2 Current and Voltage

2.1 Water Analogy

In the previous sections we looked at static electric charges, obtained from rubbing combs and other objects, and we looked at the elementary investigations that took place in the 1500s–1800s.

When charges *flow* we call such flow an *electric current*, and a host of interesting things happens. We will find magnetic fields, forces between wires, and even—if we want to muse and ponder—connections to Einstein's special theory of relativity! (This is because who is to say whether the charge is moving relative to us or we are moving past the charge?)

This flow of charges, or coulombs passing every second, is measured in *Amps*, after the absent-minded professor **Andre Marie Ampere** (1775–1836), who once even forgot he'd been invited to dinner with the Emperor Napoleon.

Fig. 2.1 Water analogy, illustrating voltage and current

D. Nightingale and C. Spencer, *A Kitchen Course in Electricity and Magnetism*, DOI 10.1007/978-3-319-05305-9_2, © Springer International Publishing Switzerland 2015

We make the definition

1 *Coulomb*/sec *is* 1 *Ampere* (or *Amp*)

and in the water analogy of Fig. 2.1 it would be something like "droplets/second" or "gallons/second" escaping through the little hole near the bottom of the bottle.

This current of water is caused by the pressure, which came from the height of the liquid in the bottle.

Let us briefly review a few of the important experiments concerning electric current, experiments that began in the 1700s.

2.2 Galvani's Frogs' Legs, and Volta's Experiment

In 1780, **Luigi Galvani** (1737–1798), an Italian anatomy lecturer at the University of Bologna, noted that if an electrostatic charge was applied to the muscular legs of dead frogs the legs twitched.

In a similar way, people had sometimes experienced muscle spasms due to accidental shocks when they had been trying to build up large charges with things like Leyden jars. (See Fig. 1.18 on p. 17.)

Galvani—whose name lives on with *galvanized nails*, *galvanometer*, etc.—thought he had found in the frog itself a natural source of electricity, which he might use as a battery. Indeed, there is a fish called the electric ray that does naturally produce electric charge, which paralyzes its victims. The electric eel is another animal that stuns its prey electrically, but it would be somewhat impractical to try to use either of these animals as batteries.

It was shown later by another Italian, the nobleman **Count Alessandro Giuseppe Volta** (1745–1827), that Galvani's frog's leg is not producing electricity, but is merely reacting to the *passage* of electricity, *i.e.*, to *currents*.

The pressing question in Volta's time was as follows: How could these currents be maintained?

Now Count Volta knew that his tongue was a muscle, just like the frog's leg.

Surmising that the muscle of his wet tongue might be more sensitive than a frog's leg, he experimented with different single metals, and touching more than one metal to the tongue caused a definite tingling sensation.

When the metals were removed, the tingling stopped; when put back, the tingling returned. He realized that the *dissimilar metals* somehow caused a continual source of charge.

The next step was to experiment with different metals immersed in acidic liquids and see if the setup could function for an appreciable time.

2.2.1 Tongue Experiment (After *Volta*)

Take one sample of metal, say a copper penny (pre-1982 means copper!), and another type of metal, say a piece of aluminum foil, and place the edge of each quite close together on your tongue.

You will feel the tingling sensation that Volta felt. (If you don't at first it is because the effect is extremely small! Salty water in your mouth will help.)

What is happening is that the slightly acidic saliva on your tongue is adding electrons to each metal, but in different amounts, thus leaving one metal relatively more positive than the other.

Now it was a "mechanical" loss or gain of electrons that happened in our friction experiments, but this time it is to do with the chemical reaction when acids attack metals, and this process is just what we want—if things are to be continuous.

The two different metals may be called (+) and (−), with the one having the larger number of electrons being (−). Naturally, the metals will also be slightly attracted—much too small to observe—but this is no longer where our attention lies.

As usual, the little (−) charges of course want to travel towards the (+)s. Electrons on the electron-rich metal will try to move over to the electron-poor metal continuously, and such a flow of charge goes on and on. Indeed, Volta found the tingling metallic taste all the time he held the metals on his tongue.

The above is thus a simple (but hopelessly weak) battery.

2.3 Experiment: Voltaic Cell

Instead of the mouth, use a beaker or a cup of vinegar—red or white, it doesn't matter. Use two small alligator-type clips to hold a penny (pre-1982) and some aluminum foil in the vinegar, as in Fig. 2.2. (Little alligator clips are easily obtainable from hardware stores; see p. 157.)

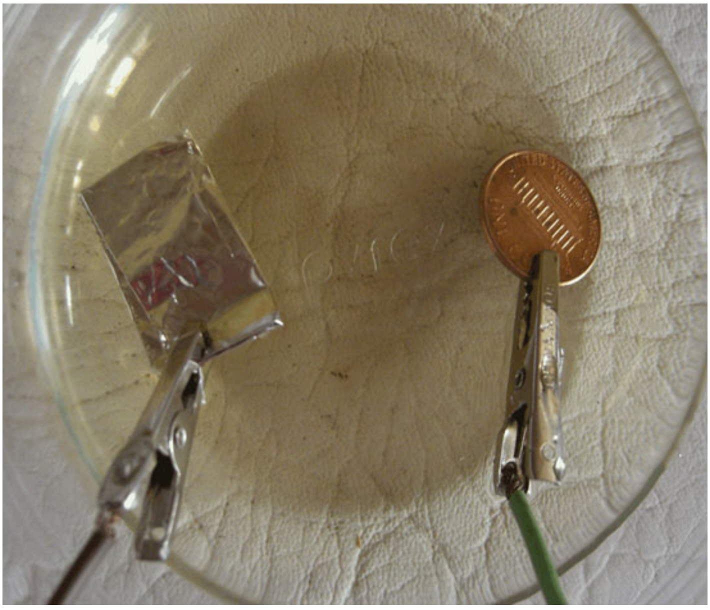

Fig. 2.2 Red vinegar and two different metals battery

Now if we had a sensitive current meter, capable of measuring less than a 1/1000 of an Amp, *i.e*., 1 milli-Amp, commonly called mA, we would detect a very small current flow between aluminum and copper.

On p. 43 we will make, for educational reasons rather than sensitivity, a crude current meter.

Meanwhile, however, we could purchase an inexpensive multimeter (see p. 158) with a sensitive scale—typically of ~100 microAmps. (A microAmp is a millionth of an Amp.) The authors found, using such a meter, that the copper coin and sliver of aluminum (as in Fig. 2.2) gave a continuous short-circuit current (short circuit means the + and – are directly connected—here through the meter) of ~45 microAmps or 45/1000 000 of an Amp. To improve matters therefore we should first make a stronger battery.

2.4 Experiment: The Voltaic Pile

The *voltaic pile* is what Volta demonstrated to Napoleon in France (Napoleon had quite an interest in electricity) and, some years later, to Faraday in London.

We will pile up more cells, as Volta did. The aluminum foil can be folded a few times onto itself to make a square roughly the size of a coin, and we sandwich them together with paper towels, or cardboard, again soaked in vinegar. It's helpful to fold the paper towel pieces a few times to make a pad of towel. (Alternatively, pads of vinegar-soaked cardboard could be used.)

Figure 2.3 shows our Voltaic pile, and we say that we have put the cells "in series" (see also p. 64 for things in series).

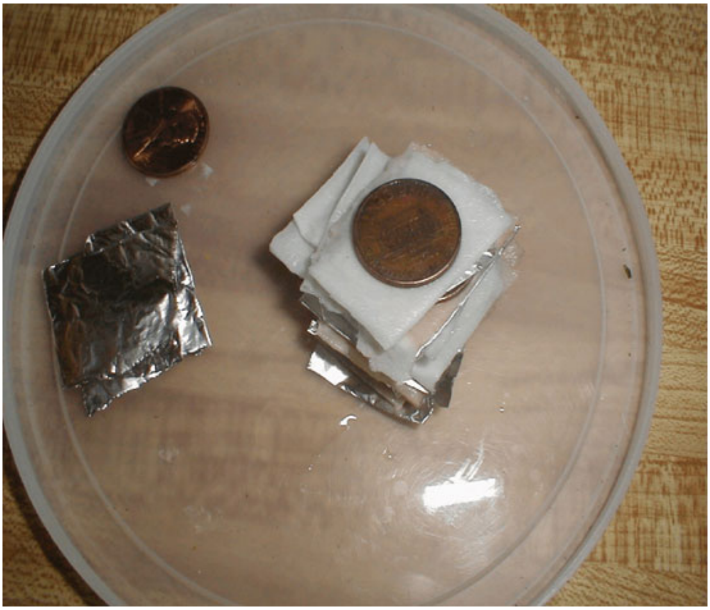

Fig. 2.3 Voltaic pile. Copper and aluminum, separated by vinegar-soaked paper towel pads

If the kitchen has a metal sink, all that is needed is to put the bottom aluminum "coin" directly on the sink, and then add a folded paper towel pad (which has been dipped in vinegar) on top of the aluminum, then the copper penny, and so on.

Notice that the "vinegared" paper towel provides the central liquid zone, the electrolyte. An electrolyte is a solution in which charged particles such as charged atoms can move about freely. Weak acids, such as dilute sulphuric acid ("battery acid"), vinegar, lemon juice, and the juice in potatoes are good electrolytes, as is common salt solution ("brine"). In fact, any charged particle migrating this way in a fluid may be called an *ion*, extending what we already said on p. 8. (The lightning strike on p. 26 is also an example of ion migration; the air first becomes ionized due to the huge separated charges and then discharges suddenly.)

The vinegar electrolyte lies between the two "coins" of dissimilar metals. Because each cell stands on top of the next cell in the stack, its aluminum coin touches the copper coin of the previous cell, and this contact makes the series connection of each cell to its neighbor.

This is our battery. If a wire is touched onto the top penny and another to the bottom aluminum "coin" (or to the sink if the sink was metal) then we should be able to detect a voltage. Lacking a voltmeter, the tingling in the tongue should be more pronounced[1].

Putting piles *in parallel* (again, see p. 64) will allow more current to pass but yield only the same small voltage. It is possible that such a current may *just* deflect the compass needle of the homemade current meter that we will shortly construct.

2.5 Humphry Davy's Voltaic Pile

After Volta, the young **Humphry Davy** (**1778–1829**) used a really large Voltaic pile around 1802 to pass large currents through various solutions. (This general process of passing a current through solutions, with an ensuing separation of elements, is called *electrolysis*, and the conducting solutions are, as we said, *electrolytes*.)

In his experiments, this Cornwall-born boy, son of a wood carver and apprentice to an apothecary, not to mention amateur painter and poet, was able to identify, and isolate, the elements potassium and sodium—all by electrolysis! Realizing the importance of what he had done it is recorded that he danced around the lab in joy[2].

Amongst Davy's many achievements he also made an incandescent lamp, using platinum as a filament, but was unable to make it last.

He is known for the discovery of "*laughing gas*" (nitrous oxide) later widely used in dentistry throughout the world as well as the *Davy lamp* for the safety of miners at risk from methane explosions. As a result of his many discoveries in both chemistry and physics, he was knighted, at the age of 34, in 1812. A short while

[1] This pile—eight pairs of penny-and-aluminum "cells" in series—yielded a voltage of ~1.5 V and a short-circuit current of about 160 microAmps (or 0.16 milliAmps).

[2] Sacks, Oliver, (2001), Uncle Tungsten, Vintage Books, p.122.

later he married a wealthy widow, and around 1814 he and his wife travelled to France to demonstrate some of his discoveries, with the 22-year-old Michael Faraday as both valet and assistant.

Faraday, of course, would (see p. 106) go on to even greater fame.

2.6 Sidebar Experiment: Electroplating

Before continuing with other ways of obtaining voltages—for example using a potato—we note that Volta's battery may, in principle, be run in reverse.

Recall that we had two different metals in an acid, giving us electricity. Now let us do things backwards, by forcing a current through the acid, using just a common 1.5 V cell. Without going into any chemistry we will find that, with some adjustments, we can cause the material of one metal to be transported across to the other (different) metal! This is called *electroplating*.

We will not use aluminum this time, because aluminum does not work well here, but we will keep copper as the (+) electrode, and the (−) electrode may be for example a kitchen fork, a coin with a surface of some alloy such as nickel, or perhaps a tool from the workshop.

Figure 2.4 shows our basic setup: a glass containing vinegar, plus a little salt to make it conducting. One wire is attached to the copper electrode (here,

Fig. 2.4 Two electrodes in vinegar. The (+) is a copper penny, and the (−) is the fork or the object to be plated

Fig. 2.5 Copper plating of various objects: A chrome–vanadium wrench, a US quarter (originally a silvery color but actually a nickel alloy), and the tines of a fork

a pre-1982 penny[3] held by a clip), and this is to be connected to the (+) of the household 1.5 V battery. The other wire will connect the object to be plated to the (−) of the battery (battery not shown in Fig. 2.4).

Vinegar is only a weak acid, but it will do the job if we are patient. A stronger acid is muriatic acid, available at hardware stores for cleaning concrete, but it would have to be treated with great caution. Wear eye protection and acid-proof gloves, and read the label.

Our plating results shown in Fig. 2.5 used muriatic acid.

2.7 Experiment: Potato Battery

Going back to our discussion of batteries, we may also make a battery from fruits and/or vegetables, the juices of which are quite rich in ions.

[3] We have cut into the penny to make sure that it really is copper. After 1982, US pennies were made of the cheaper metal, zinc.

Fig. 2.6 Making a potato battery

Take two dissimilar metals, *e.g.*, a piece of copper wire and a steel nail as in Fig. 2.6, and a potato.

Push the two metals into the potato, maybe an inch apart, and clip them to the leads of the multimeter as shown in Fig. 2.7, choosing either the 20 V range or the 2 V range. Our multimeter here is on its 20 V scale, showing 0.47 V, and so we may switch to the more sensitive 2 V scale. It will read an extra figure, such as 0.472 V, although we have no interest in that last digit here.

How did we know to clip the (+) to the copper? In these experiments the copper electrode is always the positive one, but if we had chosen wrongly, a little minus sign would have appeared on the digital meter (or the needle of the analog meter would have wanted to swing backwards).

If we had put three of these potato batteries in series (or, if short of potatoes, a lemon, a potato, and a tomato as shown in Fig. 2.8) we would have had almost 1.5 V—essentially the voltage of a typical “AA” cell. Unfortunately, such batteries are not able to pass enough current to do anything useful.

Will potato batteries go on forever? No; ultimately oxides form on the metals, and slowly the current gets blocked.

2.7.1 What Was Happening

As we saw, different metals in an acid, or what we called an electrolyte, gave us a voltage. The acid attacked the metals differently, causing one metal to gain more electrons than the other, and generally it is the copper that becomes more (+).

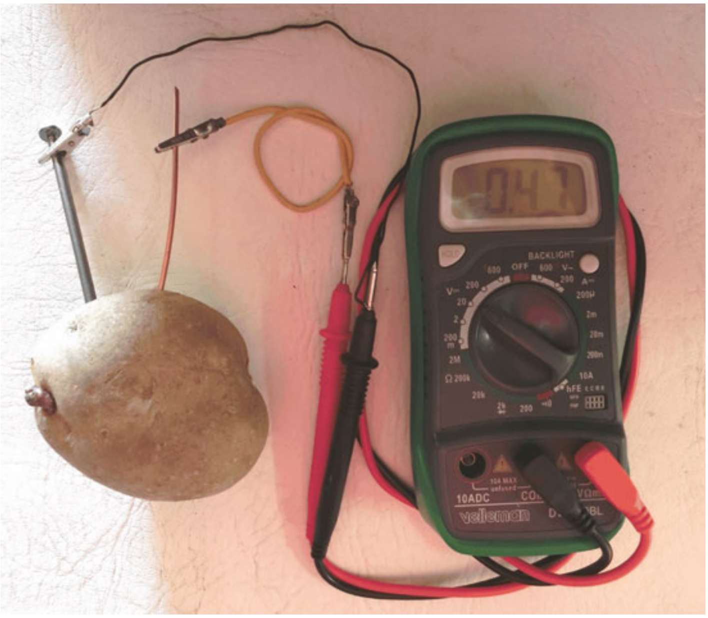

Fig. 2.7 A single-potato battery giving us just under half a Volt

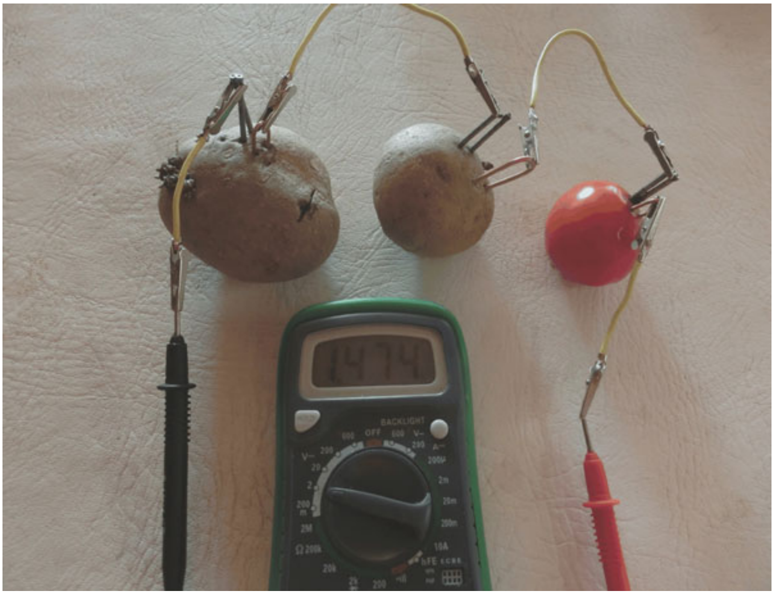

Fig. 2.8 Each fruit yields about half a Volt. Our multimeter here reads 1.47 V

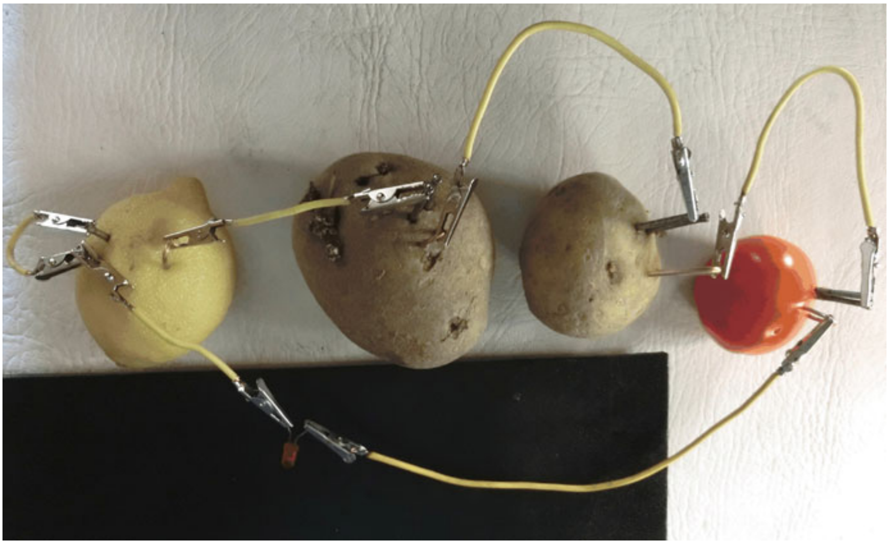

Fig. 2.9 Here we have inserted a dark background in an attempt to show the faint glow from the little red LED

An electrochemist will tell us that it is to do with the relative atomic numbers of the elements. Copper, at number 29, has 2–8–18 in its first three filled shells and the 29th electron is all alone, but steel (i.e., iron) at number 26 has three fewer outer electrons. Briefly, the copper would like to lose that 29th electron, leaving itself (+), but we will not pursue further what the other metals do to fill their shells and become relatively (−) compared to the copper. Instead, in the kitchen, we will see what happens if we try to use this electricity.

If we try to light a bulb with the improved battery of Fig. 2.8 we will be disappointed. However, if we add a fourth vegetable or fruit as in Fig. 2.9—actually here a lemon—we gain another ½ Volt. (The authors' final reading in Fig. 2.9 was actually 1.85 V.)

In principle this would be just enough voltage for an LED—to be discussed later—but there would be too small a current.

To help this we have put the electrodes closer, as well as doubled their contact area, by bending the copper and doubling the nails. The reader may now just be able to discern the little red LED glowing above a black background.

In the next section we clarify further the difference between voltage and current.

2.8 Amps, Volts, Energy, Power

Because newspaper articles commonly confuse "voltage" and "current," not to mention "power" and "energy," which are all different, let's take the water analogy one step further.

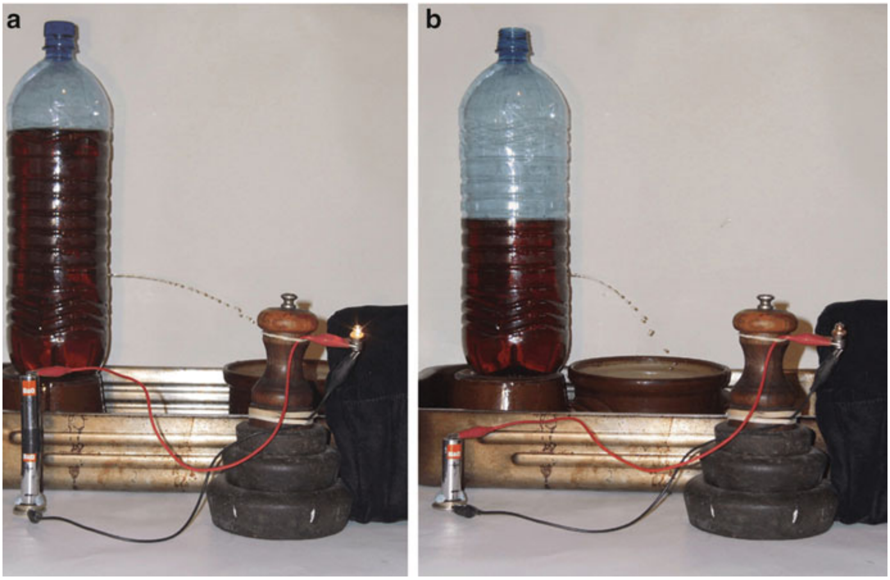

Fig. 2.10 (**a**) Higher level in bottle, and two-cell battery. (**b**) Lower level, and one-cell battery

The diluted coffee in Fig. 2.10a obviously has more *energy* than is shown in Fig. 2.10b—we can see that the two cell battery gets the flow going faster (*i.e.*, larger current, or more electrons/second), and it is thus lighting up the little bulb better than with the lower power in Fig. 2.10b.

We achieved the larger energy by filling the bottle quite high. We say that we increased the "*potential energy*" of the fluid, meaning that it has potential to do greater things, like causing faster currents.

Replace the word "coffee" with "charge." We have more coffee in the left photo or more electric charge.

Suppose we want to drive a little vane or generator in the stream of coffee flowing out of the hole. How much total energy we have available depends BOTH on the pressure (i.e., height) of the water (*potential*, measured in *Volts*) AND the total quantity of charge held in the bottle.

The product of these two is the *potential energy*, because before emerging from the bottle it has, as we said above, potential to do useful work.

So let's remember this:

$$(\textit{Amount of fluid} \times \textit{height}) \text{ is } \textit{potential energy}$$

or, same thing,

$$(\textit{amount of charge} \times \textit{potential}) \text{ is } \textit{potential energy} \text{ (or just } \textit{energy}\text{, for short).}$$

Energy is measured in *Joules*. (James Prescott Joule was introduced on p. 16.) Using standard international units, (1 Coulomb × 1 Volt) is called 1 Joule. (Using our same old symbols, this is an example of the general shorthand, $q \times V = \text{energy}$.)

As mentioned earlier, many utility companies prefer to use alternative units for energy, like kiloWatt hours (or kWh), rather than Joules (and there's an easy numerical conversion).

The energy consumed per unit of time (*i.e.*, the Joules/s), is a unit of *power*. Its name is the *Watt*, after **James Watt** (1736–1819) of steam engine fame. Note that if energy/time is power, then of course energy is (power × time).

Finally, *potential difference* is to be visualized as the difference between the height of the coffee in each case, in the bottles of Fig. 2.10. It is always measured in *Volts*.

2.9 Experiment: Current Through a Bulb

Because the Voltaic pile is impractical for experiments we resort now to everyday 1.5 V "AA" batteries, such as we find in cameras and flashlights. (We won't yet use the rectangular 9 V batteries; they are more expensive, and it is simply not necessary to have that high a voltage or pressure.)

The following experiment (Fig. 2.11) is trivial and elementary and is the circuit for connecting a bulb to a battery.

In all likelihood there is some kind of a battery-operated flashlight in the household, so let's borrow both the bulb and battery from a flashlight. If you don't have a flashlight, some of the parts that may come in useful are listed in the Appendix on p. 157.

Note: **You cannot get a shock from touching any such low-voltage battery with your hands**.

If you've hooked up the circuit correctly, the lamp will light; and it did not matter which way round the battery was connected. Note also that a switch could be inserted anywhere around the circuit to interrupt the current, but we didn't bother with this because the connection of the final alligator clip serves the same purpose. However, one would not omit a switch in a high-voltage circuit.

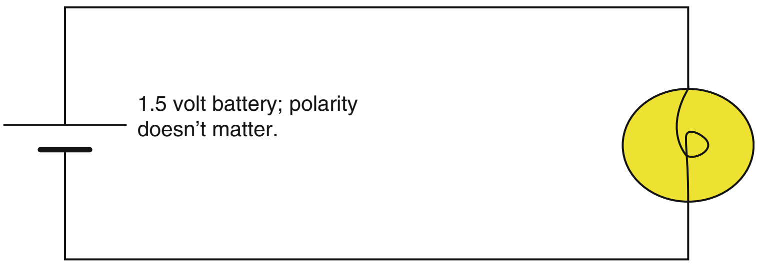

Fig. 2.11 Connecting a bulb to a battery. The polarity does not matter

Fig. 2.12 A broken 12 V automobile lamp with two filaments. Without the nitrogen-filled glass bulb the filaments would quickly burn up

2.9.1 What Is Happening

Electrons are flowing from the battery, passing through the slender filament of the incandescent (Latin *incandescere*, to glow) lamp (see Fig. 2.12), and the very thin filament is getting hot—not hot enough to melt—but hot enough to give off light and heat.

The filament was for a long time a stumbling block to **Thomas Alva Edison** (1847–1931) in his invention, or re-invention[4], of the electric lamp in the 1870s, as he tried to get it to last more than a few minutes before burning up. He ultimately discovered that the key was to remove all oxygen, for nothing can burn without oxygen. Although incandescent lamps are dying out now—they are too inefficient, with only about 5 % of the energy being light energy—most incandescent filaments are in a vacuum or in a bulb filled with an inert gas such as nitrogen.

The electrons are of course flowing from (−) to (+). All the currents we deal with, in house and car, are currents of electrons.

[4] There had been earlier experiments by Humphry Davy for example and others in different countries. In particular, a patent was issued in 1880 to Joseph Wilson Swan (1828–1914), who had served an apprenticeship in pharmacy, for a low-resistance carbon filament lamp, a lamp that, while it lasted longer than Davy's, still had a limited lifetime because of insufficient vacuum.

If we could get the positive charges to move, that would constitute a current also—but this doesn't happen here, since the (+) charges, which are the much heavier protons anchored in the nuclei of atoms, are not here free to move around.

In the 1700 and earlier 1800s, before it was known that it was the electrons moving, it was conventional to say that current went from (+) to (−). Such "conventional current" is sometimes referred to as the "mathematical current."

2.10 A Fuse

It's trivial to make a fuse from a thin strip of aluminum cooking foil, about 1/4" wide, simply by cutting a notch in it. The notch must leave only a *tiny* thickness of metal (Fig. 2.13).

Connect a battery directly across it—*i.e.*, short-circuit the battery. (Be careful: If you haven't made the "bridge" between the notches very thin, at worst, the battery could quickly overheat and, in extreme circumstances, explode.)

If the bridge between the notches is thin enough the metal will melt.

Meltable-type fuses are found in very old buildings, and under the dashboard (usually) of automobiles.

Today, houses use *circuit breakers*, which achieve the same protection by breaking the flow of current. Although we don't pursue this here, there are two basic ways such circuit breakers may work. An element may heat up and expand and thus break the circuit, or the current through them might trip the circuit by a magnetic device.

Fuses are rated by the value of the current they can pass before burning out or tripping. In the next section we construct a very basic kind of current meter, but we will also find it useful to have access to more sensitive ones, and we have photographed some typical store-bought meters on p. 159.

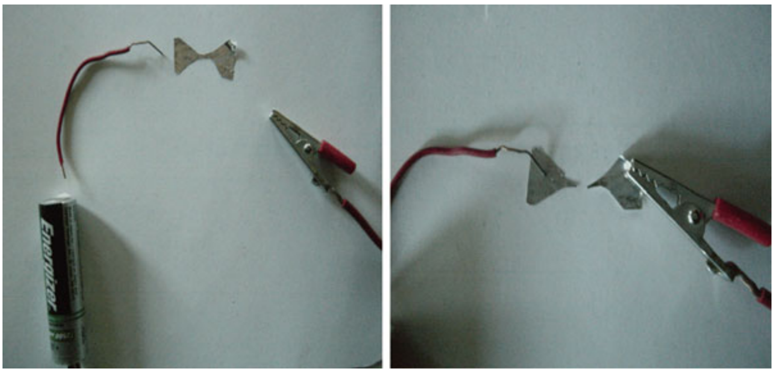

Fig. 2.13 Slice of aluminum foil as a fuse. On the *right* it has obviously burned out

2.11 Making a Current Meter

An elementary "kitchen" meter is shown in Fig. 2.14—even easier to put together than the electroscope we constructed in Chap. 1.

Assuming that there's an ordinary compass in the house, set it on the table, and allow the pointer to come to rest in its natural north–south direction. Make sure that it's away from other electrical devices in the house, such as being too close to the magnet of a radio loudspeaker or the currents associated with a refrigerator motor, etc.

Now take any coil of insulated wire—such as the coil of ordinary connecting wire we used in the experiment of Fig. 1.25—and let it have plenty of turns (the more the merrier). Its ends should be bare; unfortunately it may not be trivial to locate the inner end without having to take a few minutes completely uncoiling and rewinding it!

Now insert this coil of wire into the bulb-and-battery circuit of Fig. 2.11 by placing it in series at any place.

Obviously, the current will then have to also flow through the coil on its way around the whole circuit, as shown in Fig. 2.15.

Make sure that the coil is exactly to one side of the compass needle. If you have no bulb holder some wires can simply touch, as in the photos.

When the circuit is closed (*i.e.*, the wire is touched to the battery) the current flowing through the bulb will also be flowing through the coil—like water traveling through two or three hoses connected one after the other. It *has* to be the same current going through the coil, wire, or battery, because there were no turnoffs or alternative routes.

The bulb will light up just as brightly as before, and you have noticed that the compass needle has deflected from its previous North–South line, as shown by

Fig. 2.14 Coil of insulated wire placed as close as possible to compass (it doesn't matter if it touches the frame of the compass). This is our current meter. Note how we have set it so that the compass originally points north. (Take no notice of the brass marker)

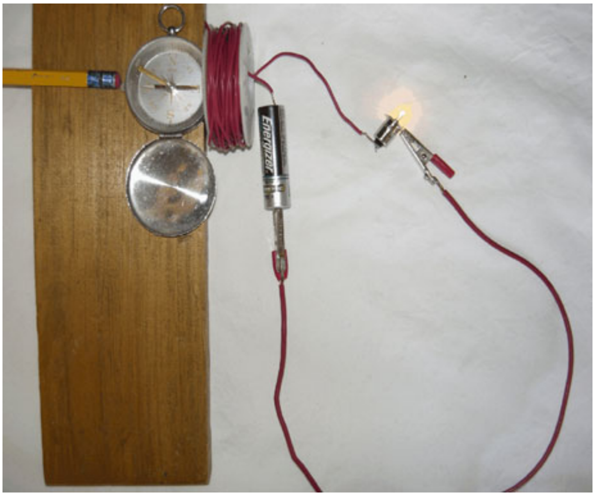

Fig. 2.15 Circuit of Fig. 2.11 modified to include our "ammeter." After connection the compass needle has swung round strongly (direction shown by *pencil direction*). Again brass marker is irrelevant

the pencil. By making a pencil mark one can see how big this deflection is. This is a direct measure, as yet uncalibrated, of the quantity of current flowing around the circuit.

Of course, our homemade meter's coil would have to be placed in exactly the same place relative to the compass each time we make a reading if we are to achieve any kind of accuracy.

With care, this meter could serve in some of our demonstrations, unless greater accuracy is called for.

2.12 Another Way to Get a Voltage: Seebeck Effect

In 1821 **Thomas Johann Seebeck** (1770–1831), a German medical doctor who enjoyed experimenting in physics, discovered that if two dissimilar wires, e.g., iron (or tin) and aluminum, or nickel and copper, were twisted together at their ends and one junction heated while the other junction was kept cool, a current flowed. (He knew this because he noticed the effect on a compass.)

We illustrate the circuit in Fig. 2.16 and a possible setup in Fig. 2.17.

Various food cans are a good kitchen source of dissimilar metals. Our apparatus, shown in Fig. 2.17, consists of two strips: one from an aluminum beer can and the other from a steel tuna fish can. **CAUTION: Not only are these kitchen metals sharp, whatever heat source is used extreme care must be taken. While the meter connections here are the cold ones, in fact the joint (top of photo) must be very hot for a detectable voltage.**

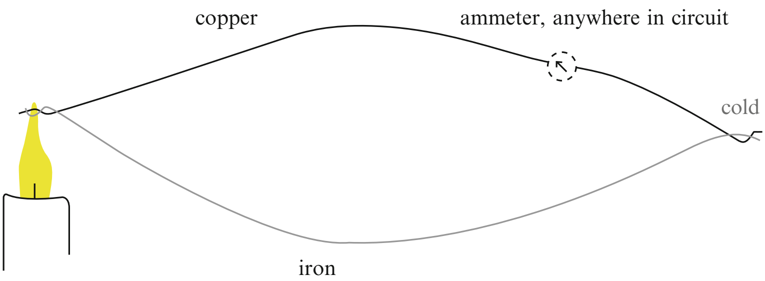

Fig. 2.16 The Seebeck effect. When one junction is hot, and the other cold, current flows round the circuit. (The meter does not have to be inserted as implied above; the *right-hand joint* can equally well be untwisted and the current meter inserted there)

Fig. 2.17 Two dissimilar metal strips, cleaned, joined firmly, and heated (here by a blowtorch). To get even a small reading on the voltmeter one joint must be very hot—**so extreme care should be taken**. The apparatus could alternatively be set up with the strips approximately horizontal, and then the hot joint could be on a gas or an electric ring

Aluminum and steel (96 % iron) make a good Seebeck pair.

Using an old pair of scissors, a 1" wide ribbon of Al was cut from the beer can, and a similar ribbon of steel from the tuna fish can—both about 6" long. Each end of each ribbon was abraded with emery paper to remove the thin plastic internal coating which stops the metal reacting with the contents. One end of each was put together, abraded areas in contact, and then the end of the double strip was crimped several times, like an old-fashioned toothpaste tube, and hammered to make sure that there was a firm mechanical and electrical contact. (With such a good electrical connection the resistance would be a small fraction of an Ohm. For the definition of an Ohm see pp. 50–52.)

From Internet data this combination is expected to give about 1.5 mV when the cold ends are at 0 °C and the hot junction at 100 °C.

One of the analog meters (see p. 159) has a 100 mV setting, and a typical digital meter has a 200 mV setting, so the Seebeck voltage should be just visible on either. However, the dissipation of the analog meter would require more current than a small Seebeck junction can supply, hence our above procedure making sure that we have a physically large junction.

It turns out that the steel end is positive. The crocodile clips of the meter needed to be clipped on to the free ends of the strips where the coating has been removed (as directed above).

As can be seen on the digital meter in the photo (Fig. 2.17) the voltage is 2.8 mV, which accords with typical data for such a junction, and our junction was considerably more than 100 °C hotter than the cold ends.

Blowlamps are available in local hardware stores, if kitchen gas or electric rings are not used. For the latter, the setup can be rotated through a right angle to heat

Fig. 2.18 Fan is powered ONLY by heat from the stove, using the Seebeck effect

from the stove or range, and it's OK to have one strip touching metal parts of the range, as long as both don't!

Although the Seebeck effect is very small it has been much improved upon since his time and can nowadays do things like drive a small fan on top of a wood-burning stove or other hot surface, (*e.g*., the Canadian-made Ecofan, Fig. 2.18).

Seebeck thermocouples can not only power little motors but could also serve, of course, as general indicators of any very high temperatures.

2.13 Peltier Effect

Jean-Claude Peltier (1785–1845), a French watchmaker who turned to physics, discovered about a dozen years after Seebeck's discovery that instead of having a hot junction and a cold junction causing a current, actually passing a current will cause one of the junctions to get cold and the other to get hot.

It is too difficult to make any kind of an effective Peltier device at home, because the temperature differences produced will be unsatisfactorily small. However, mini-refrigerators that can keep a drink cool in an automobile, etc. are available on the Internet, and these illustrate Peltier's original experiment.

2.14 Yet Another Way to Get a Voltage: Piezoelectricity

The word "piezo" comes from the Greek word for "to squash" or "to compress."

If one squashes a crystal of Rochelle salt—or quartz or cane sugar—a tiny voltage will appear across the crystal. (Rochelle salt should not be confused with rock salt—halite—which is no good for the piezo effect.)

The piezo-electric effect was investigated in the 1880s by the brothers **Pierre Curie** (1859–1906) and **Jacques Curie** (1856–1941) in Paris.

Figure 2.19 shows the basic idea.

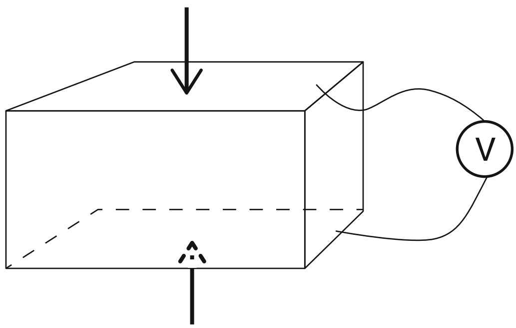

Fig. 2.19 Pressure on certain crystals, such as quartz or cane sugar, separates charges and produces a voltage

Fig. 2.20 Cane sugar and a sample of quartz

The converse effect—that a voltage would distort the crystal—was predicted in 1881 by **Gabriel Lippmann** (1845–1921)[5] and was immediately verified also by the Curie brothers.

By squashing either of the above crystals, the experimenter might think that a voltage could be detected, but this is not so easy—and it leaves one in total admiration of the experimental skills of the Curie brothers. However, a "transducer" (see footnote on p. 136) utilizes a piezo crystal and our Fig. 2.21 shows what happens when pressure is applied with a cocktail stick to a transducer. A twitch of about 1 mV has registered momentarily on the analog meter, and when the pressure was released the meter showed a twitch the other way, of about (-1) mV.

Many devices use the piezo effect, such as microphones (where the rapidly changing air pressure—or force—on the crystal causes corresponding changing voltages) and where changing voltages will cause a corresponding change in size (thus acting like a loudspeaker). We have used exactly this on p. 136.

[5] Lippmann was a professor at the Sorbonne (and later Nobel Prize winner for obtaining colors photographically by means of interference methods). He died aboard the steamer *SS France* at the age of 75 while returning from Canada to France.

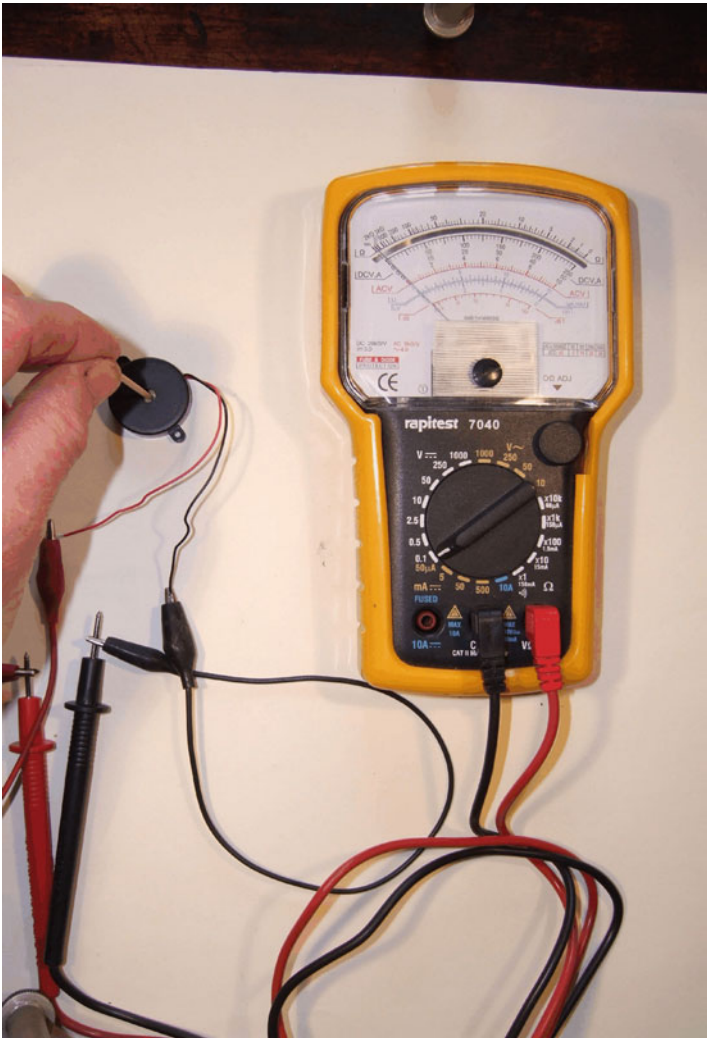

Fig. 2.21 Flicking a piezo sample

2.15 L.E.D.s vs. Bulbs

L.E.D.s, or light-emitting diodes, are increasingly used nowadays instead of bulbs, and they have one profound advantage: they use very little current for the same amount of light. The photo on the next page shows an assortment bought in a packet. So, instead of the little incandescent light bulb of Fig. 2.11, couldn't we just put a battery across one and see it light up?

Fig. 2.22 An assortment of LEDs

Emphatically NOT YET!!! (**Please wait for p. 55.**) There is every chance it will burn out, because the L.E.D. (hereafter LED) is a solid-state device, very sensitive to the current passing through it, and it will also need the battery connected with the correct polarity—which the ordinary bulb does not. All LEDs must have their current limited (by a resistor)—usually to something of the order of ~20 mA.

The working of an LED is described in detail in Chap. 4.

2.16 Concept of Resistance

Some metals allow charges to flow easily—we saw this earlier—while others are not so good (see table on p. 124).

The filament of the bulb in Fig. 2.11 allows only a limited current. We say that the filament has a certain *resistance*, measured in *Ohms*, after **George Simon Ohm** (1787–1854), a German school teacher of mathematics and son of a self-educated locksmith who managed to teach his children all he knew about mathematics, physics, chemistry, and philosophy.

Just as a bigger pressure of water forces more gallons/second to flow, as in Fig. 2.10, so a higher voltage will cause a higher current. If there's too much pressure, the water pipe may burst; and analogously, if there's too much voltage too many electrons will flow and the filament will melt.

Also, in the same way that a narrow pipe *resists* the flow of current more than a fat pipe, so a narrow wire has more *resistance* (Ohms) than a fat wire. Further, if we were to experiment with a hose, a long hose will resist the flow more than a short one. We summarize this by saying that resistance to flow is directly proportional to length but inversely proportional to cross-sectional area.

Fig. 2.23 100 Ohm resistors—five low power ("wattage") and one high wattage

A good example of the above is the cable from an automobile battery, which is fat and short. The cable has to be able to pass the huge flow of electrons taken by a starter motor—maybe 100 Amps.

2.17 Ohm's Law

Because we have that "the bigger the pressure, the bigger the current," we can write that pressure is proportional to current or

$$\text{Pressure} = \text{current} \times \textit{a constant}.$$

George Ohm called this constant the "*resistance*" of his circuit and enunciated his law in 1826. The law is used every day by people working with electricity (provided there is a direct proportionality between V and I—not the case with LEDs for example). We write

$$\textbf{Pressure} = \textbf{current} \times \textbf{resistance}$$

or

$$\textbf{voltage} = \textbf{current} \times \textbf{resistance}$$

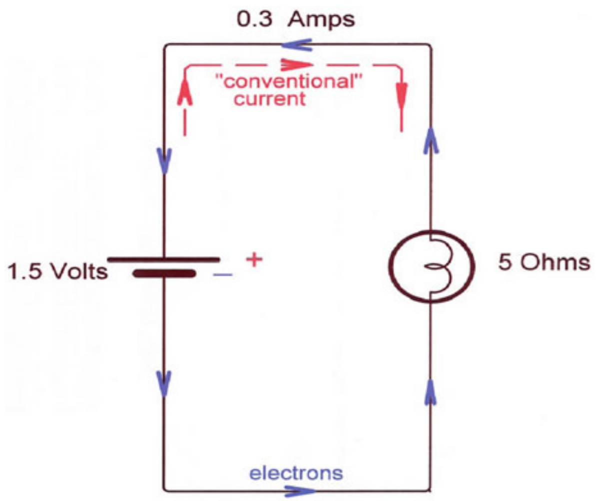

Fig. 2.24 Illustration of Ohm's law, here yielding R = 5 Ohms. Note: When a bulb is "cold," its resistance is initially small. When it reaches its final steady temperature, its resistance settles at a somewhat higher value. It is generally true that resistance goes up with temperature (there are exceptions, and there is no obvious water analogy here). This accounts for the initial brief surge of current when circuits are first switched on

or[6], using a shorthand,

$$\mathbf{V} = \mathbf{I} \times \mathbf{R}.$$

Example:

The voltage of our battery in Fig. 2.11 is 1.5 V.

The current that will pass through the bulb (it's on the package!) is ~ 300 mA (0.3 A) IF used with the 1.5 V battery.

From Ohm's law, 1.5 V = 0.3 Amps × the resistance of the filament.

From simple arithmetic, this means that the resistance (R) of the bulb must be 5 Ohms.

We should be aware that there is also some small *internal resistance*, of about 1/10 of an Ohm, in the battery itself, which can be neglected here. In an automobile battery it is even smaller—about 1/1000 of an Ohm. Figure 2.24 shows the electron flow and the values of voltage, current, and resistance.

Although we have shown a coiled filament in Fig. 2.24, the standard symbol for a resistor is given together with other common symbols on p. 63.

[6] We said "no formulae"; these are just shorthands, like acronyms. So one might be happier with V = CR, but the world always uses I for "current."

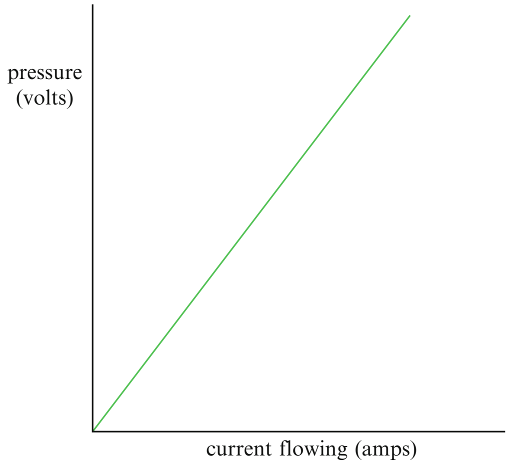

Fig. 2.25 A representation of Ohm's law. (The graph for the resistance of the filament of an actual incandescent lamp approximates this, departing slightly from linearity, particularly at the high-current end where things get hot)

2.17.1 A Graph for Ohm's Law

Notice that the bigger the pressure (vertical axis) then the bigger the current (horizontal axis). We call this straight-line graph a "linear" graph. Another word for this linear current–voltage graph is "Ohmic," and a light bulb is approximately Ohmic. However, we'll see later that things like LEDs are definitely not linear—they do not have nice straight-line graphs relating current and voltage. We call them, rather obviously, "non-Ohmic".

For comparison, the graph for a non-Ohmic device is on p. 130.

2.17.2 Experiment: Resistance of a Household Bulb

Replace the flashlight bulb of Fig. 2.15 on p. 44 with a household incandescent bulb (unscrew one from a fixture, assuming that you still have one!). It doesn't much matter whether it's a 50, 75, 100, or 150 Watt. We will find that this ordinary house bulb has a considerably higher resistance than the flashlight bulb.

When we touch the battery leads onto the terminals of the big household bulb (instead of the small bulb) the homemade compass meter will read less—considerably less. If there isn't a different reading at all with a 60 Watt bulb, try one which has a rated (*i.e.*, printed on the glass of the bulb) power of 150 Watts or so.

In any case, whichever household incandescent bulb is used, that bulb's resistance is indeed higher than that of the little flashlight bulb.

2.17.3 What Was Happening

The *power* of the heat and light radiated from a bulb depends not only on the voltage but also on the number of electrons rushing through the filament every

Fig. 2.26 Here, less current flows than in Fig. 2.15, and the pencil shows the compass needle's new position. (In this photo it happens to coincide with the brass "marker," which is irrelevant)

second, *i.e*., the current. With the flashlight bulb, there were a lot of electrons able to pass through the low-resistance filament, and of course we only needed a small electrical pressure (the voltage was only 1.5 V) to achieve this.

With the big household bulbs we observed that *less* current was passing, because the compass needle wasn't deflected as much as before. In order to achieve the higher power output of light and heat, something had to be different. What would that be?

First, notice that the pressure (*i.e*., household voltage, ~120 V in America for example) is nearly 100 times greater than the battery voltage. But this kind of pressure, surely, would cause a huge average current to flow?

No, because the bulb was designed with a bigger resistance. The makers had to provide a considerably higher resistance filament than the one in the flashlight bulb, if they wanted to keep the current flow small. After all, that's what the homeowner pays for—the current (or charge/second)—multiplied by the volts and the total time, with the result all registered by the meter outside.

2.18 Equivalent Definition of Power

As mentioned earlier, power (*Watts*) was (*charge* × *voltage*) divided by *time*. Since we learned also that (charge/time) is current, then power can equivalently be written as (*Volts* × *Amps*)—or again in shorthand (!)

$$\textbf{Power} \text{ (in } \textit{Watts}) = \mathbf{V} \times \mathbf{I},$$

a definition that will be useful to remember as general knowledge.

Equivalently, since we already know Ohm's law, we needn't use voltage at all, and we can just write the above as power = (*current* × *resistance*) × *current* = $(I \times R) \times I$.

Because "current" appears twice this is often referred to as "I squared R" heating or sometimes, as alluded to on p. 16, "Joule" heating.

2.19 Lighting the LED

We mentioned that an LED will be destroyed if we try to pass too much current through it.

In the circuit of Fig. 2.27 the voltage from the two "AA"s in series is 1.5 + 1.5 = 3, and the red LED at the top left is giving off light. The current is safely limited by the two 100 Ohm resistors in parallel (small, twisted together, top right), and this is equivalent to one 50 Ohm resistor. (The current divides into two equal paths.)

We mentioned that the LED, because it is a diode, is certainly NOT Ohmic, so its resistance is not a fixed value but depends on how much current we are pushing through it. (Again, see Chap. 4, p. 130, for the actual current–voltage graph.) These small LEDs typically need roughly 2 or 3 V across them in order to get something like 15–25 mA flowing, and such information is often given on the packet.

Fig. 2.27 Tiny red LED at *top left*; 50 Ohms at *top right*

So what is the resistance of the little diode (in Fig. 2.27) at this value of current?

We already have a 50 Ohm resistor in series in the circuit. The total resistance "seen" by the battery is therefore ~(50 + R) Ohms, where R is the diode resistance, again at these values.

In this setup the authors measured (this time with a multimeter) approximately 15 mA passing round the circuit. Thus, from Ohm's law, 0.015 Amps = Volts/resistance = 3 Volts/[50 + R] which implies that R at these values = 150 Ohms.

So our LED lights up! (If it didn't, it was the wrong way round; by convention, LED manufacturers make the (−) side flat.)

Another way to look at the above is to refer to *voltage drops*. The voltage drop across the 50 Ohm resistor is I multiplied by R (from Ohm's law, and the pure resistance is Ohmic) or $0.015 \times 50 = 0.75$ V, and the voltage drop across the LED is 0.015×150, *i.e.*, 2.25 V. These two voltages add up to 3 V, and this is an illustration of one of the two basic laws given by **Gustav Robert Kirchhoff** (1824–1887) of Konigsberg, Prussia, later a professor of physics at Heidelberg and Berlin. (Kirchhoff was a friend of Bunsen, of Bunsen burner fame, and Kirchhoff is also well known for having calculated in his early 30s that the speed of a signal along a perfectly conducting wire must approach what is now known to be the speed of light.)[7]

We don't consider Kirchhoff's laws mathematically in the kitchen, but they are easy to visualize. At a kitchen sink for example the hot water and the cold water mix at a junction and then come out of one pipe into the sink. Kirchhoff's junction law, usually referred to as his first law, says that at any joint (or junction) the total current of water flowing in is balanced by the total current of water flowing out.

Kirchhoff's second law has already been illustrated in the paragraph before the above, where we added up all the "voltage drops" (pressure changes) around a loop, and they summed algebraically to zero—*i.e.*, they "balanced." An analogy might be visualizing steps of water pressure in a multi-storey building—the pressure at the ground floor apartment might be 60 (units), the pressure at the apartment above it might be 50, at the next level might be 40, and so on, but the pressure *differences* (10 each) between each floors must add up to the *total* pressure difference between top and bottom.

The exact expression of Kirchhoff's two laws is given in Appendix F.

2.20 The Solar Cell: A (Part-Time) Battery

Instead of battery energy we can often use the energy of the sun.

When we studied electrostatics, it was friction that dislodged the electrons, and with batteries it was chemical reactions. We now know of two other possible ways

[7] The speed of light had been measured roughly by various experimenters in the eighteenth century but was not measured accurately until the late 1800s—notably by the American Nobel Prize winner A. A. Michelson, whose famous experiments took place about the time Kirchhoff died.

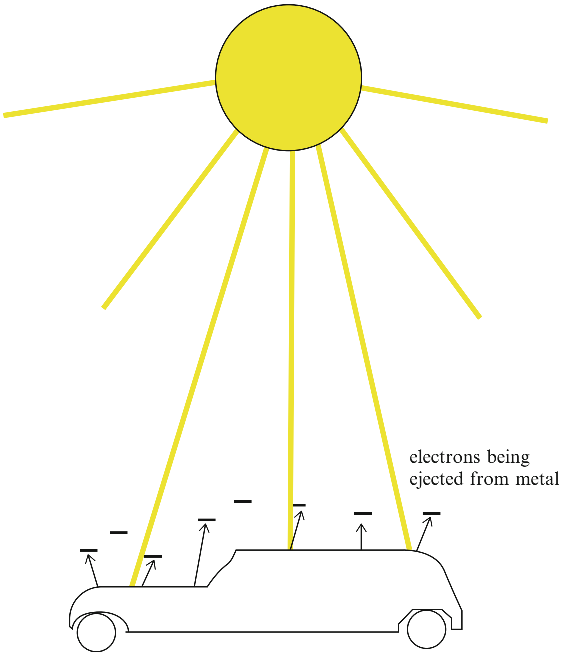

Fig. 2.28 The photoelectric effect: Radiation causing the emission of electrons. Note that this is NOT the method used with everyday photovoltaic cells

of dislodging electrons: one is by the photoelectric effect, known to Heinrich Hertz in the 1800s and explained by the young Einstein in 1905, and the other is by the use of semiconductors using (especially) silicon.

When radiation falls on various bare metals, *electrons are given off*. This is the *photoelectric effect*, shown in an ultra-simplistic way in Fig. 2.28 (assuming that the car is unpainted). **This method is NOT used to provide electricity from the sun—it's just not large enough**.

However, in 1939 the American physicist **Russell Shoemaker Ohl** (1898–1987) of Bell Labs was experimenting with a piece of silicon which had a crack in it. Specifically, he was measuring the sample's resistance. To make a long story short this cracked sample of silicon happened to have slightly different contaminants (or impurities) on each side of the crack and thus slightly different electron densities; it was a primitive "*pn*" junction. We will discuss the basic *pn* junction in detail in Chap. 4.

Now Ohl thought that, because of the different electron densities, a small current might therefore flow across the crack. But it didn't.

However, something else happened. He noticed that, when sunlight fell on his silicon sample, electrons did flow across the crack! He had stumbled across the first "solar cell" or "*photodiode*."[8] The ensuing patent he obtained was Patent #2402662, "Light Sensitive Device."

Modern *photovoltaic* (*pV*) arrays are based on this astonishing discovery.

2.21 More on pV Cells (Solar Cells or Photodiodes)

After some years, research on solar cells became more widespread. The oil embargo of the 1970s together with later oil crises forced many countries to increase efforts on alternative sources of energy. Production of semiconductor solar cells began to be increased mightily, and the price of solar cells in terms of power dropped from ~$300/Watt in the 1950s to <$4/Watt by 2012.

Conversion of light energy into electrical energy via *pV* cells is now common, and one sees small weather-detecting devices in parks and other remote places being powered by the sun. *pV* cells are increasingly seen on the roofs of buildings, legally pumping electricity back into the public grid.

We can obtain standard solar cells quite easily from stores, and here are a few points to note:

On cloudy days we obviously get only a small voltage from the ambient light, but in full sunlight we get a particular voltage (stated on the solar cell) which is able to drive a current around a circuit, depending on the total resistance of that circuit.

Figure 2.29 shows a bunch of broken solar cells (from a $10 grab bag) glued onto a piece of plywood and soldered together serially to provide enough power to charge a 1.5 V "AA" battery. (It must be a rechargeable type; it is impossible to charge ordinary batteries.)

Let's do an arithmetic example concerning a solar cell, again using only the definition of power.

Example: If a $5 solar cell can deliver 2 Volt and 1/10 Amp of short-circuit current (if we just short it out) in full sunlight, what is the electrical power being generated? What is the cost/Watt?

Answer: Power = 2 Volts × 0.1 Amps = 0.2 Watts (*i.e.*, 1/5 Watt). This corresponds to about $25 per Watt.

2.21.1 Actual Solar Cells from the Stores

Radio Shack sells a very small solar cell for about $5, which yields, in full sunlight, a "pressure" or a voltage of ~0.45 V. It can deliver a short-circuit current of as much as 0.3 Amps. (If it is connected to a load the charging current will be less than 0.3 Amps, depending on the resistance of the *external* circuit, as we saw earlier.)

[8] Photodiode is a loosely used term. It may be a small device that produces a small current, as in a bar code reader, a larger device (solar cell) that produces more current, or a device that, when current passes, produces light (LED). However, any way you look at it, it is a *pn* junction.

Fig. 2.29 Some "reject" cracked solar cells, glued onto a spare piece of plywood and soldered in series, adding up to ~2 V—enough to charge a rechargeable "AA" battery. This little set of broken pV cells has been trickle charging AA camera batteries for many years, one or two at a time (although actually four batteries appear in this photo)

Fig. 2.30 A 14 V solar panel. (In the *background* are rechargeable "AA"s plus an old ammeter)

However, we can find cheaper " \$/Watt" if we go to bigger cells, from online catalogs such as "www.herbach.com" and/or "www.excite.com" (which carries the Edmunds Scientific catalog).

This \$39 solar panel in Fig. 2.30, bought from a catalog, has a stated "full sunlight" voltage of about 14.4 V (although 17 V was measured on a particularly sunny day).

The solar cells and panels illustrated in the preceding photos have been in use by one of the authors for over 20 years, showing no degradation other than cobwebs or being knocked over by cats. Cracks are rarely a problem.

2.21.2 Note on Rechargeable Batteries: NiCad, NiMH, Li-Ion

Alkaline batteries are, as mentioned, not rechargeable. Below are some properties of commonly available rechargeable batteries:

2.21.3 Nickel Cadmium (NiCad)

The basic NiCad cell has a voltage of about 1.2 V and may be used where previously ordinary 1.5 V cells were operating cameras, etc. Their internal resistance is smaller than that of regular alkaline batteries.

NiCads sometimes suffer from a "memory" defect where they tend to only charge up to some "remembered" previous value.

Cadmium is a toxic metal, as mercury is, and is thus bad environmentally—one does not need these in landfills.

2.21.4 Nickel-Metal Hydride (NiMH)

The basic output voltage for these is still about 1.2 V, and many of the Toyota Prius models use six cells in series (*i.e.*, 7.2 V), in a bank of 28, amounting to a final DC voltage of 201.6 V. Other hybrid vehicles that use NiMH batteries are the Honda Insight (100.8 Volts) and the Ford Fusion (275 V).

NiMH batteries have almost double the capacity (*i.e.*, the amount of charge they can hold) of that of the NiCads.

They have a lesser "memory problem," although it is still there.

2.21.5 Lithium-Ion (Li-Ion)

Lithium is the lightest of all metals and has only three electrons—two in its first shell and only one in the next shell. The metal is unstable, but in ionized form—*i.e.*, having lost its outer electron—it is safe and usable.

Lithium-ion batteries are light in weight and have no "memory" effect. The voltage of the basic cell is between 3 and 4 V.

These batteries do not contain toxic materials such as cadmium or mercury.

In extreme heat all the above rechargeable batteries can explode. Related to this, they should never be short-circuited, for more than a fraction of a second. (Note that we will very briefly "tap" a regular alkaline battery in the Magnetism section, Chap. 3).

A drawback to all rechargeable batteries compared to alkaline ones is that they cannot hold a charge for a long time, whereas alkaline batteries can stay on the shelf for many years.

People using digital cameras may have noticed that a perfectly new regular alkaline "AA" very quickly causes a message "battery low." In fact, the battery is not low and could be used for many other purposes—flashlights, etc. The problem is the large current needed for the capacitor behind the flash to recharge—perhaps 0.5 Amps, and, because of the relatively high internal resistance of those "AA"s, there is quite a voltage drop as they charge this capacitor. Thus the misleading camera message is "battery low."

Interestingly, the rechargeables, even with their lower output voltage of 1.2 V, can manage this current on account of their much smaller internal resistance. However, nothing is perfect—and because the rechargeables don't hold a lot of total charge compared to the alkalines, it remains a toss-up as to which type to use in any particular application.

2.22 A Charging Circuit, and a Difficulty

What is to stop our newly charged battery from discharging back through the solar cell[9] after the sun goes down? Such a possible "leaking back" is analogous to having pumped up a tire, or a pressure tank, without a *check valve*, and the electrical analog for this check valve is the diode. Its symbol in any circuit is fairly obviously a black arrow (Fig. 2.32).

The diode has a very low resistance in one direction (the *forward* resistance) and a very high resistance in the *reverse* direction. The diode with the smallest forward resistance is actually a Schottky diode, named after the German physicist **Walter H. Schottky** (1886–1976), who did much theoretical work on early semiconductors. Its symbol is similar to the plain diode symbol but with an "S" instead of a line, as in Fig. 2.32.

The circuit of Fig. 2.31 has its diode included (either plain or, with less of a voltage drop, a Schottky diode)—and it may be inserted anywhere around the loop. Our circuit diagram also has an optional current meter, should we wish to check that the sun is actually charging the battery.

Alternatively, we could learn this merely with an LED.

A device to tell us how full a battery is after charging in the sun would be a very useful thing. In the case of a metal water tank we can of course not observe (directly) how full it is. In the case of an automobile's gas tank we might have a float giving a signal on the dash. In principle there would be ways to measure the

[9] The reader may object that solar cells are generally diodes anyway, so there can be no leaking back. However, if some of the cells are damaged, or for some reason nonfunctional, an external diode will be an insurance.

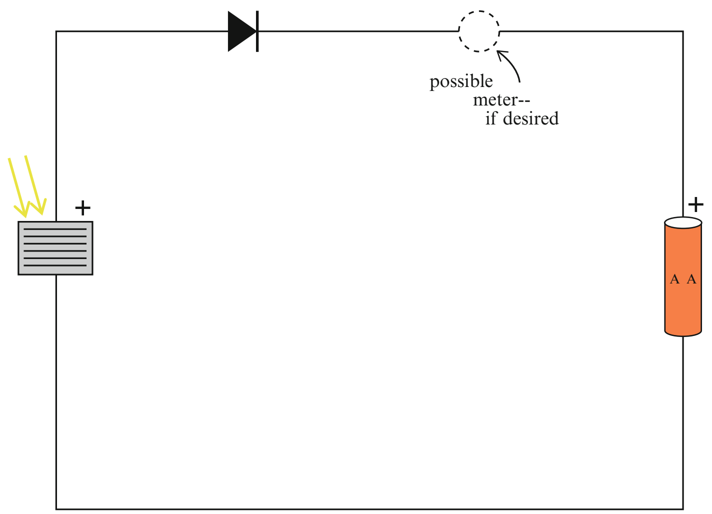

Fig. 2.31 Solar cell charging a battery

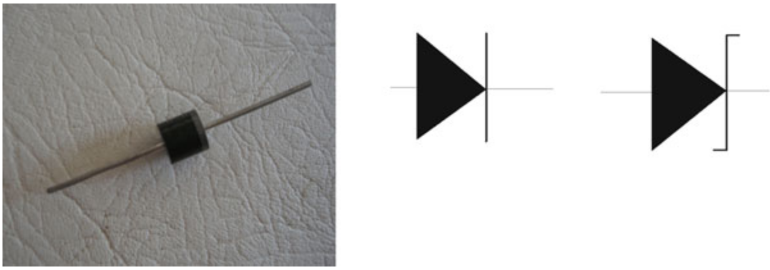

Fig. 2.32 Photograph of a plain diode, with its obvious symbol, followed by the symbol for a Schottky diode

total charge in the battery—such as by seeing how far the leaves diverge on an electroscope, but in reality it's not that simple in the kitchen.

For comparison, computers have a nice little "bar graph" for their state of battery charge, but such circuitry is more complicated than we wish to go into here.

2.23 Brief History of Electrical Diodes

The idea of a diode goes back to at least the early 1900s, when *galena*, or lead sulphide, was shown to conduct currents more easily one way than the other.

Other substances, such as carborundum, copper pyrite, and iron pyrite (fool's gold), were also observed by experimenters to have this asymmetry—in other words they were natural *rectifiers* (see p. 72, AC/DC).

In the early days of radio, where it was necessary to "rectify" modulated radio waves, galena was used in the so-called *cat's whisker* of crystal sets. In Chap. 3 we show how it's possible to actually make a cat's whisker type of radio such as was common in the 1920s. The "whisker" itself was merely the thin wire making a good contact with the galena.

In the last half of the twentieth century electronic valves (*i.e.*, vacuum tubes) were used in all radios and TVs, and these tubes allowed current to flow only one way (which of course is why they were called *valves*). Electrons came from a cathode that was heated by a hot filament, and they then flowed up to the positive anode (or *plate*); they could not flow the other way. Some of the tubes also had metal grids located between cathode and anode which could decrease and/or amplify the electron currents. Such glass-enclosed devices—triodes and pentodes—are still used today, especially in high-quality power amplifiers.

2.24 More Symbols

The devices represented by the symbols shown in Figs. 2.32 and 2.33 are based on the *pn* junction, to be discussed in Chap. 4.

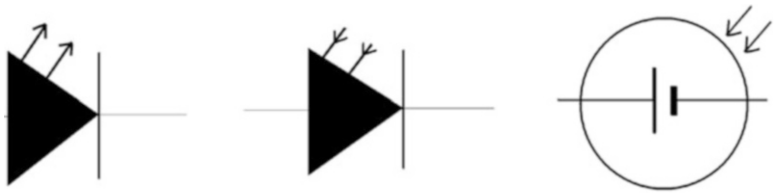

Fig. 2.33 Symbols for, respectively, LED, photodiode, and solar or pV cell

Other common symbols used in electricity are given in Fig. 2.34:

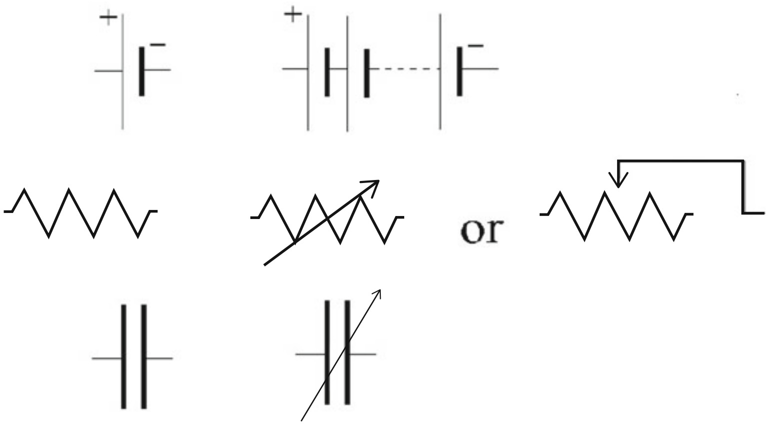

Fig. 2.34 *Top row*: Single cell, battery of cells; *middle row*: resistor, variable resistors (either/or); *bottom row*: capacitor, variable capacitor

2.24.1 Comment on the Various Uses of LEDs:

In bar code readers (see p. 163), the pattern of bars is illuminated with light from an LED and the reflected image is scanned across the sensitive area of a photodiode. When a black bar image falls on the photodiode it blocks the current in a circuit, and the bar is registered in the reader memory. When a blank space image falls on the photodiode, it allows a current to pass and registers a blank in the memory. With a fixed scanner (supermarket or library) an optical system sweeps the bar code image across the photodiode. With a handheld scanner the operator moves the scanner along the pattern.

In the solar cell (or pV cell) a voltage appears across the terminals as soon as it is illuminated (as may be seen with any meter).

Interestingly, it is not commonly known that we could, in principle, use an LED as a (quite inefficient) solar cell. If we were to place a bank of LEDs in the sunlight we would get a minuscule current.

2.25 Series and Parallel: Water Analogy

As mentioned before, in electricity we can connect things "in series" or "in parallel." In Fig. 2.35, two 1.5 V batteries are connected first *in parallel* and then *in series*:

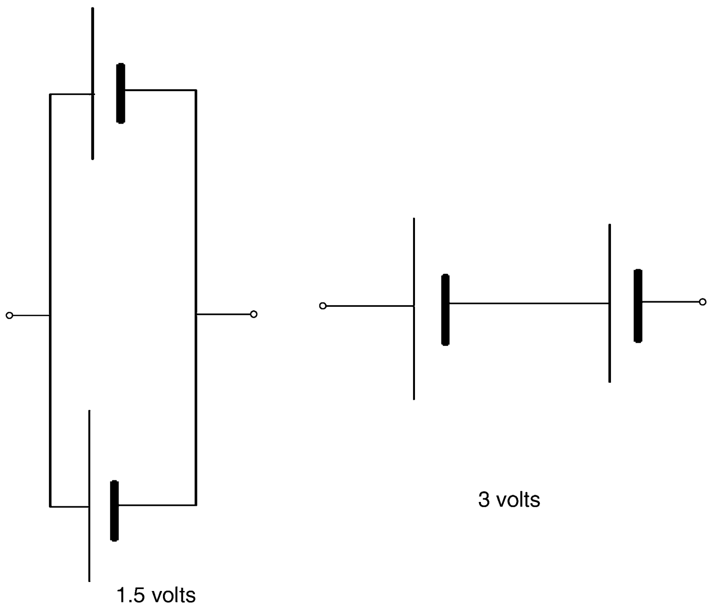

Fig. 2.35 Batteries in parallel and in series

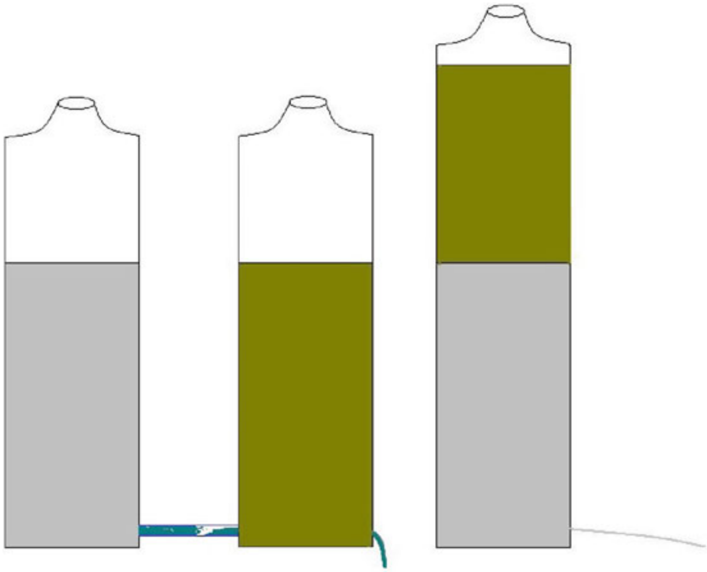

Fig. 2.36 Joined in parallel, same pressure; in series, higher pressure. (Note that in the case of two different heights in parallel, the higher level fluid would flow into the lower level bottle until their pressures equalized)

In the parallel case, the voltage remains the same, at 1.5 V. The reason for this may be found by thinking again of the water analogy. If two tanks are filled to the same height and connected "in parallel," the water pressure (which comes from the height of the water) will be unaltered.

In the series case, we add one voltage to the other—here giving us 3 V. Our analogy is to have one quantity of water directly on top of the other, giving a greater pressure, because of the height, as in Fig. 2.36:

Exercise: A 3 Volt battery is connected in series to a 1.5 Volt battery, and this combination of batteries is connected to a bulb. The bulb has a resistance of 10 Ohms. Calculate the current that flows through the bulb.

(Neglect the small internal resistance of the batteries.)

Answer:
The total voltage (or pressure or height) is (3 Volts + 1.5 Volts) = 4.5 Volts.
Therefore, from Ohm's law, $I = V/R = 4.5/10 = 0.45$ *Amps.*

2.26 Elements of Automobile Wiring

Exercise: A car battery (12 Volts in all modern automobiles) has two headlights on, plus six parking lights on—all of course connected in parallel (Fig. 2.37) to the battery.

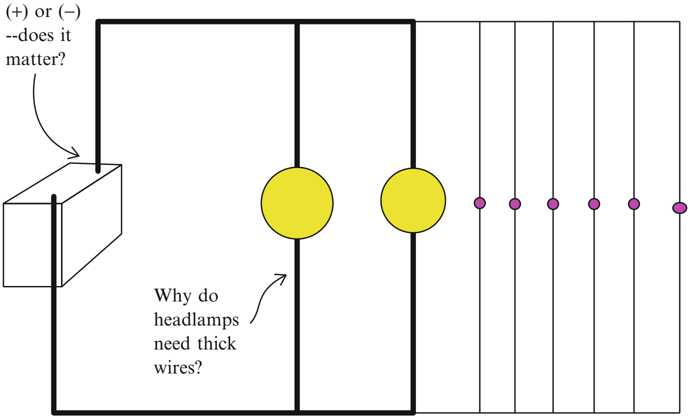

Fig. 2.37 Part of an automobile circuit

The rated power of each headlight on low beam is 60 Watts, say, and each parking light 3 Watts.

If correctly wired in parallel:

1. What is the resistance of one headlamp? (Remember that power = Volts × Amps.)
   Answer: Current through one headlamp is (60 Watts/12 Volts) = 5 Amps, and so, from arithmetic,

$$R = Volts/Amps = 12/5 = \underline{2.4\ Ohms.}$$

2. What is the resistance of one parking lamp?
   Answer: Current through parking lamp (3 Watts/12 Volts) = 0.25 Amps, so

$$R = Volts\,/\,Amps = 12/0.25 = \underline{48\ Ohms.}$$

3. Calculate the <u>total</u> current flowing through the battery. (Use Ohm's law, neglecting the internal resistance, or add up the total power.)
   Answer: Total power = 120 Watts + 18 Watts = 138 Watts.
   But 138 Watts = Volts × current = 12 × current, and thus

$$current = 138\ Watts/12\ Volts = \underline{11.5\ Amps.}$$

4. Do you think a 10 Amp fuse (for all these lights on) would be satisfactory? (Such a fuse will burn out at >10 Amps.)
   Answer: No!
5. Also, if the product of current and time ("Ampere-hours") of the battery is given by the manufacturer as 200 Ampere-hours, how long may we expect the battery to last if these lights are left on by mistake?
   Answer: 200 Amp hrs = 11.5 Amps × hrs.
   Therefore, the number of hrs = 200 Amp hrs/11.5 Amps,

$$\sim\underline{17.5\ hrs.}$$

Exercise: Suppose that the two (60 Watts each) headlamps are (incorrectly!) wired in series.

Sketch just the headlamp circuit, and find the total power delivered by the pair. (The power will no longer be the manufacturer's "60 Watts.")

Note that the alternator in a car has to produce more than 12 V—typically nearer 18 V. Also, built-in diodes prevent the charge from leaking back through the windings of the alternator.

All batteries supply current in one direction only. This is called DC or "direct current." There's no such thing as an "AC" battery! Indeed, how would the chemicals be able to "alternate" backwards and forwards?

Exercise: **Multimeter example** (The next 4 pp double as an exercise on series and parallel and may be omitted without loss of continuity.)

While digital multimeters are increasingly popular we look here at the moving coil multimeter or the so-called analog meter. We do this because a digital meter will not help us in the demonstration of, for example, Faraday's law on p. 106 (it would not respond quickly enough) and because the analog meter is an exercise on resistors in series and parallel.

In the current meter we described on p. 43 the force produced by a current flowing in a coil causes a magnet (it was actually a compass needle) to move. In a factory-produced meter it is more usual to fix the magnet and allow the coil of wire to pivot against the restraint of a spring. In fact the mechanism has some resemblance to the electric motor described later (p. 95).

In the photo of Fig. 2.38 the coil lies behind the obscured square at the bottom of the dial, and it has a pointer attached to it which shows the angular movement.

The probes are touched onto points in a circuit wherever current, voltage, or resistance (the relationship, Ohm's law, was given on p. 51) are to be measured, and

Fig. 2.38 A typical analog multimeter. (Digital multimeters use analog-to-digital converter circuits)

the large black *selector switch* is used to set the quantity you want to measure, as well as the range. (If in doubt, we set it to the largest range!)

The complete instrument depends on the use of resistors—either in series or in parallel. In the circuit diagrams following we have shown only two or three switch positions for each quantity to be measured, but in practice there may be several more.

2.27 Current Measurements

For some of the experiments in this book we will want to measure currents smaller than 100 μA (microAmps)[10] as well as occasionally as strong as 10 Amps.

The moving coil is the heart of our instrument. The strength of the fixed magnet, the number of turns in the coil, and the amount of current we pass through it will dictate how much the coil turns. The limit that it turns through is called the *full-scale deflection* (*FSD*).

Now the coil resistance may be very high, because it consists of many turns and is made from extremely fine copper wire. Many companies make multimeters, and typical values of coil resistance may be anything from about 200 Ohms (a cheap meter) to about 5000 Ohms (a more expensive one.)

For our illustrations let us assume that the coil of the meter has resistance $R_M = 1000$ Ohms.

The only thing that gives us FSD is the current through the coil, and this current is always a fixture for a particular instrument. Let us assume that in our instrument it is, say, **100 microAmps** (or **100** μ**A**, **0.1 mA**, or **0.0001 A**).

From Ohm's law V = current × resistance = (0.0001A × 1000 Ohms) = 0.1 V. This means that this particular setting of the selector switch can be for "0.1 V" (and/or "100 μA"). Note that this is a unique case where both a current and a voltage setting are electrically the same. In Fig. 2.39 it corresponds to selector position A. (On a typical multimeter look at the most sensitive current selector switch position; the makers have printed this corresponding tiny voltage reading in parentheses.)

The dashed line represents part of an external circuit in which a current circulates. In order to measure this current you have to break the circuit and feed this current into the multimeter via one probe and release the current back into the circuit via the other probe. We say that the multimeter is in series with the rest of the external circuit.

If you know that it is a tiny current, you move the selector switch to position A which is labeled 100 μA, and then the full current will flow through the meter. (The contact A leads nowhere, but you have to have a mark to turn the switch to!) So if the current happens to be as large as 100 μA, the pointer moves all the way across the scale to FSD; if the current is 25 μA, it moves one-quarter of the way, and

[10] Reminder: Milli = 1/1000 or a thousandth, and micro = 1/1000 000 or a millionth.

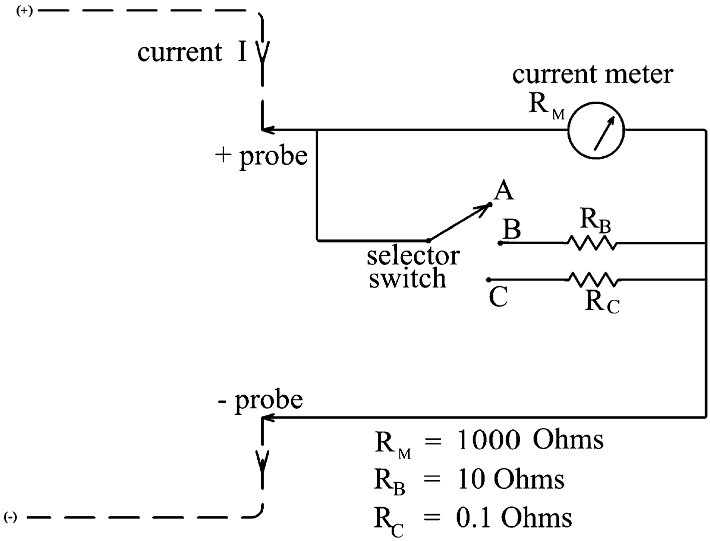

Fig. 2.39 We have cut the wire where we want to measure the current and joined it up again via our meter. For position "A" current flows in at the top left (*red* , (+)) probe, through the meter, and then out at the bottom left (*black*, (−)) probe

so on. Obviously there will also be markings 0–100 on the scale behind the pointer or the needle.

If you want to measure a larger current, without burning out the coil of the meter, it will be necessary to "shunt"[11] much of the current past the coil. Moving the selector switch to, say, position B, some of the current can now also flow through resistor R_B, in parallel with the current through the coil of the meter.

Let's say R_B is 10 Ohms. Then the current through R_B will be a hundred times greater than that through the meter (because we have said that the meter is 1000 Ohms).

If the meter reads the full "100 μA," there will be a current 100 times greater flowing in parallel through R_B, and the total current in the circuit will thus be 100 μA + (100) × (100 μA) or rather 100 μA + 0.01 A. We can ignore the first one (i.e., through just the coil), don't you think? Our meter's coil is now carrying only a hundredth part of the total current—and we can give our scale "B" markings "(0–0.01)A" with negligible approximation.

What happens if we move the selector switch to position C? If R_C has a value of 0.1 Ohms (which is another factor of 100 smaller, *i.e*., 10 000 times less than the coil resistance) the current through R_C will be 10 000 times greater than that through the meter. Thus we could now measure currents up to 1 A (with yet another scale marked "0–1 A").

[11] Any resistor in parallel with a meter is often called a shunt.

Finally, we could measure up to 10 A if we introduced a shunt of 0.01 Ohms—which we might well want to do if investigating an automobile wiring fault for example.

For measuring AC a diode would have to be included.

2.28 Voltage Measurements

Look at the example shown in Fig. 2.40. A lamp bulb is being lit up by the current from a battery. We want to know if the bulb has the correct voltage at its terminals—for if perhaps there is a bad (resistive) connection in the circuit, it won't light properly! So we set the selector to a voltage position (highest volt range to start with, for safety) and connect the probes to the bulb terminals, red probe nearest to the (+) and black nearest the (−).

We know that our multimeter is based on a current meter. Suppose we choose the voltage setting to be D and get a reading on the meter of half of the FSD (which as we know from the previous section corresponds to a current of 50 μA or 0.05 mA going through the coil).

We know that the coil resistance is **1000 Ohms**, and so using Ohm's law we can deduce the voltage between the (+) and (−) probes:

$$V = I \times R, \text{ and so}$$

V = 0.000 05 Amps × 1000 Ohms, which is 0.05 V. (FSD would obviously correspond to 0.1 V, as we saw before.)

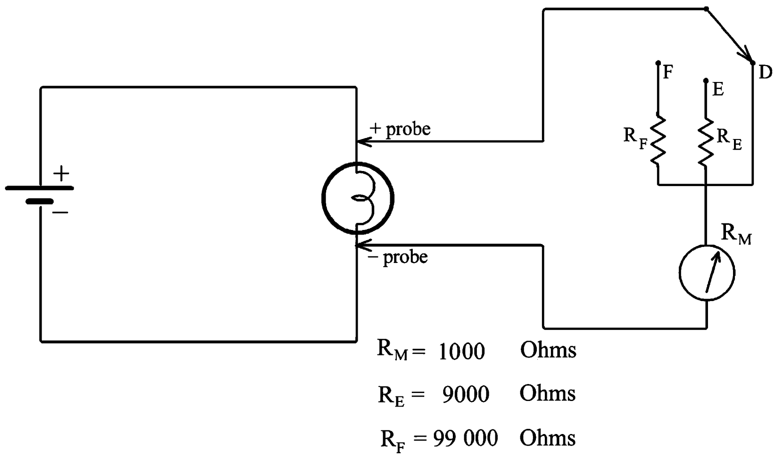

Fig. 2.40 A lamp bulb is lit up by a battery. We would like to know the volts across the bulb, so we put our probes there. Note that as always the red (+) probe must be close to the battery (+)

Very often we need to measure greater voltages, but the moving coil of the meter will be destroyed unless we can use just a fraction of the voltage at the probes. We need a potential divider (also illustrated on p. 129).

Let's move the selector to position E. We now have a resistance of 9000 Ohms in series with the 1000 Ohms of the coil. So whatever voltage is at the probes, 90 % of it will be applied to drive current through R_D and the remaining 10 % to drive the same current through R_M. (Equivalently we may say that there is a 90 % voltage drop across R_D and 10 % drop across the coil of the meter.) We have a potential divider of 90:10, and the coil "feels" 10 % of the voltage at the probes. Since our coil can feel a maximum of 0.1 V, the probes can feel up to 1 V. We need a "0–1 Volt" scale, or just read off the "0–0.1 Volt" scale and multiply by 10.

In the same way, with the selector at F, we have a potential divider giving 990:10 or 99:1, and the coil will only feel 1 % of the voltage between the probes. Thus we can now measure up to 10 V.

2.29 Resistance Measurements

We will not be able to measure resistance without an internal battery. This may typically be 1.5 V (or possibly 9 V, or a combination of these, depending on the make).

In Fig. 2.41, R_U is an unknown resistor in part of a working circuit (broken lines) whose resistance we want to measure. Importantly, we must disconnect one end of

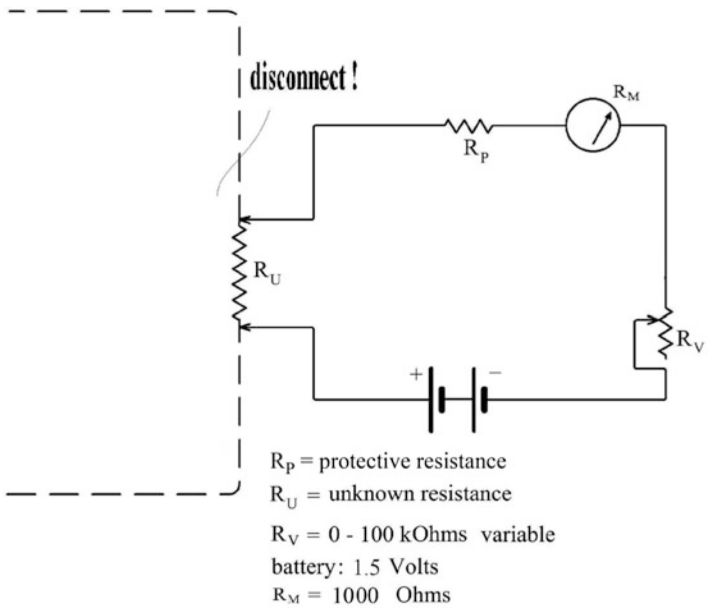

Fig. 2.41 Measuring an unknown resistance

the resistor. (Without this, there is the real possibility of other currents passing through the unknown resistor, not only distorting our readings but also breaking the meter.)

Note that the internal battery must be able to produce the FSD current of 100 μA. Note also that the resistance scale will run backwards, because a large resistor permits only a small current, and a small resistor permits a large current. We will thus have zero Ohms of resistance at the FSD position and high Ohms at the low end. Further, the markings will not be linear and will appear "squashed" at one end.

For accuracy, because a battery's health slowly dies down, we should set the zero (which is done by holding the two probes together) each time we use the multimeter. Thus, with zero Ohms between the probes, the pointer will zoom over to the right. The variable resistor R_V is adjusted by a small knob or wheel, usually on the side of the multimeter, and you twiddle this until the pointer is at exactly zero on the resistance scale.

Exercise: Figure out, just using Ohm's law as in the two previous examples, an appropriate value for the protective resistor R_P, assuming an internal battery of 1.5 V, probes together, and the "twiddle" resistance R_V adjusted to zero. Also, more ambitiously, think through what the position of the pointer should be if now a resistance of 15 kOhms is the "unknown," R_U.

Answers: [14 kOhms]; [½ FSD].

2.30 Alternating Current and Direct Current (AC and DC)

As we have commented, we know—since the time of the discovery of the electron by the Scottish Nobel Laureate **J. J. Thomson** (1856–1940) in his cathode ray experiments of the 1890s—that it is the *electrons* that move down a wire. However, as we mentioned earlier it doesn't really matter whether we assume the *mathematical* current from (+) to (−) or the *physical* current from (−) to (+).

In all households, the current supplied by the utility company flows back and forth, changing direction very fast. One moment the voltage polarity on the two parallel "slots" of the wall outlet is "+ −," and the next moment it is "− +," as in the sketch on the right-hand side of Fig. 2.42.

The right-hand diagram of Fig. 2.42 shows one *complete cycle*. In the first half of that typical cycle the voltage is positive, and in the second half it is negative. This means that current through a device will flow backwards in the second half and will go on alternating in direction until switched off.

How do we create AC? It comes from the steady rotation of a coil between the poles of a magnet. This is an example of ***electromagnetic induction*** which we discuss in detail on p. 106. It was the Serbian, **Nicola Tesla** (1856–1943), once employed by Edison, who was the major pioneer of this type of current. Indeed, when Niagara Falls was harnessed, it was Tesla's beautifully designed AC generators that were installed there by the Westinghouse Company in the 1890s.

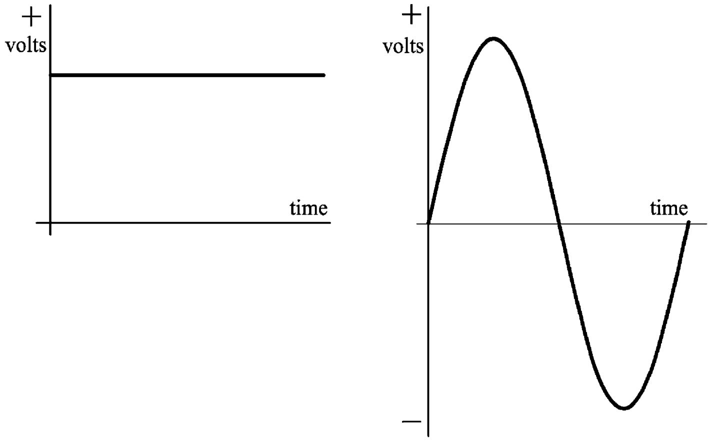

Fig. 2.42 DC voltage; AC voltage

Edison was a DC enthusiast, but DC lighting systems have severe disadvantages—notably resistance losses—energy wasted as heat (Joule heating) when the current flows through cables over long distances. Because AC can be "transformed" (see "the transformer" in Chap. 3, p. 109) into high voltages and low currents, reducing resistive losses, it didn't take long for AC to win out.

Power companies in the USA supply power at 60 complete waves, oscillations, or cycles per second, but in many other parts of the world power is supplied at 50 cycles per second. This is called the *frequency* and is measured in "cycles per second" or "Hertz," abbreviated to Hz, in honor of **Heinrich Hertz** (1857–1894). In 1887 Hertz used sparks to produce Maxwell's theoretically predicted radio waves. He died far too young, at the age of 36.

As mentioned, the coils of a generator rotate only 50 times a second in the UK, for example. This means that some American devices will not work properly in many other parts of the world. A clock designed in America to "tick" 60 times per second will only "tick" 50 times in the UK, thus running consistently slowly. And there are other differences: European voltages are all ~240 V, whereas most American devices like shavers and so on run from 120 Volts. This means that, connecting an American shaver, for example, directly (without a transformer) to a European outlet will burn it out.

You may be wondering what the value of the voltage "really" is, since we see from the previous graph that it varies up and down between + and − 170 V (in the USA) and + and − 340 V in the UK and many European countries.

So we need some kind of average, but wouldn't the average of these up-and-down variations be zero? After all, if one pushes a child back and forth on a swing, the "average" position is neither in front nor behind—it is at the center or at zero displacement.

So what we do is define an average based on the amount of energy produced, for example, in a light bulb—after all, energy is being converted whether the current is

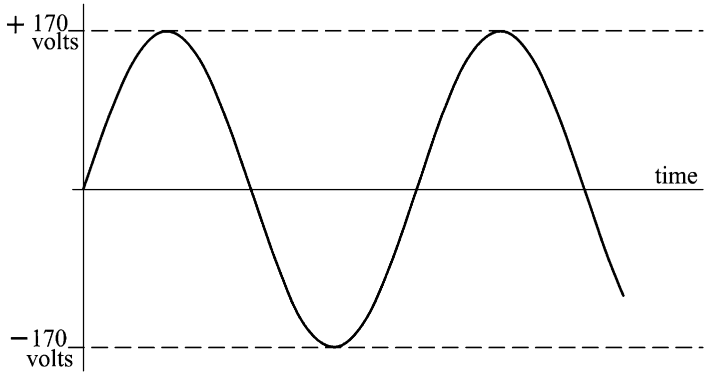

Fig. 2.43 The actual AC kitchen wall outlet varies between +170 and −170, yet we call it a 120 V supply. The reasoning behind this is indicated briefly in Appendix F

flowing backwards or forwards. After such calculations are done, the average value for voltage that people use turns out to be about 2/3 of the maximum voltage.

More exactly, we actually divide the maximum by the *square root of 2* (*i.e.*, 1.414), so our average value of voltage (again, in the USA) is[12] (170 V)/1.414 = 120 V.

The wall outlet voltage is sketched in Fig. 2.43. If we could examine the voltage in slow motion and connect a meter [**do NOT attempt this**!!—**the voltage is dangerously high**] we would in principle (but not in reality—it's too fast) see the needle of a center-reading voltmeter oscillating back and forth. Fortunately, AC scales on voltmeters read these average values, so we can completely forget about maximum values in everyday life.

2.31 Skin Effect

In a wire carrying AC nearly all the current is concentrated at the outside, and the higher the frequency of the oscillations the more pronounced is this effect. People refer to it as the *skin effect*. It does NOT take place with DC.

Clearly, in the kitchen, we don't care whether the current in our wires is in the center or near the outside, but our AC cables could in principle be hollow. However, this is not particularly meaningful at the rather low frequency of the mains—60 or 50 Hz, depending on the country—and the skin depth at these frequencies is more than a centimeter (or the thickness of a finger). Most household cables are less than the size of a finger, so any power losses are therefore negligible.

Photographs of high-power transmission lines occasionally show double cables, because engineers know that since the alternating current is restricted to the outsides,

[12] Any reader who may be familiar with calculus and trigonometry can see a reminder of the basic reason for the square root of 2, given in small print in Appendix F.

it makes sense to sometimes put in two wires, rather than one thick one. Thus we are utilizing two skins rather than the skin of one heavy and thicker cable.

This is also the reason (or one of the reasons) why some wires are stranded—the so-called *Litz* wire. Again, we then have lots of little skins rather than the single skin of a heavy wire.

Yet another reason is that stranded wire is more flexible.

2.32 An AC Experiment with LEDs

An LED will also run off AC because it is a diode. It will light up on alternate half cycles, as in Figs. 2.44 and 2.45.

If we were to connect 50 or 60 little LEDs in series they would light up directly from a regular 120 V AC outlet.

They are lighting up much too fast, of course, for us to see them switching on and off.

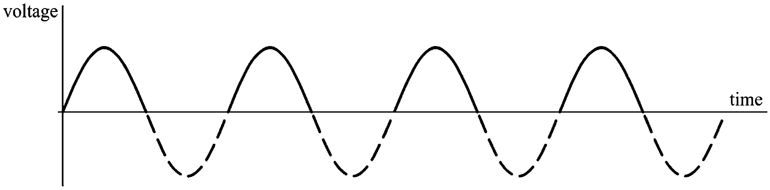

Fig. 2.44 On AC power, an LED will switch on and off every cycle—too fast for the eye not to believe this to be continuous

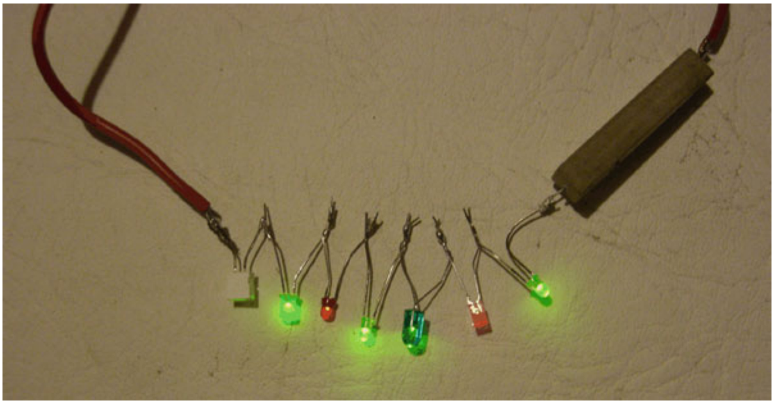

Fig. 2.45 Seven small assorted LEDs soldered together, in series with 5600 Ohms, running directly off the regular 120 Volts AC. The current flowing, from Ohm's law, would then be approximately 22 mA or 0.022 Amps. Note that a couple of the randomly selected LEDs are quite faint

Also, should one of them burn out they will all turn off, because the current would be interrupted. (Some old incandescent Christmas tree lights may not do this because they may have been uniquely designed to "melt" and yet leave some continuity.)

In Fig. 2.45, instead of 60 of them, 6 or 7 have been soldered together in series with a large resistance of 5600 Ohms.

CAUTION: **The home experimenter should not try this**! **120 Volts or more is too dangerous to even think of playing with without very great care**.

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