# 7.1 Electric Charge and the Electrical Structure of Matter

Photocopiers, laser printers, and fax machines are all designed to imprint graphic elements, such as lines and letters, onto paper. These machines are so commonplace that most of us probably take them for granted, not considering the technology that makes them work. An understanding of the electrical structure of matter plays a major role in these and future applications, such as electronic ink.

Before looking at the specific principles underlying these technologies, we will review some important concepts.

The following are the fundamental laws of electric charges (**Figure 1**):

**The Laws of Electric Charges**

Opposite electric charges attract each other.
Similar electric charges repel each other.
Charged objects attract some neutral objects.

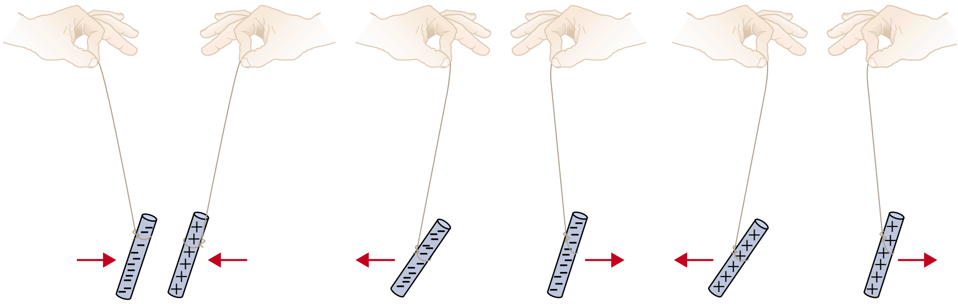


**Figure 1**
Opposite charges attract; similar charges repel.

***DID YOU KNOW?***

**Semiconductors**
Semiconductors are another category of electrical material that are intermediate between conductors and insulators in that they have very few conduction electrons for conduction in their pure, or *intrinsic*, state. Semiconductors become very useful in the conduction of electricity when a small amount of a particular impurity is added to them, in a process called "doping." Since semiconductors are solids at room temperature, the field of semiconductor physics is referred to as "solid state." The most commonly used semiconductors are silicon and germanium. Transistors and integrated circuits made from semiconductors have revolutionized electronics.

The Bohr–Rutherford model of the atom can be used to explain electrification. Consider, first, electrical effects in solids. Atomic nuclei do not move freely in a solid. Since these fixed nuclei contain all the protons, the total amount of positive charge in a solid is constant and fixed in position. However, it is possible for some of the negative charges within some solids to move because electrons, especially those farthest from the nuclei, have the ability to move from atom to atom.

Electric charges on solid objects result from an excess or deficit of electrons. Thus the charging of an object simply requires a transfer of electrons to or away from the object. If electrons are removed from the object, the object will be charged positively; if electrons are added, the object will be charged negatively. We depict neutral, negatively charged, and positively charged objects with sketches having representative numbers of positive and negative signs, as in **Figure 2**.

In such sketches, the number of + and − signs is not intended to represent the actual number of excess positive or negative charges; it conveys the general idea of balance, excess, or deficit. Notice that in **Figure 2**, the number of + signs is the same in each case, and they are fixed in position in a regular pattern.

An electric conductor is a solid in which electrons are able to move easily from one atom to another. (Most metals, such as silver, gold, copper, and aluminum, are conductors.) Some of the outer electrons in these conductors have been called "conduction electrons" for the way they can move about within the atomic framework of the solid. An insulator is a solid in which the electrons are not free to move about easily from atom to

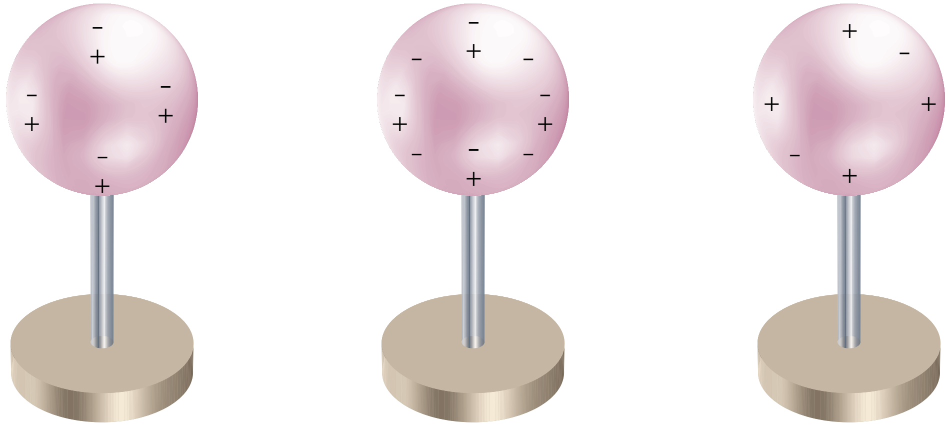



**Figure 2**
Neutral and charged objects can be represented by sketches with positive and negative signs.

atom (**Figure 3**). Plastic, cork, glass, wood, and rubber are all excellent insulators. Interestingly, the thermal properties of these materials are closely related to their electrical properties.

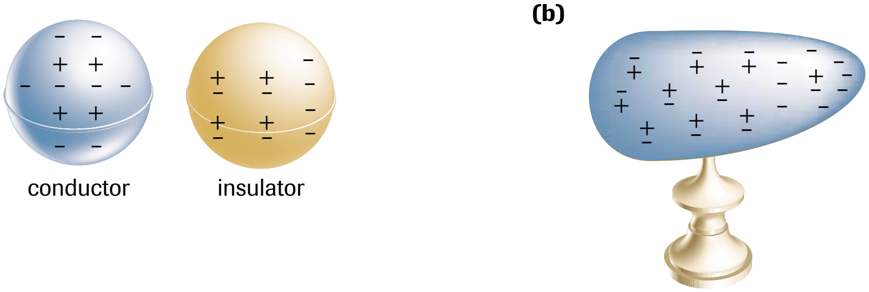



**Figure 3**
**(a)** On a spherical conductor charge spreads out evenly. On an insulator the charge remains in the spot where it was introduced.
**(b)** On conductors that are not spherical the charges tend to repel one another toward the more pointed surfaces.

Certain liquids are also conductors of electricity. The molecules of a liquid are free to move about. In an insulating liquid, these molecules are neutral. Shuffling such molecules around cannot produce a net movement of electric charge through the liquid. If, however, some of the particles in the liquid are charged, whether positively or negatively, the liquid is a conductor. Pure water contains essentially only neutral molecules and is therefore an insulator. However, when a chemical such as table salt (or copper sulphate, potassium nitrate, hydrochloric acid, chlorine, etc.) is added to the water, the solution becomes a conductor. Many substances dissociate, or break apart, into positive and negative ions—charge carriers—when dissolved in water, making it a conducting solution.

A gas can also be a conductor or insulator, depending on the electrical nature of its molecules. A charged object exposed to dry air will remain charged for a long time, which shows that air cannot discharge the object by conduction. On the other hand, if the air were exposed to X rays or nuclear radiation, the object would begin to discharge immediately. Again, the molecules of a gas are normally neutral, but the presence of X rays or other radiation can cause these neutral gas molecules to ionize, and this ionized gas becomes a good conductor. Humid air, containing a large number of water molecules in the form of vapour, is also a good conductor because water molecules are able to partially separate into positive and negative charges. More importantly, humid air usually contains dissolved materials that ionize.

**DID YOU KNOW?**

**Plasma**

A plasma is a fourth state of matter that exists at very high temperatures. It has very different properties than those of the other three states. Essentially, a plasma is a very hot collection of positive and negative ions and electrons. Examples of plasmas are gases used in neon lights, flames, and nuclear fusion reactions.

## Electronic Ink

Electronic ink technology (**Figure 4**) illustrates the basic laws of electric charge. Unlike ordinary ink, electronic ink contains clear microcapsules the diameter of a human hair, each filled with dozens of tiny white beads suspended in a dark liquid. The white beads are negatively charged. Millions of these microcapsules are sandwiched between an opaque insulating base and a clear insulating top layer.

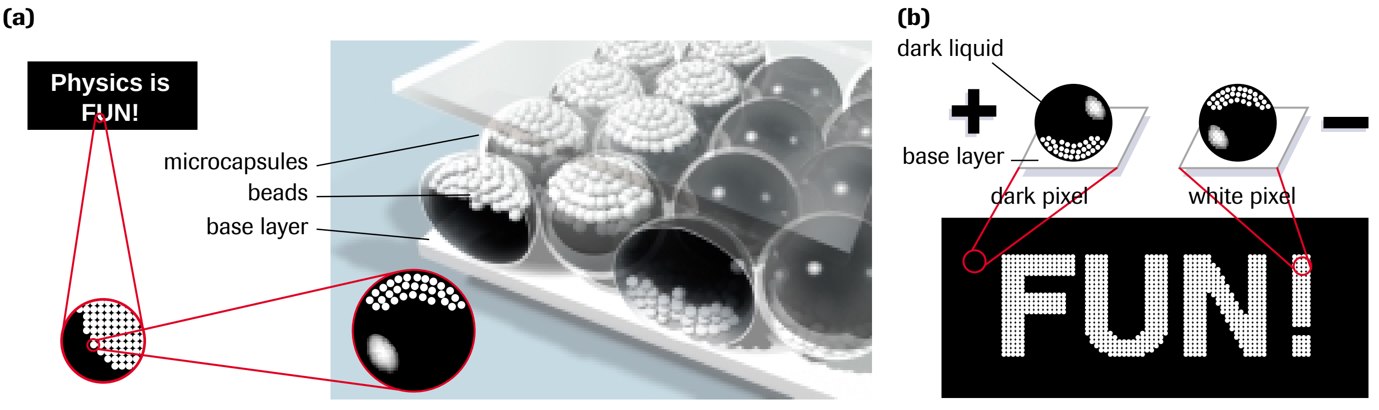



**Figure 4**
**(a)** Microcapsules in electronic ink rest on an opaque base layer, covered by a clear top layer.
**(b)** Dark pixels are formed when a positive charge is placed on the base layer. White pixels are formed when a negative charge is placed on the base layer.

Computer chips are designed to place charges in specific places on the base layer. Giving the base layer a positive charge in a certain area (a picture element, or "pixel") causes the small, negatively charged beads to sink to the bottom of the microcapsules, making the pixel, as viewed through the transparent top layer, dark. Conversely, a negative charge under the pixel drives the white beads upward in the microcapsule fluid, making the pixel white.

Placing these dark and white pixels in the correct places allows us to form characters and drawings, as on a computer screen. It is possible that in coming years, electronic ink will revolutionize publishing.

## Charging By Friction

We know that some substances acquire an electric charge when rubbed with other substances. For example, an ebonite rod becomes negatively charged when rubbed with fur. This phenomenon can be explained with the help of a model of the electrical structure of matter.

An atom holds on to its electrons by the force of electrical attraction to its oppositely charged nucleus. When ebonite and fur are rubbed together, some of the electrons originally in the fur experience a stronger attraction from atomic nuclei in the ebonite than they do from nuclei in the fur. Consquently, after the rubbing, the ebonite has an excess of electrons, and the fur has a deficit (**Figure 5**).

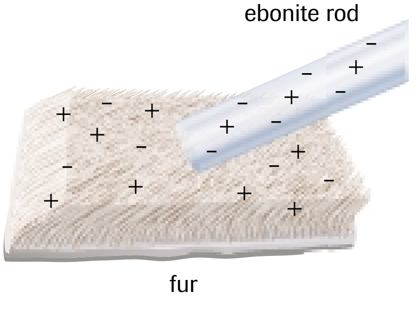



**Figure 5**
When ebonite and fur are rubbed together, some of the electrons from the fur are captured by more strongly attracting atomic nuclei in the ebonite. After the rubbing, the ebonite has an excess of electrons, and the fur has a deficit.

The same process occurs with many other pairs of substances, such as glass and silk. **Table 1** lists various substances that can be charged by friction. If two substances in the table are rubbed together, the substance that is lower in the table acquires an excess of electrons, the substance higher in the table a deficit.

**Table 1** The Electrostatic Series

| | | |
|---|---|---|
| acetate | weak hold on electrons | |
| glass | | |
| wool | | |
| cat fur, human hair | | |
| calcium, magnesium, lead | | increasing tendency |
| silk | | to gain electrons |
| aluminum, zinc | | |
| cotton | | |
| paraffin wax | | |
| ebonite | | |
| polyethylene (plastic) | | |
| carbon, copper, nickel | | |
| rubber | | |
| sulphur | | |
| platinum, gold | strong hold on electrons | |

## Induced Charge Separation

The positive charges on a solid conductor are fixed, and vibrate around their fixed positions. Some of the negative electrons are quite free to move about from atom to atom. When a negatively charged ebonite rod is brought near a neutral, metallic-coated pith ball or metal-leaf electroscope, some of the many free electrons are repelled by the ebonite rod and move to the far side of the pith ball or metal-leaf electroscope (conductor).

The separation of charge on each of these objects is caused by the presence of the negative distribution of charge on the ebonite rod. This separation is called an **induced charge separation** (**Figure 6**). A charge separation will also result from the presence of a positively charged rod (**Figure 7**).

**induced charge separation** distribution of charge that results from a change in the distribution of electrons in or on an object

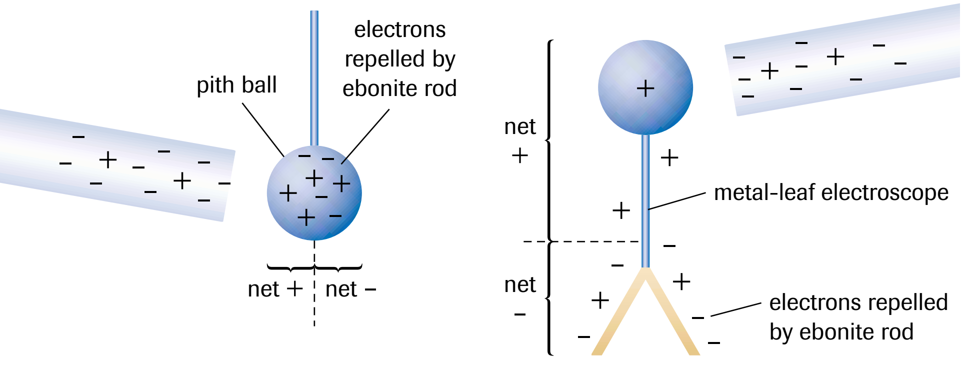



**Figure 6**
Induced charge separation caused by the approach of a negatively charged ebonite rod

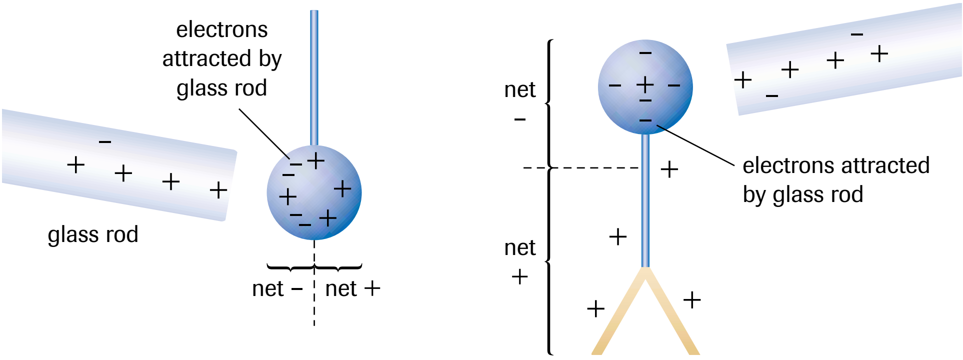



**Figure 7**
Induced charge separation caused by the approach of a positively charged glass rod

In both examples using the neutral pith ball, the charge induced on the near side of the pith ball is the opposite of the charge on the approaching rod. As a result, the pith ball is attracted to the rod, whether the rod is charged positively or negatively. This is how a charged object can attract some neutral objects (**Figure 8**).

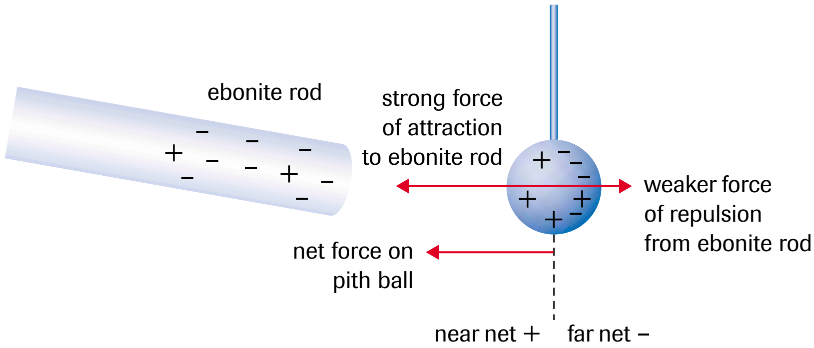



**Figure 8**
Attraction of a neutral pith ball to a negatively charged ebonite rod

It is true that there is repulsion between the rod and the similar charge on the far side of the ball. However, the strength of the electric forces between similar and opposite charges depends on the distance between the charges. As the distance increases, the magnitude of the force of attraction or repulsion decreases, as you will learn in more detail in the next section. Hence, there is a net attraction of the neutral ball.

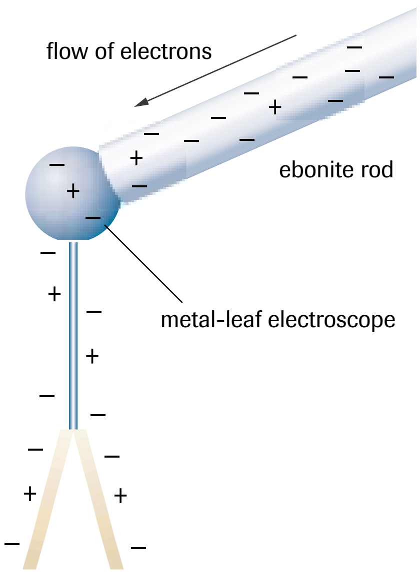



**Figure 9**
Charging by contact with a negatively charged ebonite rod

## Charging By Contact

When a charged ebonite rod makes contact with a neutral pith ball, some of the excess electrons on the ebonite rod, repelled by the proximity of their neighbouring excess electrons, move over to the pith ball. The pith ball and the ebonite rod share the excess of electrons that the charged rod previously had. Both now have some of the excess; hence, both are negatively charged. A similar sharing occurs when a charged ebonite rod makes contact with the knob of a metal-leaf electroscope (**Figure 9**).

When we perform the same operation with a positively charged glass rod, some of the free electrons on the pith ball or metal-leaf electroscope are attracted over to the glass rod to reduce its deficit of electrons (**Figure 10**). The electroscope and the rod share the deficit of electrons that the rod previously had, and both have a positive charge.

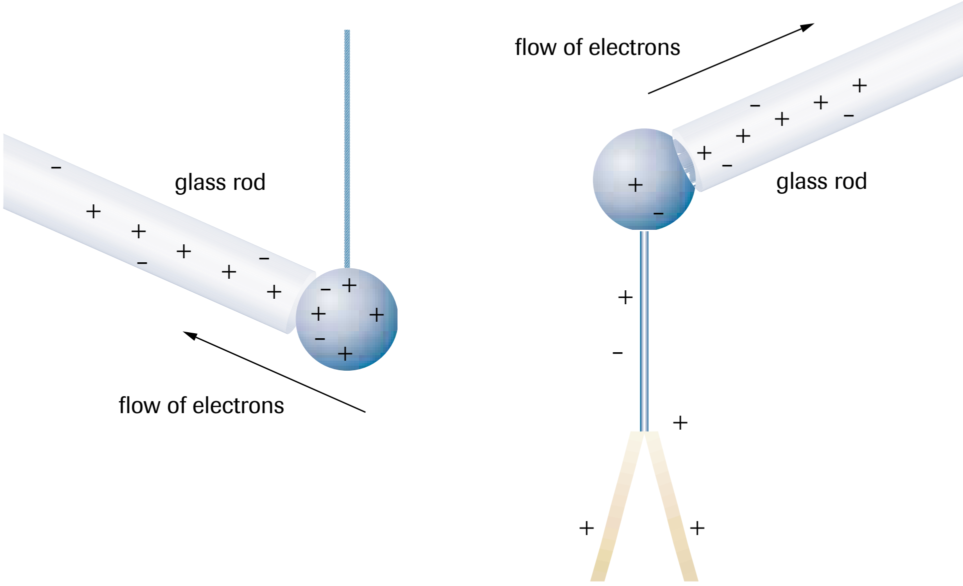



**Figure 10**
Charging by contact with a positively charged glass rod

## Charging By Induction

We learned that a charged rod can induce a charge separation on a neutral conductor. When a charged ebonite rod is brought near the knob of a neutral metal-leaf electroscope, free electrons on the electroscope move as far away as possible from the negative rod. If you touch the electroscope with your finger, keeping the ebonite rod in place, electrons are induced to vacate the electroscope and flow through your finger (**Figure 11(a)**). When your finger is removed, the electroscope is left with a deficit of electrons and, therefore, a positive charge. The leaves will remain apart even when the ebonite rod is removed.

A positively charged rod held near the knob of an electroscope induces electrons to move through your finger onto the electroscope. Now, when the finger is removed, the electroscope is left with an excess of electrons and, therefore, a negative charge (**Figure 11(b)**).

One might ask in all these methods of charging objects how the total charge at the beginning compares to the final total charge. In all the methods of charging, one object gains electrons while the other loses the same amount. As a result, the total charge is always constant. In fact, the total charge in an isolated system is always conserved; this is called the *law of conservation of charge.*

**Law of Conservation of Charge**

The total charge (the difference between the amounts of positive and negative charge) within an isolated system is conserved.

As we will see in Unit 5, this is true in all cases, not just in charging objects.

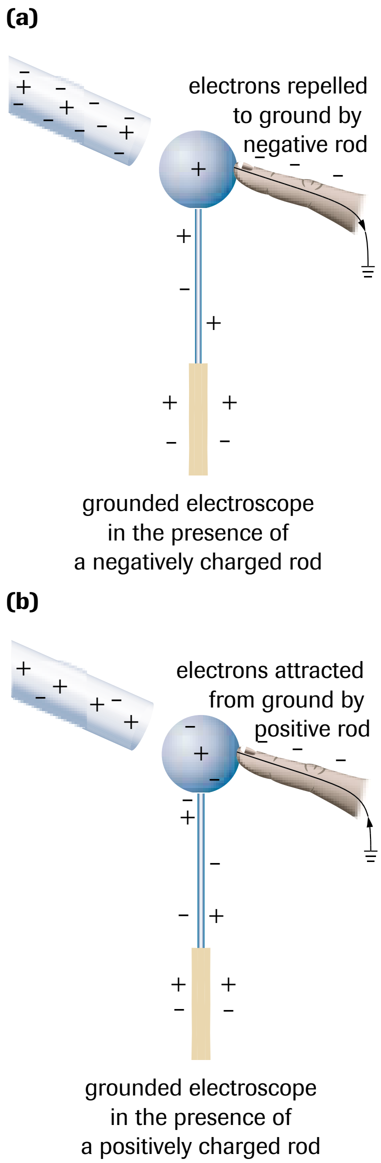



**Figure 11**
Notice that the leaves of the electroscope fall, indicating a neutral condition of the leaves while the finger is in position.

### ▶ *TRY THIS activity* — *Charging Objects*

Charge an object by friction and bring it near a stream of smoke rising from a wooden splint. What do you see? Explain why it happens.

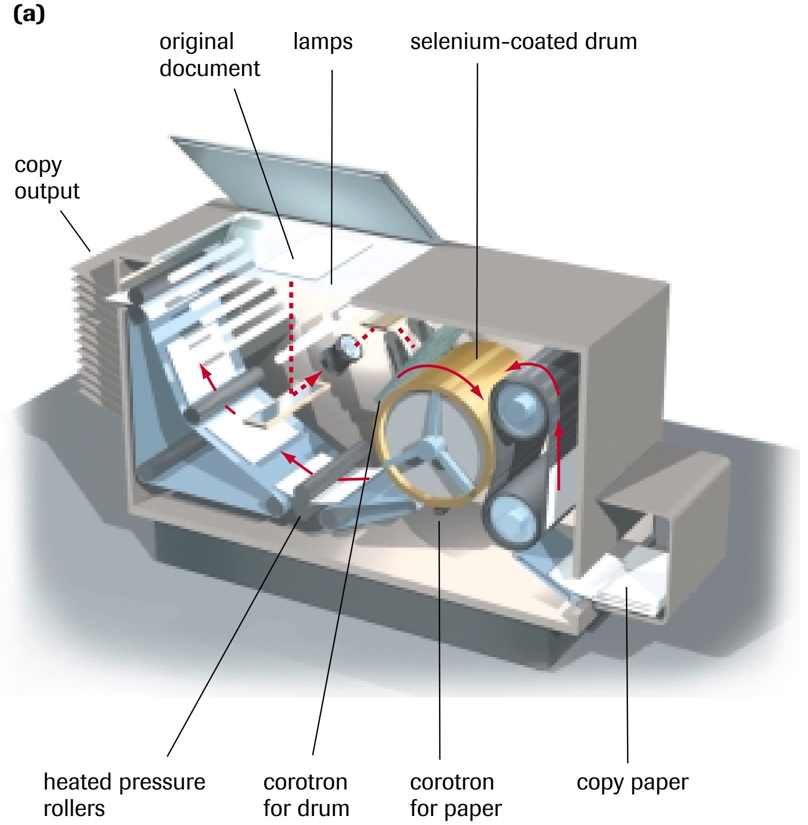
## Practice

### Understanding Concepts

1. Describe how electronic ink technology illustrates the basic laws of electric charges.
2. As you walk across a rug on a dry winter day, electrons transfer from the rug to your body.
   (a) How does the charge on your body compare to the charge on the rug?
   (b) By what method are you achieving a transfer of charge? Explain your reasoning.
   (c) Why does this method of developing a charge on your body work best when the air is dry?
3. When a negatively charged object comes into contact with the metal knob at the top of a neutral metal-leaf electroscope, the two leaves, which normally hang straight down, move apart.
   (a) Explain why the leaves move apart.
   (b) Explain how the metal-leaf electroscope can be used to indicate the amount of the charge on the object.
   (c) Is it necessary for the charged object to touch the electroscope to cause the leaves to move apart? Explain your reasoning.
4. When physically upgrading the memory in your computer, you are asked to touch the metal casing before handling the chip. Explain why.

## The Photocopier

The electrostatic photocopier illustrates the basic properties of electric charges discussed in this section. The central device in the process is an aluminum drum covered with a fine layer, less than 50 $\mu$m thick, of the photoconductive metal selenium (**Figure 12(a)**). *Photoconductors* are materials that act as a conductor when exposed to light and as an insulator in the dark. When the copier is being set up to make a copy, an electrode, called a



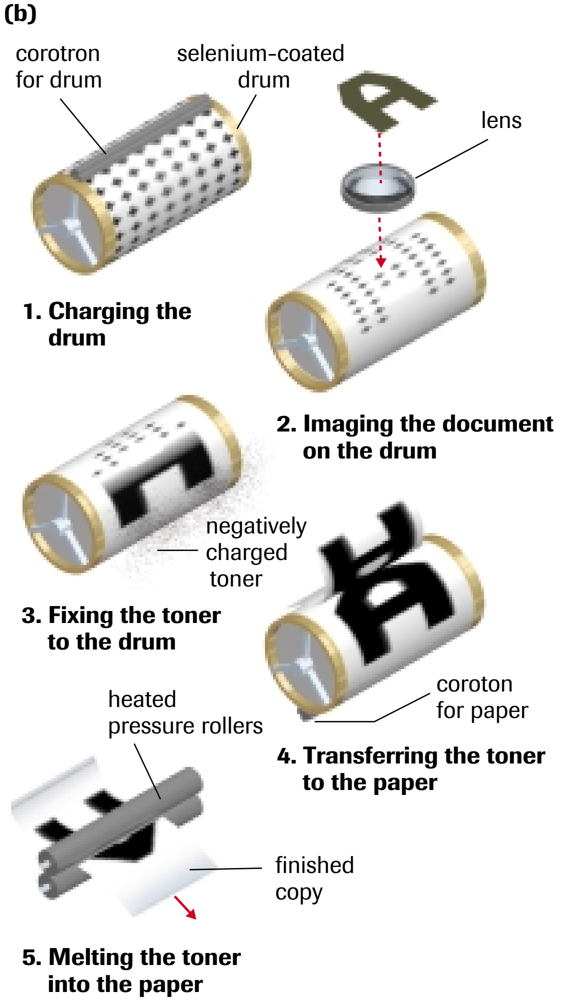




**Figure 12**
**(a)** A typical electrostatic photocopier
**(b)** Steps in making a photocopy

*corotron,* deposits a positive charge, in darkness, uniformly over the entire surface of the selenium (**Figure 12(b)**, **step 1**). The selenium will retain this charge unless exposed to light, in which case electrons from the underlying aluminum—an excellent conductor—roam through the selenium, neutralizing the positive charge.

When the copier lamp comes on and the actual copying begins, light is reflected from the document through a series of lenses and mirrors onto the selenium (**step 2**). In places where the document is white, light is strongly reflected onto the selenium drum surface, causing it to act as a conductor and lose its charge. Where the document is black, no light is reflected onto the drum, causing the charge to be retained. An electrical image of the document is thus created on the drum—neutral where the original is white, positively charged where the original is black. This image will persist as long as the drum is kept dark.

The electrical image on the drum is developed into a dry copy, using a dry black powder called "toner." Toner particles, made of plastic, are first given a negative charge, and then spread over the rotating drum (**step 3**). The particles are attracted to the charged areas of the drum but not to the neutral areas. Powder that does not adhere to the drum falls into a collecting bin for reuse.

To create a copy of this image, the toner must be transferred to paper. To do this, a second corotron gives a sheet of paper a positive charge greater than the charge on the selenium (**step 4**). As the drum rolls across this paper, toner particles that a moment ago adhered to the drum are attracted to the paper, forming an image on it.

If you were to rub your finger across the paper at this stage, the toner would smudge. To "fix," or immobilize, the image, heat from pressure rollers melts the plastic toner particles, fusing them to the paper (**step 5**).

**DID YOU KNOW?**

**Electrostatic Photocopying**

Electrostatic photocopying is also called xerography, from the Greek *xeros,* "dry," and *graphein,* "to write." Until the 1960s, photocopying required wet chemicals.

## Practice

### Understanding Concepts

5. Explain why copies emerging from an electrostatic photocopier are hot, and why they tend to stick together.
6. Which material(s) in the photocopying process have to be replenished from time to time?
7. List the properties of selenium, and explain how they are essential to the operation of an electrostatic photocopier.

### Making Connections

8. If you changed the toner on a photocopier and got some toner on your hands, should you use warm water or cold water to remove it? Explain your answer.

## SUMMARY Electric Charge and the Electrical Structure of Matter

- The laws of electric charges state: opposite electric charges attract each other; similar electric charges repel each other; charged objects attract some neutral objects.
- There are three ways of charging an object: by friction, by contact, and by induction.

## Section 7.1 Questions

### Understanding Concepts

**1.** In the following examples, explain how the charge develops on each rod and where it can be found by discussing the movement of electrons. Compare it to the charge on the material or charging object.
(a) A glass rod is rubbed with a plastic bag.
(b) An ebonite rod is rubbed with fur.
(c) A small metal rod on an insulated stand is touched by a positively charged identical metal rod.
(d) A small metal rod on an insulated stand is touched by a negatively charged large metal sphere.

**2.** Explain, with an example, how to charge an object positively using only a negatively charged object.

**3.** Explain how an electrically neutral object can be attracted to a charged object.

**4.** (a) The leaves of a charged metal-leaf electroscope will eventually lose their charge and fall back down to vertical. Explain why this occurs.
(b) Explain why the leaves of the electroscope will lose their charge faster if
(i) the humidity in the air is higher
(ii) the electroscope is at a higher altitude

**5.** (a) Identify each of the following as a conductor or insulator and explain how the properties of this type of substance are essential to photocopying:
(i) aluminum (iii) selenium (v) rubber rollers
(ii) paper (iv) toner
(b) Explain what would go wrong in the photocopying process if the substances above were the opposite of what you identified.

### Applying Inquiry Skills

**6.** Outline, using diagrams and explanations, the design of an electrostatic device suitable for filtering charged particles out of air ducts in a home. Describe any maintenance your device requires.

**7.** Two oppositely charged pith ball electroscopes are used to determine whether an object has a charge and, if it does, the type of charge. Discuss the observations expected and explain why both electroscopes are needed.

**8.** Tear a piece of paper into several small pieces. Charge a plastic pen and two other objects by rubbing them on your hair or on some fabric. Bring each charged object near the pieces of paper.
(a) Describe what you observe, listing the three materials you charged.
(b) Why are the pieces of paper attracted to the charged object?
(c) Why do some pieces of paper fall off your charged objects after a short while?
(d) When using a conducting sphere with a large charge, the paper "jumps" off instead of falling. Explain why this happens.

### Making Connections

**9.** Laser printers work on principles similar to electrostatic photocopiers. Research laser printer technology and answer the following questions:
(a) What is the role of the laser in making the printouts?
(b) Why are copies made from laser printers of such high quality?

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**10.** Fabric softener sheets claim to reduce static cling between the clothes in a dryer. Research fabric softeners and answer the following questions:
(a) Why do clothes cling to each other when they are removed from a dryer?
(b) How does a fabric softener sheet alleviate the problem?

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**11.** Long, thin conducting strips are placed near the ends of airplane wings to dissipate the charge that builds up on the plane during flight. Research this technology and answer the following questions:
(a) Why does an airplane develop a charge in flight?
(b) What feature of the atmosphere plays a role in removing the charge from the plane?
(c) Why are the conducting strips long and thin and placed near the end of the wings (**Figure 13**)?

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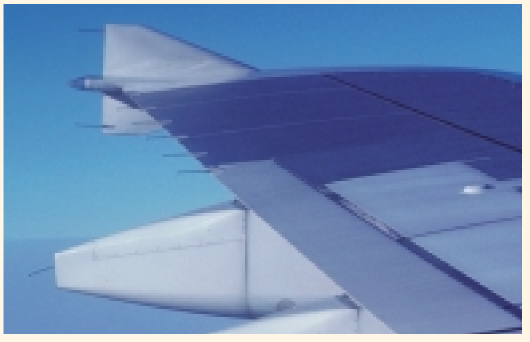

**Figure 13**
Long, thin conducting strips are placed at the end of airplane wings to reduce charge.