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A Kitchen Course in Electricity and Magnetism

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Preface

Many people's eyes glaze over when someone attempts to explain something even mildly technical, and if an equation is utilized—well, that's the end of the matter!

But it needn't be.

For those who would like a grounding in the basics—historical and modern—of electricity and magnetism as we experience them today, this book intentionally uses "no math" (except in Appendix F, which may certainly be omitted). It *does* allow the occasional "shorthand" definition, plus the simplest of arithmetic.

The work should be of interest to at least any of the following:

(a) the armchair reader (such as, but not necessarily, a curious retiree).
(b) an experimenter.
(c) school students, including the home schooled.
(d) he/she who asks such questions as "what <u>is</u> an LED light?"
(e) people taking college physics that seems too abstract.
(f) anyone whose day-to-day work involves electricity.

The emphasis throughout is on experiment and history—experimentation that can very often be repeated just with things found at home. (Hence "kitchen" in the title.) Of course, the armchair reader is not obliged to do these experiments and sometimes it's okay just to visualize them!

It's clear that we use physics constantly, and (presumably) always will. While we don't need to know any science to live comfortable lives, electricity is something worthwhile knowing the elements of—and on top of that it's fun. From bulb to LED, radio to TV, microwave oven to transistor, cell phone to photovoltaics, and much more around us—all involve electricity plus its nondetachable partner, magnetism.

So, enjoy!

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Contents

Background

Electricity is a natural part of everyone's experience. Since the dawn of mankind, the crackling sounds of lightning discharges have frightened animals, split trees, started fires, and killed sailors on the open seas as well as golfers on their golf courses. It has also electrocuted people who have mistakenly sheltered under trees—mistakenly, because although the branches may seem to offer protection, a person under a branch, as we shall see shortly, is not safe there.

Let's look first, albeit briefly, at what earlier mankind knew about electricity.

In 600 BC, **Thales**, a Greek philosopher, had written down that *amber*, a brownish-yellow fossil resin found on some seashores, attracted pieces of straw if it was rubbed. Much later, by the 1600s, it became generally known that two pieces of amber rubbed with fur, and certain other cloths, tended to repel each other—and the same repulsion happened when two pieces of glass were rubbed with silk.

In the late 1500s **Dr. William Gilbert** (1544–1603), who was a physician to the Queen of England, noticed that many substances (like diamond, opal, sapphire, etc., as well as glass and amber)—after being rubbed—attracted tiny pieces of paper. He called substances that caused such effects *electrics*.

Curiosity flowered more strongly in the following centuries, and further experiments on these so-called electrics were being done throughout the 1700s in many countries by many different people.

Amongst them it's appropriate to mention the writer–statesman **Ben Franklin** (1736–1790) in America, the botanist–chemist **Charles Dufay** (1698–1739) in France, the ex-cloth-dyer in a London poor house **Stephen Gray** (1666–1736), the French engineer who had worked in Martinique and Brittany **Charles Augustin de Coulomb** (1736–1806), the experimenter **Michael Faraday** (1791–1867) in England—and, investigating many of the same phenomena as Faraday, the youthful would-be actor from Albany, NY, and later President of the Smithsonian **Joseph Henry** (1797–1878).

Now these experimenters knew that rubbed glass not only repelled rubbed glass, but was generally *attracted* to rubbed amber. Such observations led both Dufay and Franklin independently to the conclusion that there might be two distinct electricities, or what they called *electric charges*.

Thus, since ***like*** **electric charges repelled**, **and** ***unlike*** **electric charges attracted**, they arbitrarily called these two apparent types of charge "*positive*" and "*negative*"—words we still use.

Early experiments on repulsion and attraction were ultimately summed up by Coulomb in a basic law, in 1783—Coulomb's law[1]. He stated that the force between two charges—either attractive or repulsive—was proportional to the product of the charges and inversely proportional to the (square of the) distance between them. (For those who know about gravity, this is an "inverse square law," of the same form as Newton's—100 years earlier—law of gravitation.) If the charges were of opposite sign there was attraction, and if of the same sign then repulsion.

However, we still haven't said what electric charge is. Is it some kind of particle? Or even a fluid? And how do we quantify it?

Around the 1860s, the German all-round scientist **Hermann von Helmholtz** (1821–1894) had suggested that charge might be comprised of some unique and basic type of particle. His idea took on, and such a so-far hypothetical particle came to be referred to, especially in the German literature, by the delightful name *Helmholtzsche elementarquantum*.

We know now that this suspected fundamental particle does exist, and it has a negative charge; it is called the *electron*. ("*Elektron*" is the Greek word for amber.) Despite the fact that many scientists of the nineteenth century did not want to believe there could be any particle smaller than an atom, the electron was actually isolated by the Scottish scientist **J.J. Thomson** (1856–1940) in a series of experiments in Cambridge just before 1900.

The present-day picture is that a *negatively* charged body is said to have an excess of *electrons*, and a positively charged body has a deficiency of electrons. If bodies have neither excess nor deficiency (like everything in normal everyday life) we call them, rather obviously, *neutral*.

The charge on the electron is much smaller than the basic unit of charge that we use throughout science, which is the *coulomb*. Only if we had approximately 10 *billion billion* electrons would we say we have a coulomb. (Such a large number is often written in newspapers, for example, with commas, as in *10,000,000,000,000,000,000* but we will write it here with spaces, as in *10 000 000 000 000 000 000*.) Let's begin with a few electrostatics experiments easily done at home.

[1] Formulae are not used in our introductory book, but for readers who would like to see them they may be found in the Appendix on p. 169.

Home Electrostatics 1

1.1 Static Electricity

Everyone has rubbed a balloon on his/her shirt and watched the balloon cling to a ceiling, and maybe you have shuffled across a carpet on a dry day, only to receive a shock from the next thing touched. This particularly happens in winter, when the humidity is low.

Also, on a similarly dry day, you may have combed your hair and heard a crackling sound or touched someone and there's been a spark from your hand (Fig. 1.1).

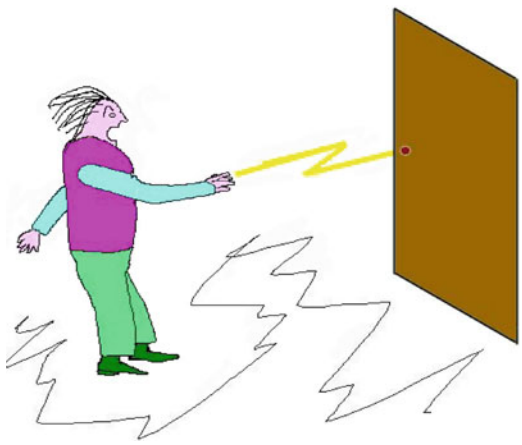

Fig. 1.1 Shuffling across a carpet and getting zapped

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1.2 A Charge Detector

There are various ways to detect electric charge, and in Fig. 1.2 we show a detector that can be assembled at home in a few minutes.

We take a strip of thin cardboard, or sturdy paper, about 4"–6" long, and fold it along its center line. We can then balance the cardboard at its center on a needle stuck in a cork, as shown.

If a charged balloon or comb that has been rubbed is brought near to either end of the charge detector, the cardboard will swing around and follow, clearly attracted, and never repelled. However, it is only a detector, and it will not tell us anything about the charge that is causing it to swing.

In the following pages we look at some different kitchen phenomena involving electrostatic charges and, after studying the atom, begin to explain them.

Fig. 1.2 A piece of thin cardboard is folded along its center and supported by a needle stuck in a cork. It will swing round towards any electric charge

1.3 Using Plastic Wrap

In Fig. 1.3 below, a piece of uncharged plastic wrap hangs freely. The home experimenter will find it quite a challenge to have this uncharged, because normally, when plastic wrap is torn from its box, friction will give it a charge. In the

Fig. 1.3 A piece of uncharged plastic wrap hangs freely

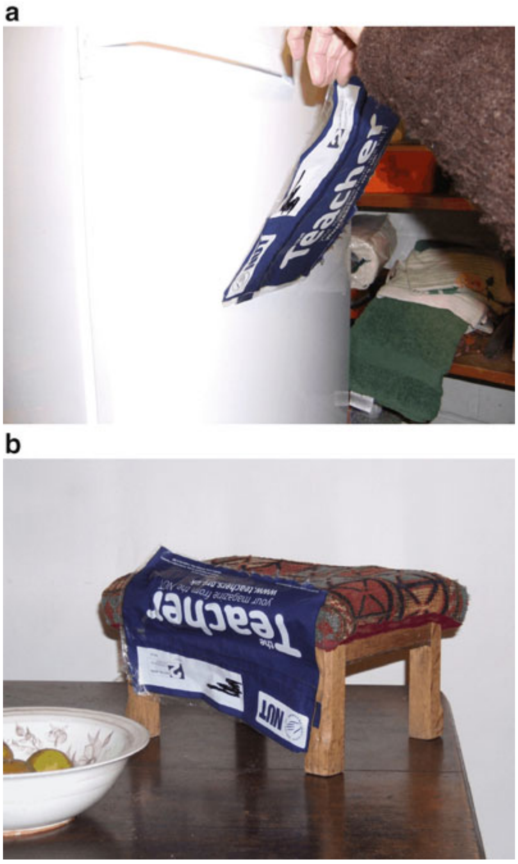

Fig. 1.4 (**a**) If the plastic has been torn recently, or dragged across a dry shirt or other cloth, it will cling to almost anything, such as the metal refrigerator or (**b**) perhaps a stool

photograph, the plastic was actually unrolled slowly and carefully, and cut with sharp scissors, avoiding friction or scraping.

However, as we said, if it has been rubbed or torn off recently, it will be charged and will cling to almost anything, as shown in Fig. 1.4a, b.

1.4 What Has Happened

When the plastic was torn too vigorously from its box, electrons were knocked either off the surface of the plastic (leaving the plastic somewhat positive) or off the box and onto the plastic (thus leaving the plastic with an excess of electrons).

As yet we haven't given any reason which of these it is. It would actually be possible later to find out, but for simplicity let us assume now that the plastic wrap is (−), *i.e.*, too many electrons.

The plastic can cling to anything, because then (+) charges in various nearby objects will try to get close to the plastic's (−)—from the results of those early experimenters who saw that *unlike charges always attract each other and like charges repel*.

Of course, the metal and/or the nonmetal stool were originally electrically neutral. So what was going on?

Consider the refrigerator first. In the left sketch of Fig. 1.5 the plastic is neutral, as is the refrigerator. (For simplicity we have not bothered to show the equal number of pluses and minuses on the plastic, although they are shown on the refrigerator.) In the right-hand figure the (−) charges of the refrigerator have now moved as far away as possible from the (−) charged plastic wrap, leaving (+) charges nearer to the plastic wrap. Of course, there is then mutual attraction.

The refrigerator is made of metal, which is a *conductor*, and *electrons are free to move in a conductor*. We will take this as the definition of a conductor (and discuss semiconductors later).

In the case of the kitchen stool (see Fig. 1.4b), which is not a conductor but rather an *insulator* (we use the word insulator for a material whose charges are NOT free to migrate from one place to another) something has obviously happened that there is still attraction.

Note that in these kitchen experiments the plastic wrap may eventually lose its attraction because some of the charges on the surface of the plastic may very slowly get neutralized, perhaps by actual contact with the metal refrigerator, and/or from

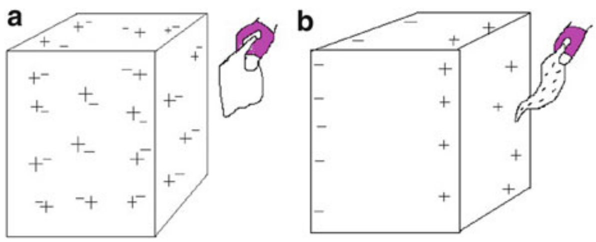

Fig. 1.5 (**a**) Original uncharged plastic, (**b**) charged plastic

Fig. 1.6 Plastic wrap still clinging weakly. (This has been here for over 3 months . . .!)

stray atoms in the air that may have lost or gained an electron. (Such atoms and/or molecules are called *ions*.)

Our Fig. 1.6 shows a piece of charged plastic still clinging to the side of a metal object after many days!

1.5 Experiment: Two Plastic Strips

Cut two strips of plastic, as shown in Fig. 1.7. It's best if these have a certain rigidity, and we have colored them only so as to render them visible against the white background.

Rub them all the way down with your bare fingers or with a sock or some kind of wool—just once or twice; this will make the strips, which are identical, repel each other, as on the left side of Fig. 1.7.

Next, bring up a kitchen knife, or some metallic object, between the strips and witness them both collapse onto the metal, as on the right of Fig. 1.7.

Take the knife away, and they will go back to repelling each other again.

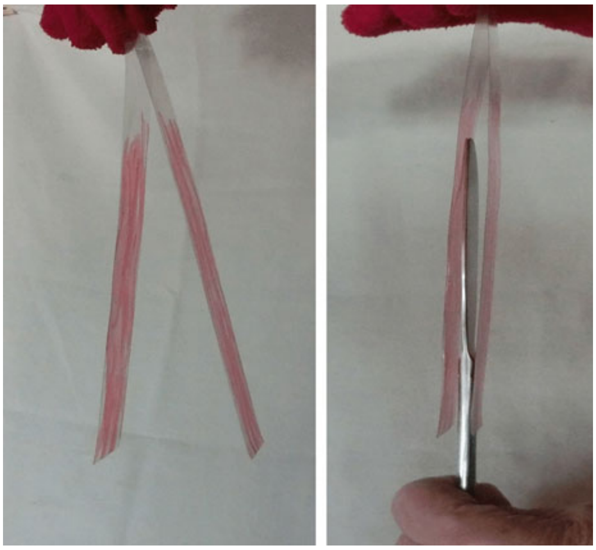

Fig. 1.7 The charged strips repel each other, but if a conductor is brought between them they will collapse onto it. When the conductor is removed, the strips repel each other once more

1.5.1 What Is Happening

The plastic is an insulator (defined on p. 4). By friction some charges were knocked off.

There must be like charges on the two pieces of plastic for them to repel.

When a conductor is brought between them the opposite sign of charge is attracted as close as possible to the charges on the plastic strips. Thus each strip is attracted to the metal—and clings to it.

When the metal is taken away, the strips return almost to their mutual repulsion. We say “almost” because there may have been a small amount of cancellation from the direct contact.

In order to understand better the previous experiments we must now digress and describe the basics of an atom.

However it should be emphasized that we have never clearly seen an atom, although photographs of “lumps” representing arrays of atoms exist now, and may be seen in modern physics texts (*e.g.*, E. Hecht’s “*Physics*,” on his p. 318.)

The Greek philosopher **Democritus** (roughly 460–370 BC)—known as the “laughing philosopher” on account of his emphasis on cheerfulness—was one of the first to believe that matter consisted of atoms. His idea was that there were just two things—atoms and void. His atoms were hard and indivisible and of different shapes and sizes, and he suggested that they could form clusters of distinct types—a precursor, perhaps of today’s *molecules*.

One of Einstein’s earliest papers (“*On Brownian Motion*,” 1905), explaining the mathematics of pollen (on the surface of water) being hit from all sides by unseen particles, helped support the belief in Democritus’ idea that matter had to be made up of atoms.

1.6 Atoms

The model of the atom commonly accepted today is due to the Danish scientist, **Niels Bohr** (1885–1962). Because we are in the kitchen we will not need to discuss the more complicated quantum mechanical model of the atom, and we will be at no disadvantage here by such omission, because Bohr gave us the essential picture.

Atoms have a central massive (+) nucleus, orbited by electrons—like planets around the sun. However, instead of gravity, the electrons are attracted to the nucleus as dictated by Coulomb's law (p. xii).

The positive particles in the nucleus are called *protons*, of equal and opposite charge to the tiny electrons—but much heavier (Fig. 1.8).

The number of protons indicates the identity of the atom. For example, the hydrogen nucleus has 1 proton, helium has 2 protons, and uranium has 92 protons.

A *special rule* controls the atom's chemical behavior. Let us look at an atom of carbon. Carbon has a total of six protons, so it must have six electrons. Two of these electrons are in its first "shell" or "radius" or "orbit," and according to the special rule—which comes from quantum mechanics—it is not allowed any more in that shell.

So the remaining four electrons have to be found in the second shell. (If we continue the rough comparison to astronomy, in our solar system Mercury would be in the first shell, Venus in the second shell, Earth in the third, and so on.)

Now carbon has a strong chemical resemblance to other atoms that also happen to have only four electrons in their outermost shell—a prime example being silicon, which has four electrons in its third shell. We will meet silicon in Chap. 4 when we deal with transistors.

As we said, the proton is much heavier than the electron—1836 times heavier.

In the nucleus there are also neutral particles, called *neutrons*. These will not concern us in our study of electricity, and we may regard them just as "ballast." The nucleus is thus even heavier than might be expected if all it had were protons.

The whole atom itself is "neutral," *i.e.*, having no net charge, so again this means that if there are 17 protons in the nucleus there must be 17 orbiting electrons in their various shells.

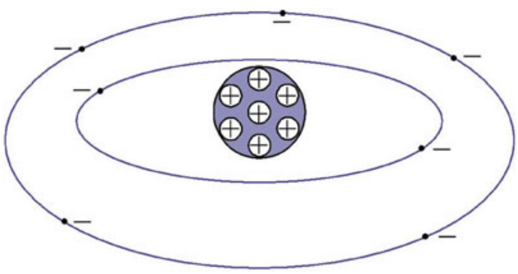

Fig. 1.8 The Bohr atom. Like planets around the sun, tiny electrons orbit the nucleus. There are also neutrons in the nucleus, which we haven't shown. This particular atom has seven electrons and is therefore nitrogen (see the Periodic Table in any encyclopedia)

We should mention that for any element, different neutron numbers are possible, and these atoms are called *isotopes* of the element (from the Greek *iso*, same, followed by "*p*" for protons—same number of protons.) For example, looking again at carbon, the most common form has six protons as well as six neutrons in its nucleus. It is customary to write it as ${}^{12}_{6}C$. A well-known isotope of carbon, ${}^{14}_{6}C$, has two extra neutrons. (This isotope is also *radioactive*, which means that its nucleus is slowly disintegrating, or rather changing, by radiating off particles.) Carbon 14 is extremely useful in dating ancient organic artifacts in archeological excavations.

The special rule that we referred to which describes the maximum number of electrons allowed in each radius or "shell" is called the *Pauli exclusion principle*, which, again, we don't discuss in the kitchen! The only point we need to remember is that there are these limits. Shells are regarded as "filled" when by that rule they are not allowed to have any more electrons. We may just mention that the number of electrons allowed in the second shell is eight, but after that the numbers become more complicated—as chemists know—and we will not pursue this here.

Finally, we mentioned that if we were to take an orbiting electron away, the atom would become *positive*, and scientists would then call it a *positive ion* rather than an atom. Similarly, if we were to somehow add an electron, the atom would obviously become negative and would be referred to as a *negative ion*.

In atoms that have many electrons some of the outer orbiting electrons are relatively easy to knock off by friction, which is what was happening in the "rubbing" examples with the plastic sheets above.

All those early experimenters who lived prior to 1900 would have been interested to know that it's just the transferring of electrons that is responsible for the effects they were observing.

The addition or the subtraction of electrons today is central to our understanding of many appliances in modern life. Electrostatic effects can be used, for example, in laser printers and photocopiers, where tiny sections of *positively* charged paper can attract sootlike "toner" particles—on the assumption that the particles have been *negatively* charged. (The resulting "image" can be "fixed," or made permanent, by applying heat.)[1]

Earlier, we noticed that our plastic wrap clung to an *insulator*, such as the stool. We will also see, in the following experiment, that something like regular water seems to be affected by electric charge. Now that we know the basics of an atom we will be able to explain these things.

1.7 Experiment: Bending Water

Turn on the kitchen faucet, and adjust the flow to a very thin continuous trickle. Run a dry comb through your dry hair (or rub the comb with wool), and bring the comb close to, but not touching, the stream (Fig. 1.9).

[1] One can find many further industrial applications described in technical encyclopedias.

Fig. 1.9 Bending water

The water has been attracted to the charged comb, and we'll see the reason after first describing a *dipole*.

1.8 Dipoles

By the definition we gave on p. 4 charges do not travel in insulators, nor in things like pure water. However, if the molecules are *dipolar*, they can act like the needle of a compass, and swing around, without leaving their position. We illustrate this below.

It is possible for one side of a molecule to be more positive (or negative) than the other, depending on the arrangement of the atoms in the particular molecule. Instead of N and S, as with a common magnet (to be studied later) some molecules may have (+) and (−) ends, as shown below in Fig. 1.10.

It is common for everyone to refer to water as H_2O, which signifies that there are two hydrogen atoms attached to one oxygen atom to make a molecule of water.

In Fig. 1.10 the electrons of the oxygen atom have an "average place" somewhat to the top left of the diagram.

Also, the region of the two hydrogen atoms is slightly more positive than if they were alone because their electrons (just one each) are actually being shared by the oxygen. Why? Because, by that rule we mentioned concerning "filled shells," the outer shell of the oxygen would prefer to have a complete set of eight electrons, and the two hydrogen atoms, with one electron each, provide just that.

The net result is that the water molecule is electrically rather like a dog bone, (+) at one end and (−) at the other, or analogous to a magnet, except that we're not talking about magnetism here. We call the water molecule *dipolar*.

Note: Substances that may not be inherently dipolar can also act in the same way as the water molecule. Figure 1.11 shows a charged comb distorting the electron cloud in a nearby atom, making the atom again rather like a "dog bone" or a dipole.

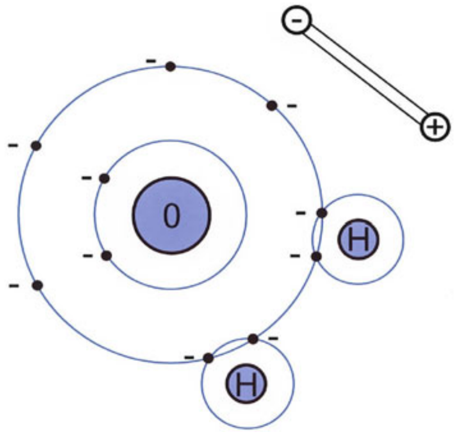

Fig. 1.10 A water molecule as a "dog bone" (or *dipole*). The "H"s constitute the (+) end, and the O is more negative, as explained below

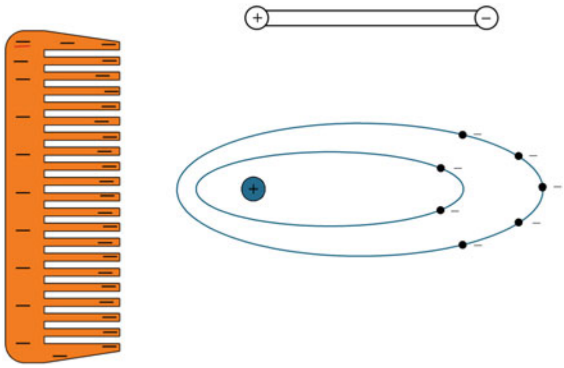

Fig. 1.11 A charged comb repelling an atom's electrons so that it acts like a dipole

This dipolar nature explains why the plastic wrap clung to the stool as well as why the water bent. The molecules in the stool and the water swung around and lined up, such that the (+) ends of the dipoles were attracted to the (−) of the comb or the plastic wrap.

Two more illustrations follow.

1.9 Experiment: Comb and Paper

Tear some tiny pieces (we mean tiny!) off the corner of the newspaper. Alternatively, use some pieces of Styrofoam, perhaps from packaging or a cup. In either case, they must be lightweight.

Then take the ordinary plastic comb, rub it again through your dry hair (or with wool), and note how it will pick up the smidgins of paper or Styrofoam. This of course is also exactly what happened with our paper charge detector on p. 2.

Further, if you wait for as much as a minute, some of the little pieces may suddenly fly off!

(Note again: ELECTROSTATICS EXPERIMENTS WORK MUCH BETTER IN THE WINTER WHEN THE HUMIDITY IS LOW.)

1.9.1 What Has Happened

If the comb were negative (say) the (+) and (−) charges of the molecules of the neutral paper became distorted, acting as dipoles. The (+) ends were attracted to the (−) comb, as shown in Fig. 1.12. And, as we said, exactly the same thing was happening with our paper "charge detector" on p. 2, where we put off the explanation.

And why did the tiny pieces of paper decide to jump off the comb a few moments later?

By contact. As they rested on the comb some of the smidgins gradually acquired, by direct touch, a negative charge, just like the comb; hence—poof!—repulsion.

Table: While doing experiments that involve charges obtained by rubbing, we should give here a list of substances which, if below in the list, are more negatively charged than the substances above. For example, frictional contact between *glass* and *silk* will leave the glass more positive.

Rabbit fur
Glass, mica, wool
Cat fur, lead, silk
Aluminum
Cotton, wood, amber, brass
Rubber
Celluloid
India rubber

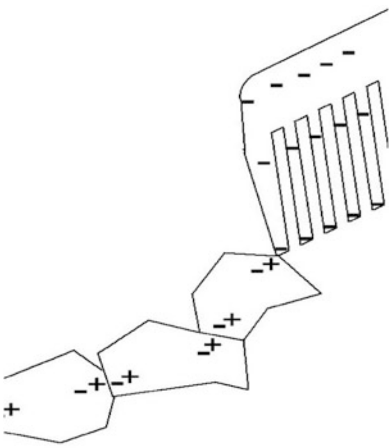

Fig. 1.12 Arrangement of charges for (−) comb picking up paper or Styrofoam