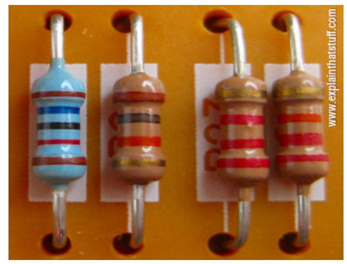
Brass Tacks

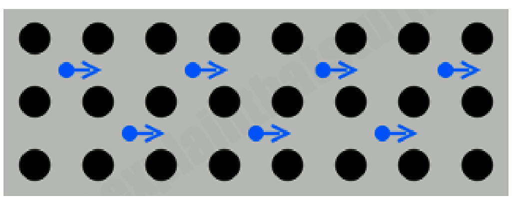
An in-depth look at Resistors with MW0JWP

Resistors



When you first learn about electricity, you discover that materials fall into two basic categories called conductors and insulators. Conductors (such as metals) let electricity flow through them; insulators (such as plastics and wood) generally do not. But nothing's quite so simple, is it? Any substance will conduct electricity if you put a big enough voltage across it: even air, which is normally an insulator, suddenly becomes a conductor when a powerful voltage builds up in the clouds—and that's what makes lightning. Rather than talking about conductors and insulators, it's often clearer to talk about resistance: the ease with which something will let electricity flow through it. A conductor has low resistance, while an insulator has much higher resistance. Devices called resistors let us introduce precisely controlled amounts of resistance into electrical circuits. Let's take a closer look at what they are and how they work!

What is resistance?



Electricity flows through a material carried by electrons, tiny charged particles inside atoms. Broadly speaking, materials that conduct electricity well are ones that allow electrons to flow freely through them.

In metals, for example, the atoms are locked into a solid, crystalline structure (a bit like a metal climbing frame in a playground). Although most of the electrons inside these atoms are fixed in place, some can swarm through the structure carrying electricity with them. That's why metals are good conductors: a metal puts up relatively little resistance to electrons flowing through it.

Plastics are entirely different. Although often solid, they don't have the same crystalline structure. Their molecules (which are typically very long, repetitive chains called polymers) are bonded together in such a way that the electrons inside the atoms are fully occupied. There are, in short, no free electrons that can move about in plastics to carry an electric current. Plastics are good insulators: they put up a high resistance to electrons flowing through them.

This is all a little vague for a subject like electronics, which requires precise control of electric currents. That's why we define resistance more precisely as the voltage in volts required to make a current of 1 amp flow through a circuit. If it takes 500 volts to make 1 amp flow, the resistance is 500 ohms (written 500 Ω). You might see this relationship written out as a mathematical equation:

$$V = I \times R$$

This is known as Ohm's Law for German physicist Georg Simon Ohm (1789–1854).

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Measuring resistance

Using a multimeter like this one, you can automatically find the resistance of an electronic component; the meter feeds a known current through the component, measures the voltage across it, and uses Ohm's law to calculate the resistance. Although multimeters are reasonably accurate, you have to remember that the leads and probes also have resistance that will introduce an error into your measurements (the smaller the resistance you're measuring, the bigger the likely error). Here, I'm measuring the resistance of a loudspeaker in a telephone, which you can see, from the digital display, is 36.4 Ω. Inset: a switch on the multimeter lets me measure a range of different resistances (200 Ω, 2000 Ω, 20K = 20,000 Ω, 200K = 200,000 Ω, and 20M = 20 million Ω).

Resistance is useless?

How many times have you heard bad guys say that in movies? It's often true in science as well. If a material has a high resistance, it means electricity will struggle to get through it. The more the electricity has to struggle, the more energy is wasted. That sounds like a bad idea, but sometimes resistance is far from "useless" and actually very helpful.

In an old-style light bulb, for example, electricity is made to flow through an extremely thin piece of wire called a filament. The wire is so thin that the electricity really has to fight to get through it. That makes the wire extremely hot—so much so, in fact, that it gives off light. Without resistance, light bulbs like this wouldn't function. Of course the drawback is that we have to waste a huge amount of energy heating up the filament. Old-style light bulbs like this make light by making heat and that's why they're called incandescent lamps; newer energy-efficient light bulbs make light without making much heat through the entirely different process of fluorescence.

The heat that filaments make isn't always wasted energy. In appliances like electric kettles, electric radiators, electric showers, coffee makers, and toasters, there are bigger and more durable versions of filaments called heating elements. When an electric current flows through them, they get hot enough to boil your water or cook your bread. In heating elements, at least, resistance is far from useless.

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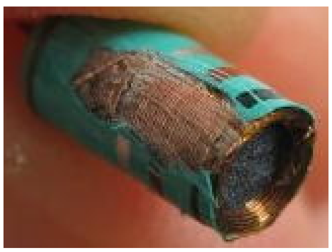
How resistors work

People who make electric or electronic circuits to do particular jobs often need to introduce precise amounts of resistance. They can do that by adding tiny components called resistors. A resistor is a little package of resistance: wire it into a circuit and you reduce the current by a precise amount. From the outside, all resistors look more or less the same. As you can see in the top photo on this page, and the one below, a resistor is a short, worm-like component with colored stripes on the side. It has two connections, one on either side, so you can hook it into a circuit.



What's going on inside a resistor? If you break one open, and scratch off the outer coating of insulating paint, you might see an insulating ceramic rod running through the middle with copper wire wrapped around the outside. A resistor like this is described as wire-wound. The number of copper turns controls the resistance very precisely: the more copper turns, and the thinner the copper, the higher the resistance. In smaller-value resistors, designed for lower-power circuits, the copper winding is replaced by a spiral pattern of carbon. Resistors like this are much cheaper to make and are called carbon-film. Generally, wire-wound resistors are more precise and more stable at higher operating temperatures.

How does the size of a resistor affect its resistance?

Suppose you're trying to force water through a pipe. Different sorts of pipes will be more or less obliging, so a fatter pipe will resist the water less than a thinner one and a shorter pipe will offer less resistance than a longer one. If you fill the pipe with, say, pebbles or sponge, water will still trickle through it but much more slowly. In other words, the length, cross-sectional area (the area you see looking into the pipe to see what's inside), and stuff inside the pipe all affect its resistance to water.

Electrical resistors are very similar—affected by the same three factors. If you make a wire thinner or longer, it's harder for electrons to wiggle through it. And, as we've already seen, it's harder for electricity to flow through some materials (insulators) than others (conductors). Although Georg Ohm is best known for relating voltage, current, and resistance, he also researched the relationship between resistance and the size and type of material from which a resistor is made. That led him to another important equation:

$$R = \rho \times L / A$$

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In simple words, the resistance (R) of a material increases as its length increases (so longer wires offer more resistance) and increases as its area decreases (thinner wires offer more resistance). The resistance is also related to the type of material from which a resistor is made, and that's indicated in this equation by the symbol ρ, which is called the resistivity, and measured in units of Ωm (ohm meters). Different materials have very different resistivities: conductors have much lower resistivity than insulators. At room temperature, aluminum comes in at about 2.8 x 10−8 Ωm, while copper (a better conductor) is significantly lower at 1.7 −8 Ωm. Silicon (a semiconductor) has a resistivity of about 1000 Ωm and glass (a good insulator) measures about 1012 Ωm. You can see from these figures how vastly different conductors and insulators are in their ability to carry electricity: silicon is about 100 billion times worse than copper and glass is about a billion times worse again!

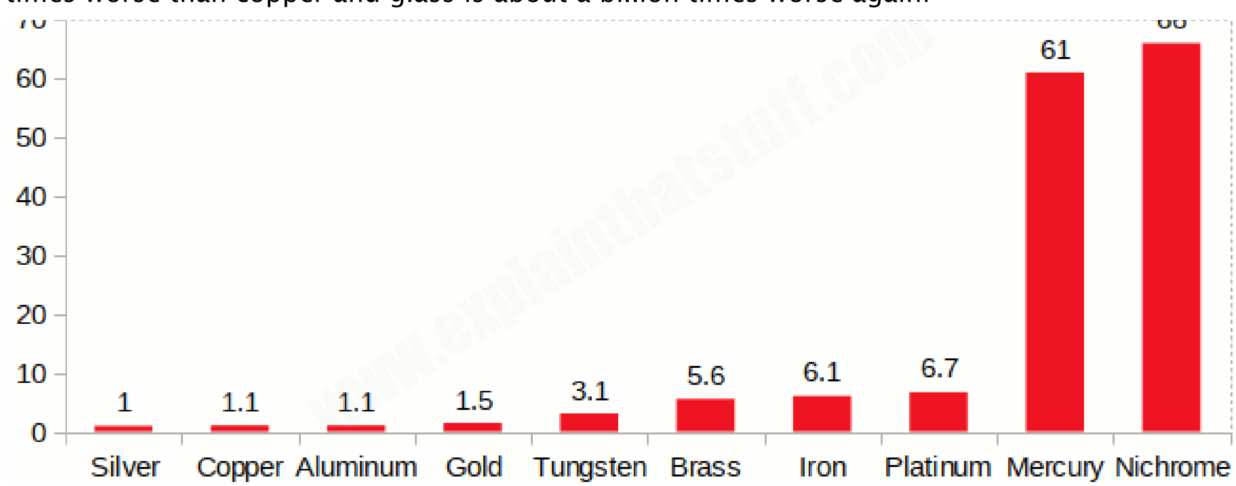
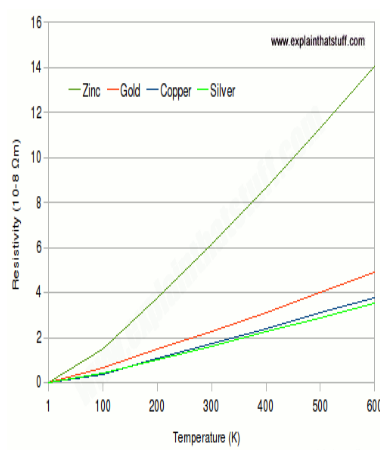


Chart showing how the resistivity of 10 common metals and alloys compares with silver at room temperature.

Resistance and temperature

The resistance of a resistor isn't constant, even if it's a certain material of a fixed length and area: it steadily increases as the temperature increases. Why? The hotter a material, the more its atoms or ions jiggle about and the harder it is for electrons to wriggle through, which translates into higher electrical resistance. Broadly speaking, the resistivity of most materials increases linearly with temperature (so if you increase the temperature by 10 degrees, the resistivity increases by a certain amount, and if you increase it by another 10 degrees, the resistivity rises by the same amount again). If you cool a material, you lower its resistivity—and if you cool it to an extremely low temperature, you can sometimes make the resistivity disappear altogether, in a phenomenon known as superconductivity.



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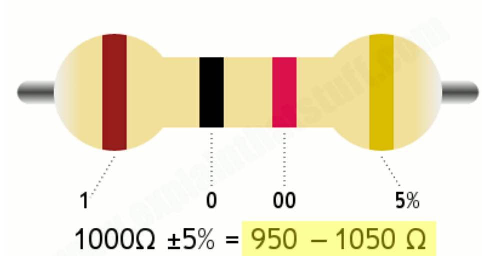
Resistor color codes

You can figure out the resistance of a resistor from the pattern of colored bands.



1. On most resistors, you'll see there are three rainbow-colored bands, then a space, then a fourth band colored brown, red, gold, or silver.
2. Turn the resistor so the three rainbow bands are on the left

1. 3. The first two of the rainbow bands tell you thefirst two digits of the resistance. Suppose you have a
resistor like the one shown here, with colored bands
that are brown, black, and red and a fourth golden
band. You can see from the color chart below that brown means 1 and black means 0, so the resistance is going to start with "10". The third band is a decimal multiplier: it tells you how many powers of ten to multiply the first two numbers by (or how many zeros to add on the end, if you prefer to think of it that way). Red means 2, so we multiply the 10 we've got already by 10 × 10 = 100 and get 1000. Our resistor is 1000 ohms.
4. The final band is called the tolerance and it tells you how accurate the resistance value you've just figured out is likely to be. If you have a final band colored gold, it means the resistance is accurate to within plus or minus 5 percent. So while the officially stated resistance is 1000 ohms, in practice, the real resistance is likely to be anywhere between 950 and 1050 ohms.
5. If there are five bands instead of four, the first three bands give the value of the resistance, the fourth band is the decimal multiplier, and the final band is the tolerance. Five-band resistors quoted with three digits and a multiplier, like this, are necessarily more accurate than four-band resistors, so they have a lower tolerance value.

RESISTOR COLOR CODES

Resistance values	Tolerance values
0 = Black	Brown ± 1%
1 = Brown	Red ±2%
2 = Red	Gold ±5%
3 = Orange	Silver ± 10%
4 = Yellow	
5 = Green	
6 = Blue	
7 = Violet	
8 = Grey	
9 = White	