How Batteries Work

by Marshall Brain

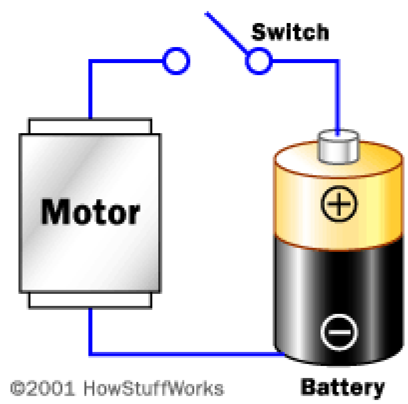
Batteries are all over the place -- in our cars, our PCs, laptops, portable MP3 players and cell phones. A battery is essentially a can full of chemicals that produce electrons. Chemical reactions that produce electrons are called **electrochemical reactions**.

In this article, you'll learn all about batteries -- from the basic concept at work to the actual chemistry going on inside a battery to what the future holds for batteries and possible power sources that could replace them!

Battery Basics

If you look at any battery, you'll notice that it has **two terminals**. One terminal is marked (+), or positive, while the other is marked (-), or negative. In an AA, C or D cell (normal flashlight batteries), the ends of the battery are the terminals. In a large car battery, there are two heavy lead posts that act as the terminals.

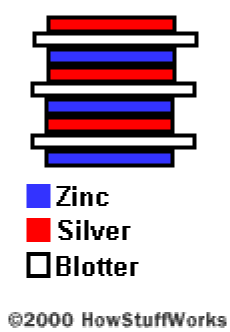
Electrons collect on the negative terminal of the battery. If you connect a wire between the negative and positive terminals, the electrons will flow from the negative to the positive terminal as fast as they can (and wear out the battery very quickly -- this also tends to be dangerous, especially with large batteries, so it is not something you want to be doing). Normally, you connect some type of **load** to the battery using the wire. The load might be something like a light bulb, a motor or an electronic circuit like a radio.



Inside the battery itself, a chemical reaction produces the electrons. The speed of electron production by this chemical reaction (the battery's **internal resistance**) controls how many electrons can flow between the terminals. Electrons flow from the battery into a wire, and must travel from the negative to the positive terminal for the chemical reaction to take place. That is why a battery can sit on a shelf for a year and still have plenty of power -- unless electrons are flowing from the negative to the positive terminal, the chemical reaction does not take place. Once you connect a wire, the reaction starts.

Battery Chemistry: Voltaic Pile

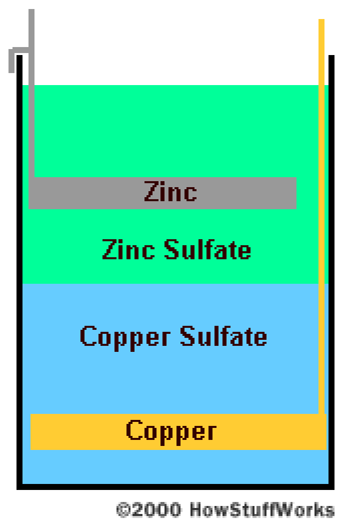
The first battery was created by Alessandro Volta in 1800. To create his battery, he made a stack by alternating layers of zinc, blotting paper soaked in salt water, and silver, like this:



This arrangement was known as a **voltaic pile**. The top and bottom layers of the pile must be different metals, as shown. If you attach a wire to the top and bottom of the pile, you can measure a voltage and a current from the pile. The pile can be stacked as high as you like, and each layer will increase the voltage by a fixed amount.

Battery Chemistry: Daniell Cell

In the 1800s, before the invention of the electrical generator (the generator was not invented and perfected until the 1870s), the **Daniell cell** (which is also known by three other names -- the "Crowfoot cell" because of the typical shape of the zinc electrode, the "gravity cell" because gravity keeps the two sulfates separated, and a "wet cell," as opposed to the modern "dry cell," because it uses liquids for the electrolytes), was extremely common for operating telegraphs and doorbells. The Daniell cell is a wet cell consisting of copper and zinc plates and copper and zinc sulphates.

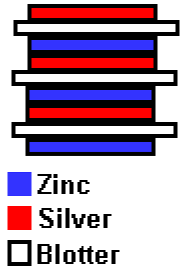


To make the Daniell cell, the copper plate is placed at the bottom of a glass jar. Copper sulfate solution is poured over the plate to half-fill the jar. Then a zinc plate is hung in the jar as shown and a zinc sulfate solution poured very carefully into the jar. Copper sulfate is denser than zinc sulfate, so the zinc sulfate "floats" on top of the copper sulfate. Obviously, this arrangement does not work very well in a flashlight, but it works fine for **stationary applications**. If you have access to zinc sulfate and copper sulfate, you can try making your own Daniell cell.

Experiments: Voltaic Pile

If you want to learn about the electrochemical reactions used to create batteries, it is easy to do experiments at home to try out different combinations. To do these experiments accurately, you will want to purchase an inexpensive ($10 to $20) **volt-ohm meter** at the local electronics or hardware store. Make sure that the meter can read low voltages (in the 1-volt range) and low currents (in the 5- to 10-milliamp range). This way, you will be able to see exactly what your battery is doing.

You can **create your own voltaic pile** using coins and paper towels. Mix salt with water (as much salt as the water will hold) and soak the paper towel in this brine. Then create a pile by alternating pennies and nickles. See what kind of voltage and current the pile produces. Try a different number of layers and see what effect it has on voltage. Then try alternating pennies and dimes and see what happens. Also try dimes and nickels. Other metals to try include aluminum foil and steel. Each metallic combination should produce a slightly different voltage.



Another simple experiment you can try involves a baby food jar (if you don't have a baby around the house, just purchase a few jars of baby food at the market and empty them out), a dilute acid, wire and nails. Fill the jar with lemon juice or vinegar (dilute acids) and place a nail and a piece of copper wire in the jar so that they are not touching. Try zinc-coated (galvanized) nails and plain iron nails. Then measure the voltage and current by attaching your volt meter to the two pieces of metal. Replace the lemon juice with salt water, and try different coins and metals as well to see the effect on voltage and current.

Battery Reactions

Probably the simplest battery you can create is called a **zinc/carbon battery**. By understanding the chemical reaction going on inside this battery, you can understand how batteries work in general.

Imagine that you have a jar of **sulfuric acid** (H_2SO_4). Stick a zinc rod in it, and the acid will immediately start to eat away at the zinc. You will see hydrogen gas bubbles forming on the zinc, and the rod and acid will start to heat up. Here's what is happening:

- The acid molecules break up into three ions: two H^+ ions and one SO_4^{--} ion.
- The zinc atoms on the surface of the zinc rod lose two electrons ($2e^-$) to become Zn^{++} ions.
- The Zn^{++} ions combine with the SO_4^{--} ion to create $ZnSO_4$, which dissolves in the acid.
- The electrons from the zinc atoms combine with the hydrogen ions in the acid to create H2 molecules (hydrogen gas). We see the hydrogen gas as bubbles forming on the zinc rod.

If you now stick a carbon rod in the acid, the acid does nothing to it. But if you connect a wire between the zinc rod and the carbon rod, two things change:

- The electrons flow through the wire and combine with hydrogen on the carbon rod, so **hydrogen gas begins bubbling** off the carbon rod.
- There is **less heat**. You can power a light bulb or similar load using the electrons flowing through the wire, and you can measure a voltage and current in the wire. Some of the heat energy is turned into electron motion.

The electrons go to the trouble to move to the carbon rod because they find it easier to combine with hydrogen there. There is a characteristic voltage in the cell of 0.76 volts. Eventually, the zinc rod dissolves completely or the hydrogen ions in the acid get used up and the battery "dies."

Voltage

In any battery, the same sort of electrochemical reaction occurs so that electrons move from one pole to the other. The actual metals and electrolytes used control the **voltage** of the battery -- each different reaction has a characteristic voltage. For example, here's what happens in one cell of a car's **lead-acid battery**:

- The cell has one plate made of lead and another plate made of lead dioxide, with a strong sulfuric acid electrolyte in which the plates are immersed.
- Lead combines with SO_4 to create $PbSO_4$ plus one electron.
- Lead dioxide, hydrogen ions and SO_4 ions, plus electrons from the lead plate, create $PbSO_4$ and water on the lead dioxide plate.
- As the battery discharges, both plates build up $PbSO_4$ (lead sulfate), and water builds up in the acid. The characteristic voltage is about 2 volts per cell, so by combining six cells you get a 12-volt battery.

A lead-acid battery has a nice feature -- the reaction is completely **reversible**. If you apply current to the battery at the right voltage, lead and lead dioxide form again on the plates so you can reuse the battery over and over. In a zinc-carbon battery, there is no easy way to reverse the reaction because there is no easy way to get hydrogen gas back into the electrolyte.

Modern Battery Chemicals

Modern batteries use a variety of chemicals to power their reactions. Typical battery chemistries include:

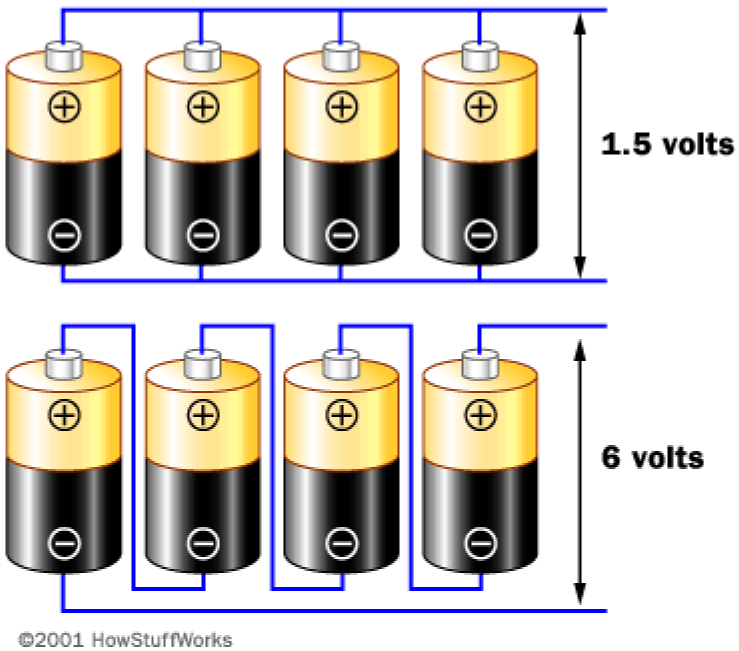
- **Zinc-carbon battery** - Also known as a **standard carbon** battery, zinc-carbon chemistry is used in all inexpensive AA, C and D dry-cell batteries. The electrodes are zinc and carbon, with an acidic paste between them that serves as the electrolyte.
- **Alkaline battery** - Used in common Duracell and Energizer batteries, the electrodes are zinc and manganese-oxide, with an alkaline electrolyte.
- **Lithium photo battery** - Lithium, lithium-iodide and lead-iodide are used in cameras because of their ability to supply power surges.
- **Lead-acid battery** - Used in automobiles, the electrodes are made of lead and lead-oxide with a strong acidic electrolyte (rechargeable).
- **Nickel-cadmium battery** - The electrodes are nickel-hydroxide and cadmium, with potassium-hydroxide as the electrolyte (rechargeable).
- **Nickel-metal hydride battery** - This battery is rapidly replacing nickel-cadmium because it does not suffer from the memory effect that nickel-cadmiums do (rechargeable).
- **Lithium-ion battery** - With a very good power-to-weight ratio, this is often found in high-end laptop computers and cell phones (rechargeable).
- **Zinc-air battery** - This battery is lightweight and rechargeable.
- **Zinc-mercury oxide battery** - This is often used in hearing-aids.

- **Silver-zinc battery** - This is used in aeronautical applications because the power-to-weight ratio is good.

- **Metal-chloride battery** - This is used in electric vehicles.

Battery Arrangements

In almost any device that uses batteries, you do not use just one cell at a time. You normally group them together serially to form higher voltages, or in parallel to form higher currents. In a **serial arrangement**, the voltages add up. In a **parallel arrangement**, the currents add up. The following diagram shows these two arrangements:



The upper arrangement is called a *parallel* arrangement. If you assume that each cell produces 1.5 volts, then four batteries in parallel will also produce 1.5 volts, but the current supplied will be four times that of a single cell. The lower arrangement is called a *serial* arrangement. The four voltages add together to produce 6 volts.

Battery Power

Normally, when you buy a pack of batteries, the package will tell you the voltage and current rating for the battery. For example, my digital camera uses four nickel-cadmium batteries that are rated at 1.25 volts and 500 milliamp-hours for each cell. The milliamp-hour rating means, theoretically, that the cell can produce 500 milliamps for one hour. You can slice and dice the milliamp-hour rating in lots of different ways. A 500 milliamp-hour battery could produce 5 milliamps for 100 hours, or 10 milliamps for 50 hours, or 25 milliamps for 20 hours, or (theoretically) 500 milliamps for 1 hour, or even 1,000 milliamps for 30 minutes.

However, batteries are not quite that linear. For one thing, all batteries have a **maximum current** they can produce -- a 500 milliamp-hour battery cannot produce 30,000 milliamps for 1 second, because there is no way for the battery's chemical reactions to happen that quickly. And at higher current levels, batteries can produce a lot of heat, which wastes some of their power. Also, many battery chemistries have longer or shorter than expected lives at very low current levels. But milliamp-hour ratings are somewhat linear over a normal range of use. Using the amp-hour rating, you can roughly estimate how long the battery will last under a given load.

If you arrange four of these 1.25-volt, 500 milliamp-hour batteries in a serial arrangement, you get 5 volts (1.25 x 4) at 500 milliamp-hours. If you arrange them in parallel, you get 1.25 volts at 2,000 (500 x 4) milliamp-hours.