

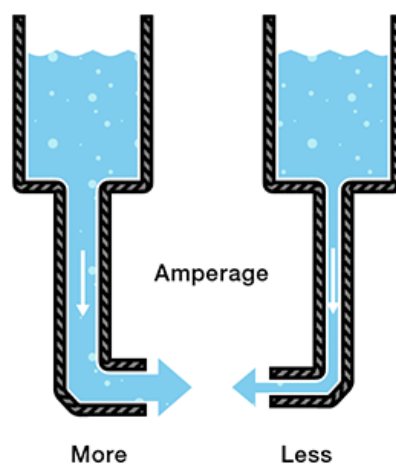
# Electrical Resistance

Dr Owen Williams – University of Wales TSD:

We can think of the amount of water flowing through a hose from a tank as current. The higher the pressure, the higher the flow, and vice-versa. With water, we would measure the volume of the water flowing through the hose over a certain period of time.

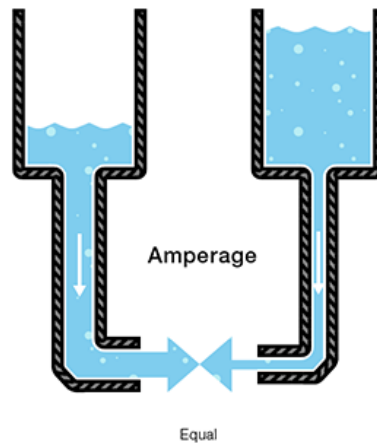
With electricity, we measure the amount of charge flowing through the circuit over a period of time. Current is measured in Amperes and an ampere is defined as  $6.241 \times 10^{18}$  electrons (1 Coulomb) per second passing through a point in a circuit. Amps are represented in equations by the letter "I".

Let's say now that we have two tanks, each with a hose coming from the bottom. Each tank has the exact same amount of water, but the hose on one tank is narrower than the hose on the other.



We measure the same amount of pressure at the end of either hose, but when the water begins to flow, the flow rate of the water in the tank with the narrower hose will be less than the flow rate of the water in the tank with the wider hose.

In electrical terms, the current through the narrower hose is less than the current through the wider hose. If we want the flow to be the same through both hoses, we have to increase the amount of water (charge) in the tank with the narrower hose.



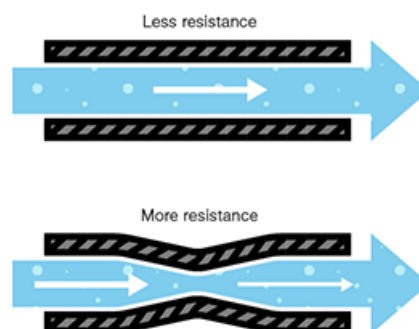
This increases the pressure (voltage) at the end of the narrower hose, pushing more water through the tank. This is analogous to an increase in voltage that causes an increase in current.

Now we're starting to see the relationship between voltage and current. But there is a third factor to be considered here: the width of the hose. In this analogy, the width of the hose is the resistance. This means we need to add another term to our model:

- Water = Charge (measured in Coulombs)
- Pressure = Voltage (measured in Volts)
- Flow = Current (measured in Amperes, or "Amps" for short)
- **Hose Width = Resistance**

It stands to reason that we can't fit as much volume through a narrow pipe than a wider one at the same pressure. This is resistance. The narrow pipe "resists" the flow of water through it even though the water is at the same pressure as the tank with the wider pipe.

#### Resistance



In electrical terms, this is represented by two circuits with equal voltages and different resistances. The circuit with the higher resistance will allow less charge to flow, meaning the circuit with higher resistance has less current flowing through it.

This brings us back to Georg Ohm. Ohm defines the unit of resistance of "1 Ohm" as the resistance between two points in a conductor where the application of 1 volt will push 1 ampere, or  $6.241 \times 10^{18}$  electrons. This value is usually represented in schematics with the Greek letter " $\Omega$ ", which is called omega, and pronounced "ohm".

Combining the elements of voltage, current, and resistance, Ohm developed the formula:

$$V = I \cdot R$$

Where

- V = Voltage in volts
- I = Current in amps
- R = Resistance in ohms

This is called Ohm's law. Let's say, for example, that we have a circuit with the potential of 1 volt, a current of 1 amp, and resistance of 1 ohm. Using Ohm's Law we can say:

$$1V = 1A \cdot 1\Omega$$

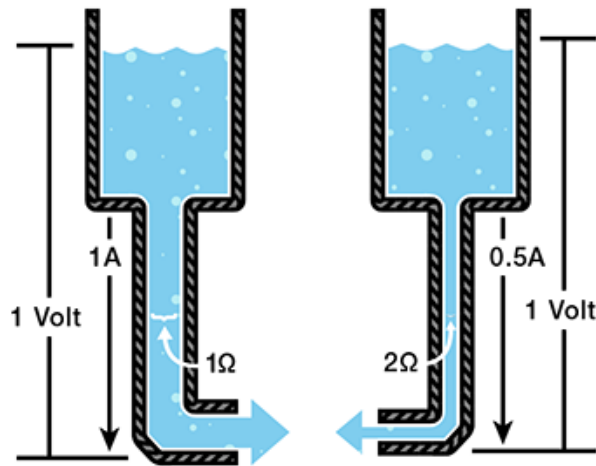
Let's say this represents our tank with a wide hose. The amount of water in the tank is defined as 1 volt and the "narrowness" (resistance to flow) of the hose is defined as 1 ohm. Using Ohms Law, this gives us a flow (current) of 1 amp.

Using this analogy, let's now look at the tank with the narrow hose. Because the hose is narrower, its resistance to flow is higher. Let's define this resistance as 2 ohms. The amount of water in the tank is the same as the other tank, so, using Ohm's Law, our equation for the tank with the narrow hose is

$$1V = ? A \cdot 2\Omega$$

But what is the current? Because the resistance is greater, and the voltage is the same, this gives us a current value of 0.5 amps:

$$1V = 0.5A \cdot 2\Omega$$



So, the current is lower in the tank with higher resistance. Now we can see that if we know two of the values for Ohm's law, we can solve for the third. Let's demonstrate this with an experiment.

### ***An Ohm's Law Experiment:***

For this experiment, we want to use a 9 volt battery to power an LED. LEDs are fragile and can only have a certain amount of current flowing through them before they burn out. In the documentation for an LED, there will always be a "current rating". This is the maximum amount of current that can flow through the particular LED before it burns out.

### **Materials Required**

In order to perform the experiments listed at the end of the tutorial, you will need:

- A multimeter
- A 9-Volt battery
- A 560-Ohm resistor (or the next closest value)
- An LED

**NOTE:** LEDs are what's known as a "non-ohmic" devices. This means that the equation for the current flowing through the LED itself is not as simple as  $V=IR$ . The LED introduces something called a "voltage drop" into the circuit, thus changing the amount of current running through it. However, in this experiment we are simply trying to protect the LED from over-current, so we will neglect the current characteristics of the LED and choose the resistor value using Ohm's Law in order to be sure that the current through the LED is safely under 20mA.

For this example, we have a 9 volt battery and a red LED with a current rating of 20 milliamps, or 0.020 amps. To be safe, we'd rather not drive the LED at its maximum current but rather its suggested current, which is listed on its datasheet as 18mA, or 0.018 amps. If we simply connect the LED directly to the battery, the values for Ohm's law look like this:

$$V = I \cdot R$$

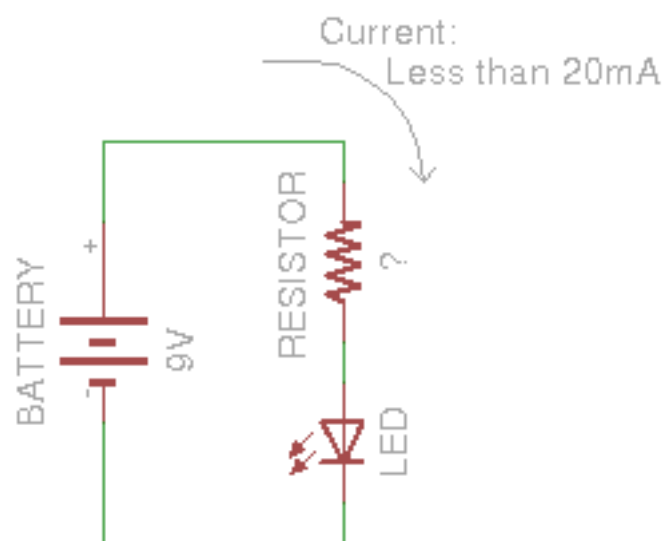
therefore:

$$I = \frac{V}{R}$$

and since we have no resistance yet:

$$I = \frac{9V}{0\Omega}$$

Dividing by zero gives us infinite current! Well, not infinite in practice, but as much current as the battery can deliver. Since we do NOT want that much current flowing through our LED, we're going to need a resistor. Our circuit should look like this:



We can use Ohm's Law in the exact same way to determine the resistor value that will give us the desired current value:

$$V = I \cdot R$$

therefore:

$$R = \frac{V}{I}$$

plugging in our values:

$$R = \frac{9V}{0.018A}$$

solving for resistance:

$$R = 500\Omega$$

So, we need a resistor value of around 500 ohms to keep the current through the LED under the maximum current rating.



500 ohms is not a common value for off-the-shelf resistors, so we use a 560 ohm resistor in its place. Here's what our device looks like all put together.



Success! We've chosen a resistor value that is high enough to keep the current through the LED below its maximum rating, but low enough that the current is sufficient to keep the LED nice and bright.

This LED/current-limiting resistor example is a common occurrence in hobby electronics. You'll often need to use Ohm's Law to change the amount of current flowing through the circuit.

Another example of this implementation is seen in the LilyPad LED boards.



With this setup, instead of having to choose the resistor for the LED, the resistor is already on-board with the LED so the current-limiting is accomplished without having to add a resistor by hand.

Current Limiting Before or After the LED?

To make things a little more complicated, you can place the current limiting resistor on either side of the LED, and it will work just the same!

Many folks learning electronics for the first time struggle with the idea that a current limiting resistor can live on either side of the LED and the circuit will still function as usual.

Imagine a river in a continuous loop, an infinite, circular, flowing river. If we were to place a dam in it, the entire river would stop flowing, not just one side. Now imagine we place a water wheel in the river which slows the flow of the river. It wouldn't matter where in the circle the water wheel is placed; it will still slow the flow on the *entire river*.

This is an oversimplification, as the current limiting resistor cannot be placed *anywhere in the circuit*; it can be placed on *either side* of the LED to perform its function.

Resistance - <https://youtu.be/8jB6hDUqNOY>

## Higher Power Electronics (Safe – RC Cars)

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**This section is really written with RC cars and other high-power model applications in mind, but as we scale up the power towards the full-scale vehicle, the same issues and precautions become relevant, though at this scale, it is unlikely to kill you. So, we start here!**

### **Will a larger battery make my vehicle faster?**

A larger (bigger or higher Amp hour capacity) battery with the same open circuit voltage will make your vehicle faster **only** if it has lower internal series resistance and can, therefore, deliver more current to the same resistance load. e.g. your motor.

Think about it using a bucket of water analogy. A fixed diameter hole (resistance), a fixed depth (voltage) below the surface, will leak water at the same rate (current) for any diameter (e.g. capacity) of bucket.

### **How do wiring and connectors affect performance?**

Though it's typically very low (only fractions of an Ohm), wires and connectors do have resistance.

Consider a 24 V battery pack with a motor that draws 25 Amps. We measure only 22.5 Volts across the motor. The rest is lost on the wiring and connectors. Ohms law tells us they have  $(24 - 22.5) = 1.5 / 25 = 0.06$  Ohms of resistance.

Let's say we can reduce their contribution 5X to 0.012 ohms. The voltage drop in the wiring is now 5 times lower. Ohm's law again,  $V = I \cdot R \Rightarrow 25 \times 0.012 = 0.3$  Volts.

Power (Watts) =  $V \times A \Rightarrow 0.3 \times 25 = 7.5$  Watts lost in the wiring and connectors compared to the  $1.5 \times 25 = 37.5$  W we started with.

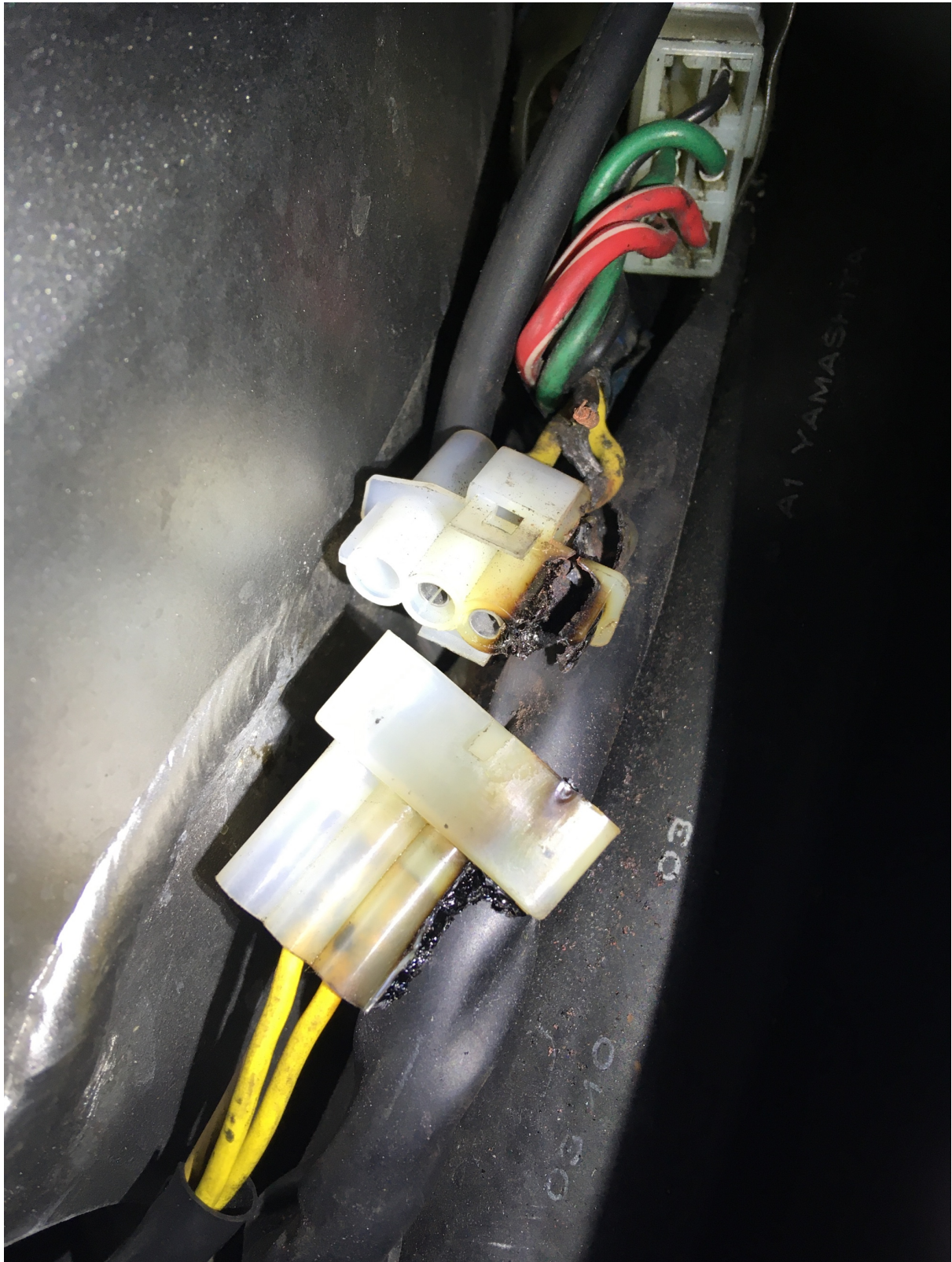
In reality the motor current and speed would go up because of the increased voltage, but the fraction of power going into your motor has gone up too and that's the goal.

So, using fat wires and low resistance connectors can pay off. Your motor gets more voltage and less of your battery's energy is going into heating your connectors and wires!

### **Why must I use connectors designed for high current?**

Like the wires they connect, connectors have resistance that's measured in Ohms. That resistance depends on the type of metals making contact and the total contact area. Other things being equal, increasing the contact pressure (from crimping or spring tension) maximizes contact surface area and thus lowers resistance.

Another benefit of higher contact pressure is reduced vibration induced (fretting) corrosion. This is because the increased pressure reduces the relative motion between the contact faces and that motion tends to create metal oxides that increase contact resistance.



Properly designed noble metal contacts (e.g. Gold plated over Nickel) or contacts with a contact lubricant minimize fretting corrosion. Increased contact resistance creates positive thermal feedback that heats and destroys contacts.

Here's an example.

A contact having a resistance of 0.015 Ohms and 35 Amps current through it means that contact must dissipate ( $P=I^2 \times R$ )  $35 \times 35 \times 0.015 = 18.4$  Watts of power!

The thermal insulation of heat shrink tubing, and being buried in your equipment gives you the equivalent of a small soldering iron getting pretty hot.

Unlike wires, a contact's resistance is developed over the tiny area that actually makes contact between the mating connectors. In a contact all that generated heat is dissipated over that tiny area rather than the whole bulk of a wire.

The heat increases the contact's resistance (since a metal's reduced stiffness at temperature reduces contact pressure) and more power in the system goes into the contact until something bad happens.

Note that the squared relationship of current to power dissipation in resistance means things change fast at higher currents.

E.g., at 49 amps the contact is dissipating 36 Watts! The current in your circuit "I" is the voltage divided by total resistance. e.g.  $I=V/R$ . (in Amps, Volts and Ohms). If your contact resistance increases, some of your battery voltage is now wasted across your contacts instead of going to your motor and its speed control.

Your maximum current is less because there's more total resistance (assuming the motor control is wide open). What gets lost is Power.

If you measure the Amps through and Volts across your connector you can find its resistance (Ohms) and power dissipation (Watts) and know Watt's what (sorry).

Yes, a "Watt meter" that can measure down to 0 volts will be a handy tool for testing these things. Armed with the above, you can measure just what your situation is and verify it isn't degrading over time.

## What's the difference between *continuous* and *intermittent* current measurement specifications?

Specifying a parameter, e.g. current, as continuous means you can expect the device to handle it, well..., continuously.

That means it shouldn't be damaged by operating at that amount.

A parameter not obviously specified as continuous **may not be!** Convention may expect it to be so (e.g. a household light bulb has a continuous voltage rating that's unstated), but you should check it as failure to be so rated could cause damage or error if used continuously.

Intermittent ratings, ideally, have a time or *duty cycle* associated with them. E.g. 100 Amps of current for 20 s per minute means the device should handle 100 Amps for a total of 20 seconds in any 60 second interval.

That is also called a 33% duty cycle over a minute because the device can handle the rated amount for  $20/60 = \text{one third}$  or 33 percent of the minute.

Here's an example.

When high currents flow in wires, their electrical resistance produces heat. That's how an incandescent light bulb filament works. A test device like a Watt meter may produce 10 Watts of heating with 100 Amps running through it due to its internal resistance. That's like a small soldering iron.

If on for a few seconds, it would barely warm up. But after 10 minutes it might have melted the case! So, it might have an *intermittent* rating of 100 Amps for say one minute in any ten or a 10% duty cycle over ten minutes.

That same Watt meter might be able to continuously handle 20 amps corresponding to 0.4 Watts of heating *continuously*.

While we have discussed current, continuous versus intermittent ratings are relevant for many specified parameters. Other examples are voltage, temperature, pressure, acidity and duration of a baby crying.