Flipping Physics Lecture Notes:

Electric Charges and Electric Fields
Review for AP Physics C: Electricity and Magnetism

http://www.flippingphysics.com/apcem-electric-charges-electric-fields.html

Let's begin with Electric Charge:

- Electric charge is a fundamental property of all matter.
- Charge carriers are protons and electrons, where protons have a positive charge and electrons have a negative charge. Both protons and electrons have the same magnitude charge called the fundamental charge:
  - $e = 1.60 \times 10^{-19} C$ (The absolute value of the charge on a proton and electron.)
  - C stands for coulombs, the unit of charge. Note: Coulombs are not a base SI unit.
  - Charge is a scalar quantity.
- Charge is quantized. It comes in discrete quantities in intervals of the fundamental charge.
  - $Q = ne$
    - Q = net charge on the object
    - n = integer number of excess positive or negative charges on the object
      - n is positive for excess protons & n is negative for excess electrons
  - In other words, an object will never have a charge of $+2.1 \times 10^{-19}$ C because that is not an integer multiple of 1.60×10^{-19} C.
- The electric charge on an object is determined by the total number of charge carriers contained in the object.
  - The electric charge on an object with 4 protons and 6 neutrons is -3.62×10^{-19} C.
  - $Q_{\text{object}} = Q_{\text{protons}} + Q_{\text{electrons}} = (+4)(e) + (-6)(e) = (-2)(e)$
  - $\Rightarrow Q_{\text{object}} = (-2)\left(1.60 \times 10^{-19}\right) = -3.20 \times 10^{-19} C$
- Many objects we work with will be considered to be point charges (even if they are made up of many charge carriers)
  - A point charge is a model of a charge where the physical size of the charge (or charged system) is small enough to be considered to be negligible.

The Law of Charges states that:

- two charges with opposite signs attract one another
- two charges with the same sign repel one another

Coulomb's Law determines the electrostatic force between two charged objects:

- $\vec{F}_e = k\dfrac{(q_1)(q_2)}{r^2}\hat{r}$ or $\left|\vec{F}_e\right| = k\left|\dfrac{q_1 q_2}{r^2}\right|$ or $\left|\vec{F}_e\right| = \left(\dfrac{1}{4\pi\varepsilon_0}\right)\left|\dfrac{q_1 q_2}{r^2}\right|$ & $k = \dfrac{1}{4\pi\varepsilon_0}$
  - F_e is the electrostatic force on each charged particle.
  - k is the Coulomb constant and it equals 8.99×10^9 N • m / C^2.
  - ε_0 is the permittivity of free space or vacuum permittivity; it equals 8.85×10^{-12} C^2 / N • m^2.
    - We will better define permittivity when we get to capacitors and dielectrics.
  - q_1 and q_2 are the charges on the two interacting charged particles.
  - r is the distance between the centers of charge of the two charges
  - $\vec{F}_e = k\dfrac{(q_1)(q_2)}{r^2}\hat{r}$ is the vector version.
    - If the two charges have the same sign, the force is positive and repulsive.
    - If the two charges have opposite signs, the force is negative and attractive.
  - $\left|\vec{F}_e\right| = k\left|\dfrac{q_1 q_2}{r^2}\right|$ is the scalar version and has no direction.
  - According to AP Physics C: Electricity and Magnetism guidelines, you will only be expected to calculate electric forces between four or fewer charged objects or systems. However, you may be required to analyze more than four charged objects in situations which have high symmetry.

The reality is that electrostatic forces, which can be determined using Coulomb's Law, cause many of the forces which we work with on a macroscopic level. For example, force normal, forces of static and kinetic friction, and the force of tension. There are just too many microscopic electrostatic forces to reasonably calculate, and we model the net force caused by all of these microscopic electrostatic forces as these macroscopic forces.

Note that Coulomb's Law is similar to Newton's Universal Law of Gravitation:

- Coulomb's Law: $\left|\vec{F}_e\right| = k\left|\frac{q_1 q_2}{r^2}\right|$ and the Universal Law of Gravitation: $\left|\vec{F}_g\right| = \frac{Gm_1 m_2}{r^2}$
- r is distance between centers of charge in the case of Coulomb's law, or distance between centers of mass in the case of the Universal Law of Gravitation.
- Electrostatic forces can be attractive or repulsive, however, gravitational forces can only be attractive.
- Notice the difference between the constants in the equations:
    - $k = 8.99 \times 10^9 \frac{N \cdot m}{C^2}$ & $G = 6.67x10^{-11} \frac{N \cdot m^2}{kg^2}$
    - The Coulomb constant is much larger than the universal gravitational constant
    - When two objects have both mass and electric charge, most often the electric force is so much larger than the gravitational force that the gravitational force is negligible.
        - However, when we are considering large scales like people, planes, pineapples, planets, and Prii[1], gravitational forces are large enough to make electric forces negligible because large scale objects are usually nearly electrically neutral. In other words, their total number of protons and electrons are nearly equal.

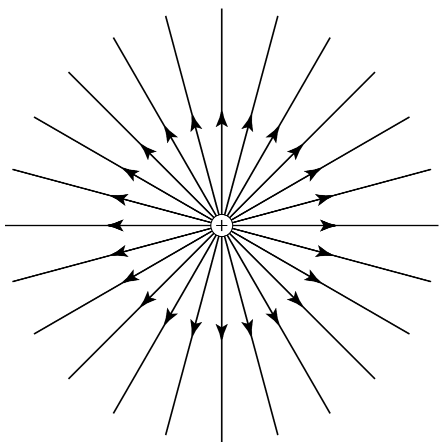
The Law of Conservation of Charge:

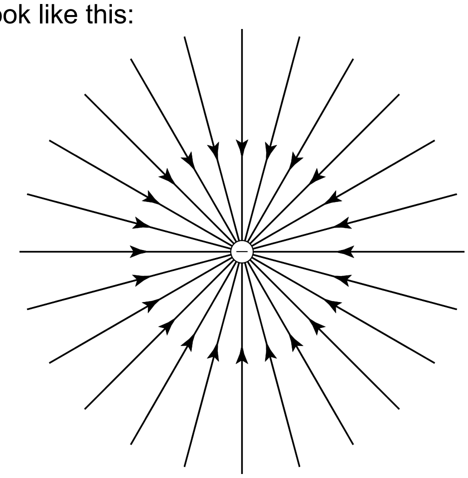
- The net charge of an isolated system does not change.
    - Typically, electrons are the charges which move in a system and if there is no way for electrons to leave or enter the system (an isolated system), then the net charge of the system will not change.
- Charging by friction involves rubbing one object on another object (fur on a balloon, for example). When this happens, electrons move from the fur to the balloon.
    - The balloon gains negative electrons and the net charge on the balloon decreases.
    - The fur loses electrons and the net charge on the fur increases.
    - The net charge on the balloon-fur system remains the same because the total number of protons and electrons in the system remains the same.
- Bringing two objects close to one another will cause electrostatic forces between charges and change the distribution of the electrons in the objects. This can polarize the objects, however, the net charge on each object will remain the same if electrons are not allowed to flow between the objects.
- When a charged object is brought close to a neutral object, charge-induced separation of charges within the neutral object can occur.
- The only way to change the charge of a system is to add or remove charged particles from the system. In the matter most familiar to us, the electrons are the charged particles that can be added or removed from the system to change its charge. In this case the system is *not* isolated, and charge is *not* conserved.
- A "ground" has, relatively speaking, an infinite number of electrons which we can pull from it, or we can give to it. We can "ground" a system by electrically connecting it to the Earth which is a "ground" or a neutrally charged, infinite well of electrons. When we ground a system, the system is *not* isolated, and charge is *not* conserved.

[1] https://pressroom.toyota.com/toyota-announces-the-plural-of-prius/

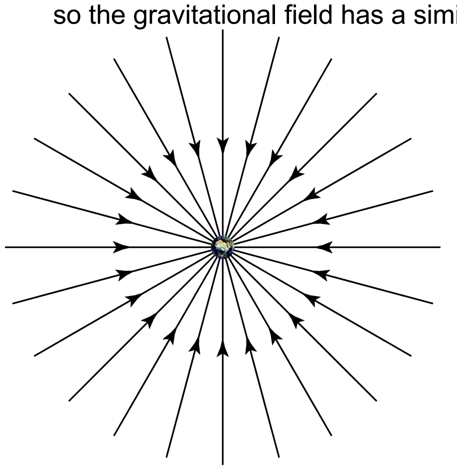
Electric Fields:

- If we were to place a positive test charge in an electric field, it would experience an electrostatic force. An electric field is the ratio of the electrostatic force the test charge would experience and the charge of the test charge.
    - A positive test charge is a charge which is small enough not to measurably change the electric field it is placed in. Electric field directions are defined according to the direction of the net electrostatic force on a positively charged test charge.
- The equation for an electric field and its units are: $\vec{E} = \frac{\vec{F}_e}{q} \Rightarrow \frac{N}{C}$
- Notice the electric field and the electrostatic force experienced by a positive charge in the electric field will be in the same direction. (Both electric field and electrostatic force are vectors in the equation.)
- That means the electric field which surrounds a point charge is: $\vec{E} = \frac{\vec{F}_e}{q} \Rightarrow E_{\text{point charge}} = \frac{\frac{kqQ}{r^2}}{q} = \frac{kQ}{r^2}$
- And the electric field maps for **isolated** point charges look like this:

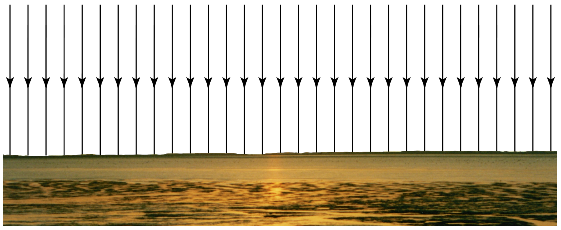


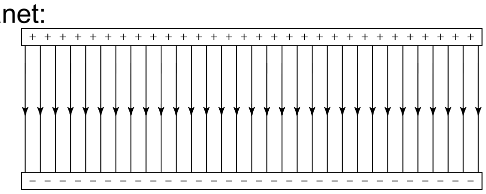


- Notice the similarity to the gravitational field around a planet. The equation has a similar format, so the gravitational field has a similar format: $g = \frac{F_g}{m} \Rightarrow g_{\text{point mass}} = \frac{\frac{GmM}{r^2}}{m} = \frac{GM}{r^2}$



- And the electric field which exists between two large, parallel, oppositely charged plates is similar to the gravitational field close to the surface of a planet:





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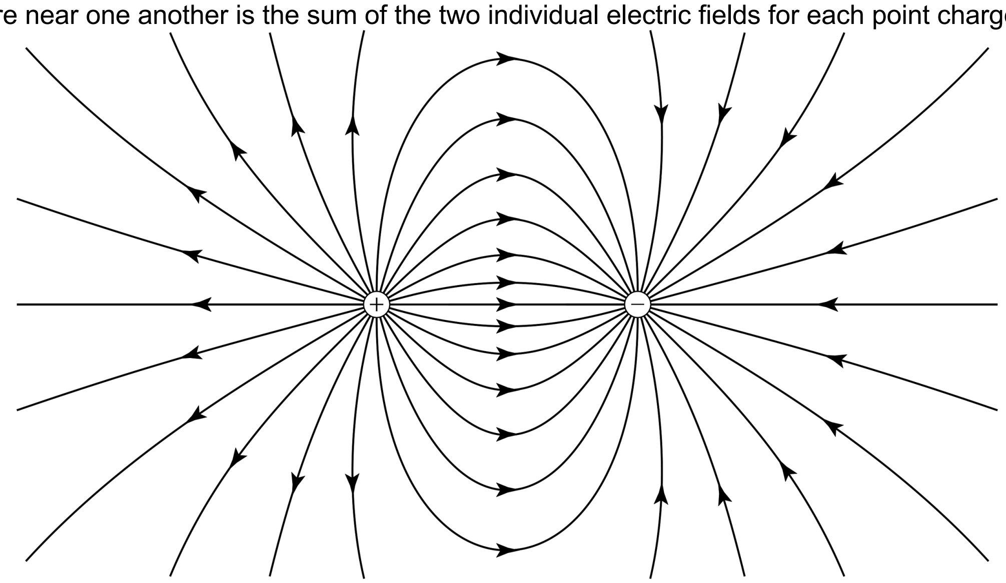
- Remember electric field is a vector which means that the electric field for two point charges which are near one another is the sum of the two individual electric fields for each point charge.



- Electric field maps like the one above are simplified models and vector maps which show the magnitude and direction of the electric field for the entire region.
- Electric Field Lines Basics:
    - In the direction a small, positive, test charge would experience an electrostatic force
    - Electric field lines per unit area is proportional to electric field strength
        - Higher density electric field lines = higher electric field strength
    - Start on a positive charge and end on a negative charge
        - or infinitely far away if more of one charge than another
    - Always start perpendicular to the surface of the charge
    - Electric field lines never cross

Conductors vs. Insulators:
- *Conductors* allow electrons to move rather easily. This is because conductors have electrons which are loosely bound to their atoms which allows electrons to flow.
    - Examples: aluminum, stainless-steel, and gold.
- *Insulators* resist the motion of electrons. Insulators have electrons which are tightly bound to their atoms which does not allow electrons to flow.
    - Examples: plastic, rubber, glass, and paper.
- *Semiconductors* are materials which are somewhere in between conductors and insulators. Electrons have some resistance to flow, and the precise resistance to flow is controlled by the composition of the materials.
    - Examples: silicon, germanium, and gallium arsenide.
    - Example uses: diodes, transistors, amplifiers, solar cells, and light emitting diodes (LEDs)