So... you just want to light up an LED. What resistor should you use?

Maybe you know the answer, or maybe everyone already assumes that you should know how to get to the answer. And in any case, it’s a question that tends to generate more questions before you actually can get an answer: What kind of LED are you using? What power supply? Battery? Plug-in? Part of a larger circuit? Series? Parallel?

Playing with LEDs is supposed to be fun, and figuring out the answers to these questions is actually part of the fun.

There’s a simple formula that you use for figuring it out, Ohm’s Law. That formula is $V = I \times R$, where $V$ is the voltage, $I$ is the current, and $R$ is the resistance. But how do you know what numbers to plug into that formula to get out the right resistor value?

To get the $V$ in our formula, we need to know two things: the voltage of our power supply, and the voltage of our LEDs.

Let’s start with a concrete example. Suppose that we are using a 2 × AA battery holder (like this one from our shop), which will provide us with a 3 V of power (with two 1.5 V AA cells in series; we add the voltages), and we’ll plan to hook up a
yellow LED (like one of these).

LEDs have a characteristic called “forward voltage” which is often shown on the datasheets as Vf. This forward voltage is the amount of voltage “lost” in the LED when operated at a certain reference current, usually defined to be about 20 milliamps (mA), i.e., 0.020 amps (A). Vf depends primarily on the color of the LED, but actually varies a bit from LED to LED, sometimes even within the same bag of LEDs. Standard red, orange, yellow and yellow-green LEDs have a Vf of about 1.8 V, while pure-green, blue, white, and UV LEDs have a Vf of about 3.3 V. So, the voltage drop from our yellow LED will be about 1.8 V.

The V in our formula is found by subtracting the LED’s forward voltage from the voltage of the power supply.

3 V (power source) − 1.8 V (LED voltage drop) = 1.2 V

In this case, we’re left with 1.2 V which we’ll plug into our V = I × R formula.

The next thing we need to know is the I, which is current we want to drive the LED at. LEDs have a maximum continuous current rating (often listed as If, or Imax on datasheets). This is often around 25 or 30 mA. What this really means is that a typical current value to aim for with a standard LED is 20 mA to 25 mA—slightly under the maximum current.

Aside: You can always give an LED less current. Running an LED near its rated maximum current gives you maximum brightness, at the cost of power dissipation (heat) and battery life (if you’re running off of batteries, of course.) If you want your batteries to last ten times longer, you can usually just pick a current that is only one tenth of the rated maximum current.

So, 25 mA is the “desired” current—what we’re hoping to get when we pick a resistor, and also the I that we’ll plug into our V = I × R formula.
1.2 V = 25 mA × R

or rephrased:

1.2 V / 25 mA = R

and when we solve that we get:

1.2 V / 25 mA = 1.2 V / 0.025 A = 48 Ω

Where “48 Ω” is 48 ohms. (The units are such that 1 V/ 1 A = 1 Ω; one volt divided by one amp equals one ohm. If you are dealing with current in mA, convert to A by dividing by 1000.)

Our version of the formula now looks like this:

(Power supply voltage ? LED voltage) / current (in amps) = desired resistor value (in ohms)

We end up with a resistor value of 48 Ω. And, that’s a fine starting resistor value for use with a yellow LED and a 3 V source.

Let’s look at resistor values for a moment. Resistors are usually available in values such as 10 Ω, 12 Ω, 15 Ω, 18 Ω, 22 Ω, 27 Ω, 33 Ω, 39 Ω, 47 Ω, 51 Ω, 56 Ω, 68 Ω, 75 Ω, and 82 Ω (and their multiples, 510 Ω, 5.1K Ω, 51K Ω, etc.), and (unless you specify higher precision while shopping) have a tolerance value of about ±5%.

If you do a lot of electronics projects, you’re likely to have a bunch of resistors lying around. If you’re just getting started, you might want to get an assortment so that you have some handy. Resistors also come rated to handle varying amounts of power—resistors rated for more power (more watts) are able to safely dissipate more heat generated within the resistor. 1/4 watt resistors are probably the most common, and are generally just fine for simple LED circuits like the ones we’re covering here. (We’ve discussed power dissipation previously—look into that when you start to move beyond these
basics.)

Now, the resistor value we calculated above was 48 \( \Omega \), which isn’t one of our common values. But that’s okay, because we’ll be using a resistor with a ±5% tolerance, so it won’t necessarily be exactly that value anyway. To be on the safe side, we generally select the next higher value that we have on hand; 51 \( \Omega \) in this example.

Let’s hook this up:

3 V battery box, 51 \( \Omega \) resistor, and yellow LED.

Now, that’s a nice little LED circuit, but how can we do this with more LEDs? Can we just add another resistor and another LED? Well, yes, to a point. Each LED will want 25 mA, so we need to figure out how much current our batteries can source.

Aside: A little digging turns up a helpful technical handbook (pdf) on alkaline batteries from Energizer. It turns out that
the harder you drive them, the faster you drain them. *Part of this is obvious:* If you continuously draw 1000 mA out of a battery, you would expect the battery to last 1/10 as long as if you draw 100 mA. But there’s actually a second effect, which is that the total energy output the battery (measured in watt-hours) decreases when you approach the limit of how much current the battery can source. In practice, with AA alkaline batteries, if you drain it at 1000 mA, it will only last about 1/20 as long as it would if you drained it at 100 mA.

For our single 25 mA LED, AA cells will last a heck of a long time. If we run four LEDs in parallel, requiring 100 mA, we should still get pretty decent battery life. For higher than 500 mA, we should think about plugging into the wall. So, we can add several of our yellow LEDs, each with its own 51 Ω resistor, and drive them happily with a 2xAA battery holder.

![Diagram of four LEDs in parallel](image)

All right, how about a 9 V battery? Let’s stick with our yellow LEDs. If we want to run one LED off of a 9 V battery, that means we have to take up a whopping 7.2 V with our resistor, which would need to be 288 Ω (or the nearest convenient value: 330 Ω, in my workshop).

9 V (power supply) − 1.8 V (yellow LED) = 7.2 V

7.2 V / 25 mA = 288 Ω (round up to 330 Ω)
Using a resistor for a voltage drop of any size dissipates that energy in the form of heat. That means that we’re just wasting that energy on heat instead of getting more light out of our LED circuit. So can we use multiple LEDs strung together? Yes! Let’s put four of the 1.8 V LEDs in series, adding up to a total of 7.2 V. When we subtract that from our supply voltage of 9 V, we’re left with 1.8 V, requiring only a 72 Ω resistor (or nearest value: 75 Ω).

\[
9 \text{ V } - (1.8 \text{ V } \times 4) = 9 \text{ V } - 7.2 \text{ V } = 1.8 \text{ V}
\]

\[
1.8 \text{ V } / 25 \text{ mA } = 72 \Omega \text{ (and we then round up to 75 Ω)}
\]

Our generalized version of the formula with multiple LEDs in series is:

\[
\text{[Power supply voltage } - (\text{LED voltage } \times \text{number of LEDs})]/\text{current } = \text{resistor value}
\]

We can even put a couple of these strings of four LEDs plus a resistor in parallel to get more light output, but the more we add, the more we’ll shorten our battery life.

But can we do five in series with a 9 V battery? Well, maybe.

The 1.8 V figure that we’ve been using is a “typical rule of thumb,” only. If you’re sure the forward voltage is exactly 1.8 V, it will work. But what if it isn’t exactly that? If the forward voltage is lower, you may overdrive them at a higher current, which can shorten their lifespan (or kill them outright). If the forward voltage is higher, the LEDs may be dim or may not even light. There are some cases where you can drive LEDs in series without a resistor, like in our LED Dining Table Circuit, but in most cases, it’s preferable and safer to use a resistor.

Let’s do one more example, this time with a white LED (you can find some here) and a 3xAA battery box (such as this one). Our power supply voltage is 4.5 V, and our LED Vf is 3.3 V. We’ll still aim for a current of 25 mA.
4.5 V \( \div \) 3.3 V = 1.2 V

1.2 V \( \div \) 25 mA = 48 \( ? \) (round up to 51 \( ? \))

So, here are the examples we’ve looked at plus few more with some other common power supply types:

<table>
<thead>
<tr>
<th>Power Supply Voltage</th>
<th>LED Color</th>
<th>LED Vf in series</th>
<th>Desired Current (calculated)</th>
<th>Resistor (calculated)</th>
<th>Resistor (rounded)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 V</td>
<td>Red, Yellow, or Yellow-Green</td>
<td>1.8 1</td>
<td>25 mA</td>
<td>48 ( ? )</td>
<td>51 ( ? )</td>
</tr>
<tr>
<td>4.5 V</td>
<td>Red, Yellow, or Yellow-Green</td>
<td>1.8 2</td>
<td>25 mA</td>
<td>36 ( ? )</td>
<td>39 ( ? )</td>
</tr>
<tr>
<td>4.5 V</td>
<td>Blue, Green, White, or UV</td>
<td>3.3 1</td>
<td>25 mA</td>
<td>48 ( ? )</td>
<td>51 ( ? )</td>
</tr>
<tr>
<td>5 V</td>
<td>Blue, Green, White, or UV</td>
<td>3.3 1</td>
<td>25 mA</td>
<td>68 ( ? )</td>
<td>68 ( ? )</td>
</tr>
<tr>
<td>5 V</td>
<td>Red, Yellow, or Yellow-Green</td>
<td>1.8 1</td>
<td>25 mA</td>
<td>128 ( ? )</td>
<td>150 ( ? )</td>
</tr>
<tr>
<td>5 V</td>
<td>Red, Yellow, or Yellow-Green</td>
<td>1.8 2</td>
<td>25 mA</td>
<td>56 ( ? )</td>
<td>56 ( ? )</td>
</tr>
<tr>
<td>9 V</td>
<td>Red, Yellow, or Yellow-Green</td>
<td>1.8 4</td>
<td>25 mA</td>
<td>72 ( ? )</td>
<td>75 ( ? )</td>
</tr>
<tr>
<td>9 V</td>
<td>Blue, Green, White, or UV</td>
<td>3.3 2</td>
<td>25 mA</td>
<td>96 ( ? )</td>
<td>100 ( ? )</td>
</tr>
</tbody>
</table>

All of these values are based on the same assumptions about forward voltages and desired current that we used in the early examples. You can work those through and check the math, or
just use it as a handy table if you think that our assumptions are reasonable.

Now, at some point someone may have told you, “Just use an online LED resistor calculator.” And indeed there are such things out there — even we have one (well, a printable papercraft version) — so why bother working through all this? For one thing, it’s much better to understand what and why that calculator is doing what it does. But it’s also near impossible to use those calculators if you don’t know what variables you’ll need to enter. Hopefully you should now be able to figure out the values you’ll need (power supply voltage, LED voltage and current) to use an LED calculator. But more importantly (1) you don’t really need one: you can do it yourself and (2) if you do use one, you can question the underlying assumptions that it may make on your behalf.

Hopefully, you’ve also seen that there is much more than just one way to light an LED. And we haven’t even gotten to things
like putting LEDs of different values in circuits together! Now, can you go back to sticking LEDs on CR2032 batteries to make LED throwies? Yes, you most definitely can. But you may want to go back and read about when you should add a resistor to even that little circuit!

Finally, let us note that in this article we’ve been talking about your basic through-hole, low-power (though possibly extremely bright) LED. Specialized types like high power LEDs may have somewhat different characteristics and requirements.

Update: corrected the common resistor value list to include more common values.

Diodes

Real Diode Characteristics

Ideally, diodes will block any and all current flowing the reverse direction, or just act like a short-circuit if current flow is forward. Unfortunately, actual diode behavior isn’t quite ideal. Diodes do consume some amount of power when conducting forward current, and they won’t block out all reverse current. Real-world diodes are a bit more complicated, and they all have unique characteristics which define how they actually operate.

Current-Voltage Relationship

The most important diode characteristic is its current-voltage (i-v) relationship. This defines what the current running
through a component is, given what voltage is measured across it. Resistors, for example, have a simple, linear \( i-v \) relationship...**Ohm’s Law**. The \( i-v \) curve of a diode, though, is entirely non-linear. It looks something like this:

![Diode Current-Voltage Relationship](image)

The current-voltage relationship of a diode. In order to exaggerate a few important points on the plot, the scales in both the positive and negative halves are not equal.

Depending on the voltage applied across it, a diode will operate in one of three regions:

1. **Forward bias**: When the voltage across the diode is positive the diode is “on” and current can run through. The voltage should be greater than the forward voltage (\( V_F \)) in order for the current to be anything significant.

2. **Reverse bias**: This is the “off” mode of the diode, where the voltage is less than \( V_F \) but greater than \(-V_{BR}\). In this mode current flow is (mostly) blocked, and the diode is
off. A very small amount of current (on the order of nA) — called reverse saturation current — is able to flow in reverse through the diode.

3. **Breakdown**: When the voltage applied across the diode is very large and negative, lots of current will be able to flow in the reverse direction, from cathode to anode.

**Forward Voltage**

In order to “turn on” and conduct current in the forward direction, a diode requires a certain amount of positive voltage to be applied across it. The typical voltage required to turn the diode on is called the *forward voltage* ($V_F$). It might also be called either the *cut-in voltage* or *on-voltage*.

As we know from the $i$-$v$ curve, the current through and voltage across a diode are interdependent. More current means more voltage, less voltage means less current. Once the voltage gets to about the forward voltage rating, though, large increases in current should still only mean a very small increase in voltage. If a diode is fully conducting, it can usually be assumed that the voltage across it is the forward voltage rating.
A **multimeter** with a diode setting can be used to measure (the minimum of) a diode’s forward voltage drop.

A specific diode’s $V_f$ depends on what semiconductor material it’s made out of. Typically, a silicon diode will have a $V_f$ around **0.6-1V**. A germanium-based diode might be lower, around 0.3V. The type of diode also has some importance in defining the forward voltage drop; light-emitting diodes can have a much larger $V_f$, while Schottky diodes are designed specifically to have a much lower-than-usual forward voltage.

**Breakdown Voltage**

If a large enough negative voltage is applied to the diode, it will give in and allow current to flow in the reverse direction. This large negative voltage is called the **breakdown voltage**. Some diodes are actually designed to operate in the breakdown region, but for most normal diodes it’s not very healthy for them to be subjected to large negative voltages.

For normal diodes this breakdown voltage is around -50V to -100V, or even more negative.
Diode Datasheets

All of the above characteristics should be detailed in the datasheet for every diode. For example, this datasheet for a 1N4148 diode lists the maximum forward voltage (1V) and the breakdown voltage (100V) (among a lot of other information):

![Datasheet Table]

A datasheet might even present you with a very familiar looking current-voltage graph, to further detail how the diode behaves. This graph from the diode’s datasheet enlarges the curvy, forward-region part of the $i$-$v$ curve. Notice how more current requires more voltage:
That chart points out another important diode characteristic – the maximum forward current. Just like any component, diodes can only dissipate so much power before they blow. All diodes should list maximum current, reverse voltage, and power dissipation. If a diode is subject to more voltage or current than it can handle, expect it to heat up (or worse; melt, smoke,…).

Some diodes are well-suited to high currents – 1A or more – others like the 1N4148 small-signal diode shown above may only be suited for around 200mA.

That 1N4148 is just a tiny sampling of all the different kinds of diodes there are out there. Next we’ll explore what an amazing variety of diodes there are and what purpose each type serves.

early every consumer device makes use of the Light Emitting
Diode (LED). This highly versatile device offers an easy way to add an indicator to any project, while drawing a relatively small amount of current. Once their operation is understood, adding them to any project is a simple task. This is an simplified explanation of how a LED works and how to select a current limiting resistor. The LED tutorial here is enough to use LEDs in a project, but is not intended to be a through explanation.

**LED Basics**

A Diode is an electronic component that only conducts electricity in one direction. The Forward Voltage rating of a Diode will determine the minimum voltage difference between the Anode and Cathode in order to allow electrons to flow. For example, if you apply +1V to the Anode and 0V (GND) to the Cathode, and the Forward Voltage of the Diode is rated at 0.7V then current will flow. However, if you apply 0V (GND) to the Anode and +1V to the Cathode, current will not flow!

A Light Emitting Diode (LED) is a variant of the basic Diode with the same characteristics. The key difference is that when the LED conducts electricity it also generates Light. When looking at the specifications for a LED, there are two key ratings to note: the “Forward Voltage” and the “Forward Current.”

**Forward Voltage**

The Forward Voltage defines the amount of voltage required in order to conduct electricity. Any voltages below this amount will cause the LED to remain “Open” and non-conductive. This also means any components in-series with the LED will not have current flowing through them either! Once the voltage dropped across the LED reaches the Forward Voltage, it will begin to
conduct electricity. Not only that, but the LED will only drop its Forward Voltage at any given time.

For example, consider a LED with a Forward Voltage rated at 3.0V. Now what happens if you attach the Anode to the Positive (+) Terminal of a AA (LR-6) Battery and the Cathode to the Negative (-) Terminal? Will the LED do anything? No! The AA (LR-6) Battery only has a nominal voltage of 1.5V. Until you add a second battery, the LED will not light up.

![Diagram of a LED connected to a battery](image)

So if you use two nominal AA (LR-6) batteries in series and connect them to this diode, it will light up and all is good, right? Well, No. What is really happening inside of the LED is that the Diode turns into a short-circuit once a Forward Voltage is applied. This means the LED will draw ALL the current it can from the Battery. This isn’t good because you are basically short-circuiting the battery! Not only will this damage the battery, but will overheat or destroy the LED!

**Forward Current (If)**

As mentioned before, when the Forward Voltage is applied to a LED, it turns into a short-circuit and allows current to flow. As a short, the LED will draw all the current the supply allows AND will damage itself. So you must limit the amount of Forward Current flowing through the LED. There is where the name “current limiting resistor” comes in. By placing a resistor in series with the LED, the current that flows through it is effectively limited.

Diodes, and LEDs, drop a constant voltage regardless of the
current that runs through them. So the Resistor and LED work together. The Resistor hold the amount of current constant and the LED holds the voltage dropped across each constant. The next question to address is, what value resistor is needed?

**Yellow LED Example**

To calculate the required *current limiting resistor*, two properties of the LED must be known: Its Forward Current (If) and Forward Voltage (Vf). Mentioned in the last section is that a LED will hold the voltage dropped across it constant. Regardless of the voltage applied, it will only drop the Forward Voltage (Vf) across itself. Using the [datasheet for a Yellow LED (available at Sparkfun)](https://www.sparkfun.com/docs/leds/yellow-led-data-sheet.pdf), we see these two values:

<table>
<thead>
<tr>
<th>ITEMS</th>
<th>Symbol</th>
<th>Absolute Maximum Rating</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward Current</td>
<td>If</td>
<td>20</td>
<td>mA</td>
</tr>
</tbody>
</table>

And..

<table>
<thead>
<tr>
<th>ITEMS</th>
<th>Symbol</th>
<th>Test condition</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward Voltage</td>
<td>Vf</td>
<td>I&lt;sub&gt;r&lt;/sub&gt;=20mA</td>
<td>1.8</td>
<td>---</td>
<td>2.2</td>
<td>V</td>
</tr>
</tbody>
</table>
The goal is to set the Forward Current for the LED at 20mA which means the LED will drop 1.8-2.2V. In this case, make the assumption THIS LED is going to drop 2V. (Please note that many LEDs will have a forward Current around 20mA. However, their voltage drop will typically vary depending on color.)

Using Ohm’s law the value of the R_LIMIT can be calculated. The R_LIMIT and LED are in series. This means their voltages add and the amount of current going through them is the same. This means the LED is dropping 2V across it and that 3V will be dropped across R_LIMIT. Since these two components are in series, 20mA of current will flow through both.

Ohm’s Law says that Resistance = Voltage / Current. This means R_LIMIT = 3.0V / 20mA = 150Ω.

Again, depending on the exact LED being used, the value of this resistor will change. Generally it will be in the range 150-470Ω. When in doubt, select a slightly large resistance value.

Conclusion
Diodes are simple, yet versatile components. LEDs extend these properties to include lights. LEDs have plenty of cool Matrix-based projects as well as more practical uses like status indicators. The information shown here shows how to find the Forward Voltage and Forward Current of an LED from its datasheet. Then Ohm’s Law is shown to calculate the correct limiting resistor.