Essential Electricity

Note: This is an expansion of the basics section from my Electronics For Contraptions tutor.

The Simplest Circuit:

We can make current flow in a circle (circuit) by connecting the terminals of a battery together. This will melt the wire, make sparks fly and maybe start a fire, so don't do it. Instead, connect something to control the current. The ability to control current is called resistance, and all materials have it to some degree--in fact we classify materials according to their resistance: those with very low resistance are conductors, those with lots of resistance are insulators. There are devices called resistors that are used in electronic gadgets--they have a resistance that is predictable. So figure 1 is a safe circuit.

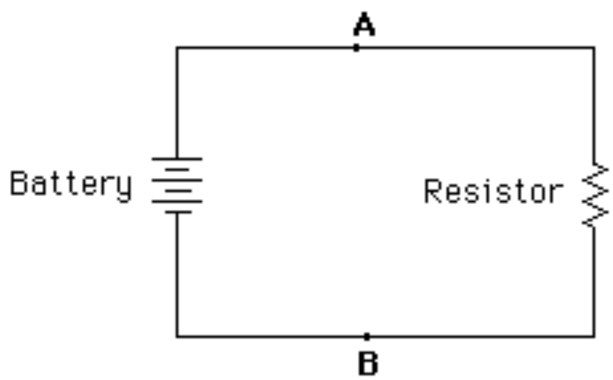


Figure 1.

The battery has a certain amount of push, called **electromotive force** or **EMF**. This is measured in units called **volts**. We indicate EMF (most commonly called **voltage**) in formulas with the letter **E**. Voltage has to be measured between two points in the circuit in the same way that height has to be measured between two points on the side of a mountain. There is no such thing as "0 volts" except that the voltage between two points is 0 if they are connected together. We put a sign with voltage to indicate the direction of current. The sign is sort of arbitrary-- + 9 volts just means we are looking at the + end of the battery. The electrons that make up current flow from - to +. Electrical engineers usually think of current as flowing from + to -.

Resistance is the opposition to the steady flow current. Everything in the circuit has resistance, but for convenience, we pretend all of the resistance of a circuit is in one device The resistor has a specific amount of resistance measured in units called **ohms**. We indicate resistance in formulas with the letter **R**, and on drawings with an omega symbol (Ω).

When current is flowing, we measure it in units called **amperes**, and indicate it with a letter **I**.

The three are related by a simple formula called Ohm's Law

$$I=E/R$$

Also written **E = IR** or **R=E/I.**

It may be easier to remember if I say:

$$\text{Current} = \frac{\text{Voltage}}{\text{Resistance}}$$

That tells us the current if we know the voltage and resistance, the voltage if we know the current and resistance, or the resistance if we know the current and voltage. If this seems a bit circular to you, you're right. We can measure current by the strength of magnetic field it will generate, but there is no yardstick for voltage other than seeing how much current flows through a known resistance. And how is a resistance known? We apply a known voltage and see how much current flows[1].

The definition of the units is circular too: 1 ampere is the amount of current that flows through a 1 ohm resistor if 1 volt is applied. Finding how much current will flow with a specified voltage and resistance is the most common calculation in electronics work.

Power

There's another calculation we need to do nearly as often. The point of pushing electricity through a wire is usually to get some work done. This requires power, which is related to the current and voltage. In fact, the power is the current times the voltage.

$$W=IE$$

or

$$\text{Watts} = \text{Volts X Amps}$$

Power is measured in watts (w), milliwatts (mw), or kilowatts (kw). We encounter power calculations in two contexts: power required to do a job (such

[1] We try to keep current flow low, unless we are building toasters. Thus, most circuits are designed for currents of a few thousandths of an amp. The unit prefix for thousandth is milli. Currents of a milliamp (ma) usually imply resistances of 1000 ohms, or a kiloOhm (kΩ). 2k = 2000 Ohms.

as light a room) and the ability of electronic components to handle power. This last is known as power rating. If we try to run more power though a component than it is rated for, it will probably fail. We discover a device's power rating by looking at the specifications. Often this is given as a current limit at a rated voltage, but it is just common to see a rating in watts[2] and we have to do the math. Ether way, we must know the limits of our components.

Two resistors in series:
The basic Ohm's law calculations get a bit more complicated if there are two resistors:

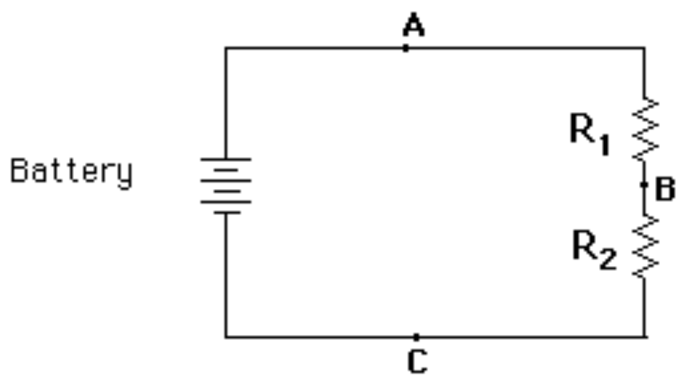


Figure 2.
Whatever the current is, it's the same at A, B, and C. (There isn't anywhere else for the current to flow.)

The voltage between A and C in figure 2 is equal to that between A and B added to that between B and C.

$$\mathbf{E}_{AC} = \mathbf{E}_{AB} + \mathbf{E}_{BC}$$

The voltages add up, just as the height[3] of a house is the sum of the heights of its stories.

The voltage across each resistor is proportional to the resistance of each resistor.

$$\mathbf{E}_{AB} \,/\, \mathbf{R}_1 = \mathbf{E}_{BC} / \,\mathbf{R}_2$$

Ohm's law is true for each part of a circuit as well as the circuit as a whole. The current in figure 2 is the same in each resistor, so the voltages will adjust themselves. This circuit is called a voltage divider. What we really want to know most of the time is the voltage at B:

$$\mathbf{E}_{BC} = \mathbf{E}_{AB} * \mathbf{R}_2 \,/\, \mathbf{R}_1 + \mathbf{R}_2$$

[2] Or VA for volts times amperes.
[3] The height metaphor is common enough that engineers often speak of "voltage drop".

The total resistance of figure 2 is $\mathbf{R}_1 + \mathbf{R}_2$.

Two Resistors in Parallel

When resistors are connected side by side, the math gets trickier;

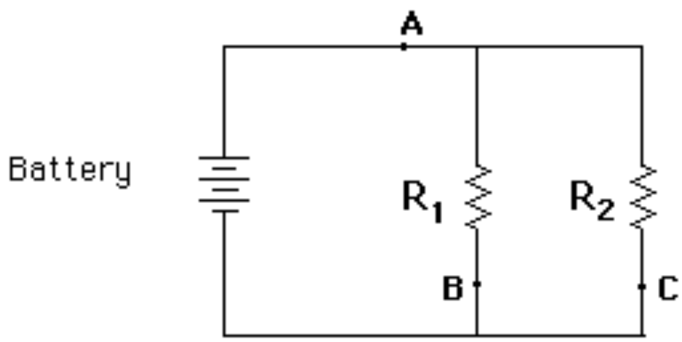


Figure 3.

The current through A in figure 3 equals the current through B plus the current through C. The current splits up and comes together, like water flowing around an island.

The voltage across $\mathbf{R}_1$ is the same as the voltage across $\mathbf{R}_2$.

$\mathbf{E}_{AB} = \mathbf{E}_{AC}$, so $\mathbf{I}_B \mathbf{R}_1 = \mathbf{I}_C \mathbf{R}_2$ and $\mathbf{I}_B / \mathbf{R}_2 = \mathbf{I}_C / \mathbf{R}_1$

In other words, the current through each resistor is inversely proportional to the values of the resistors. The point to remember is a high value resistor passes a small current.

We can solve the above for total current ($\mathbf{I}_B + \mathbf{I}_C$) and get the equivalent resistance for the two resistors:

$$\frac{1}{\frac{1}{R_1} + \frac{1}{R_2}}$$

In the special case where resistors are the same, the equivalent resistance is $\mathbf{R}_1\mathbf{/2}$. This turns up more often than you might expect.

In another special case, where R2 is more than 100 times the value of R1, R2 accounts for such a small portion of the current that we don't bother to include it in the calculations. Then we say R2 does not <u>load</u> the circuit.

A more complex example:

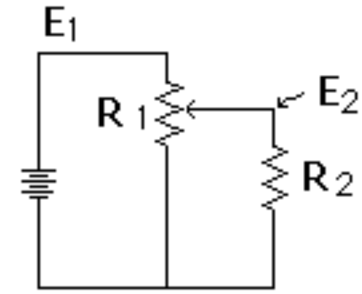


Figure 4.
In figure 4, R1 is a special type of resistor that has an adjustable tap in the middle[4]. This really makes R1 behave like two resistors in series. If we say R2 is 100 times R1, we can leave it out of the calculations, and find that the voltage E2 will vary directly with the position of the tap.

If R2 were comparable to R1 in value, we would have to figure it in, first solving R2 and the bottom part of R1 as two resistors in parallel, and using the result of that in a series calculation to find the voltage E2 and the total current. The resulting voltage curve makes a control behave oddly, so we really prefer to have an R2 that does not load the circuit. A good rule of thumb is to keep R2 10 times the value of R1. If R2 is some complex device, such as the input pin of an arduino, the effective value is specified as the *impedance* of the input. A low impedance input is 10k or less and a high impedance input would be 100k or greater. [5]

Changing Currents

Current is not always flowing, and when it flows it may often reverse and flow in the opposite direction. We generally use changes in current to convey information such as audio signals. The study of changing currents (often called AC currents) is not really necessary for contraption building, but there are a few things that are useful to know. Some devices react in odd ways when the current through them is changed. Inductors (coils of wire around a magnetic core), for instance, develop a magnetic field when current is run through them, but when the current is stopped, the collapsing magnetic field generates extra current that flows for a moment after the source is removed. When the current is first applied, it takes a while for the field to build up, so the flow of current is late getting started. This is fascinating and immensely useful for engineers designing high frequency circuits, but the main effect on our contraption building is devices that have coils in them (motors and relays) will occasionally produce unexpected spikes of current.

[4] It's called a potentiometer, or pot.
[5] Arduinos have a high input impedance unless the pull-up resistors are engaged.

Capacitors

Another device that reacts oddly to changes in current is the capacitor[6]. This is made of two conductive elements separated by an insulator. Think of a stack of three pie pans, with the outer ones made of metal and the center one glass. When a voltage is applied across the two metal pans, some electrons will be pulled out of the glass toward the positive pan, and a similar number of electrons will be stuffed into the glass on the negative side. There is a limit to the number of electrons that can be redistributed this way, which is called the capacitance of the device. When this limit is reached, the capacitor is fully charged. If the two metal pans are then wired directly together, current will flow from one to another, in the opposite of the original direction. When the current is first applied to a discharged capacitor, a large current will flow, as if the resistance were small. As the capacitor charges up the current decreases as if the resistance were increasing. Ohm's law shows the voltage increases in a curve that levels off.

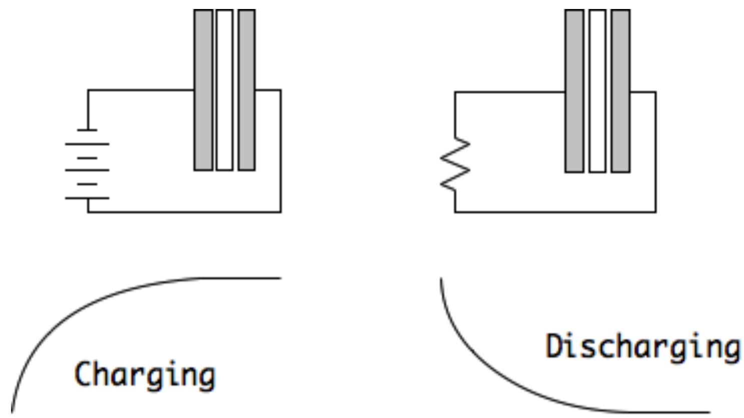
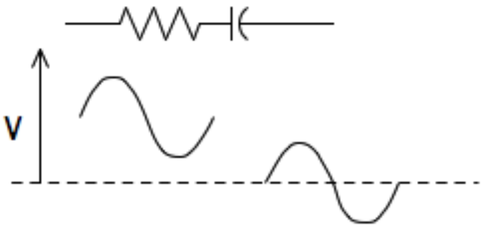


Figure 5.

We can take advantage of this effect to create a circuit where the voltage changes in a predictable amount of time. If a resistor is put in series with the capacitor, the time it takes the voltage at the point between the two to increase to 63% of the applied voltage is equal to RC, where C is capacitance in Farads and the time is in seconds. This time is known as the time constant of the circuit. We generally use capacitors in two ways: DC blocking and voltage smoothing. If you apply an AC signal to one side of a capacitive circuit with a long time constant, the AC component of the signal will appear to pass through the capacitor, but any DC component will be removed, leaving a signal that has equal positive and negative swing. We use capacitors this way to separate parts of a complex AC circuit.

[6] Also known as a condenser.



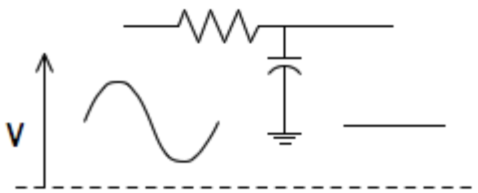


Figure 6. DC blocking Voltage smoothing

If you connect the capacitor to ground, making a voltage divider, the voltage at the connection between the resistor and capacitor will be the average voltage with the signal removed. We do this in power supplies, where we must convert AC to a steady DC.

Impedance

Inductors and capacitors both obey Ohm's law, but you can see that while the current is changing Ohm's law is bent a bit. In fact, if the current is constantly changing direction, as in an audio signal, the voltage/current relationship is quite different from what you get with steady (DC) current. We account for this with the concept of reactance, defined as opposition to changing current. Reactance depends on the frequency of the current change. The reactance of a inductor is low for low frequency signals and increases with frequency. This makes sense when you remember an inductor is a continuous coil of wire. The reactance of a capacitor is high for low frequencies and decreases with frequency. This also makes sense-- the two plates of the capacitor are not actually connected and current only flows during the charge or discharge.

The combination of reactance and resistance is impedance. There are formulas for calculating this, but we won't be using them. All we need to know is that AC signals obey Ohm's law when impedance is used instead of resistance, and the frequency must be specified to know the impedance. The symbol for impedance is Z.

$$I=E/Z$$

Power Factors

The power law also gets bent when the current is changing. Watts are still Volts x Amps, but you have to take into account the fact that the voltage and current may not be in phase. This happens when transformers and capacitors are involved. The actual power draw is measured instant by instant (it’s a differential equation actually) and that what the heating will be and what the power company will charge you for. However, if you want to figure out how heavy the wiring must be or what fuse to use, you have to allow for the peak current. Thus, instead of watts, you want to know a rating called VA or volt-amps. You can't really calculate this, but it is usually printed on a device somewhere. The ratio of watts to VA is called power factor, and is a fraction or percentage. (VA is always equal to or greater that the power.) The Power factor of a resistive load like a light bulb is 1. The Power factor of a motor driven device like a vacuum cleaner can be something like 0.35.

Divide VA by the power line voltage to get the current you need to allow for. Uninterruptable power supplies usually specify VA in addition to watts. Or maybe instead of, since it's a bigger number.)

Wiring

One time where we really need to know about current is when choosing wire. The current a wire can carry is limited by the wire cross section or gauge. Gauge is specified by a number–the larger the number, the smaller the wire. Common wire gauges are from 000 to 32. Gauge is usually printed on the insulation of big wires, but for thin wire you have to look at the reel, or check it against a sized stripper. Stranded wire is less efficient than solid wire of equal size, so it will have a higher gauge rating. Here is a chart for gauges you are likely to work with.

Gauge	Ohms/1000 ft	Max Amps
14	8.282	32
15	10.44352	28
16	13.17248	22
17	16.60992	19
18	20.9428	16
19	26.40728	14
20	33.292	11
21	41.984	9
22	52.9392	7
23	66.7808	4.7
24	84.1976	3.5
25	106.1736	2.7
26	133.8568	2.2
27	168.8216	1.7
28	212.872	1.4
29	268.4024	1.2
30	338.496	0.86
31	426.728	0.7
32	538.248	0.53

Wire heats up when current passes through it, and the amount of heat generated is proportional to I^2R, so it is important to know the resistance of wire per foot. Of course the longer or thinner the wire, the greater the resistance. Long wires will heat up, but the increase in resistance also limits the current. There is a common scenario where an extension cord is overloaded at the end, but the resistance of the wire keeps the fuse from blowing while the wire burns. Thus we have maximum lengths for extension cords of a given gauge, and wattage limits for a give length.

Wire resistance also has repercussions for hooking up speakers. That's why Monster Wire is so thick.

Wire color codes

There is a standard set of colors for the wire in extension cords–

Live (hot)	Brown or Black
Neutral	Blue or White
Safety ground	Green & Yellow or just Green

When you put a plug on a cable, connect the live wire to the brass tab or screw, the neutral wire to the silver tab or screw, and the ground to the green.