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Designed Learning

Joel Rosenberg

Courtesy of Joel Rosenberg

Key Concepts from Previous Chapters

17 Compressible and Noncompressible Fluids

18 Resistance

Electronic devices surround us: cell phones, computers, and MP3 players. While we all know that they run on electricity, many of us don't know what the electronics in our devices do, or even how electricity works. Part of the mystery is that we can't see electricity; we can only see what it does. I struggled with trying to understand electricity and electronics for years—and I'm still struggling! But by helping to create this high school engineering class, I now have a much better model for visualizing what's happening in an electric circuit, even though I still can't actually see what's going on in there.

My name is Joel Rosenberg, and I'm a curriculum writer at the Museum of Science in Boston. I've been developing the engineering class you're taking now. By telling you what I've gone through to get a grasp on electricity, I hope to make your job of understanding this stuff a little easier.

Courtesy of Joel Rosenberg

Soil moisture indicator

Electronics and Electricity

I built my first electronic circuit back in 1991, when I was in ninth grade. Everyone in my biology class had to build a "soil moisture indicator." It had a probe that was stuck into soil. If the soil wasn't moist enough, a light went on. The device was fun to build, but I didn't really learn about electronics—I just learned how to follow directions and assemble a kit of parts. My indicator worked, but I didn't understand how it worked.

I took two physics classes in high school, and electricity was a major subject in both. Afterward, I thought I had a pretty good grasp of electricity, but I still didn't completely understand how my soil moisture indicator worked. That's because there's a big difference between electricity and electronics. ***Electricity*** is what we call the electrical charge flowing in wires. ***Electronics*** is the way we control that electricity using devices such as transistors, integrated circuits, and computers.

Electricity
is what we call charge flowing through wires.

Electronics
is the way we control electricity in various devices.

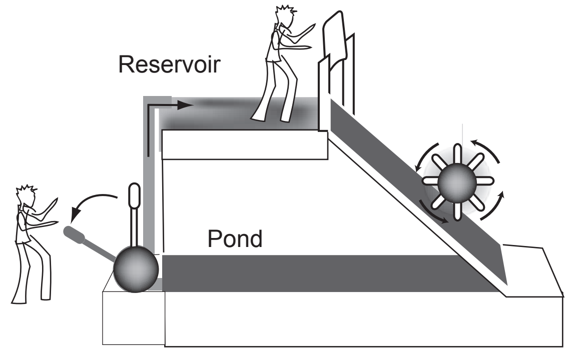
Toys and Electricity

I studied mechanical engineering in college because I liked the idea of building things. I was required to take another electricity class, but I wish I had taken an electronics class as well, because after college, I got an internship designing computer toys in a laboratory run by Intel, the computer chip company. The toys designed by people in this lab—a toy microscope, a toy sound recorder, and a toy video camera—displayed their results on computers. It struck me that these toys could be used to teach students about electricity, communications, and energy. I was excited about designing a fun and educational electronic toy, but I still didn't feel like I really understood electricity and electronics. It was time to learn.

Building a Model

I began by learning about different models that people have developed so I could get a sense of what electricity is. A model is a simplified way of thinking about a subject that makes it easier to understand. In my research, I discovered a few books that used water flow as a model for electrical charge flowing in a circuit.

In one book, a person is pumping water from a pond up a hill to a reservoir, and another person uses a gate to control the flow of water downhill. As the water flows downhill, it spins a wheel. The water returns to the pond at the bottom to be pumped upward again, completing a "circuit."



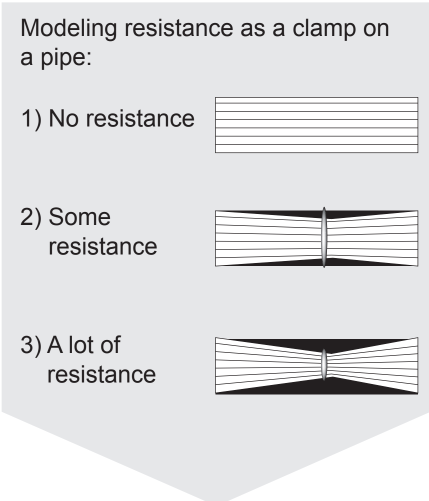
Water model

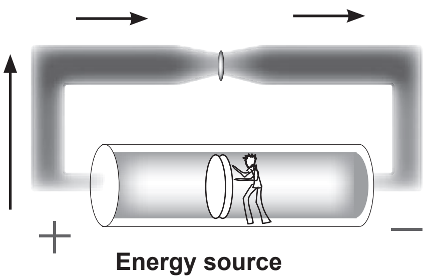
The person who controls the gate determines how fast the water flows downhill. If the gate is raised just a little, the energy will flow slowly and spin the wheel slowly. As the gate is raised, the volume of water flowing downhill increases because the gate provides a larger opening and less resistance to the water flow, so the wheel spins faster.

In this model the water represents electric ***charge*** and the wheel represents a ***load,*** such as a motor or light bulb. The gate represents ***resistance,*** because it controls the rate at which the water (charge) flows. The ***energy source,*** or battery, is the guy pumping the water. The current is the rate at which the water (charge) flows.

In some ways, it's helpful to visualize electric charge moving through a circuit as water moving around a "water circuit." But, like any model, this example has its limitations. I didn't like the falling water comparison because gravity plays no part in making electrical charge move through a circuit. So I decided to create my own model.

Revising the Model





Second water model

In my model, water flows around a closed loop of pipe lying flat on a table (so that gravity doesn't matter). Water (charge) fills the loop of pipe, but it will not move without a source of energy. The energy source is a tiny person in the pipe pushing water through a section of the pipe. The person in the "water battery" provides the energy but not the water, just as an electrical battery provides the energy but not the charge. When the person reaches the other end of the pipe, the battery would be "dead" and need more energy.

The speed or flow rate of the water is affected by just two things: how hard the person is pushing and the resistance of the pipe. The resistance of the pipe is like the resistance of the gate in the previous model. The pipe's resistance to flow can be varied by using a clamp to constrict the pipe, as shown in the diagram to the left. If the energy source always "pushes" with the same pressure, changing resistance (clamping the pipe) will change the flow of water passing through the pipe. So increasing resistance decreases the flow rate.

But if the energy source doesn't push as hard, the flow rate will decrease even if the resistance stays the same. To increase the flow of water, the tiny person, our energy source, has to push harder. Visualizing a circuit in this way was a breakthrough, because it gave me a better understanding of the relationship between resistance, energy, and current flow.

Of course, no model is perfect. Nonetheless, this model helped me better visualize what was going on in a circuit. As my understanding of electricity deepened, I gained confidence that I'd be able to teach it through the toys I had been developing.

Moving to the Museum of Science

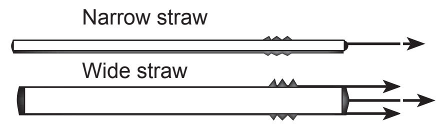
I moved to Boston and started working at the Museum of Science, teaching visitors about new technologies. When I found out the Museum was going to be creating this class, I jumped at the chance to contribute.

I have to admit that I was a bit nervous about what we were going to do for the electricity and communications unit. I realized that I needed an even better model to demonstrate what was going on in a circuit. Luckily, I found a new model that was developed by a whole team of teachers and college professors over a period of fifteen years. This new model uses air, not water, as an analogy for charge. That's a major change! Water and air are both fluids, but air is compressible and water isn't. As you'll see, air behaves more like electricity than water does.

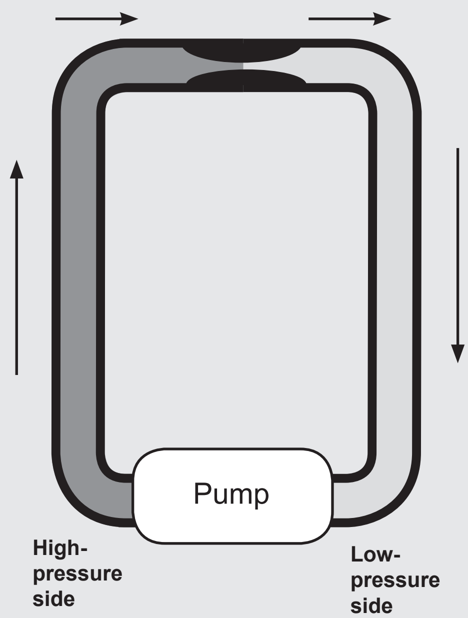
Think of an "air circuit," which is a closed pipe that is full of air. If we add an air pump into the circuit, it will create a pressure difference that will cause air to move through the circuit, from a high-pressure region on one side of the pump toward a lower-pressure region on the other side of the pump, until the pressure difference disappears.

The air moving through the pipe encounters resistance. It's harder to blow through a narrow straw than a wide straw, so reducing the diameter of the pipe increases resistance, slowing the flow of air through the pipe. Increasing the diameter reduces the resistance so the air flows more easily.

In this model the pump represents the ***battery,*** and the pressure difference represents a difference in ***voltage*** ("electric pressure difference"), which causes charge to flow. Decreasing the diameter of the pipe increases resistance to the flow of air, just as adding an electrical resistor to a circuit increases ***electrical resistance*** and decreases electrical current.

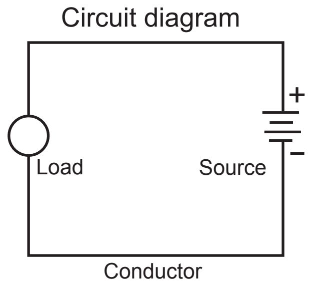


Resistance can be increased by narrowing the opening inside the pipe to resist the flow of air.



An air pump creates a pressure difference in an air circuit, just as a battery creates a voltage difference in an electrical circuit.

Air Model



So, What’s Electricity?

Electricity is an energy carrier. The ***charge*** flowing in the wires transports electrical energy from one point to another. Just as a home heating system uses water to move heat from a boiler throughout a house, in an electrical ***circuit*** the charge delivers electrical energy from a power source, such as a battery to the load. An electric circuit is a closed, continous conducting loop. Charge always flows in a loop, and the loop must be continuous and closed for charge to flow. Every circuit has a ***source,*** which provides the energy carried by the moving charge; a ***conductor,*** a material—often a wire—through which the charge can flow; and a ***load,*** a device that uses the energy supplied by the moving charge. You can’t see electricity. But you can see evidence that a charge is moving inside the wire.

In one of my classes in electricity, I learned that in the early 1800s a British scientist named Michael Faraday experimented with magnetic fields and charge. Like others before him, he observed that when you hold a compass near a wire with electricity passing through it, the compass needle deflects because of a magnetic field created by the moving charge. Faraday took these observations one step further. He was the first scientist to discover the link between magnetism and electricity. In one experiment, when he moved a magnet through a coil of wire wrapped around a paper tube, an electrical charge would flow through the wire, but the charge flowed only when the magnet was moving.

Today we use his discovery every day when we run motors that power everything from CD players to high-speed trains. His discovery also led to the invention of electrical generators that provide nearly all of the electrical energy that we use to power our homes, businesses, and industries.

Charge
flows through the circuit.

A ***circuit***

is a closed,
continuous conducting loop.

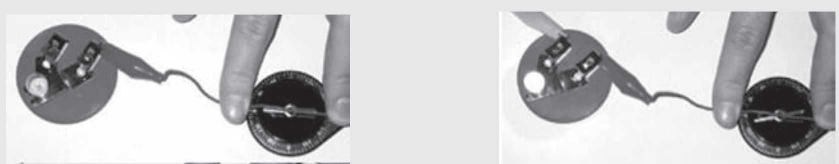
The ***source***

provides the energy carried by the moving charge.

The ***load***

uses the energy supplied by the moving charge.

You can’t see electricity. But you can see evidence that something is moving inside the wire. What moves inside the wire is called ***charge.***



Faraday discovered that a compass needle deflects when charge is flowing nearby because electricity moving through a wire produces a magnetic field.

Understanding Ohm's Law

I learned about Ohm's law in high school. Ohm's law describes the mathematical relationship between voltage (ΔV), current (I), and resistance (R). The first line shows how it's usually stated, but all three equations say the same thing.

$$\Delta V = I \times R$$

$$I = \Delta V / R$$

$$R = \Delta V / I$$

I learned the equation, and I could plug in values and solve problems on tests, but I didn't have the model to relate the equation to what's actually happening in a circuit. That's changed now that I'm using air as an analogy for charge.

With drinking straws, you provide a pressure difference by blowing. The resistance of the straw doesn't change, so if you blow harder (increase the pressure difference), more air will flow (more current). That is, if R stays the same and ΔV increases, then I increases too. If you now blow just as hard (same pressure difference) through a narrow straw (more resistance), less air will flow (less current). That is, if ΔV stays the same but R increases, then I will decrease.

Components that have a resistance that never changes are called resistors, and they obey Ohm's law, named after the man who discovered this relationship, Georg Ohm. The unit of resistance is the ohm (Ω). The unit for current is the ampere, or amp (A), and the unit for voltage (pressure difference) is the volt (V).

$\Delta V = IR$ Ohm's Law

ΔV ***Voltage difference*** is the electrical pressure difference in a circuit, measured in volts (V).

I ***Current*** is the flow rate of charge moving through a circuit. Current is measured in amps (A).

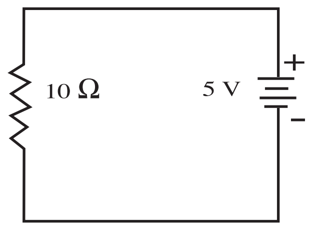
R ***Resistance*** is a property of the components of a circuit that slows the current flow. Resistance is measured in ohms (Ω).

Michael Faraday (1791–1867)

Georg Ohm (1789–1854)

Andre Marie Ampere (1775–1836)

Alessandro Volta (1745–1827)

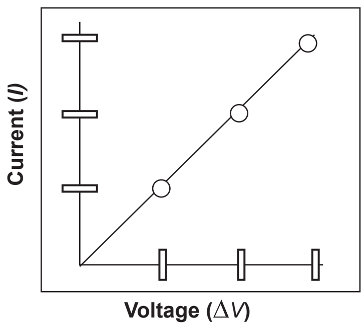


Consider an electric circuit with a 5-volt battery and a 10-ohm resistor. Using Ohm's law you can calculate the current (I) by solving the equation $I = \Delta V/R$ to find a current of 0.5 amp flowing through the resistor. If the voltage is doubled to 10 volts, the current will double to 1 amp. That is:

$$I = \Delta V / R$$

$$0.5\ \text{A} = 5\ \text{V} / 10\ \Omega$$

$$1\ \text{A} = 10\ \text{V} / 10\ \Omega$$



Current (I) and voltage (ΔV) have a linear relationship when resistance (R) is constant.

If you plot this relationship for several different values of I and ΔV, it forms a straight line, so it is called a ***linear*** relationship. However, if the resistance of a component changes when more current runs through it, the graph will no longer be a straight line. It will be a ***non-linear*** relationship, and you will not be able to use Ohm's law to make predictions about the current at different voltages.

Power

There's another equation I learned in high school that relates the power (P), current (I), and voltage difference (ΔV) in a circuit:

$$P = \Delta V \times I$$

This equation made even less sense to me than Ohm's law, but I've got it figured out now. Power (P) is the amount of energy transferred in a given amount of time. Its unit of measurement is the watt (W).

It's easiest to understand power by using an example. The outlets in our houses provide a standard voltage of 120V. That "electric pressure difference" is ready to push charge through whatever load you plug in. If you plug in a 60W bulb, you can calculate the current through the bulb using the following power equation:

$$P = \Delta V \times I$$

$$P = \Delta V \times I$$

$$60\ \text{W} = 120\ \text{V} \times I$$

$$I = 60\ \text{W} / 120\ \text{V} = 0.5\ \text{A}$$

P ***Power*** is the amount of energy transferred in a given amount of time. Power is measured in watts (W).

If you plug a 120W incandescent bulb into the same 120V outlet, then more energy transfers out of this much brighter bulb as more charge flows through it:

$$P = \Delta V \times I$$

$$120\text{ W} = 120\text{ V} \times I$$

$$I = 120\text{ W} / 120\text{ V} = 1.0\text{ A}$$

The reason I like the air model for electricity more than the water model is that it can do a better job of demonstrating power. With an electric circuit you can change a 60-watt bulb for a 120-watt bulb and expect to use up the energy twice as fast. But because water is an uncompressible fluid, the current flow is limited by the size of the pipe. If the pipe is filled with air, you can increase the pressure and rate of flow by pumping more air into the pipe.

Remember, charge and energy both flow together, and that's what we call "electricity." But energy leaves the circuit, while charge is recycled over and over again. If you forget, just think of a home heating system. Hot water is heated in a boiler. The hot water flows through pipes into a radiator, where the heat energy is transferred to the room. The cool water returns to the boiler, where it's heated again. So the water is cycled over and over again, like the electrical charge in a circuit. But the heat energy is not recycled. It flows from the boiler, through the hot water, and out into the room.

Keep On Learning

My new models have done a much better job of helping me to understand electricity. Now that you have a good grasp of batteries, circuits, inputs, and outputs, as well as current, voltage, resistance, and power, you should have a strong foundation upon which you can learn more about electricity and electronics.

And even if you don't study electricity beyond this class, you should remember one important point: Electrical circuits always require an energy source. The energy can come from the chemical reactions in a battery, turning a hand-cranked generator, the sun hitting a solar cell, or plugging your television into a wall outlet. Keep in mind that the wires behind the wall lead to a power plant. Some power plants burn coal, oil, or natural gas. Others use nuclear fuel, and in some places power is produced by running water or wind. Because we all use electricity pretty much all the time, we play a role in deciding where the energy should come from. It's an increasingly important decision as our demand for energy keeps rising. We can find ways to reduce our reliance on fuels, cut pollution, and help to protect the environment. Through our decisions we will engineer the future on this planet.

What's the Story?

1. Joel's early model of electricity used water as an analogy for charge. His current model uses air as an analogy. Why does he think air is a better analogy?

2. What's the difference between electricity and electronics?

Designing with Math and Science

3. Using words and drawings, describe voltage, current, and resistance.

4. Using Ohm's law, calculate the voltage required for a current of 3 amps to flow through a wire with a resistance of 2 ohms. Draw a diagram of this circuit.

5. Two 9-volt batteries provide power to a cordless iron. If the resistance of the iron is 36 ohms, how much current is flowing through the iron? Draw a diagram of this circuit.

Connecting the Dots

6. There are extensive electrical grids that distribute electricity from power plants to our homes. The long distances the electrical charge must move creates extremely high resistances, so very high voltages are used. Use what you've learned about the relationship between voltage, current, and resistance to explain why high voltages might be used to move an electrical charge through the distribution grid.

What Do You Think?

7. Why are models important for teaching and learning about subjects such as electricity? Can you think of other models you've used to describe or learn about other concepts in this class?