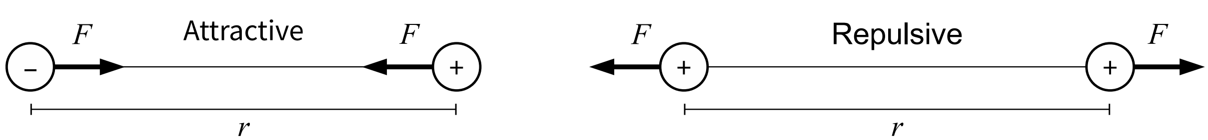
Electric and Gravitational Forces

Electric Charge and Force

Since ancient times, people observed that they could cause certain objects to exert forces on each other, even when they are not in contact. We now think of such forces, which act at a distance, as **field forces**. Magnetism is one such field force known to the ancients. They observed that bits of iron would be attracted to a certain mineral, called “lodestone.” We will study magnetism in a few chapters.

One of the field forces we will be studying today is known as **electricity**. This term comes from the Greek word for amber. The ancients observed that a piece of amber, rubbed with fur, would attract bits of feather to it. We say that the piece of amber is “electrically charged.”

We now know, through careful experimentation, that there are two types of electric charge. We distinguish these types by calling them “positive” and “negative”. Two identically prepared objects (both positively charged or both negatively charged) will repel each other when brought into contact. Two oppositely prepared objects (one positive, one negative) will attract each other. This makes sense from Newton’s third law. If object #1 pulls object #2 toward it, then object #2 will pull object #1 toward it.



We say that electricity is a **central force** because the force that #1 exerts on #2 is directed either toward or away from the center of #1 (and vice versa), along the line connecting the centers of the objects. Moreover, the strength of the force will be greater when the objects are closer, and weaker when the objects are farther apart.

Electric charge is typically denoted by q or Q and is measured in the SI unit “Coulombs” (C). The size of this unit was chosen to deal with macroscopic objects that will be studied in the

laboratory. It turns out, however, that there is a fundamental unit of charge,

$$e = 1.6 \times 10^{-19}\,\text{C} .$$

This is the charge of a proton or electron, depending on sign. In fact, we usually write

- proton charge: $+e$,
- electron charge: $-e$.

(The fact that electrons are negatively charged is purely a matter of choice. Ben Franklin introduced the notion of positive and negative charges long before protons and electrons were discovered. He could establish the sign convention however he wanted. Unfortunately, as we will see in future classes, it would have been easier for us if he had chosen the convention that would have led to positive electrons and negative protons. Oh, well, c'est la vie!)

The Gravitational Force

Isaac Newton, who along with his contemporaries was searching for an explanation of the motion of planets around the sun, realized that a force that attracted a planet directly toward the sun would account for the motion. He realized that the same force that caused objects to fall toward the center of Earth would also keep the motion in orbit around Earth. Essentially, the moon is constantly "falling toward" Earth as it orbits.

Recall that Galileo demonstrated that, in the absence of air resistance, all objects will fall under the influence of gravity with the same acceleration (independent of mass). Using Newton's 2nd law, $F = ma$, we see that the gravitational force that #1 exerts on #2 will be proportional to the mass of object #2. Newton's 3rd law requires that the same will hold for the gravitational force that #2 exerts on #1. That means that the gravitational force between #1 and #2 is proportional to the product of their masses: $F \propto m_1 m_2$.

Through a careful analysis of the orbital properties of planets around the sun, Newton was able to show that the gravitational force between two objects must also be a central force that gets weaker the farther the objects are apart. In fact, the strength of the gravitational force decreases as the **inverse square** of the distance between their centers. For example, if you double the distance between two objects, the gravitational force between them will be one-fourth as strong as before. If you triple the distance between them, the gravitational force will be one-ninth as strong as before.

That means we can write

$$F_g = \frac{G m_1 m_2}{r^2} ,$$

where r is the distance between the centers of objects #1 and #2, and $G = 6.67{\times}10^{-11}\ \text{N}{\cdot}\text{m}^2/\text{kg}^2$ is a proportionality constant known as "Newton's gravitational constant." Remember, in this formula, F_g is the *strength* of the gravitational force. The direction is always attractive. We will see how to write this in terms of vectors next time.

Coulomb's Law for Electricity

A century after Newton presented his universal law of gravitation, Coulomb published his law governing electric the force between charged objects. Coulomb's law, like Newton's, is an inverse-square law. However, the strength of the force depends on the product of the charges q_1 and q_2, not the product of the masses:

$$F_e = \frac{k_e |q_1 q_2|}{r^2} \ ,$$

where $k_e = 8.99 \times 10^9 \ \mathrm{N{\cdot}m^2/C^2}$ is a proportionality constant sometimes known as "Coulomb's constant." The absolute value symbols around the charges are there because $q_1 q_2$ could be positive or negative. Here F_e, the magnitude of the force, must be a positive number.

The direction of the force depends on the charges. If the charges have the same sign (both positive or both negative) then the product $q_1 q_2$ is positive and the force is *repulsive*. If the charges have opposite sign (one positive and one negative—it doesn't matter which) then the product $q_1 q_2$ is negative and the force is *attractive*. As with Newton's law, we will see how to write this in terms of vectors next time.

Relative Strengths

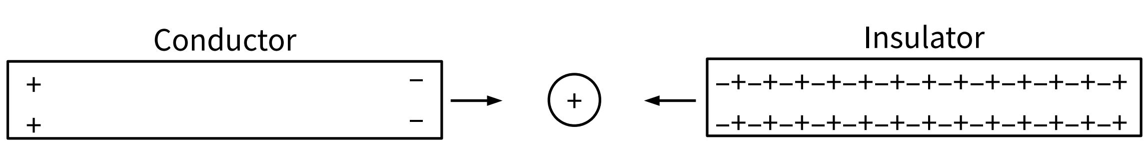
You may have heard before that, in some sense, the electrical force is stronger than the gravitational force. That's a bit of an "apples-to-oranges" comparison.

It is true that for a hydrogen atom, the electrical force between the proton and electron is around 10^{39} times stronger than the gravitational force. (This is regardless of the distance between them—can you see why that should be the case?)

However, on macroscopic scales (you, the solar system, the galaxy) the electrical force is often ignorable. That's because at any given moment, you and Earth are very nearly electrically neutral (possessing as many positive charges as negative charges).

Conductors and Insulators

Even if an object is electrically neutral, there still may be a way to attract it to a charged object. Consider the diagram below, where a positive charge is placed near a neutral conductor and a neutral insulator.



A **conductor** is a material that allows electrons to move around freely inside it. When you bring a positively charged object near a conductor (like a bit of metal), some electrons will be attracted to the object and move close to it, making a net negative charge on the side nearest the object. This side of the conductor will be attracted to the object. The opposite side of the conductor, which now has fewer electrons than protons, will have a net positive charge and will be repelled by the object. However, because the attractive side is closer, the attractive force will be greater than the repulsive force, causing a net attractive force between the conductor and the positively charged object. The same is true if you bring a negatively charged object near a conductor.

An **insulator** is different from a conductor in that charges are not allowed to move freely through an insulator. However, the atoms or molecules of insulators can still be **polarized**, causing the positive and negative charges to separate slightly. If you bring a positively charged object near an insulator (like a bit of paper), the charges in the conductor will separate just enough to give a net negative charge on the near side and a net positive charge on the far side, causing a net attraction as with the conductor above.

What happens if you put a net charge on a conductor or an insulator? Where will the charge go? If you put a charge on an insulator, the net charge stays pretty much wherever you put it because the charges are not free to move. However, if you put a net charge on a conductor, these charges will move. Say, for example, you put an excess of electrons on an initially neutral metal object. The electrons won't feel any attraction or repulsion from the neutral metal, but they will feel a repulsive force between themselves. This will push all of the electrons as far apart as possible, all the way to the edge of the conductor. *A charged conductor will always have its net charge on the surface.*