Introduction to Circuits

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1 What can you use electricity for?

Think of ways you use electricity in your daily life, and where it appears in modern infrastructure. How does electricity travel around? What does it do when it arrives in a machine?

2 What do circuits look like?

Take a look at these 6 different circuits. Do they look familiar to you? What specific components can you identify in each circuit, and what do they do? Are there similarities between some forms? Are there differences?

3 Circuit #1: LED + Resistor

Make a circuit using a 9V battery with leads, a resistor, and a red LED. Use alligator clips to connect:

- the red battery lead to the resistor,

- the resistor to the long (bent) leg of the LED, and

- the short (straight) leg of the LED to the black battery lead.

After you have it working, try the following changes, and see what happens. Don't forget to undo each change before trying the next one!

1. Disconnect one of the alligator clips.

2. Switch the battery leads.

3. Switch the resistor leads.

4. Switch the LED leads.

4 What's going on in this circuit?

The essential elements of a working circuit are a voltage source, a load, and some connectors. In this case, the battery is the voltage source, the resistor and LED are the load, and the alligator clips are the connectors.

Think of electricity like water flowing around. A voltage source is like a pump, raising it up high so it can do some work. The current flows along the wires, which are like flat canals. When it hits a resistor, it falls off a cliff and loses some of its energy. Usually this produces some heat, but it can also produce light or motion. In a closed circuit loop, the total voltage drop over all the resistors has to equal the total voltage source, otherwise it doesn't have enough energy to make it all the way around. This requirement is called Kirchoff's Voltage Law.

5   Mathematical Interlude

How can we quantify this flow of electrons around the circuit? Empirically, the current (I) in a circuit is related to the voltage (V) and total resistance (R) by $V = IR$. This is Ohm's Law. The same current flows through every part of the loop, because electrons are conserved. So the voltage drop across an individual resistor R_1 can be found using $IR_1 = V_1$.

The power P dissipated by a circuit element, as light, heat, motion, or whatever else, is the rate of work done by moving current I through a voltage V, so $P = IV$. The unit of electric power is the watt (W). For example, a 60W lightbulb generates 60W of heat and light at all times, and if turned on for 3 hours, consumes $180W \cdot h$ of energy. Conversely, batteries are rated in watt-hours as well as volts, so a typical AA cell will provide 3W for 1 hour or 1.5W for 2 hours.

6   Circuit #2: LED + More Resistors

Let's revisit the first circuit you built with alligator clips. This time, grab a different resistor out of your supply and use it in the circuit. Keep trying different resistors until you see a change in the LED brightness. How much resistance did you need to add?

Resistor Value	Color Code
$22 \times 10^1 = 220\Omega$	red red brown (gold)
$56 \times 10^1 = 560\Omega$	green blue brown (gold)
$10 \times 10^2 = 1k\Omega$	brown black red (gold)
$10 \times 10^3 = 10k\Omega$	brown black orange (gold)

Table 1: Resistors have printed stripes denoting their value. The first two or three stripes are the digits, followed by one stripe for the exponent value, and the last stripe giving the tolerance or variation.

Color	Significant figures	Multiplier	Tolerance		Temp. Coefficient (ppm/K)	
Black	0	$\times 10^0$	–		250	U
Brown	1	$\times 10^1$	±1%	F	100	S
Red	2	$\times 10^2$	±2%	G	50	R
Orange	3	$\times 10^3$	–		15	P
Yellow	4	$\times 10^4$	(±5%)	–	25	Q
Green	5	$\times 10^5$	±0.5%	D	20	Z
Blue	6	$\times 10^6$	±0.25%	C	10	Z
Violet	7	$\times 10^7$	±0.1%	B	5	M
Gray	8	$\times 10^8$	±0.05% (±10%)	A	1	K
White	9	$\times 10^9$	–		–	
Gold	–	$\times 10^{-1}$	±5%	J	–	
Silver	–	$\times 10^{-2}$	±10%	K	–	
None	–	–	±20%	M	–	

Resistor color chart from Wikipedia.

7 Safety Interlude

Try connecting the battery leads directly to each other. Keep your hand on the battery. This is called a short circuit, and it can drain the battery or cause it to blow up. Batteries, being non-ideal voltage sources, have some small internal resistance, so they produce a lot of current when short-circuited. Too much current is generally bad for any circuit component. This is why power strips and household outlets use fuses to break the circuit before an overload can damage more expensive appliances, or cause a fire.

Diodes, including the LEDs we're using, are designed to only allow current to flow in one direction. If you apply voltage in the opposite direction, it may not flow, or it may overload the diode and break it. The threshold is known as the breakdown voltage. LEDs are often preferred over incandescent bulbs because they produce a lot of light with a relatively low amount of current, but the tradeoff is that too much current can burn it out. That's why LEDs in circuits always appear next to a resistor, to limit the amount of current that reaches it. The lower the current needed to run the LED, the higher the value of the current-limiting resistor. Let's practice finding this information on the datasheet for the LED.

8 Circuit Diagrams

We've introduced the symbols for batteries, resistors, and LEDs. These are used in circuit diagrams and schematics, to present the ideal design in a standardized form to aid collaboration and manufacture. Here's the diagram for the first circuit we built.
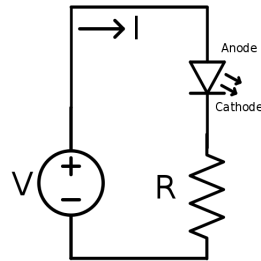

Diagram by Dmccreary at Wikimedia Commons.

How would you draw the second circuit, with more resistors?

9 Breadboards

For small-scale electronics prototyping and experimentation, you typically want something less fragile than alligator clips, but not as complex as a printed circuit board. The all-purpose tool of choice is the breadboard. It features power lines running the length of the board, and rows across the center which are connected together, like this:
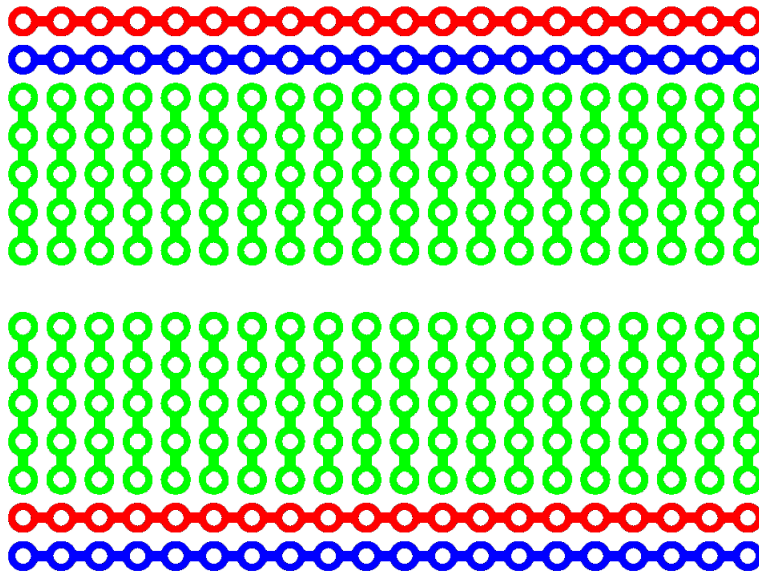

Derived from an image by McSush on Wikimedia Commons.

Go ahead and transfer your LED circuit, with one or more resistors, to the breadboard. Next, let's add a switch, so you can turn it off without disconnecting the power.

As you build more complex circuits on your breadboard, you might run into a problem: with all those component leads dangling about, it's easy to have a short circuit somewhere. To avoid damaging components, it's a good idea to build the circuit first, and connect the power to the board last. If it doesn't work, disconnect the power and double check that you've used the right components, with the right polarity, and followed the diagram carefully. If everything looks right, connect the power and start wiggling anything that might be shorted to its neighbor. You can also use a multimeter to identify spots where there's too much or too little current flowing.

10 Series and Parallel Circuits

So far, we've been building circuits with a single loop: voltage to resistance to voltage. The resistance consists of two separate elements, a resistor and an LED, connected in series. If you added extra resistors in circuit 2, those were also in series. We talked about how in a series circuit, the same current flows through every element, and the total voltage drop across all the elements equals the voltage source.
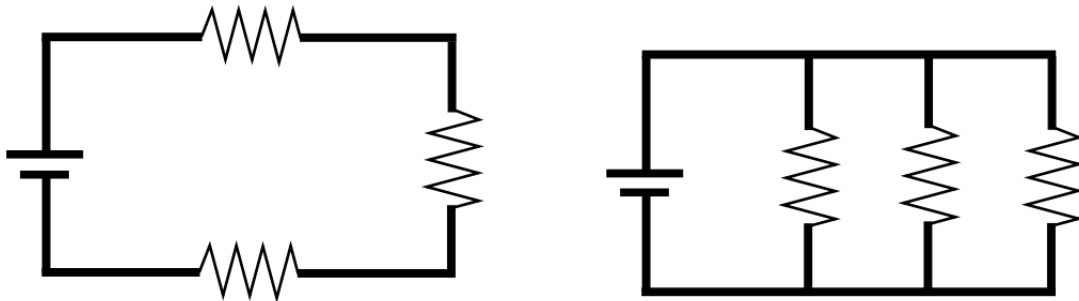
Diagrams of series and parallel circuits by Mets501 on Wikimedia Commons.

You can also connect the various elements to the voltage source in parallel. This produces the same voltage across each element, but a different current through each branch, depending on its resistance. For each of R_1, R_2, etc., $I_1 = V/R_1$. The total current flowing through the circuit is given by the sum of these branch currents, $I = I_1 + I_2 + ... = V/R_1 + V/R_2 + ...$ If you divide both sides by V, you can find the equivalent resistance of the whole network:

$$\frac{I}{V} = \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots$$

When is this equivalent resistance useful? If you're designing or analyzing a more complex circuit, you can turn several parallel elements into a single element that's in series with others. Modular design has its place in circuits, and being able to abstract away some details comes in handy. Another important concept when analyzing larger circuits is that, since current is conserved, the total current flowing into a node must equal the total current flowing out of that node. This is Kirchoff's Current Law.

11   Circuit #3: Parallel Resistors

Let's build a parallel circuit using an LED and one or more resistors, and use a multimeter to investigate how current flows through the network. Start with a single loop containing an LED and resistor. Measure the current across the LED. Add a parallel loop containing a resistor and an LED, and measure the current across each LED. Based on the resistor values, what do you calculate they should be? What will happen as you add more parallel branches?

If you measure the current across the resistor instead of the LED, you probably burnt out your light. This happens because the multimeter measure current by placing a small known resistor in parallel with the element you measure across. Since electrons take the path of least resistance, this creates a branch with low impedance and pulls a large voltage down through the LED.

12   Capacitors

Another common element in analog circuits is the capacitor. Conceptually, it stores charge by having two conductive surfaces separated by an insulator. When a voltage source is connected, positive charge accumulates on one surface, attracting negative charge on the other surface. When the voltage source is removed, the capacitor acts as a voltage source, decaying as the accumulated charge trickles away. This time-delayed action makes capacitors valuable as buffers against noisy power lines, and for various filtering and signal processing applications.

The equations describing what's going on in a capacitor are a bit more involved than those for a resistor. One key thing to remember is that the current flowing through the capacitor changes as it charges up, starting high and dropping to zero.

13   Circuit #4: Resistors + Capacitor

Let's build a circuit using a capacitor, and observe its charging and discharging. First, add a capacitor, long leg positive, after the LED in your first circuit. Connect the power and observe the LED for at least 30 seconds. Next, disconnect the battery and move the capacitor to the top of the circuit. Connect the long leg to the resistor, and the short leg to the short leg of the LED. Why can't you connect the capacitor in the other direction?