Using LEDs

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LEDs (**L**ight **E**mitting **D**iodes) have been a boon for model railroaders. They provide bright light with very little heat and are very long-lived compared to incandescent light bulbs. They cover the whole spectrum, from red to violet, and also various forms of white, from "cold" bluish-white to warmer, yellower types. However, the way LEDS are used is a bit different from light bulbs**.** This article is intended to help you use them successfully. It is in two parts. The first gives a brief overview and a table that should enable you to use LEDs in most situations. The second part has more detail and should to allow you to design more customised circuits.

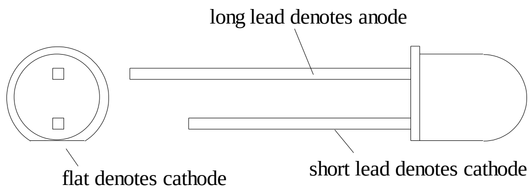
Part 1 - the basics

First things first

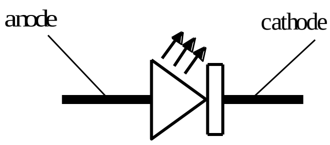
1) LEDs (**L**ight **E**mitting **D**iodes) are like other diodes in that they are designed to only pass current in one direction. However, unlike ordinary diodes, they are destroyed (usually) if the power supply is reversed. Because of this, you have to run them on direct current (dc), or rectified alternating current (ac). And, of course, you have to wire them the right way round!
2) Unlike a light bulb, you can't just connect an LED to a voltage source. You need to control the current that flows through it. You do this by connecting it in series with a resistor. (To understand why you can't just connect to a voltage source, see Part 2 of this article.)
3) I have concentrated on the more common LEDs in packages with leads. You can also get tiny surface-mount LEDs that are small enough to fit in an HO scale marker light. However, the electrical considerations for both types are the same.

Physical Description

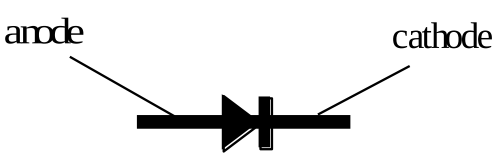
The two connections to an LED are called the "anode" and the "cathode". Here is a drawing of a typical LED that shows how to identify these connections. These LEDs come in various diameters… 3mm, 5mm, 10mm etc. and packages with different shapes



… and the official symbol for it is…

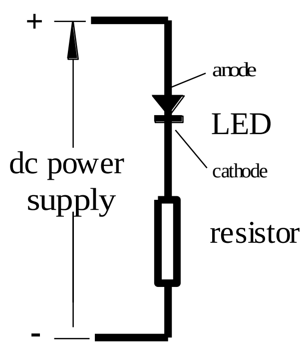


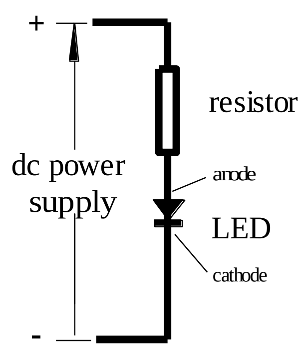
For clarity in the diagrams I will be using the simplified version below (This is actually the symbol for a regular diode.)



Electrical Considerations

To use an LED you need to connect it to a voltage supply via a resistor. The anode must be the nearer of the LED's two leads to the positive (+) side of the supply. The anode may be connected directly to the positive supply (left diagram below) or indirectly through the resistor (right diagram). These two circuits are equivalent. What you must not do is reverse the diode.





The resistor controls the current that flows through the LED. The design task is to choose the resistor value for the type of LED and the power supply you are using.

For most model railroad applications, we encounter three main types of power source:-

1) 5, 6, 9 or 12 volts dc
2) 16 volt, full-wave rectified, ac voltage
3) Rectified DCC voltage (the DCC voltage is a square-wave of approximately +/-12 volts after rectification)

The resistor values below will give currents in the range 10mA to 20mA for the voltages shown. They apply to most of the LED types and colours you will encounter, including white. These currents should provide suitable brightness. For the technical minded the table covers LEDs with forward voltages (V_f) from 2.0 volts to 4.5 volts. (For an explanation of V_f see below.)

Supply voltage	**Resistor**
9 volts	330 ohms
12 volts	470 ohms
16 volts, rectified	820 ohms
DCC voltage, rectified	470 ohms

For 5 or 6 volt power supplies it is recommended that the procedure in the second part of this article is followed.

In all cases shown, a power-rating of 0.5 watts for the resistor will be adequate. These resistors are about 6mm long by 2.5mm diameter. Resistors with higher power ratings (e.g. 1.0 watt) are acceptable and will run cooler. In some situations lower power ratings will be adequate, enabling a physically smaller resistor to be used. This will depend on the specific diode type and voltage used. Details on how to calculate this are given in Part 2 below, which also includes more general information about LEDs.

LEDs as locomotive headlights
DCC decoders usually have +12 volt outputs for use with incandescent light bulbs. You can use these with a white LED and a 470 ohm resistor as shown above and this should give a suitably bright light. Some decoders have special outputs for LEDs. These have a tiny surface-mount resistor already fitted the decoder board. This removes the problem of finding space for the one inside the locomotive. However to connect to this you usually have to solder a wire from the LED to a tiny pad on the decoder board itself. You might find this task daunting if you don't have the experience to attempt it - and very small soldering iron! In this case you can still use the normal 12 volt lighting outputs and a separate resistor. The decoder manufacturer's data sheet will show how the LEDs should be connected.
Some decoders have special outputs for low-voltage (1.5 volt) incandescent bulbs. You should not use these connections for LEDs.

Part 2 - a bit more information

Let's get technical - well, a bit

1) To make an LED light up, you have to pass a current though it from the dc power supply. Here's the key electrical characteristic of an LED in words…. ***Whatever the current that is passing through an LED, the voltage you would measure across it is pretty much constant.*** ***This is the key concept, so read it again!*** Did you get it? OK. Onward! This voltage is referred to in the LED's specification as the "forward voltage". Its symbol is V_f, and is usually measured at a specified current…. So, on data sheets, you may see something like "forward voltage, V_f = 3.6 volts at 20 milliamps".

2) To control the current, you put a resistor between the power supply and the LED as shown earlier. Note that the anode is connected (either directly or indirectly through the resistor) to the positive side of the supply.

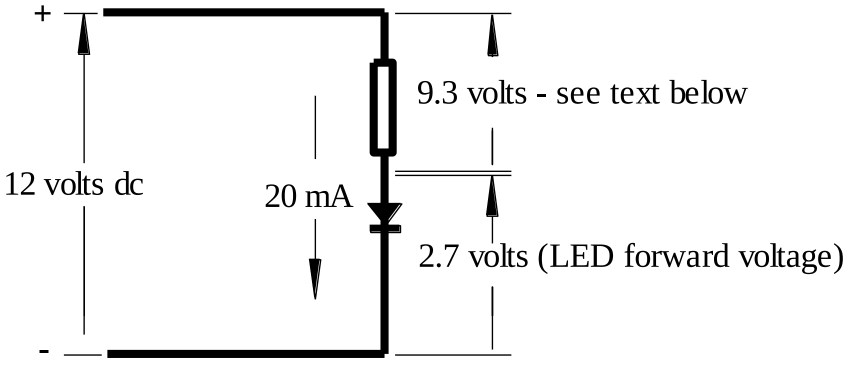
3) The brightness of an LED is determined by the physics of the device inside it and the current you pass through it. For the LEDs we will encounter it isn't related to package size. The actual LED is tiny, so even the smallest package can be very bright.

4) The higher the current, the brighter the light. However, if you make it too high the LED will burn out. The LED will have an 'absolute maximum' current rating, shown on its data sheet. For most of the LEDs we will encounter, the forward

voltage will be in the range 2 volts to 4 volts and the maximum current rating will be around 30 mA. For normal operation you keep well below this. 20mA gives a very bright light. Even 10mA is usually quite acceptable.

Calculating the resistor value.

Suppose you have a 12 volt power supply, an LED with a forward voltage V_f of 2.7 volts and want a current of 20 milliamps. The circuit is shown below. (From now on I will show the circuits with the resistor connected to the + of the supply, but remember the positions of the resistor and LED could be reversed as shown earlier but the "direction" of the LED can't be changed).



When the current flows, the voltage across the LED will be its forward voltage (V_f), which is 2.7 volts in this case. (Remember from earlier, the voltage across an LED is almost constant, at V_f, no matter what the current). The voltage across the resistor must then be 12 volts minus 2.7 volts, which is 9.3 volts. So, we need a resistor that has a voltage of 9.3 volts across it when the current flowing through it is 20 milliamps. The resistor value (using the well known law of Mr Ohm) is 9.3 volts, divided by 20 milliamps which is 465 ohms. This is close to the standard resistor value of 470 ohms. Using 470 ohms, the actual current would be 19.8 mA, which is close enough. You can use this procedure for any combination of power supply, forward voltage and current…

$$\text{Resistor in ohms} = \frac{(\text{Power supply - Forward Voltage) in volts}}{\text{Required current in amps}}$$

or, put another way

$$\text{Resistor in ohms} = \frac{(\text{Power supply - Forward Voltage) in volts}}{\text{Required current in milliamps}} \times 1000$$

A good rule in this situation is to move up to the next standard resistor value. For example, if the calculation above had resulted in, say, 520 ohms then the next larger standard value of 560 ohms would have been selected.

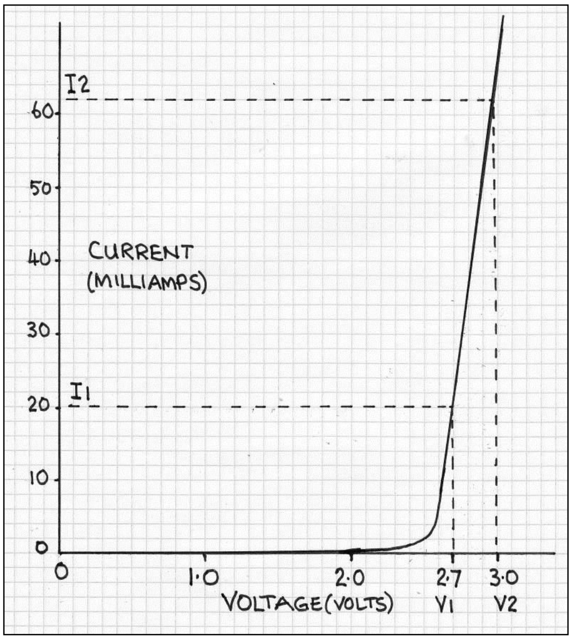
All this calculation stuff is to help you understand how the circuit works. There is an on-line calculator at http://led.linear1.org/1led.wiz *You enter your power supply, forward voltage and desired current and it tells you the standard value resistor to use. Another item I haven't gone into is that the power rating of the resistor is also a consideration. The calculator gives you that also.*

"Well", you might say, "I have an LED having a V_f of 2.7 volts at 20 milliamps. Why can't I just connect it to a 2.7 volt power supply and forget the resistor?"

Good question! Take a look at the graph. It shows the relationship between voltage and current for a typical LED. As we said earlier, the voltage doesn't change much as the current changes. (Except at very low currents, which we don't use). In the example shown, when the current varies between 20mA and 60mA the voltage only changes by less than 0.3 volts.

To get back to the question, I have marked a voltage of 2.7 volts and a resulting current for the diode described of 20 milliamps (V1 and I1).

Now, suppose the 2.7 volt supply voltage increases by about 10% to 3.0 volts, shown as V2 on the diagram. This could be because of changes in mains voltage, changes in temperature etc. The current, I2, is now enormous - something over 60mA. Our 10% increase in voltage has resulted in a 200% increase in current! This would result in a vast increase in brightness. In practice the maximum allowable current for a typical diode is around 30 mA, so this brightness might be rather brief!



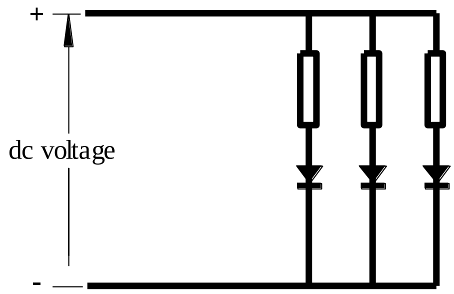
“No problem” you might say, “I will provide very tight control of that 2.7 volts”. Unfortunately that doesn’t solve the problem. The graph I have shown is for one particular diode. Another one, even of the same type, will have a slightly different curve. For example it may be moved slightly to the left. So you will again not have control of the current. A further problem is that the LED characteristics alter slightly with temperature so you don’t have good control of even an individual LED. You may come across people who say, “I have used this method for ages and haven’t had a problem”. This is like saying they have crossed the road blindfold lots of times and they are not dead, so the practice is safe. Since only the voltage is being controlled, the LED may be passing more current than it should and be under stress. Even if it’s not under stress, when you use the circuit with a different LED, that one may be. The components needed for an accurate low-voltage supply cost more than a single resistor anyway, so why not do it properly? (a resistor only costs pennies)

To completer the discussion on this, suppose that, instead of controlling the voltage, we control the current using a simple resistor circuit as shown earlier. The situation is completely different. Referring to the graph again, suppose we set the current at 20mA. The LED voltage (using the diode represented by the graph) will be 2.7 volts. If the current now increases 10% to 22 milliamps there will only be a tiny increase in voltage - to around 2.715 volts. We now have much better control of the situation and, importantly, we are controlling the current, which is what determines the brightness.

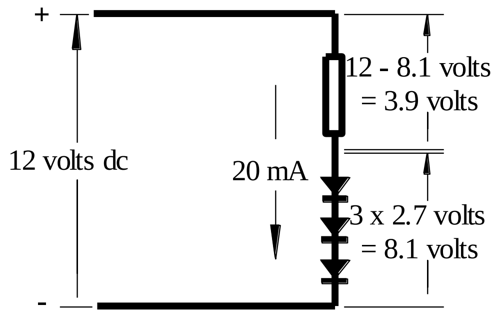
For clarity in the diagram I have emphasised the ‘knee’ around 2 volts as the LED turns on. For a real LED the curve is usually more rounded.

Multiple LEDS

One way of connecting multiple LEDS is shown below. Each LED circuit is essentially independent. The current to each LED is controlled by its associated resistor. (I am showing a 12 volt supply in the later examples for consistency with the earlier calculations, but it could be any value large enough to provide the currents needed.)

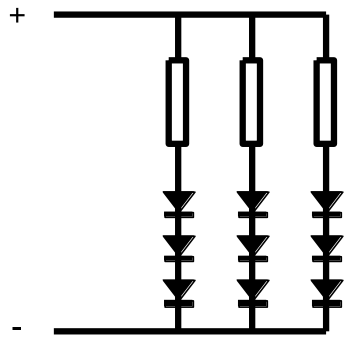


An alternative is shown below. This also shows three LEDs being powered.



In this case, the same current (20mA) flows through the all three LEDs. The calculation of the resistor is slightly different. The circuit has the same supply voltage as before but the forward voltage of each of the LEDs is 2.7 volts. As they are connected in series, the voltage across the three LEDS will be 3 x 2.7 volts = 8.1 volts. So the voltage across the resistor is 12 volts minus 8.1 volts = 3.9 volts. The resistor value becomes 3.9 volts divided by 20 milliamps equals 190 ohms. The nearest standard value is 200 ohms. For the calculation, the three LEDs in series are viewed as a single LED with three times the forward voltage. This approach saves on resistors and may be more convenient to wire, but can’t be taken to extremes. I would always make sure I had at least 3 volts or so across the resistor. In the example above three is the maximum number of LEDS. With four the LED voltage would be 10.8 volts, which is very marginal. It is possible to design transistor circuits that produce constant currents at low voltages but these are outside the scope of this article

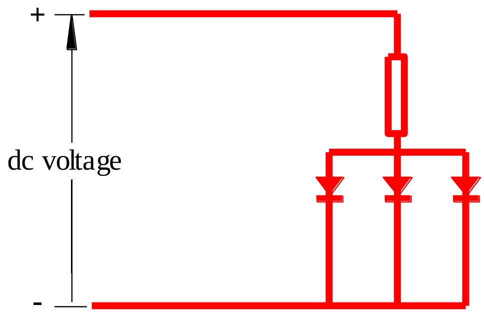
You can use combinations of these designs to control lots of LEDs… like this…



You can even have different numbers of LEDs in each 'string' or different diode types. You can calculate the appropriate resistors for the strings, depending the number and types of diodes in each one, but we are getting a bit complicated.

A poor design

In all the previous multiple LED designs, the individual LED current(s) could be predicted. In the circuit below they can't.



This circuit looks reasonable at first, and is ***supposed*** to work like this… The current down through the resistor is arranged to be three times that needed for a single LED. This current is then shared equally between the three LEDS. The problem is… it isn't!

This is because differences in the characteristics of the LEDs (even of the same type) make it extremely unlikely that the current will be shared equally. This would result in different brightness or, in an extreme case, one LED receiving a large share of the current and exceeding its maximum current rating. **This circuit is definitely not recommended. This isn't to say people don't use it.**

Odds and ends

Dimming LEDs

As you reduce the current, the LED dims. However, at very low currents strange things can happen – like the colour changing. To get round this it is necessary to use a switching approach. The 'full brightness' current is supplied to the LED but is switched on and off rapidly. The ratio of the 'on' time to 'off' time controls the brightness. This requires special circuitry. I only mention this in case you are thinking of any extreme dimming. (I believe some DCC decoders have special outputs for dimming LED headlights that operate in this way.)

Flashing LEDs

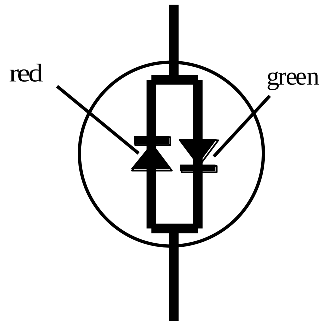
You can buy LEDs that flash on and off at a 'warning light' frequency. These have a built-in chip that runs off (usually) a 2.5 volt power supply. You need a regulated 2.5 volt supply to run these.

Constant current LEDs

These have a circuit that sets the LED current at (typically) 15 milliamps, *independent of the power supply voltage*, so you don't need a resistor. Unlike simple LEDs, you can connect these directly to a voltage source. The only ones I've seen had the circuitry in small package to which the LED was attached. Two flying leads from this package provided connection to a suitable power supply. The version I saw was only available with a red LED (eat your heart out Henry Ford) and would work with any power supply between 4 volts and 30 volts.

Multi-colour LEDs,

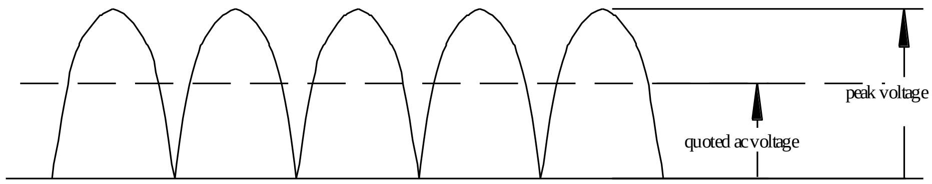
There are various forms of multicolour LEDs. One common type has red and green LEDs connected in parallel with each other as shown below. Current may flow through the combination in either direction. In one way it will show red; in the opposite green. If alternating current is applied, the red and green will flash alternatively. If the flashing is rapid enough, this will be perceived as yellow.



An alternative three-lead version allows independent control of two LEDs.

Full-wave rectified alternating voltage

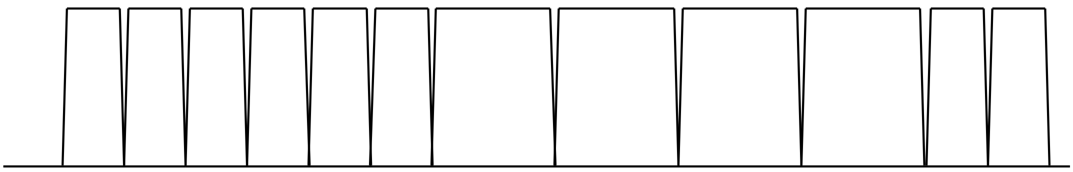
A complication arises when the standard LED plus resistor circuit runs on rectified ac. This is because of the way ac voltages are specified. A full-wave-rectified voltage looks like the waveform below. Its peak voltage is around 1.4 times the quoted voltage. Technically, the value quoted is the rms (root-mean-square) value. So a 16 volt ac voltage has a peak of around 22 volts. So, if you aren't careful, you may get a higher current than appears at first sight and may exceed the maximum rating for the LED. This has been taken into account in the table given earlier.



full-wave rectified ac (not to scale)

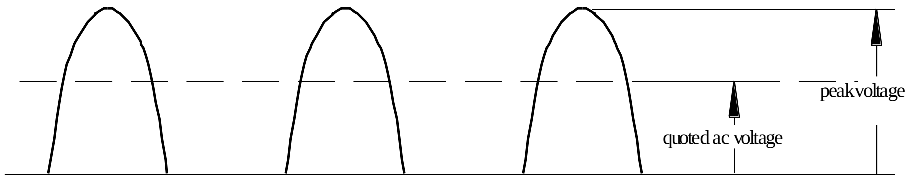
8) Full-wave rectified DCC voltage

The situation for full wave rectified DCC signal is different. A typical waveform is shown below. It consists of a train of (almost) square waves of two different widths. You can see that the average voltage is almost the same as the peak voltage. If it were not for the "notches" in the waveform it would be dc.



The effective peak voltage (after passing through a full-wave bridge rectifier) is around 12 volts. Any calculations can proceed as if the voltage were 12 volt dc.

9) Half-wave rectified voltages

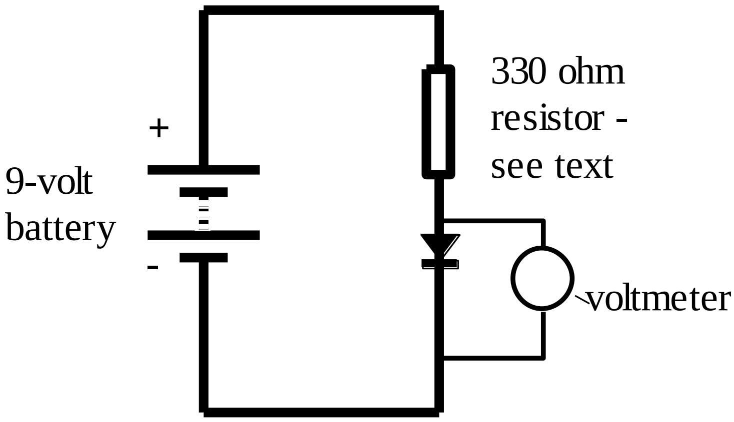


half-wave rectified ac (not to scale)

On half-wave, the amount of light will be halved. It is a good idea to use a current in the upper range of what is possible - for example 20mA, rather than 10mA. This applies to both the waveform shown and a half-wave rectified DCC square wave signal. For the waveform shown, the considerations about peak values still apply.

10) But what if I don't know the LED's forward voltage?

If you need to know the forward voltage and don't have a data sheet for your LED, it is easy to measure it. The circuit below shows how. The resistor can be any value around 300 ohms. This could be a single 330 ohm resistor or any combination of resistors that results in the same value. The actual value isn't critical. The LED should light up and the voltage you measure will be the forward voltage – or close enough for our purposes.



LED … QED