22-1: Introduction to Electricity and Magnetism

Where should we begin our study of electricity and magnetism (E&M)?
Here are three possibilities:

1. **The Historical Approach:** in the first three sections of chapter 22, your author summarizes how we became aware of the nature and behavior of electric charge. (*We also saw an excellent account of this in the video, The Story of Electricity, Episode 1 – note, we'll watch the next two episodes too.*)

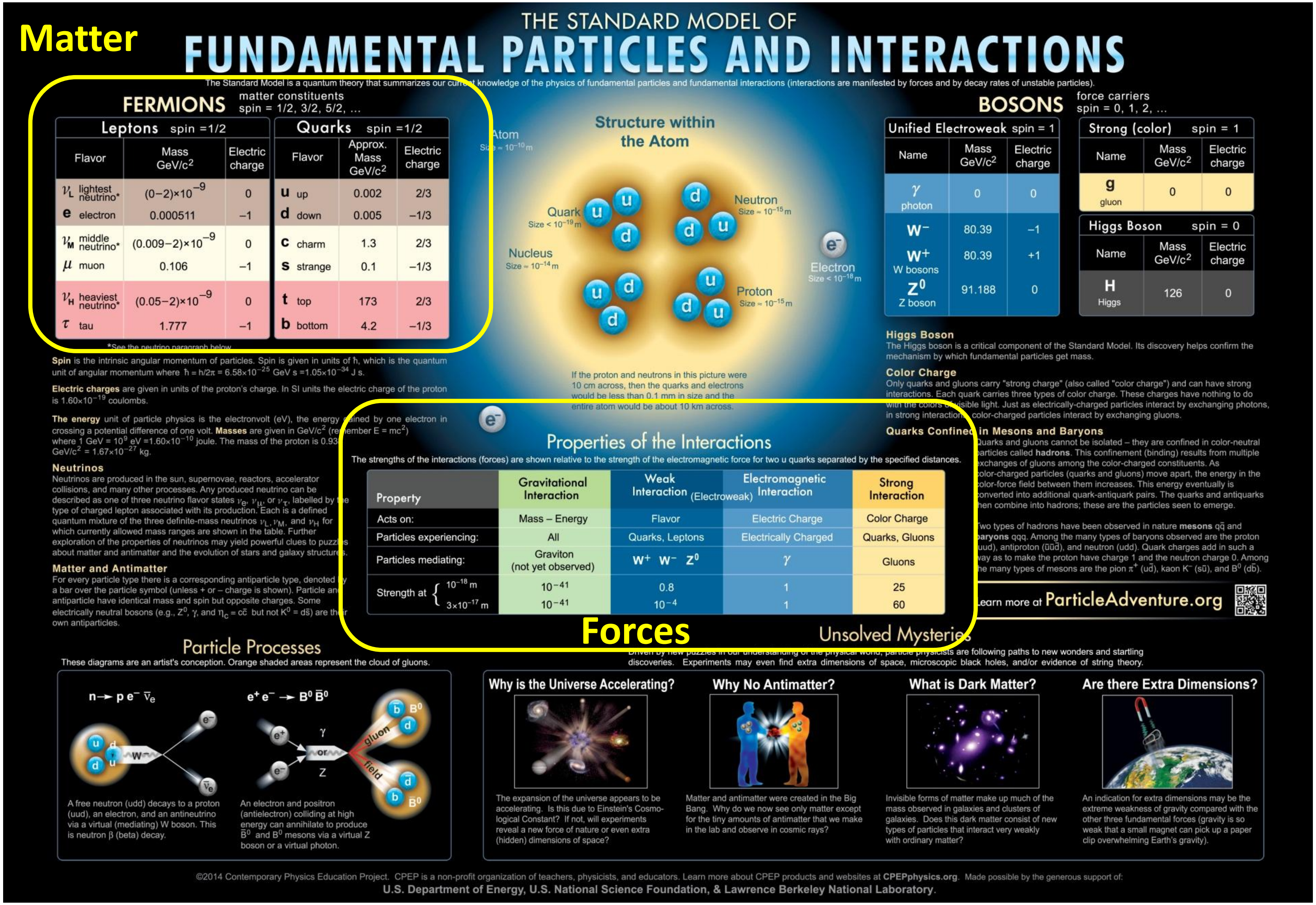
   Here is part of the discussion: **(comb & balloons)**

   From experiments like this, it was established that there are two types of electric charge, positive and negative, and that unlike charges attract each other and like charges repel. It was also found that material is of two types: conductors in which charge can freely move and insulators where the charge is stationary.

2. **The Technological Approach**: in the early 21st century, a huge part of our society runs on electricity and magnetism. We power, heat, and light our homes with it. We process information using electric currents in our computers and cell phones. Electromagnetic waves provide us virtually instant communication. **Amazingly, *all of this is done by carefully moving electrons around!***

3. **The Physics Approach:** **The Standard Model of Particle Physics**

The Standard Model of Particle Physics; a thorough, yet admittedly incomplete, summary of our state of knowledge about the nature of the stuff in the Universe



Details of this chart are at : http://www.cpepphysics.org/cpep_sm_large.html

The Elementary Particles and Fundamental Forces of the Standard Model

Matter Particles

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2			**Quarks** spin =1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0	**u** up	0.002	2/3
e electron	0.000511	−1	**d** down	0.005	−1/3
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0	**c** charm	1.3	2/3
μ muon	0.106	−1	**s** strange	0.1	−1/3
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0	**t** top	173	2/3
τ tau	1.777	−1	**b** bottom	4.2	−1/3

These twelve particles and their anti-particles are the fundamental building blocks of all the matter in the Universe *(although this is likely not the final word).*

Notice that, except for the neutrinos, all of these particles carry electric charge. Why?

No one really knows. Fundamental particles have certain properties like mass, charge, and spin that can't be changed.

The Four Fundamental Forces

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

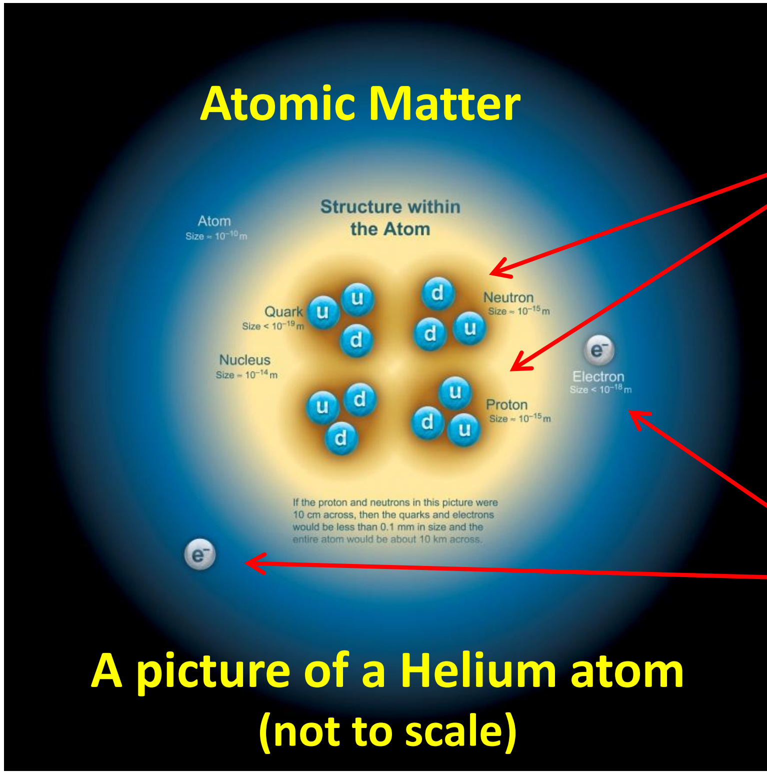
Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Elementary particles interact through four forces.

One of these is the Electromagnetic force. (note this is one word)

All of what we're going to do in the E&M part of PHY182 is because of this fundamental character of the Universe.

Wrapping things up from the Standard Model Chart



Up and down quarks bind through the **strong nuclear interaction** to form positive protons and neutral neutrons.

Neutrons and Protons bind also through the **strong interaction** to form atomic nuclei

Negative electrons bind to the positive nucleus through the **electromagnetic interaction** to make neutral atoms.

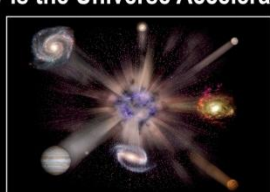
Some unanswered questions

(there are many many others)

Unsolved Mysteries

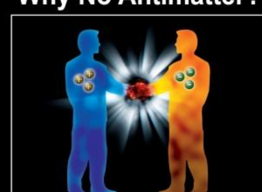
Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

Why is the Universe Accelerating?



The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?



Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

What is Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Are there Extra Dimensions?

An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces (gravity is so weak that a small magnet can pick up a paper clip overwhelming Earth's gravity).

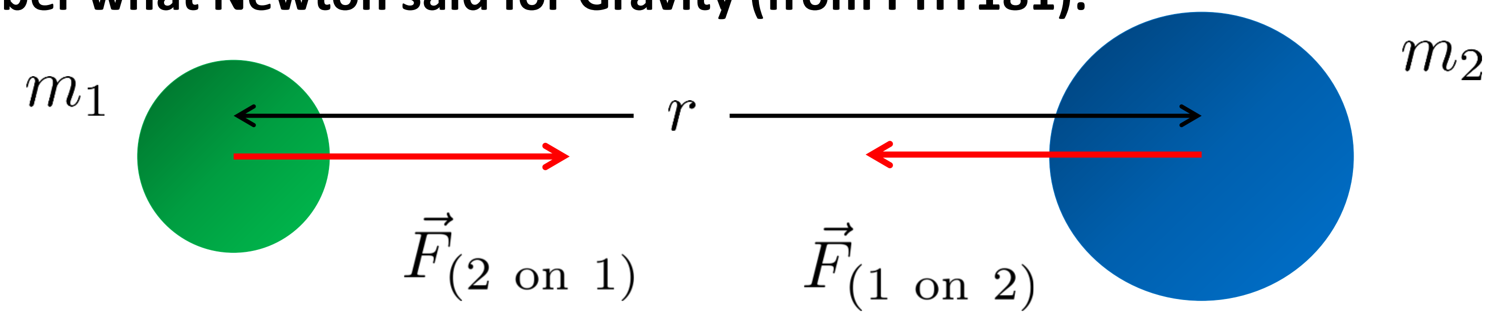
Coulomb's Law

In the late 18th century, the French scientist, Charles Coulomb, proposed the first quantitative description of the electric force between two charges.

Coulomb knew that there were both positive and negative charges and that unlike charges attracted while like charges repelled.

What did he use as a guide for the mathematical form for the force?

Remember what Newton said for Gravity (from PHY181):



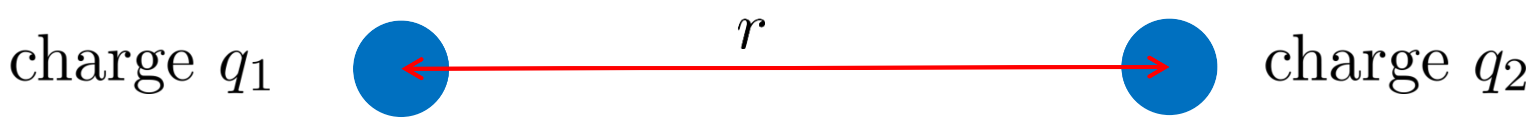
The Gravitational Force:

$$\vec{F}_{(2\ on\ 1)} = -\vec{F}_{(1\ on\ 2)} = \left\{ G\frac{m_1 m_2}{r^2}, \text{attractive} \right\}$$

Coulomb proposed something very similar for the electric force between two charges.

The Electric Force Between Two Charges

(Coulomb's Law)



Electric Force Magnitude:

$$F_{(2\ on\ 1)} = F_{(1\ on\ 2)} = K\frac{|q_1||q_2|}{r^2}$$

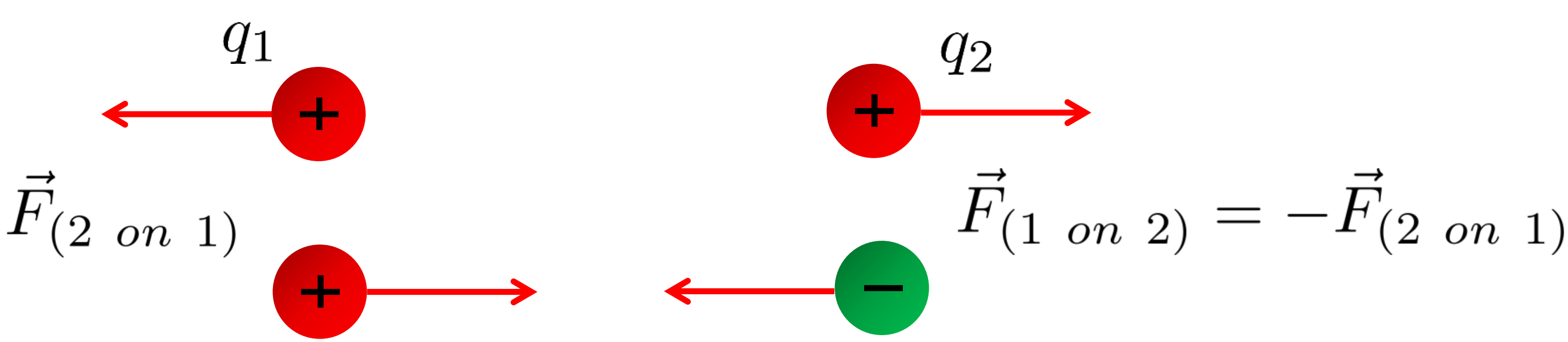
Where: q_1 and q_2 are charge in Coulombs (C)

$$K = \text{Coulomb Constant}^* = 8.99 \times 10^9\ \frac{Nm^2}{C^2}$$

Store K in your calculator

Note this equation gives only the magnitude of the electric force. The direction is along the line between the charges and is assigned by hand based on the signs of the charges.

e.g.



*Sometimes, we'll see this in a different form: $K = \frac{1}{4\pi\epsilon_0}$

Whiteboard Problem: 22-1

Two protons are 2.0 fm apart, about the distance between protons in an atomic nucleus.

a) **What is the magnitude of the electric force on one proton due to the other proton. For something really crazy, give your answer in pounds. (LC)**

b) What holds the nucleus together – maybe gravity? What is the magnitude of the gravitational force on one proton due to the other proton? **(LC)** Is the gravitational force stronger than the electric force?

(proton mass and G are on our constants sheet)

$F_E \sim 10^{36}\ F_G$

Note: the fundamental unit of charge is $e = 1.6 \times 10^{-19}\ C$

proton charge $= +e$ and the electron charge $= -e$

Store e in your calculator

So why doesn't the nucleus just fly apart?

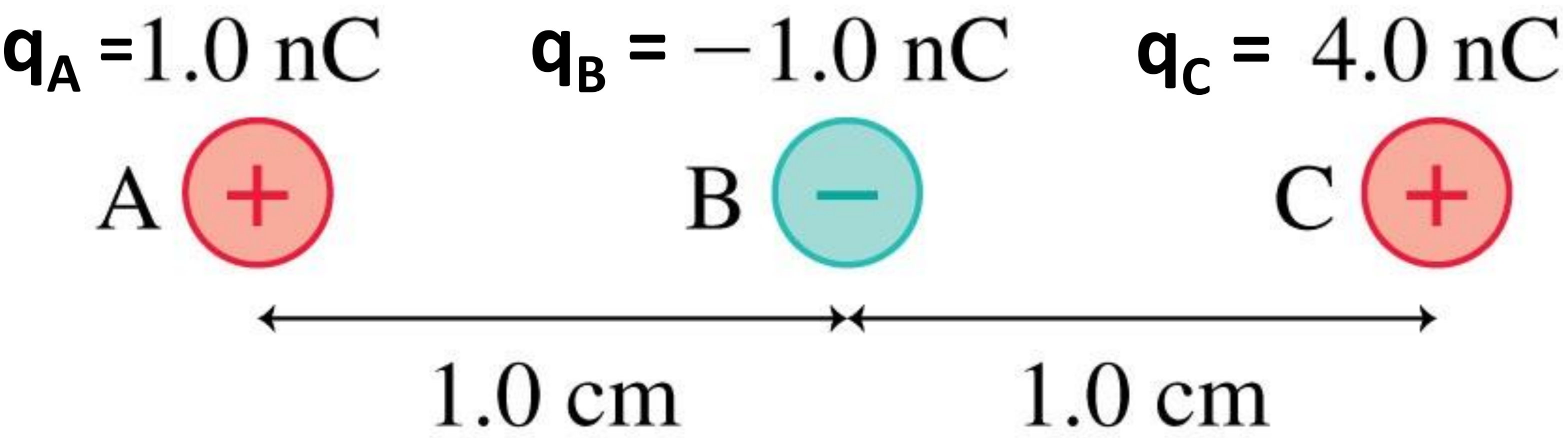
The Strong Nuclear Force is a force of attraction between all nucleons (protons and neutrons); it is very strong, but has a very short range. It holds the nucleus together.

By the way: someone should be asking a question about now. Why did the balloon stick to the wall? Only the balloon was charged – the wall was uncharged!

PhET balloon

Whiteboard Problem: 22-2

What is the **magnitude** of the net electric force on charge A? **(LC)**



Note: $1\ nC = 1 \times 10^{-9}\ C$

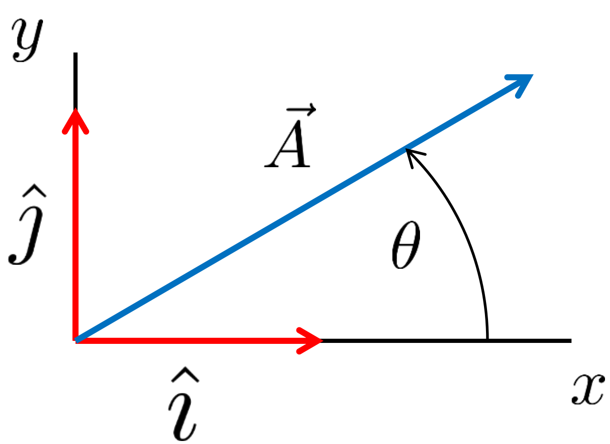
In this problem, to get the net force on charge A, you had to account correctly for direction of the two forces. How did you do this?

Maybe we should use vectors.

Review of Vectors

(it's been a while since we used vectors, you may want to go back and look at Chap 3)

We'll find rather quickly that **everything we do in our study of E&M will involve vectors**. Here are some vector topics from PHY181 that **you absolutely must know**:



A vector has both magnitude and direction:

$$\vec{A} = \{A, \theta \text{ ccw from the } +\text{x axis}\}$$

$$A \text{ (or } |\vec{A}|) = \text{magnitude (always} \geq 0)$$

Vector Components:
(with respect to some coordinate system)

$$\vec{A} = A_x\hat{\imath} + A_y\hat{\jmath} \quad = A\cos\theta\hat{\imath} + A\sin\theta\hat{\jmath}$$

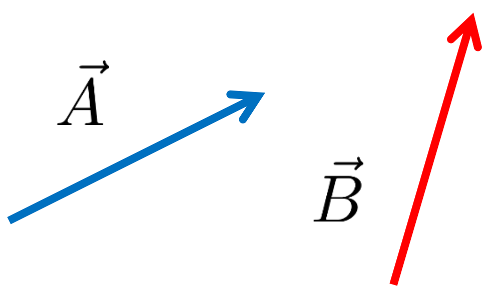
$$\text{where: } \left\{ \begin{array}{c} \hat{\imath} \\ \hat{\jmath} \end{array} \right\} \text{ are unit vectors in } \left\{ \begin{array}{c} +x \text{ direction} \\ +y \text{ direction} \end{array} \right\}$$

Magnitude and Direction from Components:

$$A = |\vec{A}| = \sqrt{A_x^2 + A_y^2} \qquad \theta = \tan^{-1}\left(\frac{A_y}{A_x}\right)$$

Review of Vectors

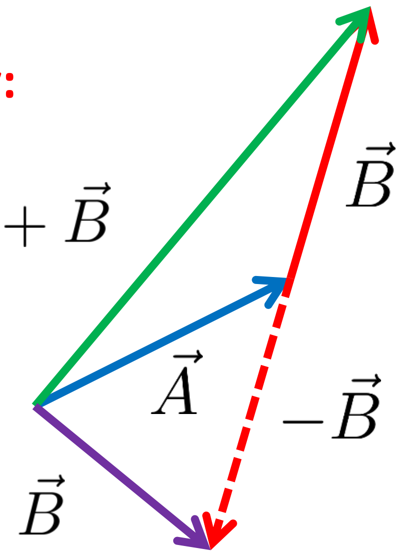
You must know how to add and subtract vectors both **graphically** and **analytically:**



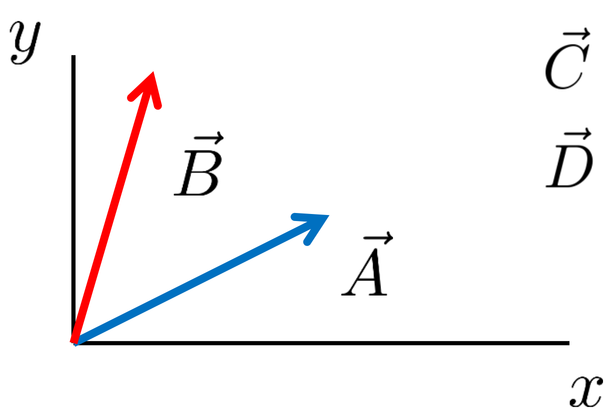
Graphically:

$$\vec{C} = \vec{A} + \vec{B}$$

$$\vec{D} = \vec{A} - \vec{B}$$



Or, analytically in terms of components:



$$\vec{C} = \vec{A} + \vec{B} = (A_x + B_x)\hat{\imath} + (A_y + B_y)\hat{\jmath}$$

$$\vec{D} = \vec{A} - \vec{B} = (A_x - B_x)\hat{\imath} + (A_y - B_y)\hat{\jmath}$$

We'll review the "dot product" and the "cross product" when we need them.

Whiteboard Problem: 22-3

For the vectors: $\vec{A} = 4\hat{\imath} - 2\hat{\jmath}$ and $\vec{B} = -3\hat{\imath} + 5\hat{\jmath}$.

a) Find the components of the vector $\vec{F}$ where $\vec{F} = \vec{A} - 4\vec{B}$. **(LC)**

b) What are the magnitude and direction of $\vec{F}$? Give the angle as measured CCW from the $+x$ axis. **(LC, angle only)**

Instructions for entering a vector in component form on LC:

For the vector:

$$\vec{E} = -5.32 \times 10^4 \hat{\imath} + 1.78 \times 10^3 \hat{\jmath}$$

Use only two significant figures and the pull down menu for powers of ten if necessary; put the components in parentheses, and use just i and j for unit vectors – no hats!

For the vector above, enter: **(-5.3 · 10^4)i + (1.8 · 10^3)j**

PROBLEM-SOLVING STRATEGY 22.1

These Steps are Really Important!

Electrostatic forces and Coulomb's law

(name them, 1,2,3, etc. or A, B, C, etc.)

MODEL Identify point charges or model objects as point charges.

VISUALIZE Use a *pictorial representation* to establish a coordinate system, show the positions of the charges, show the force vectors on the charges, define distances and angles, and identify what the problem is trying to find. This is the process of translating words to symbols.

SOLVE The mathematical representation is based on Coulomb's law:

$$F_{1\text{ on }2} = F_{2\text{ on }1} = \frac{K|q_1||q_2|}{r^2}$$

(magnitude only)

(draw them on your diagram)

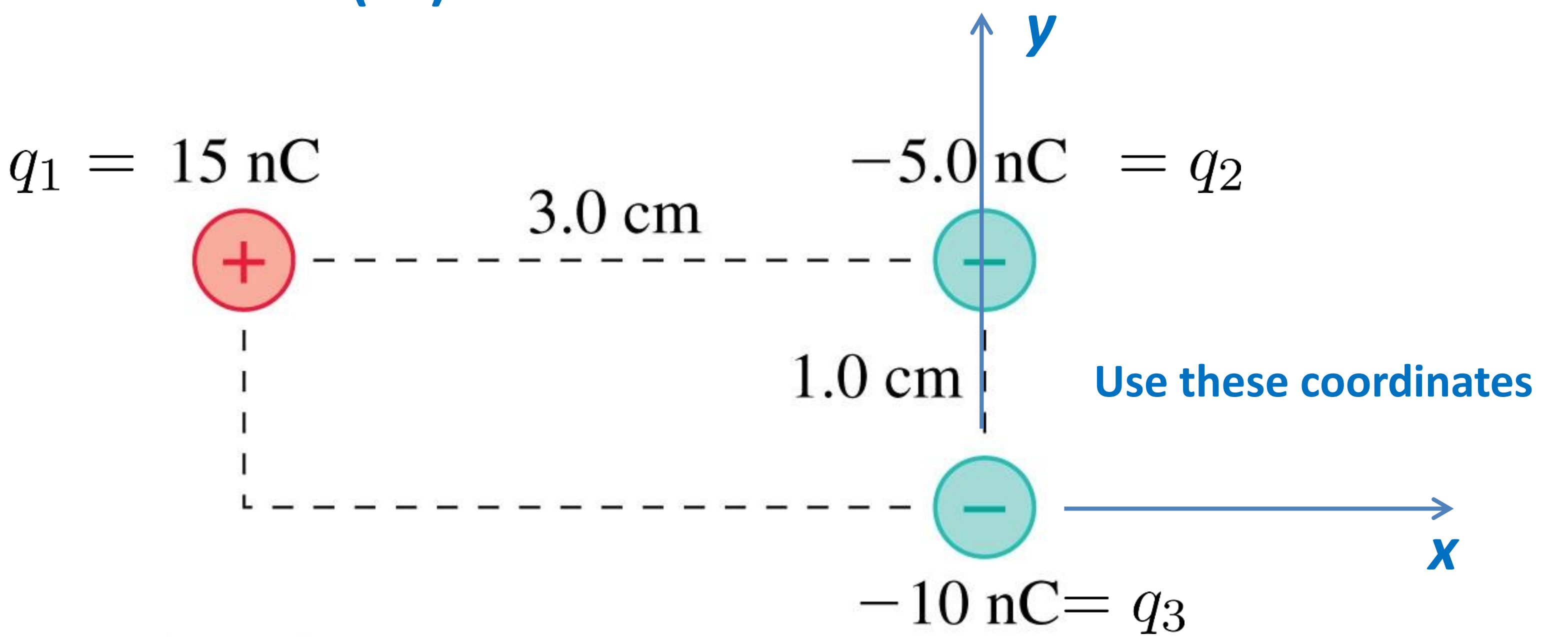
- Show the directions of the forces—repulsive for like charges, attractive for opposite charges—on the pictorial representation.
- When possible, do graphical vector addition on the pictorial representation. While not exact, it tells you the type of answer you should expect.
- Write each force vector in terms of its *x*- and *y*-components, then add the components to find the net force. Use the pictorial representation to determine which components are positive and which are negative.

ASSESS Check that your result has correct units and significant figures, is reasonable, and answers the question.

Exercise 26

Whiteboard Problem: 22-4

What is the **net force** on the charge **q_3 = -10 nC** in the figure? **Using the coordinates shown, find the force vector in component form.** **(LC)**



How NOT to do this problem:

$$F_{(2\ on\ 3)} = \frac{Kq_2q_3}{(.01\ m)^2} = 4.495 \times 10^{-3}\ N$$

$$F_{(1\ on\ 3)} = \frac{Kq_1q_3}{(.0316\ m)^2} = 1.348 \times 10^{-3}\ N$$

$$\text{So: } F_{\text{Total}} = F_{(2\ on\ 3)} + F_{(1\ on\ 3)} = 5.84 \times 10^{-3}\ N$$

What's wrong with this?

It's trying to add two vectors by adding their magnitudes!

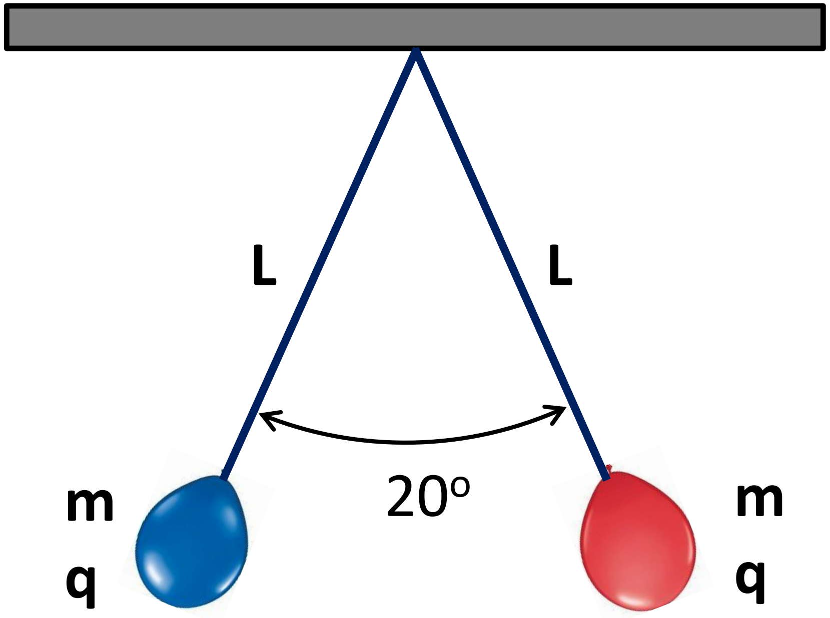
Do this right by following the steps on the previous slide.

Whiteboard Problem: 22-5; Amy's Problem

So, what does Amy do now?

The two balloons shown below have been charged by rubbing them with rabbit's fur for the same amount of time so that we can assume that they have identical charge.

The mass of each balloon is m = 0.2 grams and the length of the massless strings is L = 0.7 m. Assuming that the balloons carry the same charge, q, calculate q. (LC)



Important Hint:

Draw a Freaking Free Body Diagram of one of the balloons!