0 is the serial input line. Lines RB0 to RB7 are output since they are wired to the eight LEDs.

2. The prescaler is assigned to the Watchdog Timer so that channel TMR0 runs at full processor speed.

3. Interrupts are disabled.

Once initialized, code performs the following functions:

1. The SEND READY LED is turned on.

2. Code monitors the RECEIVE READY pushbutton switch.

3. Once the switch is pressed, the program turns on the RECEIVE READY LED.

4. Code then monitors the serial line for the first low that indicates the leading edge of the start bit.

5. Once the start bit is detected, code waits for 128 clock cycles to locate the center of the start bit. This synchronizes the receiver with the sender and accommodates small timing errors.

6. The eight data bits are then received and stored.

7. After waiting for the stop bit, code turns off the RECEIVE READY LED and sets the eight LEDs according to the data received through the serial line.

The following code fragment is the procedure rcvData from the SerialRcv program:

```assembly
;============================================================
; procedure to receive serial data
;============================================================
; ON ENTRY:
;   local variable dataReg is used to store 8-bit value
;      received through port (labeled serialLN)
; OPERATION:
;   1. The timer at register TMR0 is set to run at
;      maximum clock speed, that is, 256 clock beats.
;      The timer overflow flag in the INTCON register
;      is set when the timer cycles from 0xff to 0x00.
;   2. When the START signal is received, the code
;      waits for 128 timer beats so as to read data in
;      the middle of the send period.
;   3. Each bit (start, data, and stop bits) is read
;      at intervals of 256 timer beats.
;   4. The procedure tests the timer overflow flag
;      (tmrOVF) to determine when the timer cycle has
```
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; ended, that is when 256 clock beats have passed.
;==============================================
rcvData:
    clr TMR0 ; Reset timer
    movlw 0x08 ; Initialize bit counter
    movwf bitCount
    ;===========================================
    ; wait for START bit
    ;===========================================
startWait:
    btfsc PORTA,0 ; Is port A0 low?
    goto startWait ; No. Wait for mark
    ;===========================================
    ; offset 128 clock beats
    ;===========================================
    ; At this point the receiver has found the falling
    ; edge of the start bit. It must now wait 128 timer
    ; beats to synchronize in the middle of the sender’s
    ; data rate, as follows:
    ;    |<========== falling edge of START bit
    ;    |
    ;    |-----|<====== 128 clock beats offset
    ;    -----------. | .-------
    ;    | | <== SIGNAL
    ;    -----------
    ;    |<---256--->|
    ;
    movlw 0x80 ; 128 clock beats offset
    movwf TMR0 ; to TMR0 counter
    bcf INTCON,tmrOVF ; Clear overflow flag
offsetWait:
    btfss INTCON,tmrOVF ; Timer overflow?
    goto offsetWait ; Wait until
    btfsc PORTA,0 ; Test start bit for error
    goto offsetWait ; Recycle if a false
start
    ;===========================================
    ; receive data
    ;===========================================
    clr TMR0 ; Restart timer
    bcf INTCON,tmrOVF ; Clear overflow flag
    ; Wait for 256 timer cycles for first/next data bit
bitWait:
    btfss INTCON,tmrOVF ; Timer cycle end?
    goto bitWait ; Keep waiting
    bcf INTCON,tmrOVF ; Reset overflow flag
    movf PORTA,w ; Read Port-A into w
Neither the SerialRcv nor the SerialSnd programs contain any handshake signal. The programs rely on the user turning-on the receiver before the send function is activated. If this is not the case, the programs fail to communicate. But looking at the circuit diagram in Figure 14-7, we notice that there are available ports in both receiver and sender circuits. The circuit designer could interconnect two ports, one in the receiver and one in the sender, so as to provide a handshake signal.

For example, lines RA4 in both circuits can be interconnected. Then Port-A, line 4, in the sender circuit is defined as input and the same line as output in the receiver. The receiver could then set the handshake line high to indicate that it is ready to receive. The sender monitors this same port and does not start the transmission of each character until it reads that the handshake line is high. In this manner, the receiver can suspend transmission at any time and prevent data from being lost. At the same time, the “receiver ready” and “send ready” LEDs can be eliminated.

### 14.3.2 Program Using Shift Register ICs

The problem of handling multiple input and output lines, which was resolved in the previous example by using two PICs, can also be tackled by means of special-purpose integrated circuits. The term *shift register* refers to the fact that register input and output are connected in a way that data is shifted-down a set of flip-flops when the circuits are activated. Many variations of shift registers ICs are available, the most popular ones being serial-in to serial-out, parallel-in to parallel-out, serial-in to parallel-out, and parallel-in to serial-out. In shift register terminology the *in* and *out* terms refer to the function in the registers themselves, and are not related to the functions that these elements perform in a particular circuit. Figure 14-9 shows an input/output circuit using shift registers.

The circuit in Figure 14-9 shows the use of a parallel-to-serial IC (74HC165) that reads the state of eight input switches, and a serial-to-parallel IC (74HC164) that outputs data to eight LEDs. Without the shift register ICs, the circuit would require sixteen ports, more than those available in the 16F84. Using the shift registers, only six PIC ports are required, leaving eight ports available on the PIC. The demonstration program for the circuit in Figure 14-9 is named Serial6465.
The 74HC165 Parallel-to-Serial Shift Register

The 74HC165 (sometimes called the 165) is a parallel-in, serial-out high-speed 8-bit shift register. Shift registers are discussed in Section 6.4.7. Figure 14-10 (in the following page) shows the pin-out of the 74HC165.
In the 165, pins 3 to 6 and 11 to 14 (labeled D0 to D7) are used as parallel data input lines. Normally these pins are connected to input sources, such as switches or other two-state devices. Serial output takes place through pin number 9, labeled serial output Q. An inverted output is available at pin number 7. The shift/load control line, at pin number 1, is used to latch the data into the 165 shift registers. For example, assume that the 165’s input lines are connected to sources that can change state in time. These highs and lows are not recorded internally in the 165 until the shift/load line is pulsed. When this line is pulsed, line values are said to be latched. After the data lines are latched, the 165 clock-line is pulsed in order to sequentially shift-out each of the eight bits stored internally. Shifting takes place with the most significant bit first. The actual operations are as follows:

1. A local data storage register is cleared and a local counter is initialized for 8 data bits.
2. The 165 shift/load line is pulsed to reset the shift register.
3. The status of the serial output line (165 pin number 9) can now be read to determine the value of the bit shifted out.
4. The bit is stored in a data register and the bit counter is decremented. If the last bit was read the routine ends.
5. If not, the clock line is pulsed to shift-out the next bit. Execution continues at step number 3.

The wiring of the 165 normally requires at least three interface lines with the PIC. One line connects to the 165 serial output (pin number 9), another one to the clock line (pin number 2), and a third one to the shift/load line (pin number 1). The eight 165 data lines are normally wired to the input source.
The following code fragment lists a procedure to interface a 16F84 PIC with a 74HC165 parallel-to-serial shift register:

```assembly
; Constant definitions from wiring diagram
#define clk65LN 1 ;| — 74HC165 lines
#define loadLN 2 ;|

; 74HC165 procedure to read parallel data and send
; serially to PIC

; OPERATION:
; 1. Eight DIP switches are connected to the input
; ports of an 74HC165 IC. Its output line Hout,
; and its control lines CLK and load are connected
; to the PIC’s Port-B lines 0, 1, and 2
; respectively.
; 2. Procedure sets a counter (bitCount) for 8
; iterations and clears a data holding register
; (dataReg).
; 3. Port-B bits are read into w. Only the lsb of
; Port-B is relevant. Value is stored in a working
; register and the meaningful bit is rotated into
; the carry flag, then the carry flag bit is
; then shifted into the data register.
; 4. The iteration counter is decremented. If this
; is the last iteration the routine ends. Otherwise
; the bitwise read-and-write operation is repeated.

in165:
    clrf dataReg ; Clear data register
    movlw 0x08 ; Initialize counter
    movwf bitCount
    bcf PORTB,loadLN ; Reset shift register
    bsf PORTB,loadLN

nextBit:
    movf PORTB,w ; Read Port-B (only LOB is
                   ; meaningful in this routine)
    movwf workReg ; Store value in local
    ;register
    rrf workReg,f ; Rotate LOB bit into carry
                   ; flag
    rlf dataReg,f ; Carry flag into dataReg
    decfsz bitCount,f ; Decrement bit counter
    goto shiftBits ; Continue if not zero
```
The procedure is in the program Serial6465 listed at the end of this chapter.

**74HC164 Serial-to-Parallel Shift Register**

The circuit in Figure 14-9 also uses a 74HC164 serial-to-parallel shift register for output to the eight LEDs. Figure 14-11 shows the pin-out of the 74HC164 IC.

---

Serial input into the 164 is through the input A line (pin number 1). Parallel output is through the lines labeled Q0 to Q7. The reset/clear line (on pin 9) and the clock line (on pin 8) provide the control functions. The operations are as follows:

1. A local data storage register holds the 8-bit value that serves as data input. A local counter is initialized for 8 data bits.
2. The 164 shift register is cleared by pulsing the reset/clear line.
3. The first/next bit of the data operand is placed on the input line.
4. Bit is shifted-in by pulsing the 164 clock line.
5. Bit counter is decremented. If it goes to zero the routine ends.
6. Otherwise, the bits in the source operand are shifted and execution continues at step number 3.

The following code fragment lists a procedure to interface a 16F84 PIC with a 74HC164 serial-to-parallel shift register:

```plaintext
;=====================================================
; constant definitions from wiring diagram
;=====================================================
#define clockLN 1

; Return ; done
shiftBits:
    bsf PORTB,clk65LN ; Pulse clock
    bcf PORTB,clk65LN
    goto nextBit ; Continue
```

**Figure 14-11 74HC164 Pin Out**

Serial input into the 164 is through the input A line (pin number 1). Parallel output is through the lines labeled Q0 to Q7. The reset/clear line (on pin 9) and the clock line (on pin 8) provide the control functions. The operations are as follows:

1. A local data storage register holds the 8-bit value that serves as data input. A local counter is initialized for 8 data bits.
2. The 164 shift register is cleared by pulsing the reset/clear line.
3. The first/next bit of the data operand is placed on the input line.
4. Bit is shifted-in by pulsing the 164 clock line.
5. Bit counter is decremented. If it goes to zero the routine ends.
6. Otherwise, the bits in the source operand are shifted and execution continues at step number 3.

The following code fragment lists a procedure to interface a 16F84 PIC with a 74HC164 serial-to-parallel shift register:

```plaintext
;=====================================================;
; constant definitions from wiring diagram
;=====================================================;
define clockLN 1
```
#define clearLN 2 ;| — 74HC164 lines
#define dataLN 0 ;|
...

;============================================================
; 74HC164 procedure to send serial data
;============================================================
; ON ENTRY:
;   local variable dataReg holds 8-bit value to be
; transmitted through port labeled serialLN
; OPERATION:
;   1. A local counter (bitCount) is initialized to
;      8 bits
;   2. Code assumes that the first bit is zero by
;      setting the data line low. Then the high-order
;      bit in the data register (dataReg) is tested.
;      If set, the data line is changed to high.
;   3. Bits are shifted in by pulsing the 74HC164
;      clock line (CLK).
;   4. Data bits are then shifted left and the bit
;      counter is tested. If all 8 bits have been sent
;      the procedure returns.
out164:
; Clear 74HC164 shift register
   bcf PORTA,clearLN ; 74HC164 CLR clear low
   bsf PORTA,clearLN ; then high again
; Init counter
   movlw 0x08 ; Initialize bit counter
   movwf bitCount
sendBit:
   bcf PORTA,dataLN ; Set data line low (assume)
; Using this assumption is possible because the bit is not
; shifted in until the clock line is pulsed.
   btfsc dataReg,highBit ; test number bit 7
   bsf PORTA,dataLN ; Change assumption if set
;========================
; pulse clock line
;========================
; Bits are shifted in by pulsing the 74HC164 CLK line
   bsf PORTA,clockLN ; CLK high
   bcf PORTA,clockLN ; CLK low
;========================
; Rotate data bits left
;========================
   rlf dataReg,f ; Shift left data bits
   decfsz bitCount,f ; Decrement bit counter
   goto sendBit ; Repeat if not 8 bits
;========================
; end of transmission
It is important to note that serial communications that use shift register ICs are
described as synchronous. Synchronous serial transmission requires that the sender
and receiver use the same clock signal or that the sender provide signal or pulse so
as to indicate to the receiver when to read the next data element from the line. In the
circuits discussed in this section the shift/load, reset/clear, and clock lines provide
this synchronous interface between the PIC and the shift register IC.

The program named Serial6465, in the book's online software, is a demonstration
of PIC-to-shift register interfacing.

14.4 PIC Protocol-based Serial Programming

In the preceding sections we discussed circuits and developed software using PIC se-
rial communications that did not conform to any particular protocol or standard. This
style is adequate for stand-alone applications and circuits. On the other hand,
PIC-based circuits sometimes communicate with systems that conform to a specific
communications standard, for example, with a PC through its RS-232-C serial port. In
this case, the PIC software and hardware must conform with the protocol, at least to
an operational minimum that ensures satisfactory interfacing with the protocol-based
system.

In the context of protocol-based programming, two situations are possible: either
the PIC in use supports the communications standard or protocol or it does not. In
the case of the smaller PICs, such as the 16F84, the software emulates communications
protocols since hardware provides no support. The more complex PICs, on the
other hand, often contain hardware modules that provide a functionality equivalent
to that required by the various standards. In this sense, mid-range and high-range
PICs often include hardware support for one or more communication standards and
conventions. For instance, the 16F87X PIC family includes an MSSP (Master Syn-
chronous Serial Port) module and a USART (Universal Synchronous/asynchro-
ous Receiver and Transmitter) module.

In the sections that follow we develop circuits and programs for cases in which
the on-board PIC does not contain hardware support for the standard and for cases
in which it does. Examples with PICs that do not provide hardware support for se-
rial communications use the 16F84. Examples with PICs that provide hardware se-
rial communications support use the 16F877, which contains an MSSP and a USART
module. The 16F877 circuits and applications in the present chapter use the proces-
sor's USART module. The 16F877 MSSP module is demonstrated in the chapter on
EEPROM programming.

14.4.1 RS-232-C Communications on the 16F84

The UART (Universal Asynchronous Receiver/Transmitter) controller is a serial
communications IC found in computers and other data communication devices. In the
PC, the UART was originally National Semiconductor INS8250. With the introductions
of the PC AT, IBM changed its serial IC to the NC16450, an improved 8250. Later PCs
adopted the NS16550A UART as their serial communications controllers. Other vendors, including Intel and Western Digital, furnish clones of the NS16550A and other UARTs.

The UART-based serial port implementation and circuitry in the PC is compliant with RS/EIA232. For a PIC-based circuit to communicate with a PC’s serial port it must either implement in hardware or emulate in software the RS232 signals and protocol. One possibility is to include a UART or UART-like IC in the circuit. But this option is not simple to implement since RS-232-C requires voltage levels that are not TTL-compatible.

For PIC-based systems without a UART module, a viable approach is to emulate UART functions in software, at least those required for interfacing with the PC hardware. This is quite feasible due to the availability of dedicated ICs that provide RS-232-C-compatible signals and voltage levels in systems in which a ±12 volt source is not available. These chips, sometimes called RS-232-C Drivers/Receivers or Transceivers, are especially useful in interfacing UART and USART-based systems with PIC-based hardware.

**The RS-232-C Transceiver IC**

RS-232-C interface ICs are available from several vendors, although the ones from Dallas Semiconductors’ Maxim line are probably the most popular. These chips, sometimes called RS-232-C driver/receivers, have in common the use of so-called charge-pump DC/DC converters that generate, from the +5 volt TTL power source, the polarities and voltage levels required by RS-232-C.

One of the most popular implementations of the RS-232-C transceiver used in PIC-based systems is the MAX232 and its upgrade, the MAX202. One improvement in the MAX202 is to provide some degree of human-body electrostatic discharge protection (ESD), a desirable feature in experimenter boards. Other versions are the MAX233 and MAX203, which do not require external capacitors. Other RS-232-C transceiver ICs with various additional features, such as automatic shutdown, are available. Figure 14-12 is a pin-out of the MAX232 and 203 ICs.
Note that the MAX232 and MAX202 consist of two drivers and two receivers per chip. Lines 14 and 7 (labeled D1out and D2out) provide RS-232-C output. Lines 13 and 8 (labeled R1in and R2in) are RS-232-C input. Lines 10 and 11 (labeled D1in and D2in) are TTL (or CMOS) inputs. Lines 9 and 12 (labeled R2out and R1out) are TTL output. In this designation the letter R stands for receiver and the letter D for driver. The digit 1 indicates the first driver/receiver set and the digit 2 the second one. The lines labeled D are wired to capacitors.

A circuit using the transceiver ICs is simple and easy to build. If a single communication line is required, then the TTL input line can be wired to pin 10 (D2in) and the TTL output to pin 9 (R2out). The RS-232-C input is wired to pin 8 (R2in) and the output to pin 7 (D2out). Later in this section, we present a circuit that uses the MAX202 with a 16F84 PIC.

**PIC to PC Communications**

Often, a PIC-based circuit has to communicate with a device that conforms to a standard communications protocol. One of the most common cases is a PIC board that interfaces with a computer, usually a PC or Mac with an RS-232-C port. For example, a PIC board is placed somewhere to collect information, such as temperature, pressure, and humidity. Before the internal storage capacity of the PIC board is exhausted, it is connected to a laptop PC and the data is downloaded from the PIC board to the computer. Once this is done, then the local PIC memory is cleared so that new data can be collected and stored. This application, called a *data logger*, requires some way of transferring data from the PIC-based board to the PC. The RS-232-C line is often available on the PC end and the required interface hardware and programming is uncomplicated.

On the PC end, the communications software can be off-the-shelf applications or especially developed programs. If the purpose is simply to download data to the PC or send simple commands to the PIC board, then a standard utility is used. For example, the Windows program named *Hyper Terminal* allows sending and receiving files and commands at various baud rates and RS-232-C communications parameters. *Hyper Terminal* is included with most Windows versions or can be downloaded free from the developer’s website.

The PIC board must have a system that conforms to the communications protocol of the device, in this case, the PC. In order to use the PC’s serial port, PIC hardware and software must be able to generate required signal levels, baud rate, and other RS-232-C communications parameters. Hardware interfacing is implemented by using a transceiver chip, such as the MAX232 or 202 previously described. If the PIC contains a UART or USART module, then the communications software is easy to develop. This case is explored later in this chapter.

**An RS-232-C TTY Board**

The terms “teletype” and “teletypewriter” refer to an obsolete electro-mechanical typewriter that was used to send and receive information through a simple communication channel. In a modern sense, TTY refers to a simple style of communications where the same device sends and receives text messages interactively. The current board is actually a TTY receiver since it does not contain a keyboard that allows sending data. Figure 14-13 shows the circuit diagram for an 16F84-based PC-to-PIC serial communications board.
The circuit in Figure 14-13 contains previously discussed components. The LCD is wired in 4-bit mode, with control lines for RS (reset), E (pulse), and R/W (read/write). The MAX202 provides the TTL-to-RS-232-C conversion and vice versa. The physical connection between the PC and the PIC board is by means of a DB-9 connector and a standard null modem cable. The cable is not shown in the circuit diagram.

**Figure 14-13 PC-to-PIC Serial Communications Circuit**

**A 16F84A UART Emulation**

The 16F84A PIC contains no built-in facilities for RS-232-C communications. Therefore, a 16F84A application that communicates through the serial port using the RS-232-C protocol must emulate the protocol in software. The programs previously developed for PIC-to-PIC communications, discussed in Section 14.3.1, serve as a base for the UART emulation application. The major differences between a “free style” PIC communications program and one that complies for RS-232-C are the following:
1. Data must be transmitted and received at one of the standard RS-232-C baud rates. The most often-used baud rates in this case are: 600, 1,200, 2,400, 4,800, 9,600, and 19,200.

2. Data must be formatted according to the protocol’s conventions; that is, a start bit, 5, 6, 7, or 8 data bits, the presence or absence of a parity bit, and 1, 1½, or 2 stop bits.

3. RS-232-C communication data is transmitted and received with the least-significant-bit first.

The first problem (transmitting and receiving at a standard baud rate) often requires an approximation. The PIC’s instructions execute at the rate of its internal clock, which also determines the rate of its timer module.

The time taken by each counter iteration is obtained by dividing the PIC’s clock speed by four. For example, a PIC running on a 4 Mhz oscillator clock increments the counter every 1 Mhz. The counter register is incremented at a rate of 1µs (assuming no prescaler). If we were to use the unmodified timer rate to measure bit time, the result would be a baud rate of approximately 3,906. Since 3,906 is not a standard baud rate, the timer is adjusted to approximate one of the standard RS-232-C baud rates. For example, at 4,800 baud the bit time per bit is:

\[
\frac{1}{4,800} = 208.33\mu s.
\]

Since the timer of a PIC with a 4 Mhz clock runs at 1 µs per timer iteration, then we could count up from 0 to 208 iterations of the counter in order to approximate the bit time of 208 µs needed at 4,800 baud. In addition, we would have to calculate one-half the bit time since synchronization requires offsetting the timer from the edge to the center of the start bit (see Section 14.3.1). In this case, to delay approximately 104 µs we would count up from 0 to 104.

But counting up is inconvenient with the PIC timer/counter since the signal is produced when the counter reaches its maximum. A better solution is to preset the Timer counter (TMR0) to a calculated value such that the desired time lapse occurs when the Timer register reaches 255. So the actual delays for 4,800 baud are as follows:

<table>
<thead>
<tr>
<th>DELAY</th>
<th>CALCULATION</th>
<th>TMR0 PRESET</th>
</tr>
</thead>
<tbody>
<tr>
<td>208 µs</td>
<td>255 - 208</td>
<td>48</td>
</tr>
<tr>
<td>104 µs</td>
<td>255 - 104</td>
<td>151</td>
</tr>
</tbody>
</table>

Once we have obtained the clock rate for a standard baud rate, it is easy to obtain slower standard rates by slowing down the clock with the prescaler. For example, if the prescaler is assigned to the timer/counter register with a bit value of 000, then the counter rate is one-half the unscaled rate. This would produce a baud rate of 2,400 baud. By the same token, assigning a 1:4 prescaler to the timer produces a baud rate of 1,200 baud using the same preset values previously calculated. Faster baud rates are easily calculated by the same method.
Formatting the data transmission according to the RS-232-C protocol presents no major problem. In fact, the communications programs previously listed in this chapter use a start bit to commence character transmission, followed by eight data bits, and one stop bit to end it, with no parity bit. This same format is compatible with RS-232-C.

The third compatibility issue refers to the bit order in RS-232-C, which requires that the low-order bit be transmitted first. In previous applications, we have sent the high-order bit first by rotating the bits left inside the holding register and testing the carry flag. In the RS-232-C routine, the bits are rotated right into the carry flag and then the carry flag is rotated into the storage variable.

The demonstration program for the circuit in Figure 14-13, named TTYUsart, uses a 2-line by 16 character LCD to display the characters received from the PC through the serial line. The program initially sends the test string “Ready-” to the PC to test the data transmission routine and to let the PC user know that the PIC board is ready to receive. The program operates at 2,400 baud, one start bit, eight data bits, no parity, and one stop bit. The communications program on the PC must be set to these parameters.

**An LCD Scrolling Routine**

LCDs have limited capacity for data display. A 2-line by 16 character LCD fills the screen when 32 characters are displayed. For some applications it is convenient to have a procedure that takes some reasonable action when the LCD screen is full. One approach is to detect when the last character in the second LCD line is displayed, then move the second line to the first line, clear the second line, and continue displaying at the start of the second line. This is the standard screen handling for a computer program.

An LCD screen scroll routine can be called as each character is displayed. For the scroll to work, the program must keep track of the currently selected LCD line (variable LCDline can be 0 for line 1, and 1 for line 2), of the number of characters displayed on that line (variable LCDcount), and of the total capacity of the line (constant LCDlimit). Given this information, the logic for an LCD line scrolling routine can be as follows:

1. Add current character to LCDcount. If LCDcount is equal to LCD limit then the end of a line was reached. If not, exit routine.
2. If line end reached is for line 1, set current display address to start of line 2. Reset variable LCDcount. Exit routine.
3. If line end reached is for line 2, then copy the characters displayed in line 2 to line 1. Clear line 2. Reset the display address to the start of line 2. Reset LCDline variable to line 2. Reset variable LCD count. Exit routine.

Of these operations, copying the characters from the second line to the first one can be the most troublesome. One possibility is to read the data from the LCD directly. This approach requires that the connection between the PIC and the LCD includes the R/W line. Another option is to create a buffer in RAM and copy each character displayed to this area. In the case of an LCD with 16 characters per line
the buffer requires a capacity of 16 bytes. Since the line input is “remembered” in the buffer, the program scrolls a line by copying the contents of the buffer to the other line. This alternative does not require reading the LCD and saves implementing the R/W line.

Storing the characters received in a local buffer first requires reserving a 16-byte area (the buffer) in PIC RAM. There are several ways of accomplishing this. A simple one is using the **cblock** directive, as shown in the following code fragment:

```assembly
;=====================================================
; buffer and variables in PIC RAM
;=====================================================  
; Create a 16-byte storage area
  cblock 0x0c ; Start of first data block
  lineBuf ; buffer for text storage
endc
; Leave 16 bytes and continue with local variables;
  cblock 0x1c ; Second data block
  count1 ; Counter # 1
  count2 ; Counter # 2
. . . other variables can go here
endc  
```

In reality, the buffer is most likely accessed by indirect addressing, so a buffer name (lineBuf in this case) is not really necessary. This is due to the fact that PIC assembly language does not contain a directive for finding the address of a variable. So the buffer address has to be hard-coded or defined in a constant. But, in any case, having a buffer name does not cost storage capacity and it may help make the code clearer.

In our design, the scrolling routine depends on finding the characters in the ending line stored in the RAM area mentioned in the preceding paragraph. The buffer locations are accessed directly by referencing the address. For example, the first byte in lineBuf is stored at address 0x0c, the second one at 0x0d, and so on. A more effective way of using a buffer is by creating and keeping a **buffer pointer variable** that has the current offset from the start of the buffer. The buffer pointer is then added to the buffer’s base address in order to access the current buffer location. Indirect addressing using the FSR and the INDF registers simplify the process, as shown in the following code fragment:

```assembly
; Store character in local line buffer using indirect
; addressing. Byte to store is in rcvData variable.
; 16-byte buffer named lineBuf starts at address 0x0c
; Register variable bufPtr holds offset into buffer
  movlw 0x0c ; Buffer base address
  addwf bufPtr,w ; Add pointer in w
  movwf FSR ; Value to index register
  movf rcvData,w ; Character into w
  movwf INDF ; Store w in [FSR]
  incf bufPtr,f ; Bump pointer
```
The manipulation requires loading the base address of the buffer (0x0c in this case) in the w register, adding the value stored in the buffer pointer variable (bufPtr), and storing the sum in the FSR register. The character is then loaded into the w register and moved into the INDF register, which has the effect of storing it in the address pointed at by FSR. Conventionally, brackets are used to indicate indirect addressing, so [FSR] means the memory location referenced by the FSR register.

Once the line characters are stored locally, all that is left is the design of a line scrolling routine following the processing steps previously listed. The following procedure performs the necessary operations:

```assembly
;==========================
; scroll LCD line 2
;==========================
; Procedure to count the number of characters displayed on each LCD line. If the number reaches the value in the constant LCDlimit, then display is scrolled to the second LCD line. If at the end of the second line, then the second line is scrolled to the first line and display continues at the start of the second line reset to the first line.
LCDscroll:
    incf LCDcount,f        ; Bump counter
    movf LCDcount,w
    sublw LCDlimit          ; Count minus limit
    btfss STATUS,z          ; Is count - limit = 0
    goto scrollExit         ; Go if not at end of line

    ; At this point the end of the LCD line was reached
    ; Test if this is also the end of the second line
    movf LCDline,w
    sublw 0x01               ; Is it line 1?
    btfsc STATUS,z           ; Is LCDline minus 1 = 0?
    goto line2End            ; Go if end of second line

    ; At this point it is the end of the top LCD line
    call line2               ; Scroll to second line
    clrf LCDcount            ; Reset counter
    incf LCDline,f           ; Bump line counter
    goto scrollExit

; End of second LCD line
line2End:
; Scroll second line to first line. Characters to be scrolled are stored in buffer starting at address 0x0c.
; 16 characters are to be moved
; First clear LCD
    call initLCD
    call delay_5             ; Make sure not busy
; Set up for data
bcf PORTA,E_line ; E line low
bsf PORTA,RS_line ; RS line high for data
; Set up counter for 16 characters
movlw D'16' ; Counter = 16
movwf count2
; Get address of storage buffer
movlw 0x0c
movwf FSR ; W to FSR
getchar:
    movf INDF,w ; get character from display RAM
    ; location pointed to by file select
    ; register
call send8 ; 4-bit interface routine
; Test for 16 characters displayed
decfsz count2,f ; Decrement counter
goto nextchar ; Skipped if done
; At this point scroll operation has concluded
clf LCDcount ; Clear counters
; Stay at line 2
clf LCDline
incf LCDline,f
call line2 ; Set for second line
scrollExit:
    return
nextchar:
    incf FSR,f ; Bump pointer
goto getchar
;============================
; clear line buffer
;============================
; Use indirect addressing to store 16 blanks in the
; buffer located at 0x0c
blankBuf:
Bank0
movlw 0x0c ; Pointer to RAM
movwf FSR ; To index register
blank16:
    clrf INDF ; Clear memory pointed at by FSR
    incf FSR,f ; Bump pointer
    btfss FSR,4 ; 00000000 when bit 4 is set
    ; count reached 16
    goto blank16
    return
;============================
; Set address register
; to LCD line 1
;==================================
; ON ENTRY:
Address of LCD line 1 in constant LCD_1

line1:

bcf PORTA, E_line ; E line low
bcf PORTA, RS_line ; RS line low, set up for control

call delay_5 ; busy?

; Set to second display line
movlw LCD_1 ; Address and command bit
call send8 ; 4-bit routine

; Set RS line for data
bsf PORTA, RS_line ; Setup for data
call delay_5 ; Busy?

; Clear buffer and pointer
call blankBuf
clrwf bufPtr ; Pointer

return

;===================================
; Set address register
; to LCD line 2
;===================================

; ON ENTRY:

Address of LCD line 2 in constant LCD_2

line2:

bcf PORTA, E_line ; E line low
bcf PORTA, RS_line ; RS line low, setup for control

call delay_5 ; Busy?

; Set to second display line
movlw LCD_2 ; Address with high-bit set
call send8 ; 4-bit routine

; Set RS line for data
bsf PORTA, RS_line ; RS = 1 for data
call delay_5 ; Busy?

; Clear buffer and pointer
call blankBuf
clrwf bufPtr ; Pointer

return

The entire program, named TTYUsart, is found in the book’s online software package.

14.4.2 RS-232-C Communications on the 16F87x

The second alternative for protocol-compliant communications is using a PIC that provides hardware support for the standard. The 16F84, our workhorse in this book, contains no such facilities. However, other midrange PICs do provide hardware support to one or several serial communications protocols.
For the examples that follow, we have selected what is perhaps the second most popular PIC of the midrange family (after the 16F84): the 16F87x. The architecture and basic programming facilities of the 16F87x PIC family were discussed in Chapter 8. At this time, we should recall that 16F87x includes the PIC 16F873, 16F874, 16F876, and 16F877. For our sample programs we have selected the 16F877 since it is the most powerful one of the group. The 16F877 has an operating frequency of up to 20Mhz, 8K of flash program memory, 368 bytes of data memory, 256 bytes of EEPROM, 5 input/output ports, and contains two modules for serial communications: a Master Synchronous Serial Port and a Universal Synchronous/Asynchronous Receiver and Transmitter. We focus on the USART module and leave the MSSP for the chapter on EEPROM programming.

The 16F87x USART Module

The Universal Synchronous Asynchronous Receiver Transmitter (USART) module in the 16F87X family is also known as a Serial Communications Interface, or SCI. The USART module is useful in communicating with devices and systems that support RS-232-C communications, including computers and terminals. It can be configured as an asynchronous full-duplex device, as a synchronous half-duplex master, or as a synchronous half-duplex slave. In the synchronous mode, the USART module is used mostly in communicating with analog-to-digital and digital-to-analog integrated circuits or for accessing serial EEPROMS. Both of these functions are discussed in later chapters.

Five registers relate to USART operation in the 16F877: RCSTA, TXREG, RCREG, TXSTA, and SPBRG. The first three are located in bank 0 and the second two in bank 1. TXSTA is the Transmit Status and Control register and the RCSTA the Receive Status and Control register. Figure 14-14 shows the bitmap for the TXSTA register located at address 0x98 in bank 1.

The RCSTA register contains control and status bits for the receive function. The register is found at address 0x18 in bank 0. Figure 14-15 (in the following page) is a bitmap of the RCSTA register.

The USART Baud Rate Generator

In the USART emulation programs for the 16F84 we were forced to approximate the RS-232-C baud rate with the system clock. The USART module in the 16F87X PICs contains its own baud rate generator, but it is also dependent on the system clock.

Setting the baud rate in the USART module consists of manipulating the Baud Rate Generator (BRG) unit. The BRG is a dedicated 8-bit generator that supports both the asynchronous and synchronous modes. The SPBRG is an 8-bit register that controls the rate of a dedicated timer. In the asynchronous mode, the bit labeled BRGH in the TXSTA register (see Figure 14-14) also relates to the baud rate since it allows setting either slow-speed or high-speed baud rate. The baud-rate-speed-select bit is inactive in the synchronous mode.
The formula for computing the baud rate takes into account the system oscillator speed (Fosc), the setting of the Baud-Rate-Speed-Select bit (BRGH), which is set for the high-speed mode and cleared for slow-speed, and also the setting of the SYNC bit in TXSTA register, which selects either asynchronous or synchronous mode. The formula is as follows:

\[
ABR = \frac{Fosc}{S(x+1)}
\]

where \( ABR \) represent the Asynchronous Baud Rate, \( x \) is the value in the SPRGB register (range 0 to 255), \( S \) is 64 in the high-speed mode (BRGH bit is 1) and 16 in the slow speed mode (BRGH bit is 0). Solving the formula in terms of the value to be placed in the SPRGB register we get:

<table>
<thead>
<tr>
<th>bit 7 CSRC: Clock Source Select</th>
<th>bit 0 TX9D: 9th bit of transmit data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asynchronous mode</td>
<td>(Can be used as parity bit)</td>
</tr>
<tr>
<td>Don’t care</td>
<td></td>
</tr>
<tr>
<td>Synchronous mode:</td>
<td></td>
</tr>
<tr>
<td>1 = Master mode (internal clock)</td>
<td></td>
</tr>
<tr>
<td>0 = Slave mode (external clock)</td>
<td></td>
</tr>
<tr>
<td>bit 6 TX9: 9-bit Transmit Enable</td>
<td></td>
</tr>
<tr>
<td>1 = 9-bit transmission mode</td>
<td></td>
</tr>
<tr>
<td>0 = 8-bit transmission mode</td>
<td></td>
</tr>
<tr>
<td>bit 5 TXEN: Transmit Enable</td>
<td></td>
</tr>
<tr>
<td>1 = Transmit enabled</td>
<td></td>
</tr>
<tr>
<td>0 = Transmit disabled</td>
<td></td>
</tr>
<tr>
<td>bit 4 SYNC: USART Mode Select</td>
<td></td>
</tr>
<tr>
<td>1 = Synchronous mode</td>
<td></td>
</tr>
<tr>
<td>0 = Asynchronous mode</td>
<td></td>
</tr>
<tr>
<td>bit 3 Unimplemented: Read as '0'</td>
<td></td>
</tr>
<tr>
<td>bit 2 BRGH: Baud Rate Speed Select</td>
<td></td>
</tr>
<tr>
<td>Asynchronous mode</td>
<td></td>
</tr>
<tr>
<td>1 = High speed</td>
<td></td>
</tr>
<tr>
<td>0 = Low speed</td>
<td></td>
</tr>
<tr>
<td>Synchronous mode:</td>
<td></td>
</tr>
<tr>
<td>1 = Master mode (internal clock)</td>
<td></td>
</tr>
<tr>
<td>0 = Slave mode (external clock)</td>
<td></td>
</tr>
<tr>
<td>bit 1 TRMT: Transmit Shift Register Status</td>
<td></td>
</tr>
<tr>
<td>1 = TSR empty</td>
<td></td>
</tr>
<tr>
<td>0 = TSR full</td>
<td></td>
</tr>
<tr>
<td>Figure 14-14 Bitmap of the TXSTA Register</td>
<td></td>
</tr>
</tbody>
</table>
For example, to calculate the setting of the SPRGB register for 9,600 baud, with a 16Mhz oscillator, at the high-speed rate \( S = 64 \) the equation becomes:

\[
ABR = \frac{Fosc}{S(x + 1)}
\]

For example, to calculate the setting of the SPRGB register for 9,600 baud, with a 16Mhz oscillator, at the high-speed rate \( S = 64 \) the equation becomes:

\[
x = \left( \frac{16,000,000}{9,600 \cdot 64} \right) - 1 = 25.042 \approx 25
\]
In this case, the value to store in the SPRGB register is 25. The actual baud rate can now be calculated using the first equation, as follows:

\[
ABR = \frac{16,000,000}{64 \cdot (25 + 1)} = 9615.38
\]

The percent error in the baud rate can be estimated by dividing the difference between the desired and the actual baud rate by the desired baud rate. The percent error is 0.16.

**16F87x USART Asynchronous Transmitter**

The USART in the 16F87x PICs uses a non-return-to-zero format, consisting of one start bit, eight or nine data bits, no parity, and one stop bit. In compliance with RS-232-C the USART transmits and receives the least significant bit first. Transmitter and receiver units are functionally independent but use the same data format and baud rate.

Although parity is not directly supported by the hardware, it can be implemented in software by using the ninth data bit. Figure 14-16 shows the 16F87x registers related to asynchronous transmission.

```
<table>
<thead>
<tr>
<th>REGISTER</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
<th>bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>TXSTA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCSTA</td>
<td>SPEN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TXREG</td>
<td>TX7</td>
<td>TX6</td>
<td>TX5</td>
<td>TX4</td>
<td>TX3</td>
<td>TX2</td>
<td>TX1</td>
<td>TX0</td>
<td></td>
</tr>
<tr>
<td>PIR1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TXIF</td>
<td></td>
</tr>
<tr>
<td>PIE1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TXIE</td>
<td></td>
</tr>
<tr>
<td>SPBRG</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Baud Rate Generator)</td>
</tr>
<tr>
<td>INTCN</td>
<td>GIE</td>
<td>PEIE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

**Figure 14-16 16F87x Registers used in Asynchronous Transmission**

The transmitter function also uses the Transmit Shift register (TSR), which is not mapped in memory and is thus not accessible to code. TSR obtains its data from the read/write transmit buffer, named TXREG, which is loaded in software after the stop bit is received. Then TXREG transfers the data to TSR and becomes empty. At this time the TXIF flag bit is set. An interrupt related to the TXIF bit is enabled/disabled by setting/clearing the TXIE enable bit in the PIE1 register. However, the TXIF flag bit is set regardless of the state of the TXIE enable bit. The TXIF flag is reset automatically when new data is loaded into TXREG.
While the TXIF flag indicates the status of TXREG, the TRMT bit, in TXSTA, reflects the status of TSR. TRMT is set when TSR is empty. This is a read-only bit. No interrupts are linked to the TRMT bit, so the program has to poll this bit to determine if TSR is empty. Transmission is enabled by setting the TXEN bit in TXSTA. The actual transmission does not occur until TXREG is loaded with data and the baud rate generator (BRG) has produced a clock beat. Alternatively, transmission can be started by loading TXREG and then setting the TXEN enable bit.

When transmission starts, the (not accessible) TSR register usually is empty. Thereafter, transferring data to TXREG results in a transfer to TSR, which then produces an empty TXREG. This mechanism makes possible the back-to-back transfer. Clearing the TXEN enable bit during transmission aborts the transmission. This action also resets the transmitter and sets the TX/CK pin high.

**16F87x USART Asynchronous Receiver**

When Asynchronous mode is selected by setting the SYNC bit in TXSTA, then reception can be enabled by setting the CREN bit.

In the RCSTA register. Figure 14-17 shows the registers related to asynchronous reception.

![Figure 14-17 Registers used in Asynchronous Reception](image)

The main operational register is the **RSR (Receive Shift Register)**, which, like TSR, is not accessible to application software. As soon as the stop bit is detected in the RX/TX pin, the received data in RSR is transferred to RCREG if it is empty. In this case, the RCIF flag bit is set. The interrupt linked to the RCIF flag is enabled or disabled by means of the RCIE in the PIE1 register. The RCIF flag bit is read-only and can be cleared only by hardware; this happens when the RCREG register has been read and is empty.
RCREG is double-buffered, meaning that it is possible for two bytes of data to be started simultaneously while a third byte begins shifting to RSR. If the stop bit is detected while RCREG is not empty, then the overrun error bit (OERR) is set in RCSTA. RCREG operates in first-in-first-out order. When it is read twice the two bytes are retrieved in this order.

The overrun error bit (OERR) inhibits transfer from RSR into RCREG; therefore, it is important to clear this bit once the error is detected. The framing error bit (FERR) in the RCSTA register is set if a stop bit is not detected.

The following steps are followed in initializing and executing asynchronous reception:
1. The SPBRG register is set up for the selected baud rate.
2. Asynchronous reception is enabled by clearing the SYNC bit in the TXSTA register and setting the SPEN bit in the RCSTA register.
3. To enable the receive data interrupt, the RCIE, GIE, and PEIE bits must be set.
4. Reception is activated by setting the CREN bit in RCSTA.
5. When reception has concluded, the RCIF bit in the PIE1 register is set. At that time, an interrupt is generated if the RCIE bit was set.
6. Received data is retrieved by reading RCREG.
7. If any error occurred the CREN bit must be cleared.

**PIC-to-PC RS-232-C Communications Circuit**

To demonstrate serial communications with the RS-232-C protocol we developed a circuit consisting of a 4-by-4 keypad and a 2-line by 20-character LCD display. Characters typed on the keypad are converted to ASCII codes for the hexadecimal digit set, that is, the numeral digits and the letters A through F. When a key is pressed, the corresponding ASCII code is displayed in the LCD and transmitted through the serial port to a PC application. Characters received through the serial line are displayed on the LCD. Figure 14-18 (in the following page) is a wiring diagram of the circuit.

The program SerComLCD demonstrates the circuit in Figure 14-18:

**16F877 PIC Initialization Code**

The following code fragment shows the initialization of the UART module in the 16F877 PIC for 2400 baud, 8 bits, no parity, and one stop bit. No interrupts are used in this example.

```assembly
;==============================================================
; USART initialization procedure
;==============================================================
; Initialize serial port for 2400 baud, 8 bits, no parity,
; 1 stop
InitSerial:
    Bank1        ; Macro to select bank1
; Bits 6 and 7 of Port C are multiplexed as TX/CK and RX/DT
```
for USART operation. These bits must be set to input in the TRISC register

```assembly
movlw b'11000000' ; Bits for TX and RX
iorwf TRISC,f ; OR into Trisc register
```

The asynchronous baud rate is calculated as follows:

```
; Fosc
ABR = ------------
; S*(x+1)
```
; Where x is the value in the SPBRG register and S is 64 if the
; high baud rate select bit (BRGH) in the TXSTA control register
; is clear, and 16 if the BRGH bit is set. For setting to 9600
; baud using a 4Mhs oscillator at a high-speed baud rate the
; formula is:
; 4,000,000 4,000,000
; -------- -------- = 9,615 baud (0.16% error)
; 16\*(25+1) 416
;
; At slow speed (BRGH = 0)
; 4,000,000 4,000,000
; -------- -------- = 2,403.85 (0.16% error)
; 64\*(25+1) 1,664
;
; movlw spbrgVal ; Value in spbrgVal = 25
; movwf SPBRG ; Place in baud rate generator
;
; TXSTA (Transmit Status and Control Register) bit map:
; 7 6 5 4 3 2 1 0 <= bits
; | | | | | | | | |______ TX9D 9nth data bit on
; | | | | | | | | ? (used for parity)
; | | | | | | | | |____ TRMT Transmit Shift Register
; | | | | | | | | 1 = TSR empty
; | | | | | | | | * 0 = TSR full
; | | | | | | | | |_______ BRGH High Speed Baud Rate
; | | | | | | | | (Asynchronous mode only)
; | | | | | | | | 1 = high speed (* 4)
; | | | | | | | | * 0 = low speed
; | | | | | | | | |_______ NOT USED
; | | | | | | | | |_______ SYNC USART Mode Select
; | | | | | | | | 1 = synchronous mode
; | | | | | | | | * 0 = asynchronous mode
; | | | | | | | | |_______ TXEN Transmit Enable
; | | | | | | | | * 1 = transmit enabled
; | | | | | | | | 0 = transmit disabled
; | | | | | | | | |_______ TX9 Enable 9-bit Transmit
; | | | | | | | | 1 = 9-bit transmission mode
; | | | | | | | | * 0 = 8-bit mode
; | | | | | | | | |_______ CSRC Clock Source Select
; | | | | | | | | Not used in asynchronous mode
; | | | | | | | | Synchronous mode:
; | | | | | | | | 1 = Master Mode (internal clock)
; | | | | | | | | * 0 = Slave mode (external clock)
; Setup value: 0010 0000 = 0x20
; movlw 0x20 ; Enable transmission and high
; baud rate
; movwf TXSTA
; Bank0 ; Bank 0
USART Receive and Transmit Routines

The transmit data routine is quite simple. Code checks the TXIF bit in PIR1. If the bit is set, data is transmitted by storing the data byte in TXREG. The following procedure performs the required operations.

```assembly
; Setup value: 1001 0000 = 0x90
movlw 0x90 ; Enable serial port and continuous reception
movwf RCSTA

clrf errorFlags ; Clear local error flags register
Return
```

**USART Receive and Transmit Routines**

The transmit data routine is quite simple. Code checks the TXIF bit in PIR1. If the bit is set, data is transmitted by storing the data byte in TXREG. The following procedure performs the required operations.

```assembly
; Setup value: 1001 0000 = 0x90
movlw 0x90 ; Enable serial port and continuous reception
movwf RCSTA

clrf errorFlags ; Clear local error flags register
Return
```
Receiving data is more complicated than transmitting it. One of the reasons is that code must test for and handle several possible errors that can occur during reception. The following code fragment shows the local variables and processing required for simple data reception.

```assembly
;=======================================================
; variables in PIC RAM
;=======================================================
Local variables
  cblock 0x20 ; Start of block

; Communications variables
  newData ; not 0 if new data received
  ascVal
  errorFlags
endc

;=======================================================
; USART receive data procedure
;=======================================================
; Procedure to test line for data received and return value
; in w. Overrun and framing errors are detected and
; remembered in the variable errorFlags, as follows:
; 76543210 < = errorFlags
; — not used — | |___ overrun error
; |______ framing error
SerialRcv:
  clrf newData ; Clear new data received register
  Bank0 ; Select bank 0
  btfss PIR1,RCIF ; Check for received data
  return ; Exit if no data
; At this point data has been received. First eliminate
; possible errors: overrun and framing.
  btfsc RCSTA,OERR ; Test for overrun error
  goto OverErr ; Error handler
  btfsc RCSTA,FERR ; Test for framing error
  goto FrameErr ; Error handler
; At this point no error was detected
```
The procedures listed previously are from the program SerComLCD in the book’s online software. The applicable circuit is shown in Figure 14-18.

**The USART Receive Interrupt**

Polled routines for serial communications are adequate when the application does little else but check transmission lines. If the application has other tasks to perform, polled routines can waste processing time and even lose data. In this sense, the send function is usually less critical. An application can typically determine when to send data and have available all the data when the send operation activates. This is often not the case in receiving data, especially in applications that execute full-duplex.

A practical solution is to use interrupts for receiving characters through the serial line. The 60F87x includes facilities for implementing interrupt routines by both the send and the receive functions. To enable interrupts for the USART receive operation the following preparatory steps are necessary:

1. Peripheral and global interrupts must be enabled by setting bits 6 and 7 of the INTCON register.
2. The receive interrupt must be enabled by setting the RCIF bit in the PIE1 register.

The handler for the serial reception interrupt usually performs the following functions:
1. The context is saved. This includes, but is not limited to, the status register, the W register, the PCLATH register, and the FSR register.

2. Code tests for received data by checking the RCIF bit in the PIR1 register. If this bit is clear the interrupt did not originate in received data.

3. Code can also check if the interrupt enable bit (RCIE) is set in the RCIE register. If not enabled the interrupt is related to serial data.

4. The handler usually checks two possible errors during reception: overflow and framing error. The first one by checking the OERR bit and the second one by checking the FERR bit, both in the RCSTA register. If reception errors have taken place, the handler takes appropriate action.

5. If no error is detected then the received data can be retrieved from the RCREG.

6. On exit the interrupt handler restores the context and issues the retfie instruction.

The following code fragment lists the variables and processing routine for an interrupt handler for serial data reception:

```assembly
; variables in PIC RAM
;============================================================
; Local variables
   cblock 0x20 ; Start of block.
   .
   .
; Communications variables
   errorFlags
; Temporary storage used by interrupt handler
   tempW
   tempStatus
   tempPclath
   tempFsr
endc

; interrupt handler for received characters
;============================================================
IntServ:
   movwf tempW ; Save W
   movf STATUS,W ; Store STATUS in W
   clrf STATUS ; Select bank0
   movwf tempStatus ; Save STATUS
   movf PCLATH,W ; Store PCLATH in W
   movwf tempPclath ; Save PCLATH
   clrf PCLATH ; Select program memory page 0
   movf FSR,W ; Store FSR in W
```

---

**Communications**

387
movwf tempFsr ; Save FSR value
; Test for received data interrupt
    Bank0        ; select bank0
        7 6 5 4 3 2 1 0 <= PIR1
        |___________ (RCIF) USART receive interrupt
        flag
Btfsc PIR1,RCIF ; Test bit 5
bsf STATUS,RP0 ; Bank 1 if RCIF set
        7 6 5 4 3 2 1 0 <= PIE1
        |___________ (RCIE) Receive interrupt enable
        bit
btfss PIE1,RCIE ; Test if interrupt is enabled
goto IntExit ; Go if not enabled

;==============================
; received data
;==============================
; Routine to handler received data. Overrun and framing
; errors are detected and remembered in the variable
; errorFlags, as follows:
; 7 6 5 4 3 2 1 0 <= errorFlags
; — not used — | |___ overrun error
; |______ framing error
    Bank0 ; Select bank 0
; Test for overrun and framing errors.
; Bit 1 (OERR) of the RCSTA register detects overrun
; Bit 2 (FERR) of the RCSTA register detects framing error
btfsc RCSTA,OERR ; Test for overrun error
goto OverErr ; Error handler
btfsc RCSTA,FERR ; Test for framing error
goto FrameErr ; Error handler
; At this point no error was detected
; Received data is in the USART RCREG register
movf RCREG,w ; Received data into w
; Clear error flags
clf errorFlags
goto IntExit

;==============================
; error handlers
;==============================
; Errors are returned as bits in the errorFlags register
; 7 6 5 4 3 2 1 0 <= errorFlags
; — not used — | |___ overrun error
; |________ framing error
; Error responses to be made by main code
OverErr:
bsf errorFlags,0 ; Bit 0 is overrun error
; Reset system
bcf RCSTA,CREN ; Clear continuous receive bit
bsf RCSTA,CREN ; Set to re-enable reception

goto IntExit

FrameErr:
bsf errorFlags,1; Bit 1 is framing error
movf RCREG,W ; Read and throw away bad data

;================================
; interrupt handler exit
;================================

IntExit:

Bank0

movf tempFsr,w ; Recover FSR value
movwf FSR ; Restore in register
movf tempPclath,w ; Recover PCLATH value
movwf PCLATH ; Restore in register
movf tempStatus,W ; Recover STATUS
movwf STATUS ; Restore in register
swapf tempW,F ; Swap file register in itself
swapf tempW,W ; Restore in register
retfie

The program SerIntLCD in the book’s online software is an interrupt-driven demonstration for the circuit in Figure 14-18.

14.5 Sample Programs

The sample programs listed in the following sections refer to the programming discussed in this chapter.

14.5.1 SerialSnd Program

; File name: SerialSnd.asm
; Date: May 5, 2006
; Author: Julio Sanchez
; Processor: 16F84A
;
; Description:
; Two programs to exercise serial communications between
; two PIC 16F84A both running at 4Mhs. One program sends
; data through a single line and the other one receives
; it. This program is the sender.
;
; Circuit:
; Port A1 is the serial transmission line
; Port A2 is an active-low pushbutton switch that
; serves to initiate communications.
; Port A3 is a LED that is ON when the program is
; ready to send data. Once data starts
; being sent the LED is turned OFF.
; Port-B0-B7 is a 8 x toggle switch that provides
the data byte to be sent
; A pushbutton switch is in the 16F84 RESET line
; and serves to restart the program
;
; Communications parameters:
; Timer channel TMR0 is used for synchronizing data
; transmission. The timer runs at the maximum rate of
; 256 cycles per iteration. In a 4Mhz system the
; timer rate is 1Mhz, thus the bit rate is
; 1,000,000/256
; which is approximately 3,906 microseconds per bit.
;
;Switches

;Switches used in __config directive:
; CP_ON Code protection ON/OFF
; * CP_OFF
; * PWRT_ON Power-up timer ON/OFF
; PWRT_OFF
; WRT_ON Watchdog timer ON/OFF
; * WRT_OFF
; LP_OSC Low power crystal oscillator
; * XT_OSC External parallel resonator/crystal oscillator
;
; HS_OSC High speed crystal resonator (8 to 10 MHz)
; Resonator: Murate Erie CSA8.00M G=8 Hz
; RC_OSC Resistor/capacitor oscillator
; (simplest, 20% error)
;
; * indicates setup values presently selected

;setup and configuration

processor 16f84A
include <p16f84A.inc>
__config XT_OSC & WRT_OFF & PWRT_ON & CP_OFF

; Macros to select the register banks
Bank0 MACRO ; Select RAM bank 0
 bcf STATUS,RP0
ENDM

Bank1 MACRO ; Select RAM bank 1
bsf STATUS,RP0
constant definitions for pin wiring

#define readySW 2 ; |
#define readyLED 3 ; | — from wiring diagram
#define serialLN 1 ; |

PIC register flag equates

c equ 0 ; Carry flag
tmrOVF equ 2 ; Timer overflow bit

variables in PIC RAM

cblock 0x0d ; Start of block
bitCount ; Counter for 8 bits
dataReg ; Data to send
dec

program

org 0 ; start at address
goto main

Space for interrupt handlers
org 0x04

main:
; Port-A, bit 2 is input. Rest is output
Bank1
movlw b'00000100' ; Port-A bit 2 is input
movwf TRISA ; all others are output

movwf TRISA

; Port-B is all input
movlw b'11111111'
movwf TRISB
Bank0
bsf PORTA,1 ; Marking bit

Prepare to set prescaler
clr TMR0
clrwdt

; Setup OPTION register for full timer speed
movlw b'11011000'
; 1 1 0 1 1 0 0 0 <= OPTION bits
; ||||| |__|__|_____ PS2-PS0 (prescaler bits)
; ||||| Values for Timer0
; ||||| *000 = 1:2 001 = 1:4
; 010 = 1:8  011 = 1:16
; 100 = 1:32  101 = 1:64
; 110 = 1:128  111 = 1:256
; _______________ PSA (prescaler assign)
; *1 = to WDT
; 0 = to Timer0
; _______________ TOSE (Timer0 edge select)
; 0 = increment on low-to-high
; *1 = increment in high-to-low
; _______________ TOCS (TMR0 clock source)
; *0 = internal clock
; 1 = RA4/TOCKI bit source
; _______________ INTEDG (Edge select)
; 0 = falling edge
; *1 = raising edge
; _______________ RBPU pullups
; 0 = enabled
; *1 = disabled

; Disable interrupts
  bcf    INTCON,5 ; Timer0 overflow disabled
  bcf    INTCON,7 ; Global interrupts disabled
; Turn on ready LED
  bsf    PORTA,3 ; LED on

; wait for READY switch
; to be pressed
; ================
ready2send:
  btfsc  PORTA,readySW
  goto   ready2send
; ================
; send serial data
; ================
; At this point program proceeds to send data through
; the serial port line
; Turn off LED
  bcf    PORTA,readyLED
; Read switches and store in local variable
  movf   PORTB,w
  movwf   dataReg
; ================
; call serial output
; procedure
; ================
call    sendData ; call serial output procedure
; ================
; wait forever
Communications

;=====================================================================
endloop:
    goto endloop

;=====================================================================
; procedure to send serial data
;=====================================================================
; ON ENTRY:
;    local variable dataReg holds 8-bit value to be
;    transmitted through port labeled serialLN
; OPERATIONS:
;    1. The timer at register TMR0 is set to run at
;       maximum clock speed, that is, 256 clock beats.
;       The timer overflow flag in the INTCON register
;       is set when the timer cycles from 0xff to 0x00.
;    2. Each bit (start, data, and stop bits) is sent
;       at a rate of 256 timer beats. That is, each bit is
;       held high or low for one full timer cycle (256
;       clock beats).
;    3. The procedure tests the timer overflow flag
;       (tmrOVF) to determine when the timer cycle has
;       ended, that is when 256 clock beats have passed.
; sendData:
    movlw 0x08 ; Setup shift counter
    movwf bitCount

;=====================================================================
; send START bit
;=====================================================================
; Set line low then hold for 256 timer clock beats.
    bcf PORTA,serialLN ; Send start bit
; First reset timer
    clrf TMR0 ; Reset timer counter
    bcf INTCON,tmrOVF ; Reset TMR0 overflow flag
; Wait for 256 timer clock beats
startBit:
    btfss INTCON,tmrOVF ; timer overflow?
    goto startBit; Wait until set
; At this point timer has cycled. Start bit has ended
    bcf INTCON,tmrOVF ; Clear overflow flag

;=====================================================================
; send 8 DATA bits
;=====================================================================
; Eight data bits are sent through the serial line
; starting with the high-order bit. The data byte is
; stored in the register named dataReg. The bits are
; rotated left to the carry flag. Code assumes the bit
; is zero and sets the serial line low. Then the carry
; flag is tested. If the carry is set the serial line
; is changed to high. The line is kept low or high for
; 256 timer beats.
send8:
    rlf    dataReg,f ; bit into carry flag
    bcf    PORTA,serialLN ; 0 to serial line
; Code can assume the bit is a zero and set the line
; low since, if low is the wrong state, it will only
; remain for two timer beats. The receiver will not
; check the line for data until 128 timer beats have
; elapsed, so the error will be harmless. In any case,
; there is no assurance that the previous line state is
; the correct one, so leaving the line in its previous
; state could also be wrong.
    btfsc    STATUS,c ; test carry flag
    bsf    PORTA,serialLN ; bit is set. Fix error.
bitWait:
    btfss    INTCON,tmrOVF ; Timer cycled?
    goto    bitWait ; not yet
; At this point timer has cycled.
; Test for end of byte, if not, send next bit
    bcf    INTCON,tmrOVF ; clear overflow flag
    decfsz    bitCount,f ; Last bit?
    goto    send8 ; not yet
;============================
; hold MARKING state
;============================
; All 8 data bits have been sent. The serial line must
; now be held high (MARKING) for one clock cycle
    bsf    PORTA,serialLN ; Marking state
markWait:
    btfss    INTCON,tmrOVF ; Done?
    goto    markWait ; not yet
;============================
; end of transmission
;============================

    return ; done

;=================================================================
; end of program
;=================================================================

14.5.2 SerialRcv Program

; File name: SerialRcv.asm
; Date: May 6, 2006
; Author: Julio Sanchez
Communications

; Processor: 16F84A
;
; Description:
; Two programs to exercise serial communications between
; two PIC 16F84A both running at 4Mhs. One program sends
; data through a single line and the other one receives
; it. This program is the receiver.
;
; Circuit:
;   Port A0 is the serial transmission line
;   Port A2 is an active-low pushbutton switch that
;       serves to initiate communications.
;   Port A3 is a LED that is ON when the program is
;       ready to receive data. Once data starts
;       being received the LED is turned OFF.
;   Port B0-B7 are 8 LEDs that display the data bits
;       that have been received.
;   A pushbutton switch is in the 16F84 RESET line
;       and serves to restart the program
;
; Communications parameters:
;   Timer channel TMR0 is used for synchronizing data
;   transmission. The timer runs at the maximum rate of
;   256 cycles per iteration. In a 4Mhz system the
;   timer rate is 1Mhz, thus the bit rate is
;       1,000,000/256
;   which is approximately 3,906 microseconds per bit.
;
;   Upon receiving the START bit, the program waits for
;   one half a clock cycle (128 timer beats) to
;   synchronize with the sender.

;==============================================
; switches
;==============================================
; Switches used in __config directive:
;   _CP_ON  Code protection ON/OFF
; * _CP_OFF
; * _PWRT_ON  Power-up timer ON/OFF
; _PWRT_OFF
; _WDT_ON  Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC  Low power crystal oscillator
; * _XT_OSC  External parallel resonator/crystal oscillator
; _HS_OSC  High speed crystal resonator (8 to 10 MHz)
; Resonator: Murata Erie CSA8.00MG = 8 MHz
; _RC_OSC  Resistor/capacitor oscillator
; |
; (simplest, 20% error)
processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

MACROS

Bank0 MACRO ; Select RAM bank 0
  bcf STATUS,RP0
ENDM

Bank1 MACRO ; Select RAM bank 1
  bsf STATUS,RP0
ENDM

constant definitions for pin wiring

#define readySW 2 ;|
#define readyLED 3 ;| — from wiring diagram
#define serialLN 0 ;|

PIC register and flag equates

c equ 0 ; Carry flag
tmrOVF equ 2 ; Timer overflow bit

variables in PIC RAM

cblock 0x0c ; Start of block
   bitCount ; Counter for 8 bits
   rcvReg ; Data to send
   temp
   endc

program

org 0 ; start at address
goto main

; Space for interrupt handlers
org 0x04
main:

; Bank1
movlw b'00000101' ; Port-A setup
movwf TRISA

; Port-B is all output
movlw b'00000000' ; Port-B setup
MOVWF TRISB

Bank0

; Turn off all Port-B LEDs
clr PORTB
; And receiver register
clr rcvReg
; Prepare to set prescaler
clr TMR0
clrwdt

; Setup OPTION register for full timer speed
movlw b'11011000'

; 1 1 0 1 1 0 0 0 <= OPTION bits
; ||||| ____|____ PS2-PS0 (prescaler bits)
; ||||| Values for Timer0
; ||||| *000 = 1:2 001 = 1:4
; ||||| 010 = 1:8 011 = 1:16
; ||||| 100 = 1:32 101 = 1:64
; ||||| 110 = 1:128 111 = 1:256
; ||||| ___________ PSA (prescaler assign)
; ||||| *1 = to WDT
; ||||| 0 = to Timer0
; ||||| ___________ TOSE (Timer0 edge select)
; | | | | 0 = increment on low-to-high
; | | | | *1 = increment in high-to-low
; | | | __________ TOCS (TMR0 clock source)
; | | | *0 = internal clock
; | | | 1 = RA4/TOCKI bit source
; | | __________ INTEDG (Edge select)
; | | 0 = falling edge
; | | *1 = raising edge
; | ____________ RBPU pullups
; | 0 = enabled
; | *1 = disabled

option
; Disable interrupts
bcf INTCON,5 ; Timer0 overflow disabled
bcf INTCON,7 ; Global interrupts disabled

;==========================================
; wait for READY switch
; to be pressed
;==========================================
ready2rcv:
    btfsc PORTA,readySW ; Test switch
    goto ready2rcv ; loop
; Turn ON the ready-to-receive LED
    bsf PORTA,readyLED
;===========================
; receiving
;===========================
    call rcvData ; Call serial input procedure
;===========================
; data received
;===========================
; Turn ready to receive LED off
    bcf PORTA,readyLED
; Display received data
    movf rcvReg,w ; Byte received to w
    movwf PORTB ; display in Port-B
;===========================
; wait forever
;===========================
endloop:
    goto endloop
;============================================================
; procedure to receive serial data
;============================================================
; ON ENTRY:
;    local variable dataReg is used to store 8-bit value
; received through port (labeled serialLN)
; OPERATION:
;    1. The timer at register TMR0 is set to run at
;       maximum clock speed, that is, 256 clock beats.
;       The timer overflow flag in the INTCON register
;       is set when the timer cycles from 0xff to 0x00.
;    2. When the START signal is received, the code
;       waits for 128 timer beats so as to read data in
;       the middle of the send period.
;    3. Each bit (start, data, and stop bits) is read
;       at intervals of 256 timer beats.
;    4. The procedure tests the timer overflow flag
;       (tmrOVF) to determine when the timer cycle has
;       ended, that is when 256 clock beats have passed.
;============================================================
rcvData:
    clr TMR0 ; Reset timer
    movlw 0x08 ; Initialize bit counter
    movwf bitCount
;================================
; wait for START bit
;================================
startWait:
    btfsc PORTA,0 ; Is port A0 low?
    goto startWait ; No. Wait for mark
;================================
 ; offset 128 clock beats
;================================
 ; At this point the receiver has found the falling
 ; edge of the start bit. It must now wait 128 timer
 ; beats to synchronize in the middle of the sender’s
 ; data rate, as follows:
 ; |<========== falling edge of START bit
 ; |
 ; |------|<====== 128 clock beats offset
 ; ------- | .-------
 ; | |    | <= SIGNAL
 ; -------
 ; |<-- 256-->|
 ;
    movlw 0x80 ; 128 clock beats offset
    movwf TMR0 ; to TMR0 counter
    bcf INTCON,tmrOVF ; Clear overflow flag
offsetWait:
    btfss INTCON,tmrOVF ; timer overflow?
    goto offsetWait ; Wait until
    btfsc PORTA,0 ; Test start bit for error
    goto offsetWait ; Recycle if a false start
;================================
 ; receive data
;================================
    clrf TMR0 ; Restart timer
    bcf INTCON,tmrOVF ; Clear overflow flag
 ; Wait for 256 timer cycles for first/next data bit
bitWait:
    btfss INTCON,tmrOVF ; Timer cycle end?
    goto bitWait ; Keep waiting
 ; Timer has counter 256 beats
    bcf INTCON,tmrOVF ; Reset overflow flag
    movf PORTA,w ; Read Port-A into w
    movwf temp ; Store value read
    rrf temp,f ; Rotate bit 0 into carry flag
    rlf rcvReg,f ; Rotate carry into rcvReg 0
    decfsz bitCount,f ; 8 bits received
    goto bitWait ; Next bit
 ; Wait for one time cycle at end of reception
markWait:
    btfss INTCON,tmrOVF ; timer overflow flag
goto markWait; keep waiting

;========================
; end of reception
;========================
return

;==============================================
; end of program
;==============================================
end

14.5.3 Serial6465 Program

; File name: Serial6465.asm
; Last update: May 7, 2006
; Author: Julio Sanchez
; Processor: 16F84A

; Description:
; Program to exercise serial communications using a
; PIC 16F84A and two shift registers: a 74HC164, and a
; 74HC165. The 74HC165 inputs 8 lines from a DIP switch
; and transmits settings to PIC through a serial line.
; PIC sends data serially to an 74HC164 which is wired
; to 8 LEDs that display the received data. A total of
; 6 PIC lines are used in interfacing 8 input switches
; to 8 output LEDs.
; Circuit:
; * Port A0 is the serial transmission line which
; comes from the 74HC165.
; * Port A1 is wired to the 74HC164 CLOCK pin
; * Port A2 is wired to the 74HC164 CLEAR pin
; * 74HC164 output pins 0 to 7 are wired to LEDs.
; * Port B0 is wired to the 74HC165 Hout line
; * Port B1 is wired to the 74HC165 CLK line
; * Port B2 is wired to the 74HC165 load line
; * A pushbutton switch is in the 16F84 RESET line
; and serves to restart the program
; Communications protocol:
; Communication between PIC and the 74HC164 and
; 74HC165 is synchronous since the shift registers
; clock lines serve to shift in and out the data
; bits.
;
;===============================================
; switches
;===============================================
; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; * _CP_OFF
; * _PWRTE_ON   Power-up timer ON/OFF
; _PWRTE_OFF
; _WDT_ON     Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC    Low power crystal oscillator
; * _XT_OSC  External parallel resonator/crystal oscillator

; _HS_OSC    High speed crystal resonator (8 to 10 MHz)
; Resonator: Murate Erie CSA8.00M = 8 MHz
; _RC_OSC    Resistor/capacitor oscillator
; | (simplest, 20% error)
; |
; |____ * indicates setup values presently selected

;===============
; setup and configuration
;===============
processor 16f84A
#include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

;===============
; MACROS
;===============
Macros to select the register banks
Bank0 MACRO ; Select RAM bank 0
bcf STATUS,RP0
ENDM

Bank1 MACRO ; Select RAM bank 1
bsf STATUS,RP0
ENDM
; Note: in the case of the 16F84A the bank select macros
; do not make the code more efficient, however, they
; do serve to clarify the bank selection operations.

;==============
; constant definitions from wiring diagram
;==============
#define clockLN 1 ;|
#define clearLN 2 ;| — 74HC164 lines
#define dataLN 0 ;|

;#define clk65LN 1 ;| — 74HC165 lines
#define loadLN 2 ;|

;==============
; PIC register and flag equates
;==============
Communications
highBit equ 7 ; High order bit

;--------------------------------------------------------
; variables in PIC RAM
;--------------------------------------------------------
cblock 0x0d ; Start of block
  bitCount ; Counter for 8 bits
  dataReg ; Data to send
  workReg ; Work register for bit shifts
endc

;--------------------------------------------------------
; program
;--------------------------------------------------------
org 0 ; start at address
goto main

; Space for interrupt handlers
org 0x04

main:
; Port-A is all output
  Bank1
  movlw b'00000000'
  movwf TRISA

; Port-B line 0 is input, all others are output
  movlw b'00000001'
  movwf TRISB

  Bank0

; Make sure Port-A line 2 (clear line) is high
  movlw b'00000100'
  movwf PORTA

;==================================
; read input from 165 IC
;==================================
  call in165 ; Local procedure

; dataReg contains input
;=========================
; call serial output
; procedure
;=========================
  call out164 ; Call serial output procedure

;=====================================
; wait forever
;=====================================
endloop:
  goto endloop

;=====================================
; 74HC164 procedure to send serial data
;=====================================
; ON ENTRY:
local variable dataReg holds 8-bit value to be transmitted through port labeled serialLN

; OPERATION:
; 1. A local counter (bitCount) is initialized to 8 bits
; 2. Code assumes that the first bit is zero by setting the data line low. Then the high-order bit in the data register (dataReg) is tested.
; 3. Bits are shifted in by pulsing the 74HC164 clock line (CLK).
; 4. Data bits are then shifted left and the bit counter is tested. If all 8 bits have been sent the procedure returns.

out164:
; Clear 74HC164 shift register
bcf PORTA,clearLN ; 74HC164 CLR clear low
bsf PORTA,clearLN ; then high again

; Init counter
movlw 0x08 ; Initialize bit counter
movwf bitCount

sendBit:
bcf PORTA, dataLN ; Set data line low (assume) Using this assumption is possible because the bit is not shifted in until the clock line is pulsed.
btfsc dataReg, highBit ; test number bit 7
bsf PORTA, dataLN ; Change assumption if set

; pulse clock line

; Bits are shifted in by pulsing the 74HC164 CLK line
bsf PORTA, clockLN ; CLK high
bcf PORTA, clockLN ; CLK low

; Rotate data bits left

rlf dataReg,f ; Shift left data bits
decfsz bitCount,f ; Decrement bit counter
goto sendBit ; Repeat if not 8 bits

; end of transmission
return

; 74HC165 procedure to read parallel data and send serially to PIC

1. Eight DIP switches are connected to the input ports of an 74HC165 IC. Its output line Hout, and its control lines CLK and load are connected to the PIC’s Port-B lines 0, 1, and 2 respectively.

2. Procedure sets a counter (bitCount) for 8 iterations and clears a data holding register (dataReg).

3. Port-B bits are read into w. Only the lsb of Port-B is relevant. Value is stored in a working register and the meaningful bit is rotated into the carry flag, then the carry flag bit is then shifted into the data register.

4. The iteration counter is decremented. If this is the last iteration the routine ends. Otherwise, the bitwise read-and-write operation is repeated.

```asm
in165:
  clrf dataReg ; Clear data register
  movlw 0x08 ; Initialize counter
  movwf bitCount
  bcf PORTB,loadLN ; Reset shift register
  bsf PORTB,loadLN
nextBit:
  movf PORTB,w ; Read Port-B (only LOB is meaningful in this routine)
  movwf workReg ; Store value in local register
  rrf workReg,f ; Rotate LOB bit into carry flag
  rlf dataReg,f ; Carry flag into dataReg
  decfsz bitCount,f ; Decrement bit counter
goto shiftBits ; Continue if not zero
return ; done
shiftBits:
  bsf PORTB,clk65LN ; Pulse clock
  bcf PORTB,clk65LN
goto nextBit ; Continue
```

14.5.4 TTYUsart Program

; File name: TTYUsart.asm
; Last update: May, 2006
Communications

; Author: Julio Sanchez
; Processor: 16F84A
;
; Description:
; Program to emulate USART operation in PIC code. Uses
; PIC-to-LCD interface. Display has 2 lines, each with
; 16 characters.
; Program operation:
; Characters received from the RS232 line are displayed on
; the LCD. LCD lines scroll automatically. A pushbutton
; activates the send operation by transmitting the text
; string: Ready- which is also displayed on the LCD.
;
; Program communications and LCD parameters are stored in
; #define statements. These statements can be edited to
; accommodate a different set-up. Program uses delay loops
; for interface timing.
;
; WARNING:
; Code assumes 4Mhz clock. Delay routines must be
; edited for faster clock
;
; BAUD RATE CALCULATIONS:
; A 4Mhz clock oscillator has a clock frequency of 1 Mhz:
; Since the baud rate is the number of clock cycles per
; second, for a 4Mhz clock it is:
; 1
; bit time = ——— sec. = 208.33 microseconds
; 4,800
; Calculating one half the baud rate allows resetting the
; clock from the edge to the center of a time pulse:
;                     |<========== falling edge of start bit
;                     |              |<========== center of bit time
;                     >| |< one-half baud rate
;                      |
;                     __________. | ______. __________.
; |____________________|________________|
; 208/2 = 104
; The PIC clock counts up from 0 to 255. So to implement
; a 104 microsecond delay we must start counting at
; clock beat:
; 255 - 104 = 151
; plus one microsecond for movlw instruction used to
; initialize the clock:
; 151 + 1 = 152
; For one full baud rate delay:
; 255 - 208 = 47 + 1 = 48
The following two constants are stored in #define statements:

- halfBaud = 152
- fullBaud = 48

Setting the prescaler to TMR0 reduces the baud rate to one-half. Other prescaler values will reduce the baud rate accordingly.

Wiring diagram:

- RB4-RB7 ===> LCD data lines 4 to 7 (output)
- RB0 =======> MAX202 T2in line (output)
- RA0 =======> MAX202 R2out line (input)
- RA1 =======> LCD E line (output)
- RA2 =======> LCD RS line (output)
- RA3 =======> LCD R/W line (output - not used)
- RA4 =======> Pushbutton switch 1

    (input - active low)

Switches

Switches used in __config directive:

- _CP_ON Code protection ON/OFF
- _CP_OFF
- * _PWRTE_ON Power-up timer ON/OFF
- _PWRTE_OFF
- _WDT_ON Watchdog timer ON/OFF
- * _WDT_OFF
- _LP_OSC Low power crystal oscillator
- * _XT_OSC External parallel resonator/crystal oscillator

- _HS_OSC High speed crystal resonator (8 to 10 MHz)
- Resonator: Murate Erie CSA8.00M G=8 MHz
- _RC_OSC Resistor/capacitor oscillator

| (simplest, 20% error)
| |
| === * indicates setup values presently selected

Setup and configuration

processor 16f84A

include <p16f84A.inc>

__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

MACROS

M A C R O S
; Macros to select the register banks
Bank0  MACRO ; Select RAM bank 0
  bcf STATUS,RP0
ENDM

Bank1  MACRO ; Select RAM bank 1
  bsf STATUS,RP0
ENDM

;==============================================
; Constant definitions
; for PIC-to-LCD pin wiring and LCD line addresses
;==============================================
#define E_line 1 ;| — from wiring diagram
#define RS_line 2 ;| — from wiring diagram
#define RW_line 3 ;|
#define LCD_1 0x80 ; First LCD line constant
#define LCD_2 0xc0 ; Second LCD line constant
#define LCDlimit .16; Number of characters per line
; 4800 baud clock countdown values
; Code reduces rate to 2400 baud by entering a minimal
; prescaler to TRM0
#define halfBaud .152 ; For one-half bit time
#define fullBaud .48 ; For one full bit time
;
; Note: The constants that define the LCD display line
; addresses have the high-order bit set in
; order to facilitate the controller command
;
;==============================================
; Buffer and variables in PIC RAM
;==============================================
; Create a 16-byte storage area
  cblock 0x0c ; Start of first data block
  lineBuf ; buffer for text storage
  endc
; Leave 16 bytes and Continue with local variables
  cblock 0x1c ; Second data block
  count1 ; Counter # 1
  count2 ; Counter # 2
  J ; counter J
  K ; counter K
  store1 ; Local temporary storage
  store2 ; Storage # 2
; For LCDscroll procedure
  LCDcount ; Counter for characters per line
  LCDline ; Current display line (0 or 1)
  bufPtr ; Buffer pointer
; Variables for serial communications
  tempData ; Temporary storage for bit manipulations
  rcvData ; Final storage for received character
  bitCount ; Bit counter
  sendData ; Character to send

;=========================================================
;          m a i n  p r o g r a m
;=========================================================
org 0 ; start at address
goto main

; Space for interrupt handlers
org 0x08
main:
Bank1
  movlw b'00010001' ; Port-A lines I/O setup
  movwf TRISA

; RA0 = RS232 input (R2out)
; RA4 = Pushbutton SW # 1

  movlw b'00000000' ; Port-B lines as follow:
  movwf TRISB

; RB4-RB7 ===> LCD data lines 4 to 7 (output)
; RB0 = MAX202 T2in line (output)
      movwf TRISB

Bank0

; Clear bits in Port-A output lines
  bcf PORTA,1
  bcf PORTA,2
  bcf PORTA,3

  movlw b'00000000' ; All outputs ports low
  movwf PORTB

; Wait and initialize HD44780
  call delay_5 ; Allow LCD time to initialize itself

  call delay_5
  call initLCD ; Then do forced initialization

  call delay_5 ; Wait again

; Set Port-B, line 0 high so start bit is detected
  bsf PORTB,0

;==========================================
;  wait for start command
;==========================================

; Program waits until pushbutton number 1 is pressed
; to continue execution. Pushbutton 1 is active low
; and wired to RA4

  pb1Wait:
    btfsc PORTA,4 ; Test Port-A, line 4
goto pbiWait ; Loop if not clear

;=======================================
; display and send "Ready-"
;=======================================
; Set LCD base address
    call linel
; Initialize system for UART emulation at 2400 baud
    call initTTY
; Display on LCD and test serial transmission by sending
; the string "Ready-"
    movlw 'R'
    movwf sendData ; Store in send register
    call send8 ; Local LCD display procedure
    call sendTTY ; Local send procedure
    movlw 'e'
    movwf sendData ; Store in send register
    call send8 ; Local LCD display procedure
    call sendTTY ; Local send procedure
    movlw 'a'
    movwf sendData ; Store in send register
    call send8 ; Local LCD display procedure
    call sendTTY ; Local send procedure
    movlw 'd'
    movwf sendData ; Store in send register
    call send8 ; Local LCD display procedure
    call sendTTY ; Local send procedure
    movlw 'y'
    movwf sendData ; Store in send register
    call send8 ; Local LCD display procedure
    call sendTTY ; Local send procedure
    movlw '-'
    movwf sendData ; Store in send register
    call send8 ; Local LCD display procedure
    call sendTTY ; Local send procedure

; Init character counter and line counter variables for
; LCD line scroll procedure
    movlw 0x06 ; 6 characters already displayed
    display
    movwf LCDcount
    clrf LCDline ; LCD line counter

;=======================================
; monitor RS232 line
;=======================================
nextChar:
    call rcvTTY ; Receive character
; Store character in local line buffer using indirect
; addressing
; 16-byte buffer named lineBuf starts at address 0x0c
; Register variable bufPtr holds offset into buffer
movlw 0x0c ; Buffer base address
addwf bufPtr,w ; Add pointer in w
movwf FSR ; Value to index register
movf rcvData,w ; Character into w
movwf INDF ; Store w in [FSR]
incf bufPtr,f ; Bump pointer
; Send character (still in w)
call send8 ; Display it
call LCDscroll ; Scroll display lines
goto nextChar ; Continue

;=================================================================================================
; initialize LCD for 4-bit mode
;=================================================================================================
initLCD:
; Initialization for Densitron LCD module as follows:
; 4-bit interface
; 2 display lines of 16 characters each
; cursor on
; left-to-right increment
; cursor shift right
; no display shift
;===============================================================================================
; set command mode |
;===============================================================================================
    bcf PORTA,E_line ; E line low
    bcf PORTA,RS_line ; RS line low
    bcf PORTA,RW_line ; Write mode
call delay_125 ; delay 125 microseconds
;===============================================================================================
; FUNCTION SET |
;===============================================================================================
    movlw 0x28 ; 00101000 (FUNCTION SET)
    ; | | | |__ font select:
    ; | | | 1 = 5x10 in 1/8 or 1/11
    ; | | 0 = 1/16 dc
    ; | | |___ Duty cycle select
    ; | | 0 = 1/8 or 1/11
    ; | | 1 = 1/16
    ; | |___ Interface width
    ; | 0 = 4 bits
    ; | 1 = 8 bits
    ; |___ FUNCTION SET COMMAND
call send8 ; 4-bit send routine

; Set 4-bit mode command must be repeated
movlw 0x28
Communications

call send8

;***********************
; DISPLAY AND CURSOR ON
;***********************

movlw 0x0e ; 00001110 (DISPLAY ON/OFF)
; | | | |___ Blink character
; | | | 1 = on, 0 = off
; | | |___ Cursor on/off
; | | 1 = on, 0 = off
; |___ Display on/off
; 1 = on, 0 = off
; |___ COMMAND BIT

call send8

;***********************
; set entry mode
;***********************

movlw 0x06 ; 00000110 (ENTRY MODE SET)
; | | |___ display shift
; | | 1 = shift
; | | 0 = no shift
; |___ increment mode
; 1 = left-to-right
; 0 = right-to-left
; |___ COMMAND BIT

call send8

;***********************
; cursor/display shift
;***********************

movlw 0x14 ; 00010100 (CURSOR/DISPLAY SHIFT)
; | | | |___ don’t care
; | | |___ cursor/display shift
; | | 00 = cursor shift left
; | | 01 = cursor shift right
; | 10 = cursor and display shifted left
; | 11 = cursor and display shifted right
; |___ COMMAND BIT

call send8

;***********************
; clear display
;***********************

movlw 0x01 ; 0000001 (CLEAR DISPLAY)
; |___ COMMAND BIT

call send8
assembly language code with comments
Communications

```
goto kloop
decfsz J,f ; J = J-1, skip next if zero
goto jloop
return

;========================
; send 2 nibbles in
; 4-bit mode
;========================
; Procedure to send two 4-bit values to Port-B lines
; 7, 6, 5, and 4. High-order nibble is sent first
; ON ENTRY:
; w register holds 8-bit value to send
send8:
    movwf store1 ; Save original value
    call merge4 ; Merge with Port-B
    ; Now w has merged byte
    movwf PORTB ; w to Port-B
    call pulseE ; Send data to LCD
    ; High nibble is sent
    movf store1,w ; Recover byte into w
    swapf store1,w ; Swap nibbles in w
    call merge4
    movwf PORTB
    call pulseE ; Send data to LCD
    call delay_125
    return

;========================
; merge bits
;========================
; Routine to merge the 4 high-order bits of the
; value to send with the contents of Port-B
; so as to preserve the 4 low-bits in Port-B
; Logic:
; AND value with 1111 0000 mask
; AND Port-B with 0000 1111 mask
; Now low nibble in value and high nibble in
; PortB are all 0 bits:
; value = vvvv 0000
; PortB = 0000 bbbb
; OR value and Port-B resulting in:
; vvvv bbbb
; ON ENTRY:
; w contains value bits
; ON EXIT:
; w contains merged bits
merge4:
    andlw b'11110000' ; ANDing with 0 clears the
    ; bit. ANDing with 1 preserves
```
movwf store2 ; Save result in variable
movf PORTB,W ; Port-B to w register
andlw b’00001111’ ; Clear high nibble in Port-B
; and preserve low nibble
iorwf store2,w ; OR two operands in w
return

;========================
; Set address register
; to LCD line 1
;========================

; ON ENTRY:
;
; Address of LCD line 1 in constant LCD_1
line1:

bcf PORTA,E_line ; E line low
bcf PORTA,RS_line ; RS line low, set up for
; control
call delay_5 ; Busy?
; Set to second display line
movlw LCD_1 ; Address and command bit
call send8 ; 4-bit routine
; Set RS line for data
bsf PORTA,RS_line ; Setup for data
call delay_5 ; Busy?
; Clear buffer and pointer
call blankBuf
clf bufPtr ; Clear
return

;========================
; Set address register
; to LCD line 2
;========================

; ON ENTRY:
;
; Address of LCD line 2 in constant LCD_2
line2:

bcf PORTA,E_line ; E line low
bcf PORTA,RS_line ; RS line low, setup for
control
call delay_5 ; Busy?
; Set to second display line
movlw LCD_2 ; Address with high-bit set
call send8 ; 4-bit routine
; Set RS line for data
bsf PORTA,RS_line ; RS = 1 for data
call delay_5 ; Busy?
; Clear buffer and pointer
call blankBuf
clf bufPtr
return

;Procedure to count the number of characters displayed on 
;each LCD line. If the number reaches the value in the 
;constant LCDlimit, then display is scrolled to the second 
;LCD line. If at the end of the second line, then the 
;second line is scrolled to the first line and display 
;continues at the start of the second line 
;reset to the first line.

LCDscroll:
    incf LCDcount,f       ; Bump counter
    movf LCDcount,w
    sublw LCDlimit        ; Count minus limit
    btfss STATUS,Z        ; Is count - limit = 0
    goto scrollExit       ; Go if not at end of line

    ; At this point the end of the LCD line was reached
    ; Test if this is also the end of the second line
    movf LCDline,w
    sublw 0x01             ; Is it line 1?
    btfsc STATUS,Z         ; Is LCDline minus 1 = 0?
    goto line2End          ; Go if end of second line

    ; At this point it is the end of the top LCD line
    call line2             ; Scroll to second line
    clrf LCDcount          ; Reset counter
    incf LCDline,f         ; Bump line counter
    goto scrollExit        ; End of second LCD line

line2End:
    ; Scroll second line to first line. Characters to be 
    ; scrolled are stored in buffer starting at address 0x0c.
    ; 16 characters are to be moved
    ; First clear LCD
    call initLCD
    call delay_5           ; Make sure not busy

    ; Set up for data
    bcf PORTA,E_line       ; E line low
    bsf PORTA,RS_line      ; RS line high for data

    ; Set up counter for 16 characters
    movlw D'16'            ; Counter = 16
    movwf count2

    ; Get address of storage buffer
    movlw 0x0c             ; W to FSR
    movwf FSR

getchar:
movf INDF, w ; get character from display RAM
; location pointed to by file select register
call send8 ; 4-bit interface routine

; Test for 16 characters displayed
decfsz count2, f ; Decrement counter
goto nextchar; Skipped if done

; At this point scroll operation has concluded
clr LCDcount ; Clear counters

; Stay at line 2
clr LCDline
incf LCDline, f
call line2 ; Set for second line

scrollExit:
    return

nextchar:
    incf FSR, f ; Bump pointer
goto getchar

;============================
; clear line buffer
;============================
; Use indirect addressing to store 16 blanks in the buffer located at 0x0c
blankBuf:
    Bank0
    movlw 0x0c ; Pointer to RAM
    movwf FSR ; To index register

blank16:
    clr INDF ; Clear memory pointed at by FSR
    incf FSR, f ; Bump pointer
    btfss FSR, 4 ; 000x0000 when bit 4 is set
    goto blank16
    return

;===================================================================
; initialize for TTY
;===================================================================
; Procedure to initialize RS232 reception
; Assumes:
; 2400 baud
; 8 data bits
; no parity
; one stop bit
initTTY:
; First initialize receiver to RS-232-C line parameters
; Disable global and peripheral interrupts

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; 7 6 5 4 3 2 1 0 <= INTCON bitmap
; | _______________________ Timer0 interrupt on overflow
; |______________________ Global interrupts
bcf INTCON,5 ; Disable TMR0 interrupts
bcf INTCON,7 ; Disable global interrupts
clr TMR0 ; Reset timer
clrwdt ; Clear WDT for prescaler
assign

Bank1
; Set up the OPTION register bit map
; 7 6 5 4 3 2 1 0 <= OPTION bits
; 1 1 0 1 1 0 0 0 <= setup
; | | | | | | | | PS2-PS0 (prescaler bits)
; | | | | | | | Values for Timer0
; | | | | | | *000 = 1:2 001 = 1:4
; | | | | | | 010 = 1:8 011 = 1:16
; | | | | | 100 = 1:32 101 = 1:64
; | | | | 110 = 1:128 111 = 1:256
; | | | | PSA (prescaler assign)
; | | | 1 = to WDT
; | | | *0 = to Timer0
; | | TOSE (Timer0 edge select)
; | | 0 = increment on low-to-high
; | | *1 = increment in high-to-low
; | TOCS (TMR0 clock source)
; | *0 = internal clock
; | 1 = RA4/TOCKI bit source
; | INTEDG (Edge select)
; | 0 = falling edge
; | *1 = raising edge
; RBPU (Pullup enable)
; 0 = enabled
; *1 = disabled
movlw b'11010000' ; set up timer/counter
movwf OPTION_REG
Bank0
return

 Bank1
 ; Set up the OPTION register bit map
 ; 7 6 5 4 3 2 1 0 <= OPTION bits
 ; 1 1 0 1 1 0 0 0 <= setup
 ; | | | | | | | | PS2-PS0 (prescaler bits)
 ; | | | | | | | Values for Timer0
 ; | | | | | | *000 = 1:2 001 = 1:4
 ; | | | | | | 010 = 1:8 011 = 1:16
 ; | | | | | 100 = 1:32 101 = 1:64
 ; | | | | 110 = 1:128 111 = 1:256
 ; | | | | PSA (prescaler assign)
 ; | | | 1 = to WDT
 ; | | | *0 = to Timer0
 ; | | TOSE (Timer0 edge select)
 ; | | 0 = increment on low-to-high
 ; | | *1 = increment in high-to-low
 ; | TOCS (TMR0 clock source)
 ; | *0 = internal clock
 ; | 1 = RA4/TOCKI bit source
 ; | INTEDG (Edge select)
 ; | 0 = falling edge
 ; | *1 = raising edge
 ; RBPU (Pullup enable)
 ; 0 = enabled
 ; *1 = disabled
movlw b'11010000' ; set up timer/counter
movwf OPTION_REG
Bank0
return

Communications

Receive character

Receive a single character through the serial port.
Assumes: 4800 baud, 8 data bits, no parity, 1 stop bit.
Receiving line is Port-A, line 0
rcvTTY:
movlw 0x08 ; Counter for 8 bits
movwf bitCount
; The start of character transmission is signaled by
; the sender by setting the line low

startBit:
    btfsc PORTA,0    ; Test for low on line
    goto startBit; Go if not low

; offset to data bit

; At this point the receiver has found the falling
; edge of the start bit. It must now wait one and
; one-half the baud rate to synchronize in the center
; of the sender’s first data bit, as follows:
; |<======== falling edge of START bit
; |   |<======== center of start bit
; |   |   |<====== center of data bit
; |-----|-----|
; _______ ___________ __________
; | | | | <== SIGNAL
; ----------- ----------
; |<-- 208 -->|h| <====== ms. for 4800 baud
;
; Clock start count for one-half bit = 255 - 104 = 151
; Clock start count for one full bit = 255 - 208 = 47
; One clock cycle is added for the movwf instruction:
;     clkHalf = 152 (for one-half bit countdown)
;     clkFull = 48 (for one full bit countdown)
    movlw   halfBaud    ; Skip one-half bit
    movwf   TMR0       ; Initialize tmr0 and start count
    bcf      INTCON,2  ; Clear overflow flag

; start bit

wait1:
    btfss INTCON,2    ; Timer count overflow?
    goto wait1        ; No, keep waiting

; At this point we are at the center of the start bit
    btfsc  PORTA,0    ; Check to see if it is still low
    goto startBit; No, it is high. False start

; At this point the clock is at the center of the start
; bit. The first data bit must be read one full baud
; period later
    movlw   fullBaud    ; One full bit delay
    movwf   TMR0       ; Start timer
    bcf      INTCON,2  ; Clear tmr0 overflow flag

wait2:
    btfss INTCON,2    ; End of one full baud period?
    goto wait2        ; Wait if not end of period

; Timer is now at the center of the first/next data bit
; Timer must be reset immediately so that code will not
; lose synchronization with sender
movlw fullBaud ; Skip to next data bit
movwf TMR0 ; Restart timer
bcf INTCON,2 ; Reset overflow flag

; Now the data bit can be read and stored
movf PORTA, w ; Read Port-B
movwf tempData ; Store in temporary variable
rrf tempData, f ; Rotate bit 0 into carry flag
rrf rcvData, f ; Rotate carry flag into storage register high-order bit
decfsz bitCount, f ; End of data?
goto wait2 ; Continue until 8 bits received

;============================================================================
; stop bit
;============================================================================
stopWait:
btfss INTCON,2 ; Test time
goto stopWait ; Wait
return ; Exit

;============================================================================
; send character
;============================================================================
; Procedure to send one character through the RS232 line.
; Assumes: 2400 baud, 8 data bits, no parity, one stop bit
; Sending line is Port-B, line 0
; ON ENTRY:
; variable sendData holds character to send
sendTTY:
movlw 0x08 ; Init bit counter
movwf bitCount
bcf PORTB, 0 ; Low for start bit
movlw fullBaud ; For one baud space
movlw TMR0 ; Start timer
bcf INTCON,2 ; Clear timer flag
start2snd:
btfss INTCON,2 ; Full baud done?
goto start2snd ; No
movlw fullBaud ; Reset for one full bit period
movwf TMR0 ; Start timer
bcf INTCON,2 ; Clear flag

; At this point the start bit has been sent
; Data follows
sendOut:
rrf sendData, f ; Rotate bit into carry
bcf PORTB, 0 ; Assume data bit is 0
btfsc STATUS, c ; Test if carry set
bsf PORTB,0 ; Change bit to 1 if clear

; Hold bit for 1 baud period

timeBit:
    btfss INTCON,2 ; Wait for baud period to end
    goto timeBit ; Loop if not yet
    movlw fullBaud ; Reset timer
    movwf TMR0 ; Start timer
    bcf INTCON,2 ; Clear flag

; Test for last bit
    decfsz bitCount,f ; Count this bit
    goto sendOut ; Continue if not last bit

; Done. Send stop bit
    bsf PORTB,0 ; High for stop bit

stopBit:
    btfss INTCON,2 ; Timer done?
    goto stopBit ; No

; Set Port-B line 0 high back again
    bsf PORTB,0
    call delay_5 ; And hold
    return

End

14.5.5 SerComLCD Program

; File name: SerComLCD.asm
; Last revision: May 14, 2006
; Author: Julio Sanchez
; Processor: 16F877

; Description:
; Decode 4 x 4 keypad, display scan code in LCD, and send
; ASCII character through the serial port. Also receive
; data through serial port and display on LCD. LCD lines
; are scrolled by program.
; Default serial line setting:
; 2400 baud
; no parity
; 1 stop bit
; 8 character bits
;
; Program uses 4-bit PIC-to-LCD interface.
; Code assumes that LCD is driven by Hitachi HD44780
; controller and PIC 16F977. Display supports two lines
; each one with 20 characters. The length, wiring and base
; address of each display line is stored in #define
; statements. These statements can be edited to accommodate
; a different set-up.
; Keypad switch wiring (values are scan codes):
;  
; -- KEYPAD --
; 0 1 2 3  <= port B0 |
; 4 5 6 7  <= port B1 |-- ROWS = OUTPUTS
; 8 9 A B  <= port B2 |
; C D E F  <= port B3 |
; | | | |   |____ port B4 |
; | | | ______ port B5 |-- COLUMNS = INPUTS
; | | __________ port B6 |
; |_______________ port B7 |
;
; Operations:
; 1. Key press action generates a scan code in the range 0x0 to 0xf.
; 2. Scan code is converted to an ASCII digit and displayed on the LCD. LCD lines are scrolled as end-of-line is reached.
; 3. Characters typed on the keypad are also transmitted through the serial port.
; 4. Serial port is polled for received characters. These are displayed on the LCD.
;
; WARNING:
; Code assumes 4Mhz clock. Delay routines must be edited for faster clock. Clock speed also determines values for baud rate setting (see spbrgVal constant).
;
;=======================================
; 16F877 switches
;=======================================
; Switches used in __config directive:
;   _CP_ON            Code protection ON/OFF
;   * _CP_OFF
;   * _PWRTE_ON       Power-up timer ON/OFF
;   _PWRTE_OFF
;   _BODEN_ON        Brown-out reset enable ON/OFF
;   * _BODEN_OFF
;   * _PWRTE_ON       Power-up timer enable ON/OFF
;   _PWRTE_OFF
;   _WDT_ON          Watchdog timer ON/OFF
;   * _WDT_OFF
;   * _LPV_ON         Low voltage IC programming enable ON/OFF
;   _LPV_OFF
;   _CPD_ON         Data EE memory code protection ON/OFF
;   * _CPD_OFF
; OSCILLATOR CONFIGURATIONS:
;   _LP_OSC         Low power crystal oscillator
; _XT_OSC       External parallel resonator/crystal oscillator
; * _HS_OSC     High speed crystal resonator
; _RC_OSC       Resistor/capacitor oscillator
; |     (simplest, 20% error)
; |
; |_____ * indicates setup values presently selected

processor 16f877 ; Define processor
#include <p16f877.inc>
__CONFIG _CP_OFF & _WDT_OFF & _BODEN_OFF & _PWRTE_ON &
          _HS_OSC & _WDT_OFF & _LVP_OFF & _CPD_OFF

; __CONFIG directive is used to embed configuration data
; within the source file. The labels following the directive
; are located in the corresponding .inc file.

MACROS

Bank0 MACRO ; Select RAM bank 0
  bcf STATUS,RP0
  bcf STATUS,RP1
ENDM

Bank1 MACRO ; Select RAM bank 1
  bsf STATUS,RP0
  bcf STATUS,RP1
ENDM

Bank2 MACRO ; Select RAM bank 2
  bcf STATUS,RP0
  bsf STATUS,RP1
ENDM

Bank3 MACRO ; Select RAM bank 3
  bsf STATUS,RP0
  bsf STATUS,RP1
ENDM

constant definitions
; for PIC-to-LCD pin wiring and LCD line addresses

#define E_line 1
#define RS_line 0  ;|  - from wiring diagram
#define RW_line 2
; LCD line addresses (from LCD data sheet)
#define LCD_1 0x80 ;|  First LCD line constant
#define LCD_2 0xc0 ;|  Second LCD line constant
#define LCDlimit .20; Number of characters per line
#define spbrgVal .25; For 2400 baud on 4MHz clock
; Note: The constants that define the LCD display
; line addresses have the high-order bit set
; so as to meet the requirements of controller
; commands.
;
;============================================
; variables in PIC RAM
;============================================
; Local variables
  cblock 0x20 ; Start of block
count1 ; Counter # 1
count2 ; Counter # 2
count3 ; Counter # 3
J ; counter J
K ; counter K
store1 ; Local storage
store2

; For LCDscroll procedure
  LCDcount ; Counter for characters per line
  LCDline ; Current display line (0 or 1)

; Keypad processing variables
  keyMask ; For keypad processing
  rowMask ; For masking-off key rows
  rowCode ; Row addend for calculating scan code
  rowCount ; Counter for key rows (0 to 3)
  scanCode ; Final key code
  newScan ; 0 if no new scan code detected

; Communications variables
  newData ; not 0 if new data received
  ascVal
  errorFlags
  endc

;============================================
; PROGRAM
;============================================
org 0 ; start at address
  goto main

main:
; Wiring:
;  LCD data to Port D, lines 0 to 7
;  E line -> port E, 1
;  RW line -> port E, 2
;  RS line -> port E, 0
; Set PORTE D and E for output
; Data memory bank selection bits:
; RP1:RP0  Bank
;  0:0    0  Ports A,B,C,D, and E
;  0:1    1  Tris A,B,C,D, and E
;  1:0    2
;  1:1    3
; First, initialize Port-B by clearing latches
clr STATUS
clr PORTB
; Select bank 1 to tris Port D for output
bcf STATUS,RP1 ; Clear banks 2/3 selector
bsf STATUS,RP0 ; Select bank 1 for tris
; registers
; Tris Port D for output. Port D lines 4 to 7 are wired
to LCD data lines. Port D lines 0 to 4 are wired to LEDs.
movlw B'00000000'
movwf TRISD ; and Port D
; By default Port-A lines are analog. To configure them
; as digital code must set bits 1 and 2 of the ADCON1
; register (in bank 1)
movlw 0x06 ; binary 0000 0110 is code to
; make all Port-A lines digital
movwf ADCON1
; Port-B, lines are wired to keypad switches, as follows:
; 7 6 5 4 3 2 1 0
; | | | | | | | | switch rows (output)
; | | | | | | | | switch columns (input)
; rows must be defined as output and columns as input
movlw b'11110000'
movwf TRISB
; Tris port E for output
movlw B'00000000'
movwf TRISE ; Tris port E
; Enable Port-B pullups for switches in OPTION register
; 7 6 5 4 3 2 1 0 <= OPTION bits
; | | | | | | | | PS2-PS0 (prescaler bits)
; | | | | | | | | Values for Timer0
; | | | | | | | 000 = 1:2  001 = 1:4
; | | | | | | | 010 = 1:8  011 = 1:16
; | | | | | | 100 = 1:32 101 = 1:64
; | | | | 110 = 1:128 *111 = 1:256
; | | | PSA (prescaler assign)
; | | | *1 = to WDT
; | | | 0 = to Timer0
; | | TOSE (Timer0 edge select)
; | | *0 = increment on low-to-high
; | 1 = increment in high-to-low
Communications

;------------------------------------------------------------------------
; | | | ___________________________ TOCS (TMR0 clock source)
; | | | *0 = internal clock
; | | | 1 = RA4/TOCKI bit source
; | | | ___________________________ INTEDG (Edge select)
; | | | *0 = falling edge
; | | | ___________________________ RBPU (Pullup enable)
; | | | *0 = enabled
; | | | 1 = disabled

    movlw b'00001000'
    movwf OPTION_REG

; Back to bank 0
    bcf STATUS,RP0

; Initialize serial port for 9600 baud, 8 bits, no parity
; 1 stop
    call InitSerial

; Test serial transmission by sending “RDY-”
    movlw 'R'
    call SerialSend
    movlw 'D'
    call SerialSend
    movlw 'Y'
    call SerialSend
    movlw '-'
    call SerialSend
    movlw 0x20
    call SerialSend

; Clear all output lines
    movlw b'00000000'
    movwf PORTD
    movwf PORTE

; Wait and initialize HD44780
    call delay_5 ; Allow LCD time to initialize itself
    call initLCD ; Then do forced initialization
    call delay_5 ; (Wait probably not necessary)

; Clear character counter and line counter variables
    clrf LCDcount
    clrf LCDline

; Set display address to start of second LCD line
    call line1

;================================================================================
; scan keypad
;================================================================================

; Keypad switch wiring:
;    x x x x <= port B0 |
;    x x x x <= port B1 |--- ROWS = OUTPUTS
;    x x x x <= port B2 |
;    x x x x <= port B3 |
; | | | |
Switches are connected to Port-B lines

Clear scan code register

```plaintext
clrf scanCode
```
movf keyMask,w ; Key mask to w
movwf PORTB ; Mask-off Port-B lines

; Read Port-B lines 4 to 7 (columns are input)
btfss PORTB,4
call col0 ; Key column procedures
btfss PORTB,5
call col1
btfss PORTB,6
call col2
btfss PORTB,7
call col3

; Index to next row by adding 4 to row code
movf rowCode,w ; Code to w
addlw D'4'
movwf rowCode

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Shift row mask
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Set the carry flag
bsf STATUS,C
rlf rowMask,f ; Rotate mask bits in storage

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; End of keypad?
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Test for last key row (maximum count is 4)
decfsz rowCount,f ; Decrement counter
goto keyLoop

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Display, send, and receive data
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; At this point all keys have been tested.
; Variable newScan = 0 if no new scan code detected, else
; variable scanCode holds scan code
movf newScan,f ; Copy onto intsem (sets Z flag)
btfsc STATUS,Z ; Is it zero
goto receive

; At this point a new scan code is detected
movf scanCode,w ; To w

; If scan code is in the range 0 to 9, that is, a decimal digit, then ASCII conversion consists of adding 0x30.
; If the scan code represents one of the hex letters (0xa to 0xf) then ASCII conversion requires adding 0x37
sublw 0x09 ; 9 - w
;if w from 0 to 9 then 9 - w = positive (C flag = 1)
; if w = 0xa then 9 - 10 = -1 (C flag = 0)
; if w = 0xc then 9 - 12 = -2 (C flag = 0)
btfss STATUS,C ; Test carry flag
  goto hexLetter ; Carry clear, must be a letter
; At this point scan code is a decimal digit in the
; range 0 to 9. Convert to ASCII by adding 0x30
  movf scanCode,w ; Recover scan code
  addlw 0x30 ; Convert to ASCII
  goto displayDig

hexLetter:
  movf scanCode,w ; Recover scan code
  addlw 0x37 ; Convert to ASCII
  displayDig:
; Store so it can be sent
  movwf ascVal
  call send8 ; Display routine
call LCDscroll
call long_delay ; Debounce
; Recover ASCII
  movf ascVal,w
call SerialSend
goto scanExit

;=========================================
; receive serial data
;=========================================
receive:
; Call serial receive procedure
call SerialRcv
; HOB of newData register is set if new data
; received
  btfss newData,7
  goto scanExit
; At this point new data was received
  call send8 ; Display in LCD
call LCDscroll ; Scroll at end of line
scanExit:
  goto keyScan ; Continue

;=========================================
; calculate scan code
;=========================================
; The column position is added to the row code (stored
; in rowCode register). Sum is the scan code
col0:
  movf rowCode,w ; Row code to w
  addlw 0x00 ; Add 0 (clearly not necessary)
  movwf scanCode ; Final value
  incf newScan,f ; New scan code
return

col1:
  movf rowCode,w ; Row code to w
  addlw 0x01 ; Add 1
  movwf scanCode
  incf newScan,f
  return

col2:
  movf rowCode,w ; Row code to w
  addlw 0x02 ; Add 2
  movwf scanCode
  incf newScan,f
  return

col3:
  movf rowCode,w ; Row code to w
  addlw 0x03 ; Add 3
  movwf scanCode
  incf newScan,f
  return

;============================================================================
;============================================================================
;  LOCAL PROCEDURES
;============================================================================
;============================================================================
;==========================================================
; init LCD for 4-bit mode
;==========================================================
initLCD:
; Initialization for Densitron LCD module as follows:
; 4-bit interface
; 2 display lines of 16 characters each
; cursor on
; left-to-right increment
; cursor shift right
; no display shift
;============================================================================
; set command mode
;============================================================================

bcf PORTE,E_line ; E line low
bcf PORTE,RS_line ; RS line low
bcf PORTE,RW_line ; Write mode

call delay_125 ; delay 125 microseconds
;==========================================================
; FUNCTION SET
;==========================================================
`movlw 0x28 ; 0 0 1 0 1 0 0 0 (FUNCTION SET)
 ;    |    |__ font select:
 ;    |    | 1 = 5x10 in 1/8 or 1/11
 ;    |    | 0 = 1/16 dc
 ;    |    |___ Duty cycle select
 ;    |    | 0 = 1/8 or 1/11
 ;    |    | 1 = 1/16
 ;    |    |___ Interface width
 ;    |    | 0 = 4 bits
 ;    |    | 1 = 8 bits
 ;    |___ FUNCTION SET COMMAND
 call    send8 ; 4-bit send routine

; Set 4-bit mode command must be repeated
 movlw 0x28
 call    send8

;***************
; DISPLAY AND CURSOR ON
;***************
 movlw 0x0e ; 0 0 0 0 1 1 1 0 (DISPLAY ON/OFF)
 ;    |    |__ Blink character
 ;    |    | 1 = on, 0 = off
 ;    |    |___ Cursor on/off
 ;    |    | 1 = on, 0 = off
 ;    |    |___ Display on/off
 ;    |    | 1 = on, 0 = off
 ;    |___ COMMAND BIT
 call    send8

;***************
; set entry mode
;***************
 movlw 0x06 ; 0 0 0 0 0 1 1 0 (ENTRY MODE SET)
 ;    |    |__ display shift
 ;    |    | 1 = shift
 ;    |    | 0 = no shift
 ;    |    |___ increment mode
 ;    |    | 1 = left-to-right
 ;    |    | 0 = right-to-left
 ;    |___ COMMAND BIT
 call    send8

;***************
; cursor/display shift
;***************
 movlw 0x14 ; 0 0 0 1 0 1 0 0 (CURSOR/DISPLAY SHIFT)
Communications

; Prints a character onto the 7-segment display
; and then clears the display.

CALL send8
"clear display"
CALL send8

; Per documentation
CALL delay_5 ; Test for busy
RETURN

; Procedure to delay
; 42 microseconds
=======================
delay_125:
   MOVlw D'42'
   MOVWF count1 ; Store value in counter
REPEAT
   DECFSZ count1,F
   GOTO repeat ; Continue if not 0
RETURN ; End of delay

; Procedure to delay
; 5 milliseconds
=======================
delay_5:
   MOVlw D'42'
   MOVWF count2 ; Store in variable
DELEY
   CALL delay_125 ; Delay
   DECFSZ count2,F ; 40 times = 5 milliseconds
   GOTO delay ; End of delay
RETURN

; Pulse E line
=======================
pulseE
bsf PORTE,E_line ; Pulse E line
nop
bcf PORTE,E_line
return

;=============================
; long delay sub-routine
;=============================
long_delay
    movlw D'200' ; w delay count
    movwf J ; J = w
    jloop:
        movwf K ; K = w
        decfsz K,f ; K = K-1, skip next if zero
        goto jloop
    decfsz J,f ; J = J-1, skip next if zero
    goto jloop
    return

;=======================
; send 2 nibbles in
; 4-bit mode
;=======================
; Procedure to send two 4-bit values to Port-B lines
; 7, 6, 5, and 4. High-order nibble is sent first
; ON ENTRY:
; w register holds 8-bit value to send
send8:
    movwf store1 ; Save original value
    call merge4 ; Merge with Port-B
    ; Now w has merged byte
    movwf PORTD ; w to Port D
    call pulseE ; Send data to LCD
    ; High nibble is sent
    movf store1,w ; Recover byte into w
    swapf store1,w ; Swap nibbles in w
    call merge4
    movwf PORTD
    call pulseE ; Send data to LCD
    call delay_125
    return

;=======================
; merge bits
;=======================
; Routine to merge the 4 high-order bits of the
; value to send with the contents of Port-B
; so as to preserve the 4 low-bits in Port-B
; Logic:
; AND value with 1111 0000 mask
; AND Port-B with 0000 1111 mask
; Now low nibble in value and high nibble in
; Port-B are all 0 bits:
;    value = vvvv 0000
;    Port-B = 0000 bbbb
; OR value and Port-B resulting in:
;    vvvv bbbb
; ON ENTRY:
;    w contain value bits
; ON EXIT:
;    w contains merged bits
merge4:
    andlw b'11110000' ; ANDing with 0 clears the
    ; bit. ANDing with 1 preserves
    ; the original value
    movwf store2 ; Save result in variable
    movf PORTD,w ; Port-B to w register
    andlw b'00001111' ; Clear high nibble in Port-B
    ; and preserve low nibble
    iorwf store2,w ; OR two operands in w
    return

;==========================
; Set address register
; to LCD line 2
;==========================
; ON ENTRY:
;    Address of LCD line 2 in constant LCD_2
line2:
    bcf PORTE,E_line ; E line low
    bcf PORTE,RS_line ; RS line low, setup for
    control
    call delay_5 ; Busy?
    ; Set to second display line
    movlw LCD_2
    ; Address with high-bit set
    call send8
    ; Set RS line for data
    bsf PORTE,RS_line ; RS = 1 for data
    call delay_5 ; Busy?
    return

;==========================
; Set address register
; to LCD line 1
;==========================
; ON ENTRY:
;    Address of LCD line 1 in constant LCD_1
line1:
  bcf PORTE,E_line ; E line low
  bcf PORTE,RS_line ; RS line low, set up for control
  call delay_5 ; busy?
  ; Set to second display line
  movlw LCD_1 ; Address and command bit
  call send8 ; 4-bit routine
  ; Set RS line for data
  bsf PORTE,RS_line ; Setup for data
  call delay_5 ; Busy?
  return

;=================================
; scroll to LCD line 2
;=================================
; Procedure to count the number of characters displayed on each LCD line. If the number reaches the value in the constant LCDlimit, then display is scrolled to the second LCD line. If at the end of the second line, then LCD is reset to the first line.
LCDscroll:
  incf LCDcount,f ; Bump counter
  ; Test for line limit
  movf LCDcount,w
  sublw LCDlimit ; Count minus limit
  btfss STATUS,Z ; Is count - limit = 0
  goto scrollExit ; Go if not at end of line
  ; At this point the end of the LCD line was reached
  ; Test if this is also the end of the second line
  movf LCDline,w
  sublw 0x01 ; Is it line 1?
  btfsc STATUS,Z ; Is LCDline minus 1 = 0?
  goto line2End ; Go if end of second line
  ; At this point it is the end of the top LCD line
  call line2 ; Scroll to second line
  clrf LCDcount ; Reset counter
  incf LCDline,f ; Bump line counter
  goto scrollExit ; End of second LCD line
line2End:
  call initLCD ; Reset
  clrf LCDcount ; Clear counters
  clrf LCDline
  call line1 ; Display to first line
scrollExit:
  return
communications procedures

Initialize serial port for 2400 baud, 8 bits, no parity,

```
InitSerial:
    Bank1 ; Macro to select bank1

    ; Bits 6 and 7 of Port C are multiplexed as TX/CK and RX/DT
    ; for USART operation. These bits must be set to input in the
    ; TRISC register
    movlw b'11000000' ; Bits for TX and RX
    iorwf TRISC,f ; OR into Trisc register

    ; The asynchronous baud rate is calculated as follows:
    ;
    ;    Fosc
    ;    ABR = ---------
    ;        S*(x+1)
    ; Where x is value in the SPBRG register and S is 64 if the high
    ; baud rate select bit (BRGH) in the TXSTA control register is
    ; clear, and 16 if the BRGH bit is set. For setting to 9600 baud
    ; using a 4Mhz oscillator at a high-speed baud rate the formula
    ; is:
    ;    4,000,000 4,000,000
    ;    -------- = -------- = 9,615 baud (0.16% error)
    ;       16*(25+1) 416
    ;
    ; At slow speed (BRGH = 0)
    ;    4,000,000 4,000,000
    ;    -------- = -------- = 2,403.85 (0.16% error)
    ;       64*(25+1) 1,664
    ;
    movlw spbrgVal ; Value in spbrgVal = 25
    movwf SPBRG ; Place in baud rate generator

TXSTA (Transmit Status and Control Register) bit map:
    7 6 5 4 3 2 1 0  <=  bits

    | | | | | | | | _______ TX9D 9nth data bit on
    | | | | | | | ? (used for parity)
    | | | | | | | | | | TRMT Transmit Shift Register
    | | | | | | | | 1 = TSR empty
    | | | | | | | * 0 = TSR full
    | | | | | | | | | | | | BRGH High Speed Baud Rate
    | | | | | | | | | | (Asynchronous mode only)
    | | | | | | | | | 1 = high speed (* 4)
    | | | | | | | | | * 0 = low speed
    | | | | | | | | | | | | NOT USED
    | | | | | | | | | | | | | | SYNC USART Mode Select
    | | | | | | | | | | | 1 = synchronous mode
    | | | | | | | | | | | * 0 = asynchronous mode
    | | | | | | | | | | | | | | TXEN Transmit Enable
```
; | | * 1 = transmit enabled
; | | 0 = transmit disabled
; | | ____________ TX9 Enable 9-bit Transmit
; | | 1 = 9-bit transmission mode
; | | * 0 = 8-bit mode
; | | ____________ CSRC Clock Source Select
; | * Not used in asynchronous mode
; | | Synchronous mode:
; | | 1 = Master Mode (internal clock)
; | | * 0 = Slave mode (external clock)

movlw 0x20 ; Enable transmission and high baud rate
movwf TXSTA

movlw 0x90 ; Enable serial port and continuous reception
movwf RCSTA

; RCSTA (Receive Status and Control Register) bit map:
; 7 6 5 4 3 2 1 0 <= bits
; | | | | | | | | ______ RX9D 9th data bit received
; | | | | | | | | ??? (can be parity bit)
; | | | | | | | | ______ OERR Overrun error
; | | | | | | | | ??? 1 = error (cleared by software)
; | | | | | | | | _______ FERR Framing Error
; | | | | | | | | ??? 1 = error
; | | | | | | | | ________ NOT USED
; | | | | | | | | ________ CREN Continuous Receive Enable
; | | | | | | | | Asynchronous mode:
; | | | | | | | | * 1 = Enable continuous receive
; | | | | | | | | 0 = Disables continuous receive
; | | | | | | | | Synchronous mode:
; | | | | | | | | 1 = Enables until CREN cleared
; | | | | | | | | 0 = Disables continuous receive
; | | | | | | | | ____________ SREN Single Receive Enable
; | | | | | | | | ??? Asynchronous mode = don’t care
; | | | | | | | | Synchronous master mode:
; | | | | | | | | 1 = Enable single receive
; | | | | | | | | 0 = Disable single receive
; | | | | | | | | ____________ RX9 9th-bit Receive Enable
; | | | | | | | | 1 = 9-bit reception
; | | | | | | | | * 0 = 8-bit reception
; | | | | | | | | ____________ SPEN Serial Port Enable
; | | | | | | | | * 1 = RX/DT and TX/CK are serial pins
; | | | | | | | | 0 = Serial port disabled
; Setup value: 1001 0000 = 0x90
movlw 0x90 ; Enable serial port and continuous reception
movwf RCSTA
clrf errorFlags ; Clear local error flags
return

;==============================
; transmit data
;==============================
; Test for Transmit Register Empty and transmit data in w
SerialSend:
  Bank0 ; Select bank 0
  btfss PIR1,TXIF ; check if transmitter busy
goto $-1 ; wait until transmitter is not busy
  movwf TXREG ; and transmit the data
return

;==============================
; receive data
;==============================
; Procedure to test line for data received and return value in w. Overrun and framing errors are detected and remembered in the variable errorFlags, as follows:
; 7 6 5 4 3 2 1 0 <= errorFlags
; — not used — | || overrun error
; |____ framing error
SerialRcv:
  clrf newData ; Clear new data received register
  Bank0 ; Select bank 0
  ; Bit 5 (RCIF) of the PIR1 Register is clear if the USART receive buffer is empty. If so, no data has been received
  btfss PIR1,RCIF ; Check for received data
  return ; Exit if no data
  ; At this point data has been received. First eliminate possible errors: overrun and framing.
  ; Bit 1 (OERR) of the RCSTA register detects overrun
  ; Bit 2 (FERR) of the RCSTA register detects framing error
  btfsc RCSTA,OERR ; Test for overrun error
goto OverErr ; Error handler
  btfsc RCSTA,FERR ; Test for framing error
goto FrameErr ; Error handler
  ; At this point no error was detected
  ; Received data is in the USART RCREG register
  movf RCREG,w ; get received data
  bsf newData,7 ; Set bit 7 to indicate new data
  ; Clear error flags
  clrf errorFlags
  return

;=================================
; error handlers
OverErr:
    bsf errorFlags,0 ; Bit 0 is overrun error
    ; Reset system
    bcf RCSTA,CREN ; Clear continuous receive bit
    bsf RCSTA,CREN ; Set to re-enable reception
    return
; error because FERR framing error bit is set
; can do special error handling here - this code simply clears
; and continues
FrameErr:
    bsf errorFlags,1 ; Bit 1 is framing error
    movf RCREG,W ; Read and throw away bad data
    return

end

14.5.6 SerIntLCD Program

; File name: SerIntLCD.asm
; Last revision: May 14, 2006
; Author: Julio Sanchez
; Processor: 16F877
;
; Interrupt-driven version of the SerComLCD program
;
; Description:
; Decode 4 x 4 keypad, display scan code in LCD, and send
; ASCII character through the serial port. Also receive
; data through serial port and display on LCD. LCD lines
; are scrolled by program.
; Default serial line setting:
; 2400 baud
; no parity
; 1 stop bit
; 8 character bits
;
; Program to uses 4-bit PIC-to-LCD interface.
; Code assumes that LCD is driven by Hitachi HD44780
; controller and PIC 16F977. Display supports two lines
; each one with 20 characters. The length, wiring and base
; address of each display line is stored in #define
; statements. These statements can be edited to accommodate
; a different setup.
; Keypad switch wiring (values are scan codes):
;  -- KEYPAD --
;    0 1 2 3 <= port B0
;    4 5 6 7 <= port B1 |-- ROWS = OUTPUTS
Operations:
1. Key press action generates a scan code in the range 0x0 to 0xf.
2. Scan code is converted to an ASCII digit and displayed on the LCD. LCD lines are scrolled as end-of-line is reached.
3. Characters typed on the keypad are also transmitted through the serial port.
4. Received characters generate an interrupt. The interrupt handler displays received characters on the LCD.

WARNING:
Code assumes 4Mhz clock. Delay routines must be edited for faster clock. Clock speed also determines values for baud rate setting (see spbrgVal constant).

16F877 switches
Switches used in __config directive:
- _CP_ON Code protection ON/OFF
- _CP_OFF
- _PWRTE_ON Power-up timer ON/OFF
- _PWRTE_OFF
- _BODEN_ON Brown-out reset enable ON/OFF
- _BODEN_OFF
- _PWRTE_ON Power-up timer enable ON/OFF
- _PWRTE_OFF
- _WDT_ON Watchdog timer ON/OFF
- _WDT_OFF
- _LPV_ON Low voltage IC programming enable ON/OFF
- _LPV_OFF
- _CPD_ON Data EE memory code protection ON/OFF
- _CPD_OFF

Oscillator configurations:
- _LP_OSC Low power crystal oscillator
- _XT_OSC External parallel resonator/crystal oscillator
- _HS_OSC High speed crystal resonator
- _RC_OSC Resistor/capacitor oscillator
processor 16f877 ; Define processor

#include <p16f877.inc>
__CONFIG _CP_OFF & _WDT_OFF & _BODEN_OFF & _PWRTE_ON &
_HS_OSC & _WDT_OFF & _LVP_OFF & _CPD_OFF

; __CONFIG directive is used to embed configuration data
; within the source file. The labels following the directive
; are located in the corresponding .inc file.
;=================================================================
; MACROS
;=================================================================
; Macros to select the register banks
Bank0 MACRO ; Select RAM bank 0
bcf STATUS,RP0
bcf STATUS,RP1
ENDM

Bank1 MACRO ; Select RAM bank 1
bsf STATUS,RP0
bcf STATUS,RP1
ENDM

Bank2 MACRO ; Select RAM bank 2
bcf STATUS,RP0
bsf STATUS,RP1
ENDM

Bank3 MACRO ; Select RAM bank 3
bsf STATUS,RP0
bsf STATUS,RP1
ENDM

;=================================================================
; constant definitions
; for PIC-to-LCD pin wiring and LCD line addresses
;=================================================================
#define E_line 1 ;
#define RS_line 0 ; — from wiring diagram
#define RW_line 2 ;
; LCD line addresses (from LCD data sheet)
#define LCD_1 0x80 ; First LCD line constant
#define LCD_2 0xc0 ; Second LCD line constant
#define LCDlimit .20; Number of characters per line
#define spbrgVal .25; For 2400 baud on 4Mhz clock
; Note: The constants that define the LCD display
; line addresses have the high-order bit set
; so as to meet the requirements of controller
; commands.
;
;==================================================================
; variables in PIC RAM
;==================================================================
;
; Local variables
  cblock 0x20 ; Start of block
  count1 ; Counter # 1
  count2 ; Counter # 2
  count3 ; Counter # 3
  J ; counter J
  K ; counter K
  store1 ; Local storage
  store2

; For LCDscroll procedure
  LCDcount ; Counter for characters per line
  LCDline ; Current display line (0 or 1)

; Keypad processing variables
  keyMask ; For keypad processing
  rowMask ; For masking-off key rows
  rowCode ; Row addend for calculating scan code
  rowCount ; Counter for key rows (0 to 3)
  scanCode ; Final key code
  newScan ; 0 if no new scan code detected

; Communications variables
  ascVal
  errorFlags

; Temporary storage used by interrupt handler
  tempW
  tempStatus
  tempPclath
  tempFsr
  endc

;==================================================================
; PROGRAM
;==================================================================

  org 0 ; start at address
  goto main

; Space for interrupt handlers
  org 0x04
  InterruptCode:
    goto IntServ ; Interrupt service routine

;==================================================================
; main program
;====================================================================================================
main:
; Wiring:
; LCD data to Port D, lines 0 to 7
; E line -> port E, 1
; RW line -> port E, 2
; RS line -> port E, 0
; Set PORTE D and E for output
; Data memory bank selection bits:
; RP1:RP0
; 0:0 0  Ports A,B,C,D, and E
; 0:1 1 Tris A,B,C,D, and E
; 1:0 2
; 1:1 3
; First, initialize Port-B by clearing latches
clrf STATUS
clrf PORTB
; Select bank 1 to tris Port D for output
Bank1
; Tris Port D for output. Port D lines 4 to 7 are wired
; to LCD data lines. Port D lines 0 to 4 are wired to LEDs.
movlw B'00000000'
movwf TRISD ; and Port D
; By default Port-A lines are analog. To configure them
; as digital code must set bits 1 and 2 of the ADCON1
; register (in bank 1)
movlw 0x06 ; binary 0000 0110 is code to
; make all Port-A lines digital
movwf ADCON1
; Port-B lines are wired to keypad switches, as follows:
; 7 6 5 4 3 2 1 0
; | | | | | | | | switch rows (output)
; | | | | | | | | switch columns (input)
; rows must be defined as output and columns as input
movlw b'11110000'
movwf TRISB
movlw B'00000000'
movwf TRISE ; Tris port E for output
movwf B'00000000'
movwf TRISE ; Tris port E
; Enable Port-B pullups for switches in OPTION register
; 7 6 5 4 3 2 1 0 <= OPTION bits
; | | | | | | | | PS2-PS0 (prescaler bits)
; | | | | | | | | Values for Timer0
; | | | | | | | 000 = 1:2  001 = 1:4
; | | | | | | 010 = 1:8  011 = 1:16
; | | | | | 100 = 1:32  101 = 1:64
; | | | | 110 = 1:128 *111 = 1:256
; | | | | _____________ PSA (prescaler assign)
movlw b'00001000'
movwf OPTION_REG

; Back to bank 0
Bank0

; Initialize serial port for 9600 baud, 8 bits, no parity
; 1 stop
call InitSerial

; Test serial transmission by sending "RDY-
movlw 'R'
call SerialSend
movlw 'D'
call SerialSend
movlw 'Y'
call SerialSend
movlw '-'
call SerialSend
movlw 0x20
call SerialSend

; Clear all output lines
movlw b'00000000'
movwf PORTD
movwf PORTE

; Wait and initialize HD44780
call delay_5 ; Allow LCD time to initialize itself
call initLCD ; Then do forced initialization
call delay_5 ; (Wait probably not necessary)

; Clear character counter and line counter variables
clrf LCDcount
clrf LCDline

; Set display address to start of second LCD line
call line1

;============================================================================
; scan keypad
;============================================================================

; Keypad switch wiring:
Switches are connected to Port-B lines
; Clear scan code register
   clrf  scanCode

;=================================================================================
; scan keypad and display
;=================================================================================
keyScan:
; Port-B, lines are wired to pushbutton switches, as follows:
;  7 6 5 4 3 2 1 0
;  | | | | |_|_|_|_____ switch rows (output)
;  |_|_|_|_____________ switch columns (input)
; Keypad processing:
; switch rows are successively grounded (row = 0)
; Then column values are tested. If a column returns 0
; in a 0 row, that switch is down.
; Initialize row code addend
   clrf  rowCode       ; First row is code 0
   clrf  newScan       ; No new scan code detected
;
; Initialize row count
   movlw D'4'         ; Four rows
   movwf  rowCount    ; Register variable
   movlw b'11111110'  ; All set but LOB
   movwf  rowMask

keyLoop:
; Initialize row eliminator mask:
; The row mask is ANDed with the key mask to successively
; mask-off each row, for example:
;
;          |---- row 3
;          ||    row 2
;          |||   row 1
;          |||| row 0
;       0000 1111 <= key mask
;       AND 1111 1101 <= mask for row 1
;          ______
;       0000 1101 <= row 1 is masked off
;
; The row mask, which is initially 1111 1110, is rotated left
; through the carry in order to mask off the next row
movlw b'00001111' ; Mask off all lines
movwf keyMask ; To local register

; Set row mask for current row
movf rowMask,w ; Mask to w
andwf keyMask,f ; Update key mask
movf keyMask,w ; Key mask to w
movwf PORTB ; Mask-off Port-B lines

; Read Port-B lines 4 to 7 (columns are input)
btfss PORTB,4
call col0 ; Key column procedures
btfss PORTB,5
call col1
btfss PORTB,6
call col2
btfss PORTB,7
call col3

; Index to next row by adding 4 to row code
movf rowCode,w ; Code to w
addlw D'4'
movwf rowCode

;============================================================
; display and send data
;============================================================
; At this point all keys have been tested.
; Variable newScan = 0 if no new scan code detected, else
; variable scanCode holds scan code
movf newScan,f ; Copy onto itself
btfsc STATUS,Z ; Is it zero
goto ScanExit

; If scan code is in the range 0 to 9, that is, a decimal
digit, then ASCII conversion consists of adding 0x30.
; If the scan code represents one of the hex letters
; (0xa to 0xf) then ASCII conversion requires adding
; 0x37
sublw 0x09 ; 9 - w
; if w from 0 to 9 then 9 - w = positive (C flag = 1)
; if w = 0xa then 9 - 10 = -1 (C flag = 0)
; if w = 0xc then 9 - 12 = -2 (C flag = 0)
btfss STATUS,C ; Test carry flag
goto hexLetter ; Carry clear, must be a
letter
; At this point scan code is a decimal digit in the
; range 0 to 9. Convert to ASCII by adding 0x30
movf scanCode,w ; Recover scan code
addlw 0x30 ; Convert to ASCII
goto displayDig

hexLetter:
    movf scanCode,w ; Recover scan code
    addlw 0x37 ; Convert to ASCII
displayDig:
; Store so it can be sent
    movwf ascVal
    call send8 ; Display routine
call LCDscroll
call long_delay ; Debounce
; Recover ASCII
    movf ascVal,w
call SerialSend
ScanExit:
goto keyScan ; Continue

;===========================================
; calculate scan code
;===========================================
; The column position is added to the row code (stored
; in rowCode register). Sum is the scan code

col0:
    movf rowCode,w ; Row code to w
    addlw 0x00 ; Add 0
    movwf scanCode ; Final value
    incf newScan,f ; New scan code
    return

col1:
    movf rowCode,w ; Row code to w
    addlw 0x01 ; Add 1
    movwf scanCode
    incf newScan,f
    return

col2:
    movf rowCode,w ; Row code to w
Communications

```
addlw  0x02 ; Add 2
movwf  scanCode
incf   newScan,f
return

col3:
  movf   rowCode,w ; Row code to w
  addlw  0x03 ; Add 3
  movwf  scanCode
  incf   newScan,f
  return

;=================================================================
;=================================================================
; LOCAL PROCEDURES
;=================================================================
;==================================================================
; init LCD for 4-bit mode
;==================================================================
initLCD:
; Initialization for Densitron LCD module as follows:
;  4-bit interface
;  2 display lines of 16 characters each
;  cursor on
;  left-to-right increment
;  cursor shift right
;  no display shift
;================================
; set command mode |
;================================
  bcf    PORTE,E_line ; E line low
  bcf    PORTE,RS_line ; RS line low
  bcf    PORTE,RW_line ; Write mode
  call   delay_125 ; delay 125 microseconds
;================================
; FUNCTION SET |
;================================
  movlw  0x28 ; 0 0 1 0 1 0 0 0 (FUNCTION SET)
  ; | | | |__ font select:
  ; | | | 1 = 5x10 in 1/8 or 1/11
  ; | | | 0 = 1/16 dc
  ; | | |___ Duty cycle select
  ; | | 0 = 1/8 or 1/11
  ; | | 1 = 1/16)
  ; | |___ Interface width
  ; | 0 = 4 bits
  ; | 1 = 8 bits
```
; __ FUNCTION SET COMMAND

call send8 ; 4-bit send routine

; Set 4-bit mode command must be repeated
movlw 0x28
call send8

;*******************************
; DISPLAY AND CURSOR ON
;*******************************
movlw 0x0e ; 00001110 (DISPLAY ON/OFF)
        ; | | | |___ Blink character
        ; | | | 1 = on, 0 = off
        ; | | |___ Cursor on/off
        ; | | 1 = on, 0 = off
        ; | |___ Display on/off
        ; | 1 = on, 0 = off
        ; |___ COMMAND BIT

call send8

;*******************************
; set entry mode
;*******************************
movlw 0x06 ; 00000110 (ENTRY MODE SET)
        ; | | |___ display shift
        ; | | 1 = shift
        ; | | 0 = no shift
        ; | |___ increment mode
        ; | 1 = left-to-right
        ; | 0 = right-to-left
        ; |___ COMMAND BIT

call send8

;*******************************
; cursor/display shift
;*******************************
movlw 0x14 ; 0000 1 1 1 0 (CURSOR/DISPLAY
SHIFT)
        ; | | | |___ don’t care
        ; | | | cursor/display shift
        ; | 00 = cursor shift left
        ; | 01 = cursor shift right
        ; | 10 = cursor and display
        ; | shifted left
        ; | 11 = cursor and display
        ; | shifted right
        ; |___ COMMAND BIT

call send8

;*******************************
; clear display
;**************************
movlw 0x01 ; 0 0 0 0 0 0 0 1 (CLEAR DISPLAY)
           ; |___ COMMAND BIT
call send0
; Per documentation
call delay_5 ; Test for busy
return

;=================================
; Procedure to delay
; 42 microseconds
;=================================
delay_125:
movlw D’42’ ; Repeat 42 machine cycles
movwf count1 ; Store value in counter
repeat:
decfsz count1,f ; Decrement counter
goto repeat ; Continue if not 0
return ; End of delay

;=================================
; Procedure to delay
; 5 milliseconds
;=================================
delay_5:
movlw D’42’ ; Counter = 41
movwf count2 ; Store in variable
delay:
call delay_125 ; Delay
decfsz count2,f ; 40 times = 5 milliseconds
goto delay
return ; End of delay

;=================================
; pulse E line
;=================================
pulseE
    bsf PORTE,E_line ; Pulse E line
    nop
    bcf PORTE,E_line
return

;=================================
; long delay sub-routine
;=================================
long_delay
    movlw D’200’ ; w delay count
    movwf J       ; J = w
jloop:  
movwf K ; K = w
kloop:  
decfsz K,f ; K = K-1, skip next if zero
goto kloop
decfsz J,f ; J = J-1, skip next if zero
goto jloop
return

; =========================
; send 2 nibbles in
;  4-bit mode
; =========================
; Procedure to send two 4-bit values to Port-B lines
; 7, 6, 5, and 4. High-order nibble is sent first
; ON ENTRY:
; w register holds 8-bit value to send
send8:
movwf store1 ; Save original value
call merge4 ; Merge with Port-B
; Now w has merged byte
movwf PORTD ; w to Port D
call pulseE ; Send data to LCD
; High nibble is sent
movf store1,W ; Recover byte into w
swapf store1,W ; Swap nibbles in w
call merge4
movwf PORTD
call pulseE ; Send data to LCD
call delay_125
return

; =========================
; merge bits
; =========================
; Routine to merge the 4 high-order bits of the
; value to send with the contents of Port-B
; so as to preserve the 4 low-bits in Port-B
; Logic:
; AND value with 1111 0000 mask
; AND Port-B with 0000 1111 mask
; Now low nibble in value and high nibble in
; Port-B are all 0 bits:
; value = vvvv 0000
; Port-B = 0000 bbbb
; OR value and Port-B resulting in:
; vvvv bbbb
; ON ENTRY:
; w contains value bits
; ON EXIT:
; w contains merged bits
merge4:
  andlw b'11110000' ; ANDing with 0 clears the
           ; bit. ANDing with 1 preserves
           ; the original value
  movwf store2 ; Save result in variable
  movf PORTD,w ; Port-B to w register
  andlw b'00001111' ; Clear high nibble in Port-B
           ; and preserve low nibble
  iorwf store2,w ; OR two operands in w
return

;==========================
; Set address register
; to LCD line 2
;==========================
; ON ENTRY:
; Address of LCD line 2 in constant LCD_2
line2:
  bcf PORTE,E_line ; E line low
  bcf PORTE,RS_line ; RS line low, setup for
           ; control
  call delay_5 ; Busy?
; Set to second display line
  movlw LCD_2 ; Address with high-bit set
  call send8
; Set RS line for data
  bsf PORTE,RS_line ; RS = 1 for data
  call delay_5 ; Busy?
return

;==========================
; Set address register
; to LCD line 1
;==========================
; ON ENTRY:
; Address of LCD line 1 in constant LCD_1
line1:
  bcf PORTE,E_line ; E line low
  bcf PORTE,RS_line ; RS line low, set up for
           ; control
  call delay_5 ; busy?
; Set to second display line
  movlw LCD_1 ; Address and command bit
  call send8 ; 4-bit routine
; Set RS line for data
  bsf PORTE,RS_line ; Setup for data
call delay_5 ; Busy?
return

;========================================
;   scroll to LCD line 2
;========================================
; Procedure to count the number of characters displayed on
; each LCD line. If the number reaches the value in the
; constant LCDlimit, then display is scrolled to the second
; LCD line. If at the end of the second line, then LCD is
; reset to the first line.
LCDscroll:
  incf LCDcount,f ; Bump counter
  ; Test for line limit
  movf LCDcount,w
  sublw LCDlimit ; Count minus limit
  btfss STATUS,Z ; Is count - limit = 0
  goto scrollExit ; Go if not at end of line
  ; At this point the end of the LCD line was reached
  ; Test if this is also the end of the second line
  movf LCDline,w
  sublw 0x01 ; Is it line 1?
  btfsc STATUS,Z ; Is LCDline minus 1 = 0?
  goto line2End ; Go if end of second line
  ; At this point it is the end of the top LCD line
  call line2 ; Scroll to second line
  clrf LCDcount ; Reset counter
  incf LCDline,f ; Bump line counter
  goto scrollExit

 ; End of second LCD line
line2End:
  call initLCD ; Reset
  clrf LCDcount ; Clear counters
  clrf LCDline
  call line1 ; Display to first line
scrollExit:
  return

;========================================
; communications procedures
;========================================
; Initialize serial port for 2400 baud, 8 bits, no parity,
; 1 stop
InitSerial:
  Bank1 ; Macro to select bank1
  ; Bits 6 and 7 of Port C are multiplexed as TX/CK and RX/DT
  ; for USART operation. These bits must be set to input in the
  ; TRISC register
movlw b'11000000' ; Bits for TX and RX
iorwf TRISC,f ; OR into Trisc register

; The asynchronous baud rate is calculated as follows:
; Fosc
; ABR = ---------
; S*(x+1)

; Where x is value in the SPBRG register and S is 64 if the high
; baud rate select bit (BRGH) in the TXSTA control register is
; clear, and 16 if the BRGH bit is set. For setting to 9600 baud
; using a 4Mhs oscillator at a high-speed baud rate the formula
; is:
; 4,000,000 4,000,000
; --------- = --------- = 9,615 baud (0.16% error)
; 16*(25+1) 416
;
; At slow speed (BRGH = 0)
; 4,000,000 4,000,000
; --------- = ---------- = 2,403.85 (0.16% error)
; 64*(25+1) 1,664
;
;
; movlw spbrgVal ; Value in spbrgVal = 25
movwf SPBRG ; Place in baud rate generator

; TXSTA (Transmit Status and Control Register) bit map:
; 7 6 5 4 3 2 1 0 <= bits
; | | | | | | | | __________ TX9D 9nth data bit on
; | | | | | | | ? (used for parity)
; | | | | | | | __________ TRMT Transmit Shift Register
; | | | | | | 1 = TSR empty
; | | | | | | * 0 = TSR full
; | | | | | __________ BRGH High Speed Baud Rate
; | | | | | (Asynchronous mode only)
; | | | | 1 = high speed (* 4)
; | | | | * 0 = low speed
; | | | | __________ NOT USED
; | | | ___________ SYNC USART Mode Select
; | | | 1 = synchronous mode
; | | | * 0 = asynchronous mode
; | | ___________ TXEN Transmit Enable
; | | * 1 = transmit enabled
; | | 0 = transmit disabled
; | ___________ TX9 Enable 9-bit Transmit
; | 1 = 9-bit transmission mode
; | * 0 = 8-bit mode
; ___________ CSRC Clock Source Select
; Not used in asynchronous mode
; Synchronous mode:
; 1 = Master Mode (internal clock)
; * 0 = Slave mode (external clock)
movlw 0x20 ; Enable transmission and low baud rate
movwf TXSTA

Bank0

movlw 0x90 ; Enable serial port and
movwf RCSTA

; Enable glocal and peripheral interrupts
movlw b'11000000'
movwf INTCON

movlw b'00100000'

movwf PIE1 ; Clear error flags register
Bank0
crfl errorFlags
return

;===============================================
; transmit data
;===============================================
; Test for Transmit Register Empty and transmit data in w
SerialSend:
    Bank0 ; Select bank 0
    btfss PIR1,TXIF ; check if transmitter busy
    goto $-1 ;wait until transmitter is not busy
    movwf TXREG ;and transmit the data
    return

;=====================================================================
;=====================================================================
; interrupt handler for received characters
;=====================================================================
;=====================================================================
IntServ:
movwf tempW ; Save W
movf STATUS,W ; Store STATUS in W
clrf STATUS ; Select bank0
movwf tempStatus ; Save STATUS
movf PCLATH,W ; Store PCLATH in W
movwf tempPclath ; Save PCLATH
clrf PCLATH ; Select program memory page 0
movf FSR,W ; Store FSR in W
movwf tempFsr ; Save FSR value

; Test for received data interrupt
    Bank0 ; select bank0
    ; 7 6 5 4 3 2 1 0 <= PIR1
    ; |__________________ (RCIF) USART receive interrupt
    ; |__________________ (RCIE) Receive interrupt enable
    ;   flag
    btfsc PIR1,RCIF ; Test bit 5
    bsf STATUS,RP0 ; Bank 1 if RCIF set
    ; 7 6 5 4 3 2 1 0 <= PIE1
    ; |__________________ (RCIE) Receive interrupt enable
    ;   bit
    btfss PIE1,RCIE ; Test if interrupt is enabled
    goto IntExit ; Go if not enabled

;=====================================================================
; received data
;=====================================================================
; Routine to handle received data. Overrun and framing errors are detected and remembered in the variable errorFlags, as follows:
; 7 6 5 4 3 2 1 0 <= errorFlags
; -- not used -- | |____ overrun error
; |________ framing error

; Select bank 0
Bank0

; Test for overrun and framing errors.
; Bit 1 (OERR) of the RCSTA register detects overrun
; Bit 2 (FERR) of the RCSTA register detects framing error
btfsc RCSTA,OERR ; Test for overrun error
goto OverErr ; Error handler
btfsc RCSTA,FERR ; Test for framing error
goto FrameErr ; Error handler

; At this point no error was detected
; Received data is in the USART RCREG register
movf RCREG,w ; Received data into w
call send8 ; Display in LCD
call LCDscroll ; Scroll at end of line

; Clear error flags
clrf errorFlags
goto IntExit

;===============================================
; error handlers
;===============================================

; Errors are returned as bits in the errorFlags register
; 7 6 5 4 3 2 1 0 <= errorFlags
; -- not used -- | |____ overrun error
; |________ framing error
; Error responses to be made by main code
OverErr:
bsf errorFlags,0 ; Bit 0 is overrun error

; Reset system
bcf RCSTA,CREN ; Clear continuous receive bit
bsf RCSTA,CREN ; Set to re-enable reception
goto IntExit

FrameErr:
bsf errorFlags,1; Bit 1 is framing error
movf RCREG,w ; Read and throw away bad data

;===============================================
; interrupt handler exit
;===============================================

IntExit:
Bank0
movf tempFsr,w ; Recover FSR value
movwf FSR ; Restore in register
movf tempPclath,w ; Recover PCLATH value
movwf PCLATH ; Restore in register
movf  tempStatus,W ; Recover STATUS
movwf  STATUS ; Restore in register
swapf  tempW,F ; Swap file register in itself
swapf  tempW,W ; Restore in register
retfie

end
Chapter 15

Data EEPROM Programming

EEPROM stands for *Electrically-Erasable Programmable Read-Only Memory*. EEPROM is used in computers and digital devices as non-volatile storage. EEPROM is found in flash drives, BIOS chips, and in flash memory and EEPROM data storage memory in PICs and other microcontrollers.

EEPROM memory can be erased and programmed electrically without removing the chip. EPROM, the predecessor of EEPROM, required chip removal from the circuit and ultraviolet light exposure in order to erase the chip. In addition, EPROM requires higher-than-TTL voltages for reprogramming while EEPROM does not.

The PIC programmer regards EEPROM data memory as *onboard EEPROM memory* and EEPROM memory ICs as separate circuit components. In general, EEPROM elements are classified according to their electrical interfaces into serial and parallel. In this context we deal only with *serial EEPROMs*. The storage capacity of Serial EEPROMs ranges from a few bytes to 128 kilobytes. In PIC technology, the typical use of serial EEPROM onboard memory and EEPROM ICs is to store passwords, codes, configuration settings, and other information to be remembered after the system is turned off. For example, a PIC-based automated environment sensor can use EEPROM memory (onboard or independent) to store daily temperatures, humidity, air pressure, and other values. Later, this information could be downloaded to a PC and the EEPROM storage erased and reused for new data. In personal computers, EEPROM memory is used to store BIOS code and other system data.

Some early EEPROM could only be erased and rewritten about 100 times, while modern EEPROM tolerate thousands of erase-write cycles. EEPROM memory is different from *RAM (Random Access Memory)* in that RAM can be rewritten millions of times. Also, RAM is generally faster to write than EEPROM and considerably cheaper per unit of storage. On the other hand, RAM is volatile, so the contents are lost when power is removed.

PICs use EEPROM-type memory internally as flash program memory and as data memory. EEPROM data memory is covered in this chapter. Serial EEPROM memory
is available as separate ICs that can be placed on the circuit board and accessed through PIC ports. For example, the Microchip 24LC04B EEPROM IC is a 4K electrically erasable PROM with a 2-wire serial interface that follows the I²C convention. Programming serial EEPROM ICs is also covered in this chapter.

15.0  PIC Internal EEPROM Memory

Some PICs contain internal EEPROM data memory that is accessible to code. The amount of memory and the access mechanism varies from PIC to PIC. In fact, the mapping and access mechanisms varies even in devices belonging to the same family. In the sections that follow, we describe EEPROM data memory in the context of two different PICs of the mid-range family: the 16F84 and the 16F877.

15.0.1  EEPROM Programming on the 16F84

The 16F84 and 16F84A contain 64 bytes of EEPROM data memory. This memory is both readable and writable during normal operation. It is not mapped in the register file space, but is indirectly addressed through the Special Function Registers EECON1, EECON2, EEDATA, and EEADR. The address of EEPROM memory starts at location 0x00 and extends to the maximum contained in the PIC, in this case, 0x3f. The following registers relate to EEPROM operations:

1. EEDATA holds the data byte to be read or written.
2. EEADR contains the EEPROM address to be accessed by the read or write operation.
3. EECON1 contains the control bits for EEPROM operations.
4. EECON2 protects EEPROM memory from accidental access. This is not a physical register.

Figure 15-1 shows the bitmap of the EECON1 register in the 16F84.

The CPU continues to access EEPROM memory even if the device is code protected, but in this case the device programmer can not access EEPROM memory.

Reading EEPROM Data Memory on the 16F84

Reading an EEPROM data memory location in the 16F84 requires the following operations:

1. Bank 0 is selected and the address of the memory to be read is stored in the EEADR register.
2. Bank 1 is selected and the RD bit is set in the EECON1 register.
3. Bank 0 is selected and data is read from the EEDATA register.

The following procedure returns in the w register the data stored at the specified EEPROM memory address.

```
; ===============================
; read EEPROM 16F84
; ===============================
; Procedure to read EEPROM memory. Address of memory
; location to read is stored in local register EEMemAdd
```
Data EEPROM Programming

16F84 EEPROM Data Memory Write

Writing to 16F84 EEPROM data memory consists of the following operations:

1. Bank 0 is selected and the address of the desired memory location is stored in the EEARDR register.
2. The value to be written is stored in the EEDATA register.
3. Bank 1 is selected, interrupts are disabled, and the write enable bit (WREN) is set in the EECON1 register.

; On exit: read data in w
EERead:

bcf STATUS,RP0 ; Bank 0
movf EEMemAdd,w ; Address to w
movwf EEADR ; w to address register
bsf STATUS,RP0 ; Bank 1
bsf EECON1,RD ; EE Read
bcf STATUS,RP0 ; Bank 0
movf EEDATA,w ; W = EEDATA
return

Figure 15-1 16F84 EECON1 Register Bit Map

<table>
<thead>
<tr>
<th>bit 7-5</th>
<th>bit 4</th>
<th>bit 3</th>
<th>bit 2</th>
<th>bit 1</th>
<th>bit 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unimplemented: Read as '0'</td>
<td>EEIF: EEPROM Write Operation Interrupt Flag bit</td>
<td>WRERR: EEPROM Error Flag bit</td>
<td>WREN: EEPROM Write Enable bit</td>
<td>WR: Write Control bit</td>
<td>RD: Read Control bit</td>
</tr>
</tbody>
</table>

bit 7-5 Unimplemented: Read as '0'
bit 4 EEIF: EEPROM Write Operation Interrupt Flag bit
   1 = The write operation completed (must be cleared in software)
   0 = The write operation is not complete or has not been started

bit 3 WRERR: EEPROM Error Flag bit
   1 = write operation terminated prematurely
   0 = The write operation completed

bit 2 WREN: EEPROM Write Enable bit
   1 = Allows write cycles
   0 = Inhibit write to the EEPROM

bit 1 WR: Write Control bit
   1 = Initiates a write cycle. Bit is cleared once write is complete.
       Can only be set in software.
   0 = Write cycle to the EEPROM is complete

bit 0 RD: Read Control bit
   1 = Initiates an EEPROM read. Bit is cleared in hardware. Can only be set in software.
   0 = Does not initiate an EEPROM read
4. The special values 0x55 and 0xaa are written consecutively to the EECON2 register.

5. The WR bit is set in the EECON1 register. The EEPROM write takes place automatically after the WR bit is set.

6. Interrupts are re-enabled and bank 0 is selected.

The following procedure shows the processing for the EEPROM write.

```assembly
;==============================
; write EEPROM
;==============================
; Procedure to write ascii byte to EEPROM memory
; Address to write stored in local register EEMemAdd
; Data byte to write is in local register EEByte
EEWrite:
; Load byte to write into EE data register
    movf EEByte,w ; Data to w
    movwf EEDATA ; Write
; Set write address in EE address register
    movf EEMemAdd,w ; Address to w
    movwf EEADR ; w to address register
; Write data to EEPROM memory
    bsf STATUS,RP0 ; Bank 1
    bcf INTCON,GIE ; Disable INTs.
    bsf EECON1,WREN ; Enable Write
    movlw 0x55 ; Code # 1
    movwf EECON2 ; Write 0x55
    movlw 0xaa ; Code # 2
    movwf EECON2 ; Write 0xaa
    bsf EECON1,WR ; Set WR bit
; Write operation now takes place automatically
    bsf INTCON,GIE ; Re-enable interrupts
    bcf STATUS,RP0 ; Bank 0
    return
```

Microchip documentation recommends that critical applications should verify the write operation by reading EEPROM memory after the write operation has taken place in order to make sure that the correct value was stored.

16F84 EEPROM Demonstration Program

The program EECounter, in the book's online software, is a demonstration of EEPROM memory access on the 16F84 PIC. The program keeps track of the number of times that the code has executed by storing each iteration in EEPROM data memory. The program uses the circuit shown in Figure 15-2 (see following page).

The EECounter program increments the value stored at EEPROM address 0x00 at every iteration and displays the result on the first LCD line. The following procedure is used to convert the binary value in EEPROM to 3 ASCII digits for display.
Figure 15-2 Circuit for 16F84 EEPROM Demonstration Program

;==========================================
; binary to ASCII decimal
; conversion
;==========================================
; ON ENTRY:
; w register has binary value in range 0 to 255
; ON EXIT:
; output variables asc100, asc10, and asc1 have
; three ASCII decimal digits
; Routine logic:
; The value 100 is subtracted from the source operand
; until the remainder is < 0 (carry cleared). The number
; of subtractions is the decimal hundreds result. 100 is
; then added back to the subtrahend to compensate
; for the last subtraction. Now 10 is subtracted in the
; same manner to determine the decimal tenths result.
; The final remainder is the decimal units result.
; Variables:
; inNum  storage for source operand
; asc100 storage for hundreds position result
; asc10  storage for tenth position result
; asc1   storage for unit position result
; thisDig Digit counter
bin2asc:
  movwf inNum ; Save copy of source value
  clrf asc100 ; Clear hundreds storage
  clrf asc10 ; Tens
  clrf asc1 ; Units
  clrf thisDig
sub100:
  movlw .100
  subwf inNum,f ; Subtract 100
  btfsc STATUS,C ; Did subtract overflow?
  goto bump100 ; No. Count subtraction
  goto end100
bump100:
  incf thisDig,f ; increment digit counter
  goto sub100
end100:
  movlw .10
  addwf inNum,f ; Adjust for last subtraction
sub10:
  movlw .10
  subwf inNum,f ; Subtract 10
  btfsc STATUS,C ; Did subtract overflow?
  goto bump10 ; No. Count subtraction
  goto end10
bump10:
  incf thisDig,f ; Increment digit counter
  goto sub10
end10:
movf thisDig,w ; Digit counter contents
addlw 0x30 ; Convert to ASCII
movwf asc10 ; Store it

; Calculate and store units digit
movf inNum,w ; Store units value
addlw 0x30 ; Convert to ASCII
movwf asc1 ; Store digit

Return

15.0.2 EEPROM Programming on the 16F87x

The 16F87x PICs contain 128 or 256 bytes of EEPROM data memory. As in the 16F84, this memory is both readable and writable during normal operation. It is not mapped in the register file space but is indirectly addressed through Special Function Registers, as described later in this section.

In the 16F87x PICs both data EEPROM and flash Program Memory are readable and writable during normal operation. For data EEPROM memory, read and write operations take place one byte at a time. The write operation performs an erase-then-write cycle. No bulk erase function is available to user code.

The following Special Function Registers are used in 16F87x EEPROM data read and write operations:

1. EEDATA holds the data byte to be read or written.
2. EEADR contains the EEPROM address to be accessed by the read or write operation.
3. EECON1 contains the control bits for EEPROM operations.
4. EECON2 protects EEPROM memory from accidental access. This is not a physical register.

EEPROM data memory read and write operations do not interfere with normal PIC operations. The 16F873 and 16F874 PICs have 128 bytes of EEPROM data memory. These ICs require that the most-significant-bit of EEADR remains clear. The EEPROM data memory on these devices does not wrap around; that is, accessing EEPROM address 0x80 does not map to 0x00. The 16F876 and 16F877 devices have 256 bytes of EEPROM data memory. In these devices all 8-bits of the EEADR are used. Figure 15-3 (in the following page) is a bit map of the EECON1 register in the 16F87x.

The 16F87x EECON1 register contains one additional bit that is not present in the 16F84, named EEPGD. This bit determines if the EEPROM operation accesses program or data memory. When clear, any subsequent operations relate to EEPROM data. Otherwise, the operation accesses program memory. Read operations only require the RD bit, which initiates the read from the selected memory location. The RD bit is automatically cleared at the end of the read operation. The data in the selected memory location can be read in the EEDATA register as soon as the RD bit is set.
Write operations require two control bits, WR and WREN, and two status bits, WRERR and EEIF. The purpose of these bits is shown in Figure 15-3. Since the WREN bit enables or disables the write operation, it must be set before executing a write. The WR bit is used to initiate the write operation. This bit is automatically cleared at the end of the write. The interrupt flag bit EEIF can be used to detect when the memory write completes. The EEIF bit must be cleared by software before setting the WR bit. As soon as the WREN bit and the WR bit have been set, the desired memory address in EEADR is erased and the value in EEDATA written to the selected address.

The WRERR bit indicates when the 16F87x has been reset during a write operation. This bit should be cleared after power-on reset. The WRERR bit is set when a write operation is interrupted by a MCLR reset, or a Watchdog time-out.
Reading EEPROM Data Memory on the 16F87x

Reading an EEPROM data memory location in the 16F87x requires the following operations:

1. Write the address of the EEPROM location to be read to the EEDATA register. The address should be within the device’s memory capacity.
2. The EEPGD bit in the EECON1 registered is cleared so as to access data memory.
3. The RD bit in the EECON1 register is set to start the read operation.
4. The data can now be read from the EEDATA register.

The following code fragment shows reading EEPROM data memory in the 16F877 PIC:

```plaintext
;==============================================
; 16F877 read EEPROM data
;==============================================
; Procedure to read EEPROM on-board memory
; ON ENTRY:
; Address of EEPROM memory location to read is stored in
; local register EEMemAdd
; ON EXIT:
; Read data in w

EERead:

  Bank2
  movf   EEMemAdd,W ; EEPROM address
  movwf  EEADR ; to read from

  Bank3
  bcf    EECON1,EEPGD ; Point to Data memory
  bsf    EECON1,RD ; Start read

  Bank2
  movf   EEDATA,W ; Data to w register

  Bank0
  Return
```

Writing to EEPROM Data Memory in the 16F87x

Writing to 16F87x EEPROM data memory is more complex than on the 16F84 and much more complex than the read operation. The process consists of the following operations:

1. Make sure that a previous write operation is not in progress. This step is not necessary if write completion is checked at the end of the write routine.
2. The address to be accessed is stored in the EEADR register. Code should make certain that the address is within the device’s range.
3. The data to be written is stored in the EEDATA register.
4. The EEPGD bit in the EECON1 register is cleared to select data memory access.
5. The WREN bit in the EECON1 register is set to enable the write function.
6. Interrupts are disabled to make sure the operation is not interrupted.

7. Three special operations are now executed:
   - The value 0x55 is written to the EECON2 register.
   - The value 0xaa is written to the EECON2 register.
   - The WR bit in the EECON1 register is set.

8. Interrupts are enabled if the application uses interrupts.

9. The WREN bit is cleared to prevent accidental write operations.

10. The completion of the write operation can be ascertained either by checking that the WR bit is clear or that EEIF interrupt flag bit is set.

   The following code fragment is a procedure to write EEPROM data:

   ```assembly
   ;=================================
   ; 16F87x write EEPROM data
   ;=================================
   ; Procedure to write data byte to EEPROM memory
   ; ON ENTRY:
   ; Address to write stored in local register EEMemAdd
   ; Data byte to write is in local register EEByte
   EEWrite:
   Bank3
   Wait2Start:
   btfsc EECON1,WR ; Wait for
   goto Wait2Start ; write to finish
   Bank2
   movf EEMemAdd,w ; Address to
   movwf EEADR ; SFR
   movf EEByte,w ; Data to
   movwf EEDATA ; SFR
   Bank3
   bcf EECON1,EEPGD ; Point to Data memory
   bsf EECON1,WREN ; and enable writes
   ; Disable interrupts. Can be done in any case
   bcf INTCON,GIE
   ; Write special codes
   movlw 0x55 ; First code is 0x55
   movwf EECON2
   movlw 0xaa ; Second code is 0xaa
   movwf EECON2
   bsf EECON1,WR ; Start write operation
   nop ; Time for write
   nop
   ; Test for end of write operation
   wait2End:
   btfsc EECON1,WR ; Wait until WR clear
   ```
goto wait2End
; Re-enable interrupts if program uses interrupts
; If not, comment out next line
;      bsf INTCON,GIE
bcf EECON1,WREN   ; Prevent accidental writes
Bank0
Return

GFR Access Issue in the 16F87x

Data memory space in the 16F87x is partitioned into four separate banks, labeled bank 0 to bank 3. The RP1 and RP0 bits in the Status register are used to select which one of the banks is currently accessible. In programming the Special Functions Registers it is necessary to find out on which bank a register is located to select it. The previous code fragment (the write EEPROM data procedure) requires three bank shifts since EEPROM special function registers are located in several banks.

In this context, we sometimes forget that in some PICs the user registers, also called the General Purpose Registers, can also be located in any one of the banks, although most applications locate the GPRs in bank 0. In the 16F87x there are 96 bytes of available space in bank 0 that can be used. So if the registers used by the application are allocated in this first bank (actually in the first 80 bytes of bank 0) then code must select bank 0 before accessing this data. Had this been the case, the preceding code fragment would have required four additional bank changes.

We were able to avoid this difficulty by placing the program GPRs in the bank 0 memory space from 0x70 to 0x7f. In the 16F87x, addresses 0x70 to 0x7f (15 bytes) are mirrored in the other three banks. In contrast, any GPR allocated below address 0x70 in bank 0 can be accessed only when bank 0 is selected. The 16x84 programmer may not be aware of this fact, since in the 16F84, the memory area available for GPRs, although physically located in bank 0, is mirrored in bank 1.

In the 16F87x, it is good programming practice to locate the most used GPRs in the 0x70 to 0x7f area so as to avoid unnecessary bank changes. Since the space is limited to 15 bytes, the programmer must exercise good judgment in deciding which registers to place in this area.

15.0.3 16F87x EEPROM Circuit and Program

The program Ser2EEP, in the book’s online software, is a demonstration of EEPROM memory access on the 16F877 PIC. The program receives character data through the RS-232 line and stores them in EEPROM data memory. Received characters are echoed on the second LCD line. When the <Enter> key is detected, the text stored in EEPROM memory is displayed on the LCD. On startup, the top LCD line displays the prompt: “Receiving.”. At that time, a message “Rdy-” is sent through the serial line so as to test the connection. Serial communications run at 2400 baud, no parity, 1 stop bit, and 8 character bits. Figure 15-4 (in the following page) shows the circuit used by the Ser2EEP program.
The program’s main driver routine, constants, and user registers are as follows:

```plaintext
;============================================================================
; MACROS
;============================================================================
; Macros to select the register banks
Bank0 MACRO ; Select RAM bank 0
  bcf STATUS,RP0
  bcf STATUS,RP1
ENDM

Bank1 MACRO ; Select RAM bank 1
  bsf STATUS,RP0
  bcf STATUS,RP1
ENDM
```
Bank2 MACRO ; Select RAM bank 2
    bcf STATUS,RP0
    bsf STATUS,RP1
ENDM

Bank3 MACRO ; Select RAM bank 3
    bsf STATUS,RP0
    bsf STATUS,RP1
ENDM

;=================================================================
; constant definitions
; for PIC-to-LCD pin wiring and LCD line addresses
;=================================================================
#define E_line 1 ;|
#define RS_line 0 ;| — from wiring diagram
#define RW_line 2 ;|
; LCD line addresses (from LCD data sheet)
#define LCD_1 0x80 ; First LCD line constant
#define LCD_2 0xc0 ; Second LCD line constant
#define LCDlimit .20; Number of characters per line
#define spbrgVal .64; For 2400 baud on 10Mhz clock
; Note: The constants that define the LCD display
; line addresses have the high-order bit set
; so as to meet the requirements of controller
; commands.
;
;=================================================================
; General Purpose Variables
;=================================================================
; Local variables
; Reserve 20 bytes for string buffer
  cblock 0x20
strData
endc
; Other data
  cblock 0x34 ; Start of block
  count1 ; Counter # 1
count2 ; Counter # 2
count3 ; Counter # 3
J ; counter J
K ; counter K
bufAdd
index
store1 ; Local storage
store2
Endc
;==============================
;    Common RAM area
;==============================
; These GPRs can be accessed from any bank.
; 15 bytes are available, from 0x70 to 0x7f
   cblock 0x70
; For LCDscroll procedure
   LCDcount ; Counter for characters per line
   LCDline ; Current display line (0 or 1)
; Communications variables
   newData ; not 0 if new data received
   ascVal
   errorFlags
; EEPROM-related variables
   EEMemAdd ; EEPROM address to access
   EEByte ; Data byte to write
endc

;============================================================
; PROGRAM
;============================================================
org 0 ; start at address
goto main
; Space for interrupt handlers
org 0x08

main:
; Wiring:
; LCD data to Port-D, lines 0 to 7
; E line -> Port-E, 1
; RW line -> Port-E, 2
; RS line -> Port-E, 0
; Set PORTE D and E for output
; First, initialize Port-B by clearing latches
   clrf STATUS
   clrf PORTB
; Select bank 1 to TRIS Port-D for output
   Bank1
; TRIS Port-D for output. Port-D lines 4 to 7 are wired
; to LCD data lines. Port-D lines 0 to 4 are wired to LEDs.
   movlw b’00000000’
   movwf TRISD ; and Port-D
; By default Port-A lines are analog. To configure them
; as digital code must set bits 1 and 2 of the ADCON1
; register (in bank 1)
   movlw 0x06 ; binary 0000 0110 is code to
   movwf ADCON1 ; make all Port-A lines
digital
   movwf ADCON1
; Port-B, lines are wired to keypad switches, as follows:
; Switch rows (output)
; Switch columns (input)
; Rows must be defined as output and columns as input
movlw b'11110000'
movwf TRISB
; TRIS Port-E for output
movlw b'00000000'
movwf TRISE ; TRIS Port-E
; Enable Port-B pullups for switches in OPTION register
movlw b'00001000'
movwf OPTION_REG
; Back to bank 0
Bank0
; Initialize serial Port-for 2400 baud, 8 bits, no parity
; 1 stop
; Test serial transmission by sending “RDY-”
movlw 'R'
call SerialSend
movlw 'D'
call SerialSend
movlw 'Y'
call SerialSend
movlw '-'
call SerialSend
movlw 0x20
call SerialSend
; Clear all output lines
movlw b'00000000'
movwf PORTD
movwf PORTE
; Wait and initialize HD44780
; Allow LCD time to initialize
; Then do forced initialization
; Clear character counter and line counter variables
clrf LCDcount
clf LCLine
; Set display address to start of first LCD line
; Store address of display buffer
movlw 0x20
movwf bufAdd
; Display “Receiving:” message prompt
; Clear buffer
movlw 0x00

call storeMS1; Store message at offset
call display20; Display message

; Start address of EEPROM
clrf EEMemAdd

; Setup for display in second line
call line2
clrf LCDline
incf LCDline,f; Set scroll control for line 2

;===================================
; Receive serial data, store, and display
;===================================
receive:
; Call serial receive procedure
call SerialRcv

; HOB of newData register is set if new data received
btfss newData,7
goto scanExit

; At this point new data was received.
movwf EEByte; Save received character

; Display character on LCD
movf EEByte,w; Recover character
call send8; Display in LCD
call LCDscroll; Scroll at end of line

; Store character in EEPROM at location in EEMemAdd
call EEWrite; Local procedure
incf EEMemAdd,f; Bump to next EEPROM

; Check for <Enter> key (0x0d) and execute display function
movf EEByte,w; Recover last received
sublw 0x0d
btfsc STATUS,Z; Test if <Enter> key
goto isEnter; Go if <Enter>

; Not <Enter> key, continue processing
scanExit:
goto receive; Continue

;===================================
; Display EEPROM data
;===================================

; This routine receives control when the <Enter> key is received.

; Action:
; 1. Clear LCD
; 2. Output is set to top LCD line
; 3. Characters stored in EEPROM are displayed until 0x0d code is detected
isEnter:
call clearLCD

; Clear character counter and line counter variables

The Ser2EEP program can be tested with any PC serial communications program set for the program’s protocol parameters. We developed and tested the program using Windows Hyperterminal.

15.1 EEPROM Devices and Interfaces

In addition to onboard EEPROM memory that is available in many PICs, a circuit can contain EEPROM memory in separate integrated circuits. The reason for using separate EEPROM is the need for storing more data, since access to onboard EEPROM memory is usually faster, simpler, and requires less interface elements.

EEPROM devices are furnished in two different interface types: serial and parallel. Devices that use the parallel bus require an 8-bit data bus and an address bus wide enough to cover its entire memory space. Although parallel EEPROMS are faster than serial ones, in PIC and microcontroller technology, parallel devices are usually out of the question.

Serial EEPROMS also come in various flavors. In the PIC environment, the most used ones are I2C (Inter-Integrated Circuit), SPI (Serial Peripheral Interface), and Microwire which is a subset of SPI. Another interface called I-Wire, similar to I2C, finds some use in PIC systems.
Although of different design and having unique architectures, the several types of EEPROM devices share many features. For example, they all operate on a three-phase system that includes an opcode, an address, and a data phase. Although each type of device has a unique instruction set, the basic operations perform similar functions: enable write, enable read, get read status, get write status, read data, and write data. For this reason we have selected a single one of these interfaces: I2C. This interface, probably because of its minimal use of communications lines, seems to be the most popular one in the PIC environment.

15.1.1 The I2C Serial Interface

I2C (or I2C) is a serial computer bus and interface developed by Philips Electronics for use in TV receivers. I2C has found considerable use in embedded systems and is supported by many types of devices; including EEPROMs, thermal sensors, real-time clocks, RF tuners, video decoders, etc. I2C devices are made by Philips, National Semiconductors, Microchip, and many others. The popularity of I2C is often attributed to its simplicity, low implementation cost, and minimal use of communications resources.

The typical use of I2C is for interfacing devices on a single board or in a closed system. The interface uses a two-wire bus and two signals: SDA (serial data line) and SCL (serial clock line). These signals support serial transmission 8-bits at a time with 7-bit address-space devices. In the I2C protocol the device that initiates a transaction is called the master and the device being addressed is the slave. Normally the master controls the clock signal, but the slave can hold-off the master in the middle of a transaction by pulling the SCL line low. This is called ".." Not all I2C slave devices support this feature.

The presence of a clock signal makes I2C a synchronous protocol. Since the clock signal is part of the transmission, it can vary without disrupting data. For this reason, I2C is used in systems with imprecise clocks, such as the PIC RC oscillator.

Every I2C hardware slave device has a predefined device address, although some part of this address can be defined at the board level. At the start of every transaction, the master sends the device address of the slave it intends to access. The slave device monitors the bus and responds only to commands that include its own address. The number of available user-configurable address bits limits the number of identical devices that coexist on the same bus.

15.1.2 I2C Communications

SDA and SCL I2C signals are open-drain, that is, the master and slave devices can only drive the lines low, or leave them open (high). In operation, a termination resistor pulls the line up to Vcc if no I2C device is pulling it down. It is this mechanism that allows a slave device to suspend communications by holding down the SCL line. Furthermore, I2C lines can only be in one of two states, called "float high" and "drive low." Here again, it is the pull-up resistors that ensure that the line does not float in an unknown state.
The pull-up resistors used in I2C hardware vary according to communication speed. Typically, lines at 100 kbps require 4.7K pull-up resistors and lines at 400 kbps 1K resistors.

15.1.3 EEPROM Communications Conditions

The descriptions and examples that follow are limited to EEPROM IC2 device access. I2C is a bidirectional interface, implemented by an Acknowledge or Ack system. This system allows data to be sent in one direction to one device on the I2C bus. The device indicates that data has been received by issuing an Ack signal. This action from the receiver eliminates any doubts about whether the transmission was received or not.

Several so-called “conditions” serve to explain I2C communications. The conditions refer to the various bus states during transmission, such as start, stop, data, and acknowledge.

The START condition (represented by the letter S) indicates that an R2C device is ready to transfer data on the bus. The device initializes the transmission by pulling the SDA line low. Recall that both lines are high in the normal state. So the S condition is detected by a low SDA and a high SCL.

The STOP condition (represented by the letter P) indicates that a device has finished transferring and is releasing the bus. The P condition is detected when the SDA line is released while the SCL line remains high. Thus, by action of the pull-up resistor, the P conditions places both lines high.

The RESTART condition (represented by the letter R) indicates that a device is ready to transmit more data without releasing the line. This condition is called a Repeated Start (condition Rs) in the technical literature. The typical scenario for an R condition is when a START must be sent, but a STOP has not occurred. The RESTART condition issues a new START without releasing the line, as is the case when another data item must be sent. In the R condition, the SCL line is momentarily released while the SDA is held high.

The DATA TRANSFER condition (or just DATA condition) represents the transmission of 8 data bits by pulsing the SDA line while the SCL is high. The CLK signal and the SDA signal must be aligned so that the high and low bits on the SCL line coincide with the high state of the CLK line. The fact that the SCL line is meaningful only when the CLK signal is high allows the SCL line to change. A DATA byte can be a control code, an address, or an information element.

The ACK condition (represented by the letter A) is used to acknowledge a data reception. This condition is furnished by the device by bringing the SDA line low during the 9th clock pulse of a transmission sequence. The sequence starts with the S or R condition (one bit), followed by 8 data bits, and the 9th bit on the line requires that the SDA line be brought low, since the SDA line floats high.
The lack of the ACK signal is interpreted as NACK (represented by the letter N). NACK represents a negative acknowledge. The NACK signal is a passive response since the SDA line is normally held high. Both ACK (A) and NACK (N) refer to the previous byte of data.

15.1.4 EEPROM Write Operation

Figure 15-5 represents the I2C action sequence that takes place during a write to a small EEPROM, that is, one that requires a single address byte. Later we will see operations that access I2C EEPROMS with a 2-byte address space.

Figure 15-5 I2C Write Sequence to Small EEPROM

Note in Figure 15-5 that three bytes of information are required in the data transfer. The transmission starts with the S condition issued by the master, followed by a control byte. In the case of an EEPROM, the control byte indicates either a read or a write operation. In Figure 15-5, the control byte is labeled Control In, since it places the EEPROM device in input mode required for the write to take place. The EEPROM acknowledges the control byte by issuing the A condition. At this point, the master proceeds to transmit the address byte, which defines the EEPROM memory location at which the write operation is to take place. The slave (in this case the EEPROM) acknowledges reception of the address byte by issuing another A condition. Next, data is sent by the master and “ACKed” by the EEPROM. Finally, the master transmits the stop signal (condition P) which concludes the operation. The EEPROM does not proceed to write the data until the P signal is received.

15.1.5 EEPROM Read Operation

The read operation to a small EEPROM is similar to the write. In this case, 4 bytes of information must be exchanged: 3 from the master to the slave and one (the data item read) from the slave to the master. Figure 15-6 shows the sequence.

Figure 15-6 Read Sequence to a Small EEPROM
Note in Figure 15-6 that the first command from master to slave is a *Control In* byte to indicate that an address follows. Once the address is acknowledged, the master sends the restart command (R condition) and a *Control Out* command indicating that the master is requesting a read operation. The EEPROM then acknowledges and sends the data, to which the master responds with NACK to instruct the EEPROM that no more data is required.

In both read and write sequences, each byte transmitted requires a response from the other element. This response can be either an ACK (condition A) or a NACK (condition N). The RESTART bit that preceded the Control Out command is necessary since the P condition (STOP bit) has not been sent. The I2C protocol requires that the START condition be sent only on an idle bus, and never in the middle of a transmission.

Read and write operations to large EEPROMS, those with a two-byte address space, are identical to the ones described, except that there are two address bytes. The first one holds the high-order element and the second one the low-order. Here again, each byte transmitted must be acknowledged by the receiver.

### 15.1.6 I2C EEPROM Devices

EEPROM ICs that conform to the I2C specification are available to the PIC circuit designer. Microchip (the same company that manufactures the PIC microcontrollers) markets a series of I2C chips for this purpose. The line is designated as the 24XXX series of serial EEPROM devices. Table 15.1 lists several I2C EEPROM devices available from Microchip.

<table>
<thead>
<tr>
<th>DESIGNATION</th>
<th>MAX CLOCK</th>
<th>CAPACITY</th>
<th>PAGE SIZE (IN BYTES)</th>
<th>CASCADE</th>
</tr>
</thead>
<tbody>
<tr>
<td>24xx00</td>
<td>400kHz</td>
<td>128</td>
<td>16</td>
<td>No</td>
</tr>
<tr>
<td>24xx01</td>
<td>400kHz</td>
<td>1K</td>
<td>128</td>
<td>No/8</td>
</tr>
<tr>
<td>24xx02</td>
<td>400kHz</td>
<td>2K</td>
<td>256</td>
<td>No/8</td>
</tr>
<tr>
<td>24xx04</td>
<td>400kHz</td>
<td>4K</td>
<td>512</td>
<td>No</td>
</tr>
<tr>
<td>24xx08</td>
<td>400kHz</td>
<td>8K</td>
<td>1K</td>
<td>No</td>
</tr>
<tr>
<td>24xx16</td>
<td>400kHz</td>
<td>16K</td>
<td>2K</td>
<td>No</td>
</tr>
<tr>
<td>24xx32</td>
<td>400kHz</td>
<td>32K</td>
<td>4K</td>
<td>8</td>
</tr>
<tr>
<td>24xx64</td>
<td>400kHz</td>
<td>64K</td>
<td>8K</td>
<td>8</td>
</tr>
<tr>
<td>24xx128</td>
<td>400kHz</td>
<td>128K</td>
<td>16K</td>
<td>8</td>
</tr>
<tr>
<td>24xx256</td>
<td>400kHz</td>
<td>256K</td>
<td>32K</td>
<td>8</td>
</tr>
<tr>
<td>24xx512</td>
<td>400kHz</td>
<td>512K</td>
<td>64K</td>
<td>No/4/8</td>
</tr>
<tr>
<td>24xx1025</td>
<td>1MHz</td>
<td>1024</td>
<td>128K</td>
<td>4</td>
</tr>
</tbody>
</table>

The memory capacity of the various EEPROM ICs ranges from 16 bytes to 128K. Since up to four 128K devices can be cascaded, the total accessible memory goes up to 512K. In selecting a particular IC one must take into account several parameters, since the page size, the maximum clock speed, and the number of similar devices that can be grouped changes within the same device type. In the example developed later in this chapter, we used the 24LC04B EEPROM with a total of 512 bytes located in two memory banks.
The standard DIP package of the 24xxx EEPROMS consists of eight pins, as shown in Figure 15-7.

Lines A0 to A2 are used to encode the chip’s address when supported by the device. The three lines allow up to eight possible combinations to identify up to eight similar cascaded devices, as shown in the corresponding column of Table 15.1. Also note in Table 15.1 that several EEPROMs do not support more than one device per address bus. In these cases, pins A0 to A2 are not meaningful. In devices that support this function, the pins must be hardwired to logic 0 or logic 1. If the pins are left floating the device could malfunction.

The SDA pin is bidirectional and is used to transfer addresses and data into and out of the device. Since it is an open drain it requires a pull-up resistor to Vcc. The resistor is typically 10 kΩ for 100 kHz, 2 kΩ for 400 kHz. During data transfer the SDA line is allowed to change only while SCL is low. SDA line changes while SCL is high are used for indicating the START and STOP conditions.

The SCL line is used to synchronize the data transfer to and from the device. The WP (Write-Protect) pin provides this function when tied to ground. For normal read/write operation the WP pin is tied to the Vcc line. Read operations are not affected by this pin. The write protect function allows using the EEPROM as a serial ROM.

**15.1.7 PIC Master Synchronous Serial Port (MSSP)**

Although I2C interfaces can and have been implemented in software, this emulation is not an attractive option now that more efficient and simpler hardware versions of I2C are available in many PICs. For this reason we do not discuss the software emulation of I2C in this book.

Some PIC microcontrollers come equipped with hardware modules to implement EEPROM serial protocols, including SPI and I2C. The module that provides these interfaces is named the Master Synchronous Serial Port, or MSSP. Although the MSSP module operates in slave or master mode, in the context of EEPROM programming the MSSP is set in master mode. The MSSP module can operate in a free bus mode,
also called the multi-master function. In this section we discuss MSSP master mode operations.

I2C uses two communications lines, labeled the SDA or data line, and the SCL or clock line. The PICs that contain I2C hardware implementation multiplex two pins for these functions. In the case of the 16F877 (which we use in the forthcoming examples) the SCL line is attached to bit 3 in Port-C (16F877 pin number 18) and the SDA line to bit 4 in Port-C (16F877 pin number 23). When the PIC is used in MSSP mode, these two pins must be initialized for input by setting the corresponding TRIS register bits. The pull-up resistors for these lines must be provided externally. Figure 15-8 shows the minimal wiring diagram between a 16F877 PIC and a 24LC04B EEPROM IC.

Figure 15-8 Wiring Diagram between a 16F877 PIC and 24LC04B EEPROM IC.

Note in Figure 15-8 that the address lines (A0 to A2) in the 24LC04B IC are wired to ground. The reason is that these lines are not used in this particular EEPROM (see Table 15.1). Also wired to ground is the write protect line. This allows read and write operations. Only two connections are required between the PIC and the EEPROM: the SLK and SDL lines. The 4.7K resistors are pull-ups to implement the open drain operation on these lines.
Several 16F87x registers relate to MSSP operation in I2C mode. Figure 15-9 shows these SFRs.

In the following subsection we discuss the registers and bits that apply to MSSP operation in Master Mode.

**MSSP in Master Mode**

In the context of accessing EEPROM circuits, the MSSP is operated in master mode. At this point we should consider that although the EEPROM device operates as a slave, it is a “smart” slave since it has a control engine capable of performing operations on its own, including reading and writing to its address space, recognizing commands, and issuing the corresponding responses. For example, in a data write operation the master sends the corresponding command code, followed by the address to which the data is to be written, followed by the data itself. The peripheral (in this case the EEPROM IC) receives and acknowledges the various bytes and executes the requested operations. In the case of a read command the EEPROM fetches and returns the data from the memory address requested in the command.

One of the special function registers most used in MSSP master mode operations is the SSPCON. Figure 15-10 is a bitmap of this register when operating in I2C master mode.

---

**Figure 15-9** SFRs Associated with I2C Operations

Several 16F87x registers relate to MSSP operation in I2C mode. Figure 15-9 shows these SFRs.

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One of the special function registers most used in MSSP master mode operations is the SSPCON. Figure 15-10 is a bitmap of this register when operating in I2C master mode.
The WCOL bit is an error flag that indicates that a Write Collision has occurred. Write collisions do not take place when programming an EEPROM device. This bit is useful in multi-master systems since it can detect when more than one master device is attempting to write to the bus.

The SSPOV bit (Synchronous Serial Port Overflow) is set by the microcontroller whenever there is an overflow error. An overflow occurs whenever an I2C transfer finishes but the previous data has not been read from SSPBUF. If SSPOV bit is set, it must be cleared by application code. Data in SSPBUF is not updated until the overflow condition is cleared.

The SSPEN bit (Synchronous Serial Port Enable) is set to turn on the SSP module, as is the case in I2C communications.

The bits SSPM0 through SSPM3 (Synchronous Serial Port mode bits) determine whether the MSSP module is configured for SPI or I2C and whether it is in slave or master mode. In the master mode, the MSSP module handles all details of I2C communications, such as generating the various conditions and sending and receiving data. The Master Mode is enabled by entering the binary value 1000 in this bit field.

Another frequently used register in I2C communications is SSPCON2. Figure 15-11 is a bitmap of this register in the I2C master mode.
The ACKSTAT bit is set when an ACK or NACK has been received. This bit can be tested by application code to determine if an ACK or NACK condition was received.

When the master reads data from a device, it must acknowledge the transfer by sending an ACK or NACK condition. The ACKDT bit determines the value of the condition to be sent: if it is clear an ACK is sent; otherwise a NACK is sent.

The ACKEN bit determines when the acknowledge condition is sent.

The RCEN bit places the MSSP module into I2C receive mode. When one byte of data is received, this bit automatically clears and the PIC returns to transmit mode. Code must ACK or NACK the data then reset this bit.
Setting the PEN bit automatically sends a stop condition. This bit is automatically cleared at the end of the start condition.

The RSEN bit sends a restart condition. After the bit is set, application code must wait for the transfer to complete. This bit is reset automatically when the condition or data transfer finishes.

The SEN bit (for Start condition Enable) is equivalent to sending a start or restart condition. The SEN bit is reset after the start condition completes.

The SSPSTAT (Synchronous Serial Port Status) register contains three bits related to I2C communications in master mode. The SMP bit controls the slew rate. The slew rate is a squelch filter for the I2C waveform that improves performance when transmission takes place at 400 kbps. This bit should be set at the 400 kbps transmission rate and reset at any slower rate. The CKE bit is used to allow the MSSP module to handle SMBus peripherals. Normally, this bit should be cleared. The BF bit (buffer full) indicates the SSPBUF contains unread data. In either the master or slave mode this data must be read before any other data is sent or received. The BF flag is set and cleared by the PIC. If SSPBUF is not read before another byte is received the buffer overflows and the SSPOV bit will be set.

Finally, the SSPADD (Synchronous Serial Port Address) register has a unique function in the I2C master mode: it controls the bus speed. The value entered into the SSPADD register determines the Baud Rate according to the following formula:

\[
BaudRate = \frac{Fosc}{4 \cdot (SSPADD_{VAL} + 1)}
\]

where \(Fosc\) is the oscillator speed in MHz. Solving this formula in terms of the value to be entered into SSPADD, we have:

\[
SSPADD_{VAL} = \frac{Fosc}{4 \cdot Baud\ Rate} - 1
\]

For a baud rate of 100 kbps (equal to 100,000 MHz) the formula is:

\[
SSPADD_{VAL} = \frac{10,000,000}{4 \cdot 100,000} - 1 = \frac{100}{4} - 1 = 24
\]

In this case, the value to be entered into the SSPADD register while using a communications speed of 100 kbps, in a PIC with a 10 KHz oscillator, is 24. The calculations can be checked by substituting into the original formula:

\[
Baud\ Rate = \frac{Fosc}{4 \cdot (SSPADD_{VAL} + 1)} = \frac{10,000,000}{100} = 100,000\ MHz = 100\ kbps
\]
15.1.8 I2C Serial EEPROM Programming on the 16F877

The 16F87x PIC family contains the Master Synchronous Serial Port module, which can be set in either Serial Peripheral Interface or Inter-Integrated Circuit mode. In the I2C mode the module performs either as a master, a multi-master, or a slave. In the context of driving an I2C EEPROM device, the MSSP module is initialized in the master mode. I2C firmware modes are provided for compatibility with other mid-range products.

The demonstration program named I2CEEP in the book's on line software receives character data from a PC through the RS-232 line and stores these characters in a 24LC04B EEPROM IC. The program uses the I2C serial interface facilities provided by the PIC’s MSSP module. An on-board LCD echoes the received characters. When the PC user presses <Enter> text stored in the EEPROM IC is retrieved and displayed on the LCD.

On startup, the top LCD line displays the prompt: “Receiving:”. At that time, a message “Rdy-” is sent through the serial line so as to test the connection. The program's serial communications run at 2400 baud, no parity, 1 stop bit, and 8 character bits. The 24LC04B SDA line is wired to PIC RC4 (MSSP SDA) and the SCL line is wired to PIC RC3 (MSSP SCL). In the 24LC04B the A0-A2 are not used. In the demonstration circuit, the WP lines are wired to ground. Program provides little error checking. The circuit in Figure 15-12 is used with the demonstration program.

The I2CEEP program includes three I2C-related functions:

1. **SetupI2C**. Initializes MSSP module for I2C mode in hardware master mode, configures the I2C lines, sets the slew rate for 100kbps, and sets the baud rate for 10Mhz.

2. **WriteI2C**. Writes one byte to I2C EEPROM device. Data and address are stored in local variables.

3. **ReadI2C**. Reads one byte from I2C EEPROM device. Address is stored in a local variable and read data is returned in the w register.

As in previous 16F877 examples, we have placed the most used variables in the common RAM area, that is, in GPRs located from 0x70 to 0x7f. All three procedures use bank changing macros described and listed previously.

**I2C Initialization Procedure**

The following procedure from the I2CEEP program initializes the MSSP module for operation in I2C mode with a 24LC04B EEPROM IC. The module is initialized for master mode operation on a PIC with a 10Mhz baud rate. For use with a faster or slower oscillator the value stored in the SSPADD register must be modified according to the formula.

```plaintext
;===================================
; I2C setup procedure
;===================================
SetupI2C:
    Bank1
```
movlw b'00011000'
iorwf TRISC,f ; OR into TRISC
; Setup MSSP module for Master Mode operation
Bank0
movlw B'00101000'; Enables MSSP and uses appropriate
; 00101000 Value to install
; 76543210 = SSPCON bits in this operation
; |||| |__|__|__|___ Serial port select bits

Figure 15-12 Circuit for I2CEEP Demonstration Program
The procedures Send1I2c, WaitI2C, and the label FailI2C are listed in the subsection on the read procedure.

**I2C Write Byte Procedure**

The following procedure, from the I2CEEP program, writes one byte of data to an 24LC04B EEPROM IC, at the memory address stored in the variable EEMemAdd. The value to write is stored in the local variable EEByte.
I2C write procedure

Write one byte to I2C EEPROM 24LC04B

**Steps:**
1. Send START
2. Send control. Wait for ACK
3. Send address. Wait for ACK
4. Send data. Wait for ACK
5. Send STOP

**STEP 1:**
```
; WriteI2C:
Bank1
    bsf SSPCON2, SEN ; Produce START Condition
    call WaitI2C ; Wait for I2C to complete
```

**STEP 2:**
```
; Send control byte. Wait for ACK
movlw LC04READ ; Control byte
    call Send1I2C ; Send Byte
    call WaitI2C ; Wait for I2C to complete
    btfsc SSPCON2, ACKSTAT ; Check ACK Status bit to see if
        ; I2C failed, skip if not
        goto FailI2C
```

**STEP 3:**
```
; Send address. Wait for ACK
Bank0
    movf EEMemAdd, w ; Load Address Byte
    call Send1I2C ; Send Byte
    call WaitI2C ; Wait for I2C operation to complete
Bank1
    btfsc SSPCON2, ACKSTAT ; Check ACK Status bit to see
        ; if I2C failed, skip if not
        goto FailI2C
```

**STEP 4:**
```
; Send data. Wait for ACK
Bank0
    movf EEByte, w ; Load Data Byte
    call Send1I2C ; Send Byte
    call WaitI2C ; Wait for I2C operation to complete
Bank1
    btfsc SSPCON2, ACKSTAT ; Check ACK Status bit to see
        ; if I2C failed, skip if not
        goto FailI2C
```

**STEP 5:**
```
; Send STOP. Wait for ACK
    bsf SSPCON2, PEN ; Send STOP condition
    call WaitI2C ; Wait for I2C operation to complete
```
The procedures SendI2c, WaitI2c, and the label FailI2C are listed in the sub-section on the read procedure.

**I2C Read Byte Procedure**

The following procedure, from the I2CEEP program, reads a byte of data from the 24LC04B device. The address read is stored in the local variable EEMemAdd. The value read is returned in the w register. The listing also includes the support routines used by all three I2C procedures listed.

```assembly
;============================
; I2C read procedure
;============================
; Procedure to read one byte from 24LC04B EEPROM
; Steps:
; 1. Send START
; 2. Send control. Wait for ACK
; 3. Send address. Wait for ACK
; 4. Send RESTART + control. Wait for ACK
; 5. Switch to receive mode. Get data.
; 6. Send NACK
; 7. Send STOP
; 8. Retreive data into w register
; STEP 1:
ReadI2C
; Send RESTART. Wait for ACK
Bank1
bsf SSPCON2,RSEN ; RESTART Condition
call WaitI2C ; Wait for I2C operation
; STEP 2:
; Send control byte. Wait for ACK
movlw LC04READ ; Control byte
call SendI2C ; Send Byte
call WaitI2C ; Wait for I2C operation
; Now check to see if I2C EEPROM is ready
Bank1
btfsc SSPCON2,ACKSTAT ; Check ACK Status bit
goto ReadI2C ; ACK Poll waiting for EEPROM
        ; write to complete
; STEP 3:
; Send address. Wait for ACK
Bank0
movf EEMemAdd,w ; Load from address register
call SendI2C ; Send Byte
call WaitI2C ; Wait for I2C operation
```

; WRITE operation has completed successfully.
Bank0
return
btfsc   SSPCON2,ACKSTAT ; Check ACK Status bit
goto   FailI2C    ; failed, skipped if successful
; STEP 4:
; Send RESTART. Wait for ACK
    bsf      SSPCON2,RSEN ; Generate RESTART Condition
    call     WaitI2C   ; Wait for I2C operation
; Send output control. Wait for ACK
    movlw   LC04WRITE ; Load CONTROL BYTE (output)
    call     Send1I2C  ; Send Byte
    call     WaitI2C   ; Wait for I2C operation
Bank1
    btfsc   SSPCON2,ACKSTAT ; Check ACK Status bit
    goto   FailI2C    ; failed, skipped if successful
; STEP 5:
; Switch MSSP to I2C Receive mode
    bsf      SSPCON2,RCEN ; Enable Receive Mode (I2C)
; Get the data. Wait for ACK
    call     WaitI2C   ; Wait for I2C operation
; STEP 6:
; Send NACK to acknowledge
Bank1
    bsf      SSPCON2,ACKDT ; ACK DATA to send is 1 (NACK)
    bsf      SSPCON2,ACKEN ; Send ACK DATA now.
; Once ACK or NACK is sent, ACKEN is automatically cleared
; STEP 7:
; Send STOP. Wait for ACK
    bsf      SSPCON2,PEN ; Send STOP condition
    call     WaitI2C   ; Wait for I2C operation
; STEP 8:
; Read operation has finished
Bank0
    movf     SSPBUF,W ; Get data from SSPBUF into W
; Procedure has finished and completed successfully.
    return

;=====================================
; I2C support procedures
;=====================================
; I2C Operation failed code sequence
; Procedure hangs up. User should provide error handling.
FailI2C
Bank1
    bsf      SSPCON2,PEN ; Send STOP condition
    call     WaitI2C   ; Wait for I2C operation
fail:
    goto   fail
; Procedure to transmit one byte
Send1I2C
15.2 Sample Programs

The following sections contain the code listing for the programs discussed in this chapter.

15.2.1 EECounter Program

; File name: EECounter.asm
; Last Update: May 22, 2006
; Author: Julio Sanchez
; Processor: 16F84A
;
; Description:
; Program to demonstrate on chip EEPROM data memory read
; and write operation. Program uses LCD display to output
; results.
; Operation:
; The program keeps track and displays the inNum of times
; the code has been started.
; For LCD display parameters see the LCDTest2 program.
; WARNING:
; Code assumes 4Mhz clock. Delay routines must be
; edited for faster clock
;
;===========================
; switches
;===========================
; Switches used in __config directive:
; _CP_ON       Code protection ON/OFF
; * _CP_OFF
; * _PWRT_ON   Power-up timer ON/OFF
; _PWRT_OFF
; _WDT_ON     Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC     Low power crystal oscillator
; * _XT_OSC External parallel resonator/crystal oscillator
; _HS_OSC High speed crystal resonator (8 to 10 MHz)
; _RC_OSC Resistor/capacitor oscillator
; | (simplest, 20% error)
; |
; |________ * indicates setup values presently selected

;===================================
; setup and configuration
;===================================
processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

;===================================
; constant definitions
; for PIC-to-LCD pin wiring and LCD line addresses
;===================================
#define E_line 1 ;|
#define RS_line 2 ;| — from wiring diagram
#define RW_line 3 ;|
; LCD line addresses (from LCD data sheet)
#define LCD_1 0x80 ; First LCD line constant
#define LCD_2 0xc0 ; Second LCD line constant
; Note: The constants that define the LCD display line
; addresses have the high-order bit set in
; order to facilitate the controller command
;
;===================================
; variables in PIC RAM
;===================================
; Reserve 16 bytes for string buffer
 cblock 0x0c
 strData
dec

; Reserve three bytes for ASCII digits
 cblock 0x1d
 asc100
 asc100
 asc10
 asc1
 dec

; Continue with local variables
 cblock 0x20 ; Start of block
 count1 ; Counter # 1
 count2 ; Counter # 2
 count3 ; Counter # 3
pic_ad ; Storage for start of text area
   ; (labeled strData) in PIC RAM
J ; counter J
K ; counter K
index ; Index into text table (also used
   ; for auxiliary storage)
store1 ; Local temporary storage
store2 ; Storage # 2
; EEPROM-related variables
EEMemAdd ; EEPROM address to access
EEByte ; Data byte to write
; Storage for ASCII decimal conversion and digits
inNum ; Source operand
thisDig ; Digit counter
endc

;=============================================================
; program
;=============================================================
org 0 ; start at address
goto main

; Space for interrupt handlers
org 0x08

main:
  movlw b'00000000' ; All lines to output
  tris PORTA ; in Port-A
  tris PORTB ; and Port-B
  movlw b'00000000' ; All outputs ports low
  movwf PORTA
  movwf PORTB
; Wait and initialize HD44780
  call delay_5 ; Allow LCD time to initialize
   ; itself
  call delay_5
  call initLCD ; Then do forced initialization
  call delay_5 ; Wait again
; Store base address of text buffer in PIC RAM
  movlw 0x0c ; Start address for buffer
  movwf pic_ad ; to local variable
; Initialize EEPROM data to 0x0
  clrf EEMemAdd ; Set address to 0
;===================
; first LCD line
;==================
; Store 16 blanks in PIC RAM, starting at address stored
; in variable pic_ad
   call blank16
; Call procedure to store ASCII characters for message
; in text buffer
   movlw d'0' ; Offset into buffer
   call storeMS1

;=======================
; Read EEPROM memory
;=======================
; EEPROM memory address to use is at 10 (0x0a). Variable EEMemAdd is already initialized.
; Fill data for EEPROM is 0xff. This value indicates
; the first iteration
   call EERead ; Local procedure. Value in w
   movwf EEBYTE ; Save result
; EEPROM data still in w
   incf EEBYTE,f
   call EEWrite
; At this point iteration inNum is stored in EEBYTE
; This value must be displayed on the LCD at offset 11
; of the first line. This means it must be stored at offset
; 11 in the buffer. Since the buffer starts at 0x0c the
; iteration digit must be stored at offset 0x0c+11=0x17
ShowEEData:
; Binary data in EEBYTE
   movf EEBYTE,w ; Value to w
   call bin2asc ; Conversion routine
; At this point three ASCII digits are stored in local
; variables. Move digits to display area
   movf asc1,w ; Unit digit
   movwf 0x18 ; Store in buffer
   movf asc10,w ; same with other digits
   movwf 0x17
   movf asc100,w
   movwf 0x16
; Display line
; Set DDRAM address to start of first line
showLine:
   call line1
; Call procedure to display 16 characters in LCD
   call display16
loopHere:
   goto loopHere ; done

;============================================================
; initialize LCD for 4-bit mode
;============================================================
initLCD:
; Initialization for Densitron LCD module as follows:
; 4-bit interface
; 2 display lines of 16 characters each
; cursor on
; left-to-right increment
; cursor shift right
; no display shift
;==================================
; set command mode
;==================================
; bcf PORTA,E_line ; E line low
; bcf PORTA,RS_line ; RS line low
; bcf PORTA,RW_line ; Write mode
; call delay_125 ; delay 125 microseconds

;*******************************
; FUNCTION SET
;*******************************
; movlw 0x28 ; 0 0 1 0 1 0 0 0 (FUNCTION SET)
; call send8 ; 4-bit send routine

; Set 4-bit mode command must be repeated
; movlw 0x28
; call send8

;*******************************
; DISPLAY AND CURSOR ON
;*******************************
; movlw 0x0e ; 0 0 0 0 1 1 1 0 (DISPLAY ON/OFF)
; call send8

;*******************************
; set entry mode
;*******************************
; movlw 0x06 ; 0 0 0 0 0 1 1 0 (ENTRY MODE SET)
; call send8

;*******************************
; cursor/display shift
;*******************************
; movlw 0x14 ; 0 0 0 1 0 1 0 0 (CURSOR/DISPLAY
SHIFT)
; call send8

;*******************************
; clear display
;*******************************
; movlw 0x01 ; 0 0 0 0 0 0 0 1 (CLEAR DISPLAY)
; call send8

; Per documentation
; call delay_5 ; Test for busy
return

;=================================
; Procedure to delay
; 42 microseconds
;=================================
delay_125
    movlw  D'42' ; Repeat 42 machine cycles
    movwf  count1 ; Store value in counter
repeat
    decfsz  count1, f ; Decrement counter
    goto  repeat ; Continue if not 0
$return$ ; End of delay

;=================================
; Procedure to delay
; 5 milliseconds
;=================================
delay_5
    movlw  D'41' ; Counter = 41
    movwf  count2 ; Store in variable
delay
    call  delay_125 ; Delay
    decfsz  count2, f ; 40 times = 5 milliseconds
    goto  delay
$return$ ; End of delay

;=================================
; pulse E line
;=================================
pulseE
    bsf  PORTA, E_line ; Pulse E line
    nop
    bcf  PORTA, E_line
$return$

;=================================
; long delay sub-routine
; (for debugging)
;=================================
long_delay
    movlw  D'200' ; w = 200 decimal
    movwf  J ; J = w
jloop:
    movwf  K ; K = w
kloop:
    decfsz  K, f ; K = K-1, skip next if zero
    goto  kloop
    decfsz  J, f ; J = J-1, skip next if zero
goto jloop
return

;===============
; LCD display procedure
;===============
; Sends 16 characters from PIC buffer with address stored
; in variable pic_ad to LCD line previously selected
display16
    call delay_5 ; Make sure not busy
    ; Set up for data
    bcf PORTA,E_line ; E line low
    bsf PORTA,RS_line ; RS line high for data
    ; Set up counter for 16 characters
    movlw D’16’ ; Counter = 16
    movwf count3
    ; Get display address from local variable pic_ad
    movf pic_ad,w ; First display RAM address to W
    movwf FSR ; W to FSR
    getchar
    movf INDF,w ; get character from display RAM
    ; location pointed to by file select
    ; register
    call send8 ; 4-bit interface routine
    ; Test for 16 characters displayed
    decfsz count3,f ; Decrement counter
    goto nextchar ; Skipped if done
return
nextchar:
    incf FSR,f ; Bump pointer
    goto getchar

;========================
; send 2 nibbles in
; 4-bit mode
;========================
; Procedure to send two 4-bit values to Port-B lines
; 7, 6, 5, and 4. High-order nibble is sent first
; ON ENTRY:
; w register holds 8-bit value to send
send8:
    movwf store1 ; Save original value
    call merge4 ; Merge with Port-B
    ; Now w has merged byte
    movwf PORTB ; w to Port-B
    call pulseE ; Send data to LCD
    ; High nibble is sent
    movf store1,w ; Recover byte into w
    swapf store1,w ; Swap nibbles in w
call merge4
movwf PORTB
call pulseE ; Send data to LCD
call delay_125
return

;=================
; merge bits
;=================
; Routine to merge the 4 high-order bits of the
; value to send with the contents of Port-B
; so as to preserve the 4 low-bits in Port-B
; Logic:
;
; AND value with 1111 0000 mask
; AND Port-B with 0000 1111 mask
; Now low nibble in value and high nibble in
; Port-B are all 0 bits:
; value = vvvv 0000
; Port-B = 0000 bbbb
; OR value and Port-B resulting in:
; vvvv bbbb
; ON ENTRY:
; w contains value bits
; ON EXIT:
; w contains merged bits
merge4:
andlw b'11110000' ; ANDing with 0 clears the
; bit. ANDing with 1 preserves
; the original value
movwf store2 ; Save result in variable
movf PORTB,w ; Port-B to w register
andlw b'00001111' ; Clear high nibble in Port-b
; and preserve low nibble
iorwf store2,w ; OR two operands in w
return

;========================
; blank buffer
;========================
; Procedure to store 16 blank characters in PIC RAM
; buffer starting at address stored in the variable
; pic_ad
blank16
movlw D'16' ; Setup counter
movwf count1
movf pic_ad,w ; First PIC RAM address
movwf FSR ; Indexed addressing
movlw 0x20 ; ASCII space character
storeit
movwf INDF ; Store blank character in PIC RAM  
; buffer using FSR register  
decfsz count1,f ; Done?  
goto incfsr ; no  
return ; yes  
incfsr:  
incf FSR,f ; Bump FSR to next buffer space  
goto storeit  

;========================  
; Set address register 
; to LCD line 1  
;================================  
; ON ENTRY:  
; Address of LCD line 1 in constant LCD_1  
line1:  
bcf PORTA,E_line ; E line low  
bcf PORTA,RS_line ; RS line low, set up for  
control 
call delay_5 ; busy?  
; Set to second display line  
movlw LCD_1 ; Address and command bit  
call send8 ; 4-bit routine  
; Set RS line for data  
bsf PORTA,RS_line ; Setup for data  
call delay_5 ; Busy?  
return  

;================================  
; first text string procedure  
;================================  
storeMS1:  
; Procedure to store in PIC RAM buffer the message  
; contained in the code area labeled msg1  
; ON ENTRY:  
; variable pic_ad holds address of text buffer  
; in PIC RAM  
; w register hold offset into storage area  
; msg1 is routine that returns the string characters  
; and a zero terminator  
; index is local variable that hold offset into  
; text table. This variable is also used for  
; temporary storage of offset into buffer  
; ON EXIT:  
; Text message stored in buffer  
;  
; Store offset into text buffer (passed in the w register)  
; in temporary variable
movwf index ; Store w in index
; Store base address of text buffer in FSR
movf pic_ad,w ; first display RAM address to W
addwf index,w ; Add offset to address
movwf FSR ; W to FSR
; Initialize index for text string access
movlw 0 ; Start at 0
movwf index ; Store index in variable
; w still = 0
get_msg_char:
call msg1 ; Get character from table
; Test for zero terminator
andlw 0x0ff
btfsc STATUS,Z ; Test zero flag
goto endstr1 ; End of string
; ASSERT: valid string character in w
; store character in text buffer (by FSR)
movwf INDF ; store in buffer by FSR
incf FSR,f ; increment buffer pointer
; Restore table character counter from variable
movf index,w ; Get value into w
addlw 1 ; Bump to next character
movwf index ; Store table index in variable
goto get_msg_char ; Continue
endstr1:
return
; Routine for returning message stored in program area
; Message has 10 characters
msg1:
addwf PCL,f ; Access table
retlw 'I'
retlw 't'
retlw 'e'
retlw 'r'
retlw '.'
retlw 0x20
retlw 'N'
retlw 'o'
retlw '.'
retlw 0x20
retlw 0

;==============================
; binary to ASCII decimal
; conversion
;==============================
; ON ENTRY:
w register has binary value in range 0 to 255

ON EXIT:

output variables asc100, asc10, and asc1 have
three ASCII decimal digits

Routine logic:

The value 100 is subtracted from the source operand
until the remainder is < 0 (carry cleared). The number
of subtractions is the decimal hundreds result. 100 is
then added back to the subtrahend to compensate
for the last subtraction. Now 10 is subtracted in the
same manner to determine the decimal tenths result.
The final remainder is the decimal units result.

Variables:

inNum storage for source operand
asc100 storage for hundreds position result
asc10 storage for tenth position result
asc1 storage for unit position result
thisDig Digit counter

bin2asc:

movwf inNum ; Save copy of source value
clrf asc100 ; Clear hundreds storage
clrf asc10 ; Tens
clrf asc1 ; Units
clrf thisDig

sub100:

movlw .100
subwf inNum,f ; Subtract 100
btfsc STATUS,C ; Did subtract overflow?
goto bump100 ; No. Count subtraction
goto end100
bump100:

incf thisDig,f ;increment digit counter
goto sub100

; Store 100th digit

end100:

movf thisDig,w ; Adjusted digit counter
addlw 0x30 ; Convert to ASCII
movwf asc100 ; Store it

; Calculate tenth position value

clrf thisDig

; Adjust minuend

movlw .100 ; Minuend
addwf inNum,f ; Add value to minuend to
; compensate

for last operation

sub10:

movlw .10
subwf inNum,f ; Subtract 10
btfs  STATUS,C        ; Did subtract overflow?
goto  bump10          ; No. Count subtraction
goto  end10

bump10:
    incf  thisDig,f     ; increment digit counter
    goto  sub10

; Store 10th digit

end10:
    movlw  .10
    addwf  inNum,f      ; Adjust for last subtract
    movf  thisDig,w     ; get digit counter contents
    addlw  0x30          ; Conver to ASCII
    movwf  asc10         ; Store it

; Calculate and store units digit

movf  inNum,w         ; Store units value
addlw  0x30            ; Convert to ASCII
movwf  asc1            ; Store digit
return

;====================================================================
; EEPROM procedures
;====================================================================
;==============================
; read EEPROM
;==============================
; Procedure to read EEPROM memory. Address of memory
; location to read is stored in local register EEMemAdd
; On exit: read data in w

EERead:
    bcf    STATUS,RP0    ; Bank 0
    movf   EEMemAdd,w    ; Address to w
    movwf   EEADR        ; w to address register
    bsf    STATUS,RP0    ; Bank 1
    bsf    EECON1,RD     ; EE Read
    bcf    STATUS,RP0    ; Bank 0
    movf   EEDATA,w      ; W = EEDATA
    return

;====================================================================
; write EEPROM
;====================================================================
; Procedure to write asc1 byte to EEPROM memory
; Address to write stored in local register EEMemAdd
; Data byte to write is in local register EEByte

EEWrite:
    ; Load byte to write into EE data register
    movf    EEByte,w    ; Data to w
    movwf    EEDATA     ; Write
; Set write address in EE address register
movf EEMemAdd,w ; Address to w
movwf EEADR ; w to address register
; Write data to EEPROM memory
bsf STATUS,RP0 ; Bank 1
bcf INTCON,GIE ; Disable INTs.
bsf EECON1,WREN ; Enable Write
movlw 0x55 ; Code # 1
movwf EECON2 ; Write 0x55
movlw 0xaa ; Code # 2
movwf EECON2 ; Write 0xaa
bsf EECON1,WR ; Set WR bit
; Write operation now takes place automatically
bsf INTCON,GIE ; Re-enable interrupts
bcf STATUS,RP0 ; Bank 0
return

End

15.2.2 Ser2EEP Program

; File name: Ser2EEP.asm
; Last revision: May 26, 2006
; Author: Julio Sanchez
; PIC: 16F877
;
; Description:
; Receive character data through RS-232 line and store in
; EEPROM data memory. Received characters are echoed on
; the second LCD line. When <Enter> key is detected (code
; 0x0d) the text stored in EEPROM memory is retrieved and
; displayed on the LCD. On startup the top LCD line displays
; the prompt: “Receiving:”. At that time a message “Rdy- “ is
; sent through the serial line so as to test the connection.
;
; Default serial line setting:
; 2400 baud
; no parity
; 1 stop bit
; 8 character bits
;
; Program to use 4-bit PIC-to-LCD interface.
; Code assumes that LCD is driven by Hitachi HD44780
; controller and PIC 16F977. Display supports two lines
; each one with 20 characters. The length, wiring and base
; address of each display line is stored in #define
; statements. These statements can be edited to accommodate
; a different set-up.
WARNING:
Code assumes 10 Mhz clock. Delay routines must be
edited for a different clock. Clock speed also determines
values for baud rate setting (see spbrgVal constant).

processor 16f877 ; Define processor
#include <p16f877.inc>
__CONFIG _CP_OFF & _WDT_OFF & _BODEN_OFF & _PWRTE_ON & _HS_OSC & _WDT_OFF & _LVP_OFF & _CPD_OFF

MACROS

Macros to select the register banks
Bank0 MACRO ; Select RAM bank 0
  bcf STATUS,RP0
  bcf STATUS,RP1
ENDM

Bank1 MACRO ; Select RAM bank 1
  bsf STATUS,RP0
  bcf STATUS,RP1
ENDM

Bank2 MACRO ; Select RAM bank 2
  bcf STATUS,RP0
  bsf STATUS,RP1
ENDM

Bank3 MACRO ; Select RAM bank 3
  bsf STATUS,RP0
  bsf STATUS,RP1
ENDM

;===================================================== 
; constant definitions
; for PIC-to-LCD pin wiring and LCD line addresses 
;===================================================== 
#define E_line 1 ;| 
#define RS_line 0 ;| — from wiring diagram 
#define RW_line 2 ;| 
; LCD line addresses (from LCD data sheet) 
#define LCD_1 0x80 ; First LCD line constant 
#define LCD_2 0xc0 ; Second LCD line constant 
#define LCDlimit .20; Number of characters per line 
#define spbrgVal .64; For 2400 baud on 10Mhz clock 
; Note: The constants that define the LCD display 
; line addresses have the high-order bit set 
; so as to meet the requirements of controller 
; commands. 
;
;===================================================== 
; General Purpose Variables 
;===================================================== 
; Local variables 
; Reserve 20 bytes for string buffer 
cblock 0x20 
strData 
endc 
; Other data 
cblock 0x34 ; Start of block 
count1 ; Counter # 1 
count2 ; Counter # 2
; Counter # 3
J            ; counter J
K            ; counter K
bufAdd
index
store1       ; Local storage
store2
endc

;==============================
; Common RAM area
;==============================
; These GPRs can be accessed from any bank.
; 15 bytes are available, from 0x70 to 0x7f
      cblock 0x70
; For LCDscroll procedure
      LCDcount ; Counter for characters per line
      LCDline  ; Current display line (0 or 1)
; Communications variables
      newData  ; not 0 if new data received
      ascVal
      errorFlags
; EEPROM-related variables
      EEMemAdd ; EEPROM address to access
      EEByte   ; Data byte to write
endc

;=======================================================================
; PROGRAM
;=======================================================================
org 0        ; start at address
goto main
main:
; Wiring:
; LCD data to Port-D, lines 0 to 7
; E line -> Port-E, 1
; RW line -> Port-E, 2
; RS line -> Port-E, 0
; Set PORTE D and E for output
; First, initialize Port-B by clearing latches
      clrf STATUS
      clrf PORTB
; Select bank 1 to TRIS Port-D for output
Bank1
; TRIS Port-D for output. Port-D lines 4 to 7 are wired
; to LCD data lines. Port-D lines 0 to 4 are wired to LEDs.
      movlw B’00000000’
movwf TRISD ; and Port-D

; By default Port-A lines are analog. To configure them
; as digital code must set bits 1 and 2 of the ADCON1
; register (in bank 1)
movlw 0x06 ; binary 0000 0110 is code to
; make all Port-A lines digital
movwf ADCON1

; Port-B lines are wired to keypad switches, as follows:
; 7 6 5 4 3 2 1 0
; |||||_|_|_|_____ switch rows (output)
; |_|_|_|_____________ switch columns (input)
; rows must be defined as output and columns as input
movlw b'11110000'
movwf TRISB

; TRIS Port-E for output
movlw B'00000000'
movwf TRISE ; TRIS Port-E

; Enable Port-B pullups for switches in OPTION register
movlw b'00001000'
movwf OPTION_REG

; Back to bank 0
Bank0

; Initialize serial Port-for 2400 baud, 8 bits, no parity
; 1 stop
    call InitSerial

; Test serial transmission by sending “RDY-”
movlw ‘R’
call SerialSend
movlw ‘D’
call SerialSend
movlw ‘Y’
call SerialSend
movlw ‘-’
call SerialSend
movlw 0x20
call SerialSend

; Clear all output lines
movlw b'00000000'
movwf PORTD
movwf PORTE

; Wait and initialize HD44780
    call delay_5 ; Allow LCD time to initialize
    call initLCD ; Then do forced
    call delay_5 ; (Wait probably not
necessary)

; Clear character counter and line counter variables
clrf LCDcount
clrf LCDline
; Set display address to start of first LCD line
  call line1
; Store address of display buffer
  movlw 0x20
  movwf bufAdd
; Display "Receiving:" message prompt
  call blank20 ; Clear buffer
  movlw 0x00 ; Offset in buffer
  call storeMS1 ; Store message at offset
  call display20 ; Display message
; Start address of EEPROM
  clrf EEMemAdd
; Setup for display in second line
  call line2
  clrf LCDline
  incf LCDline,f ; Set scroll control for line 2
;============================================================================
; receive serial data, store, and display
;============================================================================
receive:
; Call serial receive procedure
  call SerialRcv
; HOB of newData register is set if new data received
  btfss newData,7
  goto scanExit
; At this point new data was received.
  movwf EEByte ; Save received character
; Display character on LCD
  movf EEByte,w ; Recover character
  call send8 ; Display in LCD
  call LCDscroll ; Scroll at end of line
; Store character in EEPROM at location in EEMemAdd
  call EEWrite ; Local procedure
  incf EEMemAdd,f ; Bump to next EEPROM
; Check for <Enter> key (0x0d) and execute display function
  movf EEByte,w ; Recover last received
  sublw 0x0d
  btfsc STATUS,Z ; Test if <Enter> key
  goto isEnter ; Go if <Enter>
; Not <Enter> key, continue processing
  scanExit:
  goto receive ; Continue
;============================================================================
; display EEPROM data
This routine receives control when the <Enter> key is received.

Action:
1. Clear LCD
2. Output is set to top LCD line
3. Characters stored in EEPROM are displayed until 0x0d code is detected

isEnter:
call clearLCD ; Clear character counter and line counter variables clrf LCDcount clrf LCDline ; Read data from EEPROM memory, starting at address 0 and display on LCD until 0x0d terminator call line1 clrf EEMemAdd ; Start at EEPROM 0

readOne:
call EERead ; Get character movf EEByte, w ; Save character ; Test for terminator sublw 0x0d btfsc STATUS, Z ; Test if 0x0d goto atEnd ; Go if 0x0d ; At this point character read is not 0x0d ; Display on LCD movf EEByte, w ; Recover character ; Display character on LCD call send8 ; Display in LCD call LCDscroll ; Scroll at end of line incf EEMemAdd, f ; Next EEPROM byte goto readOne

; End of execution
atEnd:
goto atEnd

;====================================================================================================
; LOCAL PROCEDURES
;====================================================================================================

; init LCD for 4-bit mode

initLCD:
; Initialization for Densitron LCD module as follows:
Data EEPROM Programming

; 4-bit interface
; 2 display lines of 16 characters each
; cursor on
; left-to-right increment
; cursor shift right
; no display shift
;==============
; set command mode
;==============

bcf PORTE,E_line ; E line low
bcf PORTE,RS_line ; RS line low
bcf PORTE,RW_line ; Write mode
call delay_125 ; delay 125 microseconds
movlw 0x28 ; 0 0 0 1 0 1 0 0 0 (FUNCTION SET)
call send8 ; 4-bit send routine
movlw 0x28
movlw 0x0e ; 0 0 0 0 1 1 1 0 (DISPLAY ON/OFF)
call send8
movlw 0x06 ; 0 0 0 0 0 1 1 0 (ENTRY MODE SET)
call send8
movlw 0x14 ; 0 0 0 1 0 1 0 0 (CURSOR/DISPLAY SHIFT)
call send8
movlw 0x01 ; 0 0 0 0 0 0 0 1 (CLEAR DISPLAY)
call send8
call delay_5 ; Test for busy
return

;==============
; procedure to clear LCD
;==============
clearLCD:
bcf PORTE,E_line ; E line low
bcf PORTE,RS_line ; RS line low
bcf PORTE,RW_line ; Write mode
call delay_125 ; delay 125 microseconds
movlw 0x01 ; 0 0 0 0 0 0 0 1 (CLEAR DISPLAY)
call send8
call delay_5 ; Test for busy
return

;==============
; Procedure to delay
; 42 microseconds
;================================
delay_125:
  movlw .105 ; Repeat 105 machine cycles
  movwf count1 ; Store value in counter
repeat
  decfsz count1,f ; Decrement counter
go to repeat ; Continue if not 0
return ; End of delay
;================================
; Procedure to delay
; 5 milliseconds
;================================
delay_5:
  movlw .105 ; Counter = 105 cycles
  movwf count2 ; Store in variable
delay:
  call delay_125 ; Delay
  decfsz count2,f ; 40 times = 5 milliseconds
  goto delay
return ; End of delay
;================================
; pulse E line
;================================
pulseE
  bsf PORTE,E_line ; Pulse E line
  nop
  bcf PORTE,E_line
return
;================================
; long delay sub-routine
;================================
long_delay:
  movlw D‘200’ ; w delay count
  movwf J ; J = w
jloop:
  movwf K ; K = w
kloop:
  decfsz K,f ; K = K-1, skip next if zero
  goto kloop
  decfsz J,f ; J = J-1, skip next if zero
  goto jloop
return
;================================
; send 2 nibbles in
; 4-bit mode
;================================
; Procedure to send two 4-bit values to Port-B lines
; 7, 6, 5, and 4. High-order nibble is sent first
; ON ENTRY:
; w register holds 8-bit value to send
send8:
    movwf store1 ; Save original value
    call merge4 ; Merge with Port-B
; Now w has merged byte
    movwf PORTD ; w to Port-D
    call pulseE ; Send data to LCD
; High nibble is sent
    movf store1, w ; Recover byte into w
    swapf store1, w ; Swap nibbles in w
    call merge4
    movwf PORTD
    call pulseE ; Send data to LCD
    call delay_125
    return

; merge bits

; Routine to merge the 4 high-order bits of the
; value to send with the contents of Port-B
; so as to preserve the 4 low-bits in Port-B
; Logic:
; AND value with 1111 0000 mask
; AND Port-B with 0000 1111 mask
; Now low nibble in value and high nibble in
; Port-B are all 0 bits:
; value = vvvv 0000
; Port-B = 0000 bbbb
; OR value and Port-B resulting in:
; vvvv bbbb
; ON ENTRY:
; w contain value bits
; ON EXIT:
; w contains merged bits
merge4:
    andlw b'11110000' ; ANDing with 0 clears the
    ; bit. ANDing with 1 preserves
    ; the original value
    movwf store2 ; Save result in variable
    movf PORTD, w ; Port-B to w register
    andlw b'00001111' ; Clear high nibble in Port-b
    ; and preserve low nibble
    iorwf store2, w ; OR two operands in w
    return
; Set address register to LCD line 2
; =========================================================
; ON ENTRY:
; Address of LCD line 2 in constant LCD_2
line2:
bcf PORTE,E_line ; E line low
bcf PORTE,RS_line ; RS line low, setup for
; control
call delay_5 ; Busy?
; Set to second display line
movlw LCD_2 ; Address with high-bit set
call send8
; Set RS line for data
bsf PORTE,RS_line ; RS = 1 for data
call delay_5 ; Busy?
return
;===================================
; Set address register to LCD line 1
; =========================================================
; ON ENTRY:
; Address of LCD line 1 in constant LCD_1
line1:
bcf PORTE,E_line ; E line low
bcf PORTE,RS_line ; RS line low, set up for
; control
call delay_5 ; Busy?
; Set to second display line
movlw LCD_1 ; Address and command bit
call send8 ; 4-bit routine
; Set RS line for data
bsf PORTE,RS_line ; Setup for data
call delay_5 ; Busy?
return
;===================================
; scroll to LCD line 2
; Procedure to count the number of characters displayed on
; each LCD line. If the number reaches the value in the
; constant LCDlimit, then display is scrolled to the second
; LCD line. If at the end of the second line, then LCD is
; reset to the first line.
LCDscroll:
incf LCDcount,f ; Bump counter
; Test for line limit
movf LCDcount,w
sublw LCDlimit ; Count minus limit
btfss STATUS,Z ; Is count - limit = 0
goto scrollExit ; Go if not at end of line

; At this point the end of the LCD line was reached
; Test if this is also the end of the second line
movf LCDline,w
sublw 0x01 ; Is it line 1?
btfsc STATUS,Z ; Is LCDline minus 1 = 0?
goto line2End ; Go if end of second line

; At this point it is the end of the top LCD line
call line2 ; Scroll to second line
clr LCDcount ; Reset counter
incf LCDline,f ; Bump line counter
goto scrollExit

; End of second LCD line
line2End:
call initLCD ; Reset
clr LCDcount ; Clear counters
clr LCDline
call line1 ; Display to first line

scrollExit:
return

;=============================
; LCD display procedure
;=============================
; Sends 20 characters from PIC buffer with address stored
; in variable bufAdd to LCD line previously selected
display20:
call delay_5 ; Make sure not busy

; Set up for data
bcf PORTA,E_line ; E line low
bsf PORTA,RS_line ; RS line high for data

; Set up counter for 20 characters
movlw D’20’
movwf count3

; Get display address from local variable bufAdd
movf bufAdd,w ; First display RAM address to W
movwf FSR ; W to FSR
getchar:
movf INDF,w ; get character from display RAM
; location pointed to by file select
; register
call send8 ; 4-bit interface routine

; Test for 20 characters displayed
decfsz count3,f ; Decrement counter
goto nextchar ; Skipped if done
return
nextchar:
    incf FSR,f ; Bump pointer
    goto getchar

;;;===================================
;;;  first text string procedure
;;;===================================
storeMS1:
; Procedure to store in PIC RAM buffer the message
; contained in the code area labeled msg1
; ON ENTRY:
;    variable bufAdd holds address of text buffer
;    in PIC RAM
;    w register hold offset into storage area
;    msg1 is routine that returns the string characters
;    and a zero terminator
;    index is local variable that holds offset into
;    text table. This variable is also used for
;    temporary storage of offset into buffer
; ON EXIT:
;    Text message stored in buffer
;
; Store offset into text buffer (passed in the w register)
; in temporary variable
    movwf index ; Store w in index
; Store base address of text buffer in FSR
    movf bufAdd,w ; first display RAM address to W
    addwf index,w ; Add offset to address
    movwf FSR ; W to FSR
; Initialize index for text string access
    movlw 0 ; Start at 0
    movwf index ; Store index in variable
; w still = 0
get_msg_char:
    call msg1 ; Get character from table
; Test for zero terminator
    andlw 0x0ff
    btfsc STATUS,Z ; Test zero flag
    goto endstr1 ; End of string
; ASSERT: valid string character in w
; store character in text buffer (by FSR)
    movwf INDF ; store in buffer by FSR
    incf FSR,f ; increment buffer pointer
; Restore table character counter from variable
    movf index,w ; Get value into w
    addiw 1 ; Bump to next character
    movwf index ; Store table index in variable
    goto get_msg_char ; Continue
endstr1:
    return

; Routine for returning message stored in program area
; Message has 10 characters
msg1:
    addwf PCL,f    ; Access table
    retlw 'R'
    retlw 'e'
    retlw 'C'
    retlw 'e'
    retlw 'i'
    retlw 'v'
    retlw 'i'
    retlw 'n'
    retlw 'g'
    retlw ':'
    retlw 0

;========================
; blank buffer
;========================
; Procedure to store 20 blank characters in PIC RAM
; buffer starting at address stored in the variable
; bufAdd
blank20:
    movlw D'20'    ; Setup counter
    movwf count1
    movf bufAdd,w ; First PIC RAM address
    movwf FSR      ; Indexed addressing
    movlw 0x20     ; ASCII space character
    storeit:
        movwf INDF ; Store blank character in PIC RAM
                     ; buffer using FSR register
        decfsz count1,f ; Done?
        goto incfsr ; no
        return ; yes
    incfsr:
        incf FSR,f ; Bump FSR to next buffer space
        goto storeit

;=================================================================
; communications procedures
;=================================================================
; Initialize serial Port-for 2400 baud, 8 bits, no parity,
; 1 stop
InitSerial:
    Bank1            ; Macro to select bank1
; Bits 6 and 7 of Port-C are multiplexed as TX/CK and RX/DT
; for USART operation. These bits must be set to input in the
; TRISC register
movlw b'11000000' ; Bits for TX and RX
iorwf TRISC,f ; OR into TRISc register

; The asynchronous baud rate is calculated as follows:
; Fosc
; ABR = ---------
; S*(x+1)
; where x is value in the SPBRG register and S is 64 if the high
; baud rate select bit (BRGH) in the TXSTA control register is
; clear, and 16 if the BRGH bit is set. For setting to 2400 baud
; using a 10Mhs oscillator at a slow baud rate the formula
; is:
; At slow speed (BRGH = 0)
; 10,000,000 10,000,000
; --------- = --------- = 2,403.84 (0.16% error)
; 64*(64+1) 4160
;
movlw spbrgVal ; Value in spbrgVal = 64
movwf SPBRG ; Place in baud rate generator
; Setup value: 0010 0000 = 0x20
movlw 0x20 ; Enable transmission and high baud
; rate
movwf TXSTA
Bank0 ; Bank 0
; Setup value: 1001 0000 = 0x90
movlw 0x90 ; Enable serial Port-and continuous
; reception
movwf RCSTA
;
clrf errorFlags ; Clear local error flags
; register
Return

;================================================================================
; transmit data
;================================================================================
; Test for Transmit Register Empty and transmit data in w
SerialSend:
Bank0 ; Select bank 0
btfss PIR1,TXIF ; check if transmitter busy
goto $-1 ; wait until transmitter is
not busy
movwf TXREG ; and transmit the data
return
Procedure to test line for data received and return value in w. Overrun and framing errors are detected and remembered in the variable errorFlags, as follows:

```
7 6 5 4 3 2 1 0 <= errorFlags
```

- not used — | ___ overrun error

|______ framing error

SerialRcv:
```
clrf newData ; Clear new data received
register
Bank0 ; Select bank 0
Bit 5 (RCIF) of the PIR1 Register is clear if the USART receive buffer is empty. If so, no data has been received
btfss PIR1,RCIF ; Check for received data
return ; Exit if no data

At this point data has been received. First eliminate possible errors: overrun and framing.

Bit 1 (OERR) of the RCSTA register detects overrun
Bit 2 (FERR) of the RCSTA register detects framing error
btfsc RCSTA,OERR ; Test for overrun error
goto OverErr ; Error handler
btfsc RCSTA,FERR ; Test for framing error
goto FrameErr ; Error handler

At this point no error was detected

Received data is in the USART RCREG register
movf RCREG,w ; get received data
bsf newData,7 ; Set bit 7 to indicate new data

Clear error flags
clrf errorFlags
return
```

;==============================
; error handlers
;==============================

OverErr:
```
bsf errorFlags,0 ; Bit 0 is overrun error
; Reset system
bcf RCSTA,CREN ; Clear continuous receive bit
bsf RCSTA,CREN ; Set to re-enable reception
return
```

;error because FERR framing error bit is set
;can do special error handling here - this code simply clears and continues

FrameErr:
```
bsf errorFlags,1 ; Bit 1 is framing error
movf RCREG,W ; Read and throw away bad data
```
local EEPROM data procedures

GPRs used in EEPROM-related code are placed in the common RAM area (from 0x70 to 0x7f). This makes the registers accessible from any bank.

 Procedure to read EEPROM memory

ON ENTRY:
Address of EEPROM memory location to read is stored in local register EEMemAdd

ON EXIT:
Read data in w

```
Bank2
movf EEMemAdd, W ; EEPROM address
movwf EEADR ; to read from

Bank3
bcf EECON1, EEPGD ; Point to Data memory
bsf EECON1, RD ; Start read

Bank2
movf EEDATA, W ; Data to w register

Bank0
return
```

Procedure to write data byte to EEPROM memory

ON ENTRY:
Address to write stored in local register EEMemAdd
Data byte to write is in local register EEByte

```
Bank3
Wait2Start:
btsc EECON1, WR ; Wait for
GOTO Wait2Start ; write to finish

Bank2
movf EEMemAdd, w ; Address to
movwf EEADR ; SFR
movf EEByte, w ; Data to
movwf EEDATA ; SFR

Bank3
bcf EECON1, EEPGD ; Point to Data memory
bsf EECON1, WREN ; and enable writes
```
; Disable interrupts. Can be done in any case
bcf  INTCON,GIE
; Write special codes
movlw 0x55 ; First code is 0x55
movwf EECON2
movlw 0xaa ; Second code is 0xaa
movwf EECON2
bsf EECON1,WR ; Start write operation
nop ; Time for write
nop
; Test for end of write operation
wait2End:
btfsc EECON1,WR ; Wait until WR clear
goto wait2End

; Re-enable interrupts if program uses interrupts
; If not, comment out next line
bsf INTCON,GIE

bcf EECON1,WREN ; Prevent accidental writes
Bank0
return

;============================================================
end ; END OF PROGRAM
;============================================================

15.2.3 I2CEEP Program

; File name: I2CEEP.asm
; Last revision: May 28, 2006
; Author: Julio Sanchez
; Processor: 16F877
;
; Description:
; Receive character data through RS-232 line and store in
; 24LC04B EEPROM IC, using the I2C serial protocol in the
; PIC’s MSSP module. Received characters are echoed on
; the second LCD line. When <Enter> key is detected (code
; 0x0d) the text stored in EEPROM memory is retrieved and
; displayed on the LCD. On startup the top LCD line displays
; the prompt: “Receiving:”. At that time a message “Rdy- ” is
; sent through the serial line so as to test the connection.
;
; Default serial line setting:
; 2400 baud
; no parity
; 1 stop bit
8 character bits

Wiring:
; 24LC04B SDA line is wired to PIC RC4 (MSSP SDA)
; 24LC04B SCL line is wired to PIC RC3 (MSSP SCL)
; 24LC04B A0-A2 and WP lines are not used (GND)
;
; Program to use 4-bit PIC-to-LCD interface.
; Code assumes that LCD is driven by Hitachi HD44780
; controller and PIC 16F977. Display supports two lines
; each one with 20 characters. The length, wiring and base
; address of each display line is stored in #define
; statements. These statements can be edited to accommodate
; a different set-up.
;
; WARNING:
; Code assumes 10 Mhz clock. Delay routines must be
; edited for a different clock. Clock speed also determines
; values for baud rate setting (see spbrgVal constant).
;
;===========================
; 16F877 switches
;===========================
; Switches used in __config directive:
;   _CP_ON Code protection ON/OFF
; * _CP_OFF
; *
; * _PWRT_ON Power-up timer ON/OFF
; _PWRT_OFF
; _BODEN_ON Brown-out reset enable ON/OFF
; * _BODEN_OFF
; * _PWRT_ON Power-up timer enable ON/OFF
; _PWRT_OFF
; _WDT_ON Watchdog timer ON/OFF
; * _WDT_OFF
; _LPV_ON Low voltage IC programming enable ON/OFF
; * _LPV_OFF
; _CPD_ON Data EE memory code protection ON/OFF
; * _CPD_OFF
; OSCILLATOR CONFIGURATIONS:
; _LP_OSC Low power crystal oscillator
; _XT_OSC External parallel resonator/crystal oscillator
;
; * _HS_OSC High speed crystal resonator
; _RC_OSC Resistor/capacitor oscillator
; |
; |
; |________ * indicates setup values presently selected
processor 16f877 ; Define processor
#include<p16f877.inc>
__CONFIG _CP_OFF & _WDT_OFF & _BODEN_OFF & _PWRTE_ON & _HS_OSC & _WDT_OFF & _LVP_OFF & _CPD_OFF

; __CONFIG directive is used to embed configuration data
; within the source file. The labels following the directive
; are located in the corresponding .inc file.
errorlevel -302
; Suppress bank-related warning
;=====================================================================
; MACROS
;=====================================================================
; Macros to select the register banks
Bank0 MACRO ; Select RAM bank 0
    bcf STATUS,RP0
    bcf STATUS,RP1
ENDM

Bank1 MACRO ; Select RAM bank 1
    bsf STATUS,RP0
    bcf STATUS,RP1
ENDM

Bank2 MACRO ; Select RAM bank 2
    bcf STATUS,RP0
    bsf STATUS,RP1
ENDM

Bank3 MACRO ; Select RAM bank 3
    bsf STATUS,RP0
    bsf STATUS,RP1
ENDM

;=====================================================================
; constant definitions
; for PIC-to-LCD pin wiring and LCD line addresses
;=====================================================================
#define E_line 1 ;|  
define RS_line 0 ;| — from wiring diagram
#define RW_line 2 ;|  
; LCD line addresses (from LCD data sheet)
define LCD_1 0x80 ; First LCD line constant
define LCD_2 0xc0 ; Second LCD line constant
define LCDlimit .20; Number of characters per line
#define spbrgVal .64; For 2400 baud on 10Mhz clock
; Note: The constants that define the LCD display
; line addresses have the high-order bit set
; so as to meet the requirements of controller
; commands.
;==============================================
; constants for I2C initialization
;==============================================
; I2C connected to 24LC04B EEPROM.
; The MSSP module is in I2C MASTER mode.
#define LC04READ 0xa0 ; I2C value for read control byte
#define LC04WRITE 0xa1 ; I2C value for write control byte

;==============================================
; General Purpose Variables
;==============================================
; Local variables
; Reserve 20 bytes for string buffer
 cblock 0x20
 strData
 endc
; Other data
 cblock 0x34 ; Start of block
 count1 ; Counter # 1
 count2 ; Counter # 2
 count3 ; Counter # 3
 J ; counter J
 K ; counter K
 bufAdd
 index
 store1 ; Local storage
 store2

; For LCDscroll procedure
 LCDcount ; Counter for characters per line
 LCDline ; Current display line (0 or 1)
 Endc

;==============================================
; Common RAM area
;==============================================
; These GPRs can be accessed from any bank.
; 15 bytes are available, from 0x70 to 0x7f
 cblock 0x70

; Communications variables
 newData ; not 0 if new data received
 ascVal
 errorFlags

; EEPROM-related variables
 EEMemAdd ; EEPROM address to access
 EEByte ; Data byte to write
 endc
org 0 ; start at address
goto main
org 0x08

main:
; Wiring:
; LCD data to Port-D, lines 0 to 7
; E line -> Port-E, 1
; RW line -> Port-E, 2
; RS line -> Port-E, 0
; Set PORTE D and E for output
; First, initialize Port-B by clearing latches
clrf STATUS
clrf PORTB
; Select bank 1 to TRIS Port-D for output
Bank1
; TRIS Port-D for output. Port-D lines 4 to 7 are wired
; to LCD data lines. Port-D lines 0 to 4 are wired to LEDs.
movlw B'00000000'
movwf TRISD ; and Port-D
; By default Port-A lines are analog. To configure them
; as digital code must set bits 1 and 2 of the ADCON1
; register (in bank 1)
movlw 0x06 ; binary 0000 0110 is code to
; make all Port-A lines digital
movwf ADCON1
; Port-B. lines are wired to keypad switches, as follows:
; 7 6 5 4 3 2 1 0
; | | | | | | | | switch rows (output)
; | | | | | | | switch columns (input)
; rows must be defined as output and columns as input
movlw b'11110000'
movwf TRISB
; TRIS Port-E for output
movlw B'00000000'
movwf TRISE ; TRIS Port-E
; Enable Port-B pullups for switches in OPTION register
movlw b'00001000'
movwf OPTION_REG
; Back to bank 0
Bank0
; Initialize serial port for 2400 baud, 8 bits, no parity
; 1 stop
call InitSerial
; Test serial transmission by sending "RDY-"
movlw 'R'
call SerialSend
movlw 'D'
call SerialSend
movlw 'Y'
call SerialSend
movlw '-'
call SerialSend
movlw 0x20
call SerialSend

; Clear all output lines
movlw b'00000000'
movwf PORTD
movwf PORTE

; Wait and initialize HD44780
   call delay_5 ; Allow LCD time to initialize itself
   call initLCD ; Then do forced initialization
   call delay_5

; Clear character counter and line counter variables
   clrf LCDcount
   clrf LCDline

; Set display address to start of first LCD line
   call line1

; Store address of display buffer
   movlw 0x20
   movwf bufAdd

; Display "Receiving:" message prompt
   call blank20 ; Clear buffer
   movlw 0x00 ; Offset in buffer
   call storeMS1; Store message at offset
   call display20 ; Display message

; Start address of EEPROM
   clrf EEMemAdd

; Setup for display in second line
   call line2
   clrf LCDline
   incf LCDline,f ; Set scroll control for line 2

; Initialize I2C EEPROM operation
   call SetupI2C; Local procedure

;===================================================================
; receive serial data, store, and display
;===================================================================

receive:
; Call serial receive procedure
   call SerialRcv

; HOB of newData register is set if new data
; received
   btfss newData,7
goto scanExit
; At this point new data was received.
movf EEByte, w ; Save received character
; Display character on LCD
movf EEByte, w ; Recover character
call send8 ; Display in LCD
call LCDscroll ; Scroll at end of line
; Store character in EEPROM at location in EEMemAdd
call WriteI2C ; Local procedure
incf EEMemAdd, f ; Bump to next EEPROM
; Check for <Enter> key (0x0d) and execute display function
movf EEByte, w ; Recover last received
sublw 0x0d
btfsc STATUS, Z ; Test if <Enter> key
goto isEnter ; Go if <Enter>

; Not <Enter> key, continue processing
scanExit:
goto receive ; Continue

;==================================
; display EEPROM data
;==================================
; This routine receives control when the <Enter> key is received.
; Action:
; 1. Clear LCD
; 2. Output is set to top LCD line
; 3. Characters stored in EEPROM are displayed
; until 0x0d code is detected
isEnter:
call clearLCD ; Clear character counter and line counter variables
clrf LCDcount
clrf LCDline
; Read data from EEPROM memory, starting at address 0
; and display on LCD until 0x0d terminator
call line1
clrf EEMemAdd ; Start at EEPROM 0
readOne:
call ReadI2C ; Get character
; Store character
movf EEByte, w ; Save character
; Test for terminator
sublw 0x0d
btfsc STATUS, Z ; Test if 0x0d
goto atEnd ; Go if 0x0d
; At this point character read is not 0x0d
; Display on LCD
movf EEByte, w ; Recover character
; Display character on LCD
    call    send8  ; Display in LCD
    call    LCDscroll ; Scroll at end of line
    incf    EEMemAdd,f    ; Next EEPROM byte
    goto    readOne

; End of execution
atEnd:
    goto    atEnd

;============================================================================
;============================================================================
; LOCAL PROCEDURES
;============================================================================
;============================================================================
;===================================
; init LCD for 4-bit mode
;===================================
initLCD:
; Initialization for Densitron LCD module as follows:
;  4-bit interface
;  2 display lines of 16 characters each
;  cursor on
;  left-to-right increment
;  cursor shift right
;  no display shift
;===================================
; set command mode
;===================================
    bcf    PORTE,E_line    ; E line low
    bcf    PORTE,RS_line    ; RS line low
    bcf    PORTE,RW_line    ; Write mode
    call    delay_125  ; delay 125 microseconds
    movlw    0x28 ; 00101000 (FUNCTION SET)
    call    send8 ; 4-bit send routine

; Set 4-bit mode command must be repeated
    movlw    0x28
    call    send8
    movlw    0x0e ; 0 0 0 0 0 1 1 1 0 (DISPLAY ON/OFF)
    call    send8
    movlw    0x06 ; 0 0 0 0 0 1 1 0 (ENTRY MODE SET)
    call    send8
    movlw    0x14 ; 0 0 0 1 0 1 0 0 (CURSOR/DISPLAY SHIFT)
    call    send8
    movlw    0x01 ; 0 0 0 0 0 0 0 1 (CLEAR DISPLAY)
    call    send8
    call    delay_5 ; Test for busy
return

;===========================
; procedure to clear LCD
;===========================
clearLCD:
    bcf PORTE,E_line ; E line low
    bcf PORTE,RS_line ; RS line low
    bcf PORTE,RW_line ; Write mode
    call delay_125 ; delay 125 microseconds
    movlw 0x01 ; 0 0 0 0 0 0 0 1
    call send8
    call delay_5 ; Test for busy
    return

;=======================
; Procedure to delay
; 42 microseconds
;=======================
delay_125:
    movlw .105 ; Repeat 105 machine cycles
    movwf count1 ; Store value in counter
repet:
    decfsz count1,f ; Decrement counter
    goto repet ; Continue if not 0
    return ; End of delay

;=======================
; Procedure to delay
; 5 milliseconds
;=======================
delay_5:
    movlw .105 ; Counter = 105 cycles
    movwf count2 ; Store in variable
delay:
    call delay_125 ; Delay
    decfsz count2,f ; 40 times = 5 milliseconds
    goto delay ; Continue if not 0
    return ; End of delay

;========================
; pulse E line
;========================
pulseE
    bsf PORTE,E_line ; Pulse E line
    nop
    bcf PORTE,E_line
    return
; long delay sub-routine

long_delay:
    movlw D'200' ; w delay count
    movwf J       ; J = w
jloop:
    movwf K       ; K = w
kloop:
    decfsz K,f    ; K = K-1, skip next if zero
    goto kloop
    decfsz J,f    ; J = J-1, skip next if zero
    goto jloop
return

; send 2 nibbles in
; 4-bit mode

; Procedure to send two 4-bit values to Port-B lines
; 7, 6, 5, and 4. High-order nibble is sent first
; ON ENTRY:
; w register holds 8-bit value to send
send8:
    movwf store1  ; Save original value
    call merge4   ; Merge with Port-B
    ; Now w has merged byte
    movwf PORTD   ; w to Port-D
    call pulseE   ; Send data to LCD
    ; High nibble is sent
    movf store1,w ; Recover byte into w
    swapf store1,w ; Swap nibbles in w
    call merge4
    movwf PORTD
    call pulseE   ; Send data to LCD
    call delay_125
    return

; merge bits

; Routine to merge the 4 high-order bits of the
; value to send with the contents of Port-B
; so as to preserve the 4 low-bits in Port-B
; Logic:
; AND value with 1111 0000 mask
; AND Port-B with 0000 1111 mask
; Now low nibble in value and high nibble in
; Port-B are all 0 bits:
; value = vvvv 0000
; Port-B = 0000 bbbb
; OR value and Port-B resulting in:
; vvvv bbbb
; ON ENTRY:
; w contain value bits
; ON EXIT:
; w contains merged bits

merge4:
    andlw b'11110000' ; ANDing with 0 clears the
    ; bit. ANDing with 1 preserves
    ; the original value
    movwf store2 ; Save result in variable
    movf PORTD,w ; Port-B to w register
    andlw b'00001111' ; Clear high nibble in Port-b
    ; and preserve low nibble
    iorwf store2,w ; OR two operands in w
    return

;============================================
; Set address register
; to LCD line 2
;============================================
; ON ENTRY:
; Address of LCD line 2 in constant LCD_2
line2:
    bcf PORTE,E_line ; E line low
    bcf PORTE,RS_line ; RS line low, setup for
    control
    call delay_5 ; Busy?
    ; Set to second display line
    movlw LCD_2 ; Address with high-bit set
    call send8
    ; Set RS line for data
    bcf PORTE,RS_line ; RS = 1 for data
    call delay_5 ; Busy?
    return

;============================================
; Set address register
; to LCD line 1
;============================================
; ON ENTRY:
; Address of LCD line 1 in constant LCD_1
line1:
    bcf PORTE,E_line ; E line low
    bcf PORTE,RS_line ; RS line low, set up for
    control
    call delay_5 ; busy?
    ; Set to second display line
    movlw LCD_1 ; Address and command bit
call send8 ; 4-bit routine
; Set RS line for data
bsf PORTE,RS_line ; Setup for data
call delay_5 ; Busy?
return

;=======================================
; scroll to LCD line 2
;=======================================
; Procedure to count the number of characters displayed on
; each LCD line. If the number reaches the value in the
; constant LCDlimit, then display is scrolled to the second
; LCD line. If at the end of the second line, then LCD is
; reset to the first line.
LCDscroll:
icuf LCDcount,f ; Bump counter
; Test for line limit
movf LCDcount,w
sublw LCDlimit ; Count minus limit
btfss STATUS,Z ; Is count - limit = 0
goto scrollExit ; Go if not at end of line
; At this point the end of the LCD line was reached
; Test if this is also the end of the second line
movf LCDline,w
sublw 0x01 ; Is it line 1?
btfsc STATUS,Z ; Is LCDline minus 1 = 0?
goto line2End ; Go if end of second line
; At this point it is the end of the top LCD line
call line2 ; Scroll to second line
clr2 LCDcount ; Reset counter
incf LCDline,f ; Bump line counter
goto scrollExit ; End of second LCD line
line2End:
call initLCD ; Reset
clr2 LCDcount ; Clear counters
clr2 LCDline
call line1 ; Display to first line
scrollExit:
return

;=======================================
; LCD display procedure
;=======================================
; Sends 20 characters from PIC buffer with address stored
; in variable bufAdd to LCD line previously selected
display20:
call delay_5 ; Make sure not busy
; Set up for data
    bcf PORTA,E_line ; E line low
    bsf PORTA,RS_line ; RS line high for data
; Set up counter for 20 characters
    movlw D'20'
    movwf count3
; Get display address from local variable bufAdd
    movf bufAdd,w ; First display RAM address to W
    movwf FSR ; W to FSR
getchar
    movf INDF,w ; get character from display RAM
    ; location pointed to by file select
    ; register
    call send8 ; 4-bit interface routine
; Test for 20 characters displayed
    decfsz count3,f ; Decrement counter
    goto nextchar ; Skipped if done
return
nextchar:
    incf FSR,f ; Bump pointer
    goto getchar

;================================
; First text string procedure
;================================
storeMS1:
; Procedure to store in PIC RAM buffer the message
; contained in the code area labeled msg1
; ON ENTRY:
; variable bufAdd holds address of text buffer
; in PIC RAM
; w register hold offset into storage area
; msg1 is routine that returns the string characters
; and a zero terminator
; index is local variable that hold offset into
; text table. This variable is also used for
; temporary storage of offset into buffer
; ON EXIT:
; Text message stored in buffer
;
; Store offset into text buffer (passed in the w register)
; in temporary variable
    movwf index ; Store w in index
; Store base address of text buffer in FSR
    movf bufAdd,w ; first display RAM address to W
    addwf index,w ; Add offset to address
    movwf FSR ; W to FSR
; Initialize index for text string access
movlw 0 ; Start at 0
movwf index ; Store index in variable
; w still = 0
get_msg_char:
call msg1 ; Get character from table
; Test for zero terminator
andlw 0x0ff
btfsc STATUS,Z ; Test zero flag
goto endstr1 ; End of string
; ASSERT: valid string character in w
; store character in text buffer (by FSR)
movwf INDF ; store in buffer by FSR
incf FSR,f ; increment buffer pointer
; Restore table character counter from variable
movf index,w ; Get value into w
addlw 1 ; Bump to next character
movwf index ; Store table index in variable
goto get_msg_char ; Continue
endstr1:
return

; Routine for returning message stored in program area
; Message has 10 characters
msg1:
addwf PCL,f ; Access table
retlw 'R'
retlw 'e'
retlw 'c'
retlw 'e'
retlw 'i'
retlw 'v'
retlw 'i'
retlw 'n'
retlw 'g'
retlw ':'
retlw 0

;==============================================
; blank buffer
;==============================================
; Procedure to store 20 blank characters in PIC RAM
; buffer starting at address stored in the variable
; bufAdd
blank20:
movlw D'20' ; Setup counter
movwf count1
movf bufAdd, w ; First PIC RAM address
movwf FSR  ; Indexed addressing
movlw 0x20 ; ASCII space character
storeit
movwf INDF ; Store blank character in PIC RAM
            ; buffer using FSR register
decfsz count1, f ; Done?
goto incfsr ; no
return ; yes
incfsr:
     incf FSR, f ; Bump FSR to next buffer space
goto storeit

;==============================================================================
; communications procedures
;==============================================================================
; Initialize serial port for 2400 baud, 8 bits, no parity,
; 1 stop
InitSerial:
    Bank1 ; Macro to select bank1
    ; Bits 6 and 7 of Port-C are multiplexed as TX/CK and RX/DT
    ; for USART operation. These bits must be set to input in the
    ; TRISC register
    movlw b'11000000' ; Bits for TX and RX
    iorwf TRISC, f ; OR into TRISc register
    ; The asynchronous baud rate is calculated as follows:
    ;
    ;     Fosc
    ;  ABR = ------
    ;  S*(x+1)
    ; where x is value in the SPBRG register and S is 64 if the high
    ; baud rate select bit (BRGH) in the TXSTA control register is
    ; clear, and 16 if the BRGH bit is set. For setting to 2400 baud
    ; using a 10Mhz oscillator at a slow baud rate the formula
    ; is:
    ; At slow speed (BRGH = 0)
    ;
    ; 10,000,000 10,000,000
    ; 64*(64+1)   4160
    ;
    ; 10,000,000 10,000,000
    ; 64*(64+1)   4160
    ;
    ; movlw spbrgVal ; Value in spbrgVal = 64
    ; movwf SPBRG ; Place in baud rate generator
    ; Setup value: 0010 0000 = 0x20
    ; movlw 0x20
    ; movwf TXSTA ; Enable transmission and high baud rate
    ; Bank0 ; Bank 0
    ; Setup value: 1001 0000 = 0x90
    ; movlw 0x90 ; Enable serial port and
; continuous reception
movwf RCSTA

; clear local error flags register
return

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
transmit data
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; test for transmit register empty and transmit data in w
SerialSend:
    Bank0 ; select bank 0
    btfss PIR1,TXIF ; check if transmitter busy
    goto $-1 ; wait until transmitter is not busy
    movwf TXREG ; and transmit the data
    return

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
receive data
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; procedure to test line for data received and return value in w. Overrun and framing errors are detected and remembered in the variable errorFlags, as follows:
; 7 6 5 4 3 2 1 0 << errorFlags
; — not used — | |___ overrun error
; |______ framing error
SerialRcv:
    clrf newData ; clear new data received register
    Bank0 ; select bank 0
    ; bit 5 (RCIF) of the PIR1 register is clear if the USART receive buffer is empty. If so, no data has been received
    btfss PIR1,RCIF ; check for received data
    return ; exit if no data
    ; at this point data has been received. First eliminate possible errors: overrun and framing.
    ; bit 1 (OERR) of the RCSTA register detects overrun
    ; bit 2 (FERR) of the RCSTA register detects framing error
    btfsc RCSTA,OERR ; test for overrun error
    goto OverErr ; error handler
    btfsc RCSTA,FERR ; test for framing error
    goto FrameErr ; error handler
    ; at this point no error was detected
    ; received data is in the USART RCREG register
    movf RCREG,w ; get received data
    bsf newData,7 ; set bit 7 to indicate new data
    ; clear error flags
    clrf errorFlags
    return
; error handlers
;==========================================
OverErr:
  bsf errorFlags,0 ; Bit 0 is overrun error
; Reset system
  bcf RCSTA,CREN ; Clear continuous receive bit
  bsf RCSTA,CREN ; Set to re-enable reception
  return
; error because FERR framing error bit is set
; can do special error handling here - this code simply clears
; and continues
FrameErr:
  bsf errorFlags,1 ; Bit 1 is framing error
  movf RCREG,W ; Read and throw away bad data
  return
;==========================================
; I2C EEPROM data procedures
;==========================================
; GPRs used in EEPROM-related code are placed in the common
; RAM area (from 0x70 to 0x7f). This makes the registers
; accessible from any bank.
;==========================================
; LIST OF PROCEDURES
;==========================================
; SetupI2C —- Initialize MSSP module for I2C mode
; in hardware master mode
; Configure I2C lines
; Set slew rate for 100kbps
; Set baud rate for 10Mhz
; WriteI2C —- Write byte to I2C EEPROM device
; Data is stored in EEByte variable
; Address is stored in EEMemAdd
; ReadI2C —- Read byte from I2C EEPROM device
; Address stored in EEMemAdd
; Read data returned in w register
;==========================================
; I2C setup procedure
;==========================================
SetupI2C:
Bank1
  movlw b'00011000'
  iorwf TRISC,f ; OR into TRISC
; Setup MSSP module for Master Mode operation
Bank0
  movlw B'00101000'; Enables MSSP and uses appropriate
; 0 0 1 0 1 0 0 0 Value to install
; 7 6 5 4 3 2 1 0 <= SSPCON bits in this operation
; | | | | | |__|__|__|___ Serial port select bits
; | | | | | 1000 = I2C master mode
; | | | | Clock = Fosc/(4*(SSPAD+1))
; | | | |__________ UNUSED IN MASTER MODE
; | | |__________ SSP Enable
; | | 1 = SDA and SCL pins as serial
; | |_____________________ Receive Overflow indicator
; | 0 = no overflow
; |____________________ Write collision detect
; 0 = no collision detected
    movwf SSPCON ; This is loaded into SSPCON
; Input levels and slew rate as standard I2C
    Bank1
    movlw B'10000000'
    ; 1 0 0 0 0 0 0 0 Value to install
    ; 7 6 5 4 3 2 1 0 <= SSPSTAT bits in this operation
    ; | | | | | | | |____ Buffer full status bit READ ONLY
    ; | | | | | | | |____ Unused in present application
    ; | | | | | | | |____ Read/write information READ ONLY
    ; | | | | | | | |____ Unused in MASTER MODE
    ; | | | | | | | |____ STOP bit READ ONLY
    ; | | | | | | | |____ Data address READ ONLY
    ; | | | | | | | |____ SMP bus select
    ; | | | | | | | |____ 0 = use normal I2C specs
    ; | | | | | | | |____ Slew rate control
    ; | | | | | | | |____ 0 = disabled
    movwf SSPSTAT
; Setup Baud Rate
; Baud Rate = Fosc/(4*(SSPADD+1))
; Fosc = 10Mhz
; Baud Rate = 24 for 100 kbps
    movlw .24 ; Value to use
    movwf SSPADD ; Store in SSPADD
    Bank0
    return

;====================================
; I2C write procedure
;====================================
; Write one byte to I2C EEPROM 24LC04B
; Steps:
; 1. Send START
; 2. Send control. Wait for ACK
; 3. Send address. Wait for ACK
; 4. Send data. Wait for ACK
; 5. Send STOP
; STEP 1:
WriteI2C:
; STEP 2:
; Send control byte. Wait for ACK
movlw LC04READ ; Control byte
call Send1I2C ; Send Byte
call WaitI2C ; Wait for I2C to complete
btfsc SSPCON2,ACKSTAT ; Check ACK bit to see if
; I2C failed, skip if not
goto FailI2C

; STEP 3:
; Send address. Wait for ACK
Bank0
movf EEMemAdd,w ; Load Address Byte
call Send1I2C ; Send Byte
call WaitI2C ; Wait for I2C operation to complete
Bank1
btfsc SSPCON2,ACKSTAT ; Check ACK Status bit to see
; if I2C failed, skip if not
goto FailI2C

; STEP 4:
; Send data. Wait for ACK
Bank0
movf EEByte,w ; Load Data Byte
call Send1I2C ; Send Byte
call WaitI2C ; Wait for I2C operation to complete
Bank1
btfsc SSPCON2,ACKSTAT ; Check ACK Status bit to see
; if I2C failed, skip if not
goto FailI2C

; STEP 5:
; Send STOP. Wait for ACK
bsf SSPCON2,PEN ; Send STOP condition
call WaitI2C ; Wait for I2C operation to complete

; WRITE operation has completed successfully.
Bank0
return

;============================
; I2C read procedure
;============================
; Procedure to read one byte from 24LC04B EEPROM
; Steps:
; 1. Send START
; 2. Send control. Wait for ACK
; 3. Send address. Wait for ACK
; 4. Send RESTART + control. Wait for ACK
5. Switch to receive mode. Get data.
  6. Send NACK
  7. Send STOP
  8. Retrieve data into w register

STEP 1:
ReadI2C
  ; Send RESTART. Wait for ACK
  Bank1
  bsf   SSPCON2,RSEN ; RESTART Condition
  call   WaitI2C ; Wait for I2C operation

STEP 2:
  ; Send control byte. Wait for ACK
  movlw  LC04READ    ; Control byte
  call   SendI2C ; Send Byte
  call   WaitI2C ; Wait for I2C operation
  ; Now check to see if I2C EEPROM is ready
  Bank1
  btfsc  SSPCON2,ACKSTAT ; Check ACK Status bit
  goto   ReadI2C ; ACK Poll waiting for EEPROM
            ; write to complete

STEP 3:
  ; Send address. Wait for ACK
  Bank0
  movf   EEMemAdd, w ; Load from address register
  call   SendI2C ; Send Byte
  call   WaitI2C ; Wait for I2C operation
  Bank1
  btfsc  SSPCON2,ACKSTAT ; Check ACK Status bit
  goto   FailI2C ; failed, skipped if successful

STEP 4:
  ; Send RESTART. Wait for ACK
  bsf   SSPCON2,RSEN ; Generate RESTART Condition
  call   WaitI2C ; Wait for I2C operation
  ; Send output control. Wait for ACK
  movlw  LC04WRITE ; Load CONTROL BYTE (output)
  call   SendI2C ; Send Byte
  call   WaitI2C ; Wait for I2C operation
  Bank1
  btfsc  SSPCON2,ACKSTAT ; Check ACK Status bit
  goto   FailI2C ; failed, skipped if successful

STEP 5:
  ; Switch MSSP to I2C Receive mode
  bsf   SSPCON2,RCEN ; Enable Receive Mode (I2C)
  ; Get the data. Wait for ACK
  call   WaitI2C ; Wait for I2C operation

STEP 6:
  ; Send NACK to acknowledge
bsf SSPCON2,ACKDT ; ACK DATA to send is 1 (NACK)
bsf SSPCON2,ACKEN ; Send ACK DATA now.
; Once ACK or NACK is sent, ACKEN is automatically cleared
; STEP 7:
; Send STOP. Wait for ACK
bsf SSPCON2,PEN ; Send STOP condition
call WaitI2C ; Wait for I2C operation
; STEP 8:
; Read operation has finished
Bank0
movf SSPBUF,W ; Get data from SSPBUF into W
; Procedure has finished and completed successfully.
return

;=================================================================================
; I2C support procedures
;=================================================================================
; I2C Operation failed code sequence
; Procedure hangs up. User should provide error handling.
FailI2C
Bank1
bsf SSPCON2,PEN ; Send STOP condition
call WaitI2C ; Wait for I2C operation
fail:
    goto fail

; Procedure to transmit one byte
Send1I2C
Bank0
movwf SSPBUF ; Value to send to SSPBUF
return

; Procedure to wait for the last I2C operation to complete.
; Code polls the SSPIF flag in PIR1.
WaitI2C
Bank0
btfss PIR1,SSPIF ; Check if I2C operation done
goto $-1 ; I2C module is not ready yet
bcf PIR1,SSPIF ; I2C ready, clear flag
return

;=============================================================================
end ; END OF PROGRAM
;=============================================================================
Chapter 16

Analog to Digital and Realtime Clocks

Digits are a human invention; nature does not count or measure using numbers. We measure natural forces and phenomena using digital representations, but the forces and phenomena themselves are continuous. Time, pressure, voltage, current, temperature, humidity, gravitational attraction, all exist as continuous entities which we measure in volts, pounds, hours, amperes, or degrees, so as to better understand them and to be able to perform numerical calculations.

In this sense, natural phenomena occur in analog quantities. Sometimes they are digitized so as to facilitate measurements and manipulations. For example, a potentiometer in an electrical circuit allows reducing the voltage level from the circuit maximum to ground, or zero level. In order to measure and control the action of the potentiometer, we need to quantify its action by producing a digital value within the physical range of the circuit; that is, we need to convert an analog quantity that varies continuously between 0 and 5 volts, to a discrete digital value range. If, in this case, the voltage range of the potentiometer is from 5 to 0 volts, we can digitize its action into a numeric range of 0 to 500 units, or measure the angle or rotation of the potentiometer disk in degrees from 0 to 180. The device that performs either conversion is called an A/D or analog-to-digital converter. The reverse process, digital-to-analog, is also necessary, although not as often as A/D. In this chapter we explore A/D conversions in PIC software and hardware.

The second topic of this chapter is the measurement of time in discrete (albeit, digital) units. In this context we speak of “realtime” as years, days, hours, minutes, and so on. So a realtime clock measures time in hours, minutes, and seconds, and a realtime calendar measures it in years, months, weeks, and days. Since time is a continuum that escapes our comprehension, we must divide it into measurable chunks that can be manipulated and calculated. However, not all time units are in proportional relation with one another. There are 60 seconds in a minute and 60 minutes in an hour, but 24 hours in a day and 28, 29, 30, or 31 days in a month. Furthermore, the months and the days of the week have traditional names. Finally, the Gregorian calendar requires adding a 29th day to February on any year that is evenly divisible by 4. The device or software to perform all of these time calculations is referred to as a realtime clock. In this chapter we discuss the use of realtime clocks in PIC circuits.
In electronics, the typical A/D or ADC converter is a device that takes a voltage input and returns a binary digital number. Figure 16-1 is a block diagram of an A/D converter.

The electronic A/C converter requires an input in the form of an electrical voltage. Non-electric quantities must be changed into a voltage level before the conversion can be performed. The device that performs this conversion is called a transducer. For example, a digital barometer must be equipped with a transducer that converts the measurement into voltage levels. The voltage levels can then be fed into an A/D converter and the result output in digital form.

### 16.0.1 Converter Resolution

An ideal A/D converter outputs into an infinite number of discrete steps that exactly represent the analog quantity. Needless to say, such a device cannot exist, and a real A/D converter must be limited to a numeric range. For example, the device in Figure 16-1 outputs a voltage range of 0 to +5 volts in four binary digits that represent values between 0 and 15. Another A/D converter may produce output in eight binary digits, and another in sixteen binary digits. The number of discrete values in the conversion is called the resolution. The converter's resolution is usually expressed in bits. Figure 16-2 represents an A/C converter with a voltage range of 0 to +5 volts and a resolution of three bits.

Suppose that a value of 2.5 volts were input into the A/D converter in Figure 16-2. Since the output has a resolution in the range 0 to 7, the converter's output would be either 4 or 5. The non-linear characteristic of the output determines a quantization error that increases as the converter resolution decreases. Converters used in PIC circuits have a resolution of either 8, 10, or 12 bits. In each case the output range, or quantization level, is 0 to 255, 0 to 1023, or 0 to 4095. The voltage resolution of the converter is its maximum voltage range divided by the number of quantization levels. A device with a voltage range of 5 volts and a range of 255 levels has a voltage resolution of:
16.0.2 ADC Implementation

The analog-to-digital converter performs accurately only if the input voltage is within the converter's valid range. This range is usually selected by setting high and low voltage references on converter pins. For example, if +4 volts is input into the converter's positive reference pin and +2 volts into the negative reference pin, then the converter's voltage range lies between these values. In many PIC applications the converter range is selected as the system's supply voltage and ground, that is, +5 and 0 volts. When a different range is externally referenced, there is a general restriction that the range cannot exceed the system's positive and negative limits (Vdd and Vss). Also, a minimum difference is required between the high and low voltage references.

The output of the ADC is a digital representation of the original analog signal. In this context, the term quantization refers to subdividing a range into small but measurable increments. The quantization process can introduce a quantization error, which is similar to a rounding error.

The time required for the holding capacitor on the ADC to charge is called the acquisition time. The holding capacitor on the ADC must be given sufficient time to settle to the analog input voltage level before the actual conversion is initiated. Otherwise, the conversion is not accurate. The acquisition time is determined by the impedance of the internal multiplexer and that of the analog source. The exact acquisition time can be determined from the device's data sheet, although 10K ohms is the maximum recommended source impedance for 8- and 10-bit converters and 2.5K ohms for 12-bit converters.

\[ \text{voltage resolution} = \frac{5}{255} = 0.01960 \text{ volts} = 19.60\text{mV} \]
Most analog-to-digital converters in PIC applications, either internal or external, are of the successive approximation type. The successive approximation algorithm performs a conversion on one bit at a time, beginning with the most significant bit and ending with the least significant bit. To determine each bit in the range, the value of the input signal is tested to see if it is in the upper or lower portion of this range. If in the upper portion, the conversion bit is a 1, otherwise it is a 0. The next most significant bit is then tested in the lower half of the remaining range. The process is continued until the least-significant bit has been determined.

### 16.1 A/D Integrated Circuits

Several popular integrated circuits are used to perform as A/D converters, among them the ADC0831, the LTC1298, and the MAX 190 and MAX 191. The variations consist in the resolution and interfacing of the different ICs. Of these, the ADC0831, from National Semiconductor, is an 8-bit resolution, serial interface A/D quite suited to applications for small, mid-range PICs such as the 16F84. The input range of the 0831 is 0 to 5 volts, which matches the TTL voltage levels used in PIC circuits. The 0831 pin diagram is shown in Figure 16-3.

![ADC0831 Pin Diagram](image)

Figure 16-3 ADC0831 Pin Diagram

The ADC0831 uses three control lines, labeled **DO (data out)**, **CLK (clock)**, and **CS (chip select)** in Figure 16-3. Interfacing the ADC0831 requires three I/O lines. Of these, two can be multiplexed with other functions or with other ADC0831. Actually, only the chip-select (CS) pin requires a dedicated line. This allows for several ADCs to be multiplexed on the CLK and DO lines as long as each one has its own CS connection to the microcontroller. In this case, the controller determines which device is being read by the port to which CS line is connected.

The input voltage range of the ADC0831 is determined by the **Vref (positive voltage reference line)** and **Vin- (negative voltage reference line)** pins. Vref is used to set the maximum level and Vin- the minimum. Since the ADC0831 has an 8-bit range, the voltage reading that matches the Vref value is read as 255 and the one that matches the Vin- value is read as 0. The minimum difference between the voltage limits is of 1 volt.
16.1.1 ADC0331 Sample Circuit and Program

A simple circuit to illustrate the action of an analog-to-digital converter consists of connecting a potentiometer with the positive voltage reference line, as shown in Figure 16-4. In the circuit the potentiometer was selected so as to produce a voltage range between 0 and +5 volts. Vref was wired to the circuit’s +5 V source and Vin- was wired to ground. The potentiometer variable line was connected to the ADC0831 Vin+ line and the other ADC lines to the corresponding 16F84 Port-B pins.

The sample program is named ADF84, and can be found in the book’s online software. The ADF84 program uses the ADC0831 to convert the analog voltage from the potentiometer, in the range +5 to 0 volts, into a digital value in the range 0 to 255. The value read is then displayed on the LCD. The initialization routine defines
Port-B, line 0 as input since this is the one connected to the DO line. The remaining lines in ports A and B are defined as output. ADC0831 processing consists of a single procedure that reads the analog line and returns an 8-bit digital value. The processing required is performed in the following steps:

1. The data return register (named rcvdata) is cleared and the bit counter register is initialized to count 8 bits.
2. The ADC0831 is prepared by bringing the CS line low and pulsing the CLK line.
3. The CLK line is pulsed and one bit is read from the low-order bit (DO line) of Port-B.
4. The bit is shifted into the data return register and the bit counter is decremented.
5. If the bit counter is exhausted, execution ends and the ADC is turned off. Otherwise processing continues at step 3.

The following procedure, from the ADF84 program, reads digital data from the ADC0831:

```assembly
;=================================
;procedure to read and convert analog line
;=================================
;ON ENTRY:
;Code assumes that the ADC0831 DO line is initialized for input, while CLK and CS lines are output
;From ADC0831 wiring diagram. All lines in Port-B
;DO = RB0 ==> INPUT
;CLK = RB1 <= OUTPUT
;CS = RB2 <= OUTPUT
;ON EXIT:
;Returns 8-bit digital value in the register rcvdata

ana2dig:
;Clear data register and init counter for 8 bits
clrf rcvdata ; Clear register
movlw 0x08 ; Initialize counter
movwf bitCount

;Prepare to read analog line
bcf PORTB,CS ; CS pin low to enable ADC
nop ; Delay for 4MHz clock
bsf PORTB,CLK ; Set CLK high

bcf PORTB,CLK ; Reset CLK to start conversion
nop

nextB:
;Pulse CLK line to read bit from ADC
bsf PORTB,CLK ; CLK high
nop bcf PORTB,CLK ; CLK low

;Read analog line and store data, bit by bit
```
16.2 PIC On-Board A/D Hardware

A few years ago, A/D conversions always required the use of devices such as the ones described in the previous sections. Nowadays, many PIC microcontrollers come with onboard A/D hardware. One of the advantages of using onboard A/D converters is saving interface lines. The circuit shown in Figure 16-4 requires devoting three lines to the interface between the ADC0831 and the PIC 16F84. On the other hand, a similar circuit can be implemented in a PIC with internal A/D conversion by simply connecting the analog device to the corresponding PIC port. In the PIC world, where I/O lines are often in short supply, this advantage is not insignificant.

At the time we are writing, PICs equipped with A/D converters have either 8- or 10-bit resolution and can receive analog input in 2 to 16 different channels. The 16F877 with eight analog input channels at a 10-bit resolution is discussed. Nowadays, these PICs are easy to obtain. On the other hand, if the resolution required exceeds 10-bits then the designer has to resort to an independent A/D IC, such as the LTC1298, which has a 12-bit resolution, or to others with even higher numbers of output bits.

16.2.1 A/D Module on the 16F87x

The PICs of the 16F87x family are equipped with an analog-to-digital converter module. The number of lines depends on the specific version of the device: 28-pin devices have five A/D lines and all others have eight lines. The converter uses a sample and hold capacitor to store the analog charge and performs a successive approximation algorithm to produce the digital result. The converter resolution is 10 bits, which are stored in two 8-bit registers. One of the registers has only four significant bits.

The A/D module has high- and low-voltage reference inputs that are selected by software. The module can operate while the processor is in SLEEP mode, but only if the A/D clock pulse is derived from its internal RC oscillator. The module contains four registers accessible to the application:
• ADRESH - Result High Register
• ADRESL - Result Low Register
• ADCON0 - Control Register 0
• ADCON1 - Control Register 1

Of these, it is the ADCON0 register that controls most of the operations of the A/C module. Port-A pins RA0 to RA5 and Port-E pins RE0 to RE2 are multiplexed as analog input pins into the A/C module. In the 28-pin versions of the 16F87x, port pins RA0 to RA5 provide the five input channels. In all other implementations of the 16F87X, Port-E pins RE0 to RE2 provide the three additional channels.

Figure 16-5 shows the registers associated with A/D module operations.

<table>
<thead>
<tr>
<th>REGISTER NAME</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0 bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTCON</td>
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<td>PIR1</td>
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<td>ADCON0</td>
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<tr>
<td>ADRESH</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>A/D Result Register High Byte</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADRESL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A/D Result Register Low Byte</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADCON1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ADFM</td>
<td>PCFG3</td>
<td>PCFG2</td>
<td>PCFG1</td>
<td>PCFG0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CHS2</td>
<td>CHS1</td>
<td>CHS0</td>
<td>GO/DONE</td>
<td>ADON</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ADSC1</td>
<td>ADSC0</td>
<td>CHS2</td>
<td>CHS1</td>
<td>CHS0</td>
<td>GO/DONE</td>
<td>ADON</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 16-5** Registers Related to A/C Module Operations

**The ADCON0 Register**

The ADCON0 register is located in bank 0, at address 0x1f. Seven of the eight bits are meaningful in A/D control and status operations. Figure 16-6 is a bitmap of the ADCON0 register.

In Figure 16-6, bits 7 and 6, labeled ADSC1 and ADSC0, are the selection bits for the A/D conversion clock. The conversion time per bit is defined as TAD in PIC documentation. A/D conversion requires a minimum of 12 TAD in a 10-bit ADC. The source of the A/D conversion clock is software selected. The four possible options for TAD are:

1. Fosc/2
2. Fosc/8
3. Fosc/32
4. Internal A/D module RC oscillator (varies between 2 and 6 µs)
The conversion time is the analog-to-digital clock period multiplied by the number of bits of resolution in the converter, plus the two to three additional clock periods for settling time, as specified in the data sheet of the specific device. The various sources for the analog-to-digital converter clock represent the main oscillator frequency divided by 2, 8, or 32. The third choice is the use of a dedicated internal RC clock that has a typical period of 2 to 6 µs. Since the conversion time is determined by the system clock, a faster clock results in a faster conversion time.

The A/D conversion clock must be selected to ensure a minimum Tad time of 1.6 µs. The formula for converting processor speed (in MHz) into Tad microseconds is as follows:

$$Tad = \frac{1}{\frac{T_{osc}}{T_{div}}}$$
Where \( T_{ad} \) is A/D conversion time, \( T_{osc} \) is the oscillator clock frequency in MHz, and \( T_{div} \) is the divisor determined by bits ADSC1 and ADSC0 of the ADCON0 register. For example, in a PIC running at 10MHz if we select the \( T_{osc}/8 \) option (divisor equal 8) the A/D conversion time per bit is calculated as follows:

\[
T_{ad} = \frac{1}{\frac{5\text{MHz}}{8}} = 1.6\text{ }\mu\text{s}
\]

In this case, the minimum recommended conversion speed of 1.6 \( \mu\text{s} \) is achieved. However, in a PIC with an oscillator speed of 10MHz, this option produces a conversion speed of 0.8 \( \mu\text{s} \), less than the recommended minimum. In this case we would have to select the divisor 32 option, giving a conversion speed of 3.2 \( \mu\text{s} \).

**Table 16.1**

<table>
<thead>
<tr>
<th>OPERATION</th>
<th>ADCS1:ADCS0</th>
<th>20MHZ</th>
<th>10MHZ</th>
<th>5MHZ</th>
<th>1.25MHZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fosc/2</td>
<td>00</td>
<td>0.1</td>
<td>0.2</td>
<td>0.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Fosc/8</td>
<td>01</td>
<td>0.4</td>
<td>0.8</td>
<td>1.6</td>
<td>6.4</td>
</tr>
<tr>
<td>Fosc/32</td>
<td>10</td>
<td>1.6</td>
<td>3.2</td>
<td>6.4</td>
<td>25.6</td>
</tr>
<tr>
<td>RC</td>
<td>11</td>
<td>2-6</td>
<td>2-6</td>
<td>2-6</td>
<td>2-6</td>
</tr>
</tbody>
</table>

Note: values in bold are within the recommended limits

In Table 16.1, converter speeds of less than 1.6 \( \mu\text{s} \) or higher than 10 \( \mu\text{s} \) are not recommended. Recall that the \( T_{ad} \) speed of the converter is calculated per bit, so the total conversion time in a 10-bit device (such as the 16F87x) is approximately the \( T_{ad} \) speed multiplied by 10 bits, plus 3 additional cycles. Therefore, a device operating at a \( T_{ad} \) speed of 1.6 \( \mu\text{s} \) requires 1.6 \( \mu\text{s} \times 13 \), or 20.8 \( \mu\text{s} \) for the entire conversion.

Bits CHS2 to CHS0 in the ADCON0 register (see Figure 16-6) determine which of the analog channels is selected. This is required, since there are several channels for analog input but only one A/2 converter circuitry. So the setting of this bit field determines which of six or eight possible channels is currently read by the A/C converter. An application can change the setting of these bits in order to read several analog inputs in succession.

Bit 2 of the ADCON0 register, labeled GO/DONE, is both a control and a status bit. Setting the GO/DONE bit starts A/D conversion. Once conversion has started, the bit indicates if it is still in progress. Code can test the status of the GO/DONE bit in order to determine if conversion has concluded.

Bit 0 of the ADCON0 register turns the A/D module on and off. The initialization routine of an A/D-enabled application turns on this bit. Programs that do not use the A/D conversion module leave the bit off to conserve power.

**The ADCON1 Register**

The ADCON1 register also plays an important role in programming the A/D module. Bit 7 of the ADCON1 register is used to determine the bit justification of the digital re-
result. This is possible because the 10-bit result is returned in two 8-bit registers; therefore, the six unused bits can be placed either on the left- or the right-hand side of the 16-bit result. If ADCON1 bit 7 is set then the result is right-justified; otherwise it is left-justified. Figure 16-7 shows the location of the significant bits.

<table>
<thead>
<tr>
<th>ADRESH</th>
<th>ADRESL</th>
</tr>
</thead>
<tbody>
<tr>
<td>V V V V V V V V</td>
<td>V V 0 0 0 0 0 0</td>
</tr>
</tbody>
</table>

Left-justified (ADFM bit = 0)

<table>
<thead>
<tr>
<th>ADRESH</th>
<th>ADRESL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 0 0 0 0 V V</td>
<td>V V V V V V V V</td>
</tr>
</tbody>
</table>

Right-justified (ADFM bit = 1)

Legend:
- V = valid digit
- 0 = digit always cleared

Figure 16-7 Left- and Right-justification of A/D Result

One common use of right justification is to reduce the number of significant bits in the conversion result. For example, an application on the 16F877 that uses the A/D conversion module requires only 8-bit accuracy in the result. In this case, code can left-justify the conversion result, read the ADRESH register, and ignore the low-order bits in the ADRESL register. By ignoring the two low-order bits, the 10-bit accuracy of the A/D hardware is reduced to eight bits and the converter performs as an 8-bit accuracy unit.

The bit field labeled PCFG3 to PCFG0 in the ADCON1 register determines port configuration as analog or digital and the mapping of the positive and negative voltage reference pins. The number of possible combinations is limited by the four bits allocated to this field, so the programmer and circuit designer must select the option that is most suited to the application when the ideal one is not available. Table 16.2 (in the following page) shows the port configuration options.

For example, there is a circuit that calls for two analog inputs, wired to ports RA0 and RA1, with no reference voltages. In Table 16.2 we can find two options that select ports RA0 and RA1 and are analog inputs: these are the ones selected with PCFG bits 0100 and 0101. The first option also selects port RA3 as analog input, even though not required in this case. The second one also selects port RA3 as a positive voltage reference, also not required.

Either option works in this case; however, any pin configured for analog input produces incorrect results if used as a digital source. Therefore, a channel configured for analog input cannot be used for non-analog purposes. On the other hand, a
channel configured for digital input should not be used for analog data since extra current is consumed by the hardware. Finally, channels to be used for analog-to-digital conversion must be configured for input in the corresponding TRIS register.

**SLEEP Mode Operation**

The A/D module can be made to operate in SLEEP mode. As mentioned previously, SLEEP mode operation requires that the A/D clock source be set to RC by setting both ADCS bits in the ADCON0 register. When the RC clock source is selected, the A/D module waits one instruction cycle before starting the conversion. During this period, the SLEEP instruction is executed, thus eliminating all digital switching noise from the conversion. The completion of the conversion is detected by testing the GO/DONE bit. If a different clock source is selected, then a SLEEP instruction causes the conversion-in-progress to be aborted and the A/D module to be turned off.

### 16.2.2 A/D Module Sample Circuit and Program

The circuit in Figure 16-8 is designed to demonstrate the use of the A/D converter module in PICs of the 16F87x family.
Comparing Figure 16-8 with Figure 16-4, which uses the ADC0831 IC, we notice the economy of resources that results from selecting a PIC with an onboard A/D module. In the circuit of Figure 16-4 three microcontroller I/O ports must be used to connect the converter IC to the PIC. In the circuit of Figure 16-8, the potentiometer is connected directly to a single PIC port, saving two I/O lines. Considering the number of different PIC architectures that are equipped with onboard A/D converters, the circuit designer should explore this possibility before deciding on using a separate converter IC. At the same time, recall that two of the three input lines used by converter ICs can be shared. In a design with more than one converter IC the use of input lines is not a 3 to 1 ratio.

The circuit in Figure 16-8 consists of a 5K potentiometer wired to analog port RA0 of a 16F877 PIC. The LCD display is used to show three digits, in the range 0 to 255,
that represent the relative position of the potentiometer's disk. The program named A2DinLCD, in the book's online software, uses the built-in A/D module.

Programming the A/D module consists of the following steps:

1. Configure the PIC I/O lines to be used in the conversion. All analog lines are initialized as input in the corresponding TRIS registers.

2. Select the ports to be used in the conversion by setting the PCFGx bits in the ADCON1 register. Selects right- or left-justification.

3. Select the analog channels, select the A/D conversion clock, and enable the A/D module.

4. Wait the acquisition time.

5. Initiate the conversion by setting the GO/DONE bit in the ADCON0 register.

6. Wait for the conversion to complete.

7. Read and store the digital result.

The following procedure from the A2DinLCD program initialized the A/D module for the required processing:

```assembly
;============================
; init A/D module
;============================
; 1. Procedure to initialize the A/D module, as follows:
;     Configure the PIC I/O lines. Init analog lines as input
; 2. Select ports to be used by setting the PCFGx bits in the
;     ADCON1 register. Selects right- or left-justification.
; 3. Select the analog channels, select the A/D conversion
;     clock, and enable the A/D module.
; 4. Wait the acquisition time.
; 5. Initiate the conversion by setting the GO/DONE bit in the
;     ADCON0 register.
; 6. Wait for the conversion to complete.
; 7. Read and store the digital result.
InitA2D:
    Bank1 ; Select bank for TRISA register
    movlw b'00000001'
    movwf TRISA ; Set Port-A, line 0, as input
; Select the format and A/D port configuration bits in
; the ADCON1 register
; Format is left-justified so that ADRESH bits are the
; most significant
; 0 x x x 1 1 1 0 <= value installed in ADCON1
; 7 6 5 4 3 2 1 0 <= ADCON1 bits
; |__|__|__|____ RA0 is analog.
; Vref+ = Vdd
; Vref- = Vss
; 0 = left-justified
; ADCON1 is in bank 1
```
movlw b'00001110'
movwf ADCON1 ; RA0 is analog. All others digital
 ; Vref+ = Vdd
; Select D/A options in ADCON0 register
; For a 10Mhz clock the Fosc32 option produces a conversion
; speed of 1/(10/32) = 3.2 microseconds, which is within the
; recommended range of 1.6 to 10 microseconds.
; 1 0 0 0 0 0 0 1 <= value installed in ADCON0
; 7 6 5 4 3 2 1 0 <= ADCON0 bits
; | | | | | | |____ A/D function select
; | | | | | | 1 = A/D ON
; | | | | |____________ A/D status bit
; | | |______________________ Analog Channel Select
; | | 000 = Chanel 0 (RA0)
; |________________________ A/D Clock Select
; 10 = Fosc/32
; ADCON0 is in bank 0
Bank0
movlw b'10000001'
movwf ADCON0 ; Channel 0, Fosc/32, A/D enabled
; Delay for selection to complete
call delayAD ; Local procedure
return

Once the module is initialized, the analog line is read by the following procedure:

;============================
; read A/D line
;============================
; Procedure to read the value in the A/D line and convert
; to digital
ReadA2D:
; Initiate conversion
Bank0 ; Bank for ADCON0 register
bsf ADCON0,GO ; Set the GO/DONE bit
; GO/DONE bit is cleared automatically when conversion ends
cnvWait:
btfsc ADCON0,GO ; Test bit
goto cnvWait; Wait if not clear
; At this point conversion has concluded
; ADRESH register (bank 0) holds 8 MSBs of result
; ADRESL register (bank 1) holds 4 LSBs.
; In this application value is left-justified. Only the
; MSBs are read
movf ADRESH,W ; Digital value to w register
return
The delay routine required in this case is coded as follows:

```
; delay procedure
; For a 10Mhz clock the Fosc32 option produces a conversion speed of 1/(10/32) = 3.2 microseconds. At 3.2 ms per bit; 13 bits require approximately 41 ms. The instruction time; at 10Mhz is 10 ms. 4/10 = 0.4 ms per instruction. To delay; 41 ms a 10Mhz PIC must execute 11 instructions. Add one; more for safety.

delayAD:
  movlw .12  ; Repeat 12 machine cycles
  movwf count1 ; Store value in counter
repeat11:
  decfsz count1,f ; Decrement counter
  goto repeat11 ; Continue if not 0
return
```

16.3 Realtime Clocks

In the context of microcontrollers and embedded systems, *realtime clocks* (also called *RTCs*) are integrated circuits designed to keep track of time in conventional hours, that is, in years, days, hours, minutes, and seconds. Many realtime clock ICs are available with various characteristics, data formats, modes of operation, and interfaces. Most of the ones used in PIC circuits have a serial interface in order to save access ports. Most RTC chips provide a battery connection so that time can be kept when the system is turned off.

In the sections that follow, we discuss one popular RTC chip: the NJU6355, but this is by no means the only option for embedded systems.

16.3.1 The NJU6355 Realtime Clock

The NJU6355 series is a serial I/O realtime clock used in microcontroller-based embedded systems. The IC includes its own quartz crystal oscillator, counter, shift register, voltage regulator, and interface controller. The PIC interface requires four lines. Operating voltage is TTL level so it can be wired directly on the typical PIC circuit. The output data includes year, month, day-of-week, hour, minutes, and seconds. Figure 16-9 is the pin diagram for the NJU6355.

NJU6355 output is in packed BCD format, that is, each decimal digit is represented by a 4-bit binary number. The chip’s logic correctly calculates the number of days in each month as well as the leap years. All unused bits are reported as binary 0. Figure 16-10 is a bitmap of the formatted timer data.
Timer data is read when the I/O line is low and the CE line is high. Output from the 6355 is LSB first. A total of 52 significant bits are read in bottom-up order for data as shown in Figure 16-10. That is, the first bit received is the least-significant bit of the year, then the month, then the day, and so forth. All date items are eight bits, except the day of week which is four bits. Non-significant bits in each field are reported as zero; this means that the value for the 10th month (October) is encoded as binary digits 00001010. Reporting unused digits as zero simplifies the conversion into BCD and ASCII.

**Figure 16-9** NJU6355 Pin Diagram

**Figure 16-10** NJU6355 Timer Data Format
The NJU6355 does not report valid time data until after it has been initialized, even if there are power and clock signals into the chip. Initialization requires writing data into the 6355 registers. In order to write to the IC, code must set the I/O and the CE lines high. At this moment all clock updates stop and the RTC goes into the write mode. Input data is latched in LSB first, starting with the year and concluding with the minutes. There is no provision for writing seconds into the RTC, so the total number of bits written is 44.

The 6355 contains a mechanism for detecting conditions that could compromise the clock's operation, such as low power. In this case, the special value 0xee is written into each digit of the internal registers to inform processing routines that the timer has been compromised.

The NJU6355 requires the installation of an external crystal oscillator. The crystal must have a frequency of 32.768 kHz. The time-keeping accuracy of the RTC is determined by the quartz oscillator. The capacity of the oscillator must match that of the RTC and of the circuit. A standard crystal with a capacitance of 12.5pF works well for applications that do not demand high clock accuracy. For more exacting applications the 6355 can be programmed to check the clock frequency and determine its error. The chip's frequency-checking mode is described in an NJU6355 Application Note available from New Japan Radio Co., Ltd.

16.3.2 RTC Demonstration Circuit and Program

The circuit shown in Figure 16-11 is a simple application of the 6355 RTC. The circuit uses a NJU6355 in conjunction with a 16F86 PIC and an LCD. The demonstration program, named RTC2LCD, sets up RTC and reads clock data in an endless loop. The hours, minutes, and seconds are displayed at the top line of the LCD as follows:

\[ H:xx \quad M:xx \quad S:xx \]

where \( xx \) represents the two BCD digits read from the clock and converted to ASCII decimal for display. The program initializes the 6355 to some arbitrary values contained in the corresponding `#define` statements. These values are copied into program variables by a local procedure and then used to initialize the RTC registers. Two procedures relate to RTC operation: one to initialize the clock hardware and the other one to read the current time. In addition, two auxiliary procedures are implemented: one to read clock data and one to write clock data. Since clock data can be in 8- or 4-bit formats each procedure contains a separate entry point to handle the 4-bit option. The procedure to initialize and the one to write clock data are coded as follows:

```plaintext
;=============
; init RTC
;=============
; Procedure to initialize the real time clock chip. If chip
; is not initialized it will not operate and the values
; read will be invalid.
; Since the 6355 operates in BCD format the stored values must
; be converted to packed BCD.
; According to wiring diagram
```
Figure 16-11 Real-time Clock Demonstration Circuit

; NJU6355 Interface for setting time:
; DAT        PORTB, 0   Output
; CLK        PORTB, 1   Output
; CE         PORTB, 2   Output
; IO         PORTB, 3   Output

setRTC:
    Bank1
    movlw b'000000000'    ; All lines are output
    movlw TRISB
    Bank0
    ; Writing to the 6355 requires that the CLK bit be held
    ; low while the IO and CE lines are high
    bcf PORTB, CLK        ; CLK low
    call delay_5
bsf PORTB, IO ; IO high
 call delay_5
 bsf PORTB, CE ; CE high

; Data is stored in RTC as follows:
; year 8 bits (0 to 99)
; month 8 bits (1 to 12)
; day 8 bits (1 to 31)
; dayOfWeek 4 bits (1 to 7)
; hour 8 bits (0 to 23)
; minutes 8 bits (0 to 59)

; Total 44 bits
; Seconds cannot be written to RTC. RTC seconds register
; is automatically initialized to zero
 movf year, w ; Get item from storage
 call bin2bcd ; Convert to BCD
 movwf temp1
 call writeRTC

 movf month, w
 call bin2bcd
 movwf temp1
 call writeRTC

 movf day, w
 call bin2bcd
 movwf temp1
 call writeRTC

 movf dayOfWeek, w ; dayOfWeek of week is 4-bits
 call bin2bcd
 movwf temp1
 call write4RTC

 movf hour, w
 call bin2bcd
 movwf temp1
 call writeRTC

 movf minutes, w
 call bin2bcd
 movwf temp1
 call writeRTC

; Done
 bcf PORTB, CLK ; Hold CLK line low
 call delay_5
 bcf PORTB, CE ; and the CE line
 ; to the RTC
call delay_5
bcf PORTB,IO ; RTC in output mode
return

;============================================
; write 4/8 bits to RTC
;============================================
; Procedure to write 4 or 8 bits to the RTC registers
; ON ENTRY:
; temp1 register holds value to be written
; ON EXIT:
; nothing
writeRTC:
movlw .4 ; Init for 4 bits
goto allBits
writeRTC:
movlw .8 ; Init for 8 bits
allBits:
movf counter ; Store in bit counter
writeBits:
bcf PORTB,CLK ; Clear the CLK line
call delay_5 ; Wait
bsf PORTB,DAT ; Set the data line to RTC
btfss temp1,0 ; Send LSB
bcf PORTB,DAT ; Clear data line
call delay_5 ; Wait for operation to complete
bsf PORTB,CLK ; Bring CLK line high to validate
rrf temp1,f ; Rotate bits in storage
decfsz counter,1 ; Decrement bit counter
goto writeBits ; Continue if not last bit
return

The following procedures are used by the RTC2LCD program to read the data in the RTC registers:

;============================================
; read RTC data
;============================================
; Procedure to read the current time from the RTC and store data (in packed BCD format) in local time registers.
; According to wiring diagram
; NJU6355 Interface for read operations:
; DAT PORTB,0 Input
; CLK PORTB,1 Output
; CE PORTB,2 Output
; IO PORTB,3 Output
Get_Time
; Clear Port-B
movlw b'00000000'
movwf PORTB
; Make data line input
Bank1
movlw b'00000001'
movwf TRISB
Bank0
; Reading RTC data requires that the IO line be low and the
; CE line be high. CLK line is held low
bcf PORTB,CLK ; CLK low
call delay_125
bcf PORTB,IO ; IO line low
call delay_125
bsf PORTB,CE ; and CE line high
; Data is read from RTC as follows:
; year 8 bits (0 to 99)
; month 8 bits (1 to 12)
; day 8 bits (1 to 31)
; dayOfWeek 4 bits (1 to 7)
; hour 8 bits (0 to 23)
; minutes 8 bits (0 to 59)
; seconds 8 bits (0 to 59)
; ======
; Total 52 bits
;
call readRTC
movwf year
call delay_125

call readRTC
movwf month
call delay_125

call readRTC
movwf day
call delay_125
; dayOfWeek of week is a 4-bit value
call read4RTC
movwf dayOfWeek
call delay_125

call readRTC
movwf hour
call delay_125

call readRTC
movwf minutes
call delay_125

call readRTC
movwf seconds
bcf PORTB,CE ; CE line low to end output
return

============================
; Procedure to read 4/8 bits stored in 6355 registers
; Value returned in w register
readRTC:
    movlw .4 ; 4 bit read
    goto anyBits

anyBits:
    movlw .8 ; 8 bits read

movwf counter
; Read 6355 read operation requires the IO line be set low
; and the CE line high. Data is read in the following order:
; year, month, day, day-of-week, hour, minutes, seconds
readBits:
    bsf PORTB,CLK; Set CLK high to validate data
    bsf STATUS,C ; Set the carry flag (bit = 1)
    btfss PORTB,DAT ; Is data line high?
    ; Leave carry set (1 bit) if high
    bcf STATUS,C ; Clear the carry bit (make bit 0)
    ; At this point the carry bit matches the data line
    bcf PORTB,CLK ; Set CLK low to end read
    ; The carry bit is now rotated into the temp1 register
    rrf temp1,1
    decfsz counter,1 ; Decrement the bit counter
    goto readBits; Continue if not last bit
    ; At this point all bits have been read (8 or 4)
    movf temp1,0 ; Result to w
    return

BCD Conversion Procedures

In addition to the RTC procedures to initialize the clock registers and to read clock data, the application requires auxiliary procedures to manipulate and display data in BCD format. BCD encodings, covered in Section 3.4, are a way of representing decimal digits in binary form. Two common BCD formats are used: packed and unpacked. In
the unpacked format each byte encodes a single BCD value. In packed form two BCD digits are encoded per byte. The 6355 uses the packed BCD format.

Since program data is usually in binary form, it is useful to have a routine to convert binary data into BCD form. A simple algorithm for converting binary to BCD is as follows:

1. The value 10 is subtracted from the source operand until the remainder is less than 0 (carry cleared). The number of subtractions is the high-order BCD digit.
2. The value 10 is then added back to the subtrahend to compensate for the last subtraction.
3. The final remainder is the low-order BCD digit.

The binary to BCD conversion procedure is coded as follows:

```assembly
;============================
; binary to BCD conversion
;============================
; Convert a binary number into two packed BCD digits
; ON ENTRY:
; w register has binary value in range 0 to 99
; ON EXIT:
; output variables bcdLow and bcdHigh contain two
; unpacked BCD digits
; w contains two packed BCD digits
; Routine logic:
; The value 10 is subtracted from the source operand
; until the remainder is < 0 (carry cleared). The number
; of subtractions is the high-order BCD digit. 10 is
; then added back to the subtrahend to compensate
; for the last subtraction. The final remainder is the
; low-order BCD digit
; Variables:
; inNum storage for source operand
; bcdHigh storage for high-order nibble
; bcdLow storage for low-order nibble
; thisDig Digit counter
bin2bcd:
    movwf inNum ; Save copy of source value
    clrf bcdHigh ; Clear storage
    clrf bcdLow
    clrf thisDig
min10:
    movlw .10
    subwf inNum,f ; Subtract 10
    btfsc STATUS,C ; Did subtract overflow?
    goto sum10 ; No. Count subtraction
    goto fin10
sum10:
```
incf thisDig,f ; Increment digit counter
goto min10
; Store 10th digit
fin10:
    movlw .10
    addwf inNum,f ; Adjust
    movf thisDig,w ; Get digit counter contents
    movwf bcdHigh ; Store it
; Calculate and store low-order BCD digit
    movf inNum,w ; Store units value
    movwf bcdLow ; Store digit
; Combine both digits
    swapf bcdHigh,w ; High nibble to HOBs
    iorwf bcdLow,w ; OR in low nibble
    return

Since the program requires displaying values encoded in BCD format, a routine is necessary to convert two packed BCD digits into two ASCII decimal digits. The conversion logic is quite simple since the BCD digit is converted to ASCII by adding 0x30 to its value. All that is necessary is to shift bits in the packed BCD operand so as to isolate each digit and then add 0x30 to each one. The routine’s code is as follows:

;==============================
; BCD to ASCII decimal
; conversion
;==============================
; ON ENTRY:
; w register has two packed BCD digits
; ON EXIT:
; output variables asc10, and asc1 have two ASCII decimal digits
; Routine logic:
; The low order nibble is isolated and the value 30H added to convert to ASCII. The result is stored in the variable asc1. Then the same is done to the high-order nibble and the result is stored in the variable asc10

Bcd2asc:
    movwf store1 ; Save input
    andlw b’00001111’ ; Clear high nibble
    addlw 0x30 ; Convert to ASCII
    movwf asc1 ; Store result
    swapf store1,w ; Recover input and swap digits
    andlw b’00001111’ ; Clear high nibble
    addlw 0x30 ; Convert to ASCII
    movwf asc10 ; Store result
    return
16.4 Sample Programs

The following sections contain the sample programs discussed in this chapter.

16.4.1 ADF84 Program

; File name: ADCF84.asm
; Last Update: June 8, 2006
; Author: Julio Sanchez
; Processor: 16F84A

; Description:
; Program to demonstrate use of the ADC0831 Analog to
; Digital converter with the 16F84 PIC. Program reads the
; value of a potentiometer connected to Port-A, line 0
; and displays resistance in the range 0 to 255 on the
; attached LCD.
; Circuit:
; ADC0831 16F84 CIRCUIT
; PIN  LINE
; 6  DO  ----------- RB0
; 7  CLK ----------- RB1
; 1  CS ----------- RB2
; 2  Vin+  ----------------------------- POT2
; 3  Vin-  ------------------------------- GND
; 5  Vref  ------------------------------- +5v
; 8  Vcc  ------------------------------- +5v

; For LCD display parameters see the LCDTest2 program.
; WARNING:
; Code assumes 4MHz clock. Delay routines must be
; edited for faster clock
;
;============================================
; switches
;============================================
; Switches used in __config directive:
; _CP_ON     Code protection ON/OFF
; * _CP_OFF
; * _PWRT_ON  Power-up timer ON/OFF
; _PWRT_OFF
; _WDT_ON    Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC    Low power crystal oscillator
; * _XT_OSC   External parallel resonator/crystal oscillator
; _HS_OSC    High speed crystal resonator (8 to 10 MHz)
; Resonator: Murate Erie CSA8.00M G=8M Hz
; _RC_OSC    Resistor/capacitor oscillator
;  |          (simplest, 20% error)
;  |
;  |_____ * indicates setup values presently selected

;=========================  
; setup and configuration  
;=========================  
processor 16f84A
include <p16f84A.inc>
__config __XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

errorlevel -302
; Suppress bank-related warning
;=========================================================================
;          MACROS
;=========================================================================
; Macros to select the register banks in 16F84
Bank0 MACRO ; Select RAM bank 0
  bcf STATUS,RP0
ENDM
Bank1 MACRO ; Select RAM bank 1
  bsf STATUS,RP0
ENDM
;=========================================================================
; constant definitions
; for PIC-to-LCD pin wiring and LCD line addresses
;=========================================================================
#define E_line 1 ;|
#define RS_line 2 ;| — from circuit wiring diagram
#define RW_line 3 ;|
; LCD line addresses (from LCD data sheet)
#define LCD_1 0x80 ; First LCD line constant
#define LCD_2 0xc0 ; Second LCD line constant
; Note: The constants that define the LCD display line
; addresses have the high-order bit set in
; order to facilitate the controller command

; Defines from ADC0831 wiring diagram
; all lines in Port-A
#define DO 0 ;|
#define CLK 1 ;| — from circuit wiring diagram
#define CS 2 ;|

;=========================================================================
; variables in PIC RAM
;=========================================================================
; Reserve 16 bytes for string buffer
; Reserve three bytes for ASCII digits
  cblock 0x1d
  asci100
  asci10
  asci1
  endc

; Continue with local variables
  cblock 0x20 ; Start of block
  count1 ; Counter # 1
  count2 ; Counter # 2
  count3 ; Counter # 3
  pic_ad ; Storage for start of text area
  J ; counter J
  K ; counter K
  index ; Index into text table (also used
         ; for auxiliary storage)
  store1 ; Local temporary storage
  store2 ; Storage # 2
  rcvdata ; Received data
  bitCount ; Storage for ASCII decimal conversion and digits
  inNum ; Source operand
  thisDig ; Digit counter
  endc

;=====================================================================
; program
;=====================================================================
org 0 ; start at address
 swollen
Bank1
movlw b'00000000' ; All lines to output
movwf TRISA ; in Port-A
movlw b'00000001' ; B line 0 to input
movwf TRISB
Bank0
movlw b'00000000' ; All outputs ports low
movwf PORTA
movwf PORTB
; Wait and initialize HD44780
call delay_5 ; Allow LCD time to initialize
; itself
call delay_5

; Then do forced initialization

call delay_5

call initLCD

; Wait again

; Store base address of text buffer in PIC RAM
movlw 0x0c
movwf pic_ad

to local variable

;=======
; first LCD line

; Store 16 blanks in PIC RAM, starting at address stored in variable pic_ad

call blank16

; Call procedure to store ASCII characters for message in text buffer
movlw d'0'
call storeMS1

; Initialize ADC0831

nextAna:
call ana2dig

call delay_125

; Display result
movf rcvdata, w
call bin2asc

; At this point three ASCII digits are stored in local variables. Move digits to display area
movf asc1, w
movwf .26
movf asc10, w
movwf .25
movf asc100, w
movwf .24

; Display line
; Set DDRAM address to start of first line

call line1

call display16
call long_delay
goto nextAna

; Initializing for Densitron LCD module as follows:

; 4-bit interface

; 2 display lines of 16 characters each
; cursor on
bcf PORTA, E_line ; E line low
bcf PORTA, RS_line ; RS line low
bcf PORTA, RW_line ; Write mode
call delay_125 ; delay 125 microseconds

movlw 0x28 ; 0 0 1 0 0 1 0 0 (FUNCTION SET)
call send8 ; 4-bit send routine

movlw 0x28
call send8

movlw 0x0e ; 0 0 0 0 1 1 1 0 (DISPLAY ON/OFF)
call send8

movlw 0x06 ; 0 0 0 0 0 1 1 0 (ENTRY MODE SET)
call send8

movlw 0x14 ; 0 0 0 1 0 1 0 0 (CURSOR/DISPLAY SHIFT)
call send8

movlw 0x01 ; 0 0 0 0 0 0 0 1 (CLEAR DISPLAY)
call send8

; Per documentation
call delay_5 ; Test for busy
return

; Procedure to delay
; 42 microseconds
;================================
delay_125
    movlw D'42'
    movwf count1
repeat
    decfsz count1,f
    goto repeat
    return
;================================
; Procedure to delay
; 5 milliseconds
;================================
delay_5:
    movlw D'41'
    movwf count2
delay:
    call delay_125
    decfsz count2,f
    goto delay
    return
;================================
; pulse E line
;================================
pulseE
    bsf PORTA,E_line
    nop
    bcf PORTA,E_line
    return
;================================
; long delay sub-routine
; (for debugging)
;================================
long_delay
    movlw D'200'
    movwf J
jloop:
    movwf K
kloop:
    decfsz K,f
    goto kloop
    decfsz J,f
    goto jloop
    return
;================================
; LCD display procedure
;=============================================  
; Sends 16 characters from PIC buffer with address stored  
; in variable pic_ad to LCD line previously selected  
; display16  
call delay_5                   ; Make sure not busy  
; Set up for data  
bcf PORTA, E_line            ; E line low  
bsf PORTA, RS_line           ; RS line high for data  
; Set up counter for 16 characters  
movlw D'16'                ; Counter = 16  
movwf count3  
getchar:  
movf INDF, w                    ; get character from display RAM  
; location pointed to by file select  
; register  
call send8                      ; 4-bit interface routine  
; Test for 16 characters displayed  
decfsz count3, f               ; Decrement counter  
goto nextchar; Skipped if done  
return  
nextchar:  
ingf FSR, f                        ; Bump pointer  
goto getchar  

;=============================================  
; send 2 nibbles in  
; 4-bit mode  
;=============================================  
; Procedure to send two 4-bit values to Port-B lines  
; 7, 6, 5, and 4. High-order nibble is sent first  
; ON ENTRY:  
; w register holds 8-bit value to send  
send8:  
movwf store1                    ; Save original value  
call merge4                    ; Merge with Port-B  
; Now w has merged byte  
movwf PORTB                    ; w to Port-B  
call pulseE                    ; Send data to LCD  
; High nibble is sent  
movf store1, w; Recover byte into w  
swapf store1, w; Swap nibbles in w  
call merge4  
movwf PORTB                    ; Send data to LCD  
call delay_125
return

; merge bits

; Routine to merge the 4 high-order bits of the value to send with the contents of Port-B so as to preserve the 4 low-bits in Port-B

; Logic:
; AND value with 1111 0000 mask
; AND Port-B with 0000 1111 mask
; Now low nibble in value and high nibble in Port-B are all 0 bits:
; value = vvvv 0000
; Port-B = 0000 bbbb
; OR value and Port-B resulting in:
; vvvv bbbb

; ON ENTRY:
; w contain value bits
; ON EXIT:
; w contains merged bits

merge4:

andlw b'11110000' ; ANDing with 0 clears the bit. ANDing with 1 preserves the original value
movwf store2 ; Save result in variable
movf PORTB,w ; Port-B to w register
andlw b'00001111' ; Clear high nibble in Port-B and preserve low nibble
iorwf store2,w ; OR two operands in w
return

; blank buffer

; Procedure to store 16 blank characters in PIC RAM
; buffer starting at address stored in the variable pic_ad

blank16:

movlw D'16' ; Setup counter
movwf count1
movf pic_ad,w ; First PIC RAM address
movwf FSR ; Indexed addressing
movlw 0x20 ; ASCII space character
storeit:

movwf INDF ; Store blank character in PIC RAM

; buffer using FSR register

decfsz count1,f ; Done?
goto incfsr ; no
return ; yes

incfsr:
    incf FSR,f ; Bump FSR to next buffer

space
    goto storeit

;=====================================
; Set address register
; to LCD line 1
;=====================================
; ON ENTRY:
; Address of LCD line 1 in constant LCD_1
line1:
    bcf PORTA,E_line ; E line low
    bcf PORTA,RS_line ; RS line low, set up for
                        ; control
    call delay_5 ; busy?
; Set to second display line
    movlw LCD_1 ; Address and command bit
    call send8 ; 4-bit routine
; Set RS line for data
    bsf PORTA,RS_line ; Setup for data
    call delay_5 ; Busy?
return

;=====================================
; first text string procedure
;=====================================
storeMS1:
; Procedure to store in PIC RAM buffer the message
; contained in the code area labeled msg1
; ON ENTRY:
; variable pic_ad holds address of text buffer
; in PIC RAM
; w register hold offset into storage area
; msg1 is routine that returns the string characters
; and a zero terminator
; index is local variable that hold offset into
; text table. This variable is also used for
; temporary storage of offset into buffer
; ON EXIT:
; Text message stored in buffer
;
; Store offset into text buffer (passed in the w register)
; in temporary variable
    movwf index ; Store w in index
; Store base address of text buffer in FSR
movf pic_ad,w ; first display RAM address to W
addwf index,w ; Add offset to address
movwf FSR ; W to FSR
; Initialize index for text string access
movlw 0 ; Start at 0
movwf index ; Store index in variable
; w still = 0
get_msg_char:
call msg1 ; Get character from table
; Test for zero terminator
andlw 0x0ff
btfsc STATUS,Z ; Test zero flag
goto endstr1 ; End of string
; ASSERT: valid string character in w
; store character in text buffer (by FSR)
movf INDF ; store in buffer by FSR
incf FSR,f ; increment buffer pointer
; Restore table character counter from variable
movf index,w ; Get value into w
addlw 1 ; Bump to next character
movwf index ; Store table index in variable
goto get_msg_char ; Continue
endstr1:
return
; Routine for returning message stored in program area
; Message has 10 characters
msg1:
addwf PCL,f ; Access table
retlw 'P'
retlw 'o'
retlw 't'
retlw '
retlw 'R'
retlw 'e'
retlw 's'
retlw 'i'
retlw 's'
retlw 't'
retlw ':'
retlw 0
;=====================================
; binary to ASCII decimal
; conversion
;=====================================
; ON ENTRY:
; w register has binary value in range 0 to 255
ON EXIT:

output variables asc100, asc10, and asc1 have
three ASCII decimal digits

Routine logic:
The value 100 is subtracted from the source operand
until the remainder is < 0 (carry cleared). The number
of subtractions is the decimal hundreds result. 100 is
then added back to the subtrahend to compensate
for the last subtraction. Now 10 is subtracted in the
same manner to determine the decimal tenths result.
The final remainder is the decimal units result.

Variables:

inNum storage for source operand
asc100 storage for hundreds position result
asc10 storage for tenth position result
asc1 storage for unit position result
thisDig Digit counter

bin2asc:

movwf inNum ; Save copy of source value
clrf asc100 ; Clear hundreds storage
clrf asc10 ; Tens
clrf asc1 ; Units
clrf thisDig

sub100:

movlw .100
subwf inNum,f ; Subtract 100
btfsc STATUS,C ; Did subtract overflow?
goto bump100 ; No. Count subtraction

end100:

movf thisDig,w ; Adjusted digit counter
addlw 0x30 ; Convert to ASCII
movwf asc100 ; Store it

Calculate tenth position value

clrf thisDig

; Adjust minuend
movlw .100 ; Minuend
addwf inNum,f ; Add value to minuend to
; compensate for last

operation

sub10:

movlw .10
subwf inNum,f ; Subtract 10
btfsc STATUS,C ; Did subtract overflow?
goto bump10 ; No. Count subtraction
goto end10

bump10:
    incf thisDig,f ;increment digit counter
goto sub10

; Store 10th digit
end10:
    movlw .10
    addwf inNum,f ; Adjust for last subtract
    movf thisDig,w ; get digit counter contents
    addlw 0x30 ; Convert to ASCII
    movwf asc10 ; Store it

; Calculate and store units digit
    movf inNum,w ; Store units value
    addlw 0x30 ; Convert to ASCII
    movwf asc1 ; Store digit
    return

;===================================================================
; ADC0831 procedures
;===================================================================
;===================================================================
; procedure to read and
; convert analog line
;===================================================================
; ON ENTRY:
; Code assumes that the ADC0831 DO line is initialized for
; input, while CLK and CS lines are output
; From ADC0831 wiring diagram. All lines in Port-B
; DO = RB0 ==> INPUT
; CLK = RB1 <= OUTPUT
; CS = RB2 <= OUTPUT
; ON EXIT:
; Returns 8-bit digital value in the register rcvdata
;
ana2dig:
; Clear data register and init counter for 8 bits
    clrf rcvdata ; Clear register
    movlw 0x08 ; Initialize counter
    movwf bitCount

; Prepare to read analog line
    bcf PORTB,CS ; CS pin low to enable ADC
    nop ; Delay for 4Mhz clock
    bsf PORTB,CLK ; Set CLK high
    nop
    bcf PORTB,CLK ; Reset CLK to start
conversion
    nop
nextB:
; Pulse CLK line to read bit from ADC
  bsf PORTB,CLK      ; CLK high
  nop
  bcf PORTB,CLK      ; CLK low
  nop
; Read analog line and store data, bit by bit
  movf PORTB, w      ; Read all Port-B bits
  movwf store1       ; Store value for later
  rrf store1,f       ; Rotate bit into carry flag
  rlf rcvdata,f      ; Rotate carry flag into
                      ; register
  decfsz bitCount,f  ; Bump counter, skip next
                      ; if counter zero
  goto nextB
; Value read is stored in rcvdata register
  bsf PORTB,CLK      ; Final clock pulse
  nop
  bcf PORTB,CLK
  nop
  bsf PORTB,CS       ; Turn off ADC
  call long_delay;  ; Time to settle
  return
end

16.4.2 A2DinLCD Program

; File name: A2DinLCD.asm
; Last revision: June 2, 2006
; Author: Julio Sanchez
; Processor: 16F877
;
; Description:
; Program to demonstrate use of the Analog to Digital
; Converter (A/D) module on the 16F877. Program reads the
; value of a potentiometer connected to Port-A, line 0
; and displays resistance in the range 0 to 255 on the
; attached LCD.
;
; WARNING:
; Code assumes 10Mhz clock. Delay routines must be
; edited for faster clock. Clock speed is also used to
; set up the A/D converter clock.
;
;===========================
; 16F877 switches
;=====================================================================
; Switches used in __config directive:
;   _CP_ON  Code protection ON/OFF
;   * _CP_OFF
;   * _PWRT_ON  Power-up timer ON/OFF
;   _PWRT_OFF
;   _BODEN_ON  Brown-out reset enable ON/OFF
;   * _BODEN_OFF
;   * _PWRT_On  Power-up timer enable ON/OFF
;   _PWRT_OFF
;   _WDT_ON  Watchdog timer ON/OFF
;   * _WDT_OFF
;   _LPV_ON  Low voltage IC programming enable ON/OFF
;   * _LPV_OFF
;   _CPD_ON  Data EE memory code protection ON/OFF
;   * _CPD_OFF
; OSCILLATOR CONFIGURATIONS:
;   _LP_OSC  Low power crystal oscillator
;   _XT_OSC  External parallel resonator/crystal oscillator
;   * _HS_OSC  High speed crystal resonator
;   _RC_OSC  Resistor/capacitor oscillator
;   (simplest, 20% error)
;   ------- * indicates setup values presently selected

processor 16f877 ; Define processor
#include <p16f877.inc>
__CONFIG _CP_OFF & _WDT_OFF & _BODEN_OFF & _PWRT_ON &
   _HS_OSC & _WDT_OFF & _LPV_OFF & _CPD_OFF
; __CONFIG directive is used to embed configuration data
; within the source file. The labels following the directive
; are located in the corresponding .inc file.

errorlevel -302
; Suppress bank-related warning
;=====================================================================
; MACROS
;=====================================================================
; Macros to select the register banks
Bank0 MACRO ; Select RAM bank 0
  bcf STATUS,RP0
  bcf STATUS,RP1
ENDM

Bank1 MACRO ; Select RAM bank 1
  bsf STATUS,RP0
  bcf STATUS,RP1

Analog to Digital and Realtime Clocks
ENDM

Bank2 MACRO ; Select RAM bank 2
  bcf STATUS,RP0
  bsf STATUS,RP1
ENDM

Bank3 MACRO ; Select RAM bank 3
  bsf STATUS,RP0
  bsf STATUS,RP1
ENDM

;=====================================================
; constant definitions
; for PIC-to-LCD pin wiring and LCD line addresses
;=====================================================
#define E_line 1 ;|
#define RS_line 0 ;| — from wiring diagram
#define RW_line 2 ;|
; LCD line addresses (from LCD data sheet)
#define LCD_1 0x80 ; First LCD line constant
#define LCD_2 0xc0 ; Second LCD line constant
#define LCDlimit .20; Number of characters per line
#define spbrgVal .64; For 2400 baud on 10Mhz clock
; Note: The constants that define the LCD display
; line addresses have the high-order bit set
; so as to meet the requirements of controller
; commands.
;=====================================================
; variables in PIC RAM
;=====================================================
; Reserve 20 bytes for string buffer
  cblock 0x20
    strData
  endc

; Reserve three bytes for ASCII digits
  cblock 0x34
    asc100
    asc10
    asc1
  endc

; Data
  cblock 0x37 ; Start of block
    count1 ; Counter # 1
    count2 ; Counter # 2
    count3 ; Counter # 3
    pic_ad
J ; counter J
K ; counter K
index
store1 ; Local storage
store2
; For LCDscroll procedure
  LCDcount ; Counter for characters per line
  LCDline ; Current display line (0 or 1)
endc

; Common RAM area for most critical variables
cblock  0x70
; Storage for ASCII decimal conversion and digits
  inNum ; Source operand
  thisDig ; Digit counter
endc

============================================================
| PROGRAM |
============================================================
org   0 ; start at address
goto main
; Space for interrupt handlers
org  0x08
main:
; Wiring:
;   LCD data to Port-D, lines 0 to 7
;   E line -> Port-E, 1
;   RW line -> Port-E, 2
;   RS line -> Port-E, 0
; Set PORTE D and E for output
; First, initialize Port-B by clearing latches
  clrf STATUS
  clrf PORTB
; Select bank 1 to tris Port-D for output
  Bank1
; Tris Port-D for output. Port-D lines 4 to 7 are wired
to LCD data lines. Port-D lines 0 to 4 are wired to LEDs.
  movlw B’00000000’
movwf TRISD ; and Port-D
; By default Port-A lines are analog. To configure them
; as digital code must set bits 1 and 2 of the ADCON1
; register (in bank 1)
  movlw 0x06 ; binary 0000 0110 is code to
             ; make all Port-A lines
digital
  movwf ADCON1
; Port-B, lines are not used by this application. Init
; to output
    movlw b'00000000'
    movwf TRISB
; Tris Port-E for output. LCD lines are in Port-E
    movwf TRISE ; Tris Port-E
; Enable Port-B pullups for switches in OPTION register
    ; 7 6 5 4 3 2 1 0 <= OPTION bits
    ; | | | | | | | PS2-PS0 (prescaler bits)
    ; | | | | | | 000 = 1:2 001 = 1:4
    ; | | | | | 010 = 1:8 011 = 1:16
    ; | | | | 100 = 1:32 101 = 1:64
    ; | | | 110 = 1:128 *111 = 1:256
    ; | | | |______________ PSA (prescaler assign)
    ; | | | *1 = to WDT
    ; | | 0 = to Timer0
    ; | | |______________ TOSE (Timer0 edge select)
    ; | | *0 = increment on low-to-high
    ; | 1 = increment in high-to-low
    ; | | |______________ TOCS (TMR0 clock source)
    ; | | *0 = internal clock
    ; | 1 = RA4/TOCKI bit source
    ; | |______________ INTEDG (Edge select)
    ; | *0 = falling edge
    ; |______________ RBPU (Pullup enable)
    ; *0 = enabled
    ; 1 = disabled
    movlw b'00001000'
    movwf OPTION_REG
; Back to bank 0
    Bank0
; Clear all output lines
    movlw b'00000000'
    movwf PORTD
    movwf PORTE
; Wait and initialize HD44780
    call delay_5 ; Allow LCD time to initialize itself
    call initLCD ; Then do forced initialization
    call delay_5 ; (Wait probably not necessary)
; Clear character counter and line counter variables
    clrf LCDcount
    clrf LCDline
; Initialize A/D conversion lines
    call InitA2D ; Local procedure
; Store base address of text buffer in PIC RAM
movlw 0x20 ; Start address for buffer
movwf pic_ad ; to local variable
; Store 20 blanks in PIC RAM, starting at address stored
; in variable pic_ad
call blank20
; Call procedure to store ASCII characters for message
; in text buffer
movlw d’0’ ; Offset into buffer
call storeMS1
;==================================
; read POT digital value
;==================================
readPOT:
call ReadA2D ; Local procedure
; w has digital value read from analog line RA0
; Display result
call bin2asc ; Conversion routine
; At this point three ASCII digits are stored in local
; variables. Move digits to display area
movf asc1,w ; Unit digit
movwf 0x2e ; Store in buffer
movf asc10,w ; same with other digits
movwf 0x2d
movf asc100,w
movwf 0x2c
; Display line
; Set DDRAM address to start of first line
showLine:
call line1
; Call procedure to display 16 characters in LCD
call display20
goto readPOT
;==================================
; LOCAL PROCEDURES
;==================================
; init LCD for 4-bit mode
; initLCD:
; Initialization for Densitron LCD module as follows:
; 4-bit interface
; 2 display lines of 20 characters each
; cursor on
; left-to-right increment
; cursor shift right
; no display shift
;=======================
; set command mode
;=======================
bcf    PORTE,E_line ; E line low
bcf    PORTE,RS_line ; RS line low
bcf    PORTE,RW_line ; Write mode
call   delay_125 ; delay 125 microseconds
;***********************
; FUNCTION SET
;***********************
movlw 0x28 ; 0 0 1 0 1 0 0 0 (FUNCTION SET)
call   send8 ; 4-bit send routine

; Set 4-bit mode command must be repeated
movlw 0x28
call   send8
;***********************
; DISPLAY AND CURSOR ON
;***********************
movlw 0x0e ; 0 0 0 0 1 1 1 0 (DISPLAY ON/OFF)
call   send8
;***********************
; set entry mode
;***********************
movlw 0x06 ; 0 0 0 0 0 1 1 0 (ENTRY MODE SET)
call   send8
;***********************
; cursor/display shift
;***********************
movlw 0x14 ; 0 0 0 1 0 1 0 0 (CURSOR/DISPLAY SHIFT)
call   send8
;***********************
; clear display
;***********************
movlw 0x01 ; 0 0 0 0 0 0 0 1 (CLEAR DISPLAY)
call   send8
; Per documentation
call   delay_5 ; Test for busy
return

;***********************
; Procedure to delay
; 125ms. at 10Mhz
;***********************
delay_125:
movlw .110 ; Repeat 110 machine cycles
movwf count1 ; Store value in counter
repeat:
decfsz count1,f ; Decrement counter
goto repeat ; Continue if not 0
return ; End of delay

;=======================
; Procedure to delay
; 5 milliseconds
;=======================
delay_5:
  movlw .110 ; Counter = 110
  movwf count2 ; Store in variable
delay:
  call delay_125 ; Delay
decfsz count2,f ; 40 times = 5 milliseconds
goto delay
return ; End of delay

;========================
; pulse E line
;========================
pulseE:
  bsf PORTE,E_line ; Pulse E line
  nop
  bcf PORTE,E_line
  return

;=============================
; long delay sub-routine
;=============================
long_delay:
  movlw .200 ; w delay count
  movwf J ; J = w
jloop:
  movwf K ; K = w
kloop:
  decfsz K,f ; K = K-1, skip next if zero
goto kloop
decfsz J,f ; J = J-1, skip next if zero
goto jloop
return

;=============================
; display buffer on LCD
;=================================
; Sends 20 characters from PIC buffer with address stored
; in variable pic_ad to LCD line previously selected
display20:
call delay_5 ; Make sure not busy

; Set up for data
  bcf PORTA, E_line ; E line low
  bsf PORTA, RS_line ; RS line high for data

; Set up counter for 20 characters
  movlw D'20'
  movwf count3

; Get display address from local variable pic_ad
  movf pic_ad, w ; First display RAM address to W
  movwf FSR ; W to FSR

getchar
  movf INDF, w ; get character from display RAM
  ; location pointed to by file select
  ; register
  call send8 ; 4-bit interface routine

; Test for 16 characters displayed
  decfsz count3, f ; Decrement counter
  goto nextchar ; Skipped if done
  return

nextchar:
  incf FSR, f ; Bump pointer
  goto getchar

;========================
; send 2 nibbles in
; 4-bit mode
;========================
; Procedure to send two 4-bit values to Port-B lines
; 7, 6, 5, and 4. High-order nibble is sent first
; ON ENTRY:
; w register holds 8-bit value to send
send8:
  movwf store1 ; Save original value
  call merge4 ; Merge with Port-B

; Now w has merged byte
  movwf PORTD ; w to Port-D
  call pulseE ; Send data to LCD

; High nibble is sent
  movf store1, w ; Recover byte into w
  swapf store1, w ; Swap nibbles in w
  call merge4
  movwf PORTD
  call pulseE ; Send data to LCD
  call delay_125
  return

;========================
; merge bits
;========================

; Routine to merge the 4 high-order bits of the value to send with the contents of Port-B so as to preserve the 4 low-bits in Port-B
; Logic:
;   AND value with 1111 0000 mask
;   AND Port-B with 0000 1111 mask
;   Now low nibble in value and high nibble in Port-B are all 0 bits:
;   value = vvvv 0000
;   Port-B = 0000 bbbb
;   OR value and Port-B resulting in:
;      vvvv bbbb
; ON ENTRY:
;   w contain value bits
; ON EXIT:
;   w contains merged bits
merge4:
   andlw b'11110000' ; ANDing with 0 clears the bit. ANDing with 1 preserves the original value
   movwf store2 ; Save result in variable
   movf PORTD,w ; Port-B to w register
   andlw b'00001111' ; Clear high nibble in Port-B and preserve low nibble
   iorwf store2,w ; OR two operands in w
   return
;==========================
; Set address register to LCD line 1
;==========================
; ON ENTRY:
; Address of LCD line 1 in constant LCD_1
line1:
   bcf PORTE,E_line ; E line low
   bcf PORTE,RS_line ; RS line low, set up for control
   call delay_5 ; busy?
   movlw LCD_1 ; Address and command bit
   call send8 ; 4-bit routine
   ; Set RS line for data
   bsf PORTE,RS_line ; Setup for data
   call delay_5 ; Busy?
   return
;=================================================================
; first text string procedure
;=================================================================
storeMS1:
; Procedure to store in PIC RAM buffer the message contained in the code area labeled msg1
; ON ENTRY:
; variable pic_ad holds address of text buffer in PIC RAM
; w register hold offset into storage area
; msg1 is routine that returns the string characters and a zero terminator
; index is local variable that hold offset into text table. This variable is also used for temporary storage of offset into buffer
; ON EXIT:
; Text message stored in buffer
; Store offset into text buffer (passed in the w register) in temporary variable
movwf index ; Store w in index
; Store base address of text buffer in FSR
movf pic_ad,w ; first display RAM address to W
addwf index,w ; Add offset to address
movwf FSR ; W to FSR
; Initialize index for text string access
movlw 0 ; Start at 0
movwf index ; Store index in variable
; w still = 0
get_msg_char:
call msg1 ; Get character from table
; Test for zero terminator
andlw 0x0ff
btfsc STATUS,Z ; Test zero flag
goto endstr1 ; End of string
; ASSERT: valid string character in w
; store character in text buffer (by FSR)
movwf INDF ; store in buffer by FSR
incf FSR,f ; increment buffer pointer
; Restore table character counter from variable
movf index,w ; Get value into w
addlw 1 ; Bump to next character
movwf index ; Store table index in variable
goto get_msg_char ; Continue
endstr1:
return
; Routine for returning message stored in program area
; Message has 10 characters
msg1:
addwf PCL,f ; Access table
retlw 'P'
retlw 'o'
retlw 't'
retlw ','
retlw 'R'
retlw 'e'
retlw 's'
retlw 'i'
retlw 's'
retlw 't'
retlw ':'
retlw 0

;====================================
; blank buffer
;====================================
; Procedure to store 20 blank characters in PIC RAM
; buffer starting at address stored in the variable
; pic_ad
blank20:
    movlw D'20' ; Setup counter
    movwf count1
    movf pic_ad,w ; First PIC RAM address
    movwf FSR ; Indexed addressing
    movlw 0x20 ; ASCII space character
storeit:
    movwf INDF ; Store blank character in PIC RAM buffer using FSR register
    decfsz count1,f ; Done?
    goto incfsr ; no
    return ; yes
incfsr:
    incf FSR,f ; Bump FSR to next buffer space
    goto storeit

;====================================
; binary to ASCII decimal
; conversion
;====================================
; ON ENTRY:
;  w register has binary value in range 0 to 255
; ON EXIT:
;  output variables asc100, asc10, and asc1 have
;  three ASCII decimal digits
; Routine logic:
;  The value 100 is subtracted from the source operand
;  until the remainder is < 0 (carry cleared). The number
;  of subtractions is the decimal hundreds result. 100 is
;  then added back to the subtrahend to compensate
;  for the last subtraction. Now 10 is subtracted in the
;  same manner to determine the decimal tenths result.
The final remainder is the decimal units result.

Variables:

- `inNum` storage for source operand
- `asc100` storage for hundreds position result
- `asc10` storage for tenth position result
- `asc1` storage for unit position result
- `thisDig` Digit counter

```assembly
bin2asc:
  movwf inNum ; Save copy of source value
  clrf asc100 ; Clear hundreds storage
  clrf asc10 ; Tens
  clrf asc1 ; Units
  clrf thisDig

sub100:
  movlw .100 ; Minuend
  subwf inNum,f ; Subtract 10
  btsc STATUS,C ; Did subtract overflow?
  goto bump100 ; No. Count subtraction
  goto end100

bump100:
  incf thisDig,f ; Increment digit counter
  goto sub100

; Store 100th digit
end100:
  movf thisDig,w ; Adjusted digit counter
  addlw 0x30 ; Convert to ASCII
  movwf asc100 ; Store it

; Calculate tenth position value
  clrf thisDig

; Adjust minuend
sub10:
  movlw .10 ; Minuend
  addwf inNum,f ; Add value to minuend to
  ; Compensate for last operation

bump10:
  incf thisDig,f ; Increment digit counter
  goto sub10

; Store 10th digit
end10:
  movlw .10 ; Adjust for last subtract
  addwf inNum,f
  movf thisDig,w ; get digit counter contents
  addlw 0x30 ; Convert to ASCII
```
movwf  ascl0        ; Store it
movf   inNum,w      ; Store units value
addlw  0x30         ; Convert to ASCII
movwf  ascl1        ; Store digit
return

;==============================================================================
;  Analog to Digital Procedures
;==============================================================================

; init A/D module
;==============================================================================
; 1. Procedure to initialize the A/D module, as follows:
;    Configure the PIC I/O lines. Init analog lines as input
; 2. Select ports to be used by setting the PCFGX bits in the
;    ADCON1 register. Selects right- or left-justification.
; 3. Select the analog channels, select the A/D conversion
;    clock, and enable the A/D module.
; 4. Wait the acquisition time.
; 5. Initiate the conversion by setting the GO/DONE bit in the
;    ADCON0 register.
; 6. Wait for the conversion to complete.
; 7. Read and store the digital result.
InitA2D:
   Bank1         ; Select bank for TRISA register
   movlw b'00000001'
   movwf TRISA    ; Set Port-A, line 0, as input
   ; Select the format and A/D port configuration bits in
   ; the ADCON1 register
   ; Format is left-justified so that ADRESH bits are the
   ; most significant
   ; 0 x x x 1 1 1 0 <= value installed in ADCON1
   ; 7 6 5 4 3 2 1 0 <= ADCON1 bits
   ; |      |__|__|__|__|____ RA0 is analog.
   ; |      Vref+ = Vdd
   ; |_________________________ 0 = left-justified
   ; ADCON1 is in bank 1
   movlw b'000001110'
   movwf ADCON1     ; RA0 is analog. All others ;
                      ; digital
                      ; Vref+ = Vdd
   ; Select D/A options in ADCON0 register
   ; For a 10Mhz clock the Fosc32 option produces a conversion
   ; speed of 1/(10/32) = 3.2 microseconds, which is within the
   ; recommended range of 1.6 to 10 microseconds.
   ; 1 0 0 0 0 0 0 1 <= value installed in ADCON0
; 7 6 5 4 3 2 1 0 <= ADCON0 bits
; | | | | | | |____ A/D function select
; | | | | | | 1 = A/D ON
; | | | | |__________ A/D status bit
; | | |____|__________ Analog Channel Select
; | | 000 = Channel 0 (RA0)
; | |______________________ A/D Clock Select
; 10 = Fosc/32

; ADCON0 is in bank 0
; Bank0
movlw b'10000001'
movwf ADCON0 ; Channel 0, Fosc/32, A/D
; enabled

; Delay for selection to complete. (Existing routine provides
; more than 20 microseconds required)
call delayAD ; Local procedure
return

;================================
; read A/D line
;================================
; Procedure to read the value in the A/D line and convert
; to digital
ReadA2D:
; Initiate conversion
Bank0 ; Bank for ADCON0 register
bsf ADCON0,GO ; Set the GO/DONE bit
; GO/DONE bit is cleared automatically when conversion ends
convWait:
btfsc ADCON0,GO ; Test bit
goto convWait ; Wait if not clear
; At this point conversion has concluded
; ADRESH register (bank 0) holds 8 MSBs of result
; ADRESL register (bank 1) holds 4 LSBs.
; In this application value is left-justified. Only the
; MSBs are read
movf ADRESH,W ; Digital value to w register
return

;================================
; delay procedure
;================================
; For a 10MHz clock the Fosc32 option produces a conversion
; speed of 1/(10/32) = 3.2 microseconds. At 3.2 ms per bit
; 13 bits require approximately 41 ms. The instruction time
; at 10MHz is 10 ms. 4/10 = 0.4 ms per instruction. To delay
; 41 ms a 10MHz PIC must execute 11 instructions. Add one
; more for safety.
delayAD:
movlw .12 ; Repeat 12 machine cycles
movwf count1 ; Store value in counter
repeat11:
decfsz count1,f ; Decrement counter
go to repeat11; Continue if not 0
return

;=============================================================================
end ; END OF PROGRAM
;=============================================================================

16.4.3 RTC2LCD Program

; File name: RTC2LCD.asm
; Last Update: June 6, 2006
; Author: Julio Sanchez
; Processor: 16F84A
;
; Description:
; Program to demonstrate use of the NJU6355 Real Time Clock IC. Program uses LCD to display results of hours, minutes, and seconds, as follows:
; Top LCD line: H:xx M:yy S:zz
;
; Initialization values are in #define statements that start with i, such as iYear, iMonth, etc.
;
; For LCD display parameters see the LCDTest2 program.
;
; WARNING:
; Code assumes 4Mhz clock. Delay routines must be edited for faster clock
;
;=============================================================================
; switches
;=============================================================================
; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; _CP_OFF
; * _PWRTE_ON Power-up timer ON/OFF
; _PWRTE_OFF
; _WDT_ON Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC Low power crystal oscillator
; * _XT_OSC External parallel resonator/crystal oscillator
; _HS_OSC High speed crystal resonator (8 to 10 MHz)
; Resonator: Murate Erie CSA8.00M G=8M Hz
; _RC_OSC Resistor/capacitor oscillator
processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF
errorlevel -302
; Suppress bank-related warning
MACROS
Bank0 MACRO ; Select RAM bank 0
  bcf STATUS,RP0
ENDM
Bank1 MACRO ; Select RAM bank 1
  bsf STATUS,RP0
ENDM

MACROS
constant definitions
; for PIC-to-LCD pin wiring and LCD line addresses
#define E_line 1 ;| — from circuit wiring diagram
#define RS_line 2 ;| — from circuit wiring diagram
#define RW_line 3 ;| — from circuit wiring diagram
#define LCD_1 0x80 ; First LCD line constant
#define LCD_2 0xc0 ; Second LCD line constant
; Note: The constants that define the LCD display line
; addresses have the high-order bit set in
; order to facilitate the controller command

Defines from realtime clock wiring diagram
; all lines in Port-B
#define DAT 0 ;| — from circuit wiring diagram
#define CLK 1 ;| — from circuit wiring diagram
#define CE 2 ;|
#define IO 3 ;|
; Defines for RTC initialization (values are arbitrary)
#define iYear .7
#define iMonth .6
```c
#define iDay .5
#define iDoW .4
#define iHour .3
#define iMin .2
#define iSec .1

;=====================================================
; PIC register equates
;=====================================================
; variables in PIC RAM
;=====================================================
; Reserve 16 bytes for string buffer
 cblock 0x0c
 strData
 endc
; Reserve three bytes for ASCII digits
 cblock 0x1d
 asc100
 asc10
 asc1
 endc
; Continue with local variables
 cblock 0x20
 count1 ; Counter # 1
 count2 ; Counter # 2
 count3 ; Counter # 3
 pic_ad ; Storage for start of text area
 J ; counter J
 K ; counter K
 index ; Index into text table (also used
 ; for auxiliary storage)
 store1 ; Local temporary storage
 store2 ; Storage # 2
; Storage for BCD digits
 bcdLow ; low-order nibble of packed BCD
 bcdHigh ; High-order nibble
; Variables for Real-Time Clock
 year
 month
 day
 dayOfWeek ; Sunday to Saturday (1 to 7)
 hour
 minutes
 seconds
 temp1
 counter
; Storage for BCD conversion routine
 inNum ; Source operand
```
thisDig ; Digit counter
endc

;==============================================================================
; program
;==============================================================================
org 0 ; start at address
goto main

; Space for interrupt handlers
org 0x08

main:
    movlw b'00000000' ; All lines to output
    Bank1
    movwf TRISA ; in Port-A
    movwf TRISB ; and Port-B
    Bank0
    movlw b'00000000' ; All outputs ports low
    movwf PORTA
    movwf PORTB

    ; Wait and initialize HD44780
    call delay_5 ; Allow LCD time to initialize itself
    call delay_5
    call initLCD ; Then do forced initialization
    call delay_5 ; Wait again

    ; Store base address of text buffer in PIC RAM
    movlw 0x0c ; Start address for buffer
    movwf pic_ad ; to local variable

    ;============================================================================
    ; first LCD line
    ;============================================================================
    ; Store 16 blanks in PIC RAM, starting at address stored
    ; in variable pic_ad
    call blank16
    ; Call procedure to store ASCII characters for message
    ; in text buffer
    movlw d'0' ; Offset into buffer
    call storeMS1 ; Store message text in buffer

    ; Initialize real time clock
    call initRTC ; Initialize variables
    call setRTC ; Start clock
    call delay_5 ; Wait for operation to conclude

newTime:
    ; Get variables from RTC
    call Get_Time


call delay_5 ; Wait
movf hour,w ; Get hours
call Bcd2asc ; Conversion routine
;
At this point three ASCII digits are stored in local
; variables. Move digits to display area
movf asc1,w ; Unit digit
movwf .15 ; Store in buffer
movf asc10,w ; Same with other digit
movwf .14
call delay_5
movf minutes,w
movf Bcd2asc ; Conversion routine
;
At this point three ASCII digits are stored in local
; variables. Move two digits to display area
movf asc1,w ; Unit digit
movwf .20 ; Store in buffer
movf asc10,w ; Same with other digit
movwf .19
call delay_5
movf seconds,w
movf Bcd2asc ; Conversion routine
;
Move digits to display area
movf asc1,w ; Unit digit
movwf .25 ; Store in buffer
movf asc10,w ; Same with other digit
movwf .24
call delay_5
;
Set DDRAM address to start of first line
call line1
;
Call procedure to display 16 characters in LCD
;
call display16
goto newTime

Initializing LCD for 4-bit mode

Initialization for Densitron LCD module as follows:
4-bit interface
2 display lines of 16 characters each
cursor on
left-to-right increment
cursor shift right
no display shift

;====================================
; set command mode
;====================================
bcf PORTA,E_line ; E line low
bcf PORTA,RS_line ; RS line low
bcf PORTA,RW_line ; Write mode
call delay_125 ; delay 125 microseconds

;***********************
; FUNCTION SET
;***********************
movlw 0x28 ; 0 0 1 0 1 0 0 0 (FUNCTION SET)
call send8 ; 4-bit send routine

; Set 4-bit mode command must be repeated
movlw 0x28
call send8

;***********************
; DISPLAY AND CURSOR ON
;***********************
movlw 0x0e ; 0 0 0 0 1 1 1 0 (DISPLAY ON/OFF)
call send8

;***********************
; set entry mode
;***********************
movlw 0x06 ; 0 0 0 0 0 1 1 0 (ENTRY MODE SET)
call send8

;***********************
; cursor/display shift
;***********************
movlw 0x14 ; 0 0 0 1 0 1 0 0 (CURSOR/DISPLAY SHIFT)
call send8

;***********************
; clear display
;***********************
movlw 0x01 ; 0 0 0 0 0 0 0 1 (CLEAR DISPLAY)
call send8

; Per documentation
   call delay_5 ; Test for busy
return

;=======================
; Procedure to delay
; 42 microseconds
;=======================
delay_125
movlw D'42'
movwf count1 ; Store value in counter
repeat:
  decfsz count1,f ; Decrement counter
  goto repeat ; Continue if not 0
  return ; End of delay

;=======================
; Procedure to delay
; 5 milliseconds
;=======================
delay_5:
  movlw D'41' ; Counter = 41
  movwf count2 ; Store in variable
delay:
  call delay_125 ; Delay
  decfsz count2,f ; 40 times = 5 milliseconds
  goto delay
  return ; End of delay

;=======================
; pulse E line
;=======================
pulseE:
  bsf PORTA,E_line ; Pulse E line
  nop
  bcf PORTA,E_line
  return

;=============================
; long delay sub-routine
; (for debugging)
;=============================
long_delay:
  movlw D'200' ; w = 200 decimal
  movwf J ; J = w
jloop:
  movwf K ; K = w
kloop:
  decfsz K,f ; K = K-1, skip next if zero
  goto kloop
  decfsz J,f ; J = J-1, skip next if zero
  goto jloop
  return

;=============================
; LCD display procedure
;=============================
; Sends 16 characters from PIC buffer with address stored
; in variable pic_ad to LCD line previously selected
display16
  call delay_5 ; Make sure not busy
; Set up for data
    bcf PORTA,E_line ; E line low
    bsf PORTA,RS_line ; RS line high for data
; Set up counter for 16 characters
    movlw D'16' ; Counter = 16
    movwf count3
; Get display address from local variable pic_ad
    movf pic_ad,w ; First display RAM address to W
    movwf FSR ; W to FSR
getchar:
    movf INDF,w ; get character from display RAM
    ; location pointed to by file select
    ; register
    call send8 ; 4-bit interface routine
; Test for 16 characters displayed
    decfsz count3,f ; Decrement counter
    goto nextchar ; Skipped if done
    return
nextchar:
    incf FSR,f ; Bump pointer
    goto getchar

;=================================
; send 2 nibbles in
; 4-bit mode
;=================================
; Procedure to send two 4-bit values to Port-B lines
; 7, 6, 5, and 4. High-order nibble is sent first
; ON ENTRY:
; w register holds 8-bit value to send
send8:
    movwf store1 ; Save original value
    call merge4 ; Merge with Port-B
    ; Now w has merged byte
    movwf PORTB ; w to Port-B
    call pulseE ; Send data to LCD
    ; High nibble is sent
    movf store1,w ; Recover byte into w
    swapf store1,w ; Swap nibbles in w
    call merge4
    movwf PORTB
    call pulseE ; Send data to LCD
    call delay_125
    return
;=================================
; merge bits
;=================================
; Routine to merge the 4 high-order bits of the
value to send with the contents of Port-B
so as to preserve the 4 low-bits in Port-B

Logic:

AND value with 1111 0000 mask
AND Port-B with 0000 1111 mask
Now low nibble in value and high nibble in
Port-B are all 0 bits:
value = vvvv 0000
Port-B = 0000 bbbb
OR value and Port-B resulting in:
vvvv bbbb

ON ENTRY:

w contain value bits

ON EXIT:

w contains merged bits

merge4:

andlw b'11110000' ; ANDing with 0 clears the
                    ; bit. ANDing with 1 preserves
                    ; the original value
movwf store2 ; Save result in variable
movf PORTB,w ; Port-B to w register
andlw b'00001111' ; Clear high nibble in Port-b
                    ; and preserve low nibble
iorwf store2,w ; OR two operands in w
return

;------------------------
; blank buffer
;------------------------

; Procedure to store 16 blank characters in PIC RAM
; buffer starting at address stored in the variable
; pic_ad
blank16

movlw D'16' ; Setup counter
movwf count1
movf pic_ad,w ; First PIC RAM address
movwf FSR ; Indexed addressing
movlw 0x20 ; ASCII space character
storeit

movwf INDF ; Store blank character in PIC RAM
            ; buffer using FSR register
decfsz count1,f ; Done?
goto incfsr ; no
return ; yes
incfsr

incf FSR,f ; Bump FSR to next buffer space
goto storeit
;===============
; Set address register
; to LCD line 1
;===============

; ON ENTRY:
;
; Address of LCD line 1 in constant LCD_1

line1:
  bcf PORTA,E_line ; E line low
  bcf PORTA,RS_line ; RS line low, set up for
                     ; control
  call delay_5 ; busy?

; Set to second display line
  movlw LCD_1 ; Address and command bit
  call send8 ; 4-bit routine

; Set RS line for data
  bsf PORTA,RS_line ; Setup for data
  call delay_5 ; Busy?
return

;===============
; first text string procedure
;===============
storeMS1:
; Procedure to store in PIC RAM buffer the message
; contained in the code area labeled msg1

; ON ENTRY:
;
; variable pic_ad holds address of text buffer
; in PIC RAM
;
; w register hold offset into storage area
;
; msg1 is routine that returns the string characters
; and a zero terminator
;
; index is local variable that hold offset into
; text table. This variable is also used for
; temporary storage of offset into buffer

; ON EXIT:
;
; Text message stored in buffer
;
; Store offset into text buffer (passed in the w register)
; in temporary variable

  movwf index ; Store w in index

; Store base address of text buffer in FSR
  movf pic_ad,w ; first display RAM address to W
  addwf index,w ; Add offset to address
  movwf FSR ; W to FSR

; Initialize index for text string access
  movlw 0 ; Start at 0
  movwf index ; Store index in variable

; w still = 0
get_msg_char:
    call  msg1 ; Get character from table
; Test for zero terminator
    andlw 0x0ff
    btfsc STATUS,Z ; Test zero flag
    goto  endstr1 ; End of string
; ASSERT: valid string character in w
; store character in text buffer (by FSR)
    movwf INDF ; store in buffer by FSR
    incf FSR,f ; increment buffer pointer
; Restore table character counter from variable
    movf index,w ; Get value into w
    addlw 1 ; Bump to next character
    movwf index ; Store table index in variable
    goto  get_msg_char ; Continue
endstr1:
    return

; Routine for returning message stored in program area
; Message has 10 characters
msg1:
    addwf PCL,f ; Access table
    retlw 'H'
    retlw ':'
    retlw '
    retlw 'M'
    retlw ':'
    retlw '
    retlw 'S'
    retlw ':'
    retlw 0

;==============================================
; BCD to ASCII decimal
; conversion
;==============================================
; ON ENTRY:
; w register has two packed BCD digits
; ON EXIT:
; output variables asc10, and asc1 have two ASCII decimal digits
; Routine logic:
; The low order nibble is isolated and the value 30H
; added to convert to ASCII. The result is stored in
; the variable asc1. Then the same is done to the
; high-order nibble and the result is stored in the
; variable asc10

Bcd2asc:
    movwf    store1    ; Save input
    andlw    b'00001111'    ; Clear high nibble
    addlw    0x30    ; Convert to ASCII
    movwf    asc1    ; Store result
    swapf    store1,w    ; Recover input and swap digits
    andlw    b'00001111'    ; Clear high nibble
    addlw    0x30    ; Convert to ASCII
    movwf    asc10    ; Store result
    return

;============================================================================
;  6355 RTC procedures
;============================================================================
;============================================================================
; init RTC
;============================================================================
; Procedure to initialize the real time clock chip. If chip
; is not initialized it will not operate and the values
; read will be invalid.
; Since the 6355 operates in BCD format the stored values must
; be converted to packed BCD.
; According to wiring diagram
; NJU6355 Interface for setting time:
; DAT PORTB,0 Output
; CLK PORTB,1 Output
; CE PORTB,2 Output
; IO PORTB,3 Output

setRTC:
    Bank1
    movlw    b'00000000'    ; All output bits
    movlw    TRISB
    Bank0
    ; Writing to the 6355 requires that the CLK bit be held
    ; low while the IO and CE lines are high
    bcf    PORTB,CLK    ; CLK low
    call    delay_5
    bsf    PORTB,IO ; IO high
    call    delay_5
    bsf    PORTB,CE ; CE high
    ; Data is stored in RTC as follows:
    ; year 8 bits (0 to 99)
    ; month 8 bits (1 to 12)
movf year, w ; Get item from storage
call bin2bcd ; Convert to BCD
movwf temp1
call writeRTC

movf month, w
call bin2bcd
movwf temp1
call writeRTC

movf day, w
call bin2bcd
movwf temp1
call writeRTC

movf dayOfWeek, w ; dayOfWeek of week is 4-bits
call bin2bcd
movwf temp1
call write4RTC

movf hour, w
call bin2bcd
movwf temp1
call writeRTC

movf minutes, w
call bin2bcd
movwf temp1
call writeRTC

; Done
bcf PORTB, CLK ; Hold CLK line low
call delay_5
call delay_5
bcf PORTB, CE ; and the CE line

; to the RTC
call delay_5
bcf PORTB, IO ; RTC in output mode
return

; ==============================================================
; read RTC data
; ==============================================================

; ==============================================================
; days cannot be written to RTC. RTC seconds register
; is automatically initialized to zero
; Total 44 bits
; Procedure to read the current time from the RTC and store
; data (in packed BCD format) in local time registers.
; According to wiring diagram
; NJU6355 Interface for read operations:
; DAT PORTB,0 Input
; CLK PORTB,1 Output
; CE PORTB,2 Output
; IO PORTB,3 Output
Get_Time
; Clear Port-B
movlw b'00000000'
movwf PORTB
; Make data line input
Bank1
movlw b'00000001'
movwf TRISB
Bank0
; Reading RTC data requires that the IO line be low and the
; CE line be high. CLK line is held low
bcf PORTB,CLK ; CLK low
call delay_125
bcf PORTB,IO ; IO line low
call delay_125
bsf PORTB,CE ; and CE line high
; Data is read from RTC as follows:
; year 8 bits (0 to 99)
; month 8 bits (1 to 12)
; day 8 bits (1 to 31)
; dayOfWeek 4 bits (1 to 7)
; hour 8 bits (0 to 23)
; minutes 8 bits (0 to 59)
; seconds 8 bits (0 to 59)
; ======
; Total 52 bits
`call readRTC
movwf year
`call delay_125
`call readRTC
movwf month
`call delay_125
`call readRTC
movwf day
`call delay_125
; dayOfWeek of week is a 4-bit value
`call read4RTC
movwf dayOfWeek
call delay_125

call readRTC
movwf hour
call delay_125

call readRTC
movwf minutes

call delay_125

call readRTC
movwf seconds

bcf PORTB,CE ; CE line low to end output
return

;=============
; read 4/8 bits from RTC
;=============
; Procedure to read 4/8 bits stored in 6355 registers
; Value returned in w register
read4RTC
movlw .4 ; 4 bit read
goto anyBits
readRTC
movlw .8 ; 8 bits read
anyBits:
movwf counter

; Read 6355 read operation requires the IO line be set low
; and the CE line high. Data is read in the following order:
; year, month, day, day-of-week, hour, minutes, seconds
readBits:
    bsf PORTB,CLK; Set CLK high to validate data
    bsf STATUS,C ; Set the carry flag (bit = 1)
    btfss PORTB,DAT ; Is data line high?
                    ; Leave carry set (1 bit) if high
    bcf STATUS,C ; Clear the carry bit (make bit 0)
    ; At this point the carry bit matches the data line
    bcf PORTB,CLK ; Set CLK low to end read
    ; The carry bit is now rotated into the temp1 register
    rrf temp1,1
decfsz counter,1 ; Decrement the bit counter
    goto readBits; Continue if not last bit
    ; At this point all bits have been read (8 or 4)
movf    temp1,0 ; Result to w
return

;============================================
; write 4/8 bits to RTC
;============================================
; Procedure to write 4 or 8 bits to the RTC registers
; ON ENTRY:
;    temp1 register holds value to be written
; ON EXIT:
;    nothing
write4RTC
    movlw .4 ; Init for 4 bits
goto    allBits
writeRTC
    movlw .8 ; Init for 8 bits
allBits:
    movwf counter ; Store in bit counter
writeBits:
    bcf    PORTB,CLK ; Clear the CLK line
call    delay_5    ; Wait
bsf    PORTB,DAT ; Set the data line to RTC
btfss   temp1,0 ; Send LSB
    bcf    PORTB,DAT ; Clear data line
call    delay_5    ; Wait for operation to
    ; complete
bsf    PORTB,CLK ; Bring CLK line high to
    ; validate
rrf    temp1,f ; Rotate bits in storage
decfsz  counter,1 ; Decrement bit counter
goto    writeBits ; Continue if not last bit
return

;============================================
; init time variables
;============================================
; Procedure to initialize time variables for testing
; Constants used in initialization are located in
; #define statements.
initRTC:
    movlw    iYear
    movwf    year
    movlw    iMonth
    movwf    month
    movlw    iDay
    movwf    day
    movlw    iDoW
    movwf    dayOfWeek
movlw  iHour
movwf  hour
movlw  iMin
movwf  minutes
movlw  iSec
movwf  seconds
return

;===============================================
; binary to BCD conversion
;===============================================
; Convert a binary number into two packed BCD digits
; ON ENTRY:
;    w register has binary value in range 0 to 99
; ON EXIT:
;    output variables bcdLow and bcdHigh contain two
;    packed unpacked BCD digits
;    w contains two packed BCD digits
; Routine logic:
;  The value 10 is subtracted from the source operand
;  until the reminder is < 0 (carry cleared). The number
;  of subtractions is the high-order BCD digit. 10 is
;  then added back to the subtrahend to compensate
;  for the last subtraction. The final reminder is the
;  low-order BCD digit
; Variables:
;  inNum       storage for source operand
;  bcdHigh     storage for high-order nibble
;  bcdLow      storage for low-order nibble
;  thisDig     Digit counter
bin2bcd:
    movwf  inNum ; Save copy of source value
    clrf   bcdHigh ; Clear storage
    clrf   bcdLow
    clrf   thisDig
min10:
    movlw  .10
    subwf  inNum,f ; Subtract 10
    btfsc  STATUS,C ; Did subtract overflow?
    goto   sum10 ; No. Count subtraction
    goto   fin10
sum10:
    incf   thisDig,f ;increment digit counter
    goto   min10
fin10:
    movlw  .10
    addwf  inNum,f ; Adjust for last subtract
    movf   thisDig,w ; get digit counter contents
movwf  bcdHigh   ; Store it

; Calculate and store low-order BCD digit
movf  inNum,w    ; Store units value
movwf  bcdLow   ; Store digit

; Combine both digits
swapf  bcdHigh,w ; High nibble to HOBs
iorwf  bcdLow,w ; OR in low nibble
return

;======================================================================
end        ; END OF PROGRAM

;======================================================================
Resistor Color Codes

The resistor color coding system applies to carbon film, metal oxide film, fusible, precision metal film, and wirewound resistors of the axial lead type. This system is employed when the surface area is not sufficient to print the actual resistance value. Several color codes are used, the most common ones are the 4-band and 5-band codes. In the 4-band code the first two bands represent the magnitude of the resistance, the third band is a multiplier for this value, and the fourth one encodes the error tolerance. In the 5-band code the first three bands represent the magnitude, the fourth one serves as a multiplier, and the fifth one is the error tolerance.

The color codes for the various bands are as follows:
<table>
<thead>
<tr>
<th>COLOR</th>
<th>MAGNITUDE</th>
<th>MULTIPLIER</th>
<th>TOLERANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Brown</td>
<td>1</td>
<td>10</td>
<td>1%</td>
</tr>
<tr>
<td>Red</td>
<td>2</td>
<td>100</td>
<td>2%</td>
</tr>
<tr>
<td>Orange</td>
<td>3</td>
<td>1K</td>
<td></td>
</tr>
<tr>
<td>Yellow</td>
<td>4</td>
<td>10K</td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>5</td>
<td>100K</td>
<td>0.5%</td>
</tr>
<tr>
<td>Blue</td>
<td>6</td>
<td>1M</td>
<td>0.25%</td>
</tr>
<tr>
<td>Violet</td>
<td>7</td>
<td>10M</td>
<td>0.10%</td>
</tr>
<tr>
<td>Grey</td>
<td>8</td>
<td></td>
<td>0.05%</td>
</tr>
<tr>
<td>White</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gold</td>
<td>0.1</td>
<td></td>
<td>5%</td>
</tr>
<tr>
<td>Silver</td>
<td>0.01</td>
<td></td>
<td>10%</td>
</tr>
</tbody>
</table>

To read the resistance value first determine if it is a 4-band or a 5-band encoding. Then proceed to identify the tolerance band, which is usually either gold or silver. Starting at the opposite end, read the two or three magnitude bands and multiply this value by the multiplier band. For example, a resistor with four color bands: red, orange, brown, and gold is a 230 Ohm resistor with a 5% error tolerance.

There are several calculators on line that allow you to easily find the resistance value. You can locate these calculators by searching for the keywords: resistor color codes.
Building Your Own Circuit Boards

Several methods have been developed for making printed circuit boards on a small scale, as would be convenient for the experimenter and prototype developer. If you look through the pages of any electronics supply catalog you will find kits and components based on different technologies of various levels of complexity. The method we describe in this appendix is perhaps the simplest one since it does not require a photographic process.

The process consists of the following steps:
1. The circuit diagram is drawn on the PC using a general-purpose or a specialized drawing program.
2. A printout is made of the circuit drawing on photographic paper.
3. The printout is transferred to a copper-clad circuit board blank by ironing over the backside with a household clothes iron.
4. The resulting board is placed in an etching bath that eats away all the copper, except the circuit image ironed onto the board surface.
5. The board is washed of etchant, cleaned, drilled, and the components soldered to it in the conventional manner.
6. Optionally another image can be ironed onto the backside of the board to provide component identification, logos, etc.

The following URL contains detailed information on making your own PCBs:

Http://www.fullnet.com/u/tomg/gooteedr.htm

Drawing the Circuit Diagram

Any computer drawing program serves this purpose. We have used CorelDraw but there are several specialized PCB drawing programs available on the Internet. The following is a circuit board drawing used by us for a PIC flasher circuit described in the text:
Note in the drawing that the circuit locations where the components are to be soldered consist of small circular pads, usually called solder pads. The following illustration zooms into the lower corner of the drawing to show the details of the solder pads.

Figure B-2 Detail of Circuit Board Pads

Quite often it is necessary for a circuit line to cross between two standard pads. In this case the pads can be modified so as to allow it. The modified pads are shown in Figure B-3.
The circuit diagram must be printed using a laser printer. Inkjet toners do not produce an image that resists the action of the etchant. Although in our experiments we used LaserJet printers it is well documented that virtually any laser printer will work. Laser copiers have also been used successfully for creating the PCB circuit image.

With the method we are describing, the width of the traces can become an issue. The traces in the PCB image of Figure B-1 are 2 points, which is 0.027". Traces half that width and less have been used successfully with this method but as the traces become thinner the entire process becomes more critical. For most simple circuits 0.020" traces should be a useful limit. Also be careful not to touch the glossy side of the paper or the printed image with fingers.

Note that the pattern is drawn as if you were looking from the component side of the board.

Users of this method state that one of the most critical elements is the paper used in printing the circuit. Pinholes in some papers can degrade the image to the point that the circuit lines (especially if they are very thin) do not etch correctly. Another problem relates to removing the ironed-on paper from the board without damaging the board surface.

Glossy, coated inkjet-printer paper works well. Even better results can be obtained with glossy photo paper. We use a common high-gloss photographic paper available from Staples and sold under the name of "picture paper". The 30 sheets, 8-by-10 size, have the Staples number B031420197 1713. The UPC barcode is: 7 18103 02238 5.
Transferring the image onto the board blank is done by applying heat from a common clothes iron, set on the hottest setting, onto the paper/board sandwich. In most irons the hottest setting is labeled “linen.” After going over the back of the paper several times with the hot iron, the paper becomes fused to the copper side of the blank board. The board/paper sandwich is then allowed to soak in water for about 10 minutes, after which the paper can be removed by peeling or light scrubbing with a toothbrush. It has been mentioned that Hewlett-Packard toner cartridges with microfine particles work better than the store-brand toner cartridges.

**Etching the Board**

Once the paper has been removed and the board washed it is time to prepare the board for etching. The preliminary operations consist of rubbing the copper surface of the board with Scotchbrite plastic abrasive pad and then scrubbing the surface with a paper towel soaked with Acetone solvent.

When the board is rubbed and clean, it is time to etch the circuit. The etching solution contains Ferric Chloride and is available from Radio Shack as a solution and from Jameco Electronics as a powder to be mixed by the user. PCB Ferric Chloride etchant should be handled with rubber gloves and rubber apron since it stains the skin and utensils. Also, concentrated acid fumes from Ferric Chloride solution are toxic and can cause severe burns. These chemicals should be handled according to cautions and warnings posted in the containers.

The Ferric Chloride solution should be stored and used in a plastic or glass container, never metal. Faster etching is accomplished if the etching solution is first warmed by placing the bottle in a tub of hot water. Once the board is in the solution, face up, the container is rocked back and forth. It is also possible to aid in the copper removal by rubbing the surface with a rubber-gloved finger.

**Finishing the Board**

The etched board should be washed well, first in water and then in Lacquer Thinner or Acetone; either solvent works. It is better to just rub the board surface with a paper towel soaked in the solvent. Keep in mind that most solvents are flammable and explosive, and also toxic.

After the board is clean the mounting holes can be drilled using the solder pads as a guide. A small electric drill at high revolutions, such as a Dremmel tool, works well for this operation. The standard drill size for the mounting holes is 0.035”. A #60 drill (0.040”) also works well. Once all the holes are drilled, the components can be mounted from the backside and soldered at the pads.

**The Backside Image**

The component side (backside) of the PCB can be printed with an image of the components to be mounted or with logos or other text. A single-sided blank board has no copper coating on the backside so the image is just ironed on without etching. Probably the best time to print the backside image is after the board has been etched and drilled but before mounting the components.
Since the image is to be transferred directly to the board, it must be a mirror image of the desired graphics and text. Most drawing programs contain a mirroring transformation so the backside image can be drawn using the component side as a guide, and then mirrored horizontally before ironing it on the backside of the board. Figure B-4 shows the backside image of the sample circuit board, before and after mirroring.

![Figure B-4 Graphics and Text for Board Backside Image](image)

Note on the left-side image in Figure B-4 that a lighter copy of the circuit diagram was used to lay out the image of the backside. Once drawn, the backside drawing was mirrored horizontally, as shown in the right-side image.
Appendix C

Mid-range Instruction Set

This Appendix describes the instructions in the PIC mid-range family. Not all instructions are implemented in all devices but all of them work in the specific PICs discussed in the text, that is, the 16F84A and the 16F877.

Table C.1
Mid-range PIC Instruction Set

<table>
<thead>
<tr>
<th>MNEMONIC</th>
<th>OPERAND</th>
<th>DESCRIPTION</th>
<th>CYCLES</th>
<th>BITS AFFECTED</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BYTE-ORIENTED OPERATIONS:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADDWF</td>
<td>f,d</td>
<td>Add w and f</td>
<td>1</td>
<td>C,DC,Z</td>
</tr>
<tr>
<td>ANDWF</td>
<td>f,d</td>
<td>AND w with f</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>CLRF</td>
<td>f</td>
<td>Clear f</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>CLRW</td>
<td>-</td>
<td>Clear w</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>COMF</td>
<td>f,d</td>
<td>Complement f</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>DECF</td>
<td>f,d</td>
<td>Decrement f</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>DECFSZ</td>
<td>f,d</td>
<td>Decrement, skip if 0</td>
<td>1(2)</td>
<td>-</td>
</tr>
<tr>
<td>INCF</td>
<td>f,d</td>
<td>Increment f</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>INCFSZ</td>
<td>f,d</td>
<td>Increment, skip if 0</td>
<td>1(2)</td>
<td>-</td>
</tr>
<tr>
<td>IORWF</td>
<td>f,d</td>
<td>Inclusive OR w and f</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>MOVF</td>
<td>f,d</td>
<td>Move f</td>
<td>1</td>
<td>Z</td>
</tr>
<tr>
<td>MOVWF</td>
<td>f</td>
<td>Move w to f</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>NOP</td>
<td>-</td>
<td>No operation</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>RLF</td>
<td>f,d</td>
<td>Rotate left through carry</td>
<td>1</td>
<td>C</td>
</tr>
<tr>
<td>RRF</td>
<td>f,d</td>
<td>Rotate right through carry</td>
<td>1</td>
<td>C</td>
</tr>
<tr>
<td>SUBWF</td>
<td>f,d</td>
<td>Subtract w from f</td>
<td>1</td>
<td>C,DC,Z</td>
</tr>
<tr>
<td>SWAPF</td>
<td>f,d</td>
<td>Swap nibbles in f</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>XORWF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>BIT-ORIENTED OPERATIONS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BCF</td>
<td>f,b</td>
<td>Bit clear in f</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>BSF</td>
<td>f,b</td>
<td>Bit set in f</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>BTFSC</td>
<td>f,b</td>
<td>Bit test, skip if clear</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>BTFSS</td>
<td>f,b</td>
<td>Bit test, skip if set</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td><strong>LITERAL AND CONTROL OPERATIONS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADDLW</td>
<td>k</td>
<td>Add literal and w</td>
<td>1</td>
<td>C,DC,Z</td>
</tr>
</tbody>
</table>

(continues)
Table C.1

Mid-range PIC Instruction Set (continued)

<table>
<thead>
<tr>
<th>MNEMONIC</th>
<th>OPERAND</th>
<th>DESCRIPTION</th>
<th>CYCLES</th>
<th>BITS</th>
<th>AFFECTED</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANDLW k</td>
<td></td>
<td>AND literal and w</td>
<td>1</td>
<td>Z</td>
<td></td>
</tr>
<tr>
<td>CALL k</td>
<td></td>
<td>Call procedure</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLRWDT</td>
<td>-</td>
<td>Clear watchdog timer</td>
<td>1</td>
<td>TO,PD</td>
<td></td>
</tr>
<tr>
<td>GOTO k</td>
<td></td>
<td>Go to address</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IORLW k</td>
<td></td>
<td>Inclusive OR literal with w</td>
<td>1</td>
<td>Z</td>
<td></td>
</tr>
<tr>
<td>MOVLW k</td>
<td></td>
<td>Move literal to w</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RETFIE</td>
<td>-</td>
<td>Return from interrupt</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RETLWk</td>
<td>-</td>
<td>Return literal in w</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RETURN</td>
<td>-</td>
<td>Return from procedure</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLEEP</td>
<td>-</td>
<td>Go into SLEEP mode</td>
<td>1</td>
<td>TO,PD</td>
<td></td>
</tr>
<tr>
<td>SUBLW k</td>
<td></td>
<td>Subtract literal and w</td>
<td>1</td>
<td>C,DC,Z</td>
<td></td>
</tr>
<tr>
<td>XORLW k</td>
<td></td>
<td>Exclusive OR literal with w</td>
<td>1</td>
<td>Z</td>
<td></td>
</tr>
</tbody>
</table>

Legend:
- f = file register
- d = destination: 0 = w register, 1 = file register
- b = bit position
- k = 8-bit constant
### Table C.2

**Conventions used in Instruction Descriptions**

<table>
<thead>
<tr>
<th>FIELD</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>f</td>
<td>Register file address (0x00 to 0x7F)</td>
</tr>
<tr>
<td>w</td>
<td>Working register (accumulator)</td>
</tr>
<tr>
<td>b</td>
<td>Bit address within an 8-bit file register (0 to 7)</td>
</tr>
<tr>
<td>k</td>
<td>Literal field, constant data or label (may be either an 8-bit or an 11-bit value)</td>
</tr>
<tr>
<td>x</td>
<td>Don't care (0 or 1)</td>
</tr>
<tr>
<td>d</td>
<td>Destination select; d = 0: store result in W, d = 1: store result in file register f.</td>
</tr>
<tr>
<td>dest</td>
<td>Destination either the W register or the specified register file location</td>
</tr>
<tr>
<td>label</td>
<td>Label name</td>
</tr>
<tr>
<td>TOS</td>
<td>Top of Stack</td>
</tr>
<tr>
<td>PC</td>
<td>Program Counter</td>
</tr>
<tr>
<td>PCLATH</td>
<td>Program Counter High Latch</td>
</tr>
<tr>
<td>GIE</td>
<td>Global Interrupt Enable bit</td>
</tr>
<tr>
<td>WDT</td>
<td>Watchdog Timer</td>
</tr>
<tr>
<td>!TO</td>
<td>Time-out bit</td>
</tr>
<tr>
<td>!PD</td>
<td>Power-down bit</td>
</tr>
<tr>
<td>[]</td>
<td>Optional element</td>
</tr>
<tr>
<td>[XXX]</td>
<td>Contents of memory location pointed at by XXX register</td>
</tr>
<tr>
<td>()</td>
<td>Contents</td>
</tr>
<tr>
<td>-&gt;</td>
<td>Assigned to</td>
</tr>
<tr>
<td>&lt;&gt;</td>
<td>Register bit field</td>
</tr>
</tbody>
</table>

italics User defined term
## ADDLW

**Add Literal and w**

<table>
<thead>
<tr>
<th>Syntax:</th>
<th>[label] ADDLW     k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operands:</td>
<td>k in range 0 to 255</td>
</tr>
<tr>
<td>Operation:</td>
<td>(w) + k -&gt; w</td>
</tr>
<tr>
<td>Status Affected:</td>
<td>C, DC, Z</td>
</tr>
<tr>
<td>Description:</td>
<td>The contents of the w register are added to the eight bit literal 'k' and the result is placed in the w register</td>
</tr>
<tr>
<td>Words:</td>
<td>1</td>
</tr>
<tr>
<td>Cycles:</td>
<td>1</td>
</tr>
</tbody>
</table>

**Example 1:**

```
ADDLW 0x15
Before Instruction: w = 0x10
After Instruction:  w = 0x25
```

**Example 2:**

```
ADDLW var1
Before Instruction: w = 0x10
var1 is data memory variable
var1 = 0x37
After Instruction  w = 0x47
```
**ADDWF**  Add w and f

**Syntax:**  
[ label ] ADDWF f,d

**Operands:**  
f in range 0 to 127  
d = 0 / 1

**Operation:**  
(W) + (f) -> destination

**Status Affected:**  
C, DC, Z

**Description:**  
Add the contents of the W register with register 'f'. If 'd' is 0 the result is stored in the w register. If 'd' is 1 the result is stored back in register 'f'.

**Words:**  
1

**Cycles:**  
1

**Example 1:**

ADDWF FSR, 0  
Before Instruction:  
w = 0x17  
FSR = 0xc2  
After Instruction  
W = 0xd9  
FSR = 0xc2

**Example 2:**

ADDWF INDF, 1  
Before Instruction:  
W = 0x17  
FSR = 0xC2  
Contents of Address (FSR) = 0x20  
After Instruction  
W = 0x17  
FSR = 0xC2  
Contents of Address (FSR) = 0x37
**BCF**  
Bit Clear f

Syntax:  
[ label ] BCF f,b

Operands:  
f in range 0 to 127  
b in range 0 to 7

Operation:  
0 ->f<b>

Status Affected:  
None

Description:  
Bit 'b' in register 'f' is cleared.

Words:  
1

Cycles:  
1

Example 1:

```
BCF reg1,7
```

Before Instruction:  
reg1 = 0xc7 (1100 0111)

After Instruction:  
reg1 = 0x47 (0100 0111)

Example 2:

```
BCF INDF,3
```

Before Instruction:  
w = 0x17  
FSR = 0xc2

[FSR] = 0x2f

After Instruction:  
w = 0x17  
FSR = 0xc2

[FSR] = 0x27
BSF

Bit Set f

Syntax: [ label ] BSF f, b
Operands: f in range 0 to 127
b in range 0 to 7
Operation: 1 -> f<b>
Status Affected: None
Description: Bit 'b' in register 'f' is set.
Words: 1
Cycles: 1

Example 1:
BSF reg1, 6
Before Instruction: reg1 = 0011 1010
After Instruction: reg1 = 0111 1010

Example 2:
BSF INDF, 3
Before Instruction:
  w = 0x17
  FSR = 0xc2
  [FSR] = 0x20
After Instruction:
  w = 0x17
  FSR = 0xc2
  [FSR] = 0x28
**BTFSC** Bit Test f, Skip if Clear

Syntax: \[ \text{[ label ] BTFSC f,b} \]

Operands:  
- \(f\) in range 0 to 127  
- \(b\) in range 0 to 7

Operation: skip next instruction if \((f < b) = 0\)

Status Affected: None

Description: If bit 'b' in register 'f' is '0' then the next instruction is skipped. If bit 'b' is '0' then the next instruction (fetched during the current instruction execution) is discarded, and a NOP is executed instead, making this a 2 cycle instruction.

Words: 1

Example 1:

```
repeat:
   btfsc reg1,4
   goto repeat
```

Case 1: Before Instruction  
\(PC = \$\)
\(\text{reg1} = \text{xxx0 xxxx}\)

After Instruction  
Since \(\text{reg1}<4> = 0\),  
\(PC = \$ + 2\) (goto skipped)

Case 2: Before Instruction  
\(PC = \$\)
\(\text{reg1} = \text{xxx1 xxxx}\)

After Instruction  
Since \(\text{FLAG}<4> = 1\),  
\(PC = \$ + 1\) (goto executed)
BTFSS

Bit Test f, Skip if Set

Syntax: [ label ] BTFSC f,b
Operands: f in range 0 to 127
b in range 0 to 7
Operation: skip next instruction if (f<b>) = 1
Status Affected: None
Description: If bit 'b' in register 'f' is '1' then the next
instruction is skipped. If bit 'b' is '0' then the
next instruction (fetched during the current
instruction execution) is discarded, and a NOP
is executed instead, making this a 2 cycle
instruction.
Words: 1
Cycles: 1(2)

repeat:
   btfss reg1,4
   goto repeat
Case 1: Before Instruction
   PC = $
   Reg1 = xxx1 xxxx
After Instruction
   Since Reg1<4>= 1,
   PC = $ + 2 (goto skipped)
Case 2: Before Instruction
   PC = $
   Reg1 = xxx0 xxxx
After Instruction
   Since Reg1<4>=0,
   PC = $ + 1 (goto executed)
CALL Call Subroutine

Syntax: [ label ] CALL k
Operands: k in range 0 to 2047
Operation: (PC) + -> TOS,
k-> PC<10:0>,
(PCLATH<4:3>)-> PC<12:11>
Status Affected: None
Description: Call Subroutine. First, the 13-bit return address (PC+1) is pushed onto the stack. The eleven bit immediate address is loaded into PC bits <10:0>. The upper bits of the PC are loaded from PCLATH<4:3>. CALL is a two cycle instruction.

Words: 1
Cycles: 2
Example 1:

Here:
call There
Before Instruction
PC = AddressHere
After Instruction
TOS = Address Here + 1
PC = Address There
**CLRF**  
Clear f

Syntax: \[ label \] CLRF \ f  
Operands: f in range 0 to 127  
Operation: \( 00h \rightarrow f \)  
1 -> Z  
Status Affected: Z  
Description: The contents of register 'f' are cleared and the Z bit is set.  
Words: 1  
Cycles: 1  
Example 1:
```
clr f reg1
Before Instruction: reg1 = 0x5a  
After Instruction: reg1 = 0x00  
Z = 1
```
Example 2:
```
Cl rf INDF
Before Instruction: FSR = 0xc2  
[FSR] = 0xAA  
After Instruction: FSR = 0xc2  
[FSR] = 0x00  
Z = 1
```
**CLRW**  
Clear w

Syntax:  
[ label ] CLRW

Operands:  
None

Operation:  
00h -> w

1-> Z

Status Affected:  
Z

Description:  
w register is cleared. Zero bit (Z) is set.

Words:  
1

Cycles:  
1

Example 1:

CLRW

Before Instruction:  
w = 0x5A

After Instruction:  
w = 0x00

Z = 1
**CLRWDT** Clear Watchdog Timer

Syntax: [ label ] CLRWDT
Operands: None
Operation: 00h -> WDT
0 -> WDT prescaler count,
1 -> TO
1 -> PD
Status Affected: TO, PD
Description: CLRWDT instruction clears the Watchdog Timer. It also clears the prescaler count of the WDT. Status bits TO and PD are set. The instruction does not change the assignment of the WDT prescaler.

Words: 1
Cycles: 1
Example 1:

```
CLRWDT
Before Instruction: WDT counter= x
WDT prescaler = 1:128
After Instruction: WDT counter=0x00
WDT prescaler count=0
TO = 1
PD = 1
WDT prescaler = 1:128
```
COMF

Complement f

Syntax: \([ \text{label} ] \text{COMF } f,d\)

Operands:
- \(f\) in range 0 to 127
- \(d\) is 0 or 1

Operation: \((f) \rightarrow \text{destination}\)

Status Affected: \(Z\)

Description: The contents of register 'f' are 1's complemented. If 'd' is 0 the result is stored in \(w\). If 'd' is 1 the result is stored back in register 'f'.

Words: 1

Cycles: 1

Example 1:

\[
\begin{align*}
\text{comf } & \text{reg1,0} \\
\text{Before Instruction:} & \quad \text{reg1 = 0x13} \\
\text{After Instruction:} & \quad \begin{array}{l}
\text{reg1 = 0x13} \\
\text{w = 0xEC}
\end{array}
\end{align*}
\]

Example 2:

\[
\begin{align*}
\text{comf } & \text{INDF,1} \\
\text{Before Instruction:} & \quad \begin{array}{l}
\text{FSR = 0xc2} \\
[\text{FSR}] = 0xAA
\end{array} \\
\text{After Instruction:} & \quad \begin{array}{l}
\text{FSR = 0xc2} \\
[\text{FSR}] = 0x55
\end{array}
\end{align*}
\]

Example 3:

\[
\begin{align*}
\text{comf } & \text{reg1,1} \\
\text{Before Instruction:} & \quad \text{reg1 = 0xff} \\
\text{After Instruction:} & \quad \text{reg1 = 0x00}
\end{align*}
\]
**DECF**

Decrement f

Syntax: 
[ label ] DECF f,d

Operands:  
f in range 0 to 127  
d is either 0 or 1

Operation:  
(f) - 1 -> destination

Status Affected:  
Z

Description:  
Decrement register 'f'. If 'd' is 0 the result is stored in the w register. If 'd' is 1 the result is stored back in register 'f'.

Words:  
1

Cycles:  
1

Example 1:

decf count,1  
Before Instruction:  
count = 0x01  
Z = 0  
After Instruction:  
count = 0x00  
Z = 1

Example 2:

decf INDF,1  
Before Instruction:  
FSR = 0xc2  
[FSR] = 0x01  
Z = 0  
After Instruction:  
FSR = 0xc2  
[FSR] = 0x00  
Z = 1

Example 3:

decf count,0  
Before Instruction:  
count = 0x10  
w = x  
Z = 0  
After Instruction:  
count = 0x10  
w = 0x0f
**DECFSZ**  
Decrement f, Skip if 0

Syntax: `[ label ] DECFSZ f,d  
Operands: f in the range 0 to 127  
d is either 0 or 1  
Operation: (f) - 1 -> destination; skip if result = 0  
Status Affected: None  
Description: The contents of register 'f' are decremented. If 'd' is 0 the result is placed in the w register. If 'd' is 1 the result is placed back in register 'f'. If the result is 0, then the next instruction (fetched during the current instruction execution) is discarded and a NOP is executed instead, making this a 2 cycle instruction.

Words: 1  
Cycles: 1(2)  
Example

```
here:   
       decfsz count,1  
goto   here

Case 1:  
Before Instruction: PC = $  
count = 0x01  
After Instruction:  
count = 0x00  
PC = $ + 2 (goto skipped)

Case 2:  
Before Instruction: PC = $  
count = 0x04  
After Instruction:  
count = 0x03  
PC = $ + 1 (goto executed)
```
### GOTO

**Unconditional Branch**

- **Syntax:** \[ label \] GOTO k
- **Operands:** 0 £ k £ 2047
- **Operation:**
  - k -> PC<10:0>
  - PCLATH<4:3> -> PC<12:11>
- **Status Affected:** None
- **Description:**
  GOTO is an unconditional branch. The eleven bit immediate value is loaded into PC bits <10:0>. The upper bits of PC are loaded from PCLATH<4:3>.
  GOTO is a two cycle instruction.

<table>
<thead>
<tr>
<th>Words</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

**Example**

```
goto There
```

**After Instruction:** PC = address of There
INCF

Increment f

Syntax:  [ label ] INCF f,d
Operands:  f in range 0 to 127
          d is either 0 or 1
Operation:  (f) + 1 -> destination
Status Affected:  Z
Description:  The contents of register 'f' are incremented. If 'd' is 0 the result is placed in the w register. If 'd' is 1 the result is placed back in register 'f'.
Words:  1
Cycles:  1

Example 1

incf  count,1
Before Instruction:  count = 0xff
                   Z = 0
After Instruction:  count = 0x00
                   Z = 1

Example 2

incf  INDF,1
Before Instruction:  FSR = 0xC2
                    [FSR] = 0xff
                   Z = 0
After Instruction:  FSR = 0xc2
                    [FSR] = 0x00
                   Z = 1

Example 3

incf  count,0
Before Instruction:  count = 0x10
                    w = x
                   Z = 0
After Instruction:  count = 0x10
                    w = 0x11
                   Z = 0
INCFSZ  Increment f, Skip if 0

Syntax:  [ label ] INCFSZ f,d
Operands:  f in range 0 to 127
           d is either 0 or 1
Operation:  (f) + 1 -> destination, skip if result = 0
Status Affected:  None
Description:  The contents of register 'f' are incremented. If 'd' is 0 the result is placed in the w register. If 'd' is 1 the result is placed back in register 'f'. If the result is 0, then the next instruction (fetched during the current instruction execution) is discarded and a NOP is executed instead, making this a 2 cycle instruction.

Words:  1
Cycles:  1(2)
Example

Here:
    incfsz count,1
    goto Here

Case 1:
Before Instruction:  PC = $
                   count = 0x10
After Instruction:  count = 0x11
                   PC = $ + 1 (goto executed)

Case 2:
Before Instruction:  PC = $
                   count = 0x00
After Instruction:  count = 0x01
                   PC = $ + 2 (goto skipped)
**IORLW**  Inclusive OR Literal with w

Syntax:  [ label ] IORLW k  
Operands:  k is in range 0 to  255  
Operation:  (w).OR. k -> w  
Status Affected:  Z  
Description:  The contents of the w register is OR’ed with the eight bit literal 'k'. The result is placed in the w register.  

Words:  1  
Cycles:  1  

Example 1  
iorlw 0x35  
Before Instruction:  w = 0x9a  
After Instruction:  w = 0xbfF  
Z = 0

Example 2  
iorlw myreg  
Before Instruction:  w = 0x9a  
Myreg is a variable representing a location in PIC RAM.  
[Myreg] = 0x37  
After Instruction:  w = 0x9F  
Z = 0

Example 3  
iorlw 0x00  
Before Instruction:  w = 0x00  
After Instruction:  w = 0x00
IORWF  Inclusive OR w with f

Syntax:  [ label ] IORWF f,d
Operands:  f is in range 0 to 127
d is either 0 or 1
Operation:  (W).OR. (f) -> destination
Status Affected:  Z
Description:  Inclusive OR the w register with register 'f'. If 'd'
is 0 the result is placed in the w register. If 'd' is
1 the result is placed back in register 'f'.
Words:  1
Cycles:  1

Example 1

iorwf result,0
Before Instruction:  result = 0x13
                   w = 0x91
After Instruction:  result = 0x13
                   w = 0x93
                   Z = 0

Example 2

iorwf INDF,1
Before Instruction:  w = 0x17
                   FSR = 0xc2
                   [FSR] = 0x30
After Instruction:  w = 0x17
                   FSR = 0xc2
                   [FSR] = 0x37
                   Z = 0

Example 3

iorwf result,1
Case 1:  Before Instruction:  result = 0x13
         w = 0x91
After Instruction:  result = 0x93
         w = 0x91
         Z = 0
Case 2:  Before Instruction:  result = 0x00
         w = 0x00
After Instruction:  result = 0x00
         w = 0x00
         Z = 1
**MOVF**  Move f

Syntax:  
[ label ] MOVF f,d

Operands:  
f is in range 0 to 127  
d is either 0 or 1

Operation:  
(f) -> destination

Status Affected:  
Z

Description:  
The contents of register 'f' is moved to a destination dependent upon the status of 'd'. If 'd' = 0, destination is W register. If 'd' = 1, the destination is file register 'f' itself. 'd' = 1 is useful to test a file register since status flag Z is affected.

Words:  
1

Cycles:  
1

Example 1

```
movf FSR,0
Before Instruction:  w = 0x00  
FSR = 0xc2
After Instruction:  w = 0xc2  
Z = 0
```

Example 2

```movf INDF,0
Before Instruction:  w = 0x17  
FSR = 0xc2  
[FSR] = 0x00
After Instruction:  w = 0x17  
FSR = 0xc2  
[FSR] = 0x00  
Z = 1
```

Example 3

```movf FSR,1
Case 1: Before Instruction:  FSR = 0x43
After Instruction:  FSR = 0x43  
Z = 0
Case 2: Before Instruction:  FSR = 0x00
After Instruction:  FSR = 0x00  
Z = 1
```
**MOVLW**  
Move Literal to w

Syntax: \[ label \] MOVLW k
Operands: k in range 0 to 255
Operation: k → w
Status Affected: None
Description: The eight bit literal 'k' is loaded into W register.
The don’t cares will assemble as 0’s.

Words: 1
Cycles: 1

Example 1

```assembly
movlw 0x5a
After Instruction: w = 0x5A
```

Example 2

```assembly
movlw myreg
Before Instruction: w = 0x10
[myreg] = 0x37
After Instruction: w = 0x37
```
MOVWF

Move w to f

Syntax: [ label ] MOVWF f
Operands: f in range 0 to 127
Operation: (w) -> f
Status Affected: None
Description: Move data from W register to register 'f'.
Words: 1
Cycles: 1

Example 1

movwf OPTION_REG
Before Instruction: OPTION_REG = 0xff
w = 0x4f
After Instruction: OPTION_REG = 0x4f
w = 0x4f

Example 2

movwf INDF
Before Instruction: w = 0x17
FSR = 0xC2
[FSR] = 0x00
After Instruction: w = 0x17
FSR = 0xC2
[FSR] = 0x17
NOP | No Operation

| Syntax: | [ label ] NOP |
| Operands: | None |
| Operation: | No operation |
| Status Affected: | None |
| Description: | No operation. |
| Words: | 1 |
| Cycles: | 1 |

**Example**

```
nop
Before Instruction: PC = $
After Instruction: PC = $ + 1
```
### OPTION

**Load Option Register**

| Syntax:     | [ label ] OPTION |
| Operands:   | None             |
| Operation:  | (w) -> OPTION_REG |
| Status Affected: | None          |
| Description:| The contents of the w register are loaded in the OPTION_REG register. This instruction is supported for code compatibility with PIC16C5X products. Since OPTION_REG is a Readable/writable register, code can directly address it without using this instruction. |

Words: 1  
Cycles: 1

Example:

```asm
movlw b'01011100'
option
```
**RETFIE**  Return from Interrupt

Syntax:  
[ label ] RETFIE

Operands:  None

Operation:  TOS -> PC,
            1 -> GIE

Status Affected:  None

Description:  Return from Interrupt. The 13-bit address at the
              Top of Stack (TOS) is loaded in the PC. The
              Global Interrupt Enable bit, GIE (INTCON<7>),
              is automatically set, enabling Interrupts. This is
              a two cycle instruction.

Words:  1

Cycles:  2

Example

    retfie

    After Instruction:  
                          PC = TOS
                          GIE = 1
**RETLW**  Return with Literal in W

Syntax:  \[ label \] RETLW k  
Operands:  k in range 0 to 255  
Operation:  k -> w;  
\( \text{TOS} \rightarrow \text{PC} \)  
Status Affected:  None  
Description:  The w register is loaded with the eight bit literal 'k'. The program counter is loaded 13-bit address at the Top of Stack (the return address). This is a two cycle instruction.  
Words:  1  
Cycles:  2  
Example

```assembly
movlw 2 ; Load w with desired 
         ; Table offset
    call table ; When call returns w
         ; contains value stored
         ; in table

Table:
    addwf pc ; w = offset
    retlw .22 ; First table entry
    retlw .23 ; Second table entry
    retlw .24

    .
    .
    .
    retlw .29 ; Last table entry
```

Before Instruction:  \( w = 0x02 \)  
After Instruction:  \( w = .24 \)
**RETURN**  
Return from Subroutine

<table>
<thead>
<tr>
<th>Syntax:</th>
<th>[ label ] RETURN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operands:</td>
<td>None</td>
</tr>
<tr>
<td>Operation:</td>
<td>TOS -&gt; PC</td>
</tr>
<tr>
<td>Status Affected</td>
<td>None</td>
</tr>
<tr>
<td>Description:</td>
<td>Return from subroutine. The stack is POPed and the top of the stack (TOS) is loaded into the program counter. This is a two cycle instruction.</td>
</tr>
<tr>
<td>Words:</td>
<td>1</td>
</tr>
<tr>
<td>Cycles:</td>
<td>2</td>
</tr>
</tbody>
</table>

**Example**

```
return
```

**After Instruction:**  
PC = TOS
**RLF**  
**Rotate Left f through Carry**

**Syntax:**  
[ label ] RLF f,d

**Operands:**  
f in range 0 to 127  
d is either 0 or 1

**Operation:**  
See description below

**Status Affected:**  
C

**Description:**  
The contents of register 'f' are rotated one bit to the left through the Carry Flag. If 'd' is 0 the result is placed in the W register. If 'd' is 1 the result is stored back in register 'f'.

**Words:**  
1

**Cycles:**  
1

**Example 1**

RLF reg1,0  
Before Instruction:  
reg1 = 1110 0110  
C = 0  
After Instruction:  
reg1 = 1110 0110  
w =1100 1100  
C =1

**Example 2**

RLF INDF,1  
Case 1:  
Before Instruction:  
w = xxxx xxxx  
FSR = 0xc2  
[FSR] = 0011 1010  
C = 1  
After Instruction:  
w = 0x17  
FSR = 0xc2  
[FSR] = 0111 0101  
C = 0

Case 2:  
Before Instruction:  
w = xxxx xxxx  
FSR = 0xC2  
[FSR] = 1011 1001  
C = 0  
After Instruction:  
w = 0x17  
FSR = 0xc2  
[FSR] = 0111 0010  
C = 1
**RRF**  
Rotate Right f through Carry

**Syntax:**  
[ label ] RRF f,d

**Operands:**  
f in range 0 to 127  
d is either 0 or 1

**Operation:**  
See description below

**Status Affected:**  
C

**Description:**  
The contents of register 'f' are rotated one bit to the right through the Carry Flag. If 'd' is 0 the result is placed in the w register. If 'd' is 1 the result is placed back in register 'f'.

**Words:**  
1

**Cycles:**  
1

**Example 1**

```assembly
rrf   reg1,0  
Before Instruction:  
reg1= 1110 0110
w = xxxx xxxx
C = 0

After Instruction:  
reg1= 1110 0110
w = 0111 0011
C = 0
```

**Example 2**

```assembly
rrf   INDF,1  
Case 1: Before Instruction:  
w = xxxx xxxx
FSR = 0xc2
[FSR] = 0011 1010
C = 1

After Instruction:  
w = 0x17
FSR = 0xC2
[FSR] = 1001 1101
C = 0

Case 2: Before Instruction:  
w = xxxx xxxx
FSR = 0xC2
[FSR] = 0011 1001
C = 0

After Instruction:  
w = 0x17
FSR = 0xc2
[FSR] = 0001 1100
C = 1
```
SLEEP

Syntax: [ label ] SLEEP
Operands: None
Operation: 00h -> WDT,
0 -> WDT prescaler count,
1 -> TO,
0 -> PD
Status Affected: TO, PD
Description: The power-down status bit, PD is cleared.
Time-out status bit, TO is set. Watchdog Timer
and its prescaler count are cleared. The
processor is put into SLEEP mode with the
oscillator stopped. The SLEEP instruction does
not affect the assignment of the WDT
prescaler.

Words: 1
Cycles: 1
Example: SLEEP
**SUBLW**  Subtract w from Literal

Syntax:  
[ label ] SUBLW k

Operands:  
k in range 0 to 255

Operation:  
k - (W) -> W

Status Affected:  
C, DC, Z

Description:  
The w register is subtracted (2’s complement method) from the eight bit literal ‘k’. The result is placed in the w register.

Words:  
1

Cycles:  
1

Example 1

```
sublw 0x02
```

Case 1: Before Instruction:  
w = 0x01
C = x
Z = x

After Instruction:  
w = 0x01
C = 1 if result +
Z = 0

Case 2: Before Instruction:  
w = 0x02
C = x
Z = x

After Instruction:  
w = 0x00
C = 1 ; result = 0
Z = 1

Case 3: Before Instruction:  
w = 0x03
C = x
Z = x

After Instruction:  
w = 0xff
C = 0 ; result -
Z = 0

Example 2

```
sublw myreg
```

Before Instruction:  
w = 0x10
[myreg] = 0x37

After Instruction  
w = 0x27
C = 1 ; result +
SUBWF  Subtract w from f

Syntax:  [ label ] SUBWF f,d
Operands:  f in range 0 to 127
          d is either 0 or 1
Operation:  (f) - (W) -> destination
Status Affected:  C, DC, Z
Description:  Subtract (2's complement method) w register
               from register 'f'. If 'd' is 0 the result is stored
               in the w register. If 'd' is 1 the result is stored
               back in register 'f'.

Words:  1
Cycles:  1

Example 1

    subwf  reg1,1
Case 1:  Before Instruction:  reg1 = 3
         w = 2
         C = x
         Z = x

         After Instruction:    reg1 = 1
         w = 2
         C = 1; result +
         Z = 0

Case 2:  Before Instruction:  reg1 = 2
         w = 2
         C = x
         Z = x

         After Instruction:    reg1 = 0
         w = 2
         C = 1; result = 0
         Z = 1

Case 3:  Before Instruction:  reg1 = 1
         w = 2
         C = x
         Z = x

         After Instruction:    reg1 = 0xff
         w = 2
         C = 0; result is -
         Z = 0
**SWAPF**  
Swap Nibbles in f

Syntax: \[ label \] SWAPF f,d  
Operands: f in range 0 to 127  
d is either 0 or 1  
Operation: \( (f<3:0>) \rightarrow \text{destination}<7:4>, \)  
\( (f<7:4>) \rightarrow \text{destination}<3:0> \)  
Status Affected: None  
Description: The upper and lower nibbles of register 'f' are exchanged. If 'd' is 0 the result is placed in w register. If 'd' is 1 the result is placed in register 'f'.  
Words: 1  
Cycles: 1  
Example 1

```
swapf    reg,0  
Before Instruction: reg1 = 0xa5  
After Instruction:  reg1 = 0xa5  
W = 0x5a
```

Example 2

```
Swapf    INDF,1  
Before Instruction:  w = 0x17  
FSR = 0xc2  
[FSR] = 0x20  
After Instruction:  w = 0x17  
FSR = 0xc2  
[FSR] = 0x02
```

Example 3

```
swapf    reg,1  
Before Instruction:  reg1 = 0xa5  
After Instruction:  reg1 = 0x5a
```
**TRIS**  
Load TRIS Register

<table>
<thead>
<tr>
<th>Syntax:</th>
<th>[ label ] TRIS f</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operands:</td>
<td>f in range 5 to 7</td>
</tr>
<tr>
<td>Operation:</td>
<td>(W) -&gt; TRIS register f;</td>
</tr>
<tr>
<td>Status Affected:</td>
<td>None</td>
</tr>
<tr>
<td>Description:</td>
<td>The instruction is supported for code compatibility with the PIC16C5X products. Since TRIS registers are readable and writable, code can address these registers directly</td>
</tr>
<tr>
<td>Words:</td>
<td>1</td>
</tr>
<tr>
<td>Cycles:</td>
<td>1</td>
</tr>
</tbody>
</table>
| Example          | movlw B'00000000';            
                 | tris PORTB                    |
XORLW  Exclusive OR Literal with W

Syntax: [ label] XORLW k
Operands: k in range 0 to 255
Operation: (w).XOR. k -> W
Status Affected: Z
Description: The contents of the w register are XOR'ed with the eight bit literal 'k'. The result is placed in the w register.
Words: 1
Cycles: 1

Example 1
xorlw b'10101111'
Before Instruction: w = 1011 0101
After Instruction: w = 0001 1010
Z = 0

Example 2
xorlw myreg
Before Instruction: w = 0xaf
[Myreg] = 0x37
After Instruction: w = 0x18
Z = 0
**XORWF**

**Exclusive OR w with f**

**Syntax:**

```
[ label ] XORWF f,d
```

**Operands:**

- f in range 0 to 127
- d is either 0 or 1

**Operation:**

```
(W).XOR. (f) -> destination
```

**Status Affected:**

Z

**Description:**

Exclusive OR the contents of the w register with register 'f'. If 'd' is 0 the result is stored in the w register. If 'd' is 1 the result is stored back in register 'f'.

**Words:**

1

**Cycles:**

1

---

**Example 1**

```
xorwf   reg,1
```

**Before Instruction:**

```
w = 1011 0101
reg = 1010 1111
```

**After Instruction:**

```
reg = 0001 1010
w = 1011 0101
```

---

**Example 2**

```
xorwf   reg,0
```

**Before Instruction:**

```
w = 1011 0101
reg = 1010 1111
```

**After Instruction:**

```
reg = 1010 1111
w = 0001 1010
```

---

**Example 3**

```
xorwf   INDF,1
```

**Before Instruction:**

```
w = 1011 0101
FSR = 0xc2
[FSR] = 1010 1111
```

**After Instruction:**

```
w = 1011 0101
FSR = 0xc2
[FSR] = 0001 1010
```
Appendix D

Supplementary Programs

In this Appendix we have listed several programs that were developed while writing this book and for some reason were not used in the text. They are provided to the reader as a code grab-bag in the hope some may find a useful fragment or routine among those listed. Each program contains a description of its purpose and functionality. The code for the supplementary programs is available in the book's on-line software package.

; File: SecondCnt.ASM
; Date: April 29, 2006
; Author: Julio Sanchez
;
; Description:
; Using timer0 to delay one second at a signal rate of 1,000,000 beats per second
;==========================================
; switches
;==========================================
; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; * _CP_OFF
; * _PWRTE_ON Power-up timer ON/OFF
; _PWRTE_OFF
; _WDT_ON Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC Low power crystal oscillator
; * _XT_OSC External parallel resonator/crystal oscillator
; _HS_OSC High speed crystal resonator (8 to 10 MHz)
; Resonator: Murate Erie CSA8.00MG = 8 MHz
; _RC_OSC Resistor/capacitor oscillator (simplest, 20% error)
; |________* indicates setup values
processor 16f84A
include <pl6f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

虬;=====================================================
虬PIC register equates
虬;=====================================================
虬porta equ 0x05
虬portb equ 0x06
虬status equ 0x03
虬zequ 0x02
虬cequ 0x00
虬tmr0 equ 0x01
虬; countL equ 0x01 ; Alias for tmr0
虬;
虬;===================================================== 
虬variables in PIC RAM
虬;===================================================== 
虬Local variables 
虬cblock 0x0d ; Start of block
虬J ; counter J
虬K ; counter K
虬; 3-byte auxiliary counter. Low order byte is kept
虬; in the timer0 register
虬countM ; Medium byte
虬countH ; High byte

虬endc
虬;===================================================== 
虬main program
虬;===================================================== 
虬org 0 ; start at address 0
虬goto main
虬;
虬;===================================================== 
虬interrupt handler
虬; ==============================================================
虬org 0x04
虬goto IntServ
虬; ==============================================================
虬main program
虬; ==============================================================
虬main:
虬; Clear the watchdog timer and reset prescaler
虬clrf tmr0
虬clrwdt
虬; Set up the OPTION register bit map
movlw b'11011000'
; 7 6 5 4 3 2 1 0 <= OPTION bits
; | | | | | |__|__|______ PS2-PS0 (prescaler bits)
; | | | | | Values for Timer0
; | | | | | 000 = 1:2 001 = 1:4
; | | | | | 010 = 1:8 011 = 1:16
; | | | | | 100 = 1:32 101 = 1:64
; | | | | | 110 = 1:128 *111 = 1:256
; | | | | |_|__________ PSA (prescaler assign)
; | | | | 1 = to WDT
; | | | | *0 = to Timer0
; | | | ______________ TOSE (Timer0 edge select)
; | | 0 = increment on low-to-high
; | | *1 = increment in high-to-low
; | ____________ TOCS (TMR0 clock source)
; | *0 = internal clock
; | 1 = RA4/TOCKI bit source
; | ____________ INTEDG (Edge select)
; | *0 = falling edge
; ________________ RBPU (Pullup enable)
; 0 = enabled
; *1 = disabled

option
; Setup ports
movlw 0x00 ; Set port B to output
tris portb
clrf portb ; All port B to 0
; Port A is not used in this program
mloop:
bsf portb,0
call TM0delay
bcf portb,0
call TM0delay
goto mloop

;================================================================================
; one second delay sub-routine
; using Timer0
;================================================================================

Routine logic:
; The prescaler is assigned to timer0 and setup so
; that the timer runs at 1:2 rate. This means that
; every time the counter reaches 128 (0x80) a total
; of 256 machine cycles have elapsed. The value 0x80
; is detected by testing bit 7 of the counter
; register. This method gives the routine a total of
; 128 machine cycles before the next counter beat must
; be acknowledged.

TM0delay:
; Timer is designed to count from 0 to 1,000,000
; 1,000,000 = 0x0f 0x42 0x40
;
; ----- ---- ----
; | | |___ (see note)
; | |________ countM
; |_____________ countH

; Note:
; The initial count of 0x40 (64 decimal) is ensured
; by initializing the tmr0 register to count 32 timer
; beats at the 1:2 prescaler rate. 128 - 32 = 96 = 0x60
; Initialize the counters:
    movlw 0x0f
    movwf countH
    movlw 0x42
    movwf countM
    movlw 0x60
    movwf tmr0

; Routine tests timer overflow by testing bit 7 of
; the tmr0 register.

    movlw 3
    subwf tmr0,w
    btfsc status,c
    goto cycle

; Subtract 256 from beat counter by decrementing the
; mid-order byte
    decfsz countM,f
    goto cycle ; Continue if mid-byte not
zero

; At this point the mid-order byte has overflowed.
; High-order byte must be decremented.
    decfsz countH,f
    goto cycle

; At this point one second has elapsed
    return

end
; File name: SevenSeg.asm
; Date: April 19, 2006
; Author: Julio Sanchez
;
; Reference: SevenSeg Circuit and Board
;
; Description:
; Test program for reading four toggle switches and
; displaying the represented hex number on seven-segment
; LED. Also contains a pushbutton switch to activate a
; piezo buzzer. Switches are wired active low.
;
; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; * _CP_OFF
; * _PWRTE_ON Power-up timer ON/OFF
; _PWRTE_OFF
; _WDT_ON Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC Low power crystal oscillator
; * _XT_OSC External parallel resonator/crystal oscillator

; _HS_OSC High speed crystal resonator (8 to 10 MHz)
; Resonator: Murate Erie CSA8.00M G=8M Hz
; _RC_OSC Resistor/capacitor oscillator (simplest, 20% error)
;
; | * indicates setup values
;
;=======
; setup and configuration
;========

processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

; constant definitions
; (per circuit wiring diagram)
#define Pb_sw 4 ; Port A line 4 to push button switch

; PIC register equates
;================================================================
Porta equ 0x05
Portb equ 0x06
;================================================================
;  local variables
;=================================
cblock 0x0c ; Start of block
J ; counter J
K ; counter K
endc
;=================================

org 0 ; start at address 0

main:
; Port A. Five low-order lines set for input
movlw B'00011111' ; w = 00011111 binary
tris porta ; port A (lines 0 to 4) to
input
; Port B. All eight lines for output
movlw B'00000000' ; w := 00000000 binary
tris portb ; port B to output

; Pushbutton switch processing
;=================================
pbutton:
; Push button switch on demo board is wired to port A bit 4
; Switch logic is active low
btfss porta,Pb_sw ; Test and skip if switch bit
; set
goto buzzit ; Buzz if switch ON,
; At this point port A bit 4 is set (switch is off)
call buzoff ; Buzzer off
goto readdip ; Read DIP switches
buzzit:
call buzon ; Turn on buzzer
goto pbutton

;=================================
; dip switch monitoring
;=================================
readdip:
; Read port A switches
movf porta,w ; Port A bits to w
; Since board is wired active low then all switch bits
; must be negated. This is done by XORing with 1-bits
xorlw b'11111111' ; Invert all bits in w
; Mask off 4 high-order bits
andlw b'00001111'; And with mask

; At this point the w register contains a 4-bit value
; in the range 0 to 0xf. Use this value (in w) to
; obtain seven-segment display code

;================================
; routine to returns 7-segment codes
;================================

segment:
addwf PCL,f ; PCL is program counter latch
retlw 0x3f ; 0 code
retlw 0x06 ; 1
retlw 0x5b ; 2
retlw 0x4f ; 3
retlw 0x66 ; 4
retlw 0x6d ; 5
retlw 0x7d ; 6
retlw 0x07 ; 7
retlw 0x7f ; 8
retlw 0x6f ; 9
retlw 0x77 ; A
retlw 0x7c ; B
retlw 0x39 ; C
retlw 0x5b ; D
retlw 0x79 ; E
retlw 0x71 ; F
retlw 0x7f ; Just in case all on

;============================
; piezo buzzer ON
;============================
; Routine to turn on piezo buzzer on port B bit 7

buzon:
bsf portb,7 ; Tune on bit 7, port B
return

;============================
; piezo buzzer OFF
;============================
; Routine to turn off piezo buzzer on port B bit 7

buzoff:
bcf portb,7 ; Bit 7 port b clear
return

; long delay sub-routine
; (for code testing)

long_delay

    movlw   D'200';    w = 200 decimal
    movwf   J         ; J = w

jloop:    movwf   K         ; K = w
kloop:    decfsz  K,f       ; K = K-1, skip next if zero

    goto   kloop

    decfsz  J,f       ; J = J-1, skip next

if zero

    goto   jloop
return
end
Program to test sending strings to LCD memory directly
Program uses delay loops for interface timing.
WARNING:
Code assumes 4Mhz clock. Delay routines must be
edited for faster clock

Displays: Minnesota State, Mankato

;===========================
; switches
;===========================
; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; * _CP_OFF
; * _PWRTE_ON Power-up timer ON/OFF
; * _PWRTE_OFF
; _WDT_ON Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC Low power crystal oscillator
; * _XT_OSC External parallel resonator/crystal oscillator
; _HS_OSC High speed crystal resonator (8 to 10 MHz)
; Resonator: Murate Erie CSA8.00MG = 8 MHz
; _RC_OSC Resistor/capacitor oscillator (simplest, 20%
error)
; |
; |_____ * indicates setup values

;===========================
; setup and configuration
;===========================
processor 16f84A
#include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

; constant definitions
; for PIC-to-LCD pin wiring and LCD line addresses
#define E_line 1 ;|
#define RS_line 2 ;| -- from wiring diagram
#define RW_line 3 ;|
; LCD line addresses (from LCD data sheet)
```c
#define LCD_1 0x80 ; First LCD line constant
#define LCD_2 0xc0 ; Second LCD line constant
; Note: The constants that define the LCD display line addresses have the high-order bit set in order to facilitate the controller command;
;
;PIC register equates
;
;variables in PIC RAM
;
; Reserve 16 bytes for string buffer
cblock 0x0c
   strData
endc
; Leave 16 bytes and Continue with local variables
cblock 0x1d ; Start of block
   count1 ; Counter # 1
   count2 ; Counter # 2
   count3 ; Counter # 3
   pic_ad ; Storage for start of text area
            ; (labeled strData) in PIC RAM
   J ; counter J
   K ; counter K
   index ; Index into text table (also used ; for auxiliary storage)
endc

;program
;
org 0 ; start at address
   goto main
; Space for interrupt handlers
org 0x08

main:
   movlw b'00000000' ; All lines to output
   tris porta ; in port A
   tris portb ; and port B
   movlw b'00000000' ; All outputs ports low
   movwf porta
```
movwf portb
; Wait and initialize HD44780
    call delay_5       ; Allow LCD time to initialize itself
    call initLCD       ; Then do forced initialization
    call delay_5       ; (Wait probably not necessary)
; Store base address of text buffer in PIC RAM
    movlw 0x0c          ; Start address of text buffer
    movwf pic_ad        ; to local variable
.displayName="Supplementary Programs"

;=========================;
; test routine
;=========================;
; Set DDRAM address to start of first line
    call line1
; Store characters and send directly
    movlw 'H'
    movwf portb
    call pulseE
    movlw 'e'
    movwf portb
    call pulseE
    movlw 'l'
    movwf portb
    call pulseE
    movlw 'l'
    movwf portb
    call pulseE
    movlw 'o'
    movwf portb
    call pulseE
    call delay_5
;=========================
; done!
;=========================
loopHere:
    goto loopHere       ;done

;*****************************************************************************
; INITIALIZE LCD PROCEDURE
;*****************************************************************************
initLCD
; Initialization for Densitron LCD module as follows:
;  8-bit interface
;  2 display lines of 16 characters each
; cursor on
; left-to-right increment
; cursor shift right
; no display shift
;*************************
; COMMAND MODE
;*************************
bcf porta,E_line ; E line low
bcf porta,RS_line ; RS line low for command
bcf porta,RW_line ; Write mode
call delay_125 ; delay 125 microseconds
;*************************
; FUNCTION SET
;*************************
movlw 0x38 ; 00111000 (FUNCTION SET)
; | | | |__ font select:
; | | | 1 = 5x10 in 1/8 or 1/11
; | | 0 = 1/16 dc
; | | ___ Duty cycle select
; | 0 = 1/8 or 1/11
; 1 = 1/16
; |___ Interface width
; 0 = 4 bits
; 1 = 8 bits
; ___ FUNCTION SET COMMAND
movwf portb ; 0011 1000
call pulseE ; pulseE and delay

;*************************
; DISPLAY OFF
;*************************
movlw 0x08 ; 00001000 (DISPLAY ON/OFF)
; | | | |___ Blink character
; | | | 1 = on, 0 = off
; | | ___ Cursor on/off
; | 1 = on, 0 = off
; |___ Display on/off
; 1 = on, 0 = off
; ___ COMMAND BIT
movwf portb
call pulseE ; pulseE and delay

;*************************
; DISPLAY AND CURSOR ON
;*************************
movlw 0x0e ; 000001110 (DISPLAY ON/OFF)
; | | | |___ Blink character
; | | 1 = on, 0 = off
movwf portb
    call pulseE ;pulseE and delay

;*******************************
; ENTRY MODE SET
;*******************************
    movlw 0x06 ;00000110 (ENTRY MODE SET)
        ; | | |___ display shift
        ; | | 1 = shift
        ; | | 0 = no shift
        ; | | |___ cursor increment
        ; | | 1 = left-to-right
        ; | | 0 = right-to-left
        ; | | |___ COMMAND BIT
    movwf portb ;00000110
    call pulseE

;*******************************
; CURSOR/DISPLAY SHIFT
;*******************************
    movlw 0x14 ;00010100 (CURSOR/DISPLAY SHIFT)
        ; | | | |_|___ don't care
        ; | |__ cursor/display shift
        ; | 00 = cursor shift left
        ; | 01 = cursor shift right
        ; | 10 = cursor and display shifted left
        ; | 11 = cursor and display shifted right
        ; | | |___ COMMAND BIT
    movwf portb ;0001 1111
    call pulseE

;*******************************
; CLEAR DISPLAY
;*******************************
    movlw 0x01 ;00000001 (CLEAR DISPLAY)
        ; | | |___ COMMAND BIT
    movwf portb ;0000 0001
    call pulseE
call delay_5 ;delay 5 milliseconds after init
return

;******************************************************
; DELAY AND PULSE PROCEDURES
;******************************************************

;=======================
; Procedure to delay
; 42 microseconds
;=======================
delay_125
    movlw D'42' ; Repeat 42 machine cycles
    movwf count1 ; Store value in counter
repeat
    decfsz count1,f ; Decrement counter
go to repeat ; Continue if not 0
return ; End of delay

;--------------------
; Procedure to delay
; 5 milliseconds
;--------------------
delay_5
    movlw D'41' ; Counter = 41
    movwf count2 ; Store in variable
delay
    call delay_125 ; Delay
    decfsz count2,f ; 40 times = 5 milliseconds
    goto delay
return ; End of delay

;-----------------------
; pulseE E line
;-----------------------
pulseE
    bsf porta,E_line ;pulse E line
    bcf porta,E_line
    call delay_125 ;delay 125 microseconds
return

;--------------------------
; long delay sub-routine
; (for debugging)
;--------------------------
long_delay
    movlw D'200' ; w = 200 decimal
    movwf J ; J = w
jloop:     movwf K ; K = w
kloop:    decfsz K,f ; K = K-1, skip next if zero
        goto kloop
    decfsz J,f ; J = J-1, skip next if zero
goto jloop
return

;========================================
; LCD display procedure
;========================================
; Sends 16 characters from PIC buffer with address stored
; in variable pic_ad to LCD line previously selected
display16:
; Set up for data
bcf porta,E_line ; E line low
bsf porta,RS_line ; RS line low for control
call delay_125 ; Delay
; Set up counter for 16 characters
movlw D'16' ; Counter = 16
movwf count3
; Get display address from local variable pic_ad
movf pic_ad,w ; First display RAM address to W
movwf fsr ; W to FSR
getchar:
movf indf,w ; get character from display RAM
movwf portb ; location pointed to by file select
; register
movwf portb
call pulseE ; send data to display
; Test for 16 characters displayed
decfsz count3,f ; Decrement counter
goto nextchar ; Skipped if done
return
nextchar:
incf fsr,f ; Bump pointer
goto getchar

;========================================
; blank buffer
;========================================
; Procedure to store 16 blank characters in PIC RAM
; buffer starting at address stored in the variable
; pic_ad
blank16:
movlw D'16' ; Setup counter
movwf count1
movf pic_ad,w ; First PIC RAM address
movwf fsr ; Indexed addressing
movlw 0x20 ; ASCII space character
storeit:
movwf indf ; Store blank character in PIC RAM
; buffer using fsr register
decfsz count1,f ; Done?
goto incfsr ; no
incfsr:
   incf  fsr,f  ; Bump fsr to next buffer
space
   goto   storeit

;========================
; Set address register
; to LCD line 1
;========================
; ON ENTRY:
; Address of LCD line 1 in constant LCD_1
line1:
   bcf    porta,E_line ; E line low
   bcf    porta,RS_line ; RS line low, set up for
                        ; control
   call   delay_125 ; delay 125 microseconds
; Set to second display line
   movlw   LCD_1 ; Address and command bit
   movwf   portb
   call    pulseE ; Pulse and delay
; Set RS line for data
   bsf    porta,RS_line ; Setup for data
   call    delay_125 ; Delay
   return

;========================
; Set address register
; to LCD line 2
;========================
; ON ENTRY:
; Address of LCD line 2 in constant LCD_2
line2:
   bcf    porta,E_line ; E line low
   bcf    porta,RS_line ; RS line low, setup for
                        ; control
   call   delay_125 ; delay
; Set to second display line
   movlw   LCD_2 ; Address with high-bit set
   movwf   portb
   call    pulseE ; Pulse and delay
; Set RS line for data
   bsf    porta,RS_line ; RS = 1 for data
   call    delay_125 ; delay
   return

;===============================
; first text string procedure
;===============================
storeMSU:
; Procedure to store in PIC RAM buffer the message contained in the code area labeled msg1
; ON ENTRY:
;     variable pic_ad holds address of text buffer in PIC RAM
;     w register hold offset into storage area
;     msg1 is routine that returns the string characters and a zero terminator
;     index is local variable that hold offset into text table. This variable is also used for temporary storage of offset into buffer
; ON EXIT:
;     Text message stored in buffer
;     Store offset into text buffer (passed in the w register) in temporary variable
movwf index ; Store w in index
; Store base address of text buffer in fsr
movf pic_ad,w ; first display RAM address to W
addwf index,w ; Add offset to address
movwf fsr ; W to FSR
; Initialize index for text string access
movlw 0 ; Start at 0
movwf index ; Store index in variable
; w still = 0
get_msg_char:
call msg1 ; Get character from table
; Test for zero terminator
andlw 0x0ff
btfsc status,z ; Test zero flag
goto endstr1 ; End of string
; ASSERT: valid string character in w
; store character in text buffer (by fsr)
movwf indf ; store in buffer by fsr
incf fsr,f ; increment buffer pointer
; Restore table character counter from variable
movf index,w ; Get value into w
addlw 1 ; Bump to next character
movwf index ; Store table index in variable
goto get_msg_char ; Continue
endstr1:
return

; Routine for returning message stored in program area
msg1:
addwf PCL,f ; Access table
retlw 'M'
retlw 'i'
retlw 'n'
retlw 'n'
retlw 'e'
retlw 's'
retlw 'o'
retlw 't'
retlw 'a'
retlw 0

;=================================
; second text string procedure
;=================================
storeUniv:
; Processing identical to procedure StoreMSU
    movwf index ; Store w in index
; Store base address of text buffer in fsr
    movf pic_ad,0 ; first display RAM address to W
    addwf index,0 ; Add offset to address
    movwf fsr ; W to FSR
; Initialize index for text string access
    movlw 0 ; Start at 0
    movwf index ; Store index in variable
; w still = 0
get_msg_char2:
    call msg2 ; Get character from table
; Test for zero terminator
    andlw 0x0ff
    btfsc status,z ; Test zero flag
    goto endstr2 ; End of string
; ASSERT: valid string character in w
; store character in text buffer (by fsr)
    movwf indf ; Store in buffer by fsr
    incf fsr,f ; Increment buffer pointer
; Restore table character counter from variable
    movf index,w ; Get value into w
    addlw 1 ; Bump to next character
    movwf index ; Store table index in variable
    goto get_msg_char2 ; Continue
endstr2:
    return

; Routine for returning message stored in program area
msg2:
    addwf PCL,f ; Access table
    retlw 'S'
    retlw 't'
    retlw 'a'
    retlw 't'
Supplementary Programs

retnl "e"
retnl ","
retnl 0x20
retnl "M"
retnl "a"
retnl "n"
retnl "k"
retnl "a"
retnl "t"
retnl "o"
retnl 0

done
; File: TestDemo1.asm
; Date: June 2, 2006
; Author: Julio Sanchez
; Processor: 16F84A

; Description:
; Program to exercise the demonstration circuit and board
; number 1

; Switches

Switches used in __config directive:

; _CP_ON Code protection ON/OFF
; _CP_OFF
; * _PWRTE_ON Power-up timer ON/OFF
; _PWRTE_OFF
; _WDT_ON Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC Low power crystal oscillator
; * _XT_OSC External parallel resonator/crystal oscillator
; _HS_OSC High speed crystal resonator (8 to 10 MHz)
; Resonator: Murate Erie CSA8.00MG = 8 MHz
; _RC_OSC Resistor/capacitor oscillator

; __config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

; constants

; #define dummy 100

; variables in PIC RAM

; with local variables

; cblock 0x0c ; Start of block

; hexDig ; Hex digit counter

; count1 ; Counter # 1

; j ; counter J

; k ; counter K

; endc

; PROGRAM
org 0 ; start at address 0
go to main

; Space for interrupt handlers
org 0x08
main:
; Port A (5 lob) for input
movlw B'00011111' ; w := 00001111 binary
tris PORTA ; port A (lines 0 to 4) to input
; Port bit (8 lines) for output
movlw B'00000000' ; w := 00000000 binary
tris PORTB ; port B to output

; Pushbutton switch processing
pbutton:
; Push button switch on demo board is wired to RA4
; Switch logic is active low
btfss PORTA,4 ; Test and skip if bit is set
go to buzzit ; Buzz if switch ON
; At this point port A bit 4 is set (switch is off)
call buzoff ; Buzzer off
go to readdip ; Read DIP switches
buzzit:
call buzon ; Turn on buzzer
go to pbutton

; DIP switch processing
readdip:
movf PORTA,w ; Port A bits to w
; If board uses active low then all switch bits must be negated
; This is done by XORing with 1-bits
xorlw b'11111111' ; Invert all bits in w
; Eliminate all 4 high order bits (just in case)
andlw b'00001111' ; And with mask
; Get digit into w
call segment ; get digit code
movwf PORTB ; Display digit
call delay ; Give time
; Update digit and loop counter
go to pbutton

; 7-segment table of hex codes
addwf PCL,f ; PCL is program counter latch
retlw 0x3f ; 0 code
retlw 0x06 ; 1
retlw 0x5b ; 2
retlw 0x4f ; 3
retlw 0x66 ; 4
retlw 0x6d ; 5
retlw 0x7d ; 6
retlw 0x07 ; 7
retlw 0x7f ; 8
retlw 0x6f ; 9
retlw 0x39 ; C
retlw 0x5b ; D
retlw 0x79 ; E
retlw 0x71 ; F
retlw 0x7f ; Just in case all on

; Routine to turn on piezo buzzer on port B bit 7
buzon:
bsf PORTB,7 ; Tune on bit 7, port B
return

; Routine to turn off piezo buzzer on port B bit 7
buzoff:
bcf PORTB,7 ; Bit 7 port b clear
return

delay:
movlw .200 ; w = 200 decimal
movwf j ; j = w
jloop:
movwf k ; k = w
kloop:
decfsz k,f ; k = k-1, skip next if zero
goto kloop
decfsz j,f ; j = j-1, skip next if zero
goto jloop
return
end
; File: Timer0.ASM
; Date: April 27, 2006
; Author: Julio Sanchez
; Processor: a6F84A
;
; Description:
; Program to demonstrate programming of the 16F84A
; TIMER0 module. Program flashes eight LEDs in sequence
; counting from 0 to 0xff. Timer0 is used to delay
; the count.

; switches

; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
;  * _CP_OFF
;  * _PWRTE_ON Power-up timer ON/OFF
;  _PWRTE_OFF
;  _WDT_ON Watchdog timer ON/OFF
;  * _WDT_OFF
;  _LP_OSC Low power crystal oscillator
;  * _XT_OSC External parallel resonator/crystal oscillator
;  _HS_OSC High speed crystal resonator (8 to 10 MHz)
;  Resonator: Murate Erie CSA8.00MG = 8 MHz
;  _RC_OSC Resistor/capacitor oscillator (simplest, 20%
; error)
;
; |___ * indicates setup values

processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

; variables in PIC RAM

; None in this application

; main program

org 0 ; start at address 0
goto main

; interrupt handler

org 0x08
main:

; Clear the watchdog timer and reset prescaler
clrwdt

; Set up the OPTION register bit map
movlw b'11010111'

; 7 6 5 4 3 2 1 0 <= OPTION bits
; | | | | | | | | PS2-PS0 (prescaler bits)
; | | | | | | | | Values for Timer0
; | | | | | 000 = 1:2 001 = 1:4
; | | | | | 010 = 1:8 011 = 1:16
; | | | | | 100 = 1:32 101 = 1:64
; | | | | 110 = 1:128 *111 = 1:256
; | | | | |__________ PSA (prescaler assign)
; | | | | | 0 = to WDT
; | | | | *0 = to Timer0
; | | | | |__________ TOSE (Timer0 edge select)
; | | | | 0 = increment on low-to-high
; | | | | *1 = increment in high-to-low
; | | | | |__________ TOCS (TMR0 clock source)
; | | | | *0 = internal clock
; | | | 1 = RA4/TOCKI bit source
; | | |__________ INTEDG (Edge select)
; | | *0 = falling edge
; |__________ RBPU (Pullup enable)
; | | 0 = enabled
; | *1 = disabled

; Setup ports
movlw 0x00 ; Set port B to output
tris PORTB
clrf PORTB ; All port B to 0

; Port A is not used in this program
mloop:

incf PORTB,f ; Add 1 to register value
call TM0delay
goto mloop

;******************************
; delay sub-routine
; uses Timer0
;******************************
TM0delay:

; Initialize the timer register
clrf TMR0 ; Clear SFR for Timer0

; Routine tests the value in the TMR0 register by
; subtracting 0xff from the value in TMR0. The zero flag
; is set if TMR0 = 0xff

cycle:
    movf TMR0, w       ; Timer to w
    sublw 0xff          ; Subtract max value
    btfss STATUS, Z     ; Zero flag is set if value in TMR0 = 0xff
    goto cycle         ; Repeat
return

End
Using the timer to generate a signal at 1 Mhz

Switches

Switches used in __config directive:

- _CP_ON Code protection ON/OFF
- * _CP_OFF
- * _PWRTE_ON Power-up timer ON/OFF
- _PWRTE_OFF
- _WDT_ON Watchdog timer ON/OFF
- * _WDT_OFF
- _LP_OSC Low power crystal oscillator
- * _XT_OSC External parallel resonator/crystal oscillator

- _HS_OSC High speed crystal resonator (8 to 10 MHz)
- Resonator: Murate Erie CSA8.00MG = 8 MHz
- _RC_OSC Resistor/capacitor oscillator (simplest, 20% error)

| * indicates setup values

processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

PIC register equates

porta equ 0x05
Portb equ 0x06
Status equ 0x03
z equ 0x02
tmr0 equ 0x01

variables in PIC RAM

Local variables

chblock 0x0d ; Start of block
J ; counter J
K ; counter K
countL ; Auxiliary counter
countH ; ISR counter
endc

; main program
org 0 ; start at address 0
goto main

; interrupt handler
org 0x04

goto IntServ

main:
; Clear the watchdog timer and reset prescaler
clrwdt

; Set up the OPTION register bit map
movlw b'11010011'

; Values for Timer0
000 = 1:2 001 = 1:4
010 = 1:8 011 = 1:16
100 = 1:32 101 = 1:64
110 = 1:128 *111 = 1:256

; PSA (prescaler assign)
1 = to WDT
0 = to Timer0

; TOSE (Timer0 edge select)
0 = increment on low-to-high
*1 = increment in high-to-low

; TOCS (TMRO clock source)
*0 = internal clock
1 = RA4/TOCKI bit source

; INTEDG (Edge select)
*0 = falling edge

; RBPU (Pullup enable)
0 = enabled
*1 = disabled

option

; Setup ports
movlw 0x00 ; Set port B to output
tris portb
clrf portb ; All port B to 0

; Port A is not used in this program
mloop:
bsf portb,0
call TM0delay
bcf portb,0
call TM0delay
goto mloop

;****************************
; delay sub-routine
; uses Timer0
;****************************
TM0delay:
; Initialize the timer register
    clrf tmr0 ; Clear SFR for Timer0
; Routine tests the value in the tmr0 register by
; xoring with a mask of all ones. The operation sets
; the zero flag if tmr0 is zero.
    cycle:
        movf tmr0,w ; Timer to w
        sublw 0xff ; Subtract max value
        btfss status,z ; Test for zero
        goto cycle ; Repeat
    return

end
; File name: TTYUsart.asm
; Last update: May, 2006
; Author: Julio Sanchez
; Processor: 16F84A
;
; Description:
; Program to emulate USART operation in PIC code. Uses
; PIC-to-LCD interface. Display has 2 lines, each with
; 16 characters.
; Program operation:
; Characters received from the RS232 line are displayed on
; the LCD. LCD lines scroll automatically. A pushbutton
; activates the send operation by transmitting the text
; string: Ready- which is also displayed on the LCD.
; Program communications and LCD parameters are stored in
; #define statements. These statements can be edited to
; accommodate a different set-up. Program uses delay loops
; for interface timing.
;
; WARNING:
; Code assumes 4Mhz clock. Delay routines must be
; edited for faster clock
;
; BAUD RATE CALCULATIONS:
; A 4Mhz clock oscillator has a clock frequency of 1 Mhz:
; Since the baud rate is the number of clock cycles per
; second, for a 4Mhz clock it is:
; 1
; bit time = ------ sec. = 208.33 microseconds
; 4,800
; Calculating one half the baud rate allows resetting the
; clock from the edge to the center of a time pulse:
;
; |<======== falling edge of start bit
; | |<======== center of bit time
; >| |< one-half baud rate
; | |
; ________ | __________.
; | __________|___________|
; 208/2 = 104
; The PIC clock counts up from 0 to 255. So to implement
; a 104 microsecond delay we must start counting at
; clock beat:
; 255 - 104 = 151
; plus one microsecond for movlw instruction used to
; initialize the clock:
; 151 + 1 = 152
; For one full baud rate delay:
; 255 - 208 = 47 + 1 = 48
; The following two constants are stored in #define statements:
; halfBaud = 152
; fullBaud = 48
; Setting the prescaler to TMR0 reduces the baud rate to one-half. Other prescaler values will reduce the baud rate accordingly.
;
; Wiring diagram:
; RB4-RB7 ===> LCD data lines 4 to 7 (output)
; RB0 =======> MAX202 T2in line (output)
; RA0 =======> MAX202 R2out line (input)
; RA1 =======> LCD E line (output)
; RA2 =======> LCD RS line (output)
; RA3 =======> LCD R/W line (output - not used)
; RA4 =======> Pushbutton switch 1
; (input - active low)
;
; Switches

; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; * _CP_OFF
; * _PWRTE_ON Power-up timer ON/OFF
; _PWRTE_OFF
; _WDT_ON Watchdog timer ON/OFF
; * _WDT_OFF
; _LP_OSC Low power crystal oscillator
; * _XT_OSC External parallel resonator/crystal oscillator
; _HS_OSC High speed crystal resonator (8 to 10 MHz)
; Resonator: Murate Erie CSA8.00MG = 8 MHz
; _RC_OSC Resistor/capacitor oscillator
; | (simplest, 20% error)
; |
; |____ * indicates setup values presently selected
;
;setup and configuration
;
processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_OFF & _PWRTE_ON & _CP_OFF

;============================================================================
Macros to select the register banks

Bank0 MACRO ; Select RAM bank 0
  bcf STATUS,RP0
ENDM

Bank1 MACRO ; Select RAM bank 1
  bsf STATUS,RP0
ENDM

; Constant definitions
; for PIC-to-LCD pin wiring and LCD line addresses
#define E_line 1 ; | -- from wiring diagram
#define RS_line 2 ; |
#define RW_line 3 ; |
#define LCD_1 0x80 ; First LCD line constant
#define LCD_2 0xc0 ; Second LCD line constant
#define LCDlimit .16; Number of characters per line
#define halfBaud .152 ; For one-half bit time
#define fullBaud .48 ; For one full bit time
;
; Note: The constants that define the LCD display line
; addresses have the high-order bit set in
; order to facilitate the controller command
;
; PIC register and flag equates
;z equ 2 ; Zero flag
c equ 0 ; Carry flag

; Buffer and variables in PIC RAM
;
; Create a 16-byte storage area
  cblock 0x0c ; Start of first data block
  lineBuf ; buffer for text storage
endc
;
; Leave 16 bytes and Continue with local variables
  cblock 0x1c ; Second data block
  count1 ; Counter # 1
  count2 ; Counter # 2
  J ; counter J
K ; counter K
store1 ; Local temporary storage
store2 ; Storage # 2

; For LCDscroll procedure
LCDcount ; Counter for characters per line
LCDline ; Current display line (0 or 1)
bufPtr ; Buffer pointer

; Variables for serial communications
tempData ; Temporary storage for bit manipulations
rcvData ; Final storage for received character
bitCount ; Bit counter
sendData ; Character to send

code

;============================================
; main program
;============================================
org 0 ; start at address

main:
Bank1
movlw b'00010001' ; Port A lines I/O setup
movwf TRISA
; RA0 = RS232 input (R2out)
; RA4 = Pushbutton SW # 1

movlw b'00000000' ; Port B lines as follow:
movwf TRISB

movlw b'00000000' ; Port B lines as follow:

movlw b'00010001' ; Port A lines I/O setup
movwf TRISA
; RA0 = RS232 input (R2out)
; RA4 = Pushbutton SW # 1

movlw b'00000000' ; Port B lines as follow:
movwf TRISB

Bank0

; Clear bits in port A output lines
bcf PORTA,1
bcf PORTA,2
bcf PORTA,3

movlw b'00000000' ; All outputs ports low
movwf PORTB

; Wait and initialize HD44780
call delay_5 ; Allow LCD time to initialize
; itself
call delay_5
call initLCD ; Then do forced initialization
call delay_5 ; Wait again

; Set port B, line 0 high so start bit is detected
bsf PORTB,0
Program waits until pushbutton number 1 is pressed to continue execution. Pushbutton 1 is active low and wired to RA4

```
pb1Wait:
    btfsc PORTA,4       ; Test port A, line 4
    goto pb1Wait       ; Loop if not clear
```

Display and send "Ready-

```
; Set LCD base address
    call line1

; Initialize system for UART emulation at 2400 baud
    call initTTY

; Display on LCD and test serial transmission by sending the string 'Ready-

    movlw 'R'
    movwf sendData      ; Store in send register
    call sendData      ; Local LCD display procedure
    call sendTTY      ; Local send procedure
    movlw 'e'
    movwf sendData      ; Store in send register
    call sendData      ; Local LCD display procedure
    call sendTTY      ; Local send procedure
    movlw 'a'
    movwf sendData      ; Store in send register
    call sendData      ; Local LCD display procedure
    call sendTTY      ; Local send procedure
    movlw 'd'
    movwf sendData      ; Store in send register
    call sendData      ; Local LCD display procedure
    call sendTTY      ; Local send procedure
    movlw 'y'
    movwf sendData      ; Store in send register
    call sendData      ; Local LCD display procedure
    call sendTTY      ; Local send procedure
    movlw '-'
    movwf sendData      ; Store in send register
    call sendData      ; Local LCD display procedure
    call sendTTY      ; Local send procedure

; Init character counter and line counter variables for LCD line scroll procedure
    movlw 0x06         ; 6 characters already displayed
    movwf LCDcount
    clrf LCDline     ; LCD line counter
Supplementary Programs

;==================================
; monitor RS232 line
;==================================
nextChar:
    call rcvTTY ; Receive character
; Store character in local line buffer using indirect
; addressing
; 16-byte buffer named lineBuf starts at address 0x0c
; Register variable bufPtr holds offset into buffer
    movlw 0x0c ; Buffer base address
    addwf bufPtr,w ; Add pointer in w
    movwf FSR ; Value to index register
    movf rcvData, ; Character into w
    movwf INDF ; Store w in [FSR]
    incf bufPtr,f ; Bump pointer
; Send character (still in w)
    call send8 ; Display it
    call LCDscroll ; Scroll display lines
    goto nextChar ; Continue

;==================================
; initialize LCD for 4-bit mode
;==================================
initLCD:
; Initialization for Densitron LCD module as follows:
; 4-bit interface
; 2 display lines of 16 characters each
; cursor on
; left-to-right increment
; cursor shift right
; no display shift
;=======================
; set command mode | 
;=======================
    bcf PORTA,E_line ; E line low
    bcf PORTA,RS_line ; RS line low
    bcf PORTA,RW_line ; Write mode
    call delay_125 ; delay 125 microseconds
;***********************
; FUNCTION SET |
;***********************
    movlw 0x28 ; 00101000 (FUNCTION SET)
; | | | |__ font select:
; | | | 1 = 5x10 in 1/8 or 1/11
; | | | 0 = 1/16 dc
; | | | |___ Duty cycle select
; Set 4-bit mode command must be repeated
movlw 0x28
 call send8

;***************************|
; DISPLAY AND CURSOR ON |
;***************************|
movlw 0x0e
 call send8

;***************************|
; set entry mode |
;***************************|
movlw 0x06
 call send8

;***************************|
; cursor/display shift |
;***************************|
movlw 0x14
 call send8
call send8

movlw 0x01 ; 00000001 (CLEAR DISPLAY)
call send8

; Per documentation
call delay_5 ; Test for busy
return

;=======================
; Procedure to delay
; 42 microseconds
;=======================
delay_125
movlw D'42' ; Repeat 42 machine cycles
movwf count1 ; Store value in counter
repeat
    decfsz count1,f ; Decrement counter
goto repeat ; Continue if not 0
return ; End of delay

;=======================
; Procedure to delay
; 5 milliseconds
;=======================
delay_5
movlw D'41' ; Counter = 41
movwf count2 ; Store in variable
delay
    call delay_125 ; Delay
decfsz count2,f ; 40 times = 5 milliseconds
goto delay ; End of delay

;========================
; pulse E line
;========================
pulseE
    bsf PORTA,E_line ; Pulse E line
    nop
    bcf PORTA,E_line
return

;=============================
; long delay sub-routine
Appendix D

; (for debugging)
;===============================================
long_delay
    movlw D'200'  ; w = 200 decimal
    movwf J       ; J = w
jloop:    movwf K    ; K = w
kloop:    decfsz K,f ; K = K-1, skip next if zero
        goto kloop
    decfsz J,f  ; J = J-1, skip next if zero
    goto jloop
return
;===============================================
; send 2 nibbles in
; 4-bit mode
;===============================================
; Procedure to send two 4-bit values to port B lines
; 7, 6, 5, and 4. High-order nibble is sent first
; ON ENTRY:
;  w register holds 8-bit value to send
send8:
    movwf store1 ; Save original value
    call merge4 ; Merge with port B
    ; Now w has merged byte
    movwf PORTB  ; w to port B
    call pulseE ; Send data to LCD
    ; High nibble is sent
    movf store1,w ; Recover byte into w
    swapf store1,w ; Swap nibbles in w
    call merge4
    movwf PORTB
    call pulseE ; Send data to LCD
    call delay_125
    return
;===============================================
; merge bits
;===============================================
; Routine to merge the 4 high-order bits of the
; value to send with the contents of port B
; so as to preserve the 4 low-bits in port B
; Logic:
;     AND value with 1111 0000 mask
;     AND port B with 0000 1111 mask
;     Now low nibble in value and high nibble in
; port B are all 0 bits:
;     value = vvvv 0000
;     port B = 0000 bbbb
;     OR value and port B resulting in:
;     vvvv bbbb
; ON ENTRY:
; w contain value bits
; ON EXIT:
; w contains merged bits
merge4:
    andlw b'11110000'; ANDing with 0 clears the
    ; bit. ANDing with 1 preserves
    ; the original value
    movwf store2; Save result in variable
    movf PORTB,w ; port B to w register
    andlw b'00001111'; Clear high nibble in port b
    ; and preserve low nibble
    iorwf store2,w; OR two operands in w
    return

;===========================================
; Set address register
; to LCD line 1
;===========================================
; ON ENTRY:
; Address of LCD line 1 in constant LCD_1
line1:
    bcf PORTA,E_line ; E line low
    bcf PORTA,RS_line ; RS line low, set up for
    ; control
    call delay_5 ; busy?
    ; Set to second display line
    movlw LCD_1 ; Address and command bit
    call send8 ; 4-bit routine
    ; Set RS line for data
    bsf PORTA,RS_line ; Setup for data
    call delay_5 ; Busy?
    ; Clear buffer and pointer
    call blankBuf
    clrf bufPtr ; Clear
    return

;===========================================
; Set address register
; to LCD line 2
;===========================================
; ON ENTRY:
; Address of LCD line 2 in constant LCD_2
line2:
    bcf PORTA,E_line ; E line low
    bcf PORTA,RS_line ; RS line low, setup for
    ; control
    call delay_5 ; Busy?
    ; Set to second display line
movlw LCD_2 ; Address with high-bit set
call send8

; Set RS line for data
bsf PORTA,RS_line ; RS = 1 for data
call delay_5 ; Busy?

; Clear buffer and pointer
call blankBuf
crfr bufPtr
return

;==========================
; scroll LCD line 2
;==========================
; Procedure to count the number of characters displayed on 
each LCD line. If the number reaches the value in the 
constant LCDlimit, then display is scrolled to the second 
LCD line. If at the end of the second line, then the 
second line is scrolled to the first line and display 
continues at the start of the second line 
; reset to the first line.
LCDscroll:
incf LCDcount,f ; Bump counter

; Test for line limit
movf LCDcount,w
sublw LCDlimit ; Count minus limit
btfss STATUS,z ; Is count - limit = 0
goto scrollExit ; Go if not at end of line

; At this point the end of the LCD line was reached
; Test if this is also the end of the second line
movf LCDline,w
sublw 0x01 ; Is it line 1?
btfsc STATUS,z ; Is LCDline minus 1 = 0?
goto line2End ; Go if end of second line

; At this point it is the end of the top LCD line
call line2 ; Scroll to second line
crfr LCDcount ; Reset counter
incf LCDline,f ; Bump line counter
goto scrollExit

; End of second LCD line
line2End:
; Scroll second line to first line. Characters to be 
; scrolled are stored in buffer starting at address 0x0c.
; 16 characters are to be moved
; First clear LCD
call initLCD
call delay_5 ; Make sure not busy
; Set up for data
bcf PORTA,E_line ; E line low
bsf PORTA,RS_line ; RS line high for data
; Set up counter for 16 characters
movlw D'16' ; Counter = 16
movwf count2
; Get address of storage buffer
movlw 0x0c
movwf FSR ; W to FSR

getchar:
    movf INDF,w ; get character from display RAM
    ; location pointed to by file select
    ; register
    call send8 ; 4-bit interface routine

; Test for 16 characters displayed
    decfsz count2,f ; Decrement counter
    goto nextchar ; Skipped if done
; At this point scroll operation has concluded
    clrf LCDcount ; Clear counters
; Stay at line 2
    clrf LCDline
    incf LCDline,f
    call line2 ; Set for second line

scrollExit:
    return

nextchar:
    incf FSR,f ; Bump pointer
    goto getchar

;============================================================
; clear line buffer
;============================================================
; Use indirect addressing to store 16 blanks in the
; buffer located at 0x0c
blankBuf:
    Bank0
    movlw 0x0c ; Pointer to RAM
    movwf FSR ; To index register

blank16:
    clrf INDF ; Clear memory pointed at by FSR
    incf FSR,f ; Bump pointer
    btfss FSR,4 ; 000x0000 when bit 4 is set
    ; count reached 16
    goto blank16
    return

;============================================================
; initialize for TTY
;============================================================
; Procedure to initialize RS232 reception
initTTY:
; First initialize receiver to RS-232 line parameters
; Disable global and peripheral interrupts
; 7 6 5 4 3 2 1 0 <= INTCON bitmap
; | | | | | | | | Timer0 interrupt on overflow
; | | | | | | | | Global interrupts
    bcf INTCON,5 ; Disable TMR0 interrupts
    bcf INTCON,7 ; Disable global interrupts
    clrf TMR0 ; Reset timer
    clrwdt ; Clear WDT for prescaler
    ; assign

    movlw b'11010000' ; set up timer/counter
    movwf OPTION_REG

Bank1
; Set up the OPTION register bit map
; 7 6 5 4 3 2 1 0 0 0 0 <= setup
; | | | | | | | | PS2-PS0 (prescaler bits)
; | | | | | | | | Values for Timer0
; | | | | | | | | *000 = 1:2 001 = 1:4
; | | | | | | | | 010 = 1:8 011 = 1:16
; | | | | | | | | 100 = 1:32 101 = 1:64
; | | | | | | | | 110 = 1:128 111 = 1:256
; | | | | | | | | PSA (prescaler assign)
; | | | | | | | | 1 = to WDT
; | | | | | | | *0 = to Timer0
; | | | | | | | TOSE (Timer0 edge select)
; | | | | | | | 0 = increment on low-to-high
; | | | | | | | *1 = increment in high-to-low
; | | | | | | TOCS (TMR0 clock source)
; | | | | | | *0 = internal clock
; | | | | | | 1 = RA4/TOCKI bit source
; | | | | | INTEdg (Edge select)
; | | | | | 0 = falling edge
; | | | | | *1 = raising edge
; | | | | RBPU (Pullup enable)
; | | | | 0 = enabled
; | | | | *1 = disabled

    movlw b'11010000' ; set up timer/counter
    movwf OPTION_REG
    return

;=================================================================================
; receive character
Receive a single character through the serial port.
Assumes: 4800 baud, 8 data bits, no parity, 1 stop bit.
Receiving line is Port A, line 0
rcvTTY:

```assembly
    movlw 0x08 ; Counter for 8 bits
    movwf bitCount
```

The start of character transmission is signaled by
the sender by setting the line low

```assembly
    startBit:
        btfsc PORTA,0 ; Test for low on line
        goto startBit ; Go if not low
```

At this point the receiver has found the falling
edge of the start bit. It must now wait one and
one-half the baud rate to synchronize in the center
of the sender's first data bit,

```assembly
    ; offset to data bit
    ;=========================
    ; At this point we are at the center of the start bit
    ; Clock start count for one-half bit = 255 - 104 = 151
    ; Clock start count for one full bit = 255 - 208 = 47
    ; One clock cycle is added for the movwf instruction:
    ; clkHalf = 152 (for one-half bit countdown)
    ; clkFull = 48 (for one full bit countdown)
    movlw halfBaud ; Skip one-half bit
    movwf TMR0    ; Initialize tmr0 and start count
    bcf INTCON,2  ; Clear overflow flag
    ;=========================
    ; start bit
    ;=========================
    wait1:
        btfss INTCON,2 ; Timer count overflow?
        goto wait1    ; No, keep waiting
        btfsc PORTA,0 ; Check to see it is still low
        goto startBit ; No, it is high. False start
```

At this point the clock is at the center of the start
bit. The first data bit must be read one full baud
; period later
    movlw fullBaud ; One full bit delay
    movwf TMR0 ; Start timer
    bcf INTCON,2 ; clear tmr0 overflow flag

wait2:
    btfss INTCON,2 ; End of one full baud period?
    goto wait2 ; Wait if not end of period

; Timer is now at the center of the first/next data bit
; Timer must be reset immediately so that code will not
; lose synchronization with sender
    movlw fullBaud ; Skip to next data bit
    movwf TMR0 ; Restart timer
    bcf INTCON,2 ; Reset overflow flag

; Now the data bit can be read and stored
    movf PORTA, w ; Read port B
    movwf tempData ; Store in temporary variable
    rrf tempData, f ; Rotate bit 0 into carry flag
    rrf rcvData, f ; Rotate carry flag into storage
        ; register high-order bit
    decfsz bitCount, f ; End of data?
    goto wait2 ; Continue until 8 bits received

;============================================
; stop bit
;============================================
stopWait:
    btfss INTCON,2 ; Test time
    goto stopWait ; Wait
    return ; Exit

;============================================
; send character
;============================================
; Procedure to send one character through the RS232 line.
; Assumes: 2400 baud, 8 data bits, no parity, one stop bit
; Sending line is Port B, line 0
; ON ENTRY:
;     variable sendData holds character to send
sendTTY:
    movlw 0x08 ; Init bit counter
    movwf bitCount
    bcf PORTB, 0 ; Low for start bit
    movlw fullBaud ; For one baud space
    movwf TMR0 ; Start timer
    bcf INTCON,2 ; Clear timer flag

start2snd:
    btfss INTCON,2 ; Full baud done?
    goto start2snd ; No
    movlw fullBaud ; Reset for one full bit
; period
movwf TMR0  ; Start timer
bcf INTCON,2 ; Clear flag

; At this point the start bit has been sent
; Data follows
sendOut:
    rrf sendData,f ; Rotate bit into carry
    bcf PORTB,0 ; Assume data bit is 0
    btfsc STATUS,c ; Test if carry set
    bsf PORTB,0 ; Change bit to 1 if clear

; Hold bit for 1 baud period
timeBit:
    btfss INTCON,2 ; Wait for baud period to end
    goto timeBit ; Loop if not yet
    movlw fullBaud ; Reset timer
    movwf TMR0  ; Start timer
    bcf INTCON,2 ; Clear flag

; Test for last bit
decfsz bitCount,f ; Count this bit
    goto sendOut ; Continue if not last bit

; Done. Send stop bit
stopBit:
    bsf PORTB,0  ; High for stop bit

    btfss INTCON,2 ; Timer done?
    goto stopBit ; No

; Set port B line 0 high back again
bsf PORTB,0
    call delay_5    ; And hold
return

End
; File: Watchdog.asm
; Date: May 2, 2006
; Author: Julio Sanchez
;
; Description:
; Program to demonstrate the use of the watchdog timer
; in breaking out of an endless loop.
; A LED on port B, line 1, flashes on and off at 1/2
; second intervals for 20 iterations. At that time the
; program enters an endless loop. The watchdog timer
; times-out and restarts the program

;======================================================================
; switches
;======================================================================
; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; * _CP_OFF
; * _PWRTE_ON Power-up timer ON/OFF
; _PWRTE_OFF
; * _WDT_ON Watchdog timer ON/OFF
; _WDT_OFF
; _LP_OSC Low power crystal oscillator
; * _XT_OSC External parallel resonator/crystal oscillator
; _HS_OSC High speed crystal resonator (8 to 10 MHz)
; _RC_OSC Resistor/capacitor oscillator
; |
; |_____ * indicates setup values

;======================================================================
; setup and configuration
;======================================================================

processor 16f84A
include <p16f84A.inc>
__config _XT_OSC & _WDT_ON & _PWRTE_ON & _CP_OFF

;======================================================================
; PIC register equates
;======================================================================
porta equ 0x05
Portb equ 0x06
status equ 0x03
z equ 0x02
tmr0 equ 0x01

;======================================================================
; variables in PIC RAM
Supplementary Programs

; Local variables
  cblock 0x0d ; Start of block
  J ; counter J
  K ; counter K
  count1 ; Auxiliary counter
  count2 ; Second auxiliary counter
  old_w ; Context saving
  old_status ; Idem
endc

;=================================
; main program
;=================================
org 0 ; start at address 0
goto main

;=================================
; interrupt handler
;=================================
org 0x04

;=================================
; main program
;=================================
main:
; Setting the prescaler to the watchdog timer following
; the sequence recommended by Microchip
  movlw b'10010101' ; Clock source and some
  prescaler
  option
  clrf tmr0 ; Clear timer and prescaler
  movlw b'10111101' ; WDT, do not change prescale
  option ; again
; Reset watchdog timer
  clrwdt
; Final setting of OPTION register
  movlw b'10111000'
; Set up the OPTION register bit map
  7 6 5 4 3 2 1 0 <= OPTION bits
  | | | | | | | | PS2-PS0 (prescaler bits)
  | | | | | | | Values for WDT
  | | | | | | 000 = 1:1  001 = 1:2
  | | | | | | 010 = 1:4  011 = 1:8
  | | | | | 100 = 1:16 101 = 1:32
  | | | | 110 = 1:64  *111 = 1:128
  | | | | |_______________ FSA (prescaler assign)
  | | | | |*1 = to WDT
  | | | | 0 = to Timer0
option
movlw b'00000000' ; Port B is output
tris portb ; all others are output
clr portb ; All port B to 0
; Port A is not used by this program
;============================================
; flash LED 20 times
;============================================
; Program flashes LED wired to port B, line 2
; 5 times before entering the endless loop
movlw D'5' ; Number of iterations
movwf count2 ; To counter
lights:
movlw b'00000010' ; Mask with bit 1 set
xorwf portb,f ; Complement bit 1
call long_delay
call long_delay
call long_delay
call long_delay
decfsz count2,f ; Decrement counter
goto lights
clrwdt ; Clear watchdog
;============================================
; endless loop
;============================================
endless:
goto endless
;============================================
; delay sub-routine
;============================================
long_delay
movlw D'200' ; w = 20 decimal
movwf J ; J = w
jloop: movwf K ; K = w
kloop: decfsz K,f ; K = K-1, skip next if zero
clrwdt
goto kloop
if zero
    decfsz J,f ; J = J-1, skip next
    clrwdt
    goto jloop
    return
end
; Description:
; Receive character data through RS-232 line and store in
; 24LC04B EEPROM IC, using the I2C serial protocol in the
; PIC's MSSP module. Received characters are echoed on
; the second LCD line. When <Enter> key is detected (code
; 0x0d) the text stored in EEPROM memory is retrieved and
; displayed on the LCD. On startup the top LCD line displays
; the prompt: 'Receiving:'. At that time a message 'Rdy- ' is
; sent through the serial line so as to test the connection.
;
; Default serial line setting:
; 2400 baud
; no parity
; 1 stop bit
; 8 character bits
;
; Wiring:
; 24LC04B SDA line is wired to PIC RC4 (MSSP SDA)
; 24LC04B SCL line is wired to PIC RC3 (MSSP SCL)
; 24LC04B A0-A2 and WP lines are not used (GND)
;
; Program to use 4-bit PIC-to-LCD interface.
; Code assumes that LCD is driven by Hitachi HD44780
; controller and PIC 16F977. Display supports two lines
; each one with 20 characters. The length, wiring and base
; address of each display line is stored in #define
; statements. These statements can be edited to accommodate
; a different set-up.
;
; WARNING:
; Code assumes 10 Mhz clock. Delay routines must be
; edited for a different clock. Clock speed also determines
; values for baud rate setting (see spbrgVal constant).
;
; 16F877 switches
; Switches used in __config directive:
; _CP_ON       Code protection ON/OFF
; _CP_OFF
; * _PWRTE_ON   Power-up timer ON/OFF
; * _PWRTE_OFF
; _BODEN_ON    Brown-out reset enable ON/OFF
; * _BODEN_OFF
; * _PWRT_ON    Power-up timer enable ON/OFF
; _PWRT_OFF
; _WDT_ON      Watchdog timer ON/OFF
; * _WDT_OFF
; _LPV_ON      Low voltage IC programming enable ON/OFF
; * _LPV_OFF
; _CPD_ON      Data EE memory code protection ON/OFF
; * _CPD_OFF
; OSCILLATOR CONFIGURATIONS:
; _LP_OSC      Low power crystal oscillator
; _XT_OSC      External parallel resonator/crystal oscillator
; * _HS_OSC    High speed crystal resonator
; _RC_OSC      Resistor/capacitor oscillator
; |          (simplest, 20% error)
; |
; |______ * indicates setup values presently selected

processor 16f877 ; Define processor
#include <p16f877.inc>
__CONFIG _CP_OFF & _WDT_OFF & _BODEN_OFF & _PWRT_ON & _HS_OSC & _WDT_OFF & _LPV_OFF & _CPD_OFF

; __CONFIG directive is used to embed configuration data
; within the source file. The labels following the directive
; are located in the corresponding .inc file.
errorlevel -302
; Suppress bank-related warning

;=============================================================================
; MACROS
;=============================================================================
; Macros to select the register banks
Bank0 MACRO ; Select RAM bank 0
  bcf STATUS,RP0
  bcf STATUS,RP1
ENDM

Bank1 MACRO ; Select RAM bank 1
  bsf STATUS,RP0
  bcf STATUS,RP1
ENDM

Bank2 MACRO ; Select RAM bank 2
  bcf STATUS,RP0
  bsf STATUS,RP1
ENDM
Bank3 MACRO ; Select RAM bank 3
    bsf STATUS,RP0
    bsf STATUS,RP1
ENDM

; constant definitions
; for PIC-to-LCD pin wiring and LCD line addresses
#define E_line 1 ;|
#define RS_line 0 ;| -- from wiring diagram
#define RW_line 2 ;|
; LCD line addresses (from LCD data sheet)
#define LCD_1 0x80 ; First LCD line constant
#define LCD_2 0xc0 ; Second LCD line constant
#define LCDlimit .20; Number of characters per line
#define spbrgVal .64; For 2400 baud on 10Mhz clock
; Note: The constants that define the LCD display
; line addresses have the high-order bit set
; so as to meet the requirements of controller
; commands.
;
; constants for I2C initialization
; I2C connected to 24LC04B EEPROM.
; The MSSP module is in I2C MASTER mode.
#define LC04READ 0xa0 ; I2C value for read control byte
#define LC04WRITE 0xa1 ; I2C value for write control byte

; General Purpose Variables
; Local variables
; Reserve 20 bytes for string buffer
    cblock 0x20
    strData
endc
; Other data
    cblock 0x34 ; Start of block
    count1 ; Counter # 1
    count2 ; Counter # 2
    count3 ; Counter # 3
    J ; counter J
    K ; counter K
    bufAdd
    index
    store1 ; Local storage
    store2
; For LCDscroll procedure
Supplementary Programs

LCDcount ; Counter for characters per line
LCDline ; Current display line (0 or 1)
endc

;============================================================
;
; P R O G R A M
;============================================================
org 0 ; start at address
goto main

main:
; Wiring:
; LCD data to port D, lines 0 to 7
; E line -> port E, 1
; RW line -> port E, 2
; RS line -> port E, 0
; Set PORTE D and E for output
; First, initialize port B by clearing latches
clrf STATUS
cclrf PORTB
; Select bank 1 to tris port D for output
Bank1
; Tris port D for output. Port D lines 4 to 7 are wired
to LCD data lines. Port D lines 0 to 4 are wired to LEDs.
movlw B'00000000'
movwf TRISD ; and port D
; By default port A lines are analog. To configure them
; as digital code must set bits 1 and 2 of the ADCON1
; register (in bank 1)
movlw 0x06 ; binary 0000 0110 is code to
; make all port A lines digital
movwf ADCON1
Port B, lines are wired to keypad switches, as follows:

<table>
<thead>
<tr>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
</table>

```
move b'11110000'
movwf TRISB
```

Tris port E for output

```
move B'00000000'
movwf TRISE ; Tris port E
```

Enable port B pullups for switches in OPTION register

```
move b'00001000'
movwf OPTION_REG
```

Back to bank 0

```
Bank0
```

Initialize serial port for 2400 baud, 8 bits, no parity

```
call InitSerial
```

Test serial transmission by sending 'RDY-

```
move 'R'
call SerialSend
move 'D'
call SerialSend
move 'Y'
call SerialSend
move '-'
call SerialSend
move 0x20
call SerialSend
```

Clear all output lines

```
move b'00000000'
movwf PORTD
movwf PORTE
```

Wait and initialize HD44780

```
call delay_5 ; Allow LCD time to initialize itself
call initLCD ; Then do forced initialization
call delay_5 ; (Wait probably not necessary)
```

Clear character counter and line counter variables

```
clrf LCDcount
clrf LCDline
```

Set display address to start of first LCD line

```
call line1
```

Store address of display buffer

```
move 0x20
movwf bufAdd
```

Display 'Receiving:' message prompt

```
call blank20 ; Clear buffer
move 0x00 ; Offset in buffer
```
call storeMS1 ; Store message at offset
call display20 ; Display message

; Start address of EEPROM
clrf EEMemAdd

; Setup for display in second line
clrf LCDline
incf LCDline,f ; Set scroll control for line 2

; Initialize I2C EEPROM operation
clrf LCDline
incf LCDline,f ; Set scroll control for line 2

; Initialize I2C EEPROM operation
clrf LCDline
incf LCDline,f ; Set scroll control for line 2

; Receive serial data, store, and display
receive:
call SerialRcv
btfss newData,7
goto scanExit
movf EEByte,w ; Recover character
call send8 ; Display in LCD
call LCDscroll ; Scroll at end of line
movf EEByte,w ; Save received character
movf LCDline,f ; Set scroll control for line 2

; Store character in EEPROM at location in EEMemAdd
incf EEMemAdd,f ; Bump to next EEPROM

; Check for <Enter> key (0x0d) and execute display function
movf EEByte,w ; Recover last received
sublw 0x0d
btfsc STATUS,Z ; Test if <Enter> key
isEnter:
goto receive ; Go if <Enter>

; Not <Enter> key, continue processing
scanExit:
goto receive ; Continue

; Display EEPROM data

; This routine receives control when the <Enter> key is received.
;
; Action:
; 1. Clear LCD
; 2. Output is set to top LCD line
; 3. Characters stored in EEPROM are displayed
; until 0x0d code is detected
isEnter:
call clearLCD
; Clear character counter and line counter variables
clf LCDcount
clf LCDline
; Read data from EEPROM memory, starting at address 0
; and display on LCD until 0x0d terminator
call line1
clf EEMemAdd ; Start at EEPROM 0
readOne:
call ReadI2C ; Get character
; Store character
movwf EEByte ; Save character
; Test for terminator
sublw 0x0d
btfsc STATUS,Z ; Test if 0x0d
goto atEnd ; Go if 0x0d
; At this point character read is not 0x0d
; Display on LCD
movf EEByte,w ; Recover character
; Display character on LCD
 call send8 ; Display in LCD
 call LCDscroll ; Scroll at end of line
incf EEMemAdd,f ; Next EEPROM byte
goto readOne
; End of execution
atEnd:
goto atEnd

;=================================================================================================================
;=================================================================================================================
; LOCAL PROCEDURES
;=================================================================================================================
;=================================================================================================================
;==========================================
; init LCD for 4-bit mode
;==========================================
initLCD:
; Initialization for Densitron LCD module as follows:
; 4-bit interface
; 2 display lines of 16 characters each
; cursor on
; left-to-right increment
; cursor shift right
; no display shift
;==========================================
; set command mode |
;==========================================
bcf PORTE,E_line ; E line low
bcf PORTE,RS_line ; RS line low
bcf PORTE,RW_line ; Write mode
call delay_125 ; delay 125 microseconds
movlw 0x28 ; 0 0 1 0 1 0 0 0 (FUNCTION SET)
call send8 ; 4-bit send routine
; Set 4-bit mode command must be repeated
movlw 0x28
call send8
movlw 0x0e ; 0 0 0 0 1 1 1 0 (DISPLAY ON/OFF)
call send8
movlw 0x06 ; 0 0 0 0 0 1 1 0 (ENTRY MODE SET)
call send8
movlw 0x14 ; 0 0 0 1 0 1 0 0 (CURSOR/DISPLAY SHIFT)
call send8
movlw 0x01 ; 0 0 0 0 0 0 0 1 (CLEAR DISPLAY)
        |___ COMMAND BIT
call send8
call delay_5 ; Test for busy
return

;===================================
; procedure to clear LCD
;===================================
clearLCD:
bcf PORTE,E_line ; E line low
bcf PORTE,RS_line ; RS line low
bcf PORTE,RW_line ; Write mode
call delay_125 ; delay 125 microseconds
movlw 0x01 ; 0 0 0 0 0 0 1 (CLEAR DISPLAY)
        |___ COMMAND BIT
call send8
call delay_5 ; Test for busy
return

;===================================
; Procedure to delay
; 42 microseconds
;===================================
delay_125:
    movlw .105 ; Repeat 105 machine cycles
    movwf count1 ; Store value in counter
    repeat
        decfsz count1,f ; Decrement counter
goto repeat ; Continue if not 0
    return ; End of delay
Procedure to delay 5 milliseconds

delay_5:
    movlw .105 ; Counter = 105 cycles
    movwf count2 ; Store in variable

delay
    call delay_125 ; Delay
    decfsz count2,f ; 40 times = 5 milliseconds
    goto delay
    return ; End of delay

pulseE
    bsf PORTE,E_line ; Pulse E line
    nop
    bcf PORTE,E_line
    return

long delay sub-routine

long_delay
    movlw D'200' ; w delay count
    movwf J ; J = w

jloop:    movwf K ; K = w
kloop:    decfsz K,f ; K = K-1, skip next if zero
            goto kloop
            decfsz J,f ; J = J-1, skip next if zero
            goto jloop
    return

send 2 nibbles in 4-bit mode

Procedure to send two 4-bit values to port B lines 7, 6, 5, and 4. High-order nibble is sent first

ON ENTRY:

w register holds 8-bit value to send

send8:
    movwf store1 ; Save original value
    call merge4 ; Merge with port B

; Now w has merged byte
    movwf PORTD ; w to port D
    call pulseE ; Send data to LCD

; High nibble is sent
movf store1, w ; Recover byte into w
swapf store1, w ; Swap nibbles in w
call merge4
movwf PORTD
call pulseE ; Send data to LCD
call delay_125
return

; ===========================
; merge bits
; ===========================
; Routine to merge the 4 high-order bits of the
; value to send with the contents of port B
; so as to preserve the 4 low-bits in port B
; Logic:
; AND value with 1111 0000 mask
; AND port B with 0000 1111 mask
; Now low nibble in value and high nibble in
; port B are all 0 bits:
; value = vvvv 0000
; port B = 0000 bbbb
; OR value and port B resulting in:
; vvvv bbbb
; ON ENTRY:
; w contain value bits
; ON EXIT:
; w contains merged bits
merge4:
andlw b'11110000' ; ANDing with 0 clears the
; bit. ANDing with 1 preserves
; the original value
movwf store2 ; Save result in variable
movf PORTD, w ; port B to w register
andlw b'00001111' ; Clear high nibble in port b
; and preserve low nibble
iorwf store2, w ; OR two operands in w
return

; ===========================
; Set address register
; to LCD line 2
; ===========================
; ON ENTRY:
; Address of LCD line 2 in constant LCD_2
line2:
bcf PORTE, E_line ; E line low
bcf PORTE, RS_line ; RS line low, setup for
; control
call delay_5 ; Busy?
; Set to second display line
movlw LCD_2 ; Address with high-bit set
call send8
; Set RS line for data
bsf PORTE,RS_line ; R S = 1 for data
call delay_5 ; Busy?
return

;==========================
; Set address register
; to LCD line 1
;==========================

; ON ENTRY:
;
; Address of LCD line 1 in constant LCD_1
line1:
bcf PORTE,E_line ; E line low
bcf PORTE,RS_line ; RS line low, set up for
; control
call delay_5 ; busy?
; Set to second display line
movlw LCD_1 ; Address and command bit
call send8 ; 4-bit routine
; Set RS line for data
bsf PORTE,RS_line ; Setup for data
call delay_5 ; Busy?
return

;==========================
; scroll to LCD line 2
;==========================

; Procedure to count the number of characters displayed on
; each LCD line. If the number reaches the value in the
; constant LCDlimit, then display is scrolled to the second
; LCD line. If at the end of the second line, then LCD is
; reset to the first line.
LCDscroll:
incf LCDcount,f ; Bump counter
; Test for line limit
movf LCDcount,w
sublw LCDlimit ; Count minus limit
btfss STATUS,Z ; Is count - limit = 0
goto scrollExit ; Go if not at end of line
; At this point the end of the LCD line was reached
; Test if this is also the end of the second line
movf LCDline,w
sublw 0x01 ; Is it line 1?
btfsc STATUS,Z ; Is LCDline minus 1 = 0?
goto line2End ; Go if end of second line
; At this point it is the end of the top LCD line
call line2 ; Scroll to second line
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clrf LCDcount   ; Reset counter
incf LCDline,f  ; Bump line counter
goto scrollExit
; End of second LCD line
line2End:
call initLCD    ; Reset
clrf LCDcount   ; Clear counters
clrf LCDline

call line1      ; Display to first line
scrollExit:
return

;=============
; LCD display procedure
;=============
; Sends 20 characters from PIC buffer with address stored
; in variable bufAdd to LCD line previously selected
display20:
call delay_5    ; Make sure not busy

; Set up for data
bcf PORTA,E_line ; E line low
bsf PORTA,RS_line ; RS line high for data

; Set up counter for 20 characters
movlw D'20'
movwf count3

; Get display address from local variable bufAdd
movf bufAdd,w ; First display RAM address to W
movwf FSR      ; W to FSR

call getchar

movf INDF,w    ; get character from display RAM
                ; location pointed to by file select
                ; register
call send8     ; 4-bit interface routine

; Test for 20 characters displayed
decfsz count3,f ; Decrement counter
goto nextchar   ; Skipped if done
return

nextchar:
icnf FSR,f      ; Bump pointer
goto getchar

;=============
; first text string procedure
;=============
storeMS1:
; Procedure to store in PIC RAM buffer the message
; contained in the code area labeled msg1
; ON ENTRY:
variable bufAdd holds address of text buffer
in PIC RAM
w register hold offset into storage area
msg1 is routine that returns the string characters
and a zero terminator
index is local variable that hold offset into
text table. This variable is also used for
temporary storage of offset into buffer
ON EXIT:
Text message stored in buffer

Store offset into text buffer (passed in the w register)
in temporary variable
movf index, w ; Store w in index
Store base address of text buffer in FSR
movf bufAdd, w ; first display RAM address to w
addwf index, w ; Add offset to address
movwf FSR ; W to FSR
Initialize index for text string access
movlw 0 ; Start at 0
movwf index ; Store index in variable
w still = 0
get_msg_char:
call msg1 ; Get character from table
Test for zero terminator
andlw 0x0ff
btfs Z ; Test zero flag
goto endstr1 ; End of string
ASSERT: valid string character in w
store character in text buffer (by FSR)
movf INDF ; store in buffer by FSR
incf FSR, f ; increment buffer pointer
Restore table character counter from variable
movf index, w ; Get value into w
addlw 1 ; Bump to next character
movwf index ; Store table index in variable
goto get_msg_char ; Continue
endstr1:
return

Routine for returning message stored in program area
Message has 10 characters
msg1:
addwf PCL, f ; Access table
retlw 'R'
retlw 'e'
retlw 'c'
retlw 'e'
Supplementary Programs

.................
; blank buffer
.................
; Procedure to store 20 blank characters in PIC RAM
; buffer starting at address stored in the variable
; bufAdd
blank20:
  movlw D'20' ; Setup counter
  movwf count1
  movf bufAdd, w ; First PIC RAM address
  movwf FSR ; Indexed addressing
  movlw 0x20 ; ASCII space character
  storeit
  movwf INDF ; Store blank character in PIC RAM
               ; buffer using FSR register
  decfsz count1, f ; Done?
  goto incfsr ; no
  return ; yes

incfsr
  incf FSR, f ; Bump FSR to next buffer space
  goto storeit

;============================================
; communications procedures
;============================================
; Initialize serial port for 2400 baud, 8 bits, no parity,
; 1 stop
InitSerial:
  Bank1 ; Macro to select bank1
  ; Bits 6 and 7 of Port C are multiplexed as TX/CK and RX/DT
  ; for USART operation. These bits must be set to input in the
  ; TRISC register
  movlw b'11000000' ; Bits for TX and RX
  iorwf TRISC, f ; OR into Trisc register
  ; The asynchronous baud rate is calculated as follows:
  ; FOsc
  ; ABR = ---------
  ; S*(x+1)
  ; where x is value in the SPBRG register and S is 64 if the high
  ; baud rate select bit (BRGH) in the TXSTA control register is
clear, and 16 if the BRGH bit is set. For setting to 2400 baud
using a 10Mhs oscillator at a slow baud rate the formula
is:
At slow speed (BRGH = 0)

\[
\frac{10,000,000}{64*(64+1)} = \frac{10,000,000}{4160} = 2,403.84 \text{ (0.16% error)}
\]

\[
\text{movlw spbrgVal} ; \text{Value in spbrgVal = 64}
\text{movwf SPBRG} ; \text{Place in baud rate generator}
\]
\[
\text{Setup value: 0010 0000 = 0x20}
\text{movlw 0x20} ; \text{Enable transmission and high baud}
\text{rate}
\text{movwf TXSTA}
\]
\[
\text{Bank0} ; \text{Bank 0}
\text{Setup value: 1001 0000 = 0x90}
\text{movlw 0x90} ; \text{Enable serial port and continuous}
\text{reception}
\text{movwf RCSTA}
\]
\[
\text{clrf errorFlags; Clear local error flags register}
\text{return}
\]

; Test for Transmit Register Empty and transmit data in w
SerialSend:

\[
\text{Bank0} ; \text{Select bank 0}
\text{btfss PIR1,TXIF} ; \text{check if transmitter busy}
\text{goto $-1} ; \text{wait until transmitter is not busy}
\text{movwf TXREG} ; \text{and transmit the data}
\text{return}
\]

; Procedure to test line for data received and return value in w.
SerialRcv:

\[
\text{clrf newData} ; \text{Clear new data received register}
\text{Bank0} ; \text{Select bank 0}
\text{btfss PIR1,RCIF} ; \text{Check for received data}
\]

; Not used --- 7 6 5 4 3 2 1 0 <= errorFlags
; \|____ overrun error
; \|____ framing error
return ; Exit if no data

; At this point data has been received. First eliminate possible errors: overrun and framing.
; Bit 1 (OERR) of the RCSTA register detects overrun
; Bit 2 (FERR) of the RCSTA register detects framing error
btfsc RCSTA,OERR ; Test for overrun error
goto OverErr ; Error handler
btfsc RCSTA,FERR ; Test for framing error
goto FrameErr; Error handler

; At this point no error was detected
; Received data is in the USART RCREG register
movf RCREG,w ; get received data
bsf newData,7 ; Set bit 7 to indicate new data

; Clear error flags
clrf errorFlags
return

;===============================================
; error handlers
;===============================================

OverErr:
bsf errorFlags,0 ; Bit 0 is overrun error

; Reset system
bcf RCSTA,CREN ; Clear continuous receive bit
bsf RCSTA,CREN ; Set to re-enable reception
return

; error because FERR framing error bit is set
; can do special error handling here - this code simply clears
; and continues
FrameErr:
bsf errorFlags,1; Bit 1 is framing error
movf RCREG,W ; Read and throw away bad data
return

;==================================================================================================
; I2C EEPROM data procedures
;==================================================================================================
; GPRs used in EEPROM-related code are placed in the common
; RAM area (from 0x70 to 0x7f). This makes the registers
; accessible from any bank.
;==================================================================================================
; LIST OF PROCEDURES
;==================================================================================================

; SetupI2C --- Initialize MSSP module for I2C mode
; in hardware master mode
; Configure I2C lines
; Set slew rate for 100kbps
; Set baud rate for 10Mhz
; WriteI2C --- Write byte to I2C EEPROM device
; Data is stored in EEByte variable
; Address is stored in EEMemAdd
; ReadI2C --- Read byte from I2C EEPROM device
; Address stored in EEMemAdd
; Read data returned in w register
;===============================================
; I2C setup procedure
;===============================================
SetupI2C:
    Bank1
    movlw b'00011000'
    iorwf TRISC,f ; OR into TRISC
    ; Setup MSSP module for Master Mode operation
    Bank0
    movlw B'00101000'; Enables MSSP and uses appropriate
    ; 0 0 1 0 1 0 0 0 Value to install
    ; 7 6 5 4 3 2 1 0 <= SSPCON bits in this operation
    ; | | | | | |______ Serial port select bits
    ; | | | | 1000 = I2C master mode
    ; | | | Clock = Fosc/(4*(SSPAD+1))
    ; | | ___________ UNUSED IN MASTER MODE
    ; | | SSP Enable
    ; | 1 = SDA and SCL pins as serial
    ; | ___________ Receive overflow indicator
    ; | 0 = no overflow
    ; ___________ Write collision detect
    ; 0 = no collision detected
    movwf SSPCON ; This is loaded into SSPCON
    ; Input levels and slew rate as standard I2C
    Bank1
    movlw B'10000000'
    ; 1 0 0 0 0 0 0 0 Value to install
    ; 7 6 5 4 3 2 1 0 <= SSPSTAT bits in this operation
    ; | | | | | | | | Buffer full status bit READ ONLY
    ; | | | | | | | | UNUSED in present application
    ; | | | | | | | | Read/write information READ ONLY
    ; | | | | | | | | UNUSED IN MASTER MODE
    ; | | | | | | | | STOP bit READ ONLY
    ; | | | | | | | | Data address READ ONLY
    ; | | | | | | | | SMP bus select
    ; | | | | | | | | 0 = use normal I2C specs
    ; | | | | | | | | 0 = disabled
    movwf SSPSTAT
    ; Setup Baud Rate
    ; Baud Rate = Fosc/(4*(SSPAD+1))
    ; Fosc = 10Mhz
    ; Baud Rate = 24 for 100 kbps
    movlw .24 ; Value to use
movwf SSPADD ; Store in SSPADD
Bank0
return

;============================
; I2C write procedure
;============================
; Write one byte to I2C EEPROM 24LC04B
; Steps:
; 1. Send START
; 2. Send control. Wait for ACK
; 3. Send address. Wait for ACK
; 4. Send data. Wait for ACK
; 5. Send STOP
; STEP 1:
WriteI2C:
Bank1
bsf SSPCON2,SEN ; Produce START Condition
call WaitI2C ; Wait for I2C to complete
; STEP 2:
; Send control byte. Wait for ACK
movlw LC04READ ; Control byte
call SendI2C ; Send Byte
call WaitI2C ; Wait for I2C to complete
btfsc SSPCON2,ACKSTAT ; Check ACK bit to see if
; I2C failed, skip if not
goto FailI2C
; STEP 3:
; Send address. Wait for ACK
Bank0
movf EEMemAdd, w ; Load Address Byte
call SendI2C ; Send Byte
call WaitI2C ; Wait for I2C operation to complete
Bank1
btfsc SSPCON2,ACKSTAT ; Check ACK Status bit to see
; if I2C failed, skip if not
goto FailI2C
; STEP 4:
; Send data. Wait for ACK
Bank0
movf EEByte, w ; Load Data Byte
call SendI2C ; Send Byte
call WaitI2C ; Wait for I2C operation to complete
Bank1
btfsc SSPCON2,ACKSTAT ; Check ACK Status bit to see
; if I2C failed, skip if not
goto FailI2C
; STEP 5:
; Send STOP. Wait for ACK
    bsf      SSPCON2,PEN ; Send STOP condition
    call     WaitI2C ; Wait for I2C operation to complete
; WRITE operation has completed successfully.
    Bank0
    return

;charset

I2C read procedure

Procedure to read one byte from 24LC04B EEPROM

Steps:

1. Send START
2. Send control. Wait for ACK
3. Send address. Wait for ACK
4. Send RESTART + control. Wait for ACK
5. Switch to receive mode. Get data.
6. Send NACK
7. Send STOP
8. Retreive data into w register

; STEP 1:
ReadI2C
; Send RESTART. Wait for ACK
    Bank1
    bsf      SSPCON2,RSEN ; RESTART Condition
    call     WaitI2C ; Wait for I2C operation

; STEP 2:
; Send control byte. Wait for ACK
    movlw    LC04READ ; Control byte
    call     SendI2C ; Send Byte
    call     WaitI2C ; Wait for I2C operation

; Now check to see if I2C EEPROM is ready
    Bank1
    btfsc    SSPCON2,ACKSTAT ; Check ACK Status bit
    goto     ReadI2C ; ACK Poll waiting for EEPROM
              ; write to complete

; STEP 3:
; Send address. Wait for ACK
    Bank0
    movf     EEMemAdd,w       ; Load from address register
    call     SendI2C ; Send Byte
    call     WaitI2C ; Wait for I2C operation
    Bank1
    btfsc    SSPCON2,ACKSTAT ; Check ACK Status bit
    goto     FailI2C ; failed, skipped if successful

; STEP 4:
; Send RESTART. Wait for ACK
    bsf      SSPCON2,RSEN ; Generate RESTART Condition
; Procedure to wait for the last I2C operation to complete.
; Code polls the SSPIF flag in PIR1.
WaitI2C
Bank0
btfss PIR1,SSPIF ; Check if I2C operation done
goto $-1 ; I2C module is not ready yet
bcf PIR1,SSPIF ; I2C ready, clear flag
return

;===============================================
end ; END OF PROGRAM
;===============================================

Supplementary Programs

; File name: Key2LCD.asm
; Date: May 11, 2006
; Author: Julio Sanchez
;
; Description:
; Decode 4 x 4 keypad and display scan code in LCD.
; Program to use 4-bit PIC-to-LCD interface.
; Code assumes that LCD is driven by Hitachi HD44780
; controller and PIC 16F977. Display supports two lines
; each one with 20 characters. The wiring and base
; address of each display line is stored in #define
; statements. These statements can be edited to
; accommodate a different set-up.
; Keypad switch wiring (values are scan codes):
;  --- KEYPAD --
; 0 1  2  3  <= port B0 |
; 4  5  6  7  <= port B1 |--- ROWS = OUTPUTS
; 8  9  A  B  <= port B2 |
; C  D  E  F  <= port B3 |
; | | | |___ port B4 |
; | | |_________ port B5 |--- COLUMNS = INPUTS
; |______________ port B6 |
; ___________________ port B7 |
;
; Program operations:
; 1. Key press action generates a scan code in the range
; 0x0 to 0xf.
; 2. Program converts scan code to ASCII digit and displays
; the digit on the LCD.
; 3. When the end of the first LCD line is reached, display
; continues in the second line. When the end of the
; second line is reached, LCD is reset to the first line
;
; Program uses delay loops for interface timing.
; WARNING:
; Code assumes 4Mhz clock. Delay routines must be
; edited for faster clock
;
;===========================
; 16F877 switches
;===========================
; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; * _CP_OFF
; * _PWRTE_ON Power-up timer ON/OFF
; _PWRTE_OFF
; _BODEN_ON Brown-out reset enable ON/OFF
; * _BODEN_OFF
; * _PWRT_ON   Power-up timer enable ON/OFF
; _PWRT_OFF
; _WDT_ON     Watchdog timer ON/OFF
; * _WDT_OFF
; _LPV_ON     Low voltage IC programming enable ON/OFF
; * _LPV_OFF
; _CPD_ON     Data EE memory code protection ON/OFF
; * _CPD_OFF
; OSCILLATOR CONFIGURATIONS:
; _LP_OSC    Low power crystal oscillator
; _XT_OSC    External parallel resonator/crystal oscillator
; * _HS_OSC   High speed crystal resonator
; _RC_OSC    Resistor/capacitor oscillator
; | (simplest, 20% error)
; |
; |________ * indicates setup values presently selected

processor 16f877 ; Define processor
#include <p16f877.inc>
__CONFIG _CP_OFF & _WDT_OFF & _BODEN_OFF & _PWRT_ON &
 _HS_OSC & _WDT_OFF & _LVP_OFF & _CPD_OFF

; __CONFIG directive is used to embed configuration data
; within the source file. The labels following the directive
; are located in the corresponding .inc file.

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; constant definitions
; for PIC-to-LCD pin wiring and LCD line addresses
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
#define E_line 1 ;|
#define RS_line 0 ;| -- from wiring diagram
#define RW_line 2 ;|
; LCD line addresses (from LCD data sheet)
#define LCD_1 0x80 ; First LCD line constant
#define LCD_2 0xc0 ; Second LCD line constant
#define LCDlimit .20; Number of characters per line
; Note: The constants that define the LCD display line
; addresses have the high-order bit set in
; order to facilitate the controller command
;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; PIC register equates
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
portd equ 0x08
porte equ 0x09
Supplementary Programs

fsr          equ 0x04
status       equ 0x03
indf         equ 0x00
z            equ 2
             
;=============================================================
; variables in PIC RAM
;=============================================================
; Reserve 20 bytes for string buffer
    cblock 0x20
    strData

; Leave 16 bytes and Continue with local variables
    cblock 0x34
    count1 ; Counter # 1
    count2 ; Counter # 2
    count3 ; Counter # 3
    pic_ad ; Storage for start of text area
              ; (labeled strData) in PIC RAM
    J ; counter J
    K ; counter K
    index ; Index into text table (also used
              ; for auxiliary storage)
    store1 ; Local storage
    store2

; For LCDscroll procedure
    LCDcount ; Counter for characters per line
    LCDline ; Current display line (0 or 1)

; Keypad processing variables
    keyMask ; For keypad processing
    rowMask ; For masking-off key rows
    rowCode ; Row addend for calculating scan code
    rowCount ; Counter for key rows (0 to 3)
    scanCode ; Final key code
    newScan ; 0 if no new scan code detected

;==============================================================================
;
;=============================================================================
;
; MACROS
;
;==============================================================================
;
; Macros to select the register banks
; Data memory bank selection bits:
; RP1:RP0       Bank
;  0:0          0  Ports A,B,C,D, and E
;  0:1          1  Tris A,B,C,D, and E
;  1:0          2
;  1:1          3

Bank0 MACRO    ; Select RAM bank 0
    bcf STATUS,RP0
bcf STATUS,RP1
ENDM

Bank1 MACRO ; Select RAM bank 1
bsf STATUS,RP0
bcf STATUS,RP1
ENDM

Bank2 MACRO ; Select RAM bank 2
bcf STATUS,RP0
bsf STATUS,RP1
ENDM

Bank3 MACRO ; Select RAM bank 3
bsf STATUS,RP0
bsf STATUS,RP1
ENDM

;=================================================================================================
; MAIN PROGRAM
;=================================================================================================
org 0 ; start at address
goto main

main:
; Space for interrupt handlers
org 0x08

; Wiring:
; LCD data to port D, lines 0 to 7
; E line -> port E, 1
; RW line -> port E, 2
; RS line -> port E, 0
; Set porte D and E for output
; First, initialize port B by clearing latches
clrf STATUS
clrf PORTB
; Select bank 1 to tris port D for output
Bank1
; Tris port D for output. Port D lines 4 to 7 are wired
; to LCD data lines. Port D lines 0 to 4 are wired to LEDs.
movlw B'00000000'
movwf TRISD ; and port D
; By default port A lines are analog. To configure them
; as digital code must set bits 1 and 2 of the ADCON1
; register (in bank 1)
movlw 0x06 ; binary 0000 0110 is code to
; make all
port A lines digital
movwf ADCON1
; Port B, lines are wired to keypad switches, as follows:
movlw b'11110000'
movwf TRISB

; Tris port E for output
movlw B'00000000'
movwf TRISE ; Tris port E

; Enable port B pullups for switches in OPTION register
movlw b'00001000'
movwf OPTION_REG

; Back to bank 0
Bank0

; Clear all output lines
movlw b'00000000'
movwf portd
movwf porte

; Wait and initialize HD44780
call delay_5 ; Allow LCD time to initialize itself
call initLCD ; Then do forced initialization
call delay_5 ; (Wait probably not necessary)

; Set display address to start of second LCD line
call line1

; Clear character counter and line counter variables
clr LCDcount
clr LCDline
; Keypad switch wiring:
; xxxx< = port B0 |
; xxxx< = port B1 |--- ROWS = OUTPUTS
; xxxx< = port B2 |
; xxxx< = port B3 |
; | | | |_____ port B4 |
; | | |_________ port B5 |--- COLUMNS = INPUTS
; | |_____________ port B6 |
; |_________________ port B7 |
; Switches are connected to port B lines
; Clear scan code register
    clrf    scanCode

; scan keypad and display
;============================

keyScan:
; Port B, lines are wired to pushbutton switches, as follows:
; 76543210
; |||||_|_|_|_____ switch rows (output)
; |_|_|_|_____________ switch columns (input)
; Keypad processing:
; switch rows are successively grounded (row = 0)
; Then column values are tested. If a column returns 0
; in a 0 row, that switch is down.
; Initialize row code addend
    clrf    rowCode ; First row is code 0
    clrf    newScan ; No new scan code detected

; Initialize row count
    movlw D'4' ; Four rows
    movwf    rowCount ; Register variable
    movlw b'11111110' ; All set but LOB
    movwf    rowMask

keyLoop:
; Initialize row eliminator mask:
; The row mask is ANDed with the key mask to successively
; mask-off each row, for example:
;
; |------- row 3
; |------ row 2
; ||----- row 1
; ||||--- row 0
; 0000 1111 <= key mask
; AND 1111 1101 <= mask for row 1
;
; 0000 1101 <= row 1 is masked off
;
; The row mask, which is initially 1111 1110, is rotated left
; through the carry in order to mask off the next row
movlw b'00001111' ; Mask off all lines
movwf keyMask ; To local register
; Set row mask for current row
movf rowMask,w ; Mask to w
andwf keyMask,f ; Update key mask
movf keyMask,w ; Key mask to w
movwf PORTB ; Mask-off port B lines
;
; Read port B lines 4 to 7 (columns are input)
btfss PORTB,4
    call col0 ; Key column procedures
btfss PORTB,5
    call col1
btfss PORTB,6
    call col2
btfss PORTB,7
    call col3
;
; Index to next row by adding 4 to row code
movf rowCode,w ; Code to w
addlw D'4'
movwf rowCode

;;===========================================================
;; display scan code
;;===========================================================
;
; At this point all keys have been tested.
; Variable newScan = 0 if no new scan code detected, else
; variable scanCode holds scan code
movf newScan,f ; Copy onto intseg (sets z flag)
btfsc STATUS,z ; Is it zero
goto scanExit
;
; At this point a new scan code is detected
movf scanCode, w ; To w

; If scan code is in the range 0 to 9, that is, a decimal digit, then ASCII conversion consists of adding 0x30.
; If the scan code represents one of the hex letters (0xa to 0xf) then ASCII conversion requires adding 0x37
sublw 0x09 ; 9 - w

; if w from 0 to 9 then 9 - w = positive (c flag = 1)
; if w = 0xa then 9 - 10 = -1 (c flag = 0)
; if w = 0xc then 9 - 12 = -2 (c flag = 0)
btfss STATUS, c ; Test carry flag
goto hexLetter ; Carry clear, must be a letter

; At this point scan code is a decimal digit in the range 0 to 9. Convert to ASCII by adding 0x30
movf scanCode, w ; Recover scan code
addlw 0x30 ; Convert to ASCII
goto displayDig

hexLetter:

movf scanCode, w ; Recover scan code
addlw 0x37 ; Convert to ASCII
displayDig:
call send8 ; Display routine
call LCDscroll ; Auto line scrolling procedure

scanExit:
call long_delay ; Debounce
goto keyScan ; Continue

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
calculate scan code
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
The column position is added to the row code (stored in rowCode register). Sum is the scan code
col0:

movf rowCode, w ; Row code to w
addlw 0x00 ; Add 0 (clearly not necessary)
movwf scanCode ; Final value
incf newScan, f ; New scan code
return

col1:

movf rowCode, w ; Row code to w
addlw 0x01 ; Add 1
movwf scanCode
incf newScan, f
return

col2:

movf rowCode, w ; Row code to w
Supplementary Programs

addlw 0x02 ; Add 2
movwf scanCode
incf newScan,f
return

col3:
movf rowCode,w ; Row code to w
addlw 0x03 ; Add 3
movwf scanCode
incf newScan,f
return

;===================================================================
; initialize LCD for 4-bit mode
;===================================================================
initLCD:
; Initialization for Densitron LCD module as follows:
; 4-bit interface
; 2 display lines of 16 characters each
; cursor on
; left-to-right increment
; cursor shift right
; no display shift
;===================================================================
; set command mode
;===================================================================
 bcf porte,E_line ; E line low
 bcf porte,RS_line ; RS line low
 bcf porte,RW_line ; Write mode
 call delay_125 ; delay 125 microseconds
 ;FUNCTION SET
 ;===================================================================
 movlw 0x28 ; 0 0 1 0 1 0 0 0 (FUNCTION SET)
 ; | | | |__ font select:
 ; | | | 1 = 5x10 in 1/8 or 1/11
 ; | | | 0 = 1/16 dc
 ; | | |___ Duty cycle select
 ; | | 0 = 1/8 or 1/11
 ; | 1 = 1/16
 ; |___ Interface width
 ; 0 = 4 bits
 ; | 1 = 8 bits
 ; |___ FUNCTION SET COMMAND
 call send8 ; 4-bit send routine

; Set 4-bit mode command must be repeated
movlw 0x28
call send8

;******************************
; DISPLAY AND CURSOR ON
;******************************

movlw 0x0e ; 0 0 0 0 1 1 1 0 (DISPLAY ON/OFF)

; | | | |___ Blink character
; | | | 1 = on, 0 = off
; | | |___ Cursor on/off
; | | 1 = on, 0 = off
; |___ Display on/off
; | 1 = on, 0 = off
; |___ COMMAND BIT

call send8

;******************************

movlw 0x06 ; 0 0 0 0 0 1 1 0 (ENTRY MODE SET)

; | | |___ display shift
; | | 1 = shift
; | | 0 = no shift
; |___ cursor increment
; | 1 = left-to-right
; | 0 = right-to-left
; |___ COMMAND BIT

call send8

;******************************

movlw 0x14 ; 0 0 0 1 0 1 0 0 (CURSOR/DISPLAY SHIFT)

; | | | |___ don't care
; | |___ cursor/display shift
; | 00 = cursor shift left
; | 01 = cursor shift right
; | 10 = cursor and display shifted left
; | 11 = cursor and display shifted right
; |___ COMMAND BIT

call send8

;******************************

movlw 0x01 ; 0 0 0 0 0 0 1 (CLEAR DISPLAY)

; |___ COMMAND BIT
call send8
; Per documentation
call delay_5 ; Test for busy
return

;=======================
; Procedure to delay
; 42 microseconds
;=======================
delay_125:
movlw D'42' ; Repeat 42 machine cycles
movwf count1 ; Store value in counter
repeat
  decfsz count1,f ; Decrement counter
goto repeat ; Continue if not 0
return ; End of delay

;=======================
; Procedure to delay
; 5 milliseconds
;=======================
delay_5:
movlw D'42' ; Counter = 41
movwf count2 ; Store in variable
delay
  call delay_125 ; Delay
decfsz count2,f ; 40 times = 5 milliseconds
  goto delay
return ; End of delay

;========================
; pulse E line
;========================
pulseE
  bsf porte,E_line ; Pulse E line
  Nop
  bcf porte,E_line
  return

;========================
; long delay sub-routine
; (for debugging)
;========================
long_delay
  movlw D'200' ; w delay count
  movwf J ; J = w
  jloop:
    movwf K ; K = w
  kloop:
    decfsz K,f ; K = K-1, skip next if zero
    goto kloop

decfsz J,f ; J = J-1, skip next if zero
goto jloop
return

;=======================================
; send 2 nibbles in
; 4-bit mode
;=======================================
; Procedure to send two 4-bit values to port B lines
; 7, 6, 5, and 4. High-order nibble is sent first
; ON ENTRY:
; w register holds 8-bit value to send
send8:
    movwf store1 ; Save original value
call merge4 ; Merge with port B
; Now w has merged byte
    movwf portd ; w to port D
call pulseE ; Send data to LCD
; High nibble is sent
    movf store1,w ; Recover byte into w
    swapf store1,w ; Swap nibbles in w
call merge4
    movwf portd
call pulseE ; Send data to LCD
call delay_125
return

;=======================================
; merge bits
;=======================================
; Routine to merge the 4 high-order bits of the
; value to send with the contents of port B
; so as to preserve the 4 low-bits in port B
; Logic:
; AND value with 1111 0000 mask
; AND port B with 0000 1111 mask
; Now low nibble in value and high nibble in
; port B are all 0 bits:
; value = vvvv 0000
; port B = 0000 bbbb
; OR value and port B resulting in:
; vvvv bbbb
; ON ENTRY:
; w contain value bits
; ON EXIT:
; w contains merged bits
merge4:
    andlw b'11110000' ; ANDing with 0 clears the
; bit. ANDing with 1 preserves
movwf store2 ; Save result in variable
movf portd, w ; Port B to w register
andlw b'00001111' ; Clear high nibble in port b
; and preserve low nibble
iorwf store2, w ; OR two operands in w
return

;------------------------
; Set address register
; to LCD line 1
;------------------------
; ON ENTRY:
; Address of LCD line 2 in constant LCD_2
line1:
  bcf porte, E_line ; E line low
  bcf porte, RS_line ; RS line low, setup for
  ; control
call delay_5 ; Busy?
; Set to second display line
  movlw LCD_1 ; Address with high-bit set
call send8
; Set RS line for data
  bsf porte, RS_line ; RS = 1 for data
call delay_5 ; Busy?
return

;------------------------
; Set address register
; to LCD line 2
;------------------------
; ON ENTRY:
; Address of LCD line 2 in constant LCD_2
line2:
  bcf porte, E_line ; E line low
  bcf porte, RS_line ; RS line low, setup for
  ; control
call delay_5 ; Busy?
; Set to second display line
  movlw LCD_2 ; Address with high-bit set
call send8
; Set RS line for data
  bsf porte, RS_line ; RS = 1 for data
call delay_5 ; Busy?
return

;------------------------
; Procedure to count the number of characters displayed on each LCD line. If the number reaches the value in the constant LCDlimit, then display is scrolled to the second LCD line. If at the end of the second line, then LCD is reset to the first line.

LCDscroll:
  incf LCDcount,f ; Bump counter

; Test for line limit
  movf LCDcount,w
  sublw LCDlimit ; Count minus limit
  btfss STATUS,z ; Is count - limit = 0
  goto scrollExit ; Go if not at end of line

; At this point the end of the LCD line was reached
; Test if this is also the end of the second line
  movf LCDline,w
  sublw 0x01 ; Is it line 1?
  btfsc STATUS,z ; Is LCDline minus 1 = 0?
  goto line2End ; Go if end of second line

; At this point it is the end of the top LCD line
  call line2 ; Scroll to second line
  clrf LCDcount ; Reset counter
  incf LCDline,f ; Bump line counter
  goto scrollExit

; End of second LCD line
line2End:
  call initLCD ; Reset
  clrf LCDcount ; Clear counters
  clrf LCDline
  call line1 ; Display to first line

scrollExit:
  return
end
Description:

Program to scan a 4 x 4 keypad

Keypad switch wiring (values are scan codes):

--- KEYPAD ---

   0 1 2 3 <= port B0 |
   4 5 6 7 <= port B1 |--- ROWS = OUTPUTS
   8 9 A B <= port B2 |
   C D E F <= port B3 |
   ||   |     |______ port B4 |
   ||   |   |________ port B5 |--- COLUMNS = INPUTS
   ||   |_________ port B6 |
   |_________________ port B7 |

Key press action generates a scan code in the range
0x0 to 0xf, starting at the top-left pushbutton and
increasing left-to-right and from the top down.

Scan code is displayed in LEDs wired to port D,
lines 0, 1, 2, and 3

WARNING:
Code assumes 4Mhz clock. Delay routines must be
edited for faster clock

=========================================
16F877 switches
=========================================

Switches used in _config directive:

 _CP_ON Code protection ON/OFF
 _CP_OFF
 * _PWRTE_ON Power-up timer ON/OFF
 * _PWRTE_OFF
 * _BODEN_ON Brown-out reset enable ON/OFF
 * _BODEN_OFF
 * _WDT_ON Watchdog timer ON/OFF
 * _WDT_OFF
 _LPV_ON Low voltage IC programming enable ON/OFF
 * _LPV_OFF
 _CPD_ON Data EE memory code protection ON/OFF
 * _CPD_OFF

OSCILOILLATOR CONFIGURATIONS:
; _LP_OSC     Low power crystal oscillator
; _XT_OSC     External parallel resonator/crystal oscillator
; * _HS_OSC    High speed crystal resonator
; _RC_OSC     Resistor/capacitor oscillator
; |               (simplest, 20% error)
; |
; |____  * indicates setup values presently selected

processor 16f877    ; Define processor
#include<p16f877.inc>
__CONFIG _CP_OFF & _WDT_OFF & _BODEN_OFF & _PWRTE_ON &
_HS_OSC & _WDT_OFF & _LVP_OFF & _CPD_OFF

;==============================================
; PIC register equates
;==============================================
Status equ 0x03  
c equ 0
;==============================================
; variables in PIC RAM
;==============================================
  cblock 0x20
  J    ; Counters
  K
  keyMask           ; For keypad processing
  rowMask           ; For masking-off key rows
  rowCode           ; Row addend for calculating scan code
 RowCount           ; Counter for key rows (0 to 3)
  ScanCode           ; Final key code
  endc

;==============================================
; program
;==============================================
  org 0          ; start at address
  goto main

main:
; First, initialize port B by clearing latches
  clrf STATUS
  clrf PORTB
; Select bank 1 to tris port D for output
  bcf STATUS,RP1  ; Clear banks 2/3 selector
  bsf STATUS,RP0  ; Select bank 1 for tris registers
; Tris port D for output. Port D is wired to LEDs.
movlw B'00000000'
movwf TRISD ; and port D
; Port B, lines are wired to pushbutton switches, as follows:
; 7 6 5 4 3 2 1 0
; | | | | | | | | switch rows (output)
; | | | | | | | | switch columns (input)
; rows must be defined as output and columns as input
movlw b'11110000'
movwf TRISB
; Enable port B pullups for switches in OPTION register
movlw b'00001000'
movwf OPTION_REG
; Back to bank 0
bcf STATUS,RP0

movlw b'00000000'
movwf PORTD ; Place in port
clrf scanCode

keyScan:
; Port B, lines are wired to pushbutton switches, as follows:
; 7 6 5 4 3 2 1 0
; | | | | | | | | switch rows (output)
; | | | | | | | | switch columns (input)
; Keypad processing:
; switch rows are successively grounded (row = 0)
; Then column values are tested. If a column returns 0
; in a 0 row, that switch is down.
; Initialize row code addend
clrf rowCode ; First row is code 0
; Initialize row count
movlw D'4' ; Four rows
movwf rowCount ; Register variable
movlw b'11111110' ; All set but LOB
movwf rowMask

keyLoop:
; Initialize row eliminator mask:
; The row mask is ANDed with the key mask to successively
; mask-off each row, for example:
;
; |------- row 3
; ||------ row 2
; |||----- row 1
; ||||---- row 0
; 0000 1111 <= key mask
; AND 1111 1101 <= mask for row 1
; 0000 1101 <= row 1 is masked off
;
; The row mask, which is initially 1111 1110, is rotated left
; through the carry in order to mask off the next row
movlw b'00001111' ; Mask off all lines
movwf keyMask ; To local register
; Set row mask for current row
movf rowMask,w ; Mask to w
andwf keyMask,f ; Update key mask
movf keyMask,w ; Key mask to w
movwf PORTB ; Mask-off port B lines
; Read port B lines 4 to 7 (columns are input)
btfss PORTB,4
call col0 ; Key column procedures
btfss PORTB,5
call col1
btfss PORTB,6
call col2
btfss PORTB,7
call col3
; Index to next row by adding 4 to row code
movf rowCode,w ; Code to w
addlw D'4'
movwf rowCode

; Shift row mask
;================================================================================
; Set the carry flag
bsf STATUS,c
rlf rowMask,f ; Rotate mask bits in storage
;=============
; end of keypad?
;=============
; Test for last key row (maximum count is 4)
decfsz rowCount,f ; Decrement counter
goto keyLoop
;=============
; display scan code
;=============
; At this point all keys have been tested
; variable scanCode holds scan code
movf scanCode,w
movwf PORTD
call long_delay ; Debounce
goto keyScan ; Continue

;=============
; calculate scan code
;=============
; The column position is added to the row code (stored in rowCode register). Sum is the scan code
col0:
movf rowCode,w ; Row code to w
addlw 0x00 ; Add 0 (clearly not necessary)
movwf scanCode ; Final value
return
col1:
movf rowCode,w ; Row code to w
addlw 0x01 ; Add 1
movwf scanCode
return
col2:
movf rowCode,w ; Row code to w
addlw 0x02 ; Add 2
movwf scanCode
return
col3:
movf rowCode,w ; Row code to w
addlw 0x03 ; Add 3
movwf scanCode
return

;=============
; long delay sub-routine
;=============
long_delay

movlw D'200' ; w delay count
movwf J ; J = w
jloop: movwf K ; K = w
kloop: decfsz K,f ; K = K-1, skip next if zero
goto kloop
decfsz J,f ; J = J-1, skip next if zero
goto jloop
return

End
; File name: RamDemo.asm
; Last revision: May 27, 2006
; Author: Julio Sanchez
; PIC: 16F877
;
; Description:
; Program to demonstrate access to General Purpose Register
; located in different banks. 16F877 GPR space is as
; follows:
; BANK 0 BANK 1 BANK 2 BANK 3
; 0x20 0xa0 0x110 0x190 | bank
; -- -- -- -- | related
; -- -- -- -- | related
; -- 0xef 0x16f 0x1ef |
; -- 0xf0 0x170 0x1f0 |
; 0x70 <= access registers at 0x70-0x7f
; 0x7f these GPRs are common to all banks
;
; Program is designed to be used with a debugger so that
; access to different registers can be tested
; GPR registers are named according to the following format:
;
; REGx_yyy
; | |||
; | ||| hex address (up to 3 digits)
; |__________ bank number (0 to 3)
;
; CONCLUSIONS:
; GPRs located between 0x70 and 0x7f can be accessed from
; any bank. GPRs at other addresses require previous bank
; selection
;
;===========================
; 16F877 switches
;===========================
; Switches used in __config directive:
; _CP_ON Code protection ON/OFF
; * _CP_OFF
; * _PWRT_ON Power-up timer ON/OFF
; _PWRT_OFF
; _BODEN_ON Brown-out reset enable ON/OFF
; * _BODEN_OFF
; * _PWRT_ON Power-up timer enable ON/OFF
; _PWRT_OFF
; _WDT_ON Watchdog timer ON/OFF
; * _WDT_OFF
; _LPV_ON Low voltage IC programming enable ON/OFF
; * _LPV_OFF
; _CPD_ON       Data EE memory code protection ON/OFF
; * _CPD_OFF
; OSCILLATOR CONFIGURATIONS:
; _LP_OSC       Low power crystal oscillator
; _XT_OSC       External parallel resonator/crystal oscillator
; * _HS_OSC     High speed crystal resonator
; _RC_OSC       Resistor/capacitor oscillator
; |              (simplest, 20% error)
; |
; |____  * indicates setup values presently selected

processor 16f877 ; Define processor
#include <p16f877.inc>
__CONFIG _CP_OFF & _WDT_OFF & _BODEN_OFF & _PWRTE_ON &
    _HS_OSC & _WDT_OFF & _LVP_OFF & _CPD_OFF
; __CONFIG directive is used to embed configuration data
; within the source file. The labels following the directive
; are located in the corresponding .inc file.
errorlevel -302
; Supress bank-related warning

MACROS

Bank0 MACRO ; Select RAM bank 0
    bcf STATUS,RP0
    bcf STATUS,RP1
ENDM

Bank1 MACRO ; Select RAM bank 1
    bsf STATUS,RP0
    bcf STATUS,RP1
ENDM

Bank2 MACRO ; Select RAM bank 2
    bcf STATUS,RP0
    bsf STATUS,RP1
ENDM

Bank3 MACRO ; Select RAM bank 3
    bsf STATUS,RP0
    bsf STATUS,RP1
ENDM

; PIC register equates
reg0_20 equ 0x20
reg0_50 equ 0x50
reg0_7e equ 0x7e
reg1_a0 equ 0xa0

;============================================================
; PROGRAM
;============================================================

org 0 ; start at address
goto main

; Space for interrupt handlers
org 0x08

main:

Bank0
nop
movlw 0xee ; Test value
movwf reg0_20
movwf reg0_7e

Bank1

; Register at address 0x20 in bank 0 cannot be accessed
nop
movf reg0_20,w
nop

; However, the register at 0x7e CAN be accessed
movf reg0_7e,w
nop

Bank0
movlw 0x0
movf reg0_7e,w
nop

; How about from bank 3
Bank3
movlw 0x0
movf reg0_7e,w
nop

loopHere:

goto loopHere

;============================================================
end ; END OF PROGRAM
;============================================================
; File name: RTC6355.asm
; Last revision: June 4, 2006
; Author: Julio Sanchez
; PIC: 16F877
;
; Description:
; Program to demonstrate programming of the NJU6355ED
; realtime clock IC.
;
; Operation:
;
; WARNING:
; Code assumes 10Mhz clock. Delay routines must be
; edited for faster clock. Clock speed also determines
; values for baud rate setting (see spbrgVal constant).
;
; ============================
; 16F877 switches
; ============================
;
; Switches used in __config directive:
;  _CP_ON  Code protection ON/OFF
;  * _CP_OFF
;  * _PWRTE_ON Power-up timer ON/OFF
;  _PWRTE_OFF
;  _BODEN_ON  Brown-out reset enable ON/OFF
;  * _BODEN_OFF
;  * _PWRTE_ON Power-up timer enable ON/OFF
;  _PWRTE_OFF
;  _WDT_ON  Watchdog timer ON/OFF
;  * _WDT_OFF
;  _LPV_ON  Low voltage IC programming enable ON/OFF
;  * _LPV_OFF
;  _CPD_ON  Data EE memory code protection ON/OFF
;  * _CPD_OFF
;
; OSCILLATOR CONFIGURATIONS:
;  _LP_OSC  Low power crystal oscillator
;  _XT_OSC  External parallel resonator/crystal oscillator
;  * _HS_OSC  High speed crystal resonator
;  _RC_OSC  Resistor/capacitor oscillator
;  |
;  * (simplest, 20% error)
;
; _____ * indicates setup values presently selected

processor 16f877 ; Define processor
#include<pl6f877.inc>
__CONFIG _CP_OFF & _WDT_OFF & _BODEN_OFF & _PWRTE_ON &
_HS_OSC & _WDT_OFF & _LVP_OFF & _CPD_OFF
errorlevel -302
; Supress bank-related warning

MACROS

Bank0 MACRO ; Select RAM bank 0
  bcf STATUS,RP0
  bcf STATUS,RP1
ENDM

Bank1 MACRO ; Select RAM bank 1
  bsf STATUS,RP0
  bcf STATUS,RP1
ENDM

Bank2 MACRO ; Select RAM bank 2
  bcf STATUS,RP0
  bsf STATUS,RP1
ENDM

Bank3 MACRO ; Select RAM bank 3
  bsf STATUS,RP0
  bsf STATUS,RP1
ENDM

constant definitions

#define E_line 1 ;|  -- from wiring diagram
#define RS_line 0
#define RW_line 2
; LCD line addresses (from LCD data sheet)
#define LCD_1 0x80 ; First LCD line constant
#define LCD_2 0xc0 ; Second LCD line constant
#define LCDlimit .20; Number of characters per line
#define spbrgVal .64; For 2400 baud on 10Mhz clock

; Defines from real-time clock wiring diagram
#define CLK PORTC,1
#define DAT PORTC,3
#define IO PORTC,5 ; input/output select
#define CE PORTA,2 ; chip enable bit
variables in PIC RAM

Local variables
Reserve 20 bytes for string buffer
cblock 0x20
strData
endc

Reserve three bytes for ASCII digits
cblock 0x34
asc100
asc10
asc1
endc

Data
cblock 0x37 ; Start of block
count1 ; Counter # 1
count2 ; Counter # 2
count3 ; Counter # 3
pic_ad
J ; counter J
K ; counter K
index
store1 ; Local storage
store2

For LCDscroll procedure
 LCDcount ; Counter for characters per line
 LCDline ; Current display line (0 or 1)

Communications variables
newData ; not 0 if new data received
ascVal
errorFlags

Variables for Real-Time Clock
year ; Year (00h-99h)
month ; Month (01h-12h)
day ; Day of Month (01h-31h)
dow ; Day of Week (01h-07h)
hour ; Hour (00h-23h)
min ; Minute (00h-59h)
sec ; Second (00h-59h)
T0 ; Temporary storage
T1 ; Temporary storage
endc

EEPROM-related variables are placed in common area so
they may be accessed from any bank
cblock 0x70
EEMemAdd ; EEPROM address to access
EEByte ; Data byte to write
; Storage for ASCII decimal conversion and digits
inNum ; Source operand
thisDig ; Digit counter
endc

;============================================================
; PROGRAM
;============================================================
org 0 ; start at address
goto main
; Space for interrupt handlers
org 0x08
main:
;
; Wiring:
; LCD data to port D, lines 0 to 7
; E line -> port E, 1
; RW line -> port E, 2
; RS line -> port E, 0
; Set PORTE D and E for output
; Data memory bank selection bits:
; RP1:RP0 Bank
; 0:0 0 Ports A,B,C,D, and E
; 0:1 1 Tris A,B,C,D, and E
; 1:0 2
; 1:1 3
; First, initialize port B by clearing latches
clrf STATUS
clrf PORTB
; Select bank 1 to tris port D for output
Bank1
; Tris port D for output. Port D lines 4 to 7 are wired
; to LCD data lines. Port D lines 0 to 4 are wired to LEDs.
movlw B´00000000´
movwf TRISD ; and port D
; By default port A lines are analog. To configure them
; as digital code must set bits 1 and 2 of the ADCON1
; register (in bank 1)
movlw 0x06 ; binary 0000 0110 is code to
; make all port A lines digital
movwf ADCON1
; Port B, lines are wired to keypad switches, as follows:
; 7 6 5 4 3 2 1 0
; || || | | |___|___ switch rows (output)
; |___|___|_______ switch columns (input)
; rows must be defined as output and columns as input
movlw b´11110000´
movwf TRISB
; Tris port E for output
movlw B'00000000'
movwf TRISE ; Tris port E

; NJU6355 Interface:
; CLK PORTC,1 Output
; DAT PORTC,3 Output
; IO PORTC,5 Output
; CE PORTA,2 Output
movlw b'00000000'
movwf TRISC
movlw TRISA

; Enable port B pullups for switches in OPTION register
; 7 6 5 4 3 2 1 0 <= OPTION bits
; | | | | | | | | PS2-PS0 (prescaler bits)
; | | | | | | | | Values for Timer0
; | | | | | | | 000 = 1:2  001 = 1:4
; | | | | | | 010 = 1:8  011 = 1:16
; | | | | | 100 = 1:32  101 = 1:64
; | | | | 110 = 1:128 *111 = 1:256
; | | | | ______________ PSA (prescaler assign)
; | | | | | | | *1 = to WDT
; | | | | | | 0 = to Timer0
; | | | | ______________ TOSE (Timer0 edge select)
; | | | | | *0 = increment on low-to-high
; | | | | 1 = increment in high-to-low
; | | | ______________ TOCS (TMR0 clock source)
; | | | *0 = internal clock
; | | 1 = RA4/TOCKI bit source
; | ________________ INTEDG (Edge select)
; | *0 = falling edge
; ________________ RBPU (Pullup enable)
; | *0 = enabled
; | 1 = disabled
movlw b'00001000'
movwf OPTION_REG

; Clear the write error flag (WRERR) in EECON1
Bank3
bcf EECON1,WRERR

; Back to bank 0
Bank0

; Clear all output lines
movlw b'00000000'
movwf PORTD
movwf PORTE
movwf PORTA
movwf PORTC

; Wait and initialize HD44780
call delay_5 ; Allow LCD time to initialize itself
call initLCD ; Then do forced initialization
call delay_5 ; (Wait probably not necessary)

; Clear character counter and line counter variables
clrf LCDcount
clrf LCDline

; Store base address of text buffer in PIC RAM
movlw 0x20 ; Start address for buffer
movwf pic_ad ; to local variable

; Initialize EEPROM address and data
clrf EEMemAdd ; Set address to 0
clrf EEByte

;======================
; first LCD line
;======================
; Store 20 blanks in PIC RAM, starting at address stored
; in variable pic_ad
  call blank20
; Call procedure to store ASCII characters for message
; in text buffer
  movlw d'0' ; Offset into buffer
  call storeMS1

;=======================
; Read EEPROM memory
;=======================
; EEPROM memory address to use is at 10 (0x0a). Variable
; EEMemAdd is already initialized.
; Fill data for EEPROM is 0xff. This value indicates
; the first iteration
  call EERead ; Local procedure. Value in w
  movwf EEByte ; Store value

; At this point w must be 0
; EEPROM data still in w
  clrf EEMemAdd ; Address 0
  incf EEByte,f
  call EEWrite

; At this point iteration number is stored in EEByte
; This value must be displayed on the LCD at offset 11
; of the first line. This means it must be stored at offset
; 11 in the buffer. Since the buffer starts at 0x20 the
; iteration digit must be stored at offset 0x20+11=0x2b
ShowEEData:
; Binary data in EEByte
  movf EEByte,w ; Value to w
  call bin2asc ; Conversion routine
; At this point three ASCII digits are stored in local
; variables. Move digits to display area
  movf asc1,w ; Unit digit
  movwf 0x2b ; Store in buffer
movf asc10,w ; same with other digits
movwf 0x2a
movf asc100,w
movwf 0x29

; Display line
; Set DDRAM address to start of first line

showLine:

; Testing real time clock
; call initRTC ; Initialize variables
; call Set_Time

; Wait
movlw .50
movwf count3
longWait:
call long_delay
decfsz count3,f
goto longWait

; Get variables from RTC
; call Get_Time
over1:

; Store data in EEPROM
clrf EEMemAdd ; Address 0
incf EEMemAdd,f ; Address 1
movf Hours,w
movlw 0xee
movwf EEBYTE
call EEWrite

incf EEMemAdd,f ; Address 2
movf min,w
movwf EEBYTE
call EEWrite

incf EEMemAdd,f ; Address 3
movf sec,w
movwf EEBYTE
call EEWrite

call line1
; Call procedure to display 16 characters in LCD
call display20

loopHere:
goto loopHere ;done
LOCAL PROCEDURES

init LCD for 4-bit mode

initLCD:
; Initialization for Densitron LCD module as follows:
; 4-bit interface
; 2 display lines of 16 characters each
; cursor on
; left-to-right increment
; cursor shift right
; no display shift
;************************|
; set command mode |
;************************|
    bcf PORTE,E_line ; E line low
    bcf PORTE,RS_line ; RS line low
    bcf PORTE,RW_line ; Write mode
    call delay_125 ; delay 125 microseconds
;************************|
; FUNCTION SET |
;************************|
    movlw 0x28 ; 00101000 (FUNCTION SET)
    call send8 ; 4-bit send routine
    movlw 0x28
    call send8
;************************|
; DISPLAY AND CURSOR ON |
;************************|
    movlw 0x0e ; 00001110 (DISPLAY ON/OFF)
; | | | |___ Blink character

; Set 4-bit mode command must be repeated
    movlw 0x28
    call send8
call send8
;***************************
; set entry mode
;***************************
movlw 0x06 ; 00000110 (ENTRY MODE SET)
call send8
;***************************
; cursor/display shift
;***************************
movlw 0x14 ; 00010100 (CURSOR/DISPLAY SHIFT)
call send8
;***************************
; clear display
;***************************
movlw 0x01 ; 00000001 (CLEAR DISPLAY)
call send8
; Per documentation
    call delay_5 ; Test for busy
return

;=======================
; Procedure to delay
; 42 microseconds
delay_125:
    movlw D'42' ; Repeat 42 machine cycles
    movwf count1 ; Store value in counter
repeat
    decfsz count1,f ; Decrement counter
    goto repeat ; Continue if not 0
    return ; End of delay

; Procedure to delay
; 5 milliseconds
; delay_5:
    movlw D'42' ; Counter = 41
    movwf count2 ; Store in variable
delay
    call delay_125 ; Delay
    decfsz count2,f ; 40 times = 5 milliseconds
goto delay
    return ; End of delay

; pulse E line
pulseE
    bsf PORTE,E_line ; Pulse E line
    nop
    bcf PORTE,E_line
    return

; long delay sub-routine
; long_delay
    movlw D'200' ; w delay count
    movwf J ; J = w
jloop: movwf K ; K = w
kloop: decfsz K,f ; K = K-1, skip next if zero
goto kloop
    decfsz J,f ; J = J-1, skip next
if zero
goto jloop
    return

; LCD display procedure
; Sends 20 characters from PIC buffer with address stored
; in variable pic_ad to LCD line previously selected
display20:
    call delay_5 ; Make sure not busy

; Set up for data
    bcf PORTA,E_line ; E line low
    bsf PORTA,RS_line ; RS line high for data

; Set up counter for 20 characters
    movlw D'20'
    movwf count3

; Get display address from local variable pic_ad
    movf pic_ad,w ; First display RAM address to W
    movwf FSR ; W to FSR

getchar
    movf INDF,w ; get character from display RAM
    ; location pointed to by file select
    ; register
    call send8 ; 4-bit interface routine

; Test for 16 characters displayed
    decfsz count3,f ; Decrement counter
    goto nextchar ; Skipped if done
    return

nextchar:
    incf FSR,f ; Bump pointer
    goto getchar

;========================
; send 2 nibbles in
; 4-bit mode
;========================
; Procedure to send two 4-bit values to port B lines
; 7, 6, 5, and 4. High-order nibble is sent first
; ON ENTRY:
; w register holds 8-bit value to send
send8:
    movwf store1 ; Save original value
    call merge4 ; Merge with port B

; Now w has merged byte
    movwf PORTD ; w to port D
    call pulseE ; Send data to LCD

; High nibble is sent
    movf store1,w ; Recover byte into w
    swapf store1,w ; Swap nibbles in w
    call merge4
    movwf PORTD
    call pulseE ; Send data to LCD
    call delay_125
    return
;================================================================================
; merge bits
;================================================================================
; Routine to merge the 4 high-order bits of the
; value to send with the contents of port B
; so as to preserve the 4 low-bits in port B
; Logic:
;   AND value with 1111 0000 mask
;   AND port B with 0000 1111 mask
;   Now low nibble in value and high nibble in
;   port B are all 0 bits:
;   value = vvvv 0000
;   port B = 0000 bbbb
;   OR value and port B resulting in:
;   vvvv bbbb
; ON ENTRY:
;   w contains value bits
; ON EXIT:
;   w contains merged bits
merge4:
  andlw b'11110000' ; ANDing with 0 clears the
                     ; bit. ANDing with 1 preserves
                     ; the original value
  movwf store2 ; Save result in variable
  movf PORTD,w ; port B to w register
  andlw b'00001111' ; Clear high nibble in port b
                     ; and preserve low nibble
  iorwf store2,w ; OR two operands in w
  return

;================================================================================
; Set address register
; to LCD line 2
;================================================================================
; ON ENTRY:
; Address of LCD line 2 in constant LCD_2
line2:
  bcf PORTE,E_line ; E line low
  bcf PORTE,RS_line ; RS line low, setup for
                     ; control
  call delay_5 ; Busy?
  ; Set to second display line
  movlw LCD_2 ; Address with high-bit set
  call send8
  ; Set RS line for data
  bsf PORTE,RS_line ; RS = 1 for data
  call delay_5 ; Busy?
  return
;====================================
; Set address register
; to LCD line 1
;====================================
; ON ENTRY:
; Address of LCD line 1 in constant LCD_1
line1:
    bcf PORTE,E_line ; E line low
    bcf PORTE,RS_line ; RS line low, set up for
                      ; control
    call delay_5 ; busy?
    ; Set to second display line
    movlw LCD_1      ; Address and command bit
    call send8       ; 4-bit routine
    ; Set RS line for data
    bsf PORTE,RS_line ; Setup for data
    call delay_5     ; Busy?
    return

;====================================
; scroll to LCD line 2
;====================================
; Procedure to count the number of characters displayed on
; each LCD line. If the number reaches the value in the
; constant LCDlimit, then display is scrolled to the second
; LCD line. If at the end of the second line, then LCD is
; reset to the first line.
LCDscroll:
    incf LCDcount,f ; Bump counter
    ; Test for line limit
    movf LCDcount,w
    sublw LCDlimit  ; Count minus limit
    btfss STATUS,Z ; Is count - limit = 0
    goto scrollExit ; Go if not at end of line
    ; At this point the end of the LCD line was reached
    ; Test if this is also the end of the second line
    movf LCDline,w
    sublw 0x01       ; Is it line 1?
    btfsr STATUS,Z   ; Is LCDline minus 1 = 0?
    goto line2End ; Go if end of second line
    ; At this point it is the end of the top LCD line
    call line2       ; Scroll to second line
    clrflf LCDcount  ; Reset counter
    incf LCDline,f   ; Bump line counter
    goto scrollExit ; End of second LCD line
line2End:
call initLCD ; Reset
clrf LCDcount ; Clear counters
clrf LCDline
call line1 ; Display to first line
scrollExit:
return

;==================================
; first text string procedure
;==================================
storeMS1:
; Procedure to store in PIC RAM buffer the message
; contained in the code area labeled msg1
; ON ENTRY:
;   variable pic_ad holds address of text buffer
; in PIC RAM
;   w register hold offset into storage area
;   msg1 is routine that returns the string characters
; and a zero terminator
;   index is local variable that hold offset into
;   text table. This variable is also used for
;   temporary storage of offset into buffer
; ON EXIT:
;   Text message stored in buffer
;
; Store offset into text buffer (passed in the w register)
; in temporary variable
movwf index ; Store w in index
; Store base address of text buffer in FSR
movf pic_ad,w ; first display RAM address to W
addwf index,w ; Add offset to address
movwf FSR ; W to FSR
; Initialize index for text string access
movlw 0 ; Start at 0
movwf index ; Store index in variable
; w still = 0
get_msg_char:
call msg1 ; Get character from table
; Test for zero terminator
andlw 0x0ff
btfsc STATUS,Z ; Test zero flag
goto endstr1 ; End of string
; ASSERT: valid string character in w
; store character in text buffer (by FSR)
movwf INDF ; store in buffer by FSR
incf FSR,f ; increment buffer pointer
; Restore table character counter from variable
movf index,w ; Get value into w
addlw 1 ; Bump to next character
movwf index ; Store table index in variable
goto get_msg_char ; Continue
derturn:

go to get_msg_char ; Continue

; Routine for returning message stored in program area
; Message has 10 characters
msg1:
addwf PCL,f ; Access table
retlw 'I'
retlw 't'
retlw 'e'
retlw 'r'
retlw '.'
retlw 0x20
retlw 'N'
retlw 'o'
retlw '.'
retlw 0x20
retlw 0

;========================
; blank buffer
;========================
; Procedure to store 20 blank characters in PIC RAM
; buffer starting at address stored in the variable
; pic_ad
blank20:
movlw D'20' ; Setup counter
movwf count1
movf pic_ad,w ; First PIC RAM address
movwf FSR ; Indexed addressing
movlw 0x20 ; ASCII space character
storeit
movwf INDF ; Store blank character in PIC RAM
; buffer using FSR register
decfsz count1,f ; Done?
goto incfsr ; no
return ; yes
incfsr
incf FSR,f ; Bump FSR to next buffer space
goto storeit

;==============================
; binary to ASCII decimal
; conversion
;==============================
; ON ENTRY:
w register has binary value in range 0 to 255

ON EXIT:
output variables asc100, asc10, and asc1 have three ASCII decimal digits

Routine logic:
The value 100 is subtracted from the source operand until the remainder is < 0 (carry cleared). The number of subtractions is the decimal hundreds result. 100 is then added back to the subtrahend to compensate for the last subtraction. Now 10 is subtracted in the same manner to determine the decimal tenths result.
The final remainder is the decimal units result.

Variables:
inNum storage for source operand
asc100 storage for hundreds position result
asc10 storage for tenth position result
asc1 storage for unit position result
thisDig Digit counter

bin2asc:
movwf inNum ; Save copy of source value
clrf asc100 ; Clear hundreds storage
clrf asc10 ; Tens
clrf asc1 ; Units
clrf thisDig

sub100:
movlw .100
subwf inNum,f ; Subtract 100
btfsc STATUS,C ; Did subtract overflow?
goto bump100 ; No. Count subtraction
goto end100
bump100:
incf thisDig,f ;increment digit counter
goto sub100

end100:
movf thisDig,w ; Adjusted digit counter
addlw 0x30 ; Convert to ASCII
movwf asc100 ; Store it

; Calculate tenth position value
clrf thisDig
; Adjust minuend
movlw .100 ; Minuend
addwf inNum,f ; Add value to minuend to compensate for last operation

sub10:
movlw .10
subwf inNum,f ; Subtract 10


```assembly
btfsc STATUS, C ; Did subtract overflow?
goto bump10 ; No. Count subtraction
goto end10

bump10:
    incf thisDig, f ; increment digit counter
    goto sub10
; Store 10th digit

end10:
    movlw .10
    addwf inNum, f ; Adjust for last subtract
    movf thisDig, w ; get digit counter contents
    addlw 0x30 ; Convert to ASCII
    movwf asc10 ; Store it
; Calculate and store units digit
    movf inNum, w ; Store units value
    addlw 0x30 ; Convert to ASCII
    movwf asc1 ; Store digit
    return

;============================================================================
; local EEPROM data procedures
;============================================================================
; GPRs used in EEPROM-related code are placed in the common
; RAM area (from 0x70 to 0x7f). This makes the registers
; accessible from any bank.
;============================================================================

; read local EEPROM
;============================================================================
; Procedure to read EEPROM memory
; ON ENTRY:
; Address of EEPROM memory location to read is stored in
; local register EEMemAdd
; ON EXIT:
; Read data in w

EEPRead:
    Bank2
    movf EEMemAdd, W ; EEPROM address
    movwf EEADR ; to read from
    Bank3
    bcf EECON1, EEPGD ; Point to Data memory
    bsf EECON1, RD ; Start read
    Bank2
    movf EEDATA, W ; Data to w register
    Bank0
    return

;============================================================================
; write local EEPROM
;============================================================================
```
; Procedure to write data byte to EEPROM memory
; ON ENTRY:
; Address to write stored in local register EEMemAdd
; Data byte to write is in local register EEByte
EEWrite:
    Bank3
Wait2Start:
    btfsc EECON1,WR        ; Wait for
    GOTO Wait2Start       ; write to finish
    Bank2
    movf EEMemAdd,w       ; Address to
    movwf EEADR           ; SFR
    movf EEByte,w         ; Data to
    movwf EEDATA          ; SFR
    Bank3
    bcf EECON1,EEPGD      ; Point to Data memory
    bsf EECON1,WREN       ; and enable writes
    ; Disable interrupts. Can be done in any case
    bcf INTCON,GIE
    ; Write special codes
    movlw 0x55             ; First code is 0x55
    movwf EECON2
    movlw 0xaa              ; Second code is 0xaa
    movwf EECON2
    bsf EECON1,WR           ; Start write operation
    nop                      ; Time for write
    nop
    ; Test for end of write operation
wait2End:
    btfsc EECON1,WR        ; Wait until WR clear
    goto wait2End
    ; Reenable interrupts if program uses interrupts
    ; If not, comment out next line
    ; bsf INTCON,GIE
    ;
    bcf EECON1,WREN        ; Prevent accidental writes
    Bank0
    return
;=================================================================
; 6355 RTC procedures
;=================================================================
; Write time/date to real-time clock
;
setclk
    movlw 08h              ; CE=low, IO=high
    movwf PORTA

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movlw 10h ; CE,IO,CLK,DATA=out
tris PORTA
movlw year ; INDF=year
movwf FSR
bsf IO ; Enable clock I/O
call CS3 ; Set year, month, and day
movf INDF,W ; Set day of week
call CSNI
call CS2 ; Set hr, min (zero second)
bcf IO ; Disable clock I/O
return
;
CS3 call CSB ; Set next byte and advance
CS2 call CSB ; Set next byte and advance
;
CSB movf INDF,W ; Shift out LSN
call CSN
swapf INDF,W ; Shift out MSN
CSNI incf FSR,f ; Bump storage pointer
;
CSN movwf T1 ; T1=data
movlw 4 ; T0=bit count
movwf T0
next
movb PORTA.0,T1.0 ; Output next bit
rrf T1,f ; Ready next bit
bsf CLK ; Clock bit out of clock
bcf CLK
decls T0,f ; Continue until byte done
goto next
return ; Done
;
====================================
; Read time/date from real-time clock
;====================================
getclk
movlw 00h ; CE,IO=low
movwf PORTA
movlw 11h ; CE,IO,CLK=out, DATA=in
tris PORTA
movlw year ; INDF=year
movlw FSR
bsf IO ; Enable clock I/O
call CG3 ; Get year, month, and day
call CGNI ; Get day of week
swapf dow
call CG3 ; Get hr, min, and sec
bcf IO ; Disable clock I/O
Supplementary Programs

return ; Done

; CG3 call CGB ; Get next byte and advance
call CGB ; Get next byte and advance

; CGB call CGN ; Shift LSN in
CGNI call CGN ; Shift MSN in
call CGMask ; Mask unused bits
andwf INDF
incf FSR ; Bump storage pointer
return ; Done

; CGN movlw 4 ; T0=bit count
movwf T0
next1 rrf INDF ; Shift accumulator
movb INDF.7,PORTA.0 ; Store bit to acc.
bsf CLK ; Clock next bit
bcf CLK
decfsz T0 ; Continue until done
goto next1
return ; Done

; CGMask movf FSR,W ; W=RTC reg (0=year, ...)
addlw -year
addwf PCL ; W=bit mask for register
retlw 0FFh ; Year (8 bits)
retlw 01Fh ; Month (5 bits)
retlw 03Fh ; Day of month (6 bits)
retlw 070h ; Day of week (3 bits)
retlw 03Fh ; Hour (6 bits)
retlw 07Fh ; Minute (7 bits)
retlw 07Fh ; Second (7 bits)

;=============================================================================
end ; END OF PROGRAM
;=============================================================================


Receive character data through RS-232 line and store in 24LC04B EEPROM IC, using the I2C serial protocol in the PIC's MSSP module. Received characters are echoed on the second LCD line. When <Enter> key is detected (code 0x0d) the text stored in EEPROM memory is retrieved and displayed on the LCD. On startup the top LCD line displays the prompt: 'Receiving:'. At that time a message 'Rdy- ' is sent through the serial line so as to test the connection.

Default serial line setting:
- 2400 baud
- no parity
- 1 stop bit
- 8 character bits

Wiring:
- 24LC04B SDA line is wired to PIC RC4 (MSSP SDA)
- 24LC04B SCL line is wired to PIC RC3 (MSSP SCL)
- 24LC04B A0-A2 and WP lines are not used (GND)

Program to use 4-bit PIC-to-LCD interface.
Code assumes that LCD is driven by Hitachi HD44780 controller and PIC 16F977. Display supports two lines, each one with 20 characters. The length, wiring and base address of each display line is stored in #define statements. These statements can be edited to accommodate a different set-up.

WARNING:
Code assumes 10 Mhz clock. Delay routines must be edited for a different clock. Clock speed also determines values for baud rate setting (see spbrgVal constant).

16F877 switches
Switches used in __config directive:
- _CP_ON Code protection ON/OFF
- _CP_OFF
- _PWRTE_ON Power-up timer ON/OFF
- _PWRTE_OFF
- _BODEN_ON Brown-out reset enable ON/OFF
; * _BODEN_OFF
; * _PWRTE_ON Power-up timer enable ON/OFF
; _PWRTE_OFF
; _WDT_ON Watchdog timer ON/OFF
; * _WDT_OFF
; _LPV_ON Low voltage IC programming enable ON/OFF
; * _LPV_OFF
; _CPD_ON Data EE memory code protection ON/OFF
; * _CPD_OFF
; OSCILLATOR CONFIGURATIONS:
; _LP_OSC Low power crystal oscillator
; _XT_OSC External parallel resonator/crystal oscillator
; * _HS_OSC High speed crystal resonator
; _RC_OSC Resistor/capacitor oscillator
; | (simplest, 20% error)
; |
; | _____ * indicates setup values presently selected

    processor 16f877 ; Define processor
    #include<p16f877.inc>
    __CONFIG _CP_OFF & _WDT_OFF & _BODEN_OFF & _PWRTE_ON &
    _HS_OSC & _WDT_OFF & _LVP_OFF & _CPD_OFF

; __CONFIG directive is used to embed configuration data
; within the source file. The labels following the directive
; are located in the corresponding .inc file.
    errorlevel -302
; Suppress bank-related warning

;============================================================================
; MACROS
;============================================================================
; Macros to select the register banks
Bank0 MACRO ; Select RAM bank 0
    bcf STATUS,RP0
    bcf STATUS,RP1
    ENDM

Bank1 MACRO ; Select RAM bank 1
    bsf STATUS,RP0
    bcf STATUS,RP1
    ENDM

Bank2 MACRO ; Select RAM bank 2
    bcf STATUS,RP0
    bsf STATUS,RP1
    ENDM

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Bank3 MACRO ; Select RAM bank 3
    bsf STATUS,RP0
    bsf STATUS,RP1
ENDM

;=====================================================
; constant definitions
; for PIC-to-LCD pin wiring and LCD line addresses
;=====================================================
#define E_line 1 ;|  
#define RS_line 0 ;| -- from wiring diagram  
#define RW_line 2 ;|  
; LCD line addresses (from LCD data sheet)  
#define LCD_1 0x80 ; First LCD line constant  
#define LCD_2 0xc0 ; Second LCD line constant  
#define LCDlimit .20; Number of characters per line  
#define spbrgVal .64; For 2400 baud on 10Mhz clock  
; Note: The constants that define the LCD display  
; line addresses have the high-order bit set  
; so as to meet the requirements of controller  
; commands.

;=====================================================
; local equates
;=====================================================
WRITE_ADDR equ b'10100000'; Control byte for write  
READ_ADDR equ b'10100001'; Control byte for read  
;=====================================================
; General Purpose Variables
;=====================================================
; Local variables  
; Reserve 20 bytes for string buffer  
cblock 0x20  
strData  
endc  
; Other data  
cblock 0x34 ; Start of block  
count1 ; Counter # 1  
count2 ; Counter # 2  
count3 ; Counter # 3  
J ; counter J  
K ; counter K  
bufAdd  
index  
store1 ; Local storage  
store2  
; For LCDscroll procedure  
LCDcount ; Counter for characters per line  
LCDline ; Current display line (0 or 1)
Common RAM area

These GPRs can be accessed from any bank.
15 bytes are available, from 0x70 to 0x7f

Communications variables
newData ; not 0 if new data received
ascVal
errorFlags

EEPROM-related variables
datai ; Data input byte buffer
datao ; Data output byte buffer
bytecount ; Counter for byte loops
pollcnt ; Counter for polling loops
loops ; Delay loop counter
loops2 ; Delay loop counter
EEMemAdd ; EEPROM address to access
EEByte ; Data byte to write
endc

PROGRAM

org 0 ; start at address
goingo main
; Space for interrupt handlers
org 0x08
main:

; Wiring:
; LCD data to port D, lines 0 to 7
; E line -> port E, 1
; RW line -> port E, 2
; RS line -> port E, 0
; Set PORTE D and E for output
; First, initialize port B by clearing latches
clrf STATUS
clrf PORTB
; Select bank 1 to tris port D for output
Bank1
; Tris port D for output. Port D lines 4 to 7 are wired
; to LCD data lines. Port D lines 0 to 4 are wired to LEDs.
movlw B'00000000'
movwf TRISD ; and port D
; By default port A lines are analog. To configure them
; as digital code must set bits 1 and 2 of the ADCON1
; register (in bank 1)
movlw 0x06  ; binary 0000 0110 is code to  
        ; make all port A lines digital
movwf ADCON1
; Port B, lines are wired to keypad switches, as follows:
;  7 6 5 4 3 2 1 0
;  |||||_|_|_|_____ switch rows (output)
;  |_|_|_|_____________ switch columns (input)
; rows must be defined as output and columns as input
movlw b'11110000'
movwf TRISB
; Tris port E for output
movlw B'00000000'
movwf TRISE ; Tris port E
; Enable port B pullups for switches in OPTION register
movlw b'00001000'
movwf OPTION_REG
; Back to bank 0
Bank0
; Initialize serial port for 2400 baud, 8 bits, no parity
; 1 stop
    call InitSerial
; Test serial transmission by sending 'RDY-
movlw 'R'
call SerialSend
movlw 'D'
call SerialSend
movlw 'Y'
call SerialSend
movlw '-'
call SerialSend
movlw 0x20
call SerialSend
; Clear all output lines
movlw b'00000000'
movwf PORTD
movwf PORTE
; Wait and initialize HD44780
    call delay_5 ; Allow LCD time to initialize itself
call initLCD ; Then do forced initialization
call delay_5 ; (Wait probably not necessary)
; Clear character counter and line counter variables
    clr ADCOUNT
    clr LCDLINE
; Set display address to start of first LCD line
    call line1
; Store address of display buffer
movlw 0x20
movwf buffer
; Display 'Receiving:' message prompt
  call   blank20 ; Clear buffer
  movlw  0x00 ; Offset in buffer
  call   storeMS1 ; Store message at offset
  call   display20 ; Display message

; Start address of EEPROM
  clrf   EEMemAdd
; Setup for display in second line
  call   line2
  clrf   LCDline
  incf   LCDline,f ; Set scroll control for line 2

;==========================================================================
; receive serial data, store, and display
;==========================================================================
receive:
; Call serial receive procedure
  call   SerialRcv
; HOB of newData register is set if new data received
  btfss  newData,7
  goto   scanExit
; At this point new data was received.
  movwf  EEByte ; Save received character
  movf   EEByte,w ; Recover character
  call   send8 ; Display in LCD
  call   LCDscroll ; Scroll at end of line
; Store character in EEPROM at location in EEMemAdd
  call   ic2Write ; Local procedure
  incf   EEMemAdd,f ; Bump to next EEPROM
; Check for <Enter> key (0x0d) and execute display function
  movf   EEByte,w ; Recover last received
  sublw  0x0d
  btfsc  STATUS,Z ; Test if <Enter> key
  goto   isEnter ; Go if <Enter>
; Not <Enter> key, continue processing
  scanExit:
  goto   receive ; Continue

;==========================================================================
; display EEPROM data
;==========================================================================

; This routine receives control when the <Enter> key is received.
; Action:
; 1. Clear LCD
; 2. Output is set to top LCD line
; 3. Characters stored in EEPROM are displayed
;   until 0x0d code is detected
isEnter:
call clearLCD
; Clear character counter and line counter variables
clrf LCDcount
clf LCDline
; Read data from EEPROM memory, starting at address 0
; and display on LCD until 0x0d terminator
call line1
clf EEMemAdd; Start at EEPROM 0
readOne:
call ic2Read ; Get character
; Store character
movwf EEByte ; Save character
; Test for terminator
sublw 0x0d
btfsc STATUS,Z ; Test if 0x0d
goto atEnd ; Go if 0x0d
; At this point character read is not 0x0d
; Display on LCD
movf EEByte,w ; Recover character
; Display character on LCD
call send8 ; Display in LCD
call LCDscroll ; Scroll at end of line
incf EEMemAdd,f ; Next EEPROM byte
goto readOne

; End of execution
atEnd:
goto atEnd

;=================================================================
;=================================================================
; LOCAL PROCEDURES
;=================================================================
;=================================================================
;==========================================================
; init LCD for 4-bit mode
;==========================================================
initLCD:
; Initialization for Densitron LCD module as follows:
; 4-bit interface
; 2 display lines of 16 characters each
; cursor on
; left-to-right increment
; cursor shift right
; no display shift
;==========================================================
; set command mode
;==================================
bcf PORTE,E_line ; E line low
bcf PORTE,RS_line ; RS line low
bcf PORTE,RW_line ; Write mode
call delay_125 ; delay 125 microseconds
movlw 0x28 ; 00101000 (FUNCTION SET)
call send8 ; 4-bit send routine
; Set 4-bit mode command must be repeated
movlw 0x28
call send8
movlw 0x0e ; 00001110 (DISPLAY ON/OFF)
call send8
movlw 0x06 ; 00000110 (ENTRY MODE SET)
call send8
movlw 0x14 ; 00010100 (CURSOR/DISPLAY SHIFT)
call send8
movlw 0x01 ; 00000001 (CLEAR DISPLAY)
; |___ COMMAND BIT
call send8
call delay_5 ; Test for busy
return

.;==================================
; procedure to clear LCD
;==================================
clearLCD:
bcf PORTE,E_line ; E line low
bcf PORTE,RS_line ; RS line low
bcf PORTE,RW_line ; Write mode
call delay_125 ; delay 125 microseconds
movlw 0x01 ; 00000001 (CLEAR DISPLAY)
; |___ COMMAND BIT
call send8
call delay_5 ; Test for busy
return

;==================================
; Procedure to delay
; 42 microseconds
;==================================
delay_125:
movlw .105 ; Repeat 105 machine cycles
movwf count1 ; Store value in counter
repeat
; Decrement counter
; Continue if not 0
; End of delay

; Procedure to delay
; 5 milliseconds
; ========================
delay_5:
movlw .105 ; Counter = 105 cycles
movwf count2 ; Store in variable
delay
    call delay_125 ; Delay
decfsz count2,f ; 40 times = 5 milliseconds
goto delay ; End of delay

; Procedure to send two 4-bit values to port B lines
; 7, 6, 5, and 4. High-order nibble is sent first
; ON ENTRY:
; w register holds 8-bit value to send
; 4-bit mode
; Procedure to send two 4-bit values to port B lines
; 7, 6, 5, and 4. High-order nibble is sent first
; ON ENTRY:
; w register holds 8-bit value to send
send8:
movwf store1 ; Save original value
call merge4 ; Merge with port B
; Now w has merged byte
movwf PORTD ; w to port D
call pulseE ; Send data to LCD

; High nibble is sent
movf store1,w ; Recover byte into w
swapf store1,w ; Swap nibbles in w
call merge4
movwf PORTD
call pulseE ; Send data to LCD
call delay_125
return

;==========================
; merge bits
;==========================
; Routine to merge the 4 high-order bits of the
; value to send with the contents of port B
; so as to preserve the 4 low-bits in port B
; Logic:
; AND value with 1111 0000 mask
; AND port B with 0000 1111 mask
; Now low nibble in value and high nibble in
; port B are all 0 bits:
; value = vvvv 0000
; port B = 0000 bbbb
; OR value and port B resulting in:
; vvvv bbbb
; ON ENTRY:
; w contain value bits
; ON EXIT:
; w contains merged bits
merge4:
andlw b'11110000' ; ANDing with 0 clears the
; bit. ANDing with 1 preserves
; the original value
movwf store2 ; Save result in variable
movf PORTD,w ; port B to w register
andlw b'00001111' ; Clear high nibble in port b
; and preserve low nibble
iorwf store2,w ; OR two operands in w
return

;==========================
; Set address register
; to LCD line 2
;==========================
; ON ENTRY:
; Address of LCD line 2 in constant LCD_2
line2:
bcf PORTE,E_line ; E line low
bcfPORTE,RS_line ; RS line low, setup for
; control
calldelay_5 ; Busy?
; Set to second display line
movlwLCD_2 ; Address with high-bit set
calla send8
; Set RS line for data
bsfPORTE,RS_line ; RS = 1 for data
calla delay_5 ; Busy?
return

;=========
; Set address register
to LCD line 1
;=========

; ON ENTRY:
;
Address of LCD line 1 in constant LCD_1
line1:
bcfPORTE,E_line ; E line low
bcfPORTE,RS_line ; RS line low, set up for
; control
calla delay_5 ; Busy?
; Set to second display line
movlwLCD_1 ; Address and command bit
calla send8 ; 4-bit routine
; Set RS line for data
bsfPORTE,RS_line ; Setup for data
calla delay_5 ; Busy?
return

;=========
; scroll to LCD line 2
;=========

; Procedure to count the number of characters displayed on
; each LCD line. If the number reaches the value in the
; constant LCDlimit, then display is scrolled to the second
; LCD line. If at the end of the second line, then LCD is
; reset to the first line.
LCDscroll:
incf LCDcount,f ; Bump counter
; Test for line limit
movf LCDcount,w
sublw LCDlimit ; Count minus limit
btfss STATUS,Z ; Is count - limit = 0
goto scrollExit ; Go if not at end of line
; At this point the end of the LCD line was reached
; Test if this is also the end of the second line
movf LCDline,w
sublw0x01 ; Is it line 1?
btfsc STATUS,Z    ; Is LCDline minus 1 = 0?
goto line2End    ; Go if end of second line

; At this point it is the end of the top LCD line
call line2    ; Scroll to second line
clrf LCDcount    ; Reset counter
incf LCDline,f    ; Bump line counter
goto scrollExit

; End of second LCD line
line2End:
call initLCD    ; Reset
clrf LCDcount    ; Clear counters
clrf LCDline
call line1    ; Display to first line

scrollExit:
    return

;=============================
; LCD display procedure
;=============================
; Sends 20 characters from PIC buffer with address stored
; in variable bufAdd to LCD line previously selected
display20:
call delay_5    ; Make sure not busy

; Set up for data
bcf PORTA,E_line    ; E line low
bsf PORTA,RS_line    ; RS line high for data

; Set up counter for 20 characters
movlw D'20'
movwf count3

; Get display address from local variable bufAdd
movf bufAdd,w    ; First display RAM address to W
movwf FSR    ; W to FSR
getchar
movf INDF,w    ; get character from display RAM
    ; location pointed to by file select
    ; register
call send8    ; 4-bit interface routine

; Test for 20 characters displayed
decfsz count3,f    ; Decrement counter
goto nextchar    ; Skipped if done
return

nextchar:
incf FSR,f    ; Bump pointer
goto getchar

;===============================
; first text string procedure
;===============================

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storeMS1:
; Procedure to store in PIC RAM buffer the message
; contained in the code area labeled msg1
; ON ENTRY:
; variable bufAdd holds address of text buffer
; in PIC RAM
; w register hold offset into storage area
; msg1 is routine that returns the string characters
; and a zero terminator
; index is local variable that hold offset into
; text table. This variable is also used for
; temporary storage of offset into buffer
; ON EXIT:
; Text message stored in buffer
;
; Store offset into text buffer (passed in the w register)
; in temporary variable
movwf   index       ; Store w in index
; Store base address of text buffer in FSR
movf   bufAdd,w   ; first display RAM address to W
addwf  index,w   ; Add offset to address
movwf  FSR        ; W to FSR
; Initialize index for text string access
movlw  0           ; Start at 0
movwf  index       ; Store index in variable
; w still = 0
get_msg_char:
call   msg1        ; Get character from table
; Test for zero terminator
andlw  0x0ff
btfsc  STATUS,Z   ; Test zero flag
goto   endstr1    ; End of string
; ASSERT: valid string character in w
; store character in text buffer (by FSR)
movwf  INDF        ; store in buffer by FSR
incf   FSR,f      ; increment buffer pointer
; Restore table character counter from variable
movf   index,w     ; Get value into w
addlw  1           ; Bump to next character
movwf  index       ; Store table index in
                     ; variable
goto    get_msg_char ; Continue
endstr1:
return

; Routine for returning message stored in program area
; Message has 10 characters
msg1:
addwf    PCL,f            ; Access table
retlw    'R'
retlw    'e'
retlw    'C'
retlw    'e'
retlw    'i'
retlw    'v'
retlw    'n'
retlw    'g'
retlw    ':'
retlw    0

;========================
; blank buffer
;========================
; Procedure to store 20 blank characters in PIC RAM
; buffer starting at address stored in the variable
; bufAdd
blank20:
    movlw    D'20'        ; Setup counter
    movwf    count1
    movf     bufAdd,w    ; First PIC RAM address
    movwf    FSR          ; Indexed addressing
    movlw    0x20         ; ASCII space character
storeit
    movwf    INDF         ; Store blank character in PIC RAM
    decfsz   count1,f     ; Done?
    goto     incfsr       ; no
    return
incfsr
    incf     FSR,f        ; Bump FSR to next buffer
space
    goto     storeit

;==================================================================
; communications procedures
;==================================================================
; Initialize serial port for 2400 baud, 8 bits, no parity,
; 1 stop
InitSerial:
    Bank1          ; Macro to select bank1
; Bits 6 and 7 of Port C are multiplexed as TX/CK and RX/DT
; for USART operation. These bits must be set to input in the
; TRISC register
    movlw    b'11000000' ; Bits for TX and RX
iorwf TRISC,f ; OR into Trisc register

; The asynchronous baud rate is calculated as follows:

; Fosc
; ABR = -----------
; S*(x+1)

; where x is value in the SPBRG register and S is 64 if the high
; baud rate select bit (BRGH) in the TXSTA control register is
; clear, and 16 if the BRGH bit is set. For setting to 2400 baud
; using a 10Mhs oscillator at a slow baud rate the formula
; is:

; At slow speed (BRGH = 0)
; 10,000,000 10,000,000
; ----------- = ----------- = 2,403.84 (0.16% error)
; 64*(64+1) 4160

movlw spbrgVal ; Value in spbrgVal = 64
movwf SPBRG ; Place in baud rate generator

; Setup value: 0010 0000 = 0x20
movlw 0x20 ; Enable transmission and high
; baud rate

movwf TXSTA ; Bank 0

; Setup value: 1001 0000 = 0x90
movlw 0x90 ; Enable serial port and
; continuous reception

movwf RCSTA ;

clrf errorFlags ; Clear local error flags
; register

return

;==============================
; transmit data
;==============================
;
SerialSend:
Bank0 ; Select bank 0
btfss PIR1,TXIF ; check if transmitter busy
goto $-1 ; wait until transmitter is
; not busy
movwf TXREG ; and transmit the data
return

;==============================
; receive data
;==============================
;
; Procedure to test line for data received and return value
; in w. Overrun and framing errors are detected and
; remembered in the variable errorFlags, as follows:
SerialRcv:
clrf newData ; Clear new data received
register Bank0 ; Select bank 0
; Bit 5 (RCIF) of the PIR1 Register is clear if the USART receive buffer is empty. If so, no data has been received
btfss PIR1,RCIF ; Check for received data
return ; Exit if no data
; At this point data has been received. First eliminate possible errors: overrun and framing.
; Bit 1 (OERR) of the RCSTA register detects overrun
; Bit 2 (FERR) of the RCSTA register detects framing error
btfsc RCSTA,OERR ; Test for overrun error
goto OverErr ; Error handler
btfsc RCSTA,FERR ; Test for framing error
go to FrameErr ; Error handler
; At this point no error was detected
; Received data is in the USART RCREG register
movf RCREG,w ; get received data
bsf newData,7 ; Set bit 7 to indicate new data
; Clear error flags
clrif errorFlags
return
;===============================================
; error handlers
;===============================================
OverErr:
bsf errorFlags,0 ; Bit 0 is overrun error
; Reset system
bcf RCSTA,CREN ; Clear continuous receive bit
bsf RCSTA,CREN ; Set to re-enable reception
return
; error because FERR framing error bit is set
; can do special error handling here - this code simply clears and continues
FrameErr:
bsf errorFlags,1; Bit 1 is framing error
movf RCREG,W ; Read and throw away bad data
return
;==================================================================================
; I2C EEPROM data procedures
;==================================================================================
; GPRs used in EEPROM-related code are placed in the common RAM area (from 0x70 to 0x7f). This makes the registers accessible from any bank.
;*******************Byte read test subroutine *******************
; This routine tests the byte read feature
; of the serial EEPROM device. It will read
; 1 byte of data at address 0x5AA5 from the device.
;***************************************************************
ic2Read
  call BSTART ; Generate Start condition
  bcf STATUS,RP0 ; Select Bank 00
  movlw WRITE_ADDR ; Load control byte for write
  movwf datao ; Copy to datao for output
  call TX ; Send control byte to device
  bcf STATUS,RP0 ; Select Bank 00
  movlw 0x5A ; Load 0x5A for word address
  movwf datao ; Copy to datao for output
  call TX ; Send word address high byte
  bcf STATUS,RP0 ; Select Bank 00
  movlw 0xA5 ; Load 0xA5 for word address
  movwf datao ; Copy to datao for output
  call TX ; Send word address low byte
  bcf STATUS,RP0 ; Select Bank 00
  movlw READ_ADDR ; Load control byte for read
  movwf datao ; Copy to datao for output
  call TX ; Send control byte to device
  bsf STATUS,RP0 ; Select Bank 01
  bsf SSPCON2,ACKDT ; Select to send NO ACK bit
  call RX ; Read data byte from device
  call BSTOP ; Generate Stop condition
  retlw 0

;*******************Byte write test subroutine*******************
; This routine tests the byte write feature
; of the serial EEPROM device. It will write
; 1 byte of data to the device at address 0x5AA5.
;*******************************************************
ic2Write
  call BSTART ; Generate Start condition
  bcf STATUS,RP0 ; Select Bank 00
  movlw WRITE_ADDR ; Load control byte for write
  movwf datao ; Copy to datao for output
  call TX ; Send control byte to device
  bsf STATUS,RP0 ; Select Bank 01
  bsf SSPCON2,ACKDT ; Select to send NO ACK bit
  call RX ; Read data byte from device
  call BSTOP ; Generate Stop condition
  retlw 0
bcf STATUS,RP0 ; Select Bank 00
movlw 0x5A ; Load 0x5A for word address
movwf datao ; Copy to datao for output
call TX ; Send word address low byte

bcf STATUS,RP0 ; Select Bank 00
movlw 0xA5 ; Load 0xA5 for word address
movwf datao ; Copy to datao for output
; Send word address to device
.bc9 STATUS,RP0 ; Select Bank 00
movlw 0xAA ; Load 0xAA for data byte
movwf datao ; Copy to datao for output
; Send data byte
bcf STATUS,RP0 ; Select Bank 00
movlw WRITE_ADDR ; Now send the control byte
movwf datao ; Copy control byte to buffer
call TX ; Send data byte to device
call BSTOP ; Generate Stop condition
call Poll ; Poll for write completion
retlw 0

;*******************Acknowledge Polling subroutine***************
; This subroutine polls the EEPROM device
; for an ACK bit, which indicates that the
; internal write cycle has completed. Code
; is in place for a timeout routine, just
; uncomment the 'goto TimedOut' line, and
; provide a 'TimedOut' label.
;************************************************************
Poll
bcf STATUS,RP0 ; Select Bank 00
movlw .40
movwf pollcnt ; Set max polling times to 40

polling
bcf STATUS,RP0 ; Select Bank 00
movlw WRITE_ADDR ; Now send the control byte
movwf datao ; Copy control byte to buffer
call TX ; Output control byte to device
bsf STATUS,RP0 ; Select Bank 01
btfss SSPCON2,ACKSTAT ; Was the ACK bit low?
goto exitpoll ; If yes, stop polling
; If no, check if polled 40 times
bcf STATUS,RP0 ; Select Bank 00
decfsz pollcnt,F ; Is poll counter down to zero?
goto polling ; If no, poll again
; goto TimedOut ; If yes, part didn’t respond
; in time, so take action
exitpoll
call BSTOP ; Generate stop bit
movlw .40
movwf pollcnt ; Set max polling times to 40

polling
  call BRESTART ; Generate start bit
  bcf STATUS,RP0 ; Select Bank 00
  movlw WRITE_ADDR ; Now send the control byte
  movwf datao ; Copy control byte to buffer
  call TX ; Output control byte to device
  bsf STATUS,RP0 ; Select Bank 01
  btfss SSPCON2,ACKSTAT ; Was the ACK bit low?
  goto exitpoll ; If yes, stop polling
  ; If no, check if polled 40 times
  bcf STATUS,RP0 ; Select Bank 00
  decfsz pollcnt,F ; Is poll counter down to zero?
  goto polling ; If no, poll again
  ; goto TimedOut ; If yes, part didn't respond
  ; in time, so take action

exitpoll
  call BSTOP ; Generate stop bit
  retlw 0

;***************************Initialization subroutine***************************
; This routine initializes the MSSP module
; for I2C Master mode, with a 100 kHz clock.
;*******************************************************************************
Init
  bcf STATUS,RP1 ; Select Bank 01
  bsf STATUS,RP0
  movlw b'11111111'
  movwf TRISC ; Set PORTC to all inputs
  clrf SSPSTAT ; Disable SMBus inputs
  bsf SSPSTAT,SMP ; Disable slew rate control
  movlw 0x18 ; Load 0x18 into WREG
  movwf SSPADD ; Setup 100 kHz I2C clock
  clrf SSPCON2 ; Clear control bits
  bcf STATUS,RP0 ; Select Bank 00
  movlw b'00101000'
  movwf SSPCON ; Enable SSP, select I2C Master mode
  bcf PIR1,SSPIF ; Clear SSP interrupt flag
  bcf PIR2,BCLIF ; Clear Bit Collision flag
  retlw 0

;***************************Start bit subroutine*******************************
; This routine generates a Start condition
; (high-to-low transition of SDA while SCL is still high).
;*******************************************************************************
Supplementary Programs

BSTART
bcf STATUS,RP1
bcf STATUS,RP0 ; Select Bank 00
bcf PIR1,SSPIF ; Clear SSP interrupt flag
bsf STATUS,RP0 ; Select Bank 01
bsf SSPCON2,SEN ; Generate Start condition
bcf STATUS,RP0 ; Select Bank 00

bstart_wait
btfss PIR1,SSPIF ; Check if operation completed
goto bstart_wait ; If not, keep checking
retlw 0

;******************Restart bit subroutine***********************
; This routine generates a Repeated Start
; condition (high-to-low transition of SDA
; while SCL is still high).
;************************************************************
BRESTART
bcf STATUS,RP1
bcf STATUS,RP0 ; Select Bank 00
bcf PIR1,SSPIF ; Clear SSP interrupt flag
bsf STATUS,RP0 ; Select Bank 01
bsf SSPCON2,RSEN ; Generate Restart condition
bcf STATUS,RP0 ; Select Bank 00

brestart_wait
btfss PIR1,SSPIF ; Check if operation completed
goto brestart_wait ; If not, keep checking
retlw 0

;*******************Stop bit subroutine************************
; This routine generates a Stop condition
; (low-to-high transition of SDA while SCL
; is still high).
;**************************************************************
BSTOP
bcf STATUS,RP1
bcf STATUS,RP0 ; Select Bank 00
bcf PIR1,SSPIF ; Clear SSP interrupt flag
bsf STATUS,RP0 ; Select Bank 01
bsf SSPCON2,PEN ; Generate Stop condition
bcf STATUS,RP0 ; Select Bank 00

bstop_wait
btfss PIR1,SSPIF ; Check if operation completed
goto bstop_wait ; If not, keep checking
retlw 0

;*******************Data transmit subroutine*******************
This routine transmits the byte of data stored in 'datao' to the serial EEPROM device. Instructions are also in place to check for an ACK bit, if desired. Just replace the 'goto' instruction, or create an 'ackfailed' label, to provide the functionality.

TX

```
bcf STATUS,RP1
bcf STATUS,RP0 ; Select Bank 00
bcf PIR1,SSPIF ; Clear SSP interrupt flag
movf datao,W ; Copy datao to WREG
movwf SSPBUF ; Write byte out to device
```

```
tx_wait
btfss PIR1,SSPIF ; Check if operation completed
goto tx_wait ; If not, keep checking
; bsf STATUS,RP0 ; Select Bank 01
; btfsc SSPCON2,ACKSTAT ; Check if ACK bit was received
; goto ackfailed ; This executes if no ACK received
retlw 0
```

RX

```
bcf STATUS,RP1
bcf STATUS,RP0 ; Select Bank 00
bcf PIR1,SSPIF ; Clear SSP interrupt flag
bsf STATUS,RP0 ; Select Bank 01
bsf SSPCON2,RCEN ; Initiate reception of byte
bcf STATUS,RP0 ; Select Bank 00
```

```
rx_wait
btfss PIR1,SSPIF ; Check if operation completed
goto rx_wait ; If not, keep checking
movf SSPBUF,W ; Copy byte to WREG
movwf datai ; Copy WREG to datai
bcf PIR1,SSPIF ; Clear SSP interrupt flag
bsf STATUS,RP0 ; Select Bank 01
bsf SSPCON2,ACKEN ; Generate ACK/NO ACK bit
bcf STATUS,RP0 ; Select Bank 00
```

```
rx_wait2
btfss PIR1,SSPIF ; Check if operation completed
```
goto rx_wait2 ; If not, keep checking
retd 0

;============================================================
end ; END OF PROGRAM
;============================================================
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