19.1. IntroducEtion
Identifying the electron as the part of the atom carrying negative charge helped explain many earlier experiments. In this section, we will explore how the properties of the electron explain some of the static electricity phenomena we’ve previously discussed in a macroscopic sense, and discuss how the electron participates in current.

19.2. Goals
- Understand the relationship between charge and numbers of electrons
- Understand how charge can be transferred using friction, conduction or induction
- Explain the difference between conductors and insulators.
- Understand the relationship between electrons and current.

19.3. Atomic Origin of Magnetism
Before focusing on electricity, we should make a note about an important difference between electricity and magnetism. Atoms have magnetic north and south poles. There are two mechanisms responsible for giving an atom a dipole moment: the motion of the electron about the nucleus and the rotation of the electron. The magnetic dipole isn’t associated with a part of the atom, as the charge of the atom is associated with the electron. This is why you cannot separate north and south poles, but you can separate positive and negative charges.

19.4. The Fundamental Charge
The fundamental unit of charge is \( e = 1.60 \times 10^{-19} \text{ C} \). Electrons are negative and have a charge of \(-e\). Since atoms are neutral, the positively charged material must have the same magnitude charge as all the electrons in the material have. Some atoms like acquiring electrons from other atoms, while other atoms are happy to give up some of their electrons to other atoms. An ion is an atom that has either extra electrons or is missing electrons. This information can be used to calculate out how many electrons are in a given charge.

The total charge \( Q \) of an assembly of electrons is the number of electrons \( N_e \) times the fundamental charge of the electron \(-e\).

\[
Q = -N_e e
\]  

EXAMPLE 19.1: Static electricity caused by friction produces about \(-0.100 \mu \text{C} \) of charge, all of which is due to excess electrons. How many electrons does it take to make this amount of charge?

<table>
<thead>
<tr>
<th>Draw a picture</th>
<th>No picture is necessary in this case</th>
</tr>
</thead>
<tbody>
<tr>
<td>known: Each electron has a charge of (-1.60 \times 10^{-19} \text{ C} ) ( Q = \text{total charge of all electrons} = -0.100 \mu \text{C} = -1.00 \times 10^{-7} \text{ C} ).</td>
<td>( N_e = \text{The number of electrons necessary to produce this charge} )</td>
</tr>
<tr>
<td>Equation to use</td>
<td>( Q = -N_e e )</td>
</tr>
<tr>
<td>Solve for the unknown</td>
<td>( Q = -N_e e )</td>
</tr>
<tr>
<td></td>
<td>( N_e = \frac{Q}{e} )</td>
</tr>
</tbody>
</table>
Plug in numbers.

\[ N_e = \frac{-1.00 \times 10^{-7} \text{C}}{1.60 \times 10^{-19} \text{C}} \]

\[ = 6.25 \times 10^{12} \]

**Answer:** (3 s.f.) \[ N_e = 6.25 \times 10^{11} \text{ electrons} \]

Check the answer

We know that the total charge is a lot more than the charge on one electron, so it makes sense that the answer should correspond to a large number of electrons.

### 19.5. Transferring Charge

Although the model of the atom we have at this point is incomplete, we know that electrons can be removed from atoms, leaving a positive or negative net charge. When atoms form solids, sharing electrons is one way to form bonds between atoms. In electrical conductors (such as metals), some of the electrons can leave the atom and are free to move around. Figure 19.1 shows one way to think about the electrons in a metal. The positive charges, which are left in the atom after the electron leaves, are fixed and the electrons are able to move.

**19.5.1. Transfer of Charges by Friction.**

Consider what happens when you shuffle your feet along carpeting. Initially, the carpeting and your feet are electrically neutral. Shuffling creates friction between your foot and the carpet. The carpet rubs electrons off your foot and collects them. This leaves the carpet with excess electrons, giving it a net negative charge. Your foot has lost electrons, and it is now positively charged, as shown in Figure 19.2.

It is important to realize that charge is never created or destroyed, only transferred. All of the charge that started out on the foot and the carpet is still there after the foot acquires a positive charge and the carpet acquires a negative charge. Charge is transferred from the foot to the carpeting, but no new charges are created, nor are any charges destroyed. The same electrons rubbed off the foot now reside on the carpet. Figure 19.2 shows a small number of charges for illustrative purposes. In reality, about \(10^{10}\) charges are transferred at a time during your average static electricity experience.

Why do charges transfer? We call this a transfer of charges due to friction. The electrons are essentially rubbed off one material and onto another. This happens when one material wants electrons more than the other material. The behavior of atoms can change when they are at the surface of a material compared to when they are inside the material. Since all atoms try to decrease...
their energy, some types of materials decrease their energy by giving up electrons and some by adding electrons.

**19.5.2. Getting Rid of Charge.** In general, objects don’t like having a net charge. They prefer to be electrically neutral. After charging, your foot would prefer to get enough electrons to make it neutral again. This happens primarily in two ways:

1) If it’s humid, water in the air can neutralize unbalanced charges. Dry air is a very good electrical insulator. Air becomes a better electrical conductor when it is humid. Water molecules are polarized – one end has a positive charge and one a negative – and they are able to remove charge.

2) If it is not humid, the electrons come from somewhere else. If you touch – or get close enough to – something metal, for example, electrons can jump from the metal and neutralize the positive charge. The process of electrons jumping from the metal to your foot is what causes the shock.

Important: only electrons are transferred – the positive charges don’t move from one object to another. A net positive charge means that there is a lack of electrons. A net negative charge means that there is an excess of electrons.

**19.6. Conductors and Insulators.**
Return to the example of shuffling your feet on the carpeting and touching something metal. For example, when you reach out to touch a metal doorknob, you may get a zap. What happens is shown in Figure 19.3. When the hand approaches the doorknob, electrons in the doorknob move toward the surface and eventually jump from the doorknob to your hand. This occurs because metal is a conductor – it is easy for the electrons to move inside a conductor. Almost all metals are conductors.

In an insulator – wood, plastic, rubber, etc. – electrons cannot move as easily, so fewer charges are available to move over to the hand. This is why you are unlikely to get a shock if you touch a door and much more likely to get a shock if you touch a doorknob. This is why wire is copper and has rubber or plastic on it as an insulator.

**19.7. Two Other Ways to Transfer Charge: Conduction and Induction**
There are three ways to create a net charge: friction, induction, and conduction. Friction – how the charge gets from the carpet to your foot – was explained above.

**19.7.1. Charging by Induction.** In the top part of Figure 19.4, rod 1 has a net positive charge on its right end. When rod 1 is brought close to rod 2 – which is neutral – the electrons in rod 2 will move toward the positive end of rod 1, as shown in the lower part of the figure. This leaves a positive charge at the right end of rod 2, because the electrons that would keep that end neutral have all been pulled to the left side of the rod. The left side of rod 2 is negative because there are more electrons than protons in that end of the rod. This process is called charging by induction. Rod 2 was overall neutral before induction, and is still overall neutral after induction – only the positions of the...
electrons within the rods have changed. The reason why the right end of rod 2 is positive is because the electrons have all moved down to the left side of the rod. Positive charges never move. A positive charge is due to a lack of electrons.

19.7.2. Charging by Conduction. Start with rod 1 being positively charged and rod 2 being neutral, as shown in Figure 19.5. In this case, rod 1 is deficient in electrons. There is a net positive charge for the rod as a whole. Instead of just bringing the rods close together, we allow them to touch – or at least get very, very close to each other. The electrons in rod 2 are first pulled to the left end of the rod due to induction, as described above. If the rods are close enough, the electrons move over to rod 1. This only happens when rod 1 has a stronger attraction for the electrons than rod 2, or if rod 2 has a net negative charge and would like to give up electrons to become neutral. In this case, rod 2 started off net neutral, so when the electrons transfer to rod 1, rod 2 acquires a net positive charge. This is called charging by conduction and may also be called charging by contact. For both induction and conduction, there has to be a reason for electrons to move – one of the items involved must have a net charge. The net charge may be positive or negative.

19.8. Applications

19.8.1. Molecules. Although all atoms and molecules prefer to be neutral, their charge distribution isn’t always uniform. Some molecules have a net positive electric charge on one end and a net negative charge on the other end because of how the electrons in the molecule arrange themselves. Molecules with this type of charge distribution are called polar molecules. The most familiar polar molecule is water, as shown in Figure 19.6.

19.8.2. Static Cling. When you take a load of laundry out of the dryer, sometimes some pieces of clothing stick to each other. Why? When the clothes are in the dryer, they rub against each other and can charge by friction. If two socks get opposite charges, they will attract each other. This commonly is called static cling.

Fabric softeners, dryer sheets, detergents, and hair conditioner work on the same basic principle: they prevent the materials they contact from maintaining a net charge. A detergent molecule is a long molecule that is electrically charged at one end (usually due to the atom at the end having extra electrons or missing electrons) and is neutral at the other end. The charged end clings
electrostatically to opposite charges and likes being in water. The other end is neutral and slippery, and prefers being in contact with oil. Fabric softeners, dryer sheets and hair conditioner use positively charged detergent molecules, while detergents use negatively charged detergent molecules.

Fabrics and hair generally become negatively charged when wet, so negatively charged detergent molecules clean much better than positively charged detergent molecules. Detergent molecules work because the oily part of the molecule attaches itself to dirt (especially oily dirt). The charged parts of the molecules surround the dirt, but the other ends are attracted to the water. The detergent-surrounded dirt is thus removed when the water is removed.

Positively charged detergent molecules are useful because there are times when you want something to cling well to wet fibers (clothing or hair). If the slippery end of the molecule sticks up and the other end sticks to, say, your hair, two things happen. First, the molecule turns your hair from an insulator into a very slight conductor. It’s a very small change, but enough to reduce how much charge can build up in your hair, thus reducing the static electricity that makes strands of your hair charge and repel each other. The second thing that happens is that, when you run your fingers through your hair, you’re not touching your hair – you’re touching the slick end of the molecule, causing your hair to feel silkier and smoother.

The reason that these molecules increase the conductivity is because they are good at attracting moisture and moisture neutralizes charges. Water is an electrical conductor and damp surfaces allow charge to move around and neutralize. This is why you have more problems with static cling in the winter, when it’s dry, than in the summer, when it is more humid.

**19.8.3. Lightening.** Lightening is the same phenomenon as the static electric shocks you get when you touch a metal doorknob in the winter, except much more charge is involved. Lightening occurs when a cloud acquires the opposite charge as the Earth. Although lightening is not understood completely, we believe that negative charges concentrate in the lower part of the cloud and positive charges concentrate higher up in the cloud.

If you’ve ever gotten a shock from a metal doorknob, you may have realized that you got a shock even before you actually touched the doorknob. Air is an insulator, but only up until a certain point. When two objects (like the doorknob and your hand) acquire opposite charge, they set up an electric field. Air can sustain a field up to some maximum electric field strength. Once above that strength, the air ionizes (electrons are removed or added) and a conducting path is created between the two objects. You can imagine that the amount of charge that builds up over the distance between a cloud and the Earth is large.

The electrical discharge between cloud and ground is lightening. The average maximum current is about 30,000 amperes, lasts for about 30 μs and delivers about a coulomb of charge. The large amount of charge is what makes lightening dangerous (remember that an average shock from a doorknob is one the order of $10^{-7}$ C). A lightening strike is 10 million times more charge and it occurs over a much shorter time, which concentrates all the energy contained in the lightning stoke. The average lightening stoke is 6-8 miles long. The average peak power of a lightening bolt is equal to 10 billion 100-watt light bulbs.
19.9. **The Electroscope**

The electroscope is a device that can be used to tell if two things have the same or different charge. An electroscope consists of a metal electrode attached to two pieces of very thin foil. The contraption is usually placed in a glass bulb with a rubber stopper. The two pieces of foil are very light -- air currents can make them move, so they are placed inside glass to protect them. Glass and rubber are good insulators of electricity and electrically isolate the system. If you charge the electroscope with a known charge (say by bringing a PVC rod you’ve charged with a piece of paper towel near it), you now have a known charge, let’s say a positive one. You can then take your unknown charged object and bring it near. If the charge is the same as the one already on the equipment, the leaves move further apart. If it is different, they will move closer together. Bringing the rod in contact with the ball neutralizes the ball because the charges can now move to the ball.

The electroscope can be charged positively with a negatively charge rubber rod by the following procedure: Neutralize the electroscope. Holding the negatively charged rod in one hand, bring it close to (but not touching) the ball. Negative charges on the ball/stem/leaf structure will try to move as far as possible away from the negative rod. Keeping the rod in place, touch the ball with a finger of your other hand. This allows some negative charge to escape from ball/stem/leaf, leaving it with a net positive charge. Then remove first your finger and then the rubber rod.

19.10. **Current**

Current is the flow of charges. Current measures how much charge travels through a point in a given time.

\[ I = \frac{\Delta Q}{\Delta t} \]  

(19.10.1)

If you count that the amount of charge traveling past a certain point in time \( \Delta t \) is equal to \( \Delta Q \), the current this represents is \( I \). A large current represents a lot of electrons, or electrons traveling very fast. We do not talk about positive current or negative current, so only the magnitude of the total charge is used in Equation (19.10.1). The unit for current is the ampere, where

\[ A = \frac{C}{s} \]
Note that when you are talking about numbers of charges, the number always is positive. Also, numbers of charges are integral numbers – if you get an answer like 0.34 for number of electrons, you’ve done something wrong.

**EXAMPLE 19.2:** 4.25 x 10^{19} electrons pass by a point in 10.5 seconds. What is the current?

Draw a picture

No picture is necessary in this case

- \( e \) = charge on one electron = -1.60 \times 10^{-19} \text{ C}
- \( N_e \) = number of electrons = 4.25 \times 10^{19}
- \( \Delta t = 10.5 \text{ s} \)

**known:**

**need to find:** \( I \) = the current

**Equation to use**

\[ I = \frac{\Delta Q}{\Delta t} \]

- We have to realize that the total charge is the number of electrons times the charge on each electron
- \( \Delta Q = N_e e \)

This makes the equation

\[ I = \frac{N_e e}{\Delta t} \]

Plug in numbers.

\[ I = \frac{4.25 \times 10^{19} \text{ electrons} \left(1.60 \times 10^{-19} \frac{\text{C}}{\text{electron}}\right)}{10.5 \text{ s}} \]

= 0.647619 A

**Answer:** (3 s.f.) \( I = 0.648\text{ A} \)

19.11. **SUMMARIZE**

19.11.1. **Definitions:** Define the following in your own words. Write the symbol used to represent the quantity where appropriate.

1. Ion

2. Polar molecules

3. Detergent molecules

4. Current

19.11.2. **Equations:** For each question: a) Write the equation that relates to the quantity b) Define each variable by stating what the variable stands for and the units in which it should be expressed, and c) State whether there are any limitations on using the equation.
1. The relationship between the total charge of an assembly of electrons and the number of electrons.

2. The relationship between current and the amount of charge flowing past a point in a certain amount of time.

19.11.3. Concepts: Answer the following briefly in your own words.
1. Explain why you can’t separate the north and south poles in terms of the origin of the magnetism in an atom.

2. Explain the three ways that charge can be transferred and how they are different from each other.

3. Explain how water neutralizes charges.

4. You have an electrically neutral toy. It breaks into two pieces and you notice that one piece is positively charged. What happens if you bring it near the other piece and why?

5. Why does the production of electricity by friction always produce equal amounts of positive and negative charge?

19.11.4. Your Understanding
1. What are the three most important points in this chapter?

2. Write three questions you have about the material in this chapter.

19.11.5. Questions to Think About
1. You have an electrically charged rod that you divide in two. What happens to the charge on each piece? You divide it in four. How does the charge on each piece relate to the charge on the entire rod? Is there a limit as to how many times you can continue dividing the rod where this pattern doesn’t continue? Why?

2. When two objects attract each other electrically, must they both be initially charged? Same question for two objects that repel each other electrically.

3. When you rub a balloon on the wall, it becomes charged; however, the entire balloon becomes charged, not just the spot you rubbed. Explain why this is.

4. Explain why is it safe to be in a car during a thunderstorm? It’s the same reason you won’t be injured if the plane in which you are riding is hit by lightening.
5. You rub a balloon and it sticks to the wall. When you come back the next day, it’s on the floor. Explain why.

19.11.6. Problems
1. If you could separate all the positive and negative charges in 1 g of matter, there would be about 96000 C of positive charge. a) How much negative charge would there be and why? If you placed all of the positive charges 1.50 m away from all the negative charges, how strong would be force between them be? Would it be attractive or repulsive?
2. Sensitive instruments can detect the passage of as few as 60 electrons per second. What current does this correspond to?
3. If $10^5$ electrons are added to an initially neutral object, what will the net charge of the object be?
4. What is the charge produced by one mole of electrons?
5. A rubber balloon is rubbed with a wool cloth and acquires a charge of magnitude $1.00 \times 10^{-14}$ C. Is the charge due to an excess or a lack of electrons? How many electrons are extra (or missing)?
6. A typical appliance in your house draws about 10.0 A of current. How many electrons do you use in 5.00 minutes?
1. Explain the three ways that charge can be transferred and how they are different from each other.

2. A rubber balloon is rubbed with a wool cloth and acquires a charge of $+1.00 \times 10^{-14}$ C.
   a) Is the charge due to an excess or a lack of electrons?
   b) How many extra (or missing) electrons are there?

3. A typical appliance in your house draws about 10.0 A of current. How many electrons do you use in 5.00 minutes?
19.12. **RESOURCES**
Applet for charging: http://www.shep.net/resources/curricular/physics/P30/Unit2/electroscope.html

19.13. **SUPPLEMENTARY MATERIALS**

**Electron (Orbital)**

- Moving electron creates a current
- Current produces a magnetic field

Orbital moment. Electrons move in orbits about the nucleus. A moving electron constitutes a current, so you can think of this as a ring of current around the nucleus. By the right-hand rule, a moving charge creates a magnetic field that points in the direction of the curled fingers of your right hand when your thumb points in the direction of the current. If the electron in the picture to your left is moving into the page, the magnetic field will point UP everywhere inside the circle. This creates a magnetic moment upward.

Spin Moment. While the electron is orbiting the atom, it is also spinning, in the same way that the Earth rotates about the sun, but also rotates about its own axis. The electron has a charge 1.602 x 10⁻¹⁹ C. Imagine that this charge is spread all over the surface of the electron. The rotating charge thus also forms a current, giving rise to a spin magnetic moment. All electrons have the same magnetic moment due to spin. The value of this moment is called the Bohr magneton (μ₉). This is a fundamental unit of magnetism.

19.14. **ELECTROPHORUS**
An electrophorus is a metal disk with an insulating handle. You charge the electrophorus by putting it in contact with a charged plate. PVC rubbed with paper toweling charges the electrophorus positively. Acrylic rubbed with polyethylene charges the electrophorus negatively. So I can choose which charge I want to have on the paddle.
How the Electrophorus Works: Rub the acrylic plate vigorously with a polyethylene bag. This transfers electrons (negative charges) to the plate. When the electrophorus is brought close to the plate, the negative charges on the plate drive the negative charge on the electrophorus to the far side (the side closest to the handle), leaving a net positive charge on the side of the electrophorus near the plate.

Touch the top side of the electrophorus with your finger. You will likely feel a shock as the negative charge is pulled from the surface of the electrophorus.

You are now left with a positively charged electrophorus sitting on the negatively charged plate.

When the electrophorus is removed from the plate, the positive charges will redistribute themselves all over the metal plate on both top and bottom. Since like charges repel, the charges will always try to get as far away from each other as possible.