

# 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 21<sup>st</sup> 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

## Matter

# THE STANDARD MODEL OF FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

### FERMIONS

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

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ lightest neutrino*	$(0-2) \times 10^{-9}$	0	<b>u</b> up	0.002	2/3
<b>e</b> electron	0.000511	-1	<b>d</b> down	0.005	-1/3
$\nu_\mu$ middle neutrino*	$(0.009-2) \times 10^{-9}$	0	<b>c</b> charm	1.3	2/3
$\mu$ muon	0.106	-1	<b>s</b> strange	0.1	-1/3
$\nu_\tau$ heaviest neutrino*	$(0.05-2) \times 10^{-9}$	0	<b>t</b> top	173	2/3
$\tau$ tau	1.777	-1	<b>b</b> bottom	4.2	-1/3

\*See the neutrino paragraph below.

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum where  $\hbar = h/2\pi = 6.58 \times 10^{-25}$  GeV s =  $1.05 \times 10^{-34}$  J s.

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

**The energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c<sup>2</sup> (remember  $E = mc^2$ ) where  $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10}$  joule. The mass of the proton is  $0.938 \text{ GeV}/c^2 = 1.67 \times 10^{-27}$  kg.

#### Neutrinos

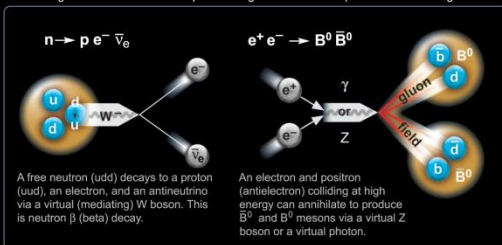
Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states  $\nu_e$ ,  $\nu_\mu$ , or  $\nu_\tau$ , labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos  $\nu_1$ ,  $\nu_2$ , and  $\nu_3$  for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structure.

#### Matter and Antimatter

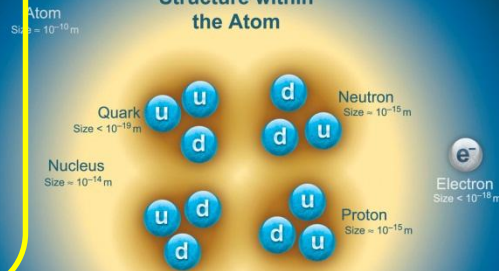
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.,  $Z^0$ ,  $\gamma$ , and  $\eta_c = c\bar{c}$  but not  $K^0 = d\bar{s}$ ) are their own antiparticles.

### Particle Processes

These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.



### Structure within the Atom



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

### BOSONS

force carriers  
spin = 0, 1, 2, ...

Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge	Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0	<b>g</b> gluon	0	0
$W^-$	80.39	-1	<b>Higgs Boson spin = 0</b>		
$W^+$	80.39	+1	Name	Mass GeV/c <sup>2</sup>	Electric charge
$Z^0$	91.188	0	<b>H</b> Higgs	126	0

#### Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.

#### Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

#### Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated -- they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature: mesons  $q\bar{q}$  and baryons  $qqq$ . Among the many types of baryons observed are the proton (uud), antiproton ( $\bar{u}\bar{u}\bar{d}$ ), and neutron (udd). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion  $\pi^+$  (u $\bar{d}$ ), kaon  $K^0$  (s $\bar{d}$ ), and  $B^0$  (db).

Learn more at [ParticleAdventure.org](http://ParticleAdventure.org)



### 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.

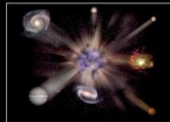
Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass - Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	$W^+$ $W^-$ $Z^0$	$\gamma$	Gluons
Strength at				
$10^{-16}$ m	$10^{-41}$	0.8	1	25
$3 \times 10^{-17}$ m	$10^{-41}$	$10^{-4}$	1	60

## Forces

## Unsolved Mysteries

Content of 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).

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U.S. Department of Energy, U.S. National Science Foundation, & Lawrence Berkeley National Laboratory.

Details of this chart are at : [http://www.cpepphysics.org/cpep\\_sm\\_large.html](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, ...					
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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

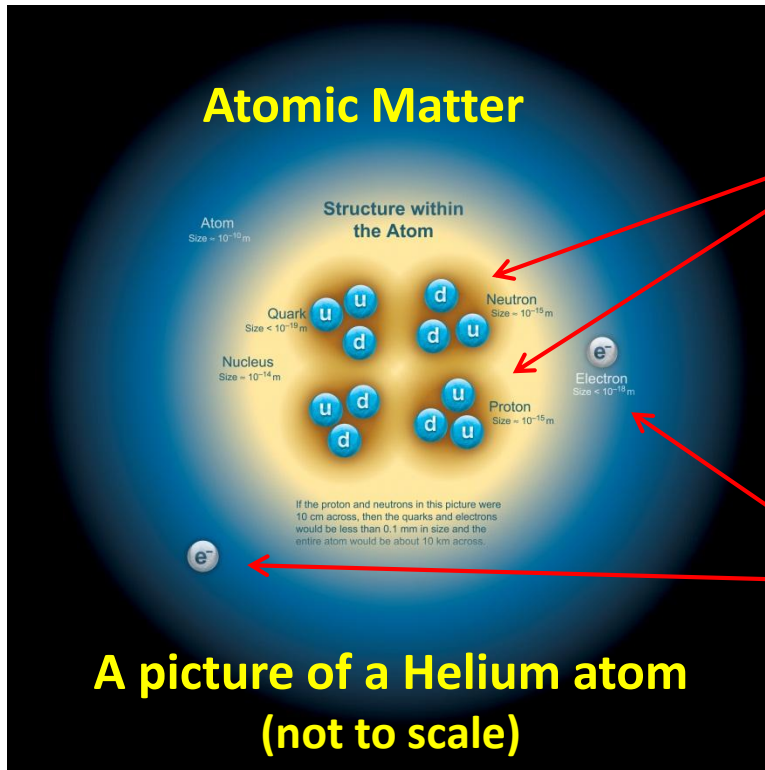
Properties of the Interactions				
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two particles separated by the specified distances.				
Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong 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)	$W^+$ $W^-$ $Z^0$	$\gamma$	Gluons
Strength at $\left\{ \begin{array}{l} 10^{-18} \text{ m} \\ 3 \times 10^{-17} \text{ m} \end{array} \right.$	$10^{-41}$ $10^{-41}$	0.8 $10^{-4}$	1 1	25 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

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# Coulomb's Law

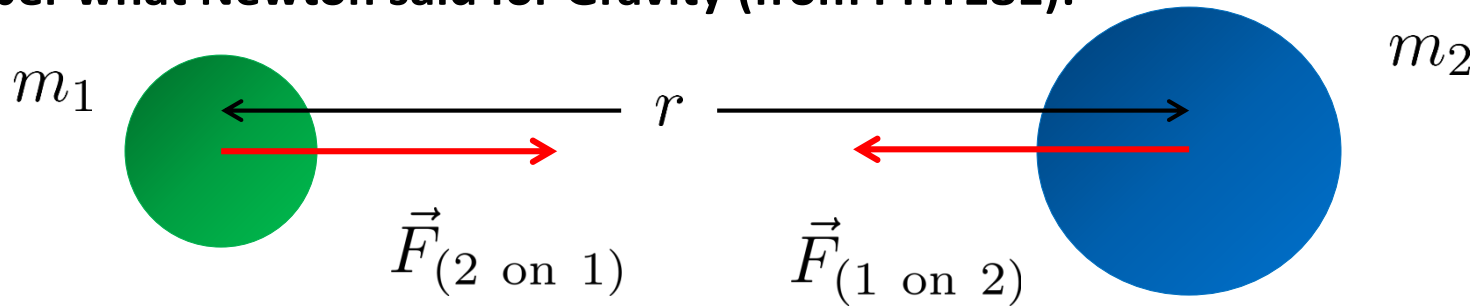
In the late 18<sup>th</sup> century, the French scientist, Charles Coulomb, proposed the first quantitative description of the **electric force between two charges**.

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):**

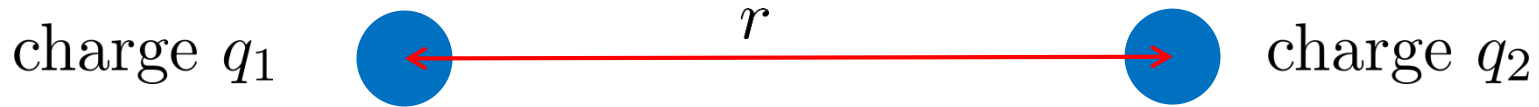


**The Gravitational Force:**

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

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

# The Electric Force Between Two Charges (Coulomb's Law)



Electric Force Magnitude:

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

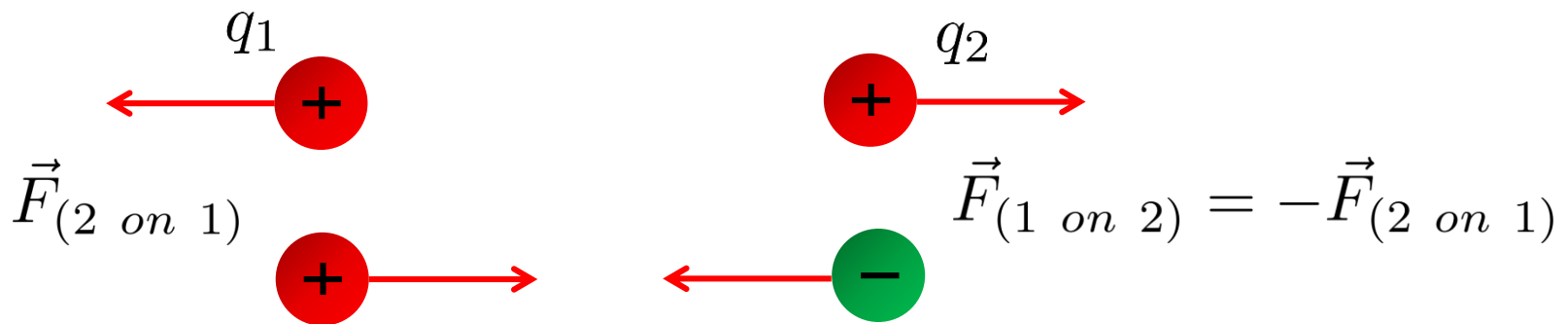
Where:  $q_1$  and  $q_2$  are charge in Coulombs (C)

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

*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?  $F_E \sim 10^{36} F_G$   
(proton mass and G are on our constants sheet)

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

**So why doesn't the nucleus just fly apart?**

*Store  $e$  in your calculator*

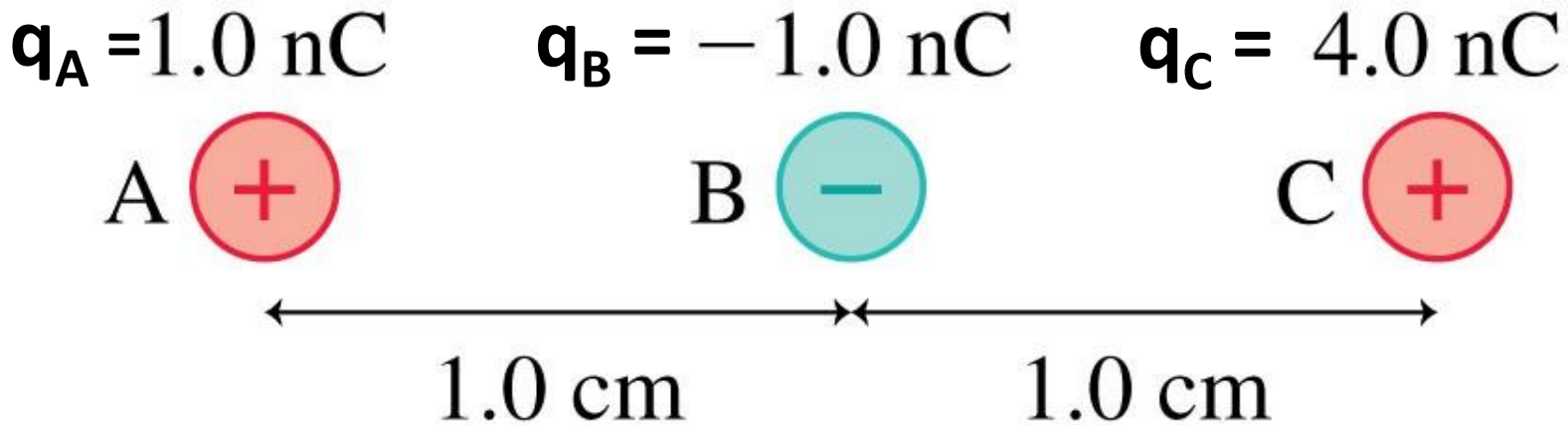
**The Strong Nuclear Force** is a force of attraction between all nucleons (protons and neutrons); it is very strong, but has a very short range. It holds the nucleus together.

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

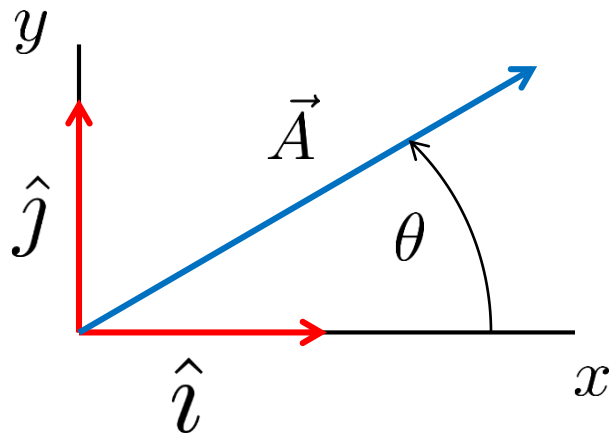
*In this problem, to get the net force on charge A, you had to account correctly for direction of the two forces. How did you do this?*

***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:**

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

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

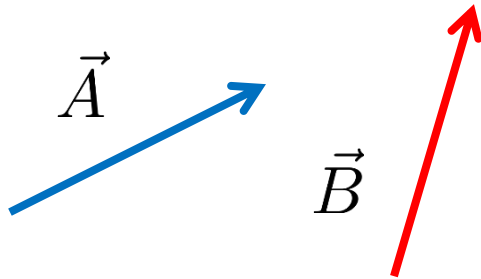
**Vector Components:**  $\vec{A} = A_x \hat{i} + A_y \hat{j} = A \cos \theta \hat{i} + A \sin \theta \hat{j}$   
(with respect to some coordinate system) where:  $\left\{ \begin{array}{c} \hat{i} \\ \hat{j} \end{array} \right\}$  are unit vectors in  $\left\{ \begin{array}{l} +x \text{ direction} \\ +y \text{ direction} \end{array} \right\}$

**Magnitude and Direction from Components:**

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

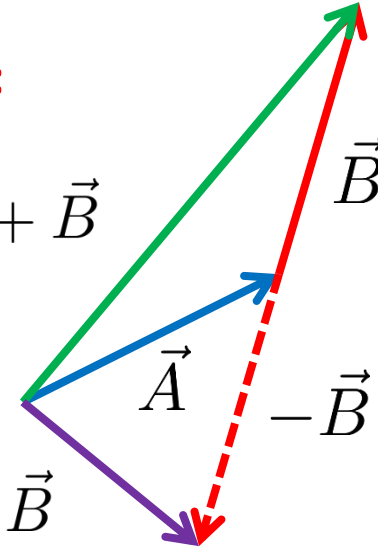
# Review of Vectors

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



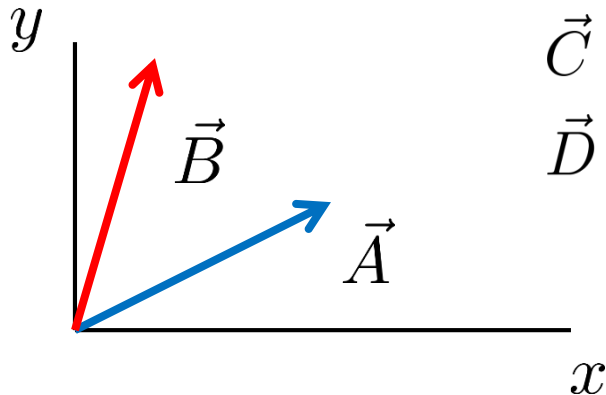
**Graphically:**

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



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

**Or, analytically in terms of components:**



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

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

*We'll review the "dot product" and the "cross product" when we need them.* 10

# Whiteboard Problem: 22-3

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

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:

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

**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:  $(-5.3 \cdot 10^4)\mathbf{i} + (1.8 \cdot 10^3)\mathbf{j}$

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:

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

(draw them on your diagram)

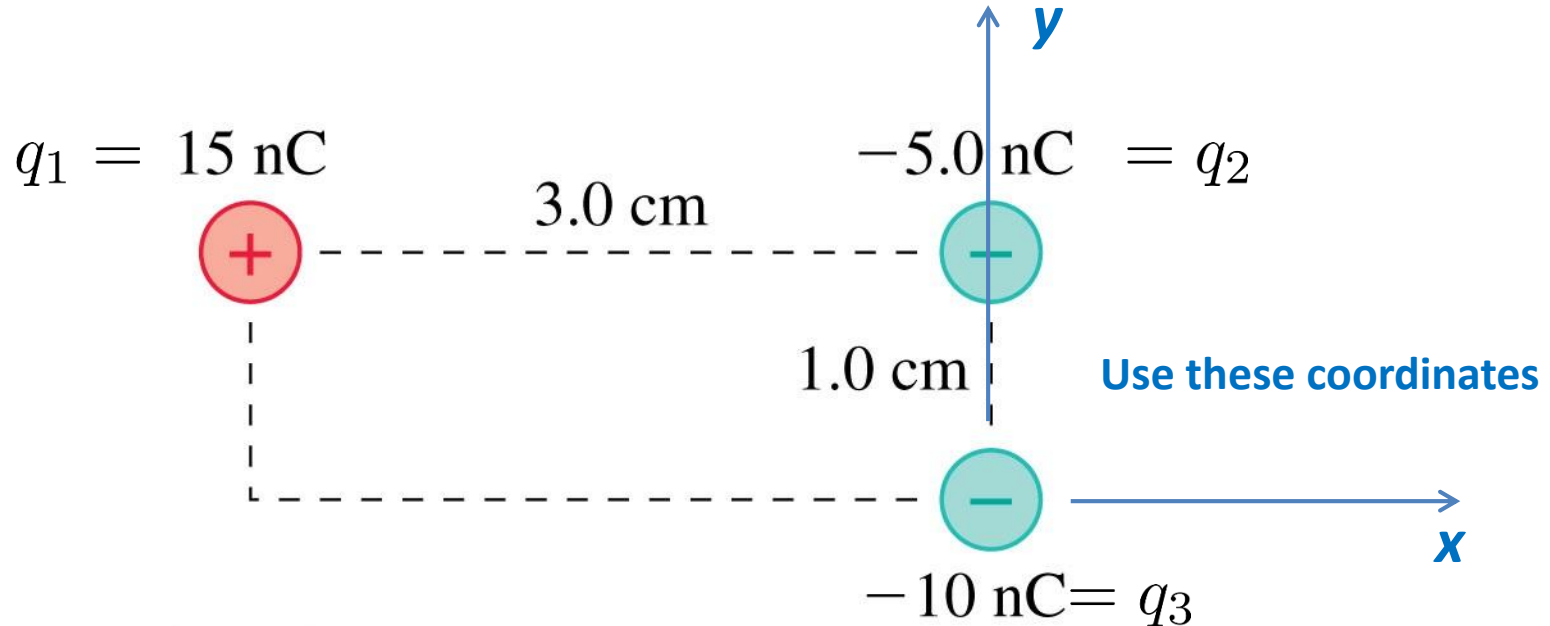
- Show the directions of the forces—repulsive for like charges, attractive for opposite charges—on the pictorial representation.
- When possible, do graphical vector addition on the pictorial representation. While not exact, it tells you the type of answer you should expect.
- Write each force vector 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.



# Whiteboard Problem: 22-4

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



**How NOT to do this problem:**

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

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

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

**What's wrong with this?**

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

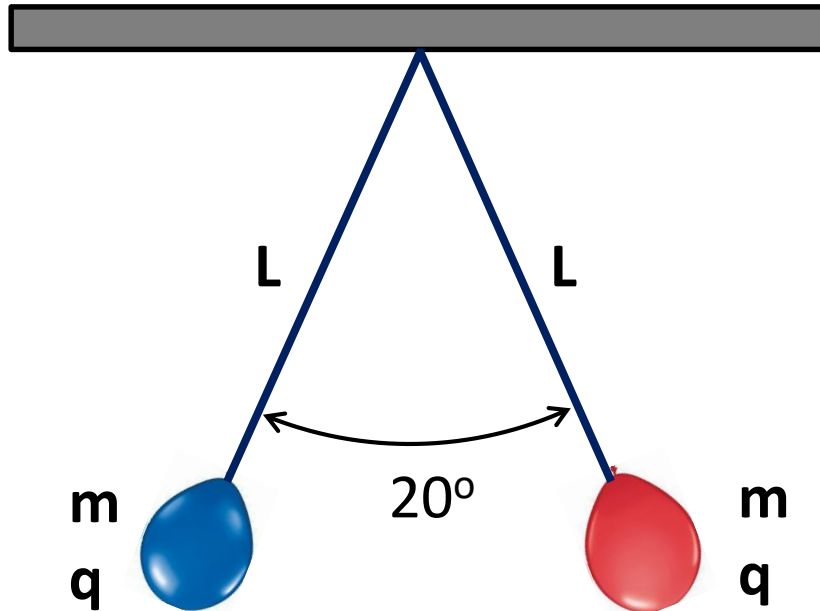
**Do this right by following the steps on the previous slide.**

# 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!**