Ion Propulsion

Charges

STUDENT READING

INTRODUCTION— During ancient, prehistoric times it was likely that a caveman rubbed against the fur of an animal skin and experienced a slight electrical shock upon touching another individual. This effect would have been identical to the shock you experience on a dry day when you shuffle your feet across a carpet and touch a metal object or another person. Certainly, the caveman did not have any idea of what was causing the shocking sensation. The ancient Greeks did not have a much better understanding, but they did record some "experiments" in which they rubbed fur against various objects, such as amber, and demonstrated that the objects could then attract other light objects, such as hair. The force of attraction was so small, however, that no practical application could be imagined; consequently, it attracted little interest. They found additionally that if they rubbed the amber long enough they could create a spark; therefore, the ancient Greeks are generally credited with discovering "charge." In fact, the word *electricity* is derived somewhat circuitously from the Greek word for amber.

The 18th century was a popular era for the study of electricity, or electrification as it was known at that time, and Benjamin Franklin is often cited as one of the foremost experts of the era. Franklin, along with others, believed that electricity was a type of invisible fluid present in all matter and that rubbing surfaces together caused the fluid to change its location. When matter contained too much of this fluid, Franklin said it was "positively" charged and when it was deficient in the fluid it was said to be "negatively" charged.



We now know that Franklin's view was incorrect. Today we understand electricity in terms of the fundamental building blocks of matter, which is composed, in part, of two kinds of electrically charged particles. Particles that carry a charge of positive electricity are called protons and those that carry a negative charge of

electricity are called electrons. Electric charge is a fundamental property of these two subatomic particles. By convention, electrons are said to have a charge of -1 and protons similarly have a charge of +1. These represent relative charges and are useful in describing atomic structure; however, the correct way to quantify charge, Q, is to use the standard SI unit of measurement—the *Coulomb*. An electron carries a charge, Q, of 1.602 $\times 10^{-19}$ Coulomb. To put it another way, it would take 6.24 $\times 10^{18}$ electrons piled up together to generate a total charge of one Coulomb. In everyday terms, a Coulomb of electrical charge is represented approximately by the amount of electricity flowing through a 120-watt light bulb in one second.

So, it is clear that one can discuss charged elementary particles as well as charged everyday objects. Furthermore, the magnitude and sign of the charge can vary. If an object carries an excess of electrons it will be said to carry a negative charge. If it is deficient in electrons, it will be left with excess positive charges and will be said to carry a positive charge. Remember that in a neutral atom the number of positive charges (protons) exactly matches the number of negative charges (electrons). Also recall that different atoms have differing tendencies to hold on to their outermost electrons. Some

atoms such as sodium tend to give up an electron rather easily. Other atoms have a strong desire to attract electrons to them. In your studies of chemistry you probably have quantified these tendencies in terms of ionization energies and electron affinities or electronegativities.

CHARGED OBJECTS—Now we can turn to the question of what shocked the caveman. While we will not go into the details, suffice it to say that today scientists believe that electrons are transferred from one object to another made of a different material by the simple act of rubbing the objects together. Recognize, however, that the number of electrons transferred is extremely limited. For example, it is estimated that if one rubs a glass rod with wool, only one electron out of 10¹⁴ atoms of glass is transferred from the glass to the wool!

The transfer of electrons occurs at the surface of contact. Vigorous rubbing serves to increase the contact between the surfaces and thus increases the extent of electron transfer. This exchange of electrons leaves the two objects with an imbalance of positive and negative charge— they are said to be charged. Static electricity or static discharge occurs when one of the charged objects is placed in close proximity to something that can accept or provide electrons to neutralize the previously acquired charge. In other words, charge (spark) leaps from one object to another to restore neutrality. Scientists have studied the ability of materials to gain or hold on to electrons and have placed materials in a *triboelectric* series. The prefix "*tribo*" means "friction." In the sidebar you will see a list of common materials placed in a triboelectric series.

If two materials are rubbed together, the one higher in the triboelectric series should give up electrons more easily than a lower one and become positively charged. Your skin and the plastic film used for wrapping are widely separated in the series, with your skin being higher. Have you ever experienced the ability of plastic film to cling to your hand? How might this be explained? Many everyday phenomena can be understood in terms of the partial charge separation that arises from the rubbing of two objects together. As one more example, consider the widely experienced effect of pulling off a woolen stocking cap during the winter and having one's hair "stand on end." What is going on? Well, your hair is higher in the

Gives up electrons more easily Very dry human hands Leather

Rabbit fur Glass Human hair Nylon Wool Silk Aluminum Paper Cotton Steel Wood Amber Hard rubber Nickel, Copper Brass, Silver Gold, Platinum Polyester Styrofoam Plastic wrap Scotch tape Silicon Teflon

Gives up electrons less easily

triboelectric series than is wool. When you remove the cap the wool rubs against your hair, and electrons move from your hair to the hat. When the hat is fully removed the resulting hair fibers are each left with positive charge. We all know that like charges repel one another. So, each hair fiber repels the next one, with the effect that the hair appears to stand on end. Can you now explain what happens when you walk across a wool carpet and then touch a metal doorknob?

QUANTITATIVE ASPECTS— It is clear that charges interact with each other—like charges repel and opposite charges attract. Since scientists usually like to put things on a quantitative footing, the question becomes one of studying the force with which charges attract or repel one another. The results of these studies are expressed today as Coulomb's law, which is a very old law that was

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formulated in 1785. This law states that the electric force acting on a point charge q_1 as a result of the presence of a second point charge q_2 is given by the equation

$$\mathbf{F} = \mathbf{k} \, \mathbf{q}_1 \mathbf{q}_2 / \mathbf{r}^2$$

where r is the distance between the point charges. When r is expressed in meters, the charge magnitudes are expressed in Coulombs, C, and the charges are placed in empty space (in a vacuum), the value of k, Coulomb's constant, is 9×10^9 N.m²/C².

Note that this satisfies Newton's third law because it implies that a force of exactly the same magnitude acts on q₂. Also note that Coulomb's law is a vector equation since the force acts along the line connecting the charges. Lastly note that the law describes a force of infinite range and is of the same form as the force of gravity. However, it differs from gravity in one important aspect. Do you know what this is?

It is instructive to consider two examples of the forces that derive from Coulomb's equation. If one computes the force of repulsion between two tiny protons whose separation is 10^{-14} meter, one obtains a value of 2.31 Newtons. Or if one computes the force of repulsion between two collections of charge represented by the light bulb example given above (1 coulomb each), one finds a force of repulsion of 9 x 10^9 Newtons, which can be converted to approximately 1 million tons! Clearly, electrical forces can be enormously large if the charges are at close range.

It is fair to ask why we do not experience these impressive displays of electrical force in our everyday life. The general answer is that nature never allows very much departure from neutrality. For example, nature never permits a Coulomb of charge to collect at a single point. It is important to recognize that only a very, very small transfer of electrons from one object to another is required to create the phenomena that we observe when our hair stands on end or when our skin attracts a sheet of plastic wrap.



SYSTEMS— In science it often is important to define one's system very carefully. Simply put, a *system* is that part of the universe that is of interest in a particular investigation. Everything else is referred to as the *surroundings*. There are three very important types of systems. An *open system* is one in which both energy (usually in the form of heat) and matter exchange freely between the system and the surroundings. An example would be an open beaker of water heated on a hot plate. A *closed system* is one in which matter is not allowed to exchange with the surroundings, but energy is permitted to enter and leave the system. A closed glass bottle containing water would be such a system since, for example, electromagnetic energy could enter the system through the glass. An *isolated system* is one in which neither matter nor energy is permitted to exchange with the surroundings. A tightly closed thermos bottle containing water approximates such a system.

The Dawn spacecraft can be viewed as an open system as long as the thruster is turned on. The spacecraft will absorb electromagnetic energy from the Sun, primarily through its photocells. It ultimately will convert this absorbed energy into kinetic energy of motion, thus propelling the spacecraft toward its ultimate destination as xenon is discharged into space from the thruster. However, under conditions where the thruster is turned off *matter will not be exchanged with the surroundings* and the spacecraft can be viewed as a closed system. These are important points to keep in mind as the operational details of the ion propulsion engine are investigated.

CONSERVATION OF CHARGE—Charge can be destroyed or created, but only in positive-negative pairs. Otherwise, nature would not be able to maintain overall neutrality. Since a spacecraft travelling in the void of outer space is not in contact with any other form of matter, it is clear that charge must be conserved in this system (the spacecraft). That is, any negative charge created by some means must be exactly matched by the creation of an equivalent amount of positive charge. Or if a given amount of negative charge is destroyed, it must be accompanied by the destruction of an exactly equal amount of positive charge. If we consider, for example, a system of 100 Na atoms from which we remove 100 negatively charged electrons, we must leave behind 100 sodium ions, each carrying a single positive charge. In other words, the NET charge of the system cannot change—it must remain zero.

Likewise, the overall charge on a spacecraft must remain zero, even though there can be charge separation within the system.

THE CONCEPT OF ELECTRICAL GROUND— Almost everyone is familiar with the term "ground" when it is applied to electrical systems. Basically, a "ground" provides a common return for charge. Here on Earth we commonly "ground" things by driving a metallic stake into the earth, in effect using the Earth as a large common return. Another way to look at it is that the Earth serves as a type of reference point against which electrical potential differences can be measured. A typical household line voltage is 120 volts. This is in respect to the Earth as a reference point. So the concept of a "ground" is easily understood when we are dealing with electrical matters on the surface of our planet.

But what happens when we consider something such as a spacecraft that is far removed from Earth? How is "ground" defined under these conditions? Once again, it is a matter of defining a reference point, and all electrical potential differences are defined with respect to that reference point. Thus, when we say that some component of a spacecraft has a voltage of, say, +1000 volts, we are simply comparing that component's voltage to a reference. As long as we use a consistent reference we can compare relative voltages on board a spacecraft.