6

PICmicro® MCU APPLICATION DESIGN AND HARDWARE INTERFACING

CONTENTS AT A GLANCE

After reading the previous two chapters and "Introduction to Electronics" on the CD-ROM, you must feel like there is nothing left to understand about designing PICmicro® MCU applications. In these chapters on the CD-ROM I have provided background on how microcontroller interfacing is carried out and some of the theories and pitfalls that you should be aware of. This chapter covers some specifics about how the PICmicro® MCU works when wired to different interfaces.

I am not trying to say that the PICmicro® MCU is a difficult microcontroller to interface to. Actually, it is one of the easiest eight-bit microcontrollers to develop interface applications for. In different versions, with built-in oscillators and reset circuits, interfaces can be unbelievably easy to implement. Despite this, you should be aware of a few things that will help you make your applications more efficient and keep you from having difficult to debug problems.

Estimating Application Power Requirements

Accurate power estimating for your applications is important because the expected power consumption affects how much heat is produced by the circuit and what kind of power supply is required by it. Although the PICmicro® MCU power can usually only be estimated to an order of a magnitude, this is usually good enough to ensure that the circuit won't overheat, the power supply won't burn out or the batteries will not be exhausted before the required execution time has passed.

For the PICmicro® MCU itself, the "intrinsic" current, what I call the current consumed by the microcontroller with nothing connected to it, is available from Microchip in the data sheets. For the PIC16F87x, rated at 4 MHz, Table 6-1 lists the IDD (the supply current or intrinsic current), according to the oscillator type.

The current rating for the oscillator type selected in the configuration fuses should be the basis for your estimate. Notice that as the clock frequency changes, the intrinsic current consumption will go up at a rate of about one mA per MHz. For estimating purposes, I recommend that you use the worst case for the oscillator selected.

Next, select the current requirements for the devices that connect directly to the PICmicro® MCU. Depending on their operation, the current requirements can change drastically. For example, an LED that is off consumes just no current, and one that is on can consume from five to 20 mA. Again, for these devices, the worst cases should be used with the estimate.

Also, note that different devices will respond differently, depending on how they are used. A very good example of this is a LCD display. Many modern LCDs have built-in pull-ups to make interfacing easier for electronic devices that have open collector outputs (such as the 8051). Typically, these devices current requirements will be quoted with the

TABLE 6–1 PICmicro® MCU Oscillator Current Consumption Comparison

OSCILLATOR	IDD	FREQUENCY
LP	52.5 μA	32 kHz
RC	5 mA	4 MHz
XT	5 mA	4 MHz
HS	13.5 mA	4 MHz

minimum value, rather than the maximum. To ensure you have an accurate estimate, you will have to check the current drain with the LCD connected and operating with the PICmicro® MCU.

Lastly, the power consumption of other devices connected to the circuit (but not the PICmicro® MCU) will have to be determined through the device's data sheets. Again, the worst-case situation should be taken into account.

Once these three current values have been found, they can be summed together to get the total application power and then multiplied by the voltage applied to get the power consumed by the application. Once I have this value, I normally multiply it by a 25- to 50-percent "derater" to ensure that I have the absolute worst case.

In the applications in this book where I have specified the current, I have continually sought out the worst case and then derated the power to make it seem even worse. This is to ensure that you will not have any problems with your application power supply. Power can really make or break an application. Incorrectly specifying a supply can lead to problems with the application not powering up properly, failing intermittently, or not running as long on batteries as expected.

Marginal power supply problems can be extremely difficult to find as well. By going with a derated worst case for my application power requirements, I have eliminated one possible point in the application from going bad.

Reset

Reset in many new PICmicro® MCU part numbers can be simply implemented, eliminating the need for a separate circuit or having a built-in brown-out reset sensor. Even putting your own reset circuit into an application is simple; only a couple of rules must be followed.

Adding external reset circuit to the PICmicro® MCU consists of a pull-up connected to the _MCLR pin of the PICmicro® MCU. As shown in Fig. 6-1, a switch pulling _MCLR to ground (to reset the device) can be implemented with a momentary on switch.

A resistor of 1 to 10 K is probably appropriate; the input is CMOS and does not draw any current through the resistor. The resistor is primarily used as a current-limiting device for the momentary-on switch.

In the configuration registers of the mid-range parts there is a bit known as *PWRTE.* This bit will insert a 72-ms delay during PICmicro® MCU power up before the first instruction is fetched and executed. The purpose of this function is to allow the PICmicro®

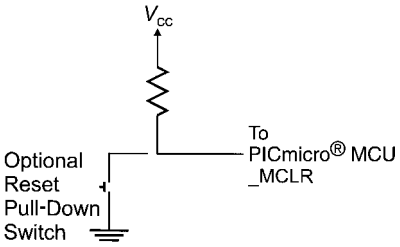


Figure 6-1

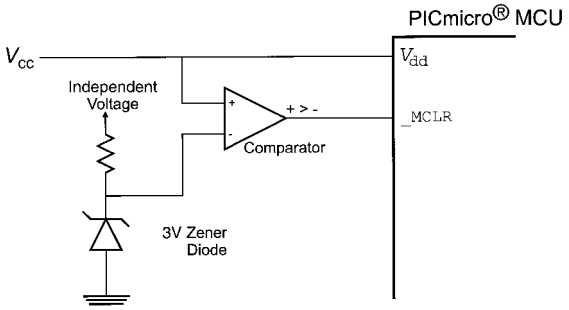


Figure 6-2 PICmicro® MCU reset with "brown out" protection

MCU's clock to stabilize before the application starts. In the low-end and high-end PICmicro® MCU's, this function is not always available.

PWRTE does not have to be enabled if a stable clock is being input to the PICmicro® MCU, such as in the case where a "canned oscillator" is used as the PICmicro® MCU's clock source instead of a crystal, ceramic resonator, or RC network.

When the _MCLR pin is made active (pulled low), the oscillator stops until the pin is brought back high. As well, the oscillator is also stopped during sleep mode to minimize power consumption. The PWRTE 72 ms delay is required in these cases, as well to ensure the clock is stable before the application's code starts executing.

If the PICmicro® MCU is run at low voltage (less than 4.0 volts), do not enable the built-in *Brown-Out Reset (BOR),* unless it is available with a low-voltage selector option. Once power drops below 4.0 volts, then circuit will become active and will hold the PICmicro® MCU reset—even though it is receiving a valid voltage for the application. The *low-voltage option* usually means that the brown-out reset will reset the PICmicro® MCU when the input voltage is below 4.0 volts or 1.8 volts.

If you are going to use low voltage and want a brown-out detect function, this can be added with a Zener diode and a comparator as is shown in Fig. 6-2.

In this circuit, voltage is reduced by the Zener diode voltage regulator to 3 volts. If V_{cc} goes below three volts, this circuit will put the PICmicro® MCU into reset. The voltage-divider values can be changed for different ratios and R can be quite high (100 K+) to minimize current drain in a battery-driven application.

The PIC12C5xx and 16C505 PICmicro® MCU's can provide an internal reset function, which uses V_{dd} as the _MCLR pin input. This frees the _MCLR pin for use as an input. The freed _MCLR pins generally cannot be used as an output.

A common use for this pin is RS-232 input using a resistor as a current limiter and providing bit-banging software to read the incoming values. If you use the _MCLR/I/O pin in this fashion, be sure that you "clamp" the pin shown in Fig. 6-3.

If the incoming negative voltage is not clamped within the PICmicro® MCU, the negative voltage could cause the PICmicro® MCU to be forced into reset mode. If the positive voltage is not clamped, then the PICmicro® MCU could go into the programming mode. The general-purpose pins are designed with clamping diodes built in and will not allow inputs to be driven outside V_{dd} or ground. Not clamping the input pins can cause some confusing problems when you first work with the PICmicro® MCU in this type of application. The use of clamping diodes for RS-232 interfacing is shown in the "Serial LCD Interface" in Chapter 16.

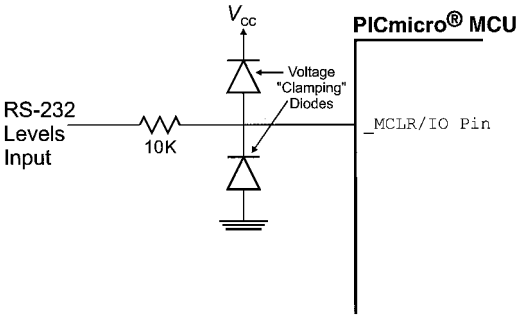


Figure 6-3 Internal reset allowing "_MCLR" pin to be used for RS-232 input

Interfacing to External Devices

The previous chapters have provided a lot of information about the peripheral hardware built into the PICmicro® MCU that will help making applications easier. Coupled with the information contained in the appendices, you would have thought I had it all covered.

The following sections cover some of the hints and tips I've learned over the years for interfacing PICmicro® MCUs to other devices. With this information, I have also included source code for the different interface hardware. This code is available on the CD-ROM as snippets that can be cut and pasted into your applications, as well as into macros that can be added to the applications.

Much of this information and code is used later in the book when I go through the experiments and projects. Some of the interfaces will seem very complex or difficult to create, but I have tried to work through many of the difficulties and provide you with sample circuits that are simple and cheap to implement.

DIGITAL LOGIC

It should not be surprising that the PICmicro® MCU can interface directly to TTL and CMOS digital logic devices. The PICmicro® MCU's parallel I/O pins provide digital output levels that can be detected properly by both logic technologies and inputs that can detect logic levels output from these logic families.

If you check the PICmicro® MCU data sheets, you will see that the output characteristics are:

V_{ol} (output low voltage) = 0.6 V (max.)
V_{oh} (output high voltage) = V_{dd} − 0.7 V (min.)

This specification is given to allow for different V_{dd} power inputs. For a V_{dd} of 5 volts, you can expect a "high" output of 4.3 volts or greater (normally, I see 4.7 volts when a PICmicro® MCU pin is not under load). If the power voltage input (V_{dd}) was reduced to 2 volts, low output would still be 0.6 volts and high output becomes 1.3 volts (V_{dd} – 0.7) or greater.

The PICmicro® MCU pins are specified to drive (source) up to 20 mA and sink (pull the output to ground) 25 mA. These current capabilities easily allow the PICmicro® MCU to drive LEDs. The total current sourced or sunk by the PICmicro® MCU should not exceed 150 mA (which is six I/O pins sinking the maximum current).

The input "threshold" voltage, the point at which the input changes from an *I* to an *O* and visa versa, is also dependent on the input power (V_{dd}) voltage level. The threshold is different for different devices and the data sheet should be consulted for precise values. In general, for a number of different PICmicro® MCU part numbers, this value is specified as being in the range:

$$0.25\ V_{dd} + 0.8\ \text{V} >= V_{threshold} >= 0.48\ V_{dd}$$

As a rule, you should use the higher value. For higher V_{dd}s, this is approximately one half V_{dd}. At lower V_{dd} voltages, (2 volts), the threshold becomes approximately two-thirds of V_{dd}.

For the most part, interfacing to conventional logic devices is very straightforward in the PICmicro® MCU. The following sections feature some special interfacing cases and how the PICmicro® MCU can be wired to other devices to take advantage of the PICmicro® MCU's electrical properties. Using these properties, applications can use standard I/O pins to simulate different interface types and, in some cases, reduce the numbers of pins required for an application.

Parallel bus devices Although the PICmicro® MCU is very well suited for stand-alone applications, many applications have to connect to external devices. There are built-in PICmicro® MCU interfaces for *Non-Return to Zero (NRZ)* asynchronous I/O and two-wire serial I/O, but sometimes the best interface is a simulated parallel I/O bus. A simulated parallel bus is useful for increasing the I/O capabilities of the PICmicro® MCU using standard I/O chips. These devices can be accessed fairly easily using an eight-bit I/O port and a few extra control pins from the PICmicro® MCU.

I realize that the PIC17Cxx has the ability to drive a parallel bus, but I tend to shy away from using these devices for this purpose because the PIC17Cxx I/O data bus is 16 bits wide and can only access the full word of data at any one time. Most parallel buses require an eight-bit bus and the PIC17Cxx devices tend to be more expensive than using the mid-range parts. Looking at the extra costs of the PIC17Cxx devices, coupled with the complexity of adding the address buffers, you're probably better off using the mid-range devices and simulating the bus as shown here.

When I create a parallel bus, I normally use PORTB for eight data bits and use other PORT pins for the _RD and _WR lines. To avoid the extra costs and complexity of decode circuitry, it is probably best to devote one I/O line to each device. Before writing from the PICmicro® MCU to the device, TRISB is set to output mode and the value to be written is output on PORTB. Next, the _CS and _WR lines are pulled low and remain active until the device's minimum access times are met. _RD is similar with TRISB being put in input mode, the _CS and _RD pins are held active until the devices minimum read access time is met, at which point the data is strobed into w, _CS, and _RD are driven high.

The circuit in Fig. 6-4 requires two parallel output bytes and one parallel input byte. This could be implemented with a 40-pin PICmicro® MCU, using the I/O pins directly, but it is much more cost effective to use an 18-pin PICmicro® MCU (such as the PIC16F84) and a tristate output buffer and two eight bit registers. In Fig. 6-4, it is assumed that data is clocked in or output with negative active signal pulses.

With this circuit, RA0 to RA2 would be set for output and initialized to 4 (high voltage) driven out. To read the eight data bits on the tristate buffer, the following code could be used:

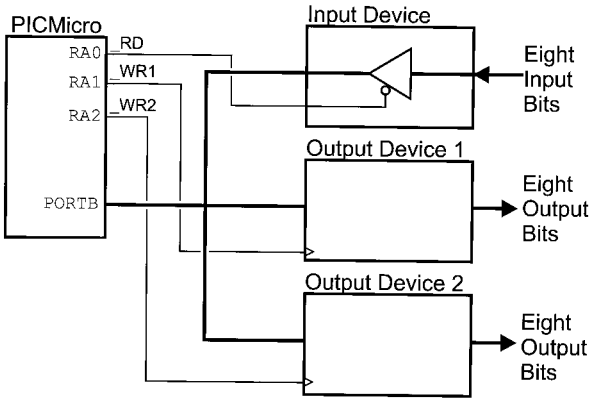


Figure 6-4 PICmicro® MCU simulated parallel 10 port

```
bsf     STATUS, RP0         ; Put PORTB into Input Mode
movlw   0x0FF
movwf   TRISB ^ 0X080
bcf     STATUS, RP0
bcf     PORTA, 0            ; Drop the "_RD" line
call    Dlay                ; Delay until Data Output Valid
movf    PORT B, w           ; Read Data from the Port
bsf     PORT A, 0           ; "_RD" = 1 (disable "_RD" Line)
```

Writing to one of the output registers is similar:

```
bsf     STATUS, RP0
clrf    TRIS B ^ 0X080      ; PORTB Output
bcf     STATUS, RP0
bcf     PORTA, 1            ; Enable the "_WR1" Line
movwf   PORTB               ; output the Data
call    Dlay                ; Wait Data Receive Valid
bsf     PORTA, 1            ; "_WR1" = 1.
```

Combining input and output Often when working on applications, you will find some situations where peripheral devices will use more than one pin for I/O. Another case would be when you are connecting two devices, one input and one output and would like to combine them somehow so that you can reduce the number of PICmicro® MCU pins required. Fewer PICmicro® MCU pins means that you can use cheaper PICmicro® MCUs and avoid complex application wiring. This section presents two techniques for doing this and the rules governing their use. This might at first appear problematic and asking for problems with bus contention, but they really do work and can greatly simplify your application.

When interfacing the PICmicro® MCU to a driver and receiver (such as a memory with a separate output and input), a resistor can be used to avoid bus contention at any of the pins (Fig. 6-5).

In this situation, when the PICmicro® MCU's I/O pin is driving out, it will be driving the Data In pin register and regardless of the output of the Data Out pin. If the PICmicro® MCU and Data Out pins are driving different logic levels, the resister will limit the current flowing between the PICmicro® MCU and the memory Data Out pin. The value received on the Data In pin will always be the PICmicro® MCU's output due to the voltage drop within the registor.

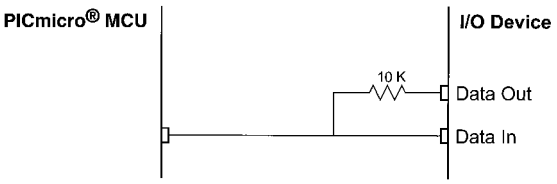


Figure 6-5 PICmicro® MCU simulated parallel 10 port

When the PICmicro® MCU is receiving data from the memory, its I/O pin will be put in input mode and the Data Out pin will drive its value to not only the PICmicro® MCU's I/O pin, but the Data In pin as well. In this situation, the Data In pin should not be latching any Data In. To avoid this, in most cases where this circuit combines input and output, the two input and output pins are on the same device and the data mode is controlled by the PICmicro® MCU to prevent invalid data from being input into the device. This is an important point because it defines how this trick should be used. The I/O pins that the PICmicro® MCU are connected to must be mutually exclusive and can never be transmitting data at the same time. A common use for this method of connection data in and data out pins is used in SPI memories, which have separate data input and output pins.

The second trick is to have button input, along with an external device receiver. As is shown in Fig. 6-6, a button can be put on the same "net" as an input device and the PICmicro® MCU pin that drives it.

When the button is open or closed, the PICmicro® MCU can drive data to the input device, the 100-K and 10-K resistors will limit the current flow between V_{cc} and ground. If the PICmicro® MCU is going to read the button high (switch open) or low (switch closed) will be driven on the bus at low currents when the pin is in input mode. If the button switch is open, then the 100-K resistor acts like a pull up and a *1* is returned. When the button switch is closed, then there will be approximately 0.5 volt across the 10-K resistor, which will be read as a *0*.

The button with the two resistors pulling up and down are like a low-current driver and the voltage produced by them is easily "overpowered" by active drivers. Like the first method, the external input device cannot receive data except when the PICmicro® MCU is driving the circuit. A separate clock or enable should be used to ensure that input data is received when the PICmicro® MCU is driving the line.

Two points about this method; this can be extrapolated to work with a switch matrix keyboard. The circuit can become very complex, but it will work. Secondly, a

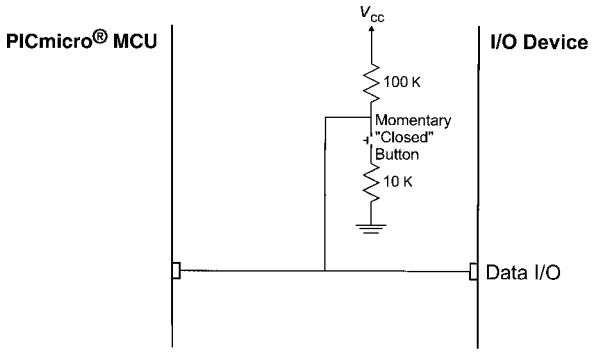


Figure 6-6 Combining button in-put with digital I/O

resistor/capacitor network for debouncing the button cannot be used with this circuit because a resistor-capacitor network will "slow down" the response of the PICmicro® MCU driving the data input pin and will cause problems with the correct value being accepted. When a button is shared with an input device; such as is shown in Fig. 6-6, software button debouncing will have been done inside the PICmicro® MCU.

Simulated open collector/open drain I/O Open collector/open drain outputs are useful in several different interfacing situations. Along with providing a node in a dotted AND bus, they are also useful to interface with I2C and other networks. I find that the single open drain pin available in the different PICmicro® MCU devices to be insufficient for many applications, which is why I find it useful to simulate an open drain driver with a standard I/O pin.

An open drain pin (shown in Fig. 6-7) consists of a N-channel MOSFET transistor with its source connected to the I/O pin. Because there is no P-channel high driver in the pin circuit, when a *1* is being output the only transistor will be turned off and the pin is allowed to float. *Floating,* in most applications, means having a pull up and multiple open-collector/open-drain drivers on the net.

When the data out bit is low (and TRIS is enabled for output), the pin is pulled low. Otherwise, it is not electrically connected to anything ("tristated").

This action can be simulated by using the following code, which enables the I/O pin output to be low if the carry flag is reset. If the carry flag is set, then the pin is put into input mode.

```
bcf         PORT#, pin              ;  Make Sure PORTB Pin Bit is "0"
bsf         STATUS, RP0
btfss       STATUS, C               ;  If Carry Set, Disable Open Collector
 goto       $ + 4                   ;  Carry Reset, Enable Open Collector
nop
bsf         TRIS ^ 0x080, pin
goto        $ + 3
bcf         TRIS ^ 0x080, pin
goto        $ + 1
bcf         STATUS, RP0
```

This code, which is designed for mid-range PICmicro® MCUs, will either set the pin to input (tristate) mode or pulled low on the sixth cycle after it has been invoked, I normally put this code into a macro, with the port and pin specified as parameters.

It will seem like I went to some lengths to ensure that the timing was the same for making the bit tristate (input mode) or pulled low to 0, as well as the state specified by the carry flag. Regardless of the execution path, this code will take eight instruction cycles and the

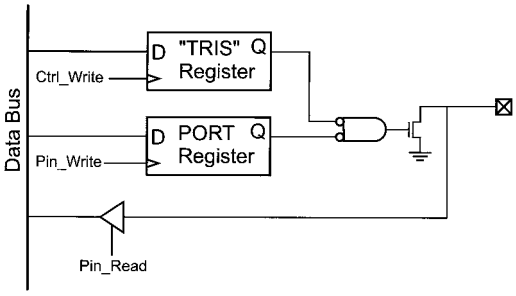


Figure 6-7 "Open Drain" no pin configuration

I/O pin value will be changed at five cycles. I did this because this function is often used with I2C or other network protocols and using the carry flag allows bits to be shifted through this code easily.

In the sample open-drain simulation code, I reset the specified pin before potentially changing its TRIS value. This is to prevent it from being the wrong value, based on reads and writes of other I/O pins. This is the "inadvertent pin changes" that I've written about elsewhere in the book.

DIFFERENT LOGIC LEVELS WITH ECL AND LEVEL SHIFTING

Often, when working with PICmicro® MCUs and other microcontrollers, you will have to interface devices of different logic families together. For standard positive voltage logic families (i.e., TTL to CMOS), this is not a problem; the devices can be connected directly. But, interfacing a negative voltage logic to a positive voltage logic family (i.e., ECL to CMOS) can cause some problems.

Although chips usually are available to provide this interface function (for both input and output), they typically only work in only one direction (which precludes bi-directional busses—even if the logic family allows it) and the chips can add a significant cost to the application.

The most typical method of providing level conversion is to match the switching threshold voltage levels of the two logic families.

As shown in Fig. 6-8, the ground level for the COMS microcontroller has been shifted below ground (the microcontroller's "ground" is actually the CMOS 0 level). The purpose of this is to place the point where the microcontroller's input logic switches between a *0* and a *1* (known as the *input logic threshold voltage*) is the same as the ECL Logic. The resistor (which is between 1 K and 10 K) is used to limit the current flow because of the different logic swings of the two different families.

Looking at the circuit block diagram, you're probably thinking that the cost of shifting the microcontroller power supply is much greater than just a few interface chips.

Actually, this isn't a big concern because of the low power requirements of modern CMOS microcontrollers. In Fig. 6-8, the microcontroller's ground reference can be produced by placing a silicon diode (which has a 0.7 voltage drop across it) between it and the ECL's 2-volt power supply negative output. The 5-volt and 2-volt supplies' positive output have a common "threshold" voltage for this circuit and the registor limits the CMOS

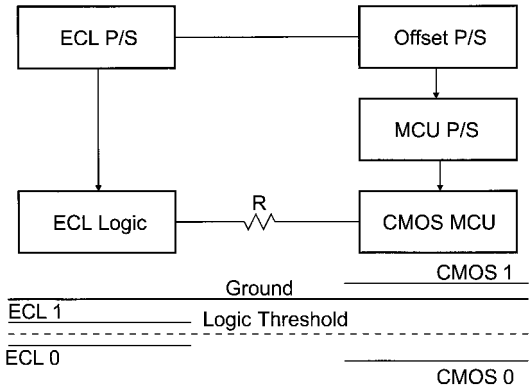


Figure 6-8 ECL to CMOS logic level conversion

logic swing to the 1 volt ECL swing. This example might seem simplistic, but it would provide the ability to connect a CMOS 0- to +5-volt microcontroller to ECL logic (and allow signals to be sent in either direction, between the PICmicro® MCU and the ECL Logic) at a very low cost.

LEDs

The most common form of output from a microcontroller is the *Light-Emitting Diode (LED).* As an output device, it is cheap and easy to wire to a microcontroller. Generally, LEDs require anywhere from 5 mA of current to light (which is within the output sink/source specification for most microcontrollers). But, what has to be remembered is, LEDs are diodes, which means that current flows in one direction only. The typical circuit that I use to control an LED from a PICmicro® MCU I/O pin is shown in Fig. 6-9.

With this circuit, the LED will light when the microcontroller's output pin is set to *0* (ground potential). When the pin is set to input or outputs a *1,* the LED will be turned off.

The 220 Ohm resistor is used for current limiting and will prevent excessive current that can damage the microcontroller, LED and the power supply. Elsewhere in the book, I have shown how this resistor value is calculated. Some microcontrollers (such as the PICmicro® MCU) already have current-limiting output pins, which lessens the need for the current-limiting resistor. But, I prefer to always put in the resistor to guarantee that a short (either to ground or V_{cc}) cannot ever damage the microcontroller of the circuit it's connected to (including the power supply).

Probably the easiest way to output numeric (both decimal and hex) data is via seven-segment LED displays. These displays were very popular in the 1970s (if you're old enough, your first digital watch probably had seven-segment LED displays), but have been largely replaced by LCDs.

Seven-segment LED displays (Fig. 6-10) are still useful devices that can be added to a circuit without a lot of software effort. By turning on specific LEDs (each of which light up a segment in the display), the display can be used to output decimal numbers.

Each one of the LEDs in the display is given an identifier and a single pin of the LED is brought out of the package. The other LED pins are connected together and wired to a common pin. This common LED pin is used to identify the type of seven-segment display (as either common cathode or common anode).

Wiring one display to a microcontroller is quite easy—it is typically wired as seven (or eight, if the decimal point, DP, is used) LEDs wired to individual pins.

The most important piece of work you'll do when setting up seven-segment LED displays is matching and documenting the microcontroller bits to the LEDs. Spending a few moments at the start of a project will simplify wiring and debugging the display later.

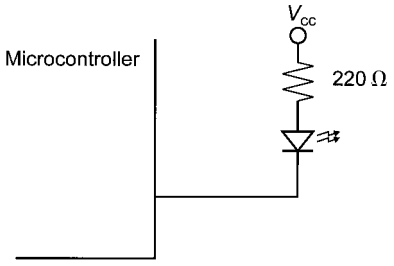


Figure 6-9 LED connection to a microcontroller

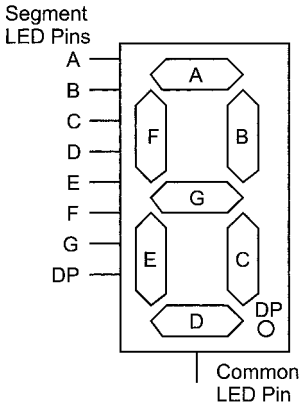


Figure 6-10 Organization of a 7 segment LED display

The typical method of wiring multiple seven-segment LED displays together is to wire them all in parallel and then control the current flow through the common pin. Because the current is generally too high for a single microcontroller pin, a transistor is used to pass the current to the common power signal. This transistor selects which display is active.

Figure 6-11 shows common-cathode seven-segment displays connected to a microcontroller.

In this circuit, the microcontroller will shift between the displays showing each digit in a very short time slice. This is usually done in a timer interrupt handler. The basis for the interrupt handler's code is:

```
Int
   - Save Context Registers
   - Reset Timer and Interrupt
   - LED_Display = 0                ; Turn Off all the LEDs
   - LED_Output = Display[ Cur ]
   - Cur = (Cur + 1) mod #Displays  ; Point to Next Sequence Display
   - LED_Display = 1 << Cur         ; Display LED for Current Display
   - Restore Context Registers
   - Return from Interrupt
```

This code will cycle through each of the digits (and displays), having current go through the transistors for each one. To avoid flicker, I generally run the code so that each digit is turned on/off at least 50 times per second. The more digits you have, the faster you have

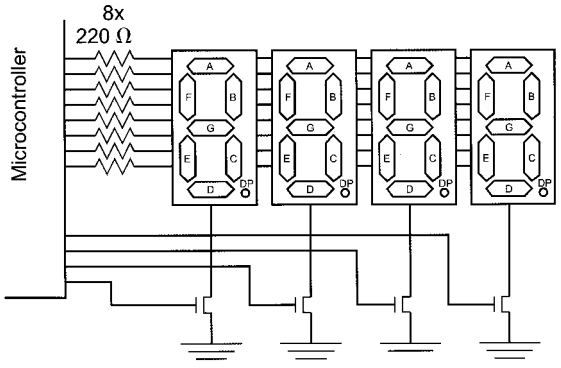


Figure 6-11 Wiring four 7 segment LED displays

to cycle the interrupt handler (i.e., eight seven-segment displays must cycle at least 400 digits per second, which is eight times as fast as a single display).

You might feel that assigning a microcontroller bit to select each display LED to be somewhat wasteful (at least I do). I have used high-current TTL demultiplexer (i.e., 74S138) outputs as the cathode path to ground (instead of discrete transistors). When the output is selected from the demultiplexer, it goes low, allowing current to flow through the LEDs of that display (and turning it on). This actually simplifies the wiring of the final application as well. The only issue is to ensure that the demultiplexer output can sink the maximum of 140 mA of current that will come through the common cathode connection.

Along with seven-segment displays, 14- and 16-segment LED displays are available, which can be used to display alphanumeric characters (A to Z and 0 to 9). By following the same rules as used when wiring up a seven-segment display, you shouldn't have any problems wiring the display to a PICmicro® MCU. Chapter 16 shows how seven- and 16-segment LEDs can be used to display letters and numbers.

Switch Bounce

When a button is opened or closed, we perceive that it is a clean operation that really looks like a step function. In reality, the contacts of a switch bounce when they make contact, resulting in a jagged signal (Fig. 6-12).

When this signal is passed to a PICmicro® MCU, the microcontroller can recognize this as multiple button presses, which will cause the application software to act as if multiple, very fast button presses have occurred. To avoid this problem the "noisy" switch press is "debounced" into an idealized "press," or the step function (Fig. 6-13). Two common methods are used to debounce button inputs.

The first is to poll the switch line at short intervals until the switch line stays at the same level for an extended period of time. A button is normally considered to be debounced if it

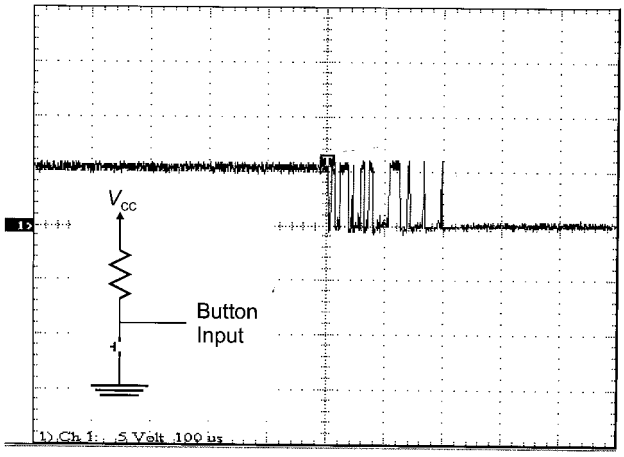


Figure 6-12 Oscilloscope picture of a switch "bounce"

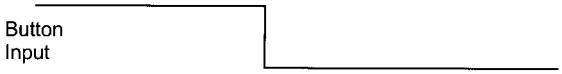


Figure 6-13 Idealized switch operation

does not change state for 20 ms or longer. By polling the line every 5 ms, this debouncing method can be conceptualized quite easily (Fig. 6-14).

The advantage of this method is that it can be done in an interrupt handler and the line can be scanned periodically with a flag set if the line is high and another flag in the line is low. For the "indeterminate" stage, neither bit would be set. This method of debouncing is good for debouncing keyboard inputs.

The second method is to continually poll the line and wait for 20 ms to go by without the line changing state. The algorithm that I use for this function is:

```
ButLoop:
   while (Button == High);    // Poll Until Button is Pressed
   for (Dlay = 0; (Dlay < 20msec) and (Button == Low); Dlay++);
   if (Dlay != 20 msec)       // Repeat Process if 20 msecs have
     goto ButLoop;            // Not gone by with Button Pressed
```

This code will wait for the button to be pressed and then poll it continuously until either 20 ms has passed or the switch has gone high again. If the switch goes high, the process is repeated until it is held low for 20 ms.

This method is well suited to applications that don't have interrupts, only have one button input, and have no need for processing while polling the button. As restrictive as it sounds, many applications fit these criteria.

This method can also be used with interrupt inputs along with TMR0 in the PICmicro® MCU, which eliminates these restrictions. The interrupt handler behaves like the following pseudo-code when one of the port changes on interrupt bits is used for the button input:

```
interrupt ButtonDebounce()           // Set Flags According to the
{                                    //   Debounced State of the Button

 if (T0IF == 1) {                    // TMR0 Overflow, Button Debounced
     T0IF = 0; T0IE = 0;             // Reset and Turn off TMR0 Interrupts
     if (Button == High) {
        Pressed = 0; NotPressed = 0; // Set the State of the Button
     } else {
       Pressed = 1; NotPressed = 0;
```

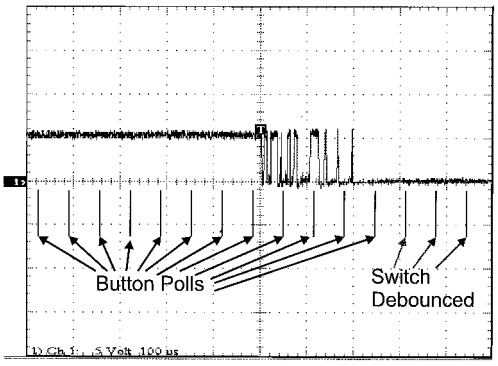


Figure 6-14 Polling to eliminate "bounce"

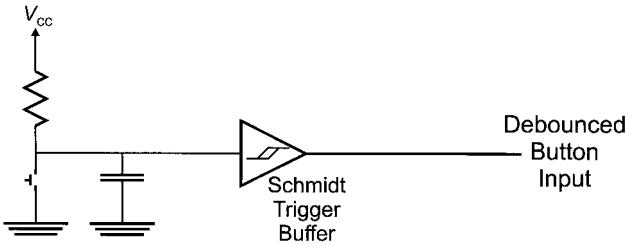


Figure 6-15 Debounced switch using a Schmidt Trigger

```
    }
  } else {                          // Port Change Interrupt
    NotPressed = 1;                 // Nothing True
    RBIF = 0;                       // Reset the Interrupt
    TMR0 = 20msecDlay;              // Reset Timer 0 for 20 ms
    T0IF = 0; T0IE = 1;             // Enable the Timer Interrupt
  }
} // End ButtonDebounce
```

This code waits for the input pin to change state and then resets the two flags that indicate the button state and starts TRM0 to request an interrupt after 20 ms. After a port change interrupt, notice that I reset the button state flags to indicate to the mainline that the button is in a transition state and is not yet debounced. If TMR0 overflows, then the button is polled for its state and the appropriate button state flags are set and reset.

The mainline code should poll the Pressed and NotPressed flags when it is waiting for a specific state. Chapter 15 shows this method of using TMR0 and how interrupts can be implemented with or without interrupts.

If you don't want to use the software approaches, you can use a capacitor to filter the bouncing signal and pass it into a Schmidt trigger input. Schmidt trigger inputs have different thresholds, depending on whether the signal is rising or falling. For rising edges, the trigger point is higher than falling. Schmidt trigger inputs have the "hysteresis" symbol put in the buffer (Fig. 6-15).

This method is fairly reliable, but requires an available Schmidt trigger gate in your circuit. A Schmidt trigger input might be available in your PICmicro® MCU, but check the data sheet to find out which states and peripheral hardware functions can take advantage of it.

Lastly, choose buttons with a positive "click" when they are pressed and released. These have reduced bouncing, often have a "self cleaning" feature to reduce poor contacts, and are a lot easier to work with than other switches that don't have this feature. I have used a number of switches over the years that don't have this click and they can be a real problem in circuits with intermittent connections and unexpected "bouncing" that occurs while the button is pressed and held down.

Matrix Keypads

Switch matrix keyboards and keypads are really just an extension of the button concepts, with many of the same concerns and issues to watch out for. The big advantage that the matrix keyboards gives you is that they provide a large number of button inputs for a rel-

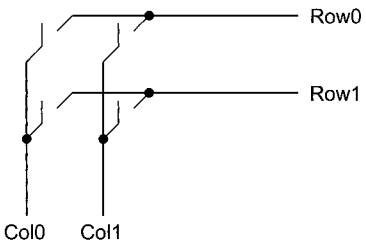


Figure 6-16 2x2 switch matrix

atively small number of PICmicro® MCU pins. The PICmicro® MCU is well designed for simply implementing switch matrix keypads, which, like LCD displays that are explained in the next section, can add a lot to your application with a very small investment in hardware and software.

A switch matrix is simply a two-dimensional matrix of wires, with switches at each vertex. The switch is used to interconnect rows and columns in the matrix (Fig. 6-16).

This diagram might not look like the simple button, but it will become more familiar when I add switchable ground connections on the columns (Fig. 6-17).

In this case, by connecting one of the columns to ground, if a switch is closed, the pull down on the row will connect the line to ground. When the row is polled by an I/O pin, a *0* or low voltage will be returned instead of a *1* (which is what will be returned if the switch in the row that is connected to the ground is open).

As stated, the PICmicro® MCU is well suited to implement switch matrix keyboards with PORTB's internal pull-ups and the ability of the I/O ports to simulate the open-drain pull-downs of the columns (Fig. 6-18). Normally, the pins connected to the columns are left in tristate (input) mode. When a column is being scanned, the column pin is output enabled driving a *0* and the four input bits are scanned to see if any are pulled low.

In this case, the keyboard can be scanned for any closed switches (buttons pressed) using the code:

```
int KeyScan()                   // Scan the Keyboard and Return when a
{                               //   key is pressed

int  i = 0;
int  key = -1;

    while (key == -1) {

      for (i = 0; (i < 4) & ((PORTB & 0x00F) == 0x0F0); i++);
```

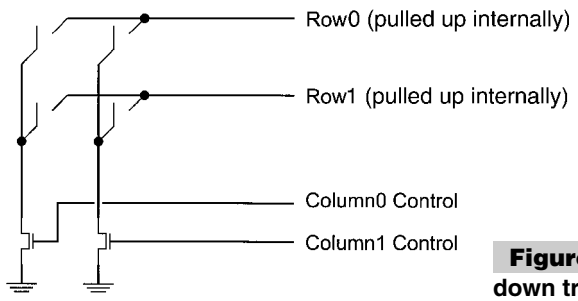


Figure 6-17 Switch matrix with pull down transistors

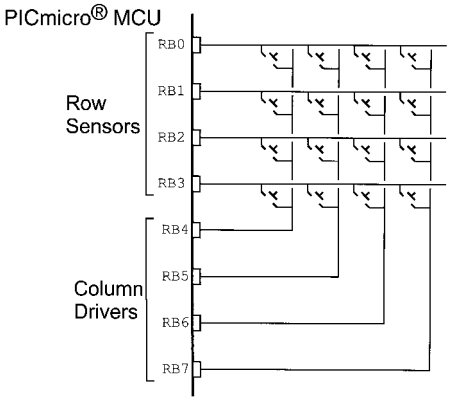


Figure 6-18 4x4 switch matrix connected to PORTB

```
    switch (PORTB & 0x00F) { // Find Key that is Pressed
      case 0x00E:            // Row 0
        key = i;
        break;
      case 0x00D:            // Row1
      case 0x00C:
        key = 0x04 + i;
        break;
      case 0x00B:            // Row2
      case 0x00A:
      case 0x009:
      case 0x008:
        key = 0x08 + i;
        break;
      else                   // Row3
        key = 0x0C + i;
        break;
    }//end switch
   }// end while

   return key;

} // End KeyScan
```

The KeyScan function will only return when a key has been pressed. This routine will not allow keys to be debounced or for other code to execute while it is running.

These issues can be resolved by putting the key scan into an interrupt handler, which executes every 5 ms:

```
Interrupt KeyScan( )           // 5 msec Interval Keyboard Scan
{

int i = 0;
int key = -1

  for (i = 0; (i <4) & ((PORTB & 0x00F) == 0x00F)); i++);
  if (PORTB & 0x00F) ! = 0x00F) {     // Key Pressed
    switch (PORTB & 0x00F) {   // Find Key that is Pressed
     case 0x00E:               // Row 0
       key = i;
```

```
        break;
      case 0x00D:              // Row1
      case 0x00C:
        key = 0x04 + i;
        break;
      case 0x00B:              // Row2
      case 0x00A:
      case 0x009:
      case 0x008:
        key = 0x08 + i;
        break;
      else                     // Row3
        key = 0x0C + i;
        break;
    }//end switch
    if (key == KeySave) {
     keycount = keycount + 1; // Increment Count
                              // <-- Put in Auto Repeat Code Here
     if (keycount == 4)
        keyvalid = key;       // Debounced Key
    } else
      keycount = 0;           // No match - Start Again
    KeySave = key;            // Save Current key for next 5 msec
  }                           // Interval
}// End KeySave
```

This interrupt handler will set the *keyvalid* variable to the row/column combination of the key button (which is known as a *scan code*) when the same value comes up four times in a row. This for time scan is the debounce routine for the keypad. If the value doesn't change for four intervals (20 ms in total), the key is determined to be debounced.

There are two things to notice about this code. First, in both routines, I handle the row with the highest priority. If multiple buttons are pressed, then the one with the highest bit number will be the one that is returned to the user.

The second point is, this code can have an auto repeat function added to it very easily. To do this, a secondary counter has to be first cleared and then incremented each time the *keycount* variable is four or greater. To add an auto repeat key every second (200 intervals), the following code is added in the interrupt handler at the comment.

```
if (keycount == 4) {
   keyrepeat = keyrepeat - 1; // Decrement the Key Auto Repeat Value
   if (keyrepeat == 0) {
     keyrepeat = 200;   // Restart the 1 second Auto Repeat Count
     keycount = 3;      // Reset the counter
     keyvalid = key;    // Return the key
   }
} else                  // Reset the Auto Repeat Counter
keyrepeat = 1;          // End Outputting the Value with Auto
                        //   Repeat
```

The code and methodology for handling switch matrix keypad scans I've outlined here probably seems pretty simple. I'm sure you'll be surprised that, with a scanned keyboard, it is most difficult to figure out the scan codes for specific keys and how to wire the keyboard. Chapter 15 demonstrates how this can be done.

LCDs

LCDs can add a lot to your application in terms of providing a useful interface for the user, debugging an application, or just giving it a professional look. The most common type of LCD controller is the Hitachi 44780, which provides a relatively simple interface between a processor and an LCD. Using this interface is often not attempted by new designers and programmers because it is difficult to find good documentation on the interface, initializing the interface can be a problem, and the displays themselves are expensive.

I have worked with Hitachi 44780-based LCDs for a while now and I don't believe any of these perceptions. LCDs can be added quite easily to an application and use as few as three digital output pins for control. As for cost, LCDs can be often pulled out of old devices or found in surplus stores for less than a dollar.

The purpose of this section is to give a brief tutorial on how to interface with Hitachi 44780-based LCDs. I have tried to provide all of the data necessary for successfully adding LCDs to your application. In the book, I use Hitachi 44780-based LCDs for a number of different projects.

The most common connector used for the 44780-based LCDs is 14 pins in a row, with pin centers 0.100" apart. The pins are wired as in Table 6-2.

As you would probably guess from this description, the interface is a parallel bus, allowing simple and fast reading/writing of data to and from the LCD.

The waveform shown in Fig. 6-19 will write an ASCII byte out to the LCD's screen. The ASCII code to be displayed is eight bits long and is sent to the LCD either four or eight bits at a time. If four-bit mode is used, two nybbles of data (sent high four bits and then low four bits with an E clock pulse with each nybble) are sent to make up a full eight-bit transfer. The E clock is used to initiate the data transfer within the LCD.

Sending parallel data as either four or eight bits are the two primary modes of operation. Although there are secondary considerations and modes, deciding how to send the data to the LCD is the most crucial decision to be made for an LCD interface application.

TABLE 6–2 Hitachi 44780 Based LCD Pinout

PIN	DESCRIPTION
1	Ground
2	Vcc
3	Contrast Voltage
4	"R/S" - Instruction/Register Select
5	"R/W" - Read/Write LCD Registers
6	"E" - Clock
7-14	D0-D7 Data Pins

Eight-bit mode is best used when speed is required in an application and 10 I/O pins are available. Four-bit mode requires six bits. To wire a microcontroller to an LCD in four-bit mode, just the top four bits (DB4-7) are written to.

The R/S bit is used to select whether data or an instruction is being transferred between the microcontroller and the LCD. If the bit is set, then the byte at the current LCD cursor position can be read or written. When the bit is reset, either an instruction is being sent to the LCD or the execution status of the last instruction is read back (whether or not it has completed).

The different instructions available for use with the 44780 are shown in Table 6-3.

The bit descriptions for the different commands are:

```
*Not used/ignored. This bit can be either 1 or 0
Set cursor move direction:
   ID   Increment the cursor after each byte written to display if set
    S   Shift display when byte written to display
Enable display/cursor
    D   Turn display on(1)/off(0)
    C   Turn cursor on(1)/off(0)
    B   Cursor blink on(1)/off(0)
Move cursor/shift display
   SC   Display shift on(1)/off(0)
   RL   Direction of shift right(1)/left(0)
Set interface length
   DL   Set data interface length 8(1)/4(0)
    N   Number of display lines 1(0)/2(1)
    F   Character font 5x10(1)/5x7(0)
Poll the busy flag
   BF   This bit is set while the LCD is processing
Move cursor to CGRAM/display
    A   Address
Read/write ASCII to the display
    H   Data
```

Reading data back is best used in applications that require data to be moved back and forth on the LCD (such as in applications that scroll data between lines). The busy flag can be polled to determine when the last instruction that has been sent has completed processing.

For most applications, there really is no reason to read from the LCD. I usually tie R/W to ground and just wait the maximum amount of time for each instruction (4.1 ms for clearing the display or moving the cursor/display to the home position, 160 μs for all other commands). As well as making my application software simpler, it also frees up a microcontroller pin for other uses. Different LCDs execute instructions at different rates and to

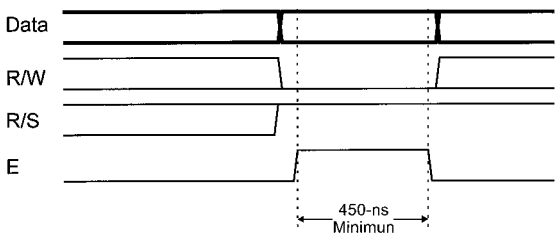


Figure 6-19 LCD data write waveform

TABLE 6–3 Hitachi 44780 Based LCD Commands

R/S	R/W	D7	D6	D5	D4	D3	D2	D1	D0	INSTRUCTION/DESCRIPTION
4	5	14	13	12	11	10	9	8	7	Pins
0	0	0	0	0	0	0	0	0	1	Clear Display
0	0	0	0	0	0	0	0	1	*	Return Cursor and LCD to Home Position
0	0	0	0	0	0	0	1	ID	S	Set Cursor Move Direction
0	0	0	0	0	0	1	D	C	B	Enable Display/Cursor
0	0	0	0	0	1	SC	RL	*	*	Move Cursor/Shift Display
0	0	0	0	1	DL	N	F	*	*	Reset/Set Interface Length
0	0	0	1	A	A	A	A	A	A	Move Cursor to CGRAM
0	0	1	A	A	A	A	A	A	A	Move Cursor to Display
0	1	BF	*	*	*	*	*	*	*	Poll the “Busy Flag”
1	0	H	H	H	H	H	H	H	H	Write Hex Character to the Display at the Current Cursor Position
1	1	H	H	H	H	H	H	H	H	Read Hex Character at the Current Cursor Positon on the Display

avoid problems later on (such as if the LCD is changed to a slower unit), I recommend just using the maximum delays listed here.

In terms of options, I have never seen a 5x10 pixel character LCD display. This means that the F bit in the *set interface* instruction should always be reset (equal to 0).

Before you can send commands or data to the LCD module, the module must be initialized. For eight-bit mode, this is done using the following series of operations:

```
1. Wait more than 15 ms after power is applied.
2. Write 0x030 to LCD and wait 5 ms for the instruction to complete.
3. Write 0x030 to LCD and wait 160 usecs for instruction to complete.
4. Write 0x030 AGAIN to LCD and wait 160 usecs or Poll the Busy Flag.
5. Set the Operating Characteristics of the LCD.
   - Write “Set Interface Length”
   - Write 0x010 to prevent shifting after character write.
   - Write 0x001 to Clear the Display
   - Write “Set Cursor Move Direction” Setting Cursor Behavior Bits
   - Write “Enable Display/Cursor” & enable Display and Optional Cursor
```

In describing how the LCD should be initialized in four-bit mode, I specify writing to the LCD in terms of nybbles. This is because initially, just single nybbles are sent (and not two nybbles, which make up a byte and a full instruction). As mentioned, when a byte is sent, the high nybble is sent before the low nybble and the E pin is toggled each time that four bits are sent to the LCD.

To initialize in four-bit mode the following nybbles are first sent to the LCD:

```
1. Wait more than 15 ms after power is applied.
2. Write 0x03 to LCD and wait 5 ms for the instruction to complete.
3. Write 0x03 to LCD and wait 160 usecs for instruction to complete.
4. Write 0x03 AGAIN to LCD and wait 160 usecs (or poll the Busy Flag).
5. Set the Operating Characteristics of the LCD.
   - Write 0x02 to the LCD to Enable Four Bit Mode
```

All following instruction/data writes require two nybble writes:

```
- Write "Set Interface Length"
- Write 0x01/0x00 to prevent shifting of the display
- Write 0x00/0x01 to Clear the Display
- Write "Set Cursor Move Direction" Setting Cursor Behavior Bits
- Write "Enable Display/Cursor" & enable Display and Optional Cursor
```

Once the initialization is complete, the LCD can be written to with data or instructions as required. Each character to display is written like the control bytes, except that the R/S line is set. During initialization, by setting the S/C bit during the *Move Cursor/Shift Display* command, after each character is sent to the LCD, the cursor built into the LCD will increment to the next position (either right or left). Normally, the S/C bit is set (equal to 1), along with the R/L bit in the *Move Cursor/Shift Display* command for characters to be written from left to right (as with a "TeleType" video display).

One area of confusion is how to move to different locations on the display and, as a follow on, how to move to different lines on an LCD display. Table 6-4 shows how different LCD displays that use a single 44780 can be set up with the addresses for specific character locations. The LCDs listed are the most popular arrangements available and the layout is given as number of columns by number of lines.

The ninth character is the position of the ninth character on the first line. Most LCD displays have a 44780 and support chip to control the operation of the LCD. The 44780 is responsible for the external interface and provides sufficient control lines for 16 characters on the LCD. The support chip enhances the I/O of the 44780 to support up to 128 characters on an LCD in two lines of eight. From Table 6-4, it should be noted that the first two entries (8x1, 16x1) only have the 44780 and not the support chip. This is why the ninth character in the 16x1 does not appear at address 8 and shows up at the address that is common for a two-line LCD.

I've included the 40 character by 4 line (40x4) LCD because it is quite common. Normally, the LCD is wired as two 40x2 displays. The actual connector is normally 16 bits wide with all the 14 connections of the 44780 in common, except for the E (strobe) pins. The E strobes are used to address between the areas of the display used by the two devices. The actual pinouts and character addresses for this type of display can vary between manufacturers and display part numbers.

When using any kind of multiple 44780 LCD display, you should probably only display one 44780's cursor at a time to avoid confusing the user.

Cursors for the 44780 can be turned on as a simple underscore at any time using the *Enable Display/Cursor* LCD instruction and setting the C bit. I don't recommend using the *B (Block mode) bit* because this causes a flashing full-character square to be displayed and it is very annoying.

The LCD can be thought of as a TeleType display because in normal operation, after a character has been sent to the LCD, the internal cursor is moved one character to the right. The *clear display* and *return cursor and LCD to home position* instructions are used to reset the cursor's position to the top right character on the display.

TABLE 6–4 Hitachi 44780 Based LCD Types and Character Locations

LCD	TOP LEFT	NINTH	SECOND LINE	THIRD LINE	FOURTH LINE	COMMENTS
8x1	0	N/A	N/A	N/A	N/A	Note 1.
16x1	0	0x040	N/A	N/A	N/A	Note 1.
16x1	0	8	N/A	N/A	N/A	Note 3.
8x2	0	N/A	0x040	N/A	N/A	Note 1.
10x2	0	0x008	0x040	N/A	N/A	Note 2.
16x2	0	0x008	0x040	N/A	N/A	Note 2.
20x2	0	0x008	0x040	N/A	N/A	Note 2.
24x2	0	0x008	0x040	N/A	N/A	Note 2.
30x2	0	0x008	0x040	N/A	N/A	Note 2.
32x2	0	0x008	0x040	N/A	N/A	Note 2.
40x2	0	0x008	0x040	N/A	N/A	Note 2.
16x4	0	0x008	0x040	0x010	0x050	Note 2.
20x4	0	0x008	0x040	0x014	0x054	Note 2.
40x4	0	N/A	N/A	N/A	N/A	Note 4.

Note 1: Single 44780/No Support Chip.
Note 2: 44780 with Support Chip.
Note 3: 44780 with Support Chip. This is quite rare.
Note 4: Two 44780s with Support Chips. Addressing is device specific.

An example of moving the cursor is shown in Fig. 6-20.

To move the cursor, the *move cursor to display* instruction is used. For this instruction, bit 7 of the instruction byte is set with the remaining seven bits used as the address of the character on the LCD the cursor is to move to. These seven bits provide 128 addresses, which matches the maximum number of LCD character addresses available. Table 6-4 should be used to determine the address of a character offset on a particular line of an LCD display.

The character set available in the 44780 is basically ASCII. I say "basically" because some characters do not follow the ASCII convention fully (probably the most significant

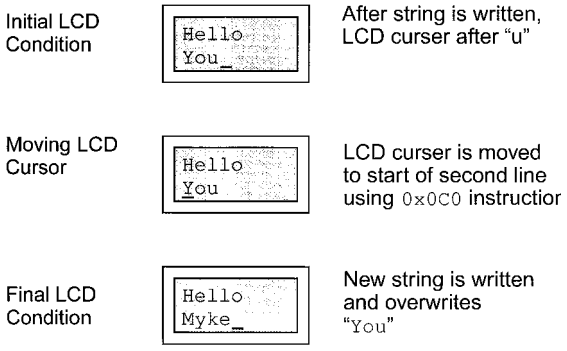


Figure 6-20 Moving an LCD cursor

Figure 6-21 LCD character set

difference is 0x05B or is not available). The ASCII control characters (0x008 to 0x01F) do not respond as control characters and might display "funny" (Japanese) characters. The LCD character set is shown in Fig. 6-21.

Eight programmable characters are available and use codes 0x000 to 0x007. They are programmed by pointing the LCD's "cursor" to the character generator RAM (CGRAM) area at eight times the character address. The next eight bytes written to the RAM are the line information of the programmable character, starting from the top (Fig. 6-22).

I like to represent this as eight squares by five. Most displays were seven pixels by five for each character, so the extra row may be confusing. Each LCD character is actually eight pixels high, with the bottom row normally used for the underscore cursor. The bottom row can be used for graphic characters, although if you are going to use a visible underscore cursor and have it at the character, I recommend that you don't use this line at all (i.e., set the line to 0x000).

Using this box, you can draw in the pixels that define your special character and then use the bits to determine what the actual data codes are. When I do this, I normally use a

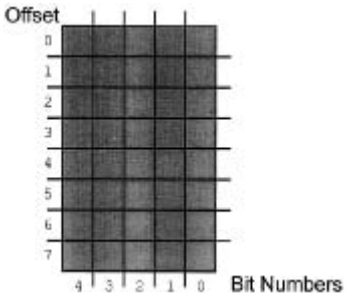


Figure 6-22 LCD character "box"

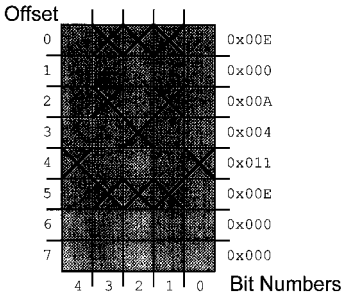


Figure 6-23 Example LCD custom character

piece of graph paper and then write hex codes for each line, as shown in the lower right diagram of a "Smiley Face" (Fig. 6-23).

For some the "animate" applications, I use character rotation for the animations. This means that, instead of changing the character each time the character moves, I simply display a different character. Doing this means that only two bytes (moving the cursor to the character and the new character to display) have to be sent to the LCD. If animation were accomplished by redefining the characters, then 10 characters would have to be sent to the LCD (one to move into the CGRAM space, the eight defining characters and an instruction returning to display RAM). If multiple characters are going to be used or more than eight pictures for the animation, then you will have to rewrite the character each time.

The user-defined character line information is saved in the LCD's CGRAM area. This 64 bytes of memory is accessed using the *move cursor into CGRAM* instruction in a similar manner to that of moving the cursor to a specific address in the memory with one important difference.

This difference is that each character starts at eight times its character value. This means that user-definable character 0 has its data starting at address 0 of the CGRAM, character 1 starts at address 8, character 2 starts at address 0x010 (16), etc. To get a specific line within the user-definable character, its offset from the top (the top line has an offset of 0) is added to the starting address. In most applications, characters are written to all at one time with character 0 first. In this case, the instruction 0x040 is written to the LCD, followed by all of the user-defined characters.

The last aspect of the LCD to discuss is how to specify a contrast voltage to the display. I typically use a potentiometer wired as a voltage divider. This will provide an easily variable voltage between ground and V_{cc}, which will be used to specify the contrast (or darkness) of the characters on the LCD screen. You might find that different LCDs work differently with lower voltages providing darker characters in some and higher voltages do the same thing in others.

There are a variety of different ways of wiring up an LCD. I noted that the 44780 could interface with four or eight bits. To simplify the demands in microcontrollers, a shift register is often used to reduce the number of I/O pins to three.

This can be further reduced by using the circuit shown in which the serial data is combined with the contents of the shift register to produce the E strobe at the appropriate in-

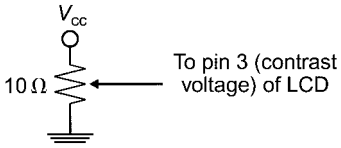


Figure 6-24 LCD contrast voltage circuit

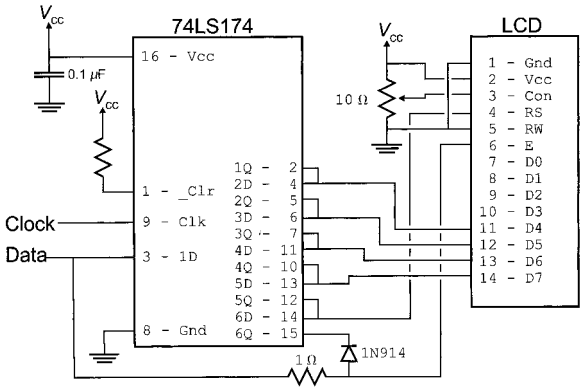


Figure 6-25 2 wire LCD interface

terval. This circuit ANDs (using the 1-K resistor and IN914 diode) the output of the sixth D-flip-flop of the 74LS174 and the data bit from the device writing to the LCD to form the E strobe. This method requires one less pin than the three-wire interface and a few more instructions of code. The two-wire LCD interface circuit is shown in Fig. 6-25.

I normally use a 74LS174 wired as a shift register (as shown in the schematic diagram) instead of a serial-in/parallel-out shift register. This circuit should work without any problems with a dedicated serial-in/parallel-out shift register chip, but the timing/clock polarities might be different. When the 74LS174 is used, notice that the data is latched on the rising (from logic low to high) edge of the clock signal. Figure 6-26 is a timing diagram for the two-wire interface and it shows the 74LS174 being cleared, loaded, and then the E strobe when the data is valid and 6Q and incoming data is high.

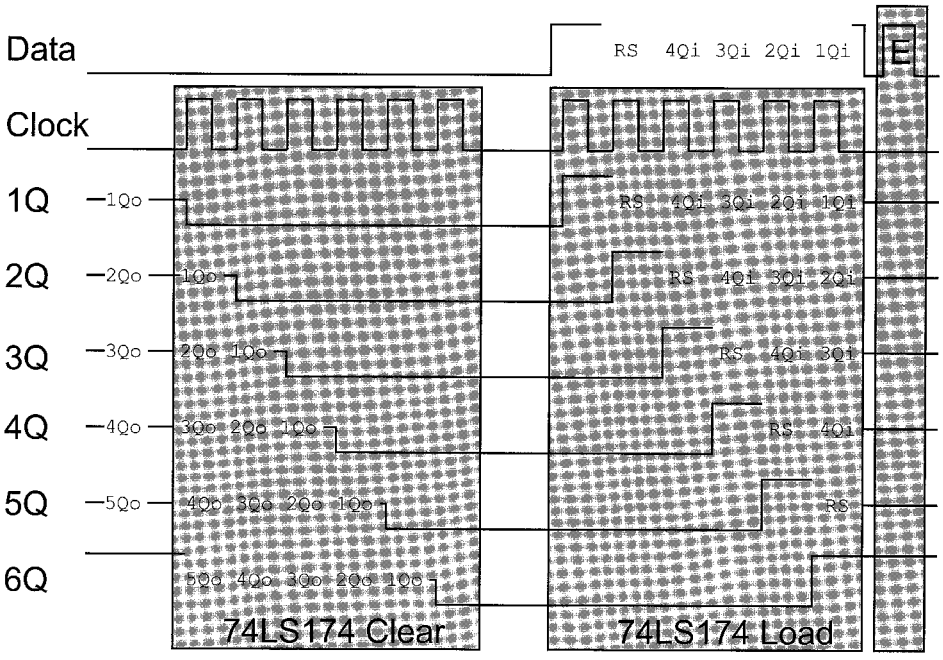


Figure 6-26 2 wire LCD write waveform

The right side of this diagram shows how the shift register is written to for this circuit to work. Before data can be written to it, loading every latch with zeros clears the shift register. Next, a *1* (to provide the E gate) is written followed by the R/S bit and the four data bits. Once the latch is loaded in correctly, the data line is pulsed to strobe the E bit. The biggest difference between the three-wire and two-wire interface is that the shift register has to be cleared before it can be loaded and the two-wire operation requires more than six times the number of clock cycles to load four bits into the LCD.

I've used this circuit with the PICmicro® MCU, Basic Stamp, 8051, and AVR, and it really makes the wiring of an LCD to a microcontroller very simple. The biggest issue to watch for is to ensure the E strobe's timing is within specification (i.e., greater than 450 ns); the shift register loads can be interrupted without affecting the actual write. This circuit will not work with open-drain only outputs (something that catches up many people).

One note about the LCD's E strobe is that in some documentation it is specified as *high-level active;* in others, it is specified as *falling-edge active.* It *seems* to be falling-edge active, which is why the two-wire LCD interface works even if the line ends up being high at the end of data being shifted in. If the falling edge is used (like in the two-wire interface) then ensure that before the E line is output on 0, there is at least a 450-ns delay with no lines changing state.

Analog I/O

Before reading through the following sections, I suggest that you familiarize yourself with *Analog-to-Digital Converters (ADCs)* and *Digital-to-Analog Converters (DACs)* in "Introduction to Electronics" on the CD-ROM. These sections will introduce you to the theory of converting analog voltages and digital values between each other and the problems that can arise with them.

The following sections introduce you to some of the practical aspects of working with analog data with the PICmicro® MCU. This includes position sensing using potentiometers. At first glance, you might think that an ADC-equipped microcontroller is required for this operation, but there are a number of ways of doing this with strictly digital inputs. The IBM PC carries out the same function (it doesn't use an ADC either) for reading joystick positions.

For analog output, I focus on the theory and operation behind *Pulse-Width Modulated (PWM)* analog control signals. This method of control is very popular and is a relatively simple way of providing analog control of a device. It can also be used to communicate analog values between devices without needing any type of communication protocol. The PICmicro® MCU has some built-in hardware that makes the implementation of pulse-width-modulated input and output quite easy to work with.

I want to make it clear that audio input and output capabilities cannot be provided in the PICmicro® MCU without significant front-end signal processing and filtering. Output from the PICmicro® MCU can be simple "beeps" and "boops" without special hardware, but anything more complex will require specialized hardware and software.

POTENTIOMETERS

One of the more useful human input devices is the *dial*. Rather than relying on some kind of digital data, like a button or character string, the dial allows users a freer range of inputs,

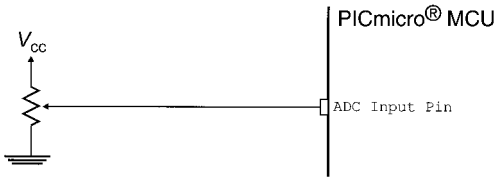


Figure 6-27 Potentiometer input to PICmicro® MCU ADC

as well as positional feedback information in a mechanical device. For most people, reading a potentiometer value requires setting the potentiometer as a voltage divider and reading the voltage between the two extremes at the "wiper" (Fig. 6-27). A very elegant way of reading a potentiometer's position using the digital input of a PICmicro® MCU is shown in this section.

Notice that I consider the measurement to be of the potentiometer's position and not its resistance. This is an important semantic point; as far as using a potentiometer as an input device, I do not care about the actual resistance of its position, just what its position is. The method of reading a potentiometer's position using a digital I/O pin that I am going to show you is very dependent on the parts used and will vary significantly between implementations.

The method of reading a potentiometer uses the characteristics of charged capacitor discharging through a resistor. If the charge is constant in the capacitor, then the time to discharge varies according to the exponential curve shown in Fig. 6-28.

The charge in a capacitor is proportional with its voltage. If a constant voltage (i.e., from a PICmicro® MCU I/O pin) can be applied to a capacitor, then its charge will be constant. This means that in the voltage discharge curve shown in Fig. 6-28, if the initial voltage is known along with the capacitance and resistance, then the voltage at any point in time can be predicted.

The equation in Fig. 6-28:

$$V_{(t)} = V_{Start}(1 - e \text{ ** } -t/RC)$$

can be reworked to find R, if V, V_{Start}, t, and C are known:

$$R = -t/C * ln[(V_{Start} - V)/V_{Start}]$$

Rather than calculate the value through, you can make the approximation of 2 ms for a resistance of 10 k and a capacitance of 0.1 μF with a PICmicro® MCU, which has a high-to-low threshold of 1.5 volts. To measure the resistance in a PICmicro® MCU, I use the circuit shown in Fig. 6-29.

For this circuit, the PICmicro® MCU's I/O pin outputs a high, which charges the capacitor (which is limited by the potentiometer).

After the capacitor is charged, the pin is changed to input, the charge in the capacitor draws through the resistor with a voltage determined by the $V_{(t)}$ formula. When the pin first changes state, the voltage across the resistor will be greater than the threshold for some period of time. When the voltage across the potentiometer falls below the voltage threshold, the input pin value returned to the software will be zero. If the time required for

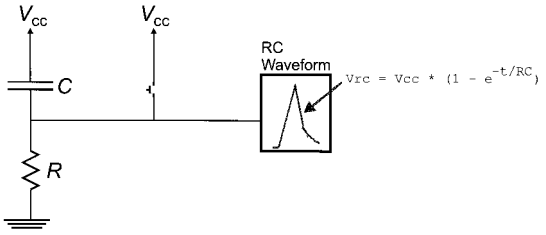


Figure 6-28 Measure RC time delay

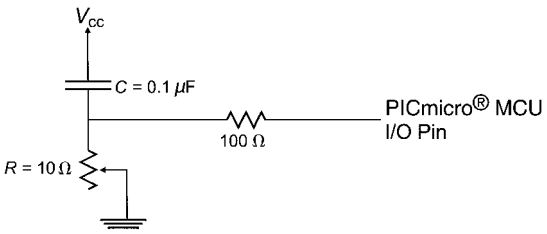


Figure 6-29 PICmicro® MCU measure of RC time delay

voltage across the pin to change from reading of 1 to a 0 is recorded, it will be proportional to the resistance between the potentiometer's wiper and the capacitor.

The pseudo code for carrying out the potentiometer read is:

```
int ReadPot()                  // Return the Potentiometer's Position
{

int i;

   pin = output; pin = 1;             // Charge the Capacitor
   for (i = 0; i < charge; i++);
   pin = input;                       // Let the Capacitor Discharge
   for ( i = 0; pin == 1; i++);

   return I ;

} // End ReadPot
```

The PICmicro® MCU assembly code for implementing this potentiometer read is not much more complex than this pseudo code. Later, the book provides some examples of how potentiometer reads are actually accomplished.

The 100-Ohm resistor between the PICmicro® MCU pin and the RC network is used to prevent any short circuits to ground if the potentiometer is set so that no resistance is in the circuit when the capacitor is changed.

This method of reading a potentiometer's position is very reliable, but not very accurate, nor is it particularly fast. When setting this up for the first time, in a specific circuit, you will have to experiment to find the actual range that it will display. This is because of part variances (including the PICmicro® MCU) and the power supply characteristics. For this reason, I do not recommend using the potentiometer/capacitor circuit in any products. Tuning the values returned will be much more expensive than the costs of a PICmicro® MCU with a built-in ADC.

PULSE-WIDTH MODULATION (PWM) I/O

The PICmicro® MCU, like most other digital devices, does not handle analog voltages very well. This is especially true for situations where high-current voltages are involved. The best way to handle analog voltages is by using a string of varying wide pulses to indicate the actual voltage level. This string of pulses is known as a *Pulse-Width-Modulated (PWM) analog signal* and it can be used to pass analog data from a digital device, control DC devices, or even output an analog voltage.

This section covers PWM signals and how they can be used with the PICmicro® MCU. In the discussion of TMR1 and TMR2, earlier in the book, I presented how PWM signals are implemented and read using the CCP built-in hardware of the PICmicro® MCU. This

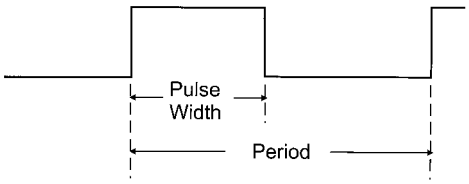


Figure 6-30 Pulse wave modulated signal waveform

section shows how PWM signals can be used for I/O in PICmicro® MCUs that do not have the CCP module built in.

A PWM signal (Fig. 6-30) is a repeating signal that is on for a set period of time that is proportional to the voltage that is being output. I call the *on time* the *pulse width* in Fig. 6-30. The *duty cycle* is the percentage of time that the on time is relative to the PWM signal's *period*.

To output a PWM signal, the following code is used:

```
Period = PWMPeriod;                 // Initialize the Output
On = PWMperiod - PWMoff;            // Parameters

while (1 == 1) {

  PWM = ON;                         // Start the Pulse
  for (i = 0; i < On; i++ );        // Output ON for "On" Period of
                                    //   Time
  PWM = off;                        // Turn off the Pulse
  For ( ; i < PWMPeriod; i++ );     // Output off for the rest of the
                                    //   PWM Period
 } // end while
```

This code can be implemented remarkably simply in the PICmicro® MCU, but rather than showing it, there is one aspect I want to change. This method is not recommended because it uses all the processor resources of the PICmicro® MCU and does not allow for any other processing.

To avoid this problem, I would recommend using the TMR0 interrupt as:

```
Interrupt PWMOutput()       // When Timer Overflows, Toggle "On" and "Off"
{                           //   and Reset Timer to the correct delay for
                            // the Value

 if (PWM == ON) {           // If PWM is ON, Turn it off and Set Timer
   PWM = off;               //   Value
   TMR0 = PWMPeriod - PWMOn;
 } else {                   // If PWM is off, Turn it ON and Set Timer
   PWM = ON;                //   Value
   TMR0 = PWMOn;
 } // end if

 INTCON.T0IF = 0;           // Reset Interrupts

} // End PWMOutput TMR0 Interrupt Handler
```

This code is quite easy to port to PICmicro® MCU assembly language. For example, if the PWM period was 1 ms (executing in a 4-MHz PICmicro® MCU), a divide-by-four prescaler value could be used with the timer and the interrupt-handler assembly-language code would be:

```
org 4
Int                         ; Interrupt Handler

   movwf _w                 ; Save Context Registers
   movf STATUS, w           ;  - Assume TMR0 is the only enabled Interrupt
   movwf _status

   btfsc PWM                ; Is PWM O/P Currently High or Low?
    goto PWM_ON
   nop                      ; Low - Nop to Match Cycles with High

   bsf PWM                  ; Output the Start of the Pulse

   movlw 6 + 6              ; Get the PWM On Period
   subwf PWMOn, w           ; Add to PWM to Get Correct Period for
                            ; Interrupt Handler Delay and Missed cycles
                            ; in maximum 1024 usec Cycles
   goto PWM_Done

PWM_ON                      ; PWM is On - Turn it Off

   bcf PWM                  ; Output the "Low" of the PWM Cycle

   movf PWMOn, w            ; Calculate the "Off" Period
   sublw 6 + 6              ; Subtract from the Period for the Interrupt
                            ; Handler Delay and Missed cycles in maximum
                            ; 1024 usec Cycles
   goto PWM_Done

PWM_Done                    ; Have Finished Changing the PWM Value

   sublw 0                  ; Get the Value to Load into the Timer
   movwf TMR0

   bcf INTCON, T0IF         ; Reset the Interrupt Handler

   movf _status, w          ; Restore the Context Registers
   movwf STATUS
   swapf _w, f
   swapf _w, w

   retfie
```

In this code, TMR0 is loaded in such a way that the PWM's period is always 1 ms (a count of 250 "ticks" with the prescaler value of four). To get the value added and subtracted from the total, I first took the difference between the number of ticks to get 1 ms (250) and the full timer range (256). Next, I counted the total number of instruction cycles of the interrupt handler (which is 23), divided it by four, and added the result to the 1-ms difference. The operation probably seems confusing because I was able to optimize the time for the PWM signal off:

```
Time Off = Period - ON
```

to:

```
movf  ON, w
sublw 6 + 6
sublw 0
movwf TMR0
```

I realize that this doesn't make any sense the first time you look at it, so I go through it by showing how it works.

Using the original equation, you should note that this calculates the number of cycles to be delayed by TMR0, but the actual value to be loaded into TMR0 is calculated as:

```
TMR0 Delay Value  = 0x0100 - (Time Off)
                  = 0x0100 - (Period – ON)
                  = 0x0100 - (256 – 250 + Interrupt Execution- ON)
                  = 0x0100 - (6 + 6 – ON)
                  = 0x0100 - (12 – ON)
                  = 0x0100 - 12 + ON
                  = 0x00F4 + ON
```

Going back to the three instructions that load TMR0, you can show that they execute as:

```
movf ON, w                ; w = ON
sublw 6 + 6               ; w = 6 + 6 - w
                          ;   = 12 - ON
                          ;   = 12 + 0x0FF ^ ON + 1
                          ;   = 13 + 0x0FF ^ ON
sublw 0                   ; w = 0 - w
                          ;   = 0 - (13 + 0x0FF ^ ON)
                          ;   = 0 + 0x0FF ^ (13 + 0x0FF ^ ON) + 1
                          ;   = 0x0FF ^ 13 + 0x0FF ^ 0x0FF ^ ON + 1
                          ;   = 0x0FF ^ 13 + ON + 1
                          ;   = 0x0F4 + ON
```

which is (surprisingly enough) the same result as what was found with the "TMR0 delay value" equation. The formula in itself is not that impressive, except that it "dovetails" very well with the *PWM on* half of the code. The process of coming up with this code probably belongs in another chapter on optimization, but to be honest with you, I came up with it using nothing but trial and error along with the feeling that this kind of optimization was possible.

This is an example of what I mean when I say that you should look for opportunities when processing data in the PICmicro® MCU. More often than not, you will come up with something like these few instructions, which are very efficient, and integrate different cases startlingly well.

Notice that, in this code, the PWM signal will never fully be on (a high DC voltage) or fully off (a ground-level DC voltage). This is because when the routine enters the subroutine handler, it changes the output, regardless of whether or not it is required for the length of the interrupt handler. In actuality, if you time it out, you will see that the 23 instruction cycles that the interrupt handler takes between changing the value works out to a 2.4-percent loss of full on and full off. This should not be significant in most applications and will serve as a "heartbeat" to let the receiver "know" the PICmicro® MCU is still functioning—even though the output is stuck at an extreme.

In this example, I have expended quite a bit of energy to ensure that the period remains the same, regardless of the on time. This was done to ensure that the changes in the duty cycle remained proportional to the changes in the on period. This is important if the PWM output is going to be passed through a low-pass filter (Fig. 6-31) to output an analog voltage.

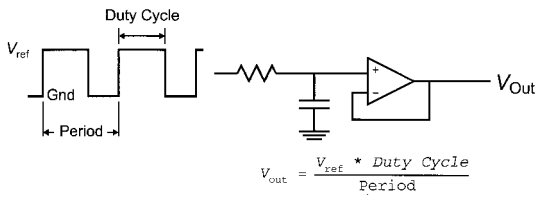


Figure 6-31 "Pulse width modulated" analog voltage

In many applications where a PWM signal is communicating with another digital device, this effort to ensure that the period is constant and is not required. In these cases, a timer is used to time the *on* period. This can be shown as the pseudo-code:

```
Int TimeOn()                          // Time the Width of an incoming Pulse
{
int i = 0;
   while (PWMIP == off);              // Wait for the Pulse to Start
   for ( ; PWMIP == ON; i++ );        // Time the Pulse Width
   return i;                          // Return the Pulse Width
} // end TimeOn
```

With the actual PICmicro® MCU assembly-language code being quite simple, but dependent on the maximum pulse width value being timed, very long pulses will require large counters or delays in between the PWM input (*PWMIP* in *TimeOn*) poll.

Passing analog data back and forth between digital devices in any format is not going to be accurate because of the errors in digitizing the value and restoring it. This is especially true for PWM signals, which can have very large errors because of the sender and receiver not being properly synched and the receiver not starting to poll at the correct time interval. In fact, the measured value could have an error of upwards of 10 percent from the actual value. This loss of data accuracy means that the analog signals should not be used for data transfers. But, as is shown in Chapters 15 and 16, PWM signals are an excellent way to control analog devices, such as lights and motors.

When using a PWM to drive an analog device, it is important to be sure that the frequency is faster than what a human can perceive. As noted in the "LED" section, this frequency is 30 Hz or more. But for motors and other devices that might have an audible "whine," the PWM signal should have a frequency of 20 kHz or more to ensure that the signal does not bother the user. In Chapter 16, I discuss this in more detail and demonstrate how an audible 10 KHz "whine" can be produced.

The problem with the higher frequencies is that the granularity of the PWM signal decreases. This is because of the inability of the PICmicro® MCU (or what ever digital device is driving the PWM output) to change the output in relatively small time increments from on to off, relative to the size of the PWM signal's period. In the previous example code, four instruction cycles (of 1 μs each) are the lowest level of granularity for the PWM signal that results in about 250 unique output values. If the PWM signal's period was decreased to 100 μs, from 1 ms, for a 10-kHz frequency, the same code would only have 25 or so unique output values that could be output. In this case, to retain the original code's granularity, the PICmicro® MCU would have to be sped up 10 times (not possible for most applications) or another way of implementing the PWM will have to be found.

AUDIO OUTPUT

When I was originally blocking out this book, I wanted to include PICmicro® MCU audio output and input. After some experimentation and a search on the Internet to see what other people have done (or not done, as in the case of audio input to the PICmicro® MCU), I have come to the conclusion that audio input is not appropriate for the PICmicro® MCU. The PICmicro® MCU could have some kind of filtering input, but it simply does not have

the processing capability to do more than respond to a specific frequency at a threshold volume. For this reason, I would discourage you from passing audio input to the PICmicro® MCU and just use the PICmicro® MCU to provide audio output using the techniques outlined in this section.

When I discuss the PICmicro® MCU's processing capabilities with regard to audio, I tend to be quite disparaging. The reason for this is the lack of hardware multipliers in the low-end and mid-range PICmicro® MCUs and the inability of all the devices to "natively" handle greater than eight bits of in a floating-point format. The PICmicro® MCU processor has been optimized to respond to digital inputs and cannot implement the real-time processing routines needed for complex analog I/O.

Despite this, you can implement some surprisingly sophisticated audio output that goes beyond simple "beeps" and "boops" (Fig. 6-32).

The circuit in Fig. 6-32 passes DC waveforms through the capacitor (which filters out the kickback spikes) to the speaker or piezo buzzer. When a tone is output, your ear will hear a reasonably good tone, but if you were to look at the actual signal on an oscilloscope, you would see the waveform shown in Fig. 6-33, both from the PICmicro® MCU's I/O pin and the piezo buzzer itself.

The PICmicro® MCU pin, capacitor, and speaker are actually a quite complex analog circuit. Notice that the voltage output on the I/O pin is changed from a straight waveform. This is because of the inductive effects of the piezo buffer. The important thing to note in Fig. 6-33 is that the upward spikes appear at the correct period for the output signal.

Timing the output signal is generally accomplished by toggling an output pin at a set period within the TMRO interrupt handler. To generate a 1-kHz signal shown in a PICmicro® MCU running a 4 MHz, you can use the code (which does not use the prescaler) for TMR0 and the PICmicro® MCU's interrupt providing the speaker charges are in the background.

```
   org 4
int
  movwf _w              ; Save Context Registers
  bcf INTCON, TOIF      ; Reset the Interrupt
  movlw 256 - (250 - 4)
  movwf TMRO            ; Reset TMRO for another 500 usecs
  btfsc SPKR            ; Toggle the Speaker
    goto $ + 2
  bsf SPKER             ; Speaker Output High
    goto $ + 2
  bcf SPKER             ; Speaker Output Low
  swapf _w, f           ; Restore Context Registers
  swapf _w, w
  retfie
```

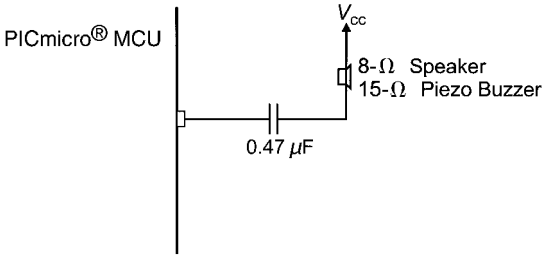


Figure 6-32 Circuit for driving PICmicro® MCU audio

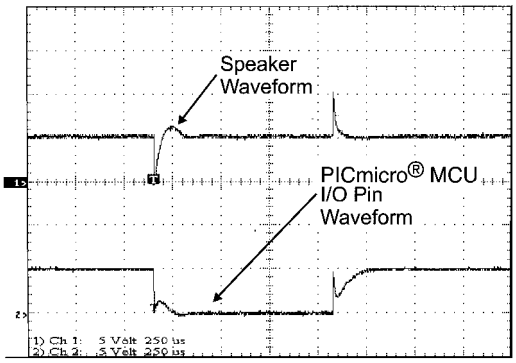


Figure 6-33 PICmicro® MCU driving a speaker output

There are two points to notice about this interrupt handler. First, I don't bother saving the STATUS register's contents because neither the zero, neither carry nor digit carry flags are changed by any of the instructions used in the handler.

The second point to notice is the reload value of TMRO to generate a 1-kHz output in a 4-MHz PICmicro® MCU (an instruction clock period of 1 μs), I have to delay 500 cycles for the wave's high and low. Because TMRO has a divide-by-two counts on its input, I have to wait a total of 250 ticks. When I record TMRO, notice that I also take into account the cycles taken to get to the reload (which is seven or eight), divide them by two and take them away from the reload value.

For this handler, the reload value might be off by one cycle, depending on how the mainline executes, for a worst-case error of 0.2% (2,000 ppm). This level of accuracy is approximately the same as what you would get for a ceramic resonator; so, the actual frequency should not be off an appreciable amount from the expected. This level of accuracy will not cause noticeable warbling (changes in the frequency) caused by the changing interrupt latency as you run the application. The actual changes are very small and not detectable by the human ear.

When developing applications that output audio signals, I try to keep the tone within the range of 500 Hz to 2 kHz. This is well within the range of human hearing and is quite easy to implement in a PICmicro® MCU. When you look at the Christmas tree project in Chapter 16, you can see how this is done to create simple tunes on the PICmicro® MCU.

I wanted to finish off this section by describing how the PICmicro® MCU can create more complex sounds, such as telephone TouchTone audio signals. The problem with TouchTones is that they are a combination of two frequencies (that are listed in the appendices). When they're added together, you get a signal like the bottom one shown in Fig. 6-34.

This signal is very hard to replicate with a digital circuit. If you want to create a complex waveform like this, I recommend mixing two PICmicro® MCU-controlled frequency outputs together or using a chip that is designed for the specific purpose that you have in mind. The Parallax Basic Stamp II and PicBasic Pro do have instructions that allow you to drive telephone TouchTones, but they require a filter circuit to work properly. I have found that even with the filter, the phone system does not recognize the data being sent very reliably.

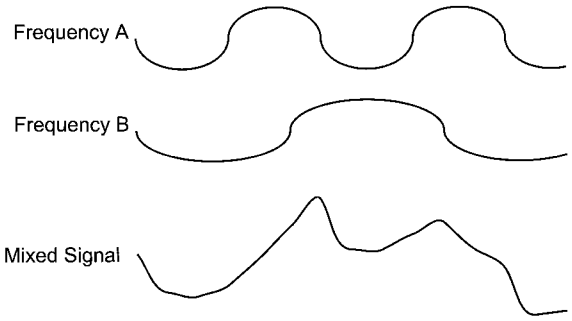


Figure 6-34 Mixed audio output

Relays and Solenoids

Some real-life devices that you might have to control by a microcontroller are electromagnetic, such as relays, solenoids, and motors. These devices cannot be driven directly by a microcontroller because of the current required and the noise generated by them. This means that special interfaces must be used to control electromagnetic devices.

The simplest method to control these devices is to just switch them on and off and by supplying power to the coil in the device. The circuit shown in Fig. 6-35 is true for relays (as shown), solenoids (which are coils that draw an iron bar into them when they are energized), or a DC motor (which will only turn in one direction).

In this circuit, the microcontroller turns on the Darlington transistor pair, causing current to pass through the relay coils, closing the contacts. To open the relay, the output is turned off (or a 0 is output). The shunt diode across the coil is used as a kick-back suppressor. When the current is turned off, the magnetic flux in the coil will induce a large back EMF (voltage), which must be absorbed by the circuit or a voltage spike will occur, which can damage the relay power supply and even the microcontroller. This diode must *never* be forgotten in a circuit that controls an electromagnetic device. The kick-back voltage is usually on the order of several hundred volts for a few nanoseconds. This voltage causes the diode to breakdown and allows current to flow, attenuating the induced voltage which can damage the PICmicro® MCU and other electronic devices in the application circuit.

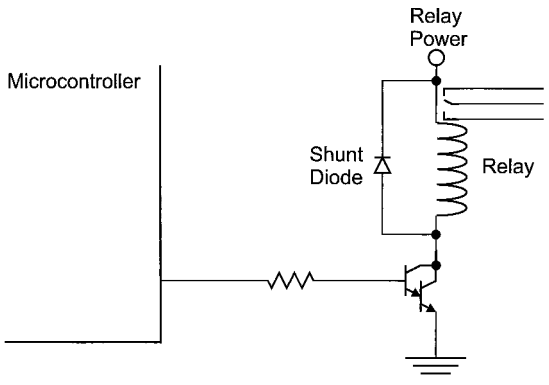


Figure 6-35 Microcontroller relay control

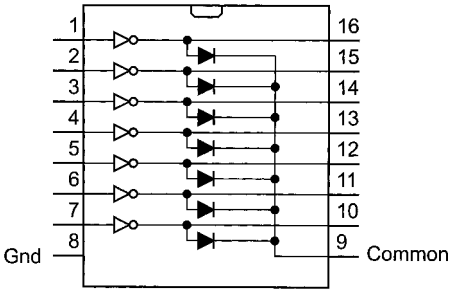


Figure 6-36 ULN2003A driver array

Rather than designing discrete circuits to carry out this function, I like to use integrated chips for the task. One of the most useful devices is the ULN2003A (Fig. 6-36) or the ULN2803 series of chips, which have Darlington transistor pairs and shunt diodes built in for multiple drivers.

DC and Stepper Motors

Motors can be controlled by exactly the same hardware as shown in the previous section, but as I noted, they will only run in one direction. A network of switches (transistors) can be used to control turning a motor in either direction; this is known as an *H-bridge* (Fig. 6-37).

In this circuit, if all the switches are open, no current will flow and the motor won't turn. If switches 1 and 4 are closed, the motor will turn in one direction. If switches 2 and 3 are closed, the motor will turn in the other direction. Both switches on one side of the bridge should *never* be closed at the same time because this will cause the motor power supply will burn out or a fuse will blow because a short circuit is directly between the motor power and ground.

Controlling a motor's speed is normally done by "pulsing" the control signals in the form of a PWM signal, as shown previously in this chapter (Fig. 6-30). This will control the average power delivered to the motors. The higher the ratio of the pulse width to the period (the duty cycle), the more power delivered to the motor.

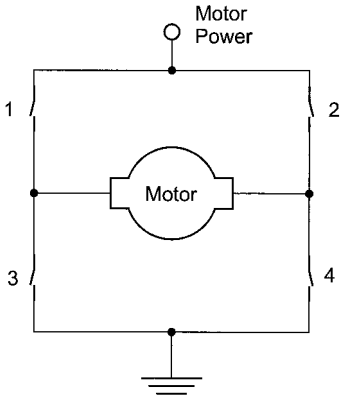


Figure 6-37 "H" bridge motor driver

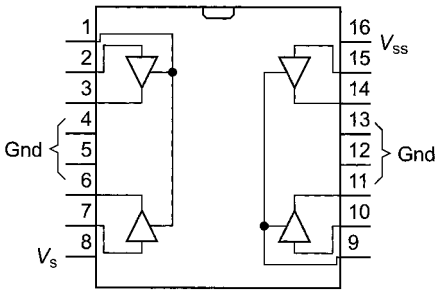


Figure 6-38 293D "H" bridge motor driver

The frequency of the PWM signal should be greater than 20 kHz to prevent the PWM from producing an audible signal in the motors as the field is turned on and off.

Like the ULN2003A simplified the wiring of a relay control, the 293D (Fig. 6-38) or 298 chips can be used to control a motor.

The 293D chip can control two motors (one on each side) connected to the buffer outputs (pins 3, 6, 11, and 14). Pins 2, 7, 10, and 15 are used to control the voltage level (the switches in the H-bridge diagram) of the buffer outputs. Pins 1 and 9 are used to control whether or not the buffers are enabled. The buffer controls can be PWM inputs, which make control of the motor speed very easy to implement.

V_S is +5 V used to power the logic in the chip and V_{SS} is the power supplied to the motors (anywhere from 4.5 to 36 volts). A maximum of 500 mA can be supplied to the motors. Like the ULN2003A, the 293D contains integral shunt diodes. This means that to attach a motor to the 293D, no external shunt diodes are required.

In this example circuit, you'll notice that I've included an optional snubber resistor and capacitor. These two components, wired across the brush contacts of the motor, will help reduce electromagnetic emissions and noise spikes from the motor. In the motor-control circuits that I have built, I have never found them to be necessary. But if you find erratic operation from the microcontroller when the motors are running, you might want to put in the 0.1-μF capacitor and 5 Ohm (2 watt) resistor snubber across the motor's brushes (as shown in the circuit).

An issue with using the 293D and 298 motor controller chips and is that they are bipolar devices with a 0.7-volt drop across each driver (1.4 to 1.5 volts for a dual driver circuit, Fig. 6-39). This drop, with the significant amount of current required for a motor, results

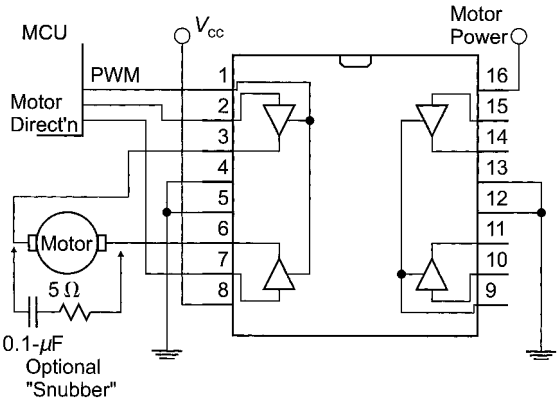


Figure 6-39 Wiring a motor to the 293D

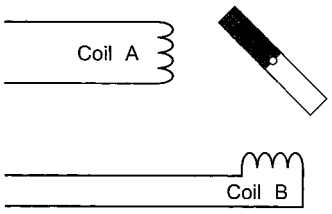


Figure 6-40 Stepper motor

in a fairly significant amount of power dissipation within the driver. The 293D is limited to 1 amp total output and the 298 is limited to 3 amps. For these circuits to work best, a large heatsink is required.

To minimize the problem of heating and power loss, I have more recently been looking at using power MOSFETS to control motors. Later, the book shows how to wire these transistors in a circuit to control a motor.

Stepper motors are much simpler to develop control software for than a regular DC motor. This is because the motor is turned one step at a time or can turn at a specific rate (specified by the speed in which the steps are executed). In terms of the hardware interface, stepper motors are a bit more complex to wire and require more current (meaning that they are less efficient), but these are offset by the advantages in software control.

A bipolar stepper motor consists of a permanent magnet on the motor's shaft that has its position specified by a pair of coils (Fig. 6-40).

To move the magnet and the shafts, the coils are energized in different patterns to attract the magnet. For the motor shown in Fig. 6-40, the following sequence would be used to turn the magnet (and the shaft) clockwise (Table 6-5).

In this sequence, coil A attracts the north pole of the magnet to put the magnet in an initial position. Then, coil B attracts the south pole, turning the magnet 90 degrees. This continues on to turn the motor 90 degrees for each step.

The output shaft of a stepper motor is often geared down so that each step causes a very small angular deflection (a couple of degrees at most, rather than the 90 degrees in the previous example). This provides more torque output from the motor and greater positional control of the output shaft.

A stepper motor can be controlled by something like a 293D (each side driving one coil). But there are also stepper-motor controller chips, such as the UC1517.

TABLE 6–5 Commands to Move a Stepper Motor

STEP	ANGLE	COIL "A"	COIL "B"
1	0	S	
2	90		N
3	180	N	
4	270		S
5	360/0	S	

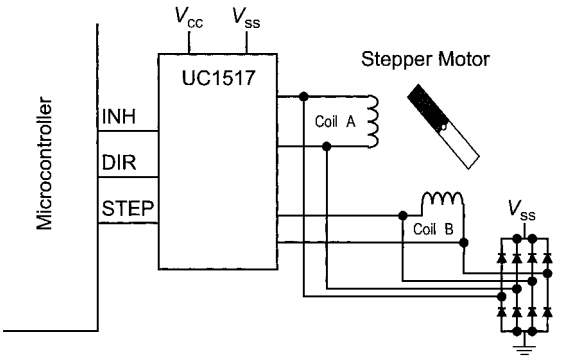


Figure 6-41 UC1517 control of a stepper motor

In this chip, a step pulse is sent from the microcontroller along with a specified direction. The INH pin will turn off the output drivers and allow the stepper shaft to be moved manually. The UC1517 is capable of outputting bilevel coil levels (which improves efficiency and reduces induced noise), as well as half stepping the motor (which involves energizing both coils to move the magnet/shaft by 45 degrees and not just 90 degrees). These options are specific to the motor/controller used (a bipolar stepper motor can have four to eight wires coming out of it). Before deciding on features to be used, a thorough understanding of the motor and its operation is required.

R/C Servo Control

Servos designed for use in radio-controlled airplanes, cars, and boats can be easily interfaced to a PICmicro® MCU. They are often used for robots and applications where simple mechanical movement is required. This might be surprising because a positional servo is considered to be an analog device.

The output of an R/C servo is usually a wheel that can be rotated from 0 to 90 degrees. (some servos can turn from 0 to 180 and others have very high torque outputs for special applications). Typically, they only require +5 V, ground, and an input signal.

An R/C servo is an analog device, the input is a PWM signal at digital voltage levels. This pulse is between 1.0 and 2.0 ms long and repeats every 20 ms (Fig. 6-42).

The length of the PWM pulse determines the position of the servo's wheel. A 1.0-ms pulse will cause the wheel to go to 0 degrees and a 2.0-ms pulse will cause the wheel to go to 90 degrees.

With the PICmicro® MCU's TMR2 capable of outputting a PWM signal, controlling a servo could be considered very easy, although the TMR2 output will probably not give you the positional accuracy that you will want.

To produce a PWM signal using a PICmicro® MCU, I normally use a timer interrupt (set every 18 ms) that outputs a 1.0- to 2.0-ms PWM signal using pseudo-code:

```
Interrupt() {                  // Interrupt Handler Code
int i = 0;
 BitOutput( Servo, 1);         // Output the Signal
```

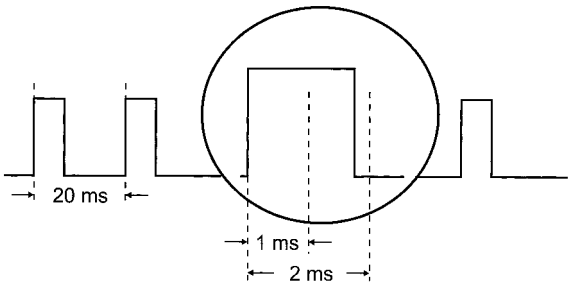


Figure 6-42 Servo PWM waveform

```
 for (i = 0; i < (1 msec + ServoDlay); i++ );
 BitOutput( Servo, 2);
 for (; i < 2 msec; i++ );   // Delay full 2 msecs
} // End Interrupt Handler
```

This code can be easily expanded to control more than one servo (by adding more output lines and *ServoDlay* variables). This method of controlling servos is also nice because the *ServoDlay* variables can be updated without affecting the operation of the interrupt handler.

The interrupt handler takes two ms out of every 20. Thus, a 10-percent cycle overhead provides the PWM function (and this doesn't change even if more servo outputs are added to the device).

Serial Interfaces

Most intersystem (or intercomputer) communications are done serially. Thus, a byte of data is sent over a single wire, one bit at a time, with the timing coordinated between the sender and the receiver. The obvious advantage of transmitting data serially is that fewer connections are required.

A number of common serial communication protocols are used by microcontrollers. In some devices, these protocols are built into the chip itself, to simplify the effort required developing software for the application.

SYNCHRONOUS

For synchronous data communications in a microcontroller, a clock signal is sent along with serial data (Fig. 6-43).

The clock signal strobes the data into the receiver and the transfer can occur on the rising or falling edge of the clock. A typical circuit, using discrete devices, could be like that shown in Fig. 6-44.

This circuit converts serial data into eight digital outputs, which all are available at the same time (When the O/P clock is strobed). For most applications, the second '374 (which

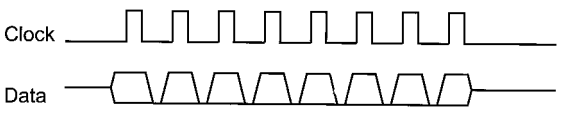


Figure 6-43 Synchronous data waveform

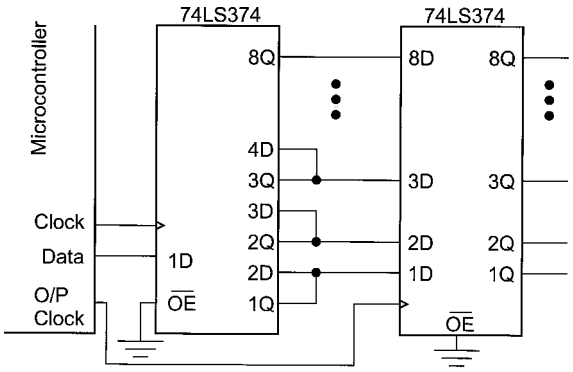


Figure 6-44 Synchronous output circuit

provides the parallel data) is not required. This serial-to-parallel conversion can also be accomplished using serial-to-parallel chips, but I prefer using eight-bit registers because they are generally easier to find than other TTL parts.

The two very common synchronous data protocols are *Microwire* and *SPI*. These methods of interfacing are used in a number of chips (such as the serial EEPROMs used in the BASIC Stamps). Although the Microwire and SPI standards are quite similar, there are a number of differences.

I consider these protocols to be methods of transferring synchronous serial data, rather than microcontroller network protocols because each device is individually addressed (even though the clock/data lines can be common between multiple devices). If the chip select for the device is not asserted, the device ignores the clock and data lines. With these protocols, only a single master can be on the bus. A possible connection of two devices is shown in Fig. 6-45.

If a synchronous serial port is built into the microcontroller, the data transmit circuitry might look like that shown in Fig. 6-46. This circuit will shift out eight bits of data. For protocols, such as Microwire, where a start bit is initially sent, the start bit is sent using direct reads and writes to the I/O pins. To receive data, a similar circuit would be used, but data would be shifted into the shift register and then read by the microcontroller.

The Microwire protocol is capable of transferring data at up to 1 Mbps. Sixteen bits are transferred at a time. To read 16 bits of data, the waveform looks like that shown in Fig. 6-47.

After selecting a chip and sending a start bit, the clock strobes out an eight-bit command byte (labeled *OP1, OP2, A5* to *A0* in the previous diagram), followed by (optionally) a

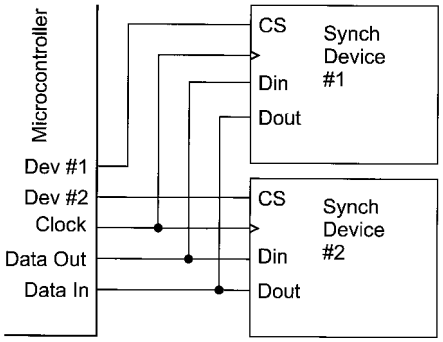


Figure 6-45 Synchronous device bus

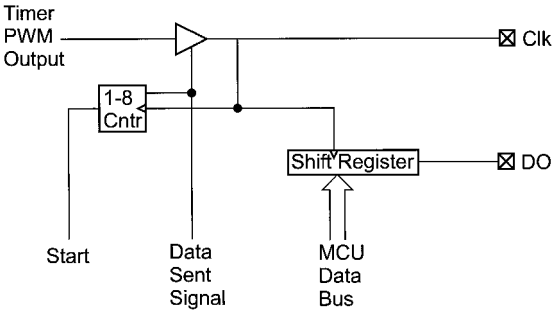


Figure 6-46 Synchronous output

16-bit address word transmitted and then another 16-bit word, either written or read by the microcontroller.

With a 1-Mbps maximum speed, the clock is both high and low for 500 ns. Transmitted bits should be sent 100 ns before the rising edge of the clock. When reading a bit, it should be checked 100 ns before the falling edge of the clock. Although these timings will work for most devices, you should understand the requirements of the device being interfaced to.

The SPI protocol is similar to Microwire, but with a few differences.

1. SPI is capable of up to 3-Mbps data-transfer rate.
2. The SPI data word size is eight bits.
3. SPI has a hold that allows transmitter to suspend data transfer.
4. Data in SPI can be transferred as multiple bytes, known as *blocks* or *pages*.

Like Microwire, SPI first sends a byte instruction to the receiving device. After the byte is sent, a 16-bit address is optionally sent, followed by eight bits of I/O. As noted, SPI does allow for multiple byte transfers. An SPI data transfer is shown in Fig. 6-48.

The SPI clock is symmetrical (an equal low and high time). Output data should be available at least 30 ns before the clock line goes high and read 30 ns before the falling edge of the clock.

When wiring a Microwire or SPI device, you can do a trick to simplify the microcontroller connection; combine the DI and DO lines into one pin. Figure 6-49 is identical to what was shown earlier in this chapter when interfacing the PICmicro® MCU into a circuit where there is another driver.

In this method of connecting the two devices, when the data pin on the microcontroller has completed sending the serial data, the output driver can be turned off and the microcontroller can read the data coming from the device. The current-limiting resistor between

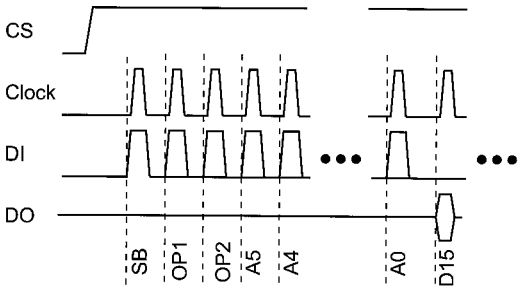


Figure 6-47 Microwire data read

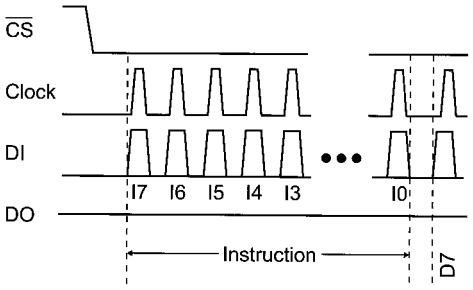


Figure 6-48 SPI data write

the data pin and DI/DO limits any current flows when both the microcontroller and device are driving the line.

I2C The most popular form of microcontroller network is *I2C (Inter-Intercomputer Communications).* This standard was originally developed by Philips in the late '70s as a method to provide an interface between microprocessors and peripheral devices without wiring full address, data, and control busses between devices. I2C also allows sharing of network resources between processors (which is known as *multi-mastering*).

The I2C bus consists of two lines, a clock line (SCL), which is used to strobe data (from the SDA line) from or to the master that currently has control over the bus. Both of these bus lines are pulled up (to allow multiple devices to drive them). An I2C-controlled stereo system might be wired as in Fig. 6-50.

The two bus lines are used to indicate that a data transmission is about to begin, as well as pass the data on the bus.

To begin a data transfer, a master puts a start condition on the bus. Normally, (when the bus is in the idle state, both the clock and data lines are not being driven (and are pulled high). To initiate a data transfer, the master requesting the bus pulls down the SDA bus line, followed by the SCL bus line. During data transmission, this is an invalid condition (because the data line is changing while the clock line is active/high).

Each bit is then transmitted to or from the slave (the device the message is being communicated with by the master) with the negative clock edge being used to latch in the data (Fig. 6-51). To end data transmission, the reverse is executed, the clock line is allowed to go high, which is followed by the data line.

Data is transmitted in a synchronous (clocked) fashion. The most-significant bit sent first and, after eight bits are sent, the master allows the data line to float (it doesn't drive it low) while strobing the clock to allow the receiving device to pull the data line low as an

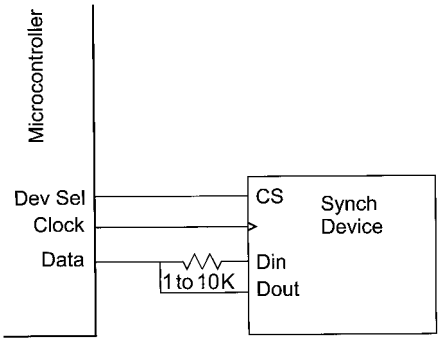


Figure 6-49 Combining "DO" & "DI"

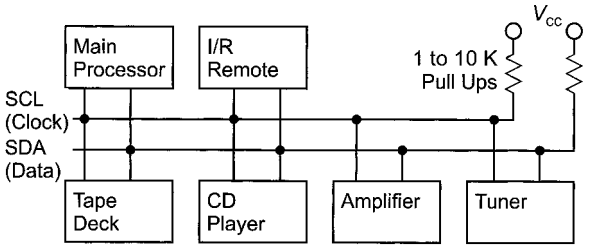


Figure 6-50 Example I2C network wiring

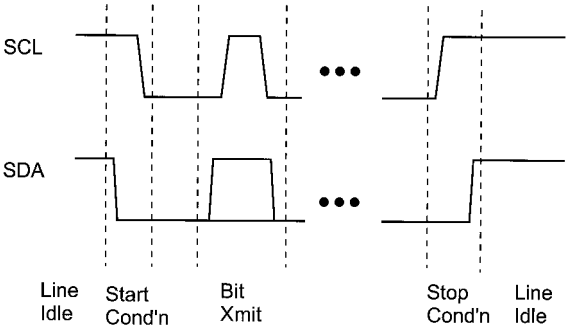


Figure 6-51 I2C signals and waveforms

acknowledgment that the data was received. After the acknowledge bit, both the clock and data lines are pulled low in preparation for the next byte to be transmitted or a stop/start condition is put on the bus. Figure 6-52 shows the data waveform.

Sometimes, the acknowledge bit will be allowed to float high—even though the data transfer has completed successfully. This is done to indicate that the data transfer has completed and the receiver (usually a slave device or a master, which is unable to initiate data transfer) can prepare for the next data request.

The two maximum speeds for I2C (because the clock is produced by a master, there really is no minimum speed) are *standard mode* and *fast mode*. Standard mode runs at up to 100 kbps and fast mode can transfer data at up to 400 kbps. Figure 6-53 shows the timing specifications for both the standard (*Std.,* 100-kHz data rate) and fast (400-kHz data rate).

A command is sent from the master to the receiver in the format shown in Fig. 6-54. The receiver address is seven bits long and is the bus address of the receiver. There is a loose standard to use the most significant four bits are used to identify the type of device; the next three bits are used to specify one-of-eight devices of this type (or further specify the device type).

As stated, this is a loose standard. Some devices require certain patterns for the second three bits and others (such as some large serial EEPROMS) use these bits to specify an ad-

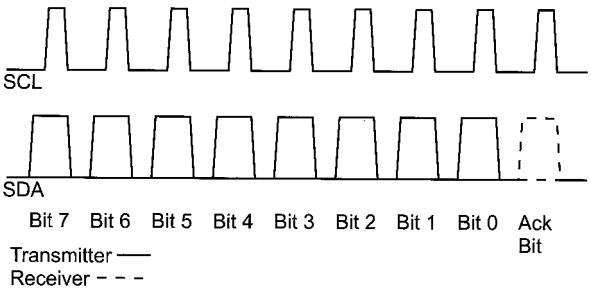


Figure 6-52 I2C data byte transmission

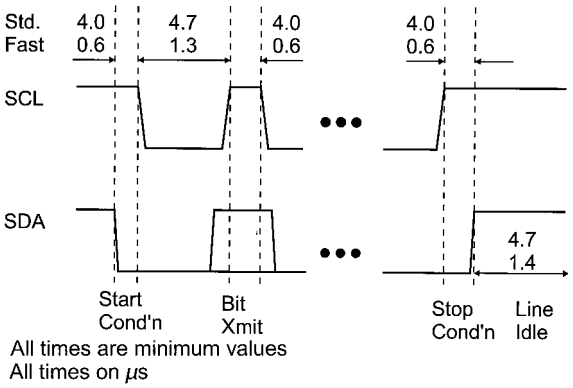


Figure 6-53 I2C signal timing

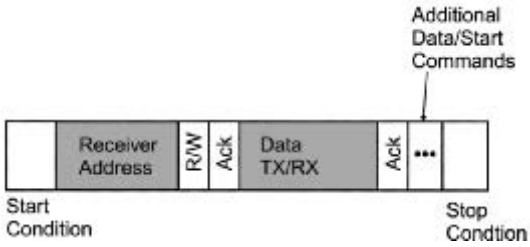


Figure 6-54 I2C data transmission

dress inside of the device. As well, there is a ten-bit address standard in which the first four bits are all set and the next bit reset. The last two are the most-significant two bits of the address, with the final eight bits being sent in a following byte. All this means is that it is very important to map out the devices to be put on the bus and all of their addresses.The first four bit patterns in Table 6-6 generally follow this convention for different devices.

This is really all there is to I2C communication, except for a few points. In some de-

TABLE 6–6 Reserved I2C Device Type Bit Patterns

0000 - Reserved Address
0010 - Voice Synthesizer
0011 - PCM Audio Interface
0100 - Audible Tone Generation
0111 - LCD/LED Displays
1000 - Video Interface
1001 - A/D and D/A interfaces
1010 - Serial Memory
1100 - RF tuning/control
1101 - Clock/Calendar
1111 - Reserved/Ten Bit Address

vices, a start bit has to be resent to reset the receiving device for the next command (i.e., in a serial EEPROM read, the first command sends the address to read from and the second reads the data at that address).

Note that I2C is *multi-mastering,* which is to say that multiple microcontrollers can initiate data transfers on a single I2C bus. This obviously results in possible collisions (which is when two devices attempt to drive the bus at the same time). Obviously, if one microcontroller takes the bus (sends a start condition) before another one attempts to do so, there is no problem. The problem arises when multiple devices initiate the start condition at the same time.

Actually, arbitration in this case is really quite simple. During the data transmission, hardware (or software) in both transmitters synchronize the clock pulses so that they match each other exactly. During the address transmission, if a bit that is expected to be a *1* by a master is actually a *0,* then it drops off the bus because another master is on the bus. The master that drops off will wait until the stop condition and then re-initiate the message. I realize that this is hard to understand with just a written description. The "CAN" section shows how this is done with an asynchronous bus, which is very analogous to this situation.

A bit-banging I2C interface can be implemented in software of the PICmicro® MCU quite easily. But, because of software overhead, the fast mode probably cannot be implemented—even the standard mode's 100 kbps will be a stretch for most devices. I find that implementing I2C in software to be best when the PICmicro® MCU is the single master in a network. That way it doesn't have to be synchronized to any other devices or accept messages from any other devices that are masters and are running a hardware implementation of I2C that might be too fast for the software slave.

ASYNCHRONOUS (NRZ) SERIAL

Asynchronous long-distance communications came about as a result of the Baudot teletype. This device mechanically (and, later, electronically) sent a string of electrical signals (now called *bits*) to a receiving printer.

This data packet format is still used today for the electrical asynchronous transmission protocols described in the following sections. With the invention of the teletype, data could be sent and retrieved automatically without having to an operator to be sitting by the teletype all night, unless an urgent message was expected. Normally, the nightly messages could be read in the morning.

Before going on, some people get unreasonably angry about the definition and usage of the terms *data rate* and *baud rate*. *Baud rate* is the maximum number of possible data-bit transitions per second. This includes the start, parity, and stop bits at the ends of the data packet shown in Fig. 6-55, as well as the five data bits in the middle. I use the term *packet* because we are including more than just data (some additional information is in there as well), so *character* or *byte* (if there were eight bits of data) are not appropriate terms.

This means that for every five data bits transmitted, eight bits in total are transmitted (thus, nearly 40% of the data-transmission bandwidth is lost in teletype asynchronous serial communications).

The *data rate* is the number of data bits that are transmitted per second. For this example, if you were transmitting at 110 baud (which is a common teletype data speed), the actual data rate is 68.75 bits per second (or, assuming five bits per character, 13.75 characters per second).

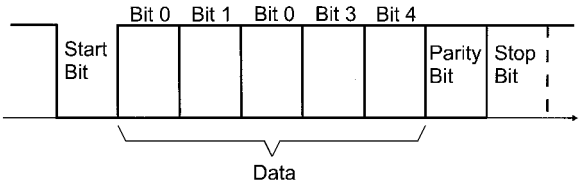


Figure 6-55 Baudot asynchronous serial data

I use the term *data rate* to describe the *baud rate*. This means that when I say *data rate*, I am specifying the number of bits of *all* types that can be transmitted in a given period of time (usually one second). I realize that this is not absolutely correct, but it makes sense to me to use it in this form and this book is consistent throughout (and I will not use the term *baud rate*).

With only five data bits, the Baudot code could only transmit up to 32 distinct characters. To handle a complete character set, a specific five-digit code was used to notify the receiving teletype that the next five-bit character would be an extended character. With the alphabet and most common punctuation characters in the primary 32, this second data packet wasn't required very often.

The data packet diagram shows three control bits. The start bit is used to synchronize the receiver to the incoming data. The PICmicro® MCU *USART (Universal Synchronous/Asynchronous Receiver/Transmitter)* has an overspeed clock (running at 16 times the incoming bit speed), which samples the incoming data and verifies whether or not the data is valid (Fig. 6-56).

When waiting for a character, the receiver hardware polls the line repeatedly at 1/16-bit period intervals until a 0 (space) is detected. The receiver then waits half a cycle before polling the line again to see if a glitch was detected and not a start bit. Notice that polling occurs in the middle of each bit to avoid problems with bit transitions (if the transmitter's clock is slightly different from the receiver's, the chance of misreading a bit will be minimized).

Once the start bit is validated, the receiver hardware polls the incoming data once every bit period multiple times (again, to ensure that glitches are not read as incorrect data).

The stop bit was originally provided to give both the receiver and the transmitter some time before the next packet is transferred (in early computers, the serial data stream was created and processed by the computers and not by custom hardware, as in modern computers).

The parity bit is a crude method of error detection that was first brought in with teletypes. The purpose of the parity bit is to indicate whether the data was received correctly. An *odd*

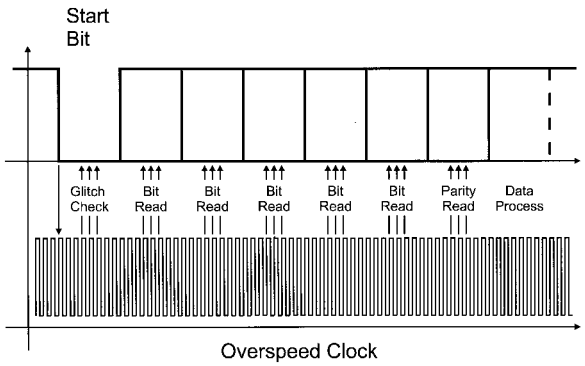


Figure 6-56 Reading an asynch data packet

parity meant that if all the data bits and parity bits set to a mark were counted, then the result would be an odd number. *Even parity* is checking all the data and parity bits and seeing if the number of mark bits is an odd number. Along with even and odd parity are mark, space, and no parity. *Mark parity* means that the parity bit is always set to a 1, *space parity* is always having a 0 for the parity bit, and *no parity* is eliminating the parity bit altogether.

The most common form of asynchronous serial data packet is *8-N-1,* which means eight data bits, no parity, and one stop bit. This reflects the capabilities of modern computers to handle the maximum amount of data with the minimum amount of overhead and with a very high degree of confidence that the data will be correct.

I stated that parity bits are a "crude" form of error detection. I said that because they can only detect one bit error (e.g., if two bits are in error, the parity check will not detect the problem). If you are working in a high-induced-noise environment, you might want to consider using a data protocol that can detect (and, ideally, correct) multiple-bit errors.

RS-232 In the early days of computing (the 1950s), although data could be transmitted at high speed, it couldn't be read and processed and continuously. So, a set of handshaking lines and protocols were developed for what became known as *RS-232 serial communications.*

With RS-232, the typical packet contains seven bits, (which is the number of bits that each ASCII character contained). This simplified the transmission of man-readable text, but made sending object code and data (which were arranged as bytes) more complex because each byte would have to be split up into two *nybbles* (which are four bits long). Further complicating this is that the first 32 characters of the ASCII character set are defined as "special" characters (e.g., carriage return, back space, etc.). This meant the data nybbles would have to be converted or (shifted up) into valid characters (this is why, if you ever see binary data transmitted from a modem or embedded in an e-mail message, data is either sent as hex codes or the letters *A* to *Q*). With this protocol, to send a single byte of data, two bytes (with the overhead bits resulting in 20 bits in total) would have to be sent.

As pointed out, modern asynchronous serial data transmission normally occur eight bits at a time, which will avoid this problem and allow transmission of full bytes without breaking them up or converting them.

The actual RS-232 communications model is shown in Fig. 6-57. In RS-232, different equipment is wired according to the functions that they perform.

DTE (Data Terminal Equipment) and is meant to be the connector used for computers (the PC uses this type of connection). *DCE (Data Communications Equipment)* was meant for modems and terminals that transfer the data.

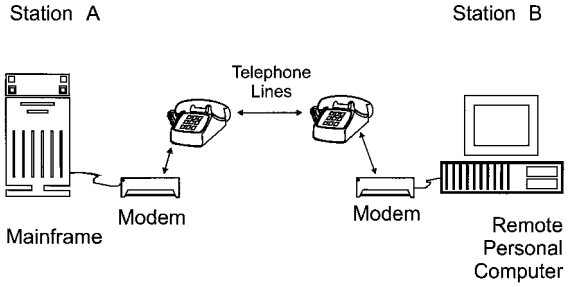


Figure 6-57 2 computer communication via modem

Understanding what the RS-232 model different equipment fits under is crucial to successfully connecting two devices by RS-232. With a pretty good understanding of the serial data, you can now look at the actual voltage signals.

As mentioned, when RS-232 was first developed into a standard, computers and the electronics that drive them were still very primitive and unreliable. Because of that, we've got a couple of legacies to deal with.

The first is the voltage levels of the data. A mark (1) is actually −12 Volts and a space (0) is +12 V (Fig. 6-58).

From Fig. 6-58, you should see that the hardware interface is not simply a TTL or CMOS-level buffer. Later, this section introduces you to some methods of generating and detecting these interface voltages. Voltages in the switching region (+/− 3 V) might not be read as a 0 or 1, depending on the device. You should always be sure that the voltages going into or out of a PICmicro® MCU RS-232 circuit are in the valid regions.

Of more concern are the handshaking signals. These six additional lines (which are at the same logic levels as the transmit/receive lines and shown in Fig. 6-58) are used to interface between devices and control the flow of information between computers.

The *Request To Send (RTS)* and *Clear To Send (CTS)* lines are used to control data flow between the computer (DCE) and the modem (DTE device). When the PC is ready to send data, it asserts (outputs a mark) on RTS. If the DTE device is capable of receiving data, it will assert the CTS line. If the PC is unable to receiver data (i.e., the buffer is full or it is processing what it already has), it will de-assert the RTS line to notify the DTE device that it cannot receive any additional information.

The *Data Transmitter Ready (DTR)* and *Data Set Ready (DSR)* lines are used to establish communications. When the PC is ready to communicate with the DTE device, it asserts DTR. If the DTE device is available and ready to accept data, it will assert DSR to notify the computer than the link is up and ready for data transmission. If a hardware error is in the link, then the DTE device will de-assert the DSR line to notify the computer of the problem. Modems, if the carrier between the receiver is lost, will de-assert the DSR line.

Two more handshaking lines are available in the RS-232 standard that you should be aware of. Even so, chances are that you will never connect anything to them. The first is the *Data Carrier Detect (DCD),* which is asserted when the modem has connected with another device (i.e., the other device has "picked up the phone"). The *Ring Indicator (RI)* is used to indicate to a PC whether or not the phone on the other end of the line is ringing or if it is busy. This line is very rarely used in PICmicro® MCU applications.

A common ground connection exists between the DCE and DTE devices. This connection is crucial for the RS-232-level converters to determine the actual incoming voltages. The ground pin should never be connected to a chassis or shield ground (to avoid large cur-

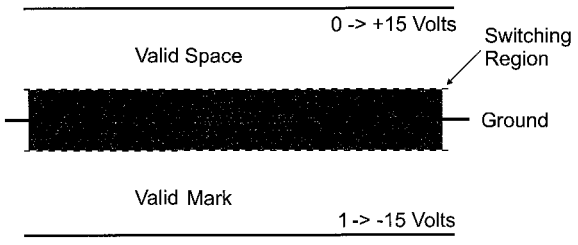


Figure 6-58 RS-232 voltage levels

rent flows or be shifted and prevent accurate reading of incoming voltage signals). Incorrect grounding of an application can result in the computer or the device it is interfacing to reset or have they power supplies blow a fuse or burn out. The latter consequences are unlikely, but I have seen it happen in a few cases.

To avoid these problems, be sure that the chassis and signal grounds are separate or connected by a high-value (hundreds of k) resistor.

Before going too much further, I should expose you to an ugly truth; the handshaking lines are almost never used in RS-232 (and not just PICmicro® MCU RS-232) communications. The handshaking protocols were added to the RS-232 standard when computers were very slow and unreliable. In this environment, data transmission had to be stopped periodically to allow the receiving equipment to catch up.

Today, this is much less of a concern. Normally, three-wire RS-232 connections are implemented (Fig. 6-59). I normally accomplish this by shorting the DTR/DSR and RTS/CTS lines together at the PICmicro® MCU end. The DCD and RI lines are left unconnected.

With the handshaking lines shorted together, data can be send and received without having to develop software to handle the different handshaking protocols.

A couple of points on three-wire RS-232 are worth noting. First, it cannot be implemented blindly. In about 20% of the RS-232 applications that I have had to do over the years, I have had to implement some subset of the total seven-wire (transmit, receive, ground, and four handshaking lines) protocol lines. Interestingly enough, I have never had to implement the full hardware protocol. This still means that four out of five times, if you wire the connection (Fig. 6-59), the application would have worked, but you have to be prepared for the other twenty percent of cases where more work is required.

With the three-wire RS-232 protocol, there might be applications where you don't want to implement the hardware handshaking (the DTR, DSR, RTS, and CTS lines), but you might want software handshaking. Two primary standards are in place. The first is known as the *XON/XOFF protocol,* in which the receiver sends an *XOFF* (DC3, character 0x013) when it can't accept any more data. When it is able to receive data, it sends an *XON* (DC1, character 0x011) to notify the transmitter that it can receive more data.

The final aspect of the RS-232 to cover here is the speeds in which data is transferred. When you first see the speeds (such as 300, 2,400, and 9,600 bits per second), they seem rather arbitrary. The original serial data speeds were chosen for teletypes because they gave the mechanical device enough time to print the current character and reset before the next one came in. Over time, these speeds have become standards and as faster devices have become available, they've just been doubled (e.g, 9,600 bps is 300 bps doubled five times).

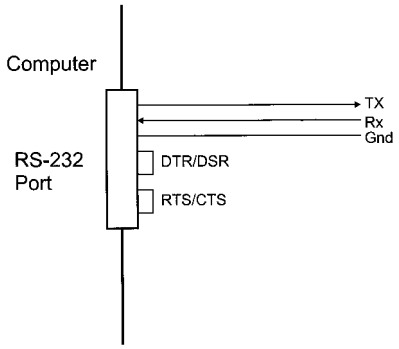


Figure 6-59 Typical RS-232 wiring

In producing these data rates, the PICmicro® MCU's USART uses clock divider to produce a clock 16 times the data rate. The PICmicro® MCU's operating clock is divided by integers to get the nominal RS-232 speeds. This might seem like it won't work out well, but because of the RS-232's strange relationship with the number 13, the situation isn't as bad as it might seem.

If you invert (to get the period of a bit) the data speeds and convert the units to microseconds, you will discover that the periods are almost exactly divisible by 13. Thus, you can use an even-MHz oscillator in the hardware to communicate over RS-232 using standard frequencies.

For example, if you had a PICmicro® MCU running with a 20-MHz instruction clock and you wanted to communicate with a PC at 9,600 bps, you would determine the number of cycles to delay by:

1. Find the bit period in microseconds. For 9,600 bps, this is 104 μs.
2. Divide this bit period by 13 to get a multiple number. For 104 μs, this is 8.

Now, if the external device is running at 20 MHz (which means a 200-ns cycle time), you can figure out the number of cycles as multiples of 8 $\times$ 13 times in the number of cycles in 1 μs. For 20 MHz, five cycles execute per microsecond. To get the total number of cycles for the 104-μs bit period, you simply evaluate:

5 cycles/μs * 13 * 8 μs/bit = 520 instruction cycles/bit

The device you are most likely to interface to is the PC. Its serial ports consist of basically the same hardware and BIOS interfaces that were first introduced with the first PC in 1981. Since that time, a nine-pin connector has been specified for the port (in the PC/AT) and one significant hardware upgrade has been introduced when the PS/2 was announced. For the most part, the serial port has changed the least of any component in the PC for the past 20 or so years.

Either a male 25-pin or male 9-pin connector is available on the back of the PC for each serial port. These connectors are shown in Fig. 6-60 and Table 6-7.

The 9-pin standard was originally developed for the PC/AT because the serial port was put on the same adapter card as the printer port. There wasn't enough room for the serial port *and* parallel port to both use 25-pin D-shell connectors. I prefer the smaller form-factor connector.

RS-232 serial communications have a reputation for being difficult to use and I have to disagree. Implementing RS-232 isn't very hard when a few rules are followed and you have a good idea of what's possible.

When implementing an RS-232 interface, you can make your life easier by doing a few simple things. The first is the connection. Whenever I do an application, I standardize by

Figure 6-60 IBM PC DB-25 and D-9 pin RS-232 connectors

TABLE 6–7 Standard RS-232 Connector Pinouts

PIN NAME	25 PIN	9 PIN	I/O DIRECTION
TxD	2	3	Output (“O”)
RxD	3	2	Input (“I”)
Gnd	7	5	
RTS	4	7	O
CTS	5	8	I
DTR	20	4	O
DSR	6	6	I
RI	22	9	I
DCD	8	1	I

using a nine-pin D-shell with the DTE interface (the one that comes out of the PC) and use standard “straight-through” cables. In doing so, I always know what my pinout is at the end of the cable when I’m about to hookup a PICmicro® MCU to a PC.

By making the external device DCE always and using a standard pinout, I don’t have to fool around with null modems or by making my own cables.

When I create the external device, I also loop back the DTR/DSR and CTS/RTS data pairs inside the external device, rather than at the PC or in the cable. This allows me to use a standard PC and cable without having to do any wiring on my own or any modifications. It actually looks a lot more professional as well.

Tying DTR/DSR and CTS/RTS also means that I can take advantage of built-in terminal emulators. All operating systems have a “dumb” terminal emulator that can be used to debug the external device without requiring the PC code to run. Getting the external device working before debugging the PC application code should simplify your work.

As I went through the RS-232 electrical standard earlier in this section, you were probably concerned about interfacing standard, modern technology (i.e., TTL and CMOS) devices to other RS-232 devices. This is a legitimate concern because, without proper voltage-level conversion, you will not be able to read from or write to external TTL or CMOS devices. Fortunately, this conversion isn’t all that difficult because there are methods to make it quite easy.

If you look at the original IBM PC RS-232 port specification, you’ll see that 1488/1489 RS-232 level-converter circuits were used for the RS-232 serial port interfaces. The pinout and wiring for these devices in a PC are shown in Fig. 6-61.

There are a few points about the 1488/1489 components that should be discussed. When transmitting data, each transceiver (except for 1) is actually a NAND gate (with the inputs being #A and #B outputting on #Y). When I wire in a 1488, I ensure that the second input to a driver is always pulled high (as I’ve done with 2B in Fig. 6-61).

The second comment has to do with the 1489 receiver. The #C input is a flow control for the gates (normally RS-232 comes in the #A pin and is driven as TTL out of #Y). This pin is normally left floating (unconnected).

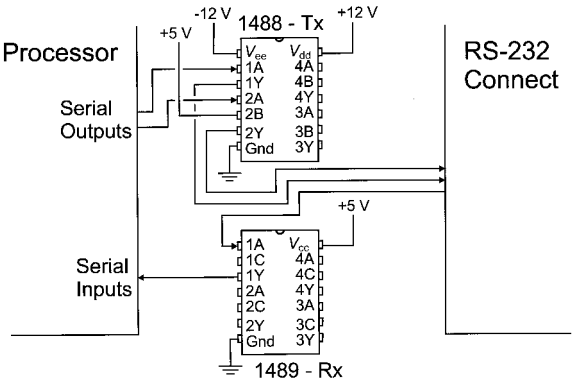


Figure 6-61 1488/1489 RS-232 connections

These chips are still available and work very well (up to 115,200 bps maximum RS-232 data rate), only I'd never use them in my own projects because the 1488 (transmitter) requires +/−12-V sources in order to produce valid RS-232 signal voltages.

This section presents three methods that you can choose from to convert RS-232 signal levels to TTL/CMOS (and back again) when you are creating PICmicro® MCU RS-232 projects. These three methods do not require I12 V. In fact, they just require the +5-V supply that is used for logic power.

The first method is using an RS-232 converter that has a built-in charge pump to create the +/−12 V required for the RS-232 signal levels. Probably the most well-known chip that is used for this function is the Maxim MAX232 (Fig. 6-62).

This chip is ideal for implementing three-wire RS-232 interfaces (or adding a simple DTR/DSR or RTS/CTS handshaking interface). The ground for the incoming signal is connected to the processor ground (which is not the case's ground).

Along with the MAX232, Maxim and some other chip vendors have a number of other RS-232 charge-pump-equipped devices that will allow you to handle more RS-232 lines (to include the handshaking lines). Some available charge-pump devices do not require the external capacitors that the MAX232 chip does, which will simplify the layout of your circuit (although these chips do cost quite a bit more).

The next method of translating RS-232 and TTL/CMOS voltage levels is to use the transmitter's negative voltage. The circuit in Fig. 6-63 shows how this can be done and is demonstrated in Chapter 15.

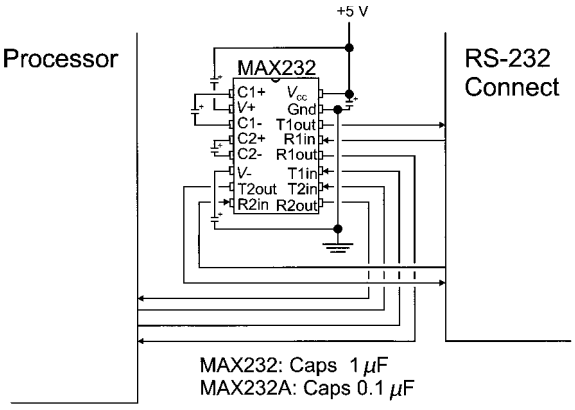


Figure 6-62 MAXIM MAX232 RS-232 connections

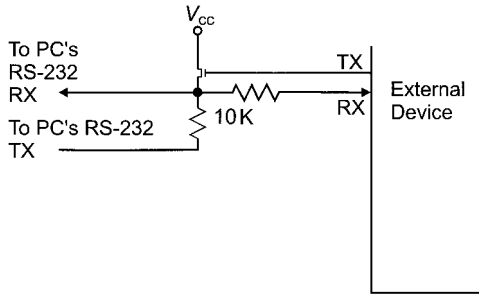


Figure 6-63 RS-232 to external device

This circuit relies on the RS-232 communications only running in half-duplex mode (i.e., only one device can transmit at a given time). When the external device "wants" to transmit to the PC, it sends the data either as a mark (leaving the voltage being returned to the PC as a negative value) or as a space (by turning on the transistor and enabling the positive voltage output to the PC's receivers). If you go back to the RS-232 voltage-specification drawing, you'll see that +5 V is within the valid voltage range for RS-232 spaces.

This method works very well (consuming just about no power) and is obviously a very cheap way to implement a three-wire RS-232 bidirectional interface. Figure 6-63 shows a NMOS device simply because it does not require a base current-limiting transistor the same way that a bipolar transistor would.

When the PICmicro® MCU transmits a byte to the external device through this circuit, it will receive the packet it's sent because this circuit connects the PICmicro® MCU's receiving pin (more or less) directly to its transmitting pin. The software running in the PICmicro® MCU (as well as the external device) will have to handle this.

You also have to be absolutely sure that you are only transmitting in half-duplex mode. If both the PICmicro® MCU and the external device attempt to transmit at the same time, then both messages will be garbled. Instead, the transmission protocol that you use should wait for requested responses, rather than sending them asynchronously (or, you could have one device, either the PC or external devices, wait for a request for data from the other).

Another issue to notice is that data out of the external device will have to be inverted to get the correct transmission voltage levels (e.g., a *0* will output a *1*) to ensure that the transistor turns on at the right time (e.g., a positive voltage for a space).

Unfortunately, this means that the built-in serial port for many microcontrollers cannot be used because they cannot invert the data output as is required by the circuit. An inverter could be put between the serial port and the RS-232 conversion circuit to avoid this problem.

The Dallas Semiconductor DS275 incorporates this circuit (with built-in inverters) into the single package shown in Fig. 6-64.

The DS1275 and the DS275 have the same pinout. Both work exactly the same way, but the DS275 is a later version of the part.

As an aside, before going on to the last interface circuit, this circuit has a big advantage. The PICmicro® MCU's RS-232 transmitter is connected to the PC's RS-232 receiver if the external device (with this circuit) is connected to a PC. Thus, the PICmicro® MCU can *ping* (send a command that is ignored by the external device) via the RS-232 port and see if the external device is connected to it. But, this technique has a hitch. Even though the circuit is connected, how do you know that the external PICmicro® MCU device is working from the PC?

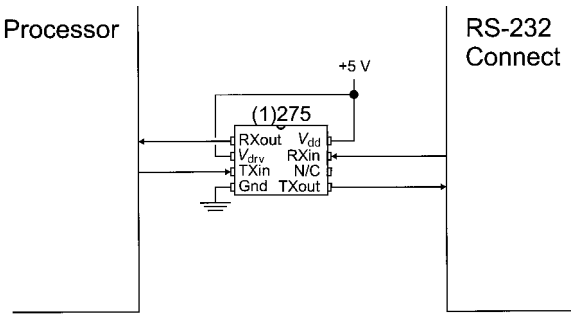


Figure 6-64 Dal Semi 1275 RS-232 interface

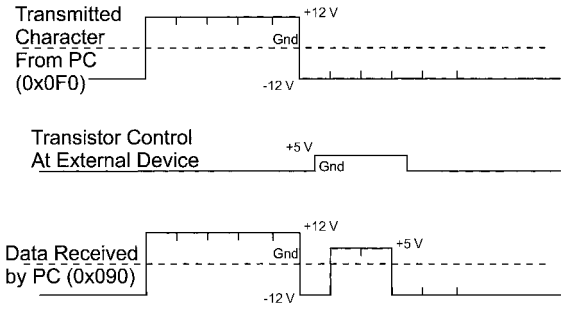


Figure 6-65 RS-232 "Ping" using transistor/ resistor TTL/CMOS voltage conversion circuit

Actually, this isn't that difficult. Simply specify the ping character as something that the external device can recognize and have it modify it so that the PC's software can recognize that the interface is working.

In the past, I have used a microcontroller with bit-banging software (described in the next section) to change some mark bits when it recognizes that a ping character is being received.

Figure 6-65 shows a ping character of 0x0F0 that is modified by the external device (by turning on the transistor) to change some bits into spaces. If the PC receives nothing or 0x0F0, then the external device is not working.

The last interface circuit presented here is simply a resistor (Fig. 6-66). This method of receiving data from an RS-232 device to a logic input probably seems absurdly simple and as if could not work. But it does and very well.

This interface works by relying on clamping diodes in the receiver holding the voltage at the maximum allowable for the receiver. The 10-K resistor limits any current flows and provides a voltage drop (Fig. 6-67).

Figure 6-68 is the actual circuit of the 10-K current-limiting resistor and PICmicro® MCU I/O pin with internal clamping diodes.

There are some things to watch out for when using this receive circuit in the PICmicro® MCU. Although most I/O pins are clamped internally, in some cases, you will have to add your own clamping diodes externally. These cases are when the open drain (RA4) I/O pin is used or the optional _MCLR I/O pin is used for input.

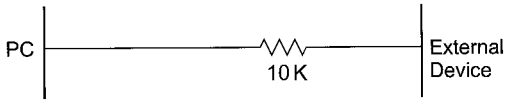
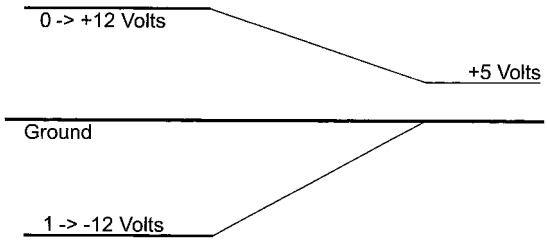


Figure 6-66 Simple RS-232 to TTL/CMOS voltage conversion



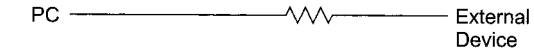


Figure 6-67 RS-232/resistor voltage conversion

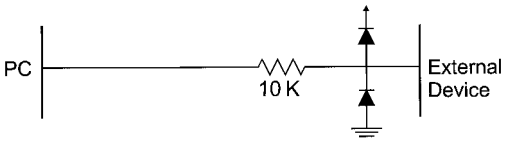


Figure 6-68 Simple RS-232 to TTL/CMOS voltage conversion with clamping diodes

There are a few rules for this implementation. Some people like to use this configuration with a 100-K resistor (or higher value) instead of the 10-K shown. Personally, I don't like to use anything higher than 10 K because of the possibilities of induced noise with a CMOS input (this is less likely with TTL) causing an incorrect bit in the stream to be read. 10 K will maximize the induced current required to change the state of the I/O pin.

With the availability of many CMOS devices requiring very minimal amounts of current to operate, you might be wondering about different options for powering your circuit. One of the most innovative that I have come across is using the PC's RS-232 ports itself as powering devices that are attached to it using the circuit shown in Fig. 6-69.

When the DTR and RTS lines are outputting a space, a positive voltage (relative to ground) is available. This voltage can be regulated and the output used to power the devices attached to the serial port (up to about 5 mA). For extra current, the Tx line can also be added into the circuit, as well with a break being sent from the PC to output a positive voltage.

The 5 mA is enough current to power the transistor/resistor type of RS-232 transmitter and a PICmicro® MCU running at 4 MHz, along with some additional hardware (such as an LCD). You will not be able to drive an LED with this circuit and you might find that some circuits that you normally use for such things as pull-ups and pull-downs will consume too much power.

Now, with this method of powering the external device, you do not have use of the handshaking lines, but the savings of not having to provide an external power supply (or battery) will outweigh the disadvantages of having to come up with a software pinging and handshaking protocol. Externally powering a device attached to the RS-232 port is ideal for input devices, such as serial mice, which do not require a lot of power.

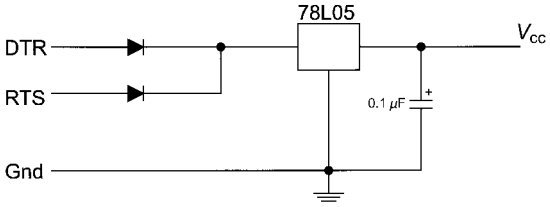


Figure 6-69 "Stealing" power from the PC's serial port

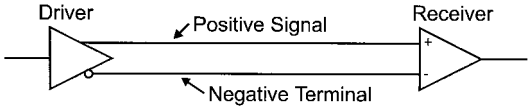


Figure 6-70 Differential pair serial data transmission

RS-485/RS-422 So far, this book has covered single-ended asynchronous serial communications methods, such as RS-232 and direct NRZ device interfaces. These interfaces work well in home and office environments, but can be unreliable in environments where power surges and electrical noise can be significant. In these environments, a double-ended or differential pair connection is optimal to ensure the most accurate communications.

A differential-pair serial communications electrical standard consists of a balanced driver with positive and negative outputs that are fed into a comparator, which outputs a *1* or a *0,* depending on whether or not the positive line is at a higher voltage than the negative. Figure 6-70 shows the normal symbols used to describe a differential pair connection.

This data-connection method has several advantages. The most obvious one is that the differential pair doubles the voltage swing sent to the receiver which increases its noise immunity. This is shown in Fig. 6-71, when the positive signal goes high and the negative voltage goes low. The change in the two receiver inputs is 10 volts, rather than the 5 volts of a single line. This is assuming that the voltage swing is 5 volts for the positive and negative terminals of the receiver. This effective doubling of the signal voltage reduces the impact that electrical interface has on the transmitted signal.

Another benefit of differential pair wiring is that if one connection breaks and there is common ground, the circuit will continue to operate (although at reduced noise reduction efficiency). This feature makes differential pairs very attractive in aircraft, and spacecraft, where loss of a connection could be catastrophic.

To minimize AC transmission-line effects, the two wires should be twisted around each other. Twisted-pair wiring can either be bought commercially or made by simply twisting two wires together. Twisted wires have a typically characteristic impedance of 300 Ohms or greater.

A common standard for differential pair communications is RS-422. This standard, which uses many commercially available chips provides:

1 Multiple receiver operation.
2 Maximum data rate of 10MBps.
3 Maximum cable length of 4000 meters (with a 100-kHz signal).

Multiple receiver operation (Fig. 6-72) allows signals to be "broadcasted" to multiple devices.

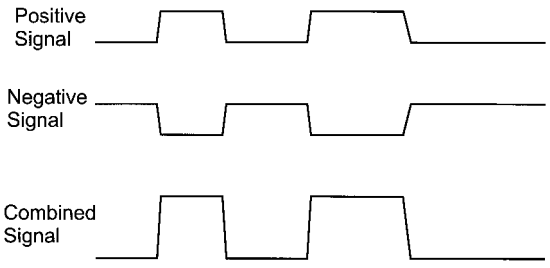


Figure 6-71 Differential data waveform

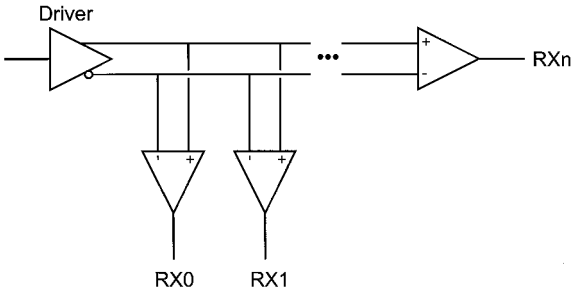


Figure 6-72 Multiple receiver RS-422

The best distance and speed changes with the number of receivers of the differential pair along with its length. The 4000 m at 100 kHz or 40 m at 10 MHz are examples of this balancing between line length and data rate. For long data lengths, a few hundred ohm terminating resistor might be required between the positive terminal and negative terminal at the end of the lines to minimize reflections coming from the receiver and affecting other receivers.

RS-422 is not as widely used as you might expect, instead, RS-485 is much more popular. RS-485 is very similar to RS-422, except that it allows multiple drivers on the same network. The common chip is the 75176, which has the ability to drive and receive on the lines (Fig. 6-73).

I have drawn the right 75176 of Fig. 6-73 with the Rx and TX and two enables tied together. This results in a two-wire differential I/O device. Normally, the 75176 s are left in RX mode (pin 2 reset), unless they are driving a signal onto the bus. When the unused 75176 s on the lines are all in receive mode, any one can "take over" the lines and transmit data.

Like RS-422, multiple 75176s (up to 32) can be on the RS-485 lines with the capability of driving or receiving. When all the devices are receiving, a high (1) is output from the 75176. This means that the behavior of the 75176 in the RS-485 (because these are multiple drivers) is similar to that of a dotted AND bus. When one driver pulls down the line, all receivers are pulled low. For the RS-485 network to be high, all unused drivers must be off or all active drivers must be transmitting a *1*. This feature of RS-485 is taken advantage in small system networks, such as CAN, which is covered later in the chapter.

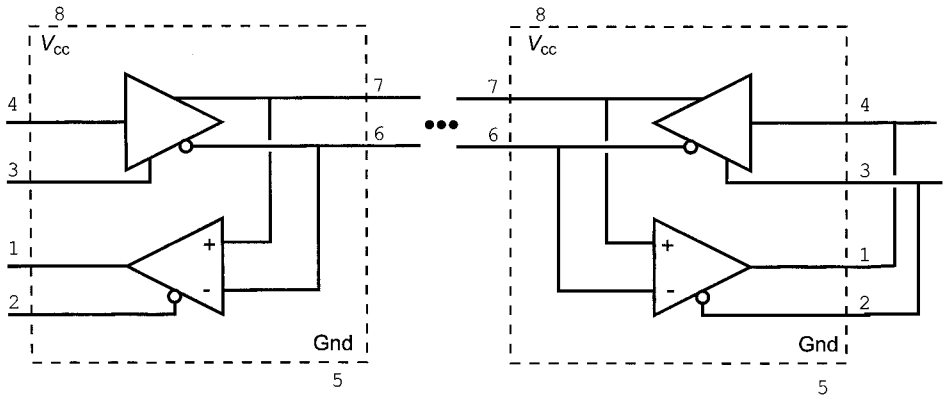


Figure 6-73 RS-485 connection using a 75176

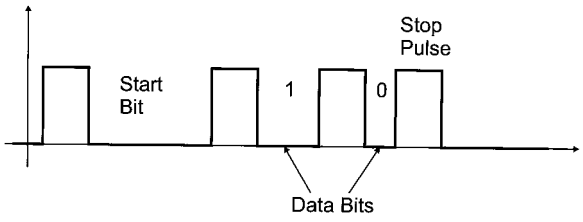


Figure 6-74 "Manchester" encoded serial data

The only issue to be on the lookout for when creating RS-485/RS-422 connections is to keep the cable polarities correct (positive to positive and negative to negative). Reversing the connectors will result in lost signals and misread transmission values.

Manchester serial data transfer Another common method of serially transmitting data asynchronously is to use the Manchester encoding format. In this type of data transfer, each bit is synchronized to a start bit and the following data bits are read with the space dependent on the value of the bit (Fig. 6-74).

In this type of data transmission, the data size is known, so the stop pulse is recognized and the space afterward is not treated as incoming data. Manchester encoding is unique in that the start bit of a packet is quantitatively different from a 1 or a 0. This allows a receiver to determine whether or not the data packet being received is actually at the start of the packet or somewhere in the middle (and should be ignored until a start bit is encountered).

Manchester encoding is well suited for situations where data is not interrupted or restarted anywhere except at the beginning. Because of this, it is the primary method of data transmission for infrared control (such as used in your TV's remote control). Chapter 16 presents two algorithms for reading a TV remote control's IR packets.

Can The *CAN (Controller Area Network)* protocol was originally developed by Bosch a number of years ago as a networking scheme that could be used to interconnect the computing systems used within automobiles. At the time, there was no single standard for linking digital devices in automobiles. Before the advent of CAN (and J1850, which is the similar North American standard) cars could contain as much as three miles of wiring, weighing 200 pounds, interconnecting the various parts and systems within the car.

CAN was designed to be:

1. Fast (1 Mbps).
2. Insensitive to electromagnetic interference.
3. Simple with few pins in connectors for mechanical reliability.
4. Devices could be added or deleted from the network easily (and during manufacturing).

Although CAN is similar to J1850 and does rely on the same first two layers of the OSI seven-layer communications model, the two standards are electrically incompatible. CAN was the first standard and is thoroughly entrenched in European and Japanese cars and is rapidly making inroads (please excuse the pun) with North American automotive manufacturers.

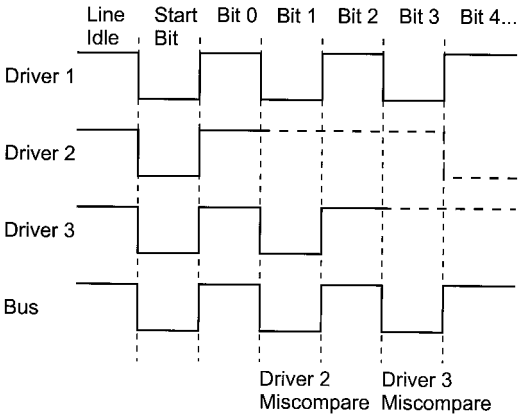


Figure 6-75 CAN transmission arbitration

CAN is built from a dotted AND bus that is similar to that used in I2C. Electrically, RS-485 drivers are used to provide a differential voltage network that will work even if one of the two conductors is shorted or disconnected (giving the network high reliability inside of the very extreme environment of the automobile). This dotted AND bus allows arbitration between different devices (when the device's "drivers" are active, the bus is pulled down, like in I2C signal). An example of how this method of arbitration works is shown in Fig. 6-75.

In this example, when a driver has a miscompare with what it is transmitting (e.g., when it is sending a *1* and a *0* shows up on the bus), then that driver stops sending data until the current message (which is known as a *frame*) has completed. This is a very simple and effective way to arbitrate multiple signals without having to retransmit all of the colliding messages over again.

The frame (Fig. 6-76) is transmitted as an asynchronous serial stream (which means that no clocking data is transmitted). Thus, both the transmitter and receiver must be working at the same speed (typically, data rates are in the range of 200 kbps to 1 Mbps).

In CAN, a *0* is known as a *dominant bit* and a *1* is known as a *recessive bit*. The different fields of the frame are defined in Table 6-8.

The last important note about CAN is that devices are not given specific names or addresses. Instead, the message is identified (using the 11- or 19-bit message identifier). This method of addressing can provide you with very flexible messaging (which is what CAN is all about).

The CAN frame is very complex, as is the checking that has to be done, both for receiving a message and transmitting a message. Although it can be done using a microcontroller and programming the functions in software, I would recommend only imple-

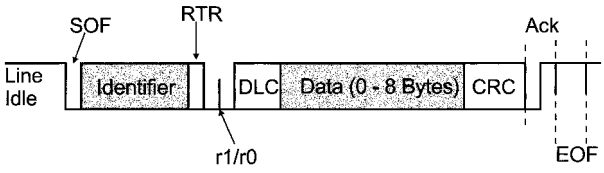


Figure 6-76 CAN 11 bit identifier frame

TABLE 6–8	CAN Frame Field Definitions
SOF	Start of Frame, A single Dominant Bit
Identifier	11 or 19 Bit Message Identifier
RTR	This Bit is set if the transmitter is also TX'ing Data
r1/r0	Reserved Bits, Should always be Dominant
DLC	Four Bits indicating the number of bytes that follow
Data	Zero to 8 Bytes of Data, Sent MSB First
CRC	15 bits pf CRC data followed by a recessive bit
Ack	Two Bit field, Dominant/ Recessive Bits
EOF	End of Frame, at least 7 Recessive Bits

menting CAN using hardware interfaces. Several microcontroller vendors provide CAN interfaces as part of the devices and quite a few different "standard" chips (the Microchip MCP2510 is a very popular device) are available to carry out CAN interface functions effectively and cheaply.

Currently, no PICmicro® MCU devices support CAN. Microchip has announced plans to create a PICmicro® MCU with CAN built in, but, as I write this, no such device is available nor are there any preliminary datasheets.

DALLAS SEMICONDUCTOR 1-WIRE INTERFACE

Dallas Semiconductor has created a line of peripherals that are very attractive for use with microcontrollers because they only require one line for transferring data. This single-wire protocol is available in a variety of devices, but the most popular are the DS1820 and DS1821 digital thermometers. These devices can be networked together on the same bus (they have a built-in serial number to allow multiple devices to operate on the same bus) and are accurate to within one degree Fahrenheit. This book demonstrates a few applications using these parts, but I wanted to first introduce you to the protocol and how the devices are used.

Probably the most substantive demonstration of what the DS1820 can do is in an application where it is connected to a PICmicro® MCU (Fig. 6-77). The DS1820 is available in

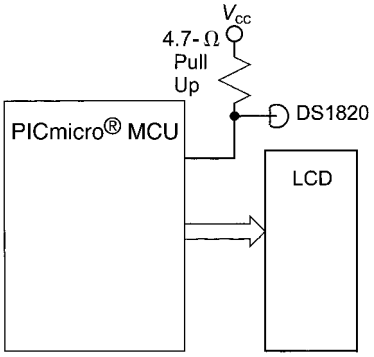


Figure 6-77 Example thermometer application

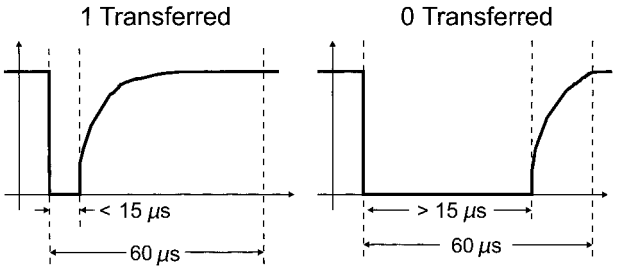


Figure 6-78 Dallas Semi. "1-Wire" data transfer

a variety of packages. The one that I use the most is a three-pin TO-92 that looks like a "tall" plastic transistor package.

The DS1820 has many features that would be useful in a variety of different applications. These include the ability of sharing the single-wire bus with other devices using a unique serial number burned into the device that allows it to be written to individually. The DS1820 has the ability to be powered by the host device. In the applications that use it in the book, I power DS1820 from V_{cc} available to the microcontroller and only have one device on the bus at a given time. I refrained from covering the single-wire bus interface in the networking section earlier in the chapter because it is specific to Dallas Semiconductor products.

Data transfers over the single-wire bus are initiated by the host system (in the application cases, this is the PICmicro® MCU) and are carried out eight bits at a time (with the least significant bit transmitted first). Each bit transfer requires at least 60 μs. The single-wire bus is pulled up externally (Fig. 6-77) and is pulled down by either the host or the peripheral device to transfer data. If the bus is pulled down for a very short interval, a *1* is being transmitted. If the bus is pulled down for more than 15 μs, then a *0* is being transmitted. The differences in the *1* and *0* bits are shown in Fig. 6-78.

All data transfers are initiated by the host system. If it is transmitting data, then it holds down the line for the specified period. If it is receiving data from the DS1820, then the host pulls down the line, releases it, and polls the line to see how long it takes for it to go back up. During data transfers, I have ensured that interrupts cannot occur (because this would affect how the data is sent or read if the interrupt takes place during the data transfer).

Before each command is set to the DS1820, a reset and presence pulse is transferred. A reset pulse consists of the host pulling down the line for 480 to 960 μs. The DS1820 replies by pulling down the line for roughly 100 μs (60 to 240 μs is the specified value). To simplify the software, I typically did not check for the presence pulse (because I knew in the application that I had the thermometer connected to the bus). In another application (where the thermometer can be disconnected), putting a check in for the presence pulse might be required.

To carry out a temperature read of a single DS1820 connected to a microcontroller, you can use the following instruction sequence:

1. Send a reset pulse and delay while the presence pulse is returned.
2. Send 0x0CC, which is the skip ROM command, which tells the DS1820 to assume that the next command is directed toward it.
3. Send 0x044, which is the *temperature conversion initiate* instruction. The current temperature will be sampled and stored for later read back.

4. Wait 500+ μs for the temperature conversion to complete.
5. Send a reset pulse and delay while the Presence pulse is returned.
6. Send 0x0CC, skip ROM command again.
7. Send 0x0BE to read the Scratchpad RAM, which contains the current temperature (in degrees Celsius times two).
8. Read the nine bytes of scratchpad RAM.
9. Display the temperature (if bit 0 of the second byte is returned from the Scratchpad RAM is set, the first byte is negated and a – is put on the LCD Display) by dividing the first byte by 2 and sending the converted value to the LCD.

The total procedure for doing a temperature measurement takes about 5 ms. A good (and simple) test of whether or not the thermometer is working is to pinch it between your fingers and see if the returned temperature value goes upward as the application is executing.

When I have implemented PICmicro® MCU code for accessing the DS1820, I have had problems ensuring that my timing delays are correct. When sending data to the DS1820, be sure that a *1* has a delay of about 10 μs and a *0* has a delay of 45 μs. This will ensure that the data the DS1820 reads is not ambiguous and doesn't have any problems with differentiating the data sent to it.