2
CHAPTER

Introduction to Electronics

Before working through all the different circuits that are used in the TAB *Electronics Build Your Own Robot Kit*, I want to go through some of the basic electronic devices and describe their characteristics and things to watch for. I am going to focus on the practical aspects of the devices rather than the theory behind them and how they are manufactured.

A *resistor* is a device that impedes current flow through a circuit. Its symbol is shown in Figure 2-1.

Resistors are not polarized, and you should have a pretty good idea of how they work from the previous sections. The only point I would like to add about them is their power rating.

Occasionally when you place a resistor in a circuit you will find that it gets very hot. This is caused by more power being dissipated than is specified for the resistor. Resistors are normally rated at $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$, 1 watt and larger with the rating dependent on the power through it as determined by the formula

$$P = I \times V$$

Substituting in Ohm's law we get:

$$P = (V ** 2) / R$$
$$= (I ** 2) \times R$$

For most applications, a $\frac{1}{4}$-watt resistor will be more than adequate, but occasionally, you will have unusual situations. For example, if the maximum current through the resistor is 40 mA, the power dissipated by the resistor is greater than $\frac{1}{4}$ watt.

$$P = (I ** 2) \times R$$
$$= 0.040 \times 0.040 \times 220$$
$$= 0.35 \text{ watts}$$

For this reason, in this circuit I have specified a $\frac{1}{2}$-watt-rated resistor rather than a normal $\frac{1}{4}$-watt resistor in this example circuit.
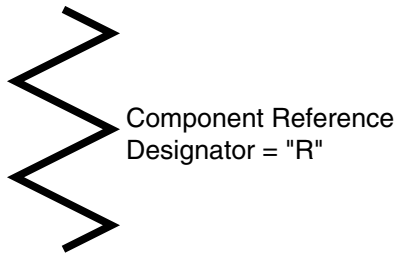
Component Reference
Designator = "R"

Figure 2-1   Resistor symbol.

Resistors normally have a series of four or five color bands printed on them. These bands are used to specify the resistance of the circuit as determined by the formula

Resistance = ((Band1 × 100) + (Band2 × 10) + (Optional Band3 × 1)) ×
(10 ** Exponent Band)

The following table lists the values for each band and their meanings in the resistor specification formula

Number	Color	Band1	Band2	Opt'l Band3	Exponent Band	Tolerance band
0	Black	N/A	0	0	10 ** 0	N/A
1	Brown	1	1	1	10 ** 1	1% tolerance
2	Red	2	2	2	10 ** 2	2% tolerance
3	Orange	3	3	3	10 ** 3	N/A
4	Yellow	4	4	4	10 ** 4	N/A
5	Green	5	5	5	10 ** 5	0.5% tolerance
6	Blue	6	6	6	10 ** 6	0.25% tolerance
7	Violet	7	7	7	10 ** 7	0.1% tolerance
8	Gray	8	8	8	10 ** 8	0.05% tolerance
9	White	9	9	9	10 ** 9	N/A
N/A	Gold	N/A	N/A	N/A	10 ** -1	5% tolerance
N/A	Silver	N/A	N/A	N/A	10 ** -2	10% tolerance

For a 220-ohm, 5% tolerance resistor, the bands would have the following colors: Red, Red, Brown, and Gold.

Remembering what the color codes are is made easier by noting that the colors are in the order of the colors of the rainbow. For all practical purposes, nobody today reads the bands and tries to figure out what the resistance is; instead the ohmmeter function of a digital multimeter is used to read the resistance value. This process is usually faster and definitely more accurate in determining the actual resistance value.

"Variable resistors" or "potentiometers" are used to change the resistance of a circuit or to provide a user selected voltage. A variable resistor symbol is shown in Figure 2-2.

I typically use very large value potentiometers (normally 10K) so the issues surrounding power dissipated by potentiometers in my circuits are not as significant as what they are with simple resistors. Most PCB-mount potentiometers can
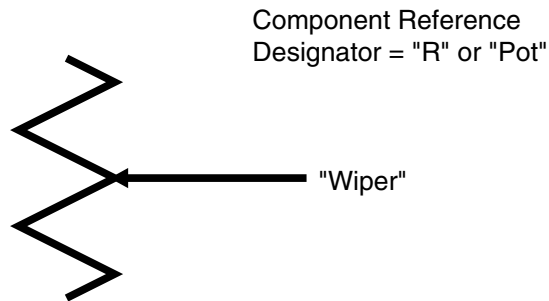
Component Reference
Designator = "R" or "Pot"

"Wiper"

Figure 2-2   Potentiometer/variable resistor symbol.

dissipate up to $\frac{1}{4}$ watt or so of power. Potentiometers that can handle much larger amounts of current are also available, but these devices tend to be expensive and difficult to work with. If I have a circuit where I want to control a DC device with varying power levels, I typically use a "pulse-width-modulated" control rather than a Potentiometer.

I am generally concerned only with two types of switches. Push buttons, normally referred to as "momentary on" or "momentary off" switches and their symbols (i.e., operation), are shown in Figure 2-3. Momentary on switches close the circuit when they are pressed and open the circuit when they are released. Momentary off switches work in the opposite manner with the circuit opened when the button is pushed.

"Slide" switches are used to make a specific contact based on the position the switch is left in. The most basic switch has one or two "throws" that result in a closed circuit. In Figure 2-4, single and double throw switches are shown.

There can be more than one "throw" or position in the switch, and multiple switches can be ganged together as multipole switches. There are many different combinations that can be built from these basic types of switches.

The most useful slide switch you will work with is the single-pole, single-throw (known as SPST) for turning on and off power or controlling basic signals. The symbol for the SPST is shown in Figure 2-5.

When you look for slide switches, you will find that most of them are single pole/double throw (SPDT) where just the "common" connection and one switched on are used.

You will have to wire multiple boards together and this is accomplished by using "connectors." There seem to be an infinite variety of different connectors available. In many cases, application developers select the connectors they feel most comfortable with. For this reason I have not specified the type of connector to be used.

The connector symbol is "J."

Fuses can be used within your application to limit current draw and to protect circuits, wiring, and power supplies. Like home fuses, electronic ones are rated in amps and are available in a variety of different board-mountable or in-line packages and "cartridges." The symbol is shown in Figure 2-6.

Fuses are not rated in volts. For a good practical joke, ask somebody to go out and buy you a "six-volt, half-amp" fuse, and tell them not to come back until they have it. If somebody asks you to go out for a six-volt, half-amp fuse, take their money, buy yourself a good dinner, return hours later and say that all the stores you went to were sold out.
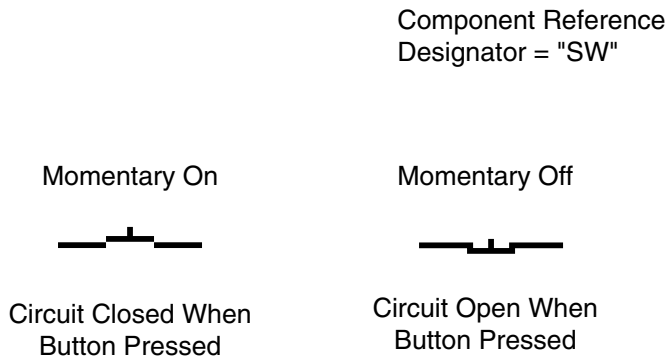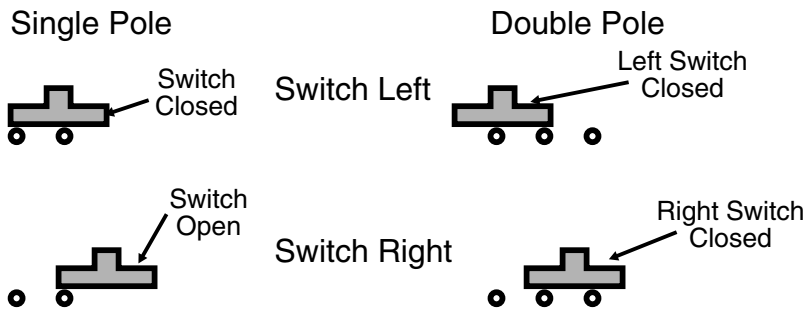
Component Reference
Designator = "SW"

Momentary On

Momentary Off

Circuit Closed When
Button Pressed

Circuit Open When
Button Pressed

Figure 2-3 Momentary switch symbols.

Single Pole

Double Pole

Switch
Closed

Switch Left

Left Switch
Closed

Switch
Open

Switch Right

Right Switch
Closed

Figure 2-4 "Throw" switch types.

Component Reference
Designator = "SW"

SPST Switch
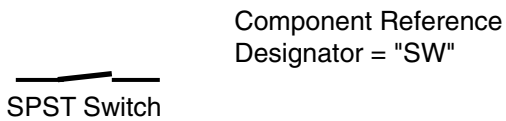
Figure 2-5 Single-pole single-throw switch.

Component Reference
Designator = "F"
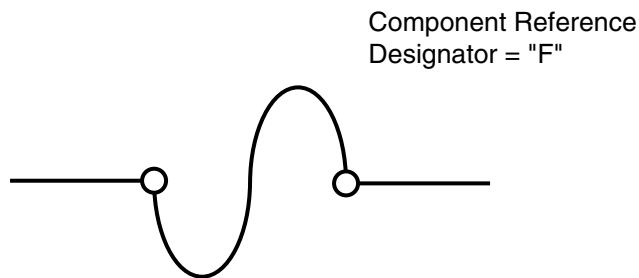
Figure 2-6 Fuse symbol.

In my own applications I prefer to avoid specifying fuses except when absolutely necessary. Instead, I prefer to use voltage regulators that shut down rather than burn out when too much current is drawn through them. This does not eliminate the need for fuses in situations where they are indicated for safety or regulatory reasons, but it does mean that they are not required in experimental applications.

Capacitors are designed for storing electrical charge. Common capacitor symbols are shown in Figure 2-7.

The charge placed in a capacitor is measured in farads (symbol "F") and is measured in the units of coulombs/volt. A "coulomb" is a measure of $1.6 \times 10 ** 19$ electrons, making one farad a very large number. This very large number is why most capacitors are measured in millionths ("μF") or trillionths ("pF") of a farad.

Capacitors consist of two metal plates (which explains the symbols shown in Figure 2-7) separated by a "dielectric." A dielectric is a material that doesn't conduct electricity. The type of dielectric used in a capacitor usually dictates their name. The most common types of capacitors are

1. Ceramic disk
2. Polyester
3. Tantalum
4. Electrolytic

Ceramic disk and polyester are the most "benign" type of capacitors you can work with. They are typically used for applications requiring small capacitance values at reasonably high frequencies. The reason for this is that these two dielectrics do not enhance the capacitance of the two plates as significantly as tantalum and electrolytic, and large capacitances (such as microfarads) would be measured in inches across and would probably weigh up to a pound. Ceramic and polyester capacitors tend also to be the least expensive of the capacitors you can buy.

Tantalum capacitors are a relatively new invention and offer excellent capacitive densities at high frequencies. Tantalum capacitors are well suited for use as
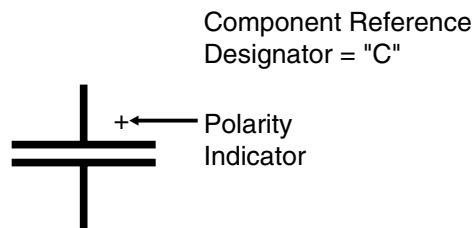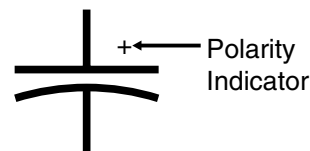

Figure 2-7   Capacitor symbol.

"decoupling" capacitors and I usually have a drawer full of 0.1 μF, 16-volt tantalum capacitors available at all times.

Tantalum capacitors do not have a good reputation with many people because of the tendency of early versions to explode because of "pin hole" shorts between the plates in the capacitor. These shorts would heat up, burn away the dielectric, and grow larger in surface area until there was a catastrophic failure. This problem is accelerated by reverse biasing the capacitor. Therefore, always make sure the side marked "+" is connected to V_{cc}.

New tantalum capacitors do not have this problem if they are properly "derated." All tantalum (and electrolytic) capacitors are given an operating voltage (for which they are designed). By derating the input voltage specification you are actually selecting devices with thicker dielectrics, which reduces significantly the likelihood of "burn through."

A good rule of thumb is to derate tantalum capacitors by 60%. This means that a tantalum cap used as a decoupling cap in a 5-volt system should be rated at 12.5 volts or more. This is why I normally use 16-volt-rated parts.

Electrolytic capacitors rely on a chemical liquid for the dielectric and are sealed in metal packages. The plates and the chemical are designed to be biased in one way to reach the desired capacitance. Reverse biasing on an electrolytic capacitor will cause the liquid to break down and the capacitor will catastrophically fail. While not as spectacular as a tantalum capacitor's explosion, you could be hit by debris or sprayed by hot electrolytic. At the very least, you will have to clean the residue formed on the circuit board.

The electrolytic capacitor's big advantage is its dense capacitance in an inexpensive package. They do not have very fast responses and are not well suited to be used for decoupling and other high-speed filtering applications.

Some capacitors have been given a set of colored bands similar to the markings used on resistors.

Another way that smaller capacitors are marked is with a three-number system. This method is similar to that used by resistors. The first two digits are the exponent multiplier while the third digit is an exponent multiplier. What makes this method of marking a bit confusing is that the base unit is picofarads. For example a capacitor marked with "103" has a value of

$$10 * (10 ** 3)\ \text{pF}$$
$$= 10{,}000\ \text{pF}$$
$$= 0.01\ \mu\text{F}$$

I recommend that you either buy capacitors with their values printed on them or segregate the parts in different marked bags or bins until you need them. Many modern digital multimeters have the capability of reading capacitor values down to 30 pF or less, which can be useful in figuring out what that old bag of parts you have contains.

Whereas a capacitor stores energy in the form of a charge, inductors (or "coils") store energy in the form of a magnetic field. Inductors, shown in Figure 2-8, are not often used in digital electronics except for "switch mode power supplies," which increase or decrease incoming power using the characteristics of coils to resist changes in current flow. Like the capacitor's "farad" unit of measurement, the normal

values of an inductor are in millionths of a "henry" for the devices to be effective in a circuit.

Inductors can be difficult to work with if you are new to electronics. I would recommend that they not be used unless specified by a chip manufacturer for a particular application.

Modern application switching is accomplished by "semiconductors." Semiconductors are so named because their conductivity can be controlled in different situations. The most basic of these circuits is the diode (Figure 2-9), which will only pass current in one direction.

Diodes are also known as "rectifiers" because they can be used to convert AC voltages into DC, (which will be discussed later in the appendix). This is accomplished by manufacturing the device out of a piece of silicon that has been chemically impregnated ("doped") with two different materials. These materials create an interface in which the energy of electrons is much higher in one material than in the other. This interface is known as the "PN junction."

To cross the boundary, electrons can only flow from the high potential (*N*-doped) side to the low potential (*P*-doped) side. If electrons enter the device from the *P* side, they cannot climb the "wall" to the *N*-doped side, thus limiting current to only flowing in one direction. This is shown in Figure 2-10.

The electron potential drop results in some voltage drop in the applied current. For silicon diodes, this drop is 0.7 volts; I often use this function of PN junctions (and diodes in general) to create simple voltage references for power supplies.

When electrons fall down from the high-potential side to the low-potential side, they release energy. This energy release, according to Professor Einstein, is a set
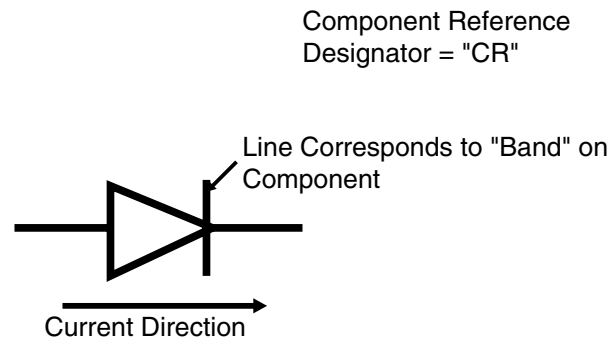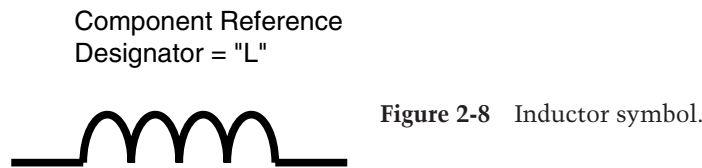
Component Reference
Designator = "L"

Figure 2-8 Inductor symbol.

Component Reference
Designator = "CR"

Line Corresponds to "Band" on
Component

Current Direction
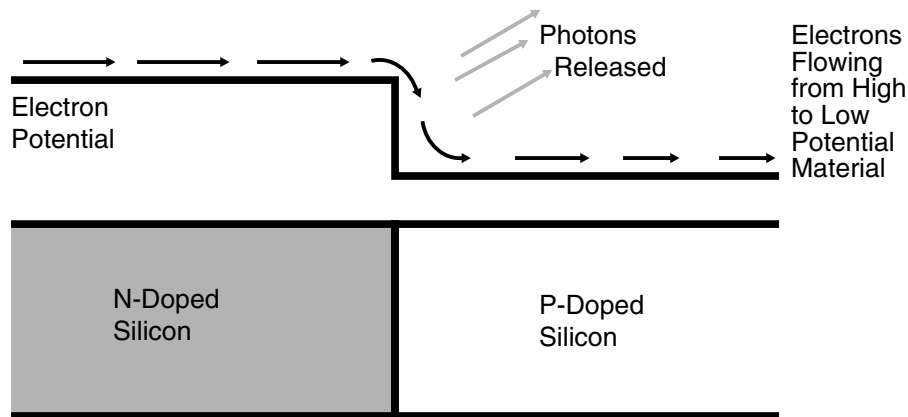
Figure 2-9 Diode symbol.

Figure 2-10   Diode operation.

amount and is released from the diode as a "quanta" of energy and takes the form of a "photon."

In Figure 2-10 the release of photons is shown as the electrons go from a higher energy state to a lower one. Standard silicon diodes release photons in the "far" infrared spectrum of light, but by changing the diode materials the photons released can be in a visible frequency of light. These diodes are known as "light-emitting" diodes (LEDs) and come in a variety of colors. An important difference between LEDs and standard silicon diodes is that the voltage drop is always greater than 0.7 volts.
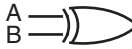
Digital Electronics

Digital electronics consists of passing a signal, which is either a "1" or a "0," depending on its voltage level, between circuits and processing them. This processing is a branch of mathematics known as *Boolean mathematics*, named after George Boole, a nineteenth-century mathematician who was looking for a way to express symbolic logic mathematically.

In boolean mathematics (which is also known as *boolean arithmetic*, *boolean logic*, or just *logic*), there are four primary operations that can be carried out. Each operation can be used to test and/or modify a digital value based on its and other values. Digital values can be represented as "1" or "True," and/or "0" or "False."

They are listed in the following table:

Operation	Electronic symbol	Description and "State Table"
NOT ("!")	A ———▷o— Output	Invert the input Signal.

Input	Output
0	1
1	0

Operation	Electronic symbol	Description and "State Table"
NOT ("!")		**Invert the input Signal.**

AND ("*")

Return "true" if both inputs are "true".

A	B	Output
0	0	0
0	1	0
1	0	0
1	1	1

OR ("+")

Return "true" if either input is "true."

A	B	Output
0	0	0
0	1	1
1	0	1
1	1	1

XOR ("^")

Return "true" if only one input is "true."

A	B	Output
0	0	0
0	1	1
1	0	1
1	1	0

These functions are available as discrete functions in a chip or combined to provide complex functions in a chip.

The logic type that is most commonly used in simple circuits is known as "TTL," which stands for "transistor-to-transistor logic." As the name would imply, TTL gates are designed as transistor "drivers," which pass the boolean logic levels to transistor "receivers." There are a number of different types of TTL logic available, each with slightly different input "threshold" and output voltages.

When you look at a catalog of TTL chips, you will find that there is a bewildering array of different chip "families" available, each starting with "74" followed by a letter code and a number. The letter code denotes the family the chip belongs to. The letter code (which may not be present, or is "S," "LS," "HC," "HCT," "AL," or "ALS") is used to denote the type of circuit and driver. Each of these families works slightly differently and each works at different speeds. They also require different amounts of current to operate.

The term "threshold" is used to specify the voltage in which an electrical signal is determined to be a "1" or "0." For "positive" logic (which TTL is), a "1" is a high voltage, while a "0" is low voltage. The term "threshold" is a bit of a misnomer because TTL digital devices are *current* driven and not voltage-driven. The correct way to explain the term "threshold" is to note that when the gate input is held at this voltage and current is allowed to flow, it will change state.

There are two types of logic circuits in common use today. "Bipolar" ("straight" TTL) uses NPN and PNP bipolar transistors for operation while "CMOS" uses *N*-Channel ("NMOS") and *P*-Channel ("PMOS") MOSFET for the logic functions. These different transistor types reflect on the speed and drive characteristics of the different families.

This difference can be seen in the "Input" circuits shown in Figure 2-11. The "bipolar" input provides a current control to the inverting amplifier's output that is passed to other gates within the chip. The "CMOS" input drives a PMOS/NMOS inverter.

Note that the "bipolar" input is internally "pulled up" while the CMOS input is not. As a rule, I will put pull-ups on the inputs of all unused circuits and not depend on any built-in pull-up circuits when adding buttons and other circuits. This is a good approach to take when you design digital circuits, since the actual circuit may or may not have an internal pull up depending on the part that is chosen. By always placing a pull-up on an input that isn't actively driven, you will avoid any issues in which a "floating" input (which has an undefined value) is encountered.

There are two types of digital output circuits as shown in Figure 2-12. The "totem pole" output provides a push-pull driver for the circuit and can both "sink" (pull down to ground) and "source" (provide from the power supply) power to the "load" (or "receiver") that it is going to drive. This circuit can be provided in either bipolar or CMOS logic.

The second type of output in Figure 2-12 is known as "open collector" because the collector of the output transistor that pulls to ground is "floating" or "open" to being externally pulled up. This CMOS equivalent is known as an "open drain" driver. This output must have a pull up when driving loads that don't have their own inter-
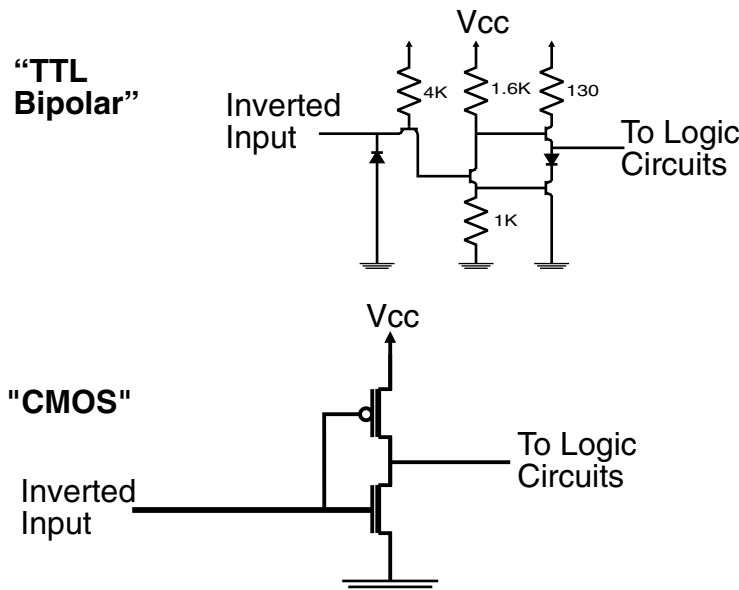

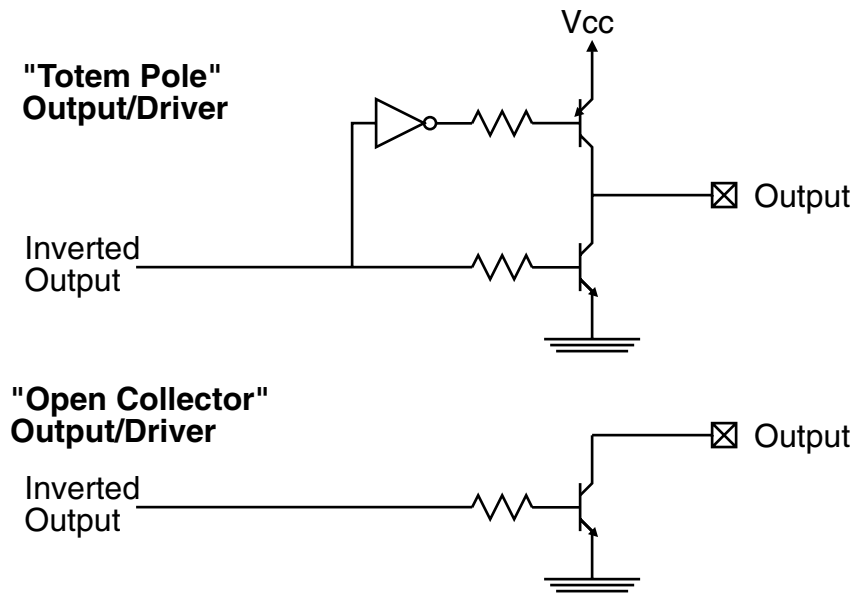**Figure 2-11**   Digital input circuits.

Figure 2-12   Digital output cicuits.

nal pull ups, and is best suited for special situations where the ability to pull down a line is required.

One of the most common of these situations is the "dotted And" bus (shown in Figure 2-13), in which multiple open-collector drivers can be tied together to provide a single logic function. This logic function is low unless every input to it is "high." Since this function simulates the "AND" logic function, and in many design systems, a "dot" would be placed on each output to show that they are connected together, this circuit is known as a "dotted And."

Breadboards

Probably the easiest way to create test applications is to use a "breadboard." This product consists of spring loaded "holes" that grip a component and provide connections to other holes so that circuits can be built out of connected components. When working with the *TAB Electronics Build Your Own Robot Kit*, you can use the Parallax "Bread Board" AppMod adapter for adding your own circuits to the robot. This feature (Figure 2-14) will be used in a project presented in the last chapter.

The breadboard consists of two sets of connected pins for "dip" chip packages. Each row of pins along with two "columns" across the top and bottom are interconnected as is shown in Figure 2-15.

To make power distribution easier, most breadboards are shipped with "bus bars" across the top and bottom. These rails connect using plastic tabs and receptacles and "lock" the parts together. Multiple rails and breadboards can be connected together to create different size prototype assembly areas.
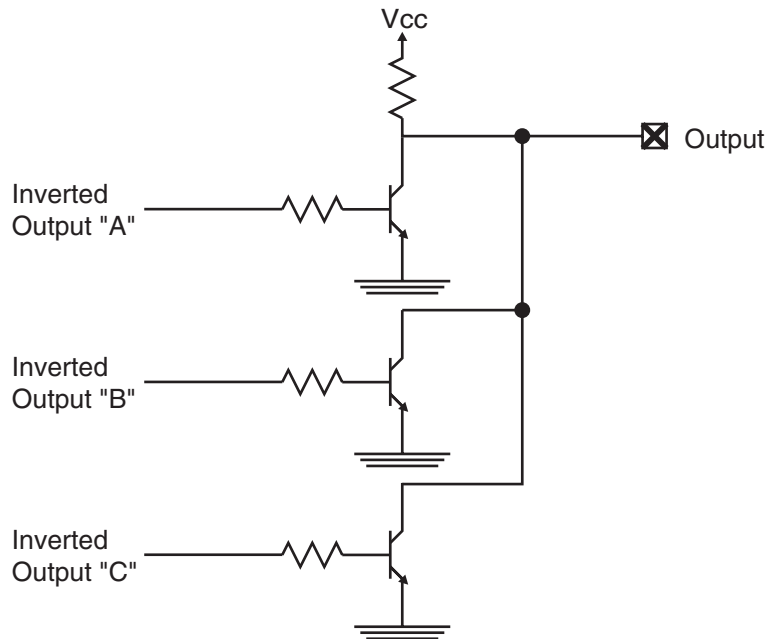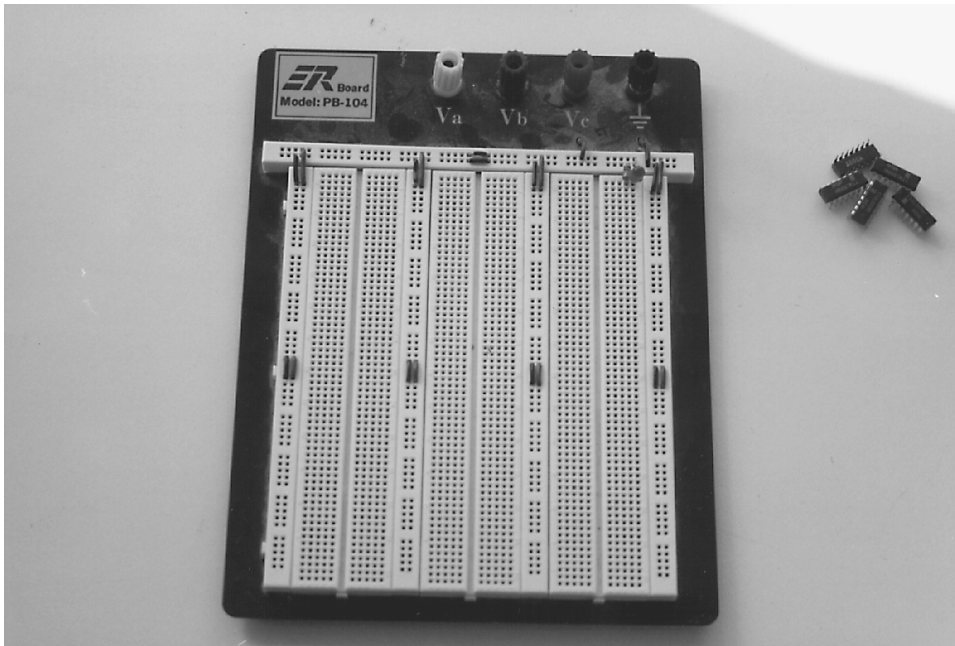
Figure 2-13 "Dotted And" digital circuits.

Figure 2-14 Commercial breadboard.

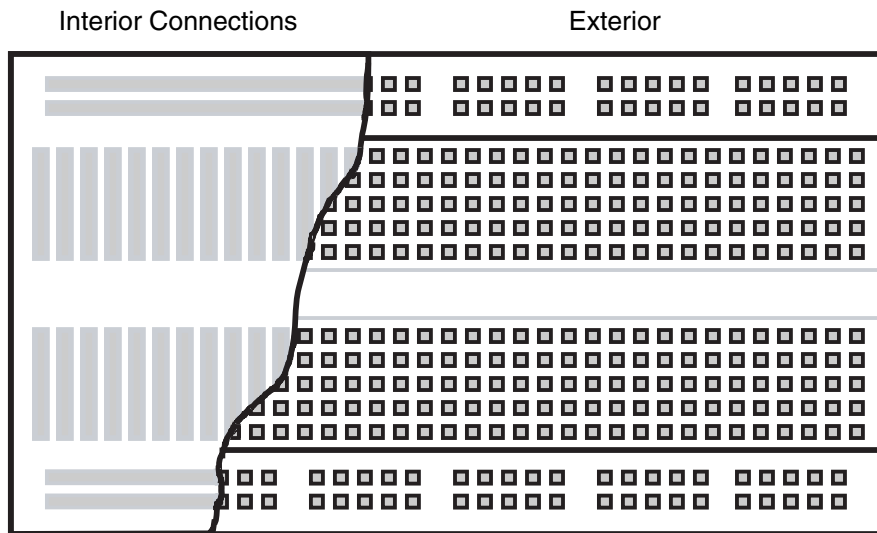Interior Connections   Exterior

Figure 2-15 "Breadboard" with interior connections shown.

The rails are available with one or two "common strips." I usually use the ones with two rows and place "V_{cc}" and "Gnd" on both sides of the breadboard. These rails may be marked with red and black (or blue) stripes to indicate that the pins are common across them. Figure 2-16 shows how this is done.

Digital Multimeters

The output of a digital multimeter (Figure 2-17) is a three- or four-digit numerical display. In many devices, the measurement is selected using a switch on the DMM, and the display's decimal point moves over it. If the value is too large for the display, something like an "I" in the left most digit will be displayed with the other digits blanked out. The table below lists what would be shown on a four-digit display for different resistor measurements:

Resistance	Range	Output	Comments
220 ohm	200	1	Value too large for display
220 ohm	2k	0.220	220 ohm = 0.22k
220 ohm	20k	0.022	

Note that the ranges start at "2," rather than "1," as you would probably expect. This is a common convention left over from when displays were more expensive and the single digit "1" added extra flexibility for minimal cost.

Some digital multimeters have up to six digits, but I must stress that as you work with the digital multimeters for your digital electronics projects, never use more than three digits. The extra accuracy is not needed, and it adds a lot to the cost of the device.

Each digit represents a power of 10. For a three digit display, the value is accurate to one part in a thousand. Accuracy greater than one part per thousand is only
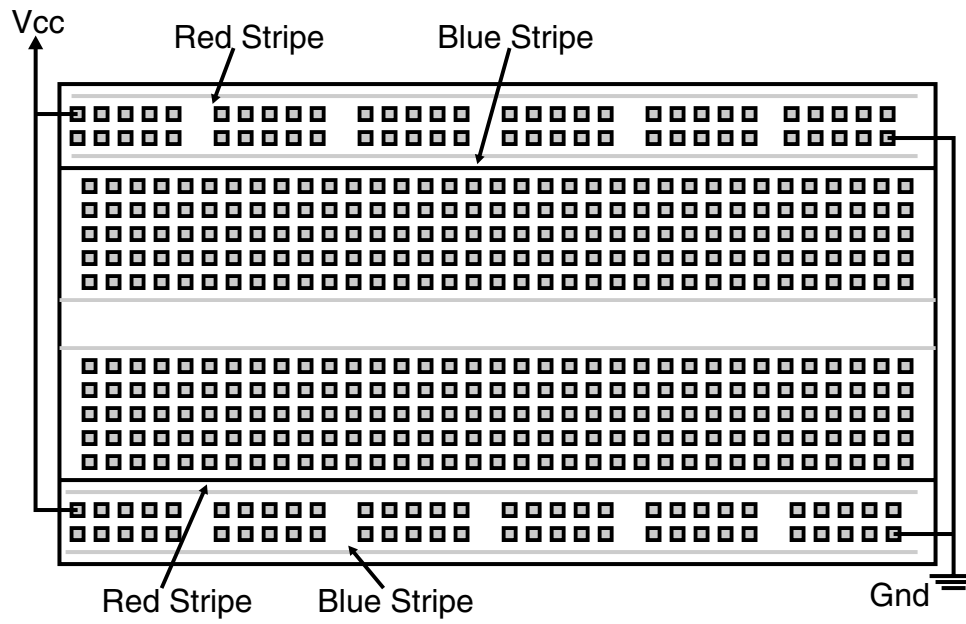
Figure 2-16 Breadboard power connection.

Figure 2-17 Digital multimeter (DMM).

required in very specialized cases. When this level of accuracy is required, precision power supplies, crystals, and components would be used alone with a specially calibrated digital multimeter. It may be interesting to see differences between devices at ten millionths of a volt, but this accuracy is not practical for any hobby circuits that I can think of.

Digital multimeters are not "fast response" devices. You may find that it can take as long as 10 sec before the display stabilizes on a value. This time to stabilize means that the digital multimeter is not capable of measuring changing digital signals unless the signal changes once every few seconds.

Along with the ability to measure current, voltage, and resistors, digital multimeters are available with the following features and capabilities:

1. Perform "autoranging" while measuring a parameter
2. Measure capacitance
3. Measure temperature
4. Measure a bipolar transistor's "beta"
5. Perform diode polarity checks
6. Measure frequency

These features are nice to have but not critical for the projects presented for the robot. If you don't currently have a digital multimeter but do have an analog meter, I highly recommend that you scrap the analog meter and buy yourself a digital multimeter to better understand what is happening in your circuit.

Logic Probes

Along with a digital multimeter, I consider a "logic probe" to be a basic tool for anyone developing digital circuits (Figure 2-18). A logic probe is a pencillike device that can be used to check different parts of a board and return a visual/audio signal that indicates whether or not a signal is logic "high," "low," or "tri-stated," or not connected to a driver or a pulled-up or pulled-down input.

There are usually two controls on a logic probe. The "pulse/continuous" switch will cause an LED to flash when a changing signal is encountered, or a single LED to light for a continuous level. Along with an LED, many logic probes have a speaker in them that will provide beeps and tones so you can tell what is going on without looking at the LEDs.

The speaker audio output is a feature I highly recommend getting.

The other switch is "TTL/CMOS" and selects which voltage threshold should be used. Normally "TTL" is 1.4 volts and "CMOS" is 2.5 volts.

Good quality logic probes can be bought for as little as $20 and I recommend you buy one rather than try to build one yourself. You may think you could build one yourself with a resistor and LED like the circuit shown in Figure 2-19.

But the actual circuit of a logic probe looks more like the one in Figure 2-20.

You could probably build the circuit in Figure 2-20 fairly easily, although you may encounter some problems getting the circuit to fit into a small enough package to be useful. Moreover, it would probably cost just as much in parts as a brand new unit.
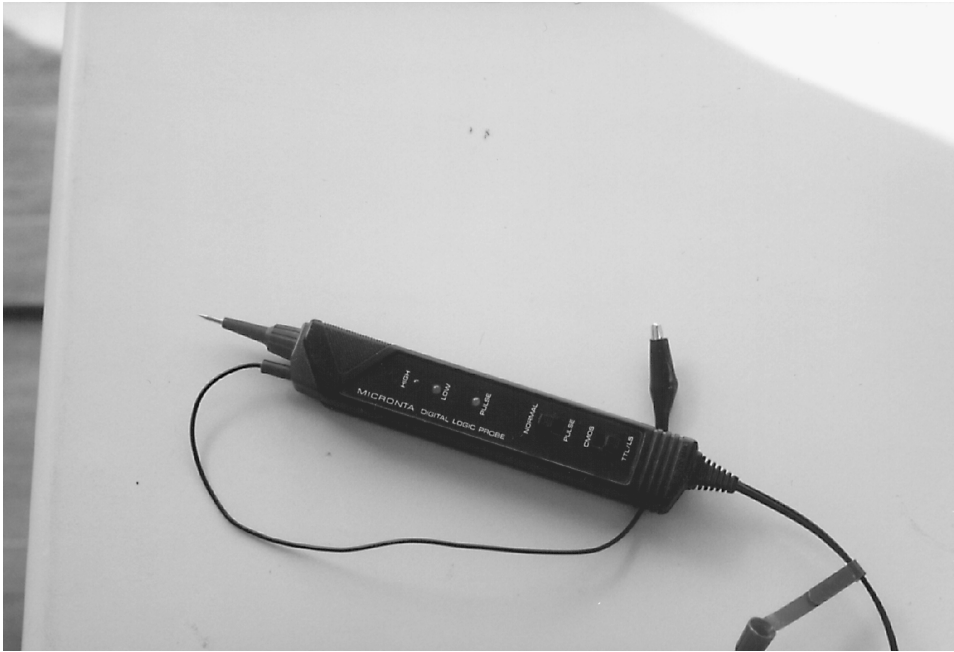
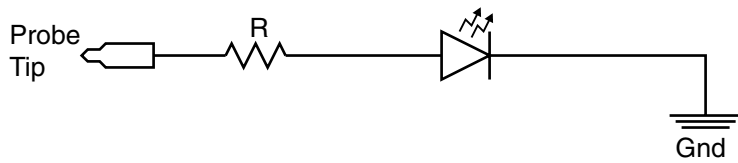**Figure 2-18** Radio Shack logic probe.
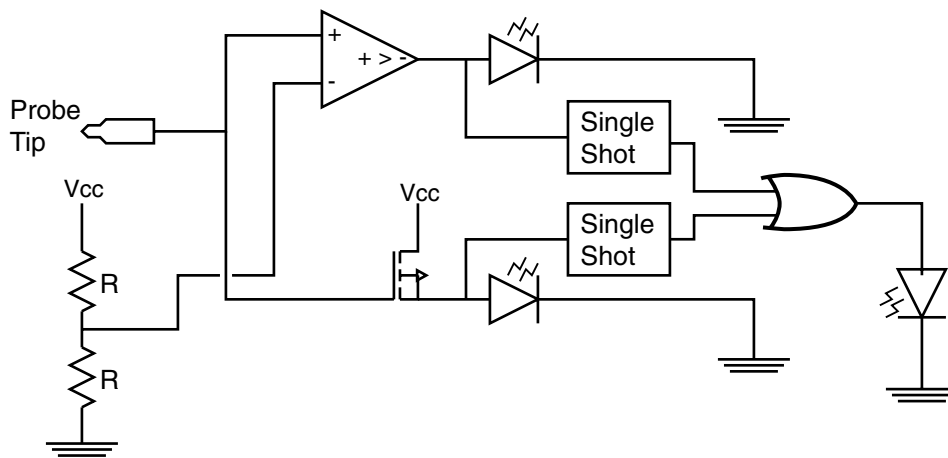

Figure 2-19 Basic logic probe.

Figure 2-20 Complete high/low sensing logic probe.

For these reasons, I recommend that you avoid the headaches of building one and just buy one ready made. The Radio Shack logic probe (part number 22-303) contains all the features I've listed here and is quite inexpensive (about $20). I've owned three of these over the years, and they are as good or better than other logic probes that cost twice as much or more.