6. Electricity & Magnetism

Electricity is ...

the cause of lightning, which has power greater than a nuclear power plant
used for all the computations done in a laptop computer
used for radio communication, and to send telephone signals through wires
the most convenient (and often the cheapest) way to transport energy, at least for short distances
able to enter our homes when needed by the flick of a switch, through nationwide circuitry so complex that it can collapse in a few seconds
so safe that we have outlets all over our homes, and yet it is still used as a gruesome method of execution for humans, and was once used to kill a "bad" elephant
used by the nerve cells in our bodies to send signals
responsible for nuclear fission energy, since the fission fragments get their energy from electric repulsion

The twentieth century could rightly be called *The Century of Electricity*. (Of course, it might also be called the century of Autos or of Airplanes or of Quantum Physics or of Antibiotics.) Most of what we call "high-tech" consists of the enslavement of electricity to do our purposes.

Equally mysterious is magnetism. Magnets also play a central role in our high-tech world.

Magnetism is ...

something that was once a military secret
the force that pushes things around in "electric" motors
used to store information on computer hard drives
the main way used to generate electricity
what Saddam Hussein planned to use in his Calutrons to get U-235
used to determine the ages of sedimentary rocks
used to run loudspeakers and earphones

Moreover, radio waves, light wave, x-rays, and gamma rays carry half of their energy in electricity and the other half in magnetism.

It was once thought that magnetism was totally unrelated to electricity. We now know that magnetism is a subtle aspect of electricity.

But what is electricity?

Electricity

Electricity usually means the movement of electrons. (It can also be the movement of other particles.) These tiny particles, about 1/2000 of the mass of atoms, can exert a huge force – the *electric force* -- on other electrons and on atoms.

Take two electrons and place them a centimeter from each other. Make sure nothing else is around. Since each has mass, the force of gravity will attract the two electrons to each other. But the electric force between them is repulsive; it pushes them apart. Moreover, this repulsive force is stronger than the attractive gravity force by a factor of approximately

$$4170000000000000000000000000000000000000000$$

I wrote the number that way to be dramatic; the same number can be written as 4.17×10^{42}. So this electric force *completely* overwhelms gravity.

Now consider an electron placed a centimeter from a proton. They will attract each other, not repel. Yet this force will be *exactly* the same as the repulsive force between two electrons. (Incidentally – we still don't know why the proton mass has exactly the opposite charge of the electron.)

Electric charge

The property of the electron that gives its force has a name: the electric *charge*. By convention, the charge of the proton is

$$q_p = 1.6 \times 10^{-19} \text{ Coulombs}$$

You won't need to know that number. The charge on the electron is exactly opposite that on the proton. In equation form we say $q_e = -q_p$. By putting the minus sign in front, we keep track of the fact that the force it exerts is opposite to the force exerted by a proton. We say that the electron charge is negative. (It is -1.6×10^{-19} Coulombs, but all you have to know is the sign.)

If we combine an electron with a proton to make a hydrogen atom, the total charge is 0. So the hydrogen atom does not "feel" an electric force from other particles, since the force on the proton and the force on the electron will be opposite and cancel each other. We say that the ***hydrogen atom is neutral***. Neutral means the total charge is zero, even if it is made up of pieces that have charge.

Neutrons have mass similar to that of the proton, but neutrons have charge 0. Why? Is it possible that the neutron is similar to a hydrogen atom? A hydrogen atom consists of a proton with charge +1, and an electron with charge -1, and the two cancel. Could a neutron also have interior charges that cancel?

We now know that the answer is *yes*. The neutron consists of three *quarks*. One of them is the u quark (also called the "up" quark), and the other two are d quarks (for "down"). We write this as udd. The u quark has a charge of +2/3 (in terms of the proton charge), and each of the d quarks has charge –1/3. So the total neutron charge is 2/3 – 1/3 -1/3 = 0 proton charges. That's why the neutron is neutral.

The proton consists of uud, with a total charge of 2/3 + 2/3 -1/3 = +1 proton charges.

charge is "quantized"

As far as we know, all charges in nature are exact multiples of the quark charge. We don't know why. This is stated in physics by saying "charge is quantized." Particles can have charge -1/3, +1/3, 1, 2, etc., but cannot have charge 1/2, 4/5, or 1.22. We don't know why this is true.

You might guess that the reason is that all particles are made of quarks. But that isn't true. Electrons are not made of quarks.

A new and, as of yet, unproven theory is that all particles are made of objects called "strings." If this theory is true, then the reason behind quantization is simply that all particles are really made of the same kind of thing.

Electric current -- Amps

When charged particles move, we call it electric current, in analogy to water current. For water, we measure current in gallons per second, or in cubic meters per second. For electric current, we measure current in electrons per second. A more practical unit is the ampere, or amp. One amp is 6 $\times 10^{18}$ electrons per second. Don't memorize this number, but you should know that the current is a measurement of electrons per second.

The current that flows through a light bulb is typically about one amp. Wires in your house carry up to about 15 amps. The current is divided among all the systems that use electricity, such as your refrigerator, lights, TV, and computer. One bolt of lightning has thousands of amps.

The current from a flashlight battery is also about 1 amp. The main reason the flashlight bulb is not as bright as a typical light bulb is that the filament is shorter, so there is less to glow.

Optional: an amp for a day

Optional: Here is an interesting coincidence. Suppose you let one ampere flow for a day. How many electrons total were there? One amp is 6 $\times 10^{18}$ electrons per second, and there are 86400 seconds per day.[1] The total number is the product of these two numbers: $6 \times 10^{18} \times 86400 \approx 5 \times 10^{23}$. That's almost one mole, [2]the number of electrons in one gram of hydrogen. Think of it in the following way: if you were to take a gram of hydrogen, and remove the electrons, you would have enough to make a flow of one ampere for one day. (I can think of no reason why this knowledge would be useful for a future president. That's why this paragraph is optional.)

Wires: electron pipes

Metals have a wondrous property: electrons can flow easily right through the solid inside of a piece of metal. (Glass has a similarly wondrous property: light can pass right through it.)

Recall from Chapter 4 that the nucleus takes up very little space in an atom, no more than a mosquito takes in a football stadium. The rest of the

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[1] 60 seconds per minute, 60 minutes per hour, 24 hours per day, gives 60 x 60 x 24 = 86400 seconds per day. Multiply this by 365 days per year to get 3.15 $\times 10^{7}$ seconds per year.

[2] A mole is 6.02 $\times 10^{23}$ atoms.

space is taken up by electrons. For metals, one of the electrons in each atom is not permanently attached, so it can move from one metal atom to another.

Electrons can move easily inside a piece of metal, but they can't easily leave the surface of the metal. They are held back by the attraction of the positively-charged nuclei. Free movement of electrons can take place only if the moving electrons are replaced by other electrons. For this reason electric current usually flows in circles or closed paths.

Have you noticed that most electric cords (e.g. those for a lamp) have two wires in them? The second one is for the electrons to return. Some computer wires are called coax cables. They also consist of two conductors, but instead of two wires, they have one wire surrounded by a cylindrical metal tube. (Coax derives from coaxial; it means that the axis of the wire is the same as the axis of the tube.) The tube serves as the electron "return path."

When a bird lands on an electric power line, some electrons will immediately flow into the bird. But with nowhere to go, the electrons soon repel other electrons from coming, so the flow will stop. Very few electrons are needed to stop the flow.

Likewise, if a person hanging on an electric power line were to touch nothing else, he would be safe. If he touches another wire (which could be the return path for the electric power) then a large current could flow through him.

Watch a mechanic attach a wire to an automobile battery. He'll be careful not to touch anything else, particularly not the metal of the car, with his other hand. That's because one side of the battery is usually attached to the metal of the car, and the mechanic does not want his body to serve as a return path. A car battery can deliver 100 amps of electric current, and that can be dangerous.

Even though the electrons in electric current move in circular paths, they can be used to carry energy and information. As electrons move through wires, you can remove some of the energy from them, much as a mill wheel can take energy from a stream of water. To send information, you vary the amount of current flowing in the circle. In a similar way you can signal someone with a hose by turning the water on and off. Telephone wires carry sound signals by varying the current to match the vibrations of sound.

Resistance to electric current flow

The easiest way to remove electron energy from current is simply from the friction caused by the electron flow. Such friction is called electric *resistance*. Some metals, such as tungsten, have lots of resistance. The filament of an ordinary incandescent light bulb is made of tungsten. When current flows through it, the resistance (friction) heats the filament enough to make it glow. Thus electric current is first turned into heat and then into light. (We'll discuss this more in the next chapter.)

Of course you don't want to heat the wires that go to the bulb, so those are usually made out of copper or another metal with low resistance.

Materials that conduct electricity well (but with resistance) are called **conductors**. Materials that don't conduct electricity very well (such as plastics, rocks, or wood) are called **insulators**. But in between metals and insulators is a group of mysterious materials called **semiconductors**. These are materials that can be made to turn from conductors to insulators and back, by applying electricity in a special way. Their ability to control electric flow is what makes them so useful in electronics from stereo systems to computers. We'll discuss these in more detail in Chapter 10.

Fuses and circuit breakers

Wires in your house are typically made out of copper, a metal with low resistance, so that they will not waste the energy of electric current. If the current is high, however, then the wires can get hot enough to start a fire in the walls. For this reason, most house wiring has a device that prevents the current from exceeding a safe value, typically 15 amps (enough for about 15 light bulbs.) The two kinds of devices used are called fuses and circuit breakers.

A fuse is a short length of high-resistance material that melts when too much current flows through it. When it melts, it breaks the connection of the wires, and the current stops flowing. To get the current flowing again, the fuse must be replaced. In common usage, to "blow" a fuse means to send enough current through it that the metal inside melts or vaporizes.

A typical circuit breaker has a wire formed into a bimetallic strip (see p. 2-14). When the bimetallic strip heats beyond the allowed limit, it bends away and breaks the connection to another wire. Unlike the fuse, the circuit breaker can be reset (the bimetallic strip placed back in contact with the wire) after it has cooled.

Superconductors

Superconductors are materials that have zero resistance--they don't impede electricity at all! Rings of superconductors have had currents flowing in them for decades, with no energy source. (The phenomenon is similar to the Earth going around the Sun; if there is no friction, it will just go on forever.)

Unfortunately, all known superconductors have the zero resistance property only at low temperatures. If we could find or manufacture a "room temperature" superconductor, it would revolutionize the way we use electricity. Right now, much energy is wasted by conducting electricity through resistive wires, and a real room-temperature superconductor would revolutionize the way energy is transported.

How can electrons flow inside a metal with zero friction? The answer was not known for many decades, but we now understand that the secret lies in quantum mechanics. We'll discuss this further in Chapter 10.

The easiest way to cool a wire is to put it in a cold liquid. The original superconductors were kept cold by immersing them in liquid helium. The liquid is made in special refrigerators, and then transported to the customer in dewars (glass containers that are similar to "Thermos" bottles). Liquid helium boils at a temperature of 4 K, i.e. only 4 degrees above absolute zero. So as long as there is liquid helium, the temperature is low. Recall from Chapter 4 that helium comes from alpha particles in the Earth's crust, and we collect it from oil and natural gas wells. When these wells run out, we will have no further source of helium. (The Sun is 10% helium, but that's not easy to get.)

Thirty years ago, most of the helium from wells was discarded, because the need for it wasn't great enough to justify the expense of trapping it. United States law now requires the oil and gas companies to recover and store the helium, because of anticipated needs for future superconductors.

“High Temperature” Superconductors

In 1987, the Nobel Prize in physics was awarded to Georg Bednorz and Karl Muller for their discovery of certain compounds that become superconducting at relatively high temperatures. Right now, the highest temperature superconductor works at a temperature of about 150 K, equal to –123 C or –189 F. That’s pretty cold for something called “high temp,” but it is the best anyone has done.

Part of the reason scientists use the word “high” for this temperature is that it’s higher than the boiling temperature of liquid nitrogen, which is 77 K. Recall that nitrogen is about 80% of air; it is extremely abundant, especially when compared to helium. Nitrogen can be liquefied for about a dollar a quart, making its cost comparable to that of milk (and some bottled water brands). Superconductors that can be kept sufficiently cold with liquid nitrogen are, in principle, much more practical.

So why aren’t we using such superconducting wires for all of our power transmission? The answer is that the high-temperature superconductors are all pretty brittle, and it has been difficult to manufacture useful wires from them. Nevertheless, it is being done for some special applications. An experiment to see if such wires can be used for commercial electric power transmission is currently underway by the Detroit Edison power company.

Of course, if liquid nitrogen is used for cooling, then some power is lost--the power needed to produce replacement liquid nitrogen when it boils off. So such transmission lines do use energy.

There is a limit to the amount of current that superconducting wires can carry. That’s because high current creates very strong magnetic fields (to be discussed shortly), and strong magnetic fields can destroy superconductivity just as much as can high temperatures. The current they carry depends on the cross-sectional area; some materials have been reported that can carry several million amperes per square centimeter of area.

> **Amusing fact:** according to theory, highly compressed hydrogen should become a metal. It is even possible that the core of the planet Jupiter consists of superconducting hydrogen.

Volt – a measure of electron energy

Amps tell you how many electrons are flowing past a point each second. Volts tell you the energy of the electrons. The energy unit called the electron volt, abbreviated[3] as eV, is defined as

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ joules}$$

(don’t memorize)

Whereas a Calorie is a typical amount of chemical energy for a gram of material, an eV is a typical amount of energy for a single atom or molecule. That fact is useful and worth memorizing!

1 eV = typical energy for a single atom or molecule

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[3] The V in eV is usually capitalized. The justification is that it was named after a person, Alessandro Volta. Yet the word *volt* usually is not capitalized. The traditions are not consistent.

Jargon: If a piece of metal has a large number of electrons, each with energy of 1 eV, you'll hear people say that the metal *is at* one volt, or sometimes they'll say it has a *voltage* of one volt, or maybe that it has a *potential* of one volt. It is OK to refer to the energy of an electron in volts, rather than in eV. Physicists will use these two terms slightly differently, but it is not important here. Remember that when a piece of metal is at one volt, it means that every electron in that metal has that energy.

Here are some key numbers about volts:

typical energy of an electron in an atom	1 volt
TNT energy per molecule	1 volt
flashlight battery	1.5 volts
U.S. house voltage	110 volts
European house voltage	220 volts
voltage inside TV tube	50,000 volts
alpha particle from nucleus	1,000,000 volts

Low volt electrons are not very dangerous. A flashlight battery has a typical voltage of 1.5 V. You can read that on the label. It produces electrons with an energy of 1.5 V. You can hold such a battery in your hand with no danger; if you touch the metal leads to your tongue, you'll feel a tingle. Don't do that with a higher voltage battery or the higher energy electrons might burn your tongue.

Finger sparks and static electricity

The sparks that sometimes fly from your finger to a doorknob are often called *static electricity*. It occurs because your feet rub on the ground in such a way that electrons come off and stick to your body. These electrons are static in the sense that they stay there, on your body, until you walk up to a good conductor like a metal doorknob. You'll pick up even more electrons if you rub your shoe on a thick carpet. You can also rub electrons onto a comb by running the comb through your hair. Try doing that--run the comb through several times quickly, and then put the comb near some very small (mm size) pieces of paper. The electrons on the comb will attract the bits of paper.

If the air is moist, the static electricity leaks off your body into the air. But on a very low humidity day (which means there is very little moisture in the air) the air is a poor conductor, and the electrons stay on your body. They can move around inside your body, since your salty blood is a pretty good conductor of electricity. But when you have these excess electrons and you put your finger near a piece of metal, they will jump off, creating the flow of current we call a spark.

For that spark, the voltage was probably between 40,000 and 100,000 V! Yet it doesn't kill you because the current is low, limited by the small number of electrons you picked up. Yet a similar voltage in the back of a TV set is very dangerous. That's because the amount of current that can flow to you is much greater.

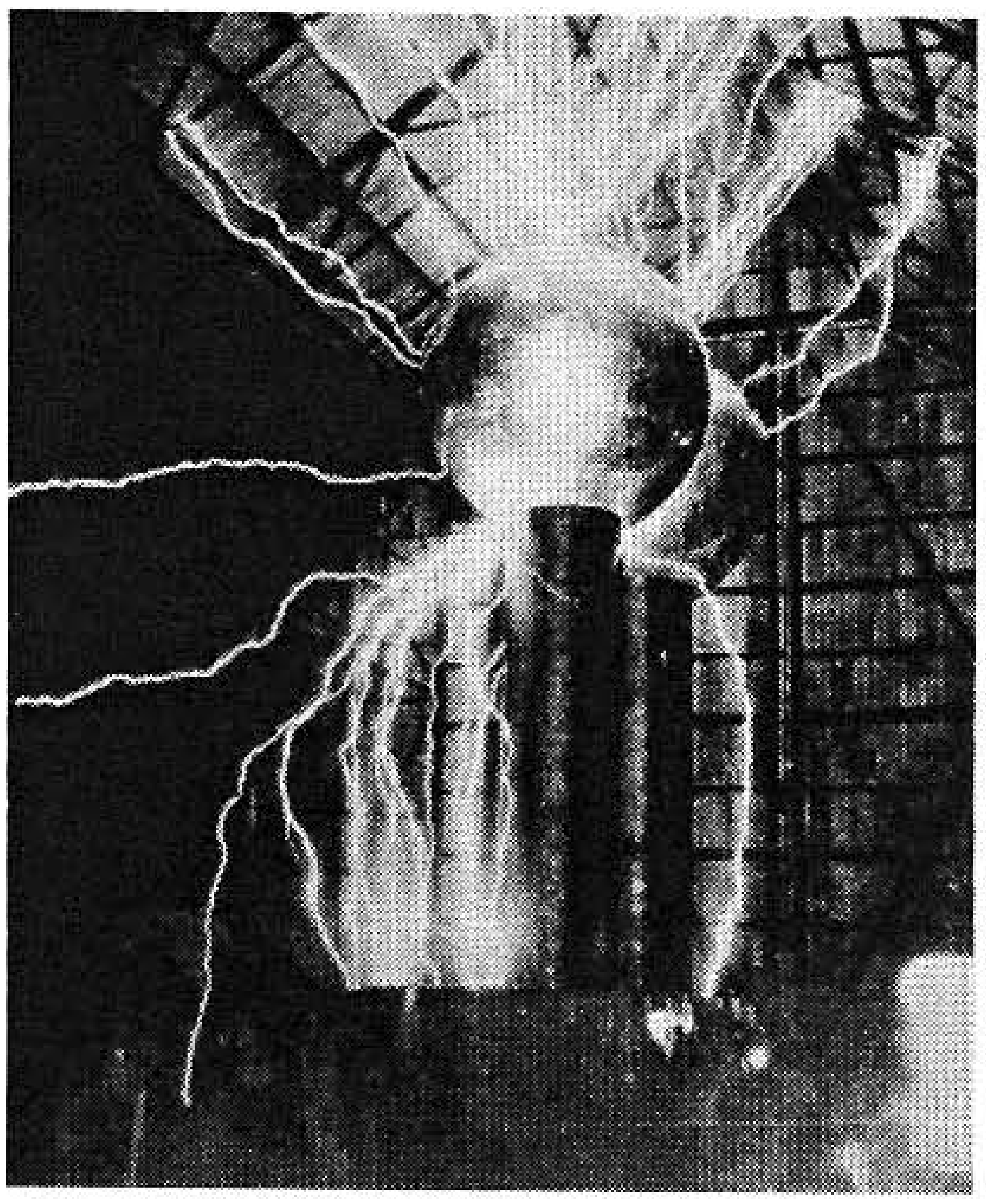

Fig. 6.1 Large Van de Graaff generator at MIT

To know the power, you must know the energy per particle AND the number of particles per second. The same is true with flowing water: you need to know the velocity of the water AND the number of gallons flowing every second.

Finger sparks can be automated for a physics demonstration by using a device called a Van de Graaff generator. In this device, a band of rubber rubs against a piece of wool continuously and the charge is taken off by a wire attached to a metal sphere. In a few seconds the sphere can reach 100,000 V. Yet the sparks are not dangerous because the amount of charge is so small. Large Van de Graaff generators were the first method used to reach a million volts.

Electric power

The power delivered by electrons depends on the energy of the electrons, and the number per second that arrive. The first is the voltage, and the second is the current. Multiply these together and you get the power.

Let's do this calculation for a small, 1-volt battery delivering 1 amp. The energy of a 1-volt electron is 1.6×10^{-19} J. The number of electrons per second is 1 amp = 6×10^{18} electrons per second. Multiply these together to get $1.6 \times 10^{-19} \times 6 \times 10^{18} \approx 1$ J/s = 1 watt (W). That's not a coincidence. The numbers were chosen to make this work out exactly.[4] So here is the important conclusion:

Power = Volts x Amps

Here is another practical example: suppose you have a light bulb that uses 110 V, and carries a current of 1 amp. Then the power is 110x1 = 110 W. If you run that bulb for an hour, you use a total energy of 110 watt hours = 0.11 kWh.

Another example: a flashlight battery works with 3 volts and uses about 1 amp. That means it uses a power of 3 volts x 1 amp = 3 watts. If the batteries last for an hour, then the energy they delivered was 3 Wh.

Note that high voltage does not always mean high power. If the amps are tiny, then high voltage can be safe. That's why I can let large sparks from a Van de Graaff generator jump to my hand without it hurting (at least, without it hurting enough to make me admit it hurts).

The energy in finger sparks, and lightning

I mentioned earlier that the energy of electrons in a finger spark can be 40,000 V or more. But there aren't usually very many of these excess electrons on your body, typically not much more than about 10^{12} of them.[5]

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[4] The energy in 1 eV is not exactly 1.6×10^{-19} J. A more accurate number is that 1 eV $\approx 1.60217733 \times 10^{-19}$ J. An ampere is not exactly 6×10^{18} electrons per second. A more accurate number is 1 amp $\approx 6.2415064 \times 10^{18}$ electrons per second.

[5] For those of you who have studied electrical engineering, here is the way I did the calculation. I assumed the electrons had an energy of V = 40,000 eV. I assume that the capacitance of your hand was about C = 10 picofarads. Then the charge in Coulombs is Q = CV. Divide by 1.6×10^{-19} to get the number of electrons. The energy in joules is $E = \frac{1}{2} C V^2$.

That may seem big, but it is much less than the number of atoms in a gram of material. The current is low enough to keep the power low.

In fact, if those electrons flowed out of at the rate of 1 milliamp (i.e. one thousandth of an amp, one thousandth of the current you get in a light bulb), you would run out of electrons in only 1/1000 of a second. The total energy of the electrons is 0.01 J, less than 2 micro Calories (2 millionths of a Calorie). It is not important that you know these numbers. It is important for you to know that high voltage is not dangerous if there isn't much current and if it doesn't last for very long.

In contrast to the little finger spark, lightning has both high voltage and high current. For typical lightning values, a million volts at 10,000 amps, we get a power of 10 gigawatts (GW)! That's more than most commercial power plants. If I assume that the lightning lasts for 1/10 of a second, then the energy is 10 GW x 0.1 s = 1 gigajoule (GJ) = 250 million Cal. That's the energy in 250 *tons* of high explosive.

Frog legs and Frankenstein

In 1786, Luigi Galvani, one of the pioneers of electricity, discovered that when he applied small sparks from static electricity to the legs of dead frogs, the legs twitched. Later, he hung frog legs on metal hooks outside his house during thunderstorms. (Electricity was not easy to get in those days; Galvani had not yet invented the battery. But Benjamin Franklin had already discovered that lightning was electricity.)

Galvani thought he had made the frog leg come alive. He hadn't. He had just delivered a signal to the muscle that made it contract. But he believed he had discovered a secret of life, and he called it "animal electricity." For some fascinating drawings of his experiments, look up "Galvani frog" on the web.

In 1817, Mary Shelley, inspired by Galvani's experiment, created one of the first science fiction classics *Frankenstein*. Just as Galvani thought electricity could bring a dead frog leg to life, Shelley's fictional character Dr. Frankenstein thought he could bring a dead person to life by using lightning.

The story of Frankenstein became a symbol of what could happen when scientists develop new technology without anticipating its applications. In honor of Frankenstein, today some people use the derisive term "frankenfood" for food that has been genetically altered.

House electric power

The electricity that comes to your home is usually kept by the power company at a average[6] of 110 volts. If you have no lights turned on, no refrigerator, no heaters, no TV, no anything, the voltage is still 110 volts--although the current is zero. The power company works very hard to keep the voltage at 110 V even when you start using more appliances. The voltage doesn't change, only the current. The power you use is equal to P = volts x current, with volts = 110, so in the US, your power is

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[6] By the "average voltage" I mean the RMS value. If you are interested, RMS stands for root mean square value. It is calculated by squaring the voltage, averaging it (since house current oscillates 60 times per second) and then taking the square root of this average value. In statistics, the average of the squares is called the variance.