Pre-lecture Notes Section 1:
Introduction to Electricity, Magnetism and Light;
Electric Charge and Electric Force

I. Review of Classical Mechanics and Introduction to Electricity, Magnetism and Light

In physics 2425 (or the equivalent course) you studied the foundations of classical mechanics, also called Newtonian mechanics.

The most basic set of principles in classical mechanics is Newton's three laws of motion. These laws describe how inertia governs the motion of objects not subject to a net external force (Newton's 1^{st} law), how interactions between objects (and the forces that accompany them) lead to changes in motion of those objects (Newton's 2^{nd} law) and how interactions between objects always cause equal and opposite forces to be exerted in a force pair (Newton's 3^{rd} law). These laws allow for a prediction of all future motion of an object once you know all of the forces acting on that object.

Of course, Newton's laws themselves do not actually give any information about which forces exist in Nature; those must ultimately be deduced from experiment. A few of the forces you learned about in physics 2425 are the gravitational force, the friction force, the normal force, etc… Of these forces, only the gravitational force is fundamental to the universe, while the others are simply complex manifestations, among many particles, of the two forces we will learn about in this course, electricity and magnetism.

The entirety of this course is devoted to understanding just two forces of Nature: the electric force and the magnetic force. Later in the course we will actually see that these two forces are highly related, and can be considered to be two "sides" of the same coin, the electromagnetic force. With this knowledge, we will be able to gain an introductory understanding of one of the great mysteries of the world: the fundamental nature of light.

As we study these two forces and learn about their properties, we need to keep Newton's mechanics in the back of our mind, always remembering that these forces, just as with any force, cause particles to accelerate according to Newton's 2^{nd} law.

In addition, another concept discussed in physics 2425 was potential energy and conservation of energy. For every conservative force, there is a potential energy function which can be defined. For instance, one defines the gravitational potential energy, based on the fact that the gravitational force is conservative. One then discovers the principle of conservation of energy, which says that the total energy in a closed system cannot change. This can be used, for instance, to find the speed of a ball after falling a certain distance in a gravitational field.

Later in the course, we will find that the electric force is also a conservative force, and therefore permits the definition of an electric potential energy. At this point we will again need to make use of our knowledge from physics 2425 to apply conservation of energy to particles.

It is useful to think of this course, therefore, not as a completely new subject, but simply as a continuation of the previous course, in which we will expand our knowledge to encompass two of Nature's fundamental forces, electricity and magnetism.

II. Electric Charge and Matter

Origins of Electricity and Electric Charge

Going back as far back as 600 B.C., ancient peoples discovered the phenomenon of electricity and electric charge. Electric charge, for now, is simply a property that some objects have.

Experiments with many types of materials revealed that electric charge comes in only two types. Benjamin Franklin called these types "positive" and "negative". These experiments also established a set of rules for the attractive and repulsive nature of this force, henceforth called the **electric force**, which occur between charged objects.

1. The interaction of two objects containing the positive type of charge will always produce a repulsive force between them, as will the interaction of two objects containing the negative type of charge.

2. The interaction of one object with positive charge and another object with negative charge will always produce an attractive force.

3. If either of the two objects does not contain any electric charges, the two objects will not experience any electric interaction, and will exert no electric force on each other.

4. These interactions are *long-range*, meaning that the objects do not have to be touching to produce the force.

Electric Charge and Matter

It was not until the early 1900's that physicists discovered that electric charge comes in discrete multiples (i.e. it is not possible to place any arbitrary amount of electric charge on an object, but only multiples of a fundamental quantity). With the discovery of the three components of the atom, the fundamental carriers of electric charge were finally understood. Here are the relevant facts about each component of the atom, as they pertain to this course:

- The electron

- Discovered in 1901, the electron contains the fundamental unit of the negative type of charge.
  - Every electron is identical and contains this fundamental quantity of negative charge.
  - The mass of the electron is very small: $m_e = 9.109 \times 10^{-31}$ kg.
- The proton
  - Discovered in 1917, the proton contains the fundamental unit of the positive type of charge.
  - Every proton is identical and contains the fundamental unit of positive charge, which is equal in magnitude to the charge of the electron.
  - The mass of the proton, while very small by macroscopic standards, is nearly 2000 times larger than that of the electron: $m_p = 1.673 \times 10^{-27}$ kg.
- The neutron
  - Discovered in 1932, contains zero electric charge (it is neutral).
  - Every neutron is identical and contains no electric charge.
  - The mass of the neutron is similar to, but slightly larger than, the mass of the proton: $m_n = 1.675 \times 10^{-27}$ kg.

A very important aspect of this discovery is that the electron and proton contain ***exactly*** the same quantity of electric charge, but of the opposite type.

Every observable object, therefore, contains some integer multiple of the magnitude of charge carried by the proton (or equivalently the electron).

Conservation of Electric Charge

Another extremely important property of electric charge, which has been verified by countless experiments, is that the total algebraic amount of electric charge in a closed system is constant. In other words, electric charge is conserved!

For instance, if you put a certain quantity of electric charge in a box, and close the box so that no electric charge escapes, then no matter what interactions occur inside the box, the electric charge in the box will remain the same at all times.

Conversely, if the quantity of charge in the box changes, then the system must be an open system and some amount of electric charge must have flowed into or out of the box.

Types of Materials

For the purposes of this course, we can broadly classify materials as belonging to one of two types: conductors and insulators.

Conductors are materials in which the outer electrons of the atoms in the material are free to move around. In other words, these electrons are not bound to their atomic nuclei. This means that if you bring a charged object near a conductor, the electrons in the conductor will accelerate in response to the electric force, and will move macroscopic distances within the conductor. If the charged object is negative, the electrons will be repelled to the opposite side of the conductor, whereas if the charged object is positive, the electrons will be attracted to the near side of the conductor. Most metals are excellent conductors.

Insulators are materials in which the electrons of the atoms in the material are tightly bound to their atomic nuclei, and cannot move freely away from them. Nevertheless, the atoms in the material can shift and rotate slightly in response to an electric force. For instance, if you bring a positively charged object near an insulator, the atoms will shift and rotate slightly, so that the electrons in the atoms will be slightly closer to the object than the protons. Some examples of insulators are wood, glass and plastic.

III. Coulomb's Law

In the previous section we qualitatively described the electric force between charged objects, but our discussion was not quantitative. In the late 1700's French physicist Augustin Coulomb discovered a number of factors which affect the magnitude of the electric force. In 1785, he published **Coulomb's law** for determining the electric force between two electric charges. It is important to note that Coulomb's law only applies to **point charges which are at rest**. By "point charges", we mean that the size of the two charges is very small compared to the separation between them. Two literal point charges (i.e. just a point in space, with no size) is the perfect limit of this ideal. The term "at rest" of course means that the charges are stationary. Coulomb's law therefore applies to the special situation known as electrostatics, meaning that all charges that produce electric forces are at rest.

Charles-Augustin de Coulomb
(1736-1806)

Coulomb found that

1. The greater the magnitudes of electric charge on the objects, the greater the force. In particular, he found that the electric force is directly proportional to the product of the magnitudes of the two charges.
2. The greater the separation distance between the charges, the smaller the force. In particular, he found that the electric force is inversely proportional to the square of the distance between them.

If we say that point charge 1 has magnitude of charge q_1 and point charge 2 has magnitude of charge q_2, then Coulomb's law for the magnitude of the electric force can be written as

$$F_E = k\frac{|q_1 q_2|}{r^2}$$

where r is the distance separating the charges, and k is a proportionality constant which depends on the units used and must be measured experimentally.

Coulomb's law is an inverse square law, meaning that the force weakens with the square of the distance between the objects. Recall from physics 2425 that this is very similar to the gravitational force law:

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

Just as the gravitational interaction occurs between any two objects which have mass, the electric interaction occurs between any two objects which have charge!

Incidentally, to find the proportionality constant k, we must specify a set of units. In SI units, force has units of Newtons and distance has units of meters, but what about charge? It turns out that the SI unit of charge is called the **Coulomb (C)**.

In terms of our fundamental charge carriers, the electron and proton, a Coulomb is an extremely large amount of charge. The magnitude of charge of the electron and proton is denoted by the letter e. In SI units, this charge is

$$e = 1.602 \times 10^{-19}\ \mathrm{C}$$

In SI units, the proportionality constant is measured to be equal to $k = 8.988 \times 10^{9}\ \mathrm{Nm^2/C^2}$.

For reasons of later convenience, we often define a new constant, ϵ_0, which relates to k in the following way:

$$k \equiv \frac{1}{4\pi\epsilon_0}$$

where $\epsilon_0 = 8.85 \times 10^{-12}\ \mathrm{C^2/Nm^2}$. With this redefinition, Coulomb's law becomes

$$\boldsymbol{F_E = \frac{1}{4\pi\epsilon_0}\frac{|q_1 q_2|}{r^2}}$$