How to Work with Light-Emitting Diodes

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Objectives:

Understand the need to limit current through light-emitting diodes.

Understand how to use transistors to switch LEDs on or off.

Understand how to multiplex LEDs and displays to conserve output pins.

An incandescent light bulb uses a filament made of tungsten to produce light. Passing electricity through the filament heats the tungsten that then radiate visible light and heat. The amount of light this type of bulb produces depends on the voltage applied to it. If you take a small 6-volt light bulb and apply six volts to it, you get a certain amount of light. As you reduce the voltage, the bulb produces less and less light.

If you place two of the 6-V bulbs in series so the electricity from a 6-V direct-current (DC) power source passes through one filament and then the other before it returns to the power supply (**Figure 1**), the two bulbs glow with about the same brightness but less bright than one bulb alone powered by six volts.

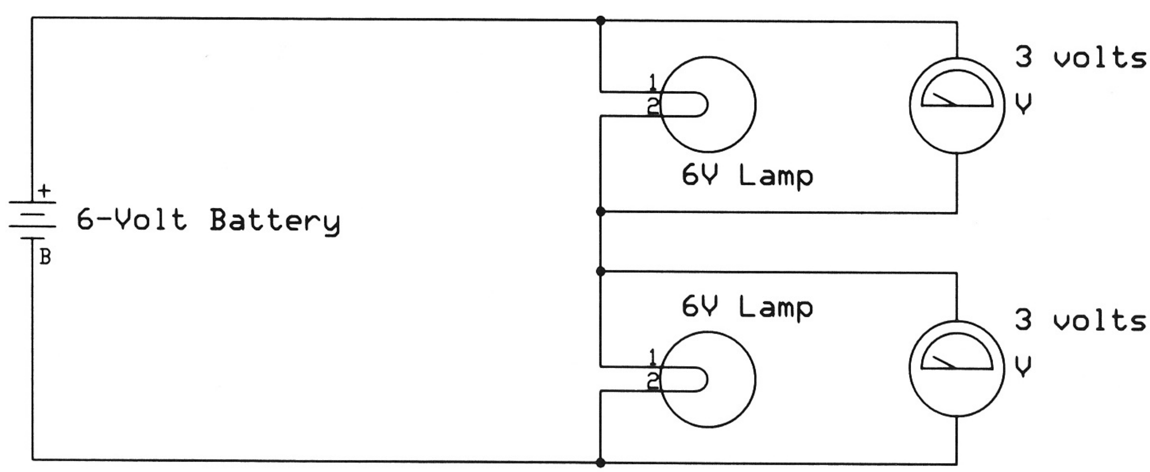

Figure 1. In the circuit above, the 6-volt bulbs "split" the voltage, so the two voltmeters measure only three volts "across" each bulb and the bulbs glow dimly. No two bulbs are exactly alike, so you might measure slightly more or less than three volts in a similar circuit.

LEDs Rely on Current

Light-emitting diodes, or LEDs, rely on current rather than voltage. When electrons flow through the semiconductor materials used to create LEDs they release photons with a specific color spectrum. Manufacturers produce red, green, blue, orange, and yellow LEDs used in products from traffic signals to washing machines to telephones. The *current* that passes through an LED determines the amount of light it produces. **Figure 2** shows the symbol engineers and others use to represent an LED on a schematic diagram. This representation combines the symbol for a semiconductor diode with several arrows that indicate light.

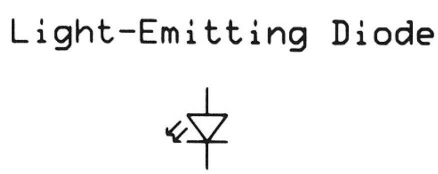

Figure 2. This symbol represents an LED in circuit diagrams. It might have the general part designation D1, D2, and so on in a circuit diagram.

If you connect, say, a 6-V power power supply directly to an LED, you will likely burn it out or at least change its characteristics. A typical LED has a low resistance and thus will draw a high current. When I powered a green LED directly with a 6-V power supply, it produced bright green light briefly and the color then changed to a deep orange, the LED's molded plastic case got hot, and the LED semiconductor element turned red, perhaps acting more like a hot filament than a semiconductor.

In practical circuits, an LED requires some sort of limit on the current it draws from a power supply, and usually a small-value resistor does the job, as shown in **Figure 3**.

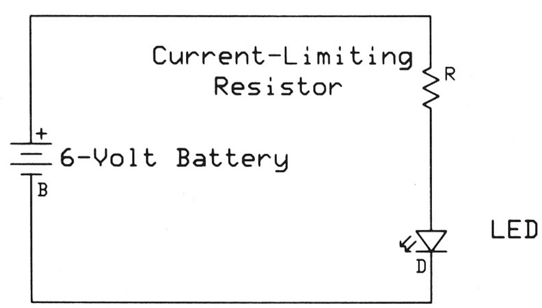

Figure 3. Almost all LEDs require a current-limiting resistor in series. Without a limit on the current through an LED, it could burn out. Special LEDs can include a current-limit circuit or even a flasher circuit.

Determine a Resistance Value

But how can you determine the proper amount of current for a given LED? Manufacturers provide data sheets for the LEDs they produce so equipment designers and electrical engineers can determine the proper current level for a given LED. You can find data sheets on company Web sites.

The data sheet for the Avago Technologies HLMP-ELxx family of LEDs specifies a current of 20 milliamperes, or 20 mA as a test condition, with a 30 mA average current in actual use. Now that you have the current value--we'll use 30 mA--you need one more quantity before you can use Ohm's Law to calculate the proper resistance value.

Remember in the case of the two incandescent bulbs connected in series, the bulbs acted like a voltage divider and so each bulb had about three volts applied to it. The same thing happens when you place an LED and a resistor in series. But, because the LED contains a semiconductor diode, the voltage across it remains the same as long as the power supply provides a voltage greater than this "diode voltage drop." In the Avago HLMP-ELxx LED family, the data sheet shows a forward voltage drop of 2.4V. (That value is consistent for most LEDs.)

Thus if you use a 6-volt power supply, you would measure 2.4 volts across the LED, and 3.6 volts across the resistor. Now you can use Ohm's Law (I = E/R) to determine the resistance value you need to limit the current to 30 mA. Remember you can write 30 mA as 0.030 A. Ohm's Law uses units of amperes (A), volts (V), and ohms (R). When you use Ohm's Law, you must use those units and not milliamps, microvolts, and so on. Engineers use the letter I to represent current and E to represent voltage in equations.

By using algebra, you can rearrange Ohm's Law from I = E / R to R = E / I. Now you can substitute the the voltage across the resistor ($V_{power} - V_{LED}$) for E and the required current through the LED (I_{LED}) in the Ohm's Law equation:

$$R = E / I$$

$$R = (V_{power} - V_{LED}) / I_{LED}$$

$$R = (6.0\ V - 2.4\ V) / 0.030\ A \quad \text{or} \quad R = 3.6V / 0.03\ A$$

R = 120 ohms (See **Figure 4**.)

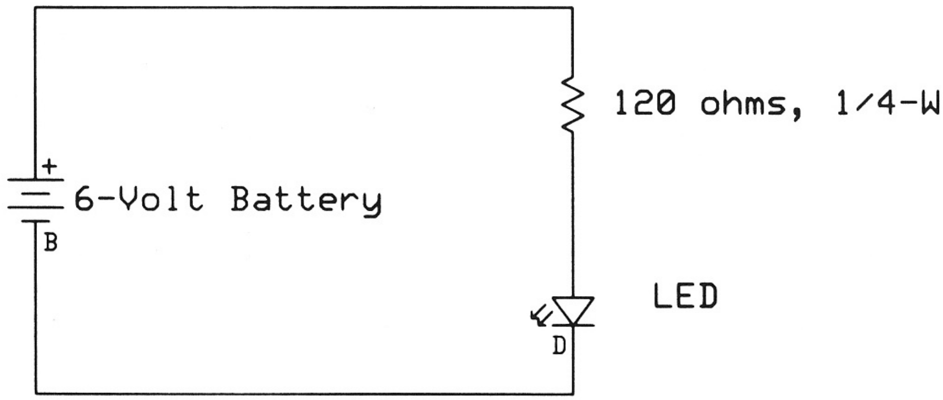

Figure 4. A 120-ohm resistor in series with this Avago LED limits current to 30 milliamps, or 30 mA.

Note that this equation lets you determine the *current through the resistor*. Because the LED and resistor operate in series, the current through the resistor must equal the current through the LED.

Determine the Proper Resistor Power Rating

In an article, "Calculating Current Limiting Resistor Values for LED Circuits," author Mark Dobrosielski (Ref. 1) noted that many hobbyists and experimenters forget to also determine how much *power* the resistor will dissipate as current passes through it. When current passes through a resistance, whether it connects to an LED or serves as a heating element in a toaster, the resistor dissipates energy as heat, measured in units of watts. (Dobrosielski's article also provides information about calculating resistor values for LEDs connected in parallel and series circuits.)

So you must determine now much energy the 120-ohm resistor will dissipate so you can choose the proper "size" resistor for the circuit. The following formula will calculate the watts of dissipated energy based on a given resistance (R) and the square of the current (I) that passes through it:

$W = I^2 * R$ or $W = I * I * R$

Working with the 120-ohm resistance value calculated above for a 30 mA current flow, you have:

W = 0.030 A * 0.030 A * 120 ohms

or about 0.11 watts. Now when you look at resistor specifications you know you need a 120-ohm resistor with a power dissipation of greater than 0.11 watts. A 0.25-W resistor would work just fine. A resistor with a lower power rating would get too hot and it could fail, perhaps by burning out. **Figure 5** shows several resistors with different power ratings.

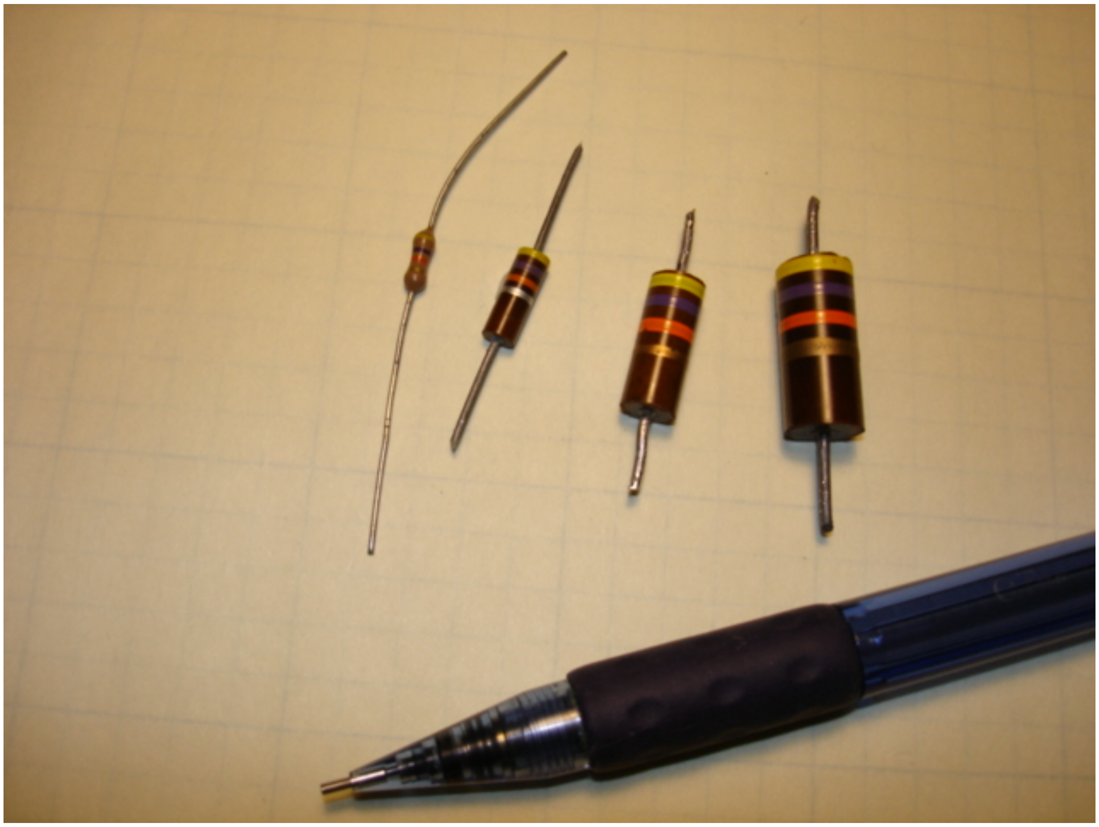

Figure 5. These 47-kohm resistors can dissipate (left to right) 1/4 W, 1/2 W, 1 W, or 2 W. The colored bands indicate the resistance value. Note the size of the pencil for size comparison.

Observe LED Polarity

An LED uses a basic semiconductor diode structure which means it conducts electricity in only one direction. So, if you connect an LED "backwards" in a circuit, it will not create any light. How do you know how to make the proper connection?

LED manufacturers have agreed on an identification method so LEDs have one electrical lead shorter than the other (**Figure 6**). The short lead is the cathode (-) side and the long lead is the anode (+) side. The flat side of the base ring on the plastic molded around an LED semiconductor "chip" also identifies the cathode (-) terminal. You connect the cathode to the lower of the two voltages applied to the LED and the anode to the higher of the two voltages. (The lower voltage might be ground, or 0 volts.)

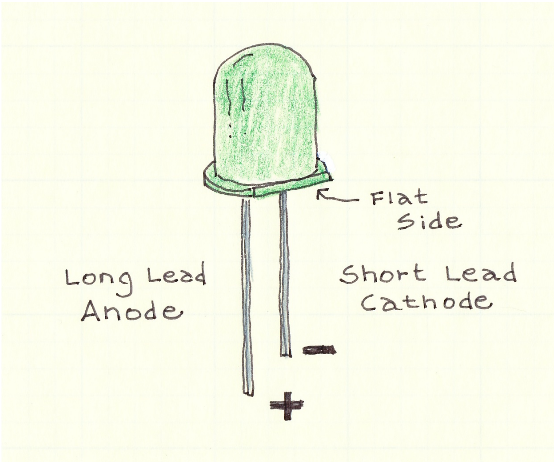

Figure 6. The flat side of a plastic LED and the short electric lead identify the cathode (-) and the long lead identifies the anode (+).

In the 6-volt circuit described above, the cathode would connect to the power supply's negative terminal (perhaps also noted as ground and marked in black), and the anode would connect *through the current-limiting resistor* to the power supply's positive terminal, usually a red terminal.

When I first learned about anodes and cathodes I memorized the relationships by thinking of a flattened-out letter C as a minus sign (-) and a collapsed A (with the sides pushed in) as a plus sign (+). In a diode symbol, the flat side of the symbol represents the cathode and the triangle represents the anode.

Use Transistor Drivers for More Current

Many microcontrollers (MCUs) can provide enough current at a high-enough voltage to directly drive an LED. Consult the MCU manufacturer's data sheets and its Web site for relevant information about the current sourcing and sinking capabilities of input-output pins and also the voltages these pins can sink or source and the maximum voltage you can apply to them.

An MCU will either "sink" or "source" current as shown in **Figure 7**.

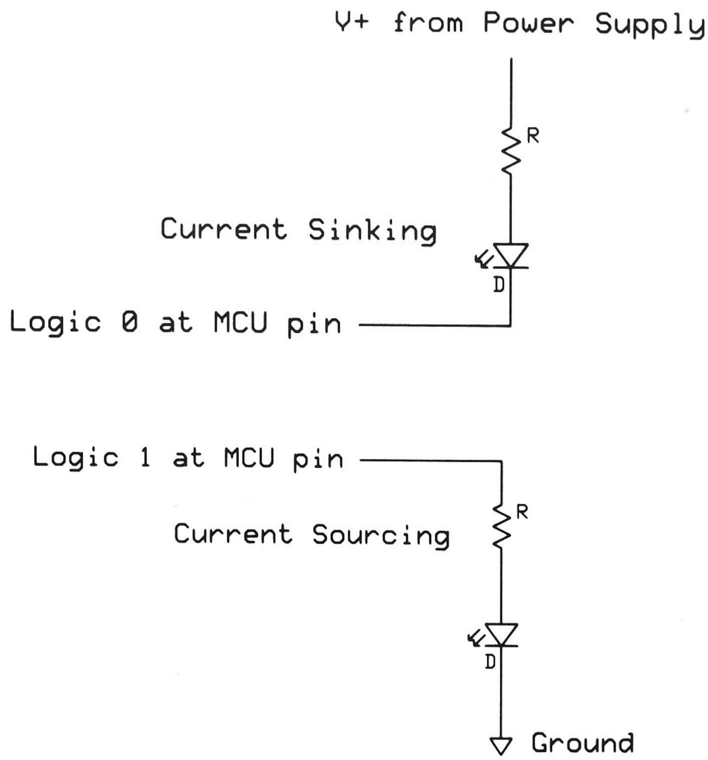

Figure 7. An MCU output pin in a logic-1 state might supply enough current to serve as a current source for an LED. Likewise, in a logic-0 state, an output might sink enough current to light an LED.

But, you might have an MCU or MCU module with limited drive current or voltage so it cannot directly control an LED. In that case, you can use an external transistor as a switch. Like an LED, a transistor operates based on current flow and it serves to "amplify" current. You can use a variety of different transistor types to control LEDs, but in this tutorial I'll cover bipolar PNP and NPN transistors. The NPN and PNP designations describe the semiconductor construction of the small transistor chip and also how current will from through it.

Both NPN and PNP transistors have the same three elements, a base, collector, and emitter, as shown in **Figure 8**. The base acts like a "valve" control and current to or from the base controls the flow of greater currents through the emitter and collector. That amplification lets engineers use transistors in many types of equipment that require amplification or current control. In the LED-driver examples, I'll use the transistors as on-off switches.

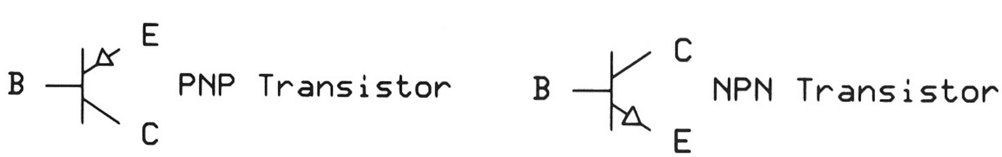

Figure 8. Bipolar NPN and PNP transistors each have a base (B), collector (C), and emitter (E). Note that the emitter is always an arrow that points to or away from the base.

The readily available and inexpensive 2N3904 NPN transistor provides a good example to work with. You can find complete data sheets for this transistor on the Web. Data sheets provide information that lets you identify the base, collector, and emitter leads.

Because a small amount of current supplied to the base of this transistor lets a larger current flow from the collector to the emitter, engineers define the current ratio--also called gain--as the current flowing into the collector (I_c) divided by the current flowing into the base (I_b), or I_c/I_b. They call this ratio beta, or β, and it has no unit, such as ohms or watts.

You can rearrange the β equation so for a given beta and required collector current you can determine the base current needed to achieve it. Under test conditions described in the 2N3904 data sheet, the β value reaches 100 at a collector current (I_c) of 10 mA and a 1.0-volt potential across the collector-to-emitter (V_{CE} in the datasheet), so I'll use those values:

$\beta = I_c/I_b$ or $I_b = I_c/\beta$ and $I_b = 0.010\ A / 100$ so $I_b = 0.0001\ A$, or 0.1 mA, or 100

microamperes, also written a 100 µA. That's a small amount of current!

Let's see how to put the equation into practice.

In a previous example, I attached a green LED and a 120-ohm resistor in series to a 6V power supply and measured the current at 28 mA, or 0.028 A. Now I set up the 2N3904 transistor as a current switch as shown in **Figure 9** and have a collector-to-emitter voltage of 6.0V.

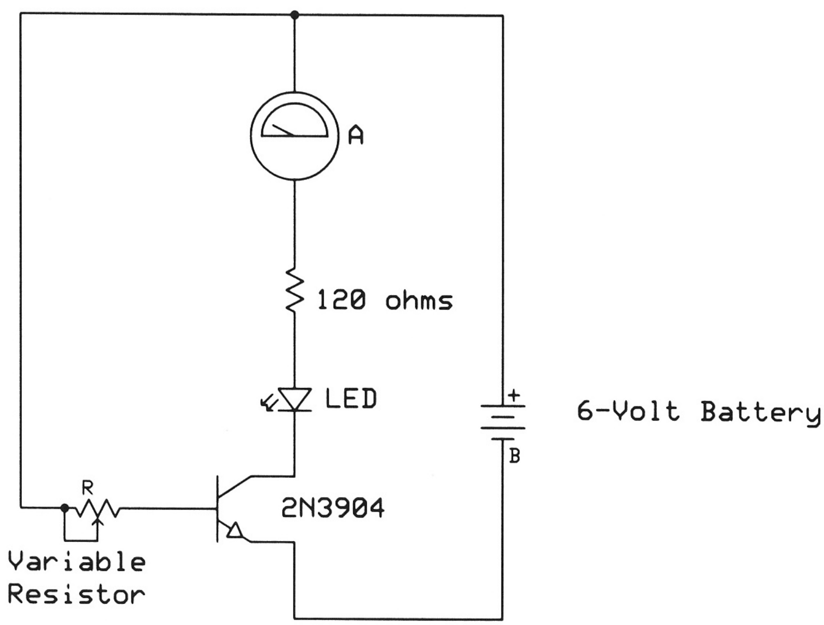

Figure 9. This circuit lets an experimenter determine the value of a resistor on the 2N3904 base connection. The resistor will set the base current and thus limit the collector-to-emitter current flow. A resistor-substitution box can substitute for the variable resistor.

Let's assume a gain of 100, so what current do I need to cause the transistor to pass the 30 mA from the LED circuit?

$I_b = I_c/\beta$ or $I_b = 0.03A / 100$ and $Ib = 0.0003$ A, or 0.3 mA.

I set up the circuit on a breadboard and used a resistor substitution box to limit current to the 2N3904 base, much like the 120-ohm resistor limits current to the LED. I started with a high resistance (1 million ohms, or 1M ohms) and measured the current through the LED with an ammeter (no, it's not an ampmeter). I decreased the resistance in steps until the LED current reached 0.027 mA, very close to the 0.028 mA measured without the transistor. Decreasing the resistance more did not increase the current through the LED because we have a current-limiting resistor in the circuit.

Next, I measured the current flowing through the resistor-substitution box at a setting of 10,000 ohms, or 10 Kohms and measured 0.47 mA. Keep in mind a resistor substitution box changes resistance in fairly large steps. But in this simple example, the results came close enough.

You might wonder why the current through the LED never got up to 0.028 A? The LED-resistor series circuit now includes the transistor, which contributes a constant voltage drop of 0.7V when turned on. As a result, the voltage across the resistor decreases slightly so the current through it decreases slightly, too. Also, given the difference between resistor values in the resistor substitution box, the transistor might not be completely "on."

Use Logic-Transistor LED Drivers

Transistor drivers can easily connect to MCU outputs to increase the power-switching capability of those outputs. So instead of driving the transistor base with current from the 6-volt power supply, I use the output from a 5-volt transistor-transistor-logic (TTL) inverter (7404) as shown in **Figure 10**. The switch (SW) in this schematic diagram only changes the state of the inverter output at pin number 2. With the switch closed, the inverter's logic-1 produced about 3.5V, so using the beta equation above as a start and by making measurements I found the circuit needed a resistor (R) between 4700 and 6800 ohms to cause the same base current to flow.

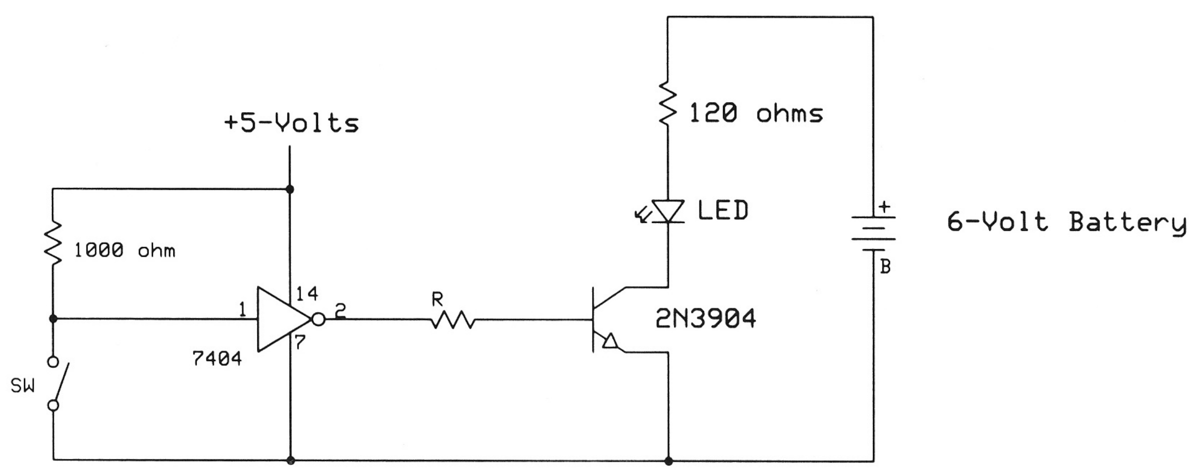

Figure 10. In this circuit, the switch (SW) changes the inverter output from a logic 1 to a logic 0 for testing. The 7404 inverter is a standard 5-volt logic integrated circuit.

In short, you can choose a resistor value and determine if it works, or you can use some math and get close to the value needed to switch a given current through an LED for a given voltage signal. The description above took a simplistic look at transistor actions and considered them only as on-off switches. You can find several good transistor tutorials on the Web. See the References section below

In this circuit, the 2N3904 transistor acts like a "low-side switch," so named because it switches the load--the LED and resistor to a lower voltage, in this case 0 volts, or ground. But a project might also need a "high-side" switch that connects a load to a power source and a PNP transistor such as the 2N3906 will do the job. In the circuit shown in **Figure 11** note that the 2N3906 PNP transistor switch is on the high side of the power supply and the LED and resistor connect directly to ground. Also, the PNP transistor's emitter connects to the high voltage and its collector connects to the lower voltage.

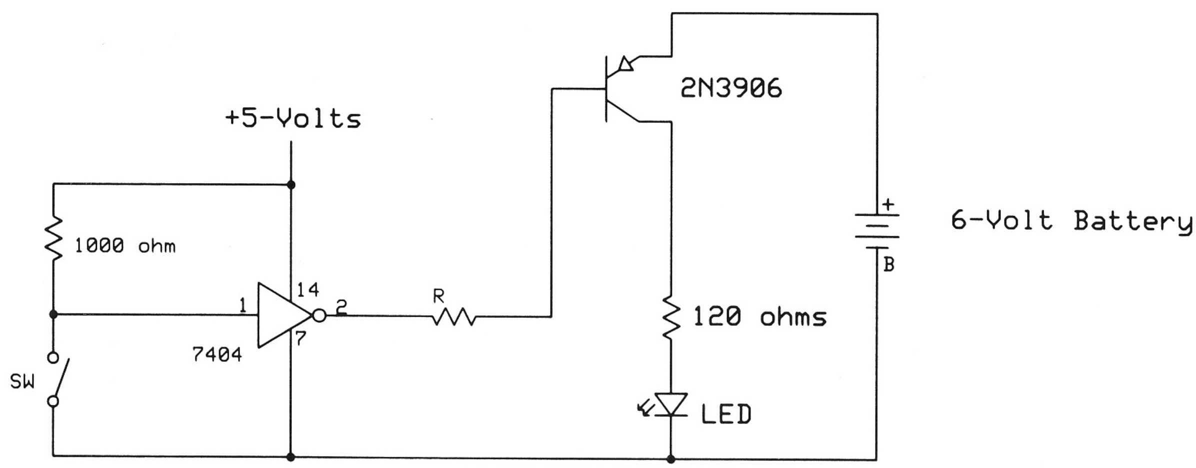

Figure 11. a high-side switch connects a load--the LED and resistor to power. The load already had a direct connection to 0 volts, or ground.

In this circuit, the current flow from the emitter to the collector increases as the 7404 inverter draws more current *from* the base. (In the 2N3904 circuit, we supplied current *to* the base.)

When you use a PNP transistor, remember you need a voltage lower than the supply voltage to provide a path for current out of the transistor. When connected to a logic circuit, you need a logic 0, or a voltage close to ground to cause the transistor to switch on. For more information about using transistors as switches, visit: "Transistor as a Switch," at http://www.electronics-tutorials.ws/transistor/tran_4.html.

Take Advantage of Transistor Drivers

Because transistors can act like on-off switches you can use them to increase the capabilities of output ports that drive individual LEDs or LEDs in displays.

Suppose a circuit must control a two-digit 7-segment LED display that shows numbers 00 through 99. Each 7-segment display module contains seven LEDs, so you would need 14 output lines to control all the segments. Suppose, though, you could turn on one display module and show its number, then quickly turn it off and turn on the second display module and show its number, and then turn it off and repeat the process so quickly that human eyes could not detect the on-off display sequencing. You can have an MCU do just that and such a design relies on software to sequence each digit on or off and provide the value to display on each module.

By controlling individual display modules, you also reduce the number of output lines needed to control displays. Circuit and software designers use this technique, called multiplexing, so both 7-segment displays appear constantly on. The schematic diagram in **Figure 12** provides the circuit.

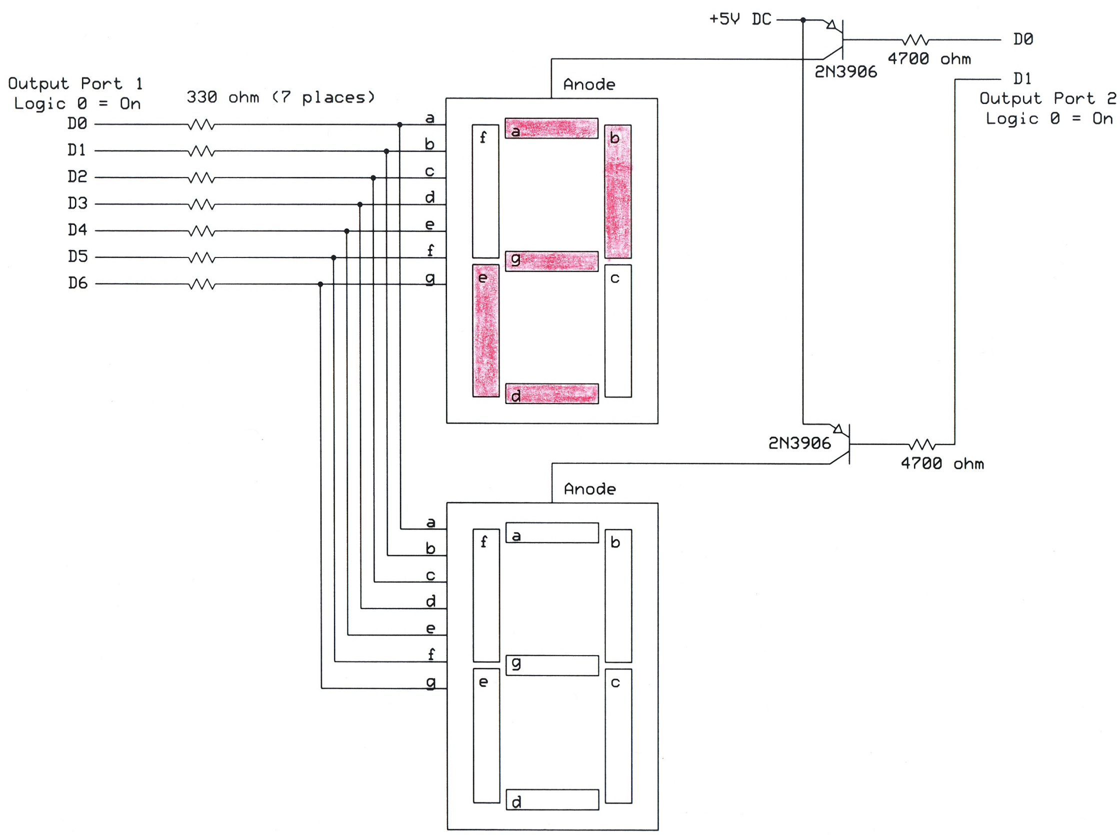

Figure 12. Output Port 1 provides the 7-bit code to light individual segments for a digit. The 2N3906 anode-driver transistors turn on power to individual display modules.

The MCU must provide a look-up table that converts a four-bit digital value 0 through 9 into a 7-bit code that will light individual display segments, a through g. The MCU sends this value to Output Port 1 and then turns on the corresponding display module by sending a logic 0 to one of the 2N3906 anode-driver transistors via a logic 0 at Output Port 2.

After a short on time, the MCU turns off this display, obtains the 7-bit code for the next digit, sends that code to Output Port 1 and turns on the other 2N3906 anode-driver transistor to display the second digit. After a short on time, the MCU turns off this digit and repeats the sequence. Displaying the digit 2, for example, requires the binary code X0100100. The X represents a "don't care" bit that you can set to a logic 1 or 0. It doesn't affect the display. The 0100100 represents the code for segments g through a. In this case, the MCU must turn on segments g, e, d, b, and a to create a "2" on one display. Note that because you can control individual segments in each display module, you also can create some letters, such as A, C, E, F, H, and so on.

By multiplexing the 7-segment displays you need only seven lines to control the segments and one additional line to turn each digit on or off. Thus the 2-digit display requires only 9 output lines, not 14. A 4-digit display would need the same 7 outputs for the seven segments and four control lines, one for each 7-segment display module.

If you need four digits you also might consider using a 2-line-to-four-line decoder that would take two input lines as a 2-bit binary code and create a 1-of-4 output that would produce a logic 0 that corresponded to each binary code. The venerable SN7442 TTL circuit provides this function. You can find a data sheet on the Web and study its inputs and outputs.

Multiplex Individual LEDs

Moving-sign displays that scroll information across a matrix of LEDs use multiplexer circuits to control individual LEDs. This technique makes sense when you have a matrix of LEDs that "measures" at least 3 LEDs per side. You need one output line per row and one output line per column. In this type of circuit, you supply power to a row of LEDs and then and turn on the low-side switch for each LED in the row you want to turn on. The diagram in **Figure 13** shows the circuit for a 3-by-3 LED matrix (9 LEDs total).

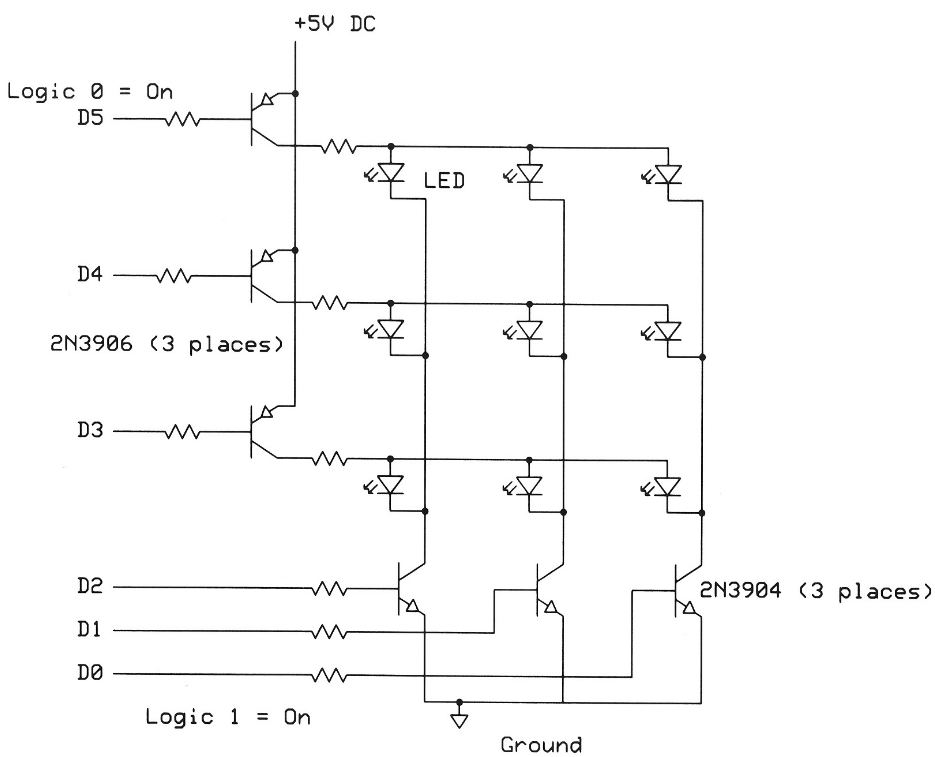

Figure 13. A logic 0 on lines D5--D3 and a logic on lines D2--D1 let you select individual LEDs to turn on. This multiplexing circuit lets you control nine LEDs with only six output lines.

You can watch a short video I created to see how the multiplexing works for a 3-by-3 matrix. Visit:

Instead of using individual transistors you can employ integrated circuits specifically built as high-side and low-side switches to drive LEDs or other devices. Examples include the ULN2003 low-side switch (seven switches per package, 5V TTL and CMOS compatible) available from ST Microelectronics and Texas Instruments, and the MC1413BPG from ON Semiconductor. If you want high-side switches, look at the TD62783APG and TD62784APG octal switches (eight per package) from Toshiba. These integrated-circuit packages make it easy to control many LEDs with only a few output lines.

At this point you should better understand how to properly use LEDs and have MCUs or MCU modules control them.

References

1. Dobrosielski, Mark, "Calculating Current Limiting Resistor Values for LED Circuits," *Nuts & Volts*, January 2005, pp. 50--52. www.nutsvolts.com.

2. van Roon, Tony, "Transistors Tutorial," 1995. http://www.sentex.ca/~mec1995/tutorial/xtor/xtor.html.

3. "Electronics Tutorial about Bipolar Junction Transistors" http://www.electronics-tutorials.ws/transistor/tran_1.html.

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