

# PHYS 1441 – Section 002

## Lecture #3

*Wednesday, Aug. 28, 2019*

*Dr. Jaehoon Yu*

- CH 21

- Charges in Atom, Insulators and Conductors & Induced Charge
- Coulomb's Law
- Electric Fields and Conductors
- Motion of a Charged Particle in an Electric Field



# Announcements

- Reading assignment: CH21 – 7
- Quiz at the beginning of the class, Wed. Sept. 4
  - Appendix A1 – A8 and what we've learned this Wednesday
  - In class, this Wednesday, Sept. 4
  - You can bring your calculator but it must not have any relevant formula pre-input
    - No phone or computers can be used as a calculator!
  - BYOF: You may bring one 8.5x11.5 sheet (front and back) of handwritten formulae and values of constants for the exam
  - No derivations, word definitions, or solutions or setups of ANY problems!
  - No additional formulae or values of constants will be provided!
- No class next Monday, Sept. 2, Labor Day



# Reminder: Extra Credit Special Project #1

- Compare the Coulomb force to the Gravitational force in the following cases by expressing Coulomb force ( $F_C$ ) in terms of the gravitational force ( $F_G$ )
  - Between two protons separated by 1m
  - Between two protons separated by an arbitrary distance  $R$
  - Between two electrons separated by 1m
  - Between two electrons separated by an arbitrary distance  $R$
- Five points each, totaling 20 points
- BE SURE to show all the details of your work, including all formulae, proper references to them and explanations
- Please staple them before the submission
- Due at the beginning of the class Wednesday, Sept. 4

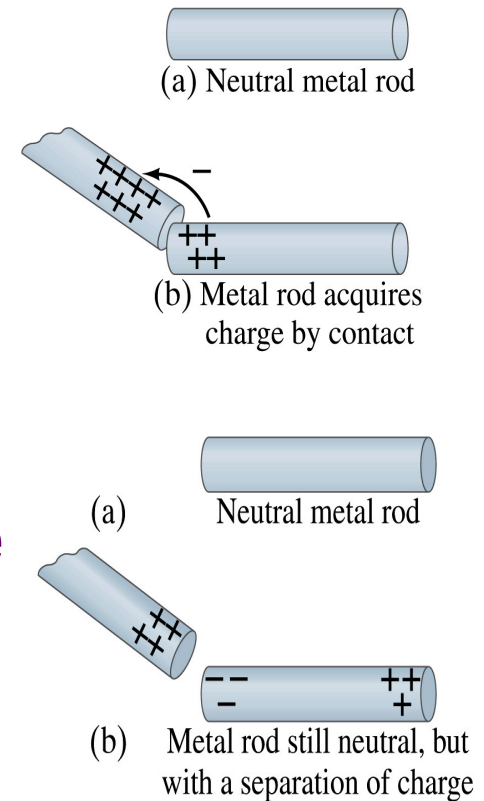
Monday, Aug. 26, 2019



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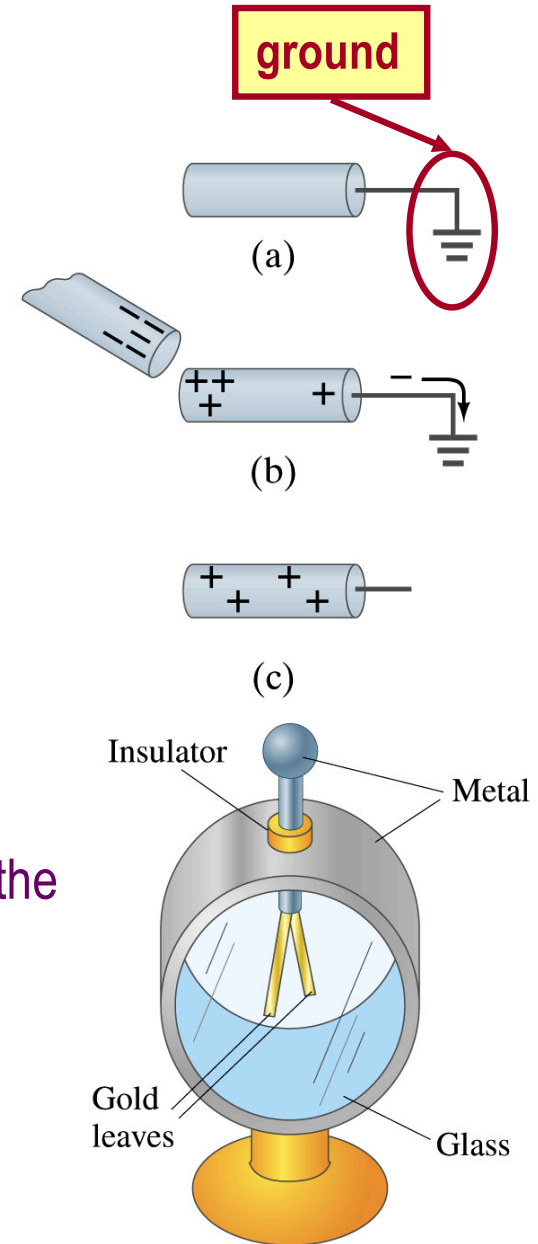
# Induced Charge

- When a positively charged metal object is brought close to an uncharged metal object
  - If two objects touch each other, the free electrons in the neutral one are attracted to the positively charged object and some will pass over to it, leaving the neutral object positively charged → Charging by conduction
  - If the objects get close, the free electrons in the neutral one still move within the metal toward the charged object leaving the opposite side of the object positively charged.
    - The charges have been “induced” in the opposite ends of the object.



# Induced Charge

- We can induce a net charge on a metal object by connecting a wire to the ground.
  - The object is “grounded” or “earthed”.
- Since the Earth is so large and conducts, it can give or accept charge.
  - The Earth acts as a reservoir of electric charge.
- If negative charge is brought close to a neutral metal
  - Positive charge will be induced toward the negatively charged metal.
  - The negative charges in the neutral metal will be gathered on the opposite side, transferring through the wire to the Earth.
  - If the wire is cut, the metal bar has net positive charge.
- An **electroscope** is a device that can be used for detecting charge and signs.
  - How does this work?



# Coulomb's Law

- Charges exert force to each other. What factors affect the magnitude of this force?
  - Any guesses?
- Charles Coulomb figured this out in 1780's.
- Coulomb found that the electric force is
  - Proportional to the multiplication of the two charges
    - If one of the charges doubles, the force doubles.
    - If both the charges double, the force quadruples.
  - Inversely proportional to the square of the distances between them.
  - Electric charge is a fundamental property of matter, just like mass.
- How would you put the above into a formula?



# Coulomb's Law – The Formula

$$F \propto \frac{Q_1 \times Q_2}{r^2} \quad \xrightarrow{\text{Formula}} \quad F = k \frac{Q_1 Q_2}{r^2}$$

- Is Coulomb force a scalar quantity or a vector quantity? Unit?
  - A vector quantity. The unit is Newtons (N)!
- The direction of electric (Coulomb) force is always along the line joining the two objects.
  - If the two charges are the same: forces are directed away from each other.
  - If the two charges are opposite: forces are directed toward each other.
- Coulomb force is precise to 1 part in  $10^{16}$ .
- Unit of charge is called Coulomb, C, in SI.
- The value of the proportionality constant,  $k$ , in SI unit is  $k = 8.988 \times 10^9 \text{ N} \cdot \text{m}^2 / \text{C}^2$
- Thus, 1C is the charge that gives  **$F \sim 9 \times 10^9 \text{ N}$**  of force when placed 1m apart from each other.

# Electric Force and Gravitational Force

$$F = k \frac{Q_1 Q_2}{r^2} \quad \longleftrightarrow \quad \text{Extremely Similar} \quad \longleftrightarrow \quad F = G \frac{M_1 M_2}{r^2}$$

- Does the electric force look similar to another force? What is it?
  - Gravitational Force
- What are the sources of the forces?
  - Electric Force: Electric charges, fundamental properties of matter
  - Gravitational Force: Masses, fundamental properties of matter
- What else is similar?
  - Inversely proportional to the square of the distance between the sources of the force → What is this kind law called?
    - Inverse Square Law
- What is the difference?
  - Gravitational force is always attractive.
  - Electric force depends on the type of the two charges. (must pay good attention to the signs due to the sign of the charge and the vector force directions!!)





# The Elementary Charge and Permittivity

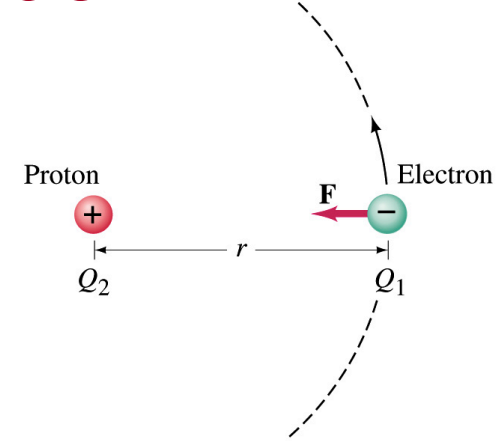
- Elementary charge, the smallest charge, is that of an electron:  $e = 1.602 \times 10^{-19} \text{ C}$ 
  - Since electron is a negatively charged particle, its charge is  $-e$ .
- Object cannot gain or lose fraction of an electron.
  - Electric charge is quantized.
    - It changes always in integer multiples of  $e$ .
- The proportionality constant  $k$  is often written in terms of another constant,  $\epsilon_0$ , the permittivity\* of free space. They are related  $k = 1/4\pi\epsilon_0$  and  $\epsilon_0 = 1/4\pi k = 8.85 \times 10^{-12} \text{ C}^2/\text{N} \cdot \text{m}^2$ .
- Thus the electric force can also be written as:  $F = \frac{1}{4\pi\epsilon_0} \frac{Q_1 Q_2}{r^2}$
- Note that this force is for “point” charges at rest.

\*Mirriam-Webster, Permittivity: The ability of a material to store electric potential energy under the influence of an electric field



# Example on Coulomb Force

- Electric force on electron by proton.** Determine the magnitude of the electric force on the electron of a hydrogen atom exerted by the single proton ( $Q_2=+e$ ) that is its nucleus. Assume the electron “orbits” the proton at its average distance of  $r=0.53\times 10^{-10}\text{m}$ .



Using Coulomb's law

$$F = \frac{1}{4\pi\epsilon_0} \frac{Q_1 Q_2}{r^2} = k \frac{Q_1 Q_2}{r^2}$$

Each charge is  $Q_1 = -e = -1.602 \times 10^{-19} \text{ C}$  and  $Q_2 = +e = 1.602 \times 10^{-19} \text{ C}$

So the magnitude of the force is

$$\begin{aligned} F &= \left| k \frac{Q_1 Q_2}{r^2} \right| = 9.0 \times 10^9 \text{ N} \cdot \text{m}^2 / \text{C}^2 \frac{(1.6 \times 10^{-19} \text{ C})(1.6 \times 10^{-19} \text{ C})}{(0.53 \times 10^{-10} \text{ m})^2} \\ &= 8.2 \times 10^{-8} \text{ N} \end{aligned}$$

Which direction? Toward each other...

# The Coulomb Force Refresher

$$F \propto \frac{Q_1 \times Q_2}{r^2} \quad \xrightarrow{\text{Formula}} \quad F = k \frac{Q_1 Q_2}{r^2}$$

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$$k = 1/4\pi\epsilon_0$$

$$\epsilon_0 = 1/4\pi k = 8.85 \times 10^{-12} \text{ C}^2 / \text{N} \cdot \text{m}^2$$

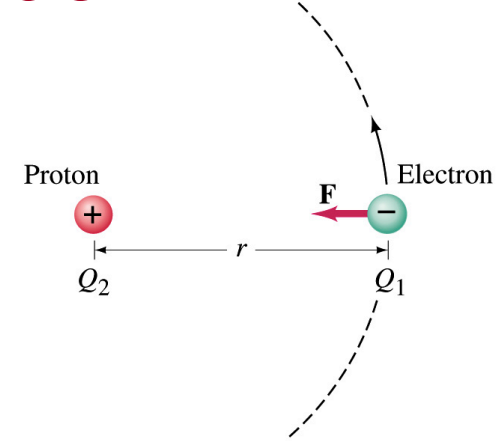
$$F = \frac{1}{4\pi\epsilon_0} \frac{Q_1 Q_2}{r^2}$$

**The Elementary Charge**

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

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Using Coulomb's law

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So the magnitude of the force is

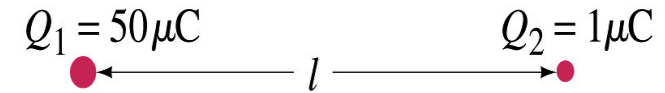
$$F = \left| k \frac{Q_1 Q_2}{r^2} \right| = 9.0 \times 10^9 \text{ N} \cdot \text{m}^2 / \text{C}^2 \frac{(1.6 \times 10^{-19} \text{ C})(1.6 \times 10^{-19} \text{ C})}{(0.53 \times 10^{-10} \text{ m})^2}$$
$$= 8.2 \times 10^{-8} \text{ N}$$

Which direction? Toward each other...

**What is the speed of the electron circling around the proton in a hydrogen atom?**

# Example 21 – 1

- Which charge exerts greater force? Two positive point charges,  $Q_1=50\mu\text{C}$  and  $Q_2=1\mu\text{C}$ , are separated by distance  $L$ . Which is larger in magnitude, the force that  $Q_1$  exerts on  $Q_2$  or the force that  $Q_2$  exerts on  $Q_1$ ?



What is the force that  $Q_1$  exerts on  $Q_2$ ?  $F_{12} = k \frac{Q_1 Q_2}{L^2}$

What is the force that  $Q_2$  exerts on  $Q_1$ ?  $F_{21} = k \frac{Q_2 Q_1}{L^2}$

Therefore the magnitudes of the two forces are identical!!

Well then what is different? The direction.

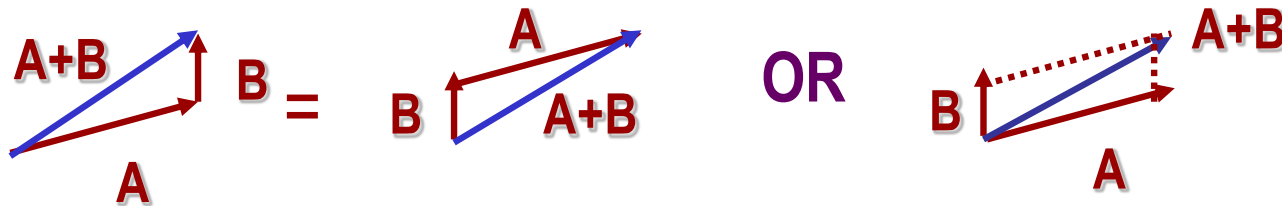
Which direction? Opposite to each other!

What is this law? Newton's third law, the law of action and reaction!!

# Vector Additions and Subtractions

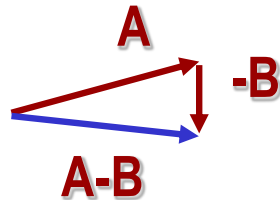
- Addition:

- Triangular Method: One can add vectors by connecting the head of one vector to the tail of the other (head-to-tail)
- Parallelogram method: Connect the tails of the two vectors and extend
- Addition is commutative: Changing order of operation does not affect the results  
 $\mathbf{A+B=B+A}$ ,  $\mathbf{A+B+C+D+E=E+C+A+B+D}$



- Subtraction:

- The same as adding a negative vector:  $\mathbf{A - B = A + (-B)}$



Since subtraction is the equivalent to adding a negative vector, subtraction is also commutative!!!

- Multiplication by a scalar is increasing the magnitude  $\mathbf{A, B=2A}$

Monda  $|\mathbf{B}| = 2|\mathbf{A}|$

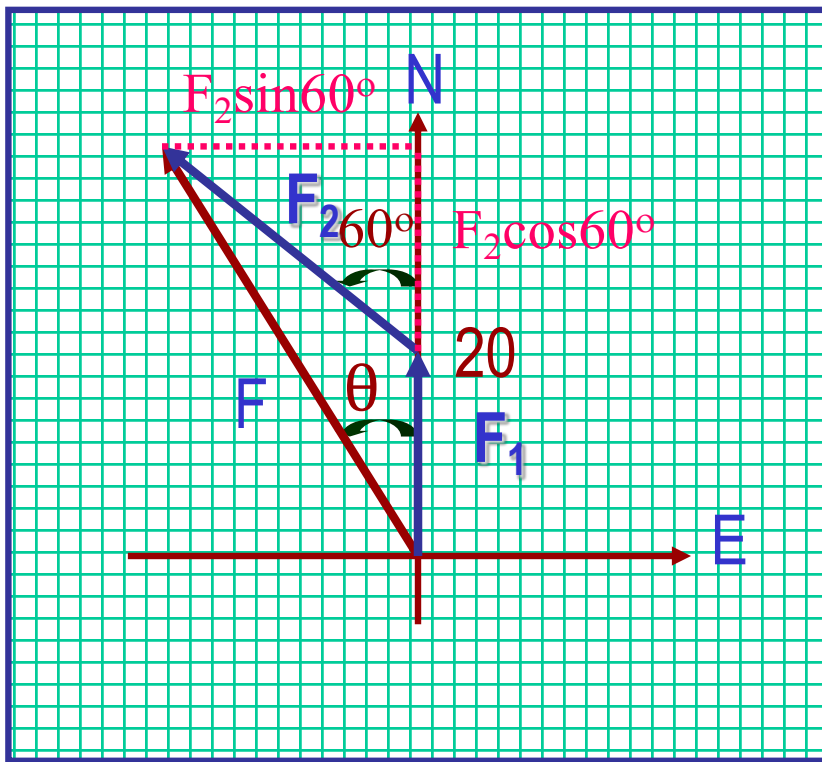


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# Example for Vector Addition

A force of 20.0N applies to north while another force of 35.0N applies in the direction 60.0° west of north. Find the magnitude and direction of resultant force.



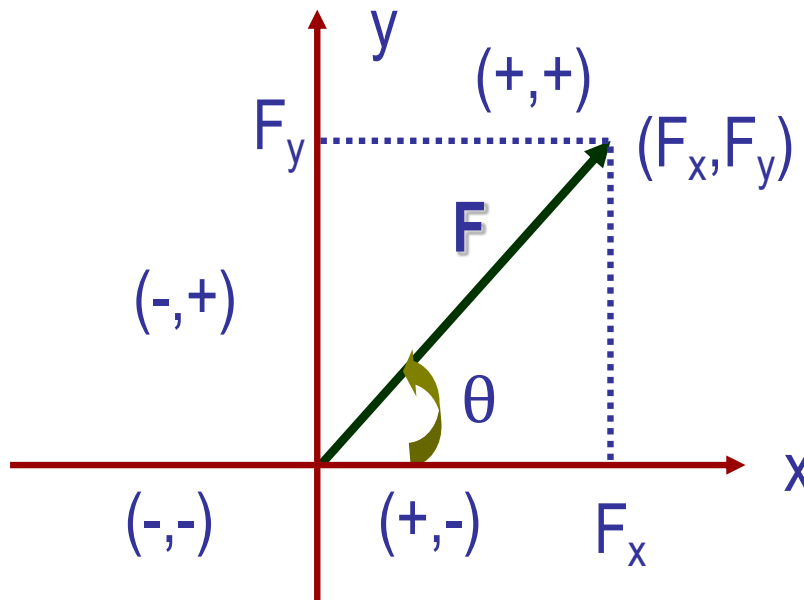
$$\begin{aligned}
 F &= \sqrt{\left(F_1 + F_2 \cos 60^\circ\right)^2 + \left(F_2 \sin 60^\circ\right)^2} \\
 &= \sqrt{F_1^2 + F_2^2 \left(\cos^2 60^\circ + \sin^2 60^\circ\right) + 2F_1F_2 \cos 60^\circ} \\
 &= \sqrt{F_1^2 + F_2^2 + 2F_1F_2 \cos 60^\circ} \\
 &= \sqrt{(20.0)^2 + (35.0)^2 + 2 \times 20.0 \times 35.0 \cos 60^\circ} \\
 &= \sqrt{2325} = 48.2(N)
 \end{aligned}$$

$$\begin{aligned}
 \theta &= \tan^{-1} \frac{|\vec{F}_2| \sin 60^\circ}{|\vec{F}_1| + |\vec{F}_2| \cos 60^\circ} \\
 &= \tan^{-1} \frac{35.0 \sin 60^\circ}{20.0 + 35.0 \cos 60^\circ} \\
 &= \tan^{-1} \frac{30.3}{37.5} = 38.9^\circ \text{ to W wrt N}
 \end{aligned}$$

Find other ways to solve this problem...

# Components and Unit Vectors

Coordinate systems are useful in expressing vectors in their components



$$F_x = |\vec{F}| \cos \theta$$

$$F_y = |\vec{F}| \sin \theta$$

} Components

$$|\vec{F}| = \sqrt{F_x^2 + F_y^2}$$

} Magnitude

$$\begin{aligned} |\vec{F}| &= \sqrt{\left(|\vec{F}| \cos \theta\right)^2 + \left(|\vec{F}| \sin \theta\right)^2} \\ &= \sqrt{|\vec{F}|^2 (\cos^2 \theta + \sin^2 \theta)} = |\vec{F}| \end{aligned}$$



# Unit Vectors

- Unit vectors are the ones that tells us the directions of the components
- Dimensionless
- Magnitudes are exactly 1
- Unit vectors are usually expressed in **i, j, k** or

$$\vec{i}, \vec{j}, \vec{k}$$

So the vector **F** can be re-written as

$$\vec{F} = F_x \vec{i} + F_y \vec{j} = |\vec{F}| \cos \theta \vec{i} + |\vec{F}| \sin \theta \vec{j}$$



# Examples of Vector Operations

Find the resultant force which is the sum of  $\mathbf{F}_1=(2.0\mathbf{i}+2.0\mathbf{j})\text{N}$  and  $\mathbf{F}_2=(2.0\mathbf{i}-4.0\mathbf{j})\text{N}$ .

$$\begin{aligned}\vec{F}_3 &= \vec{F}_1 + \vec{F}_2 = (2.0\vec{i} + 2.0\vec{j}) + (2.0\vec{i} - 4.0\vec{j}) \\ &= (2.0 + 2.0)\vec{i} + (2.0 - 4.0)\vec{j} = 4.0\vec{i} - 2.0\vec{j} \text{ (N)}\end{aligned}$$

$$\begin{aligned}|\vec{F}_3| &= \sqrt{(4.0)^2 + (-2.0)^2} \\ &= \sqrt{16 + 4.0} = \sqrt{20} = 4.5 \text{ (N)}\end{aligned}\quad \theta = \tan^{-1} \frac{F_{3y}}{F_{3x}} = \tan^{-1} \frac{-2.0}{4.0} = -27^\circ$$

Find the resultant force of the sum of three forces:  $\mathbf{F}_1=(15\mathbf{i}+30\mathbf{j}+12\mathbf{k})\text{N}$ ,  $\mathbf{F}_2=(23\mathbf{i}+14\mathbf{j}-5.0\mathbf{k})\text{N}$ , and  $\mathbf{F}_3=(-13\mathbf{i}+15\mathbf{j})\text{N}$ .

$$\begin{aligned}\vec{F} &= \vec{F}_1 + \vec{F}_2 + \vec{F}_3 = (15\vec{i} + 30\vec{j} + 12\vec{k}) + (23\vec{i} + 14\vec{j} - 5.0\vec{k}) + (-13\vec{i} + 15\vec{j}) \\ &= (15 + 23 - 13)\vec{i} + (30 + 14 + 15)\vec{j} + (12 - 5.0)\vec{k} = 25\vec{i} + 59\vec{j} + 7.0\vec{k} \text{ (N)}\end{aligned}$$

Magnitude

$$|\vec{D}| = \sqrt{(25)^2 + (59)^2 + (7.0)^2} = 65 \text{ (N)}$$