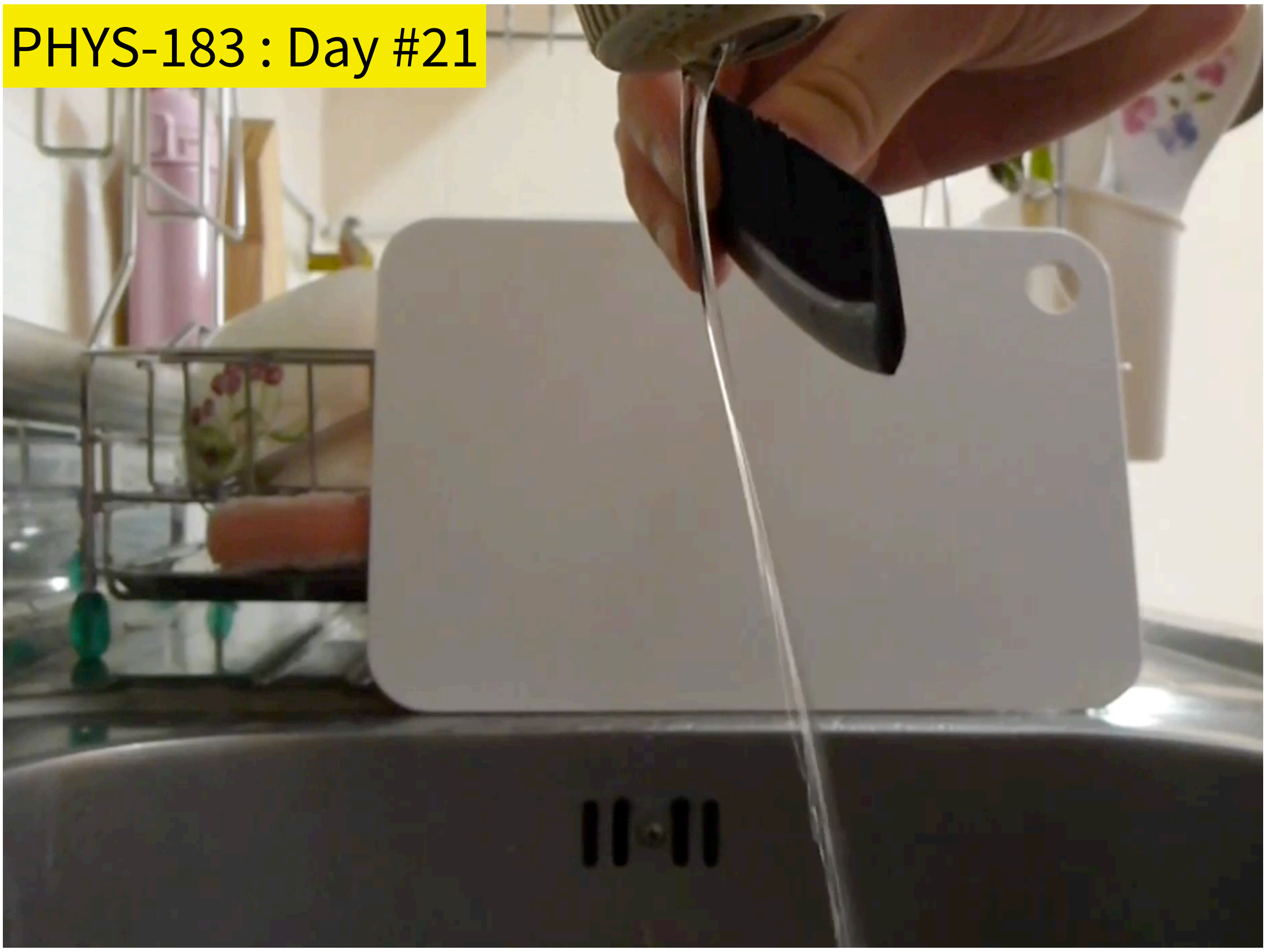


Electromagnetism:

One of the 4 fundamental forces in nature:

Gravity	Newton (1687) + Einstein (1915)
EM	Maxwell (1860)
Weak	Fermi (1930)
Strong	Feynman, Gross, Politzer, Wilczek(1970)

- Gravity always around but hard to think about.
- EM effects much more evident: lighting, magnets, sparks from clothing,...
- Known since at least 3000bc (Egyptians) via electric eels
- Electricity comes from the greek word Elecktron (Amber) "from the sun"

→ Electromagnetism, electron, electronics,...

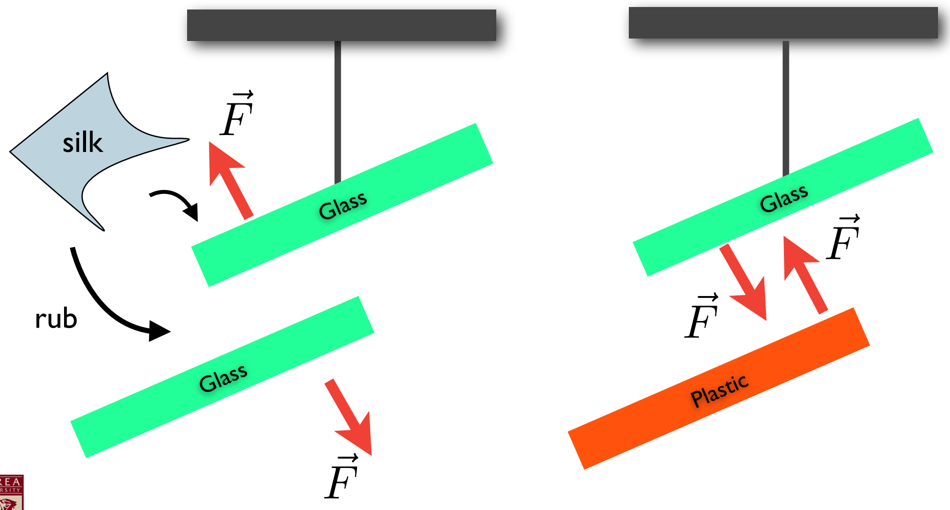

Piece of Amber

- Connection between electricity and magnetism not until 1820 from Oerstad.
- Now everything takes advantage of electromagnetism
  - Entire output of the world connected to EM

Electric Charge

- Every object contains <u>electric charge.</u>
- Charge is a fundamental property of the material out of which everything is made, just like mass.
- Everyday objects have vast amounts of charge
- The properties of charges first determined experimentally

Simple experiment:



Rods of **any** material will always repel or attract

- Situation can be described by two different types of charge that are related by a minus sign:

Attractive forces → -

Repulsive forces → +

Charges with same sign repel; opposite charges attract

- Choice of +/- for charges is arbitrary. Determined by Benjamin Franklin ($100 guy)

Positive (+) charges

Negative (-) charges

Charges usually come in equal amounts (no <u>net</u> charge)

- Objects with no net charge are called neutral
- Have seen that objects can have net charge; determined types of charge
- How are charges distributed over objects?

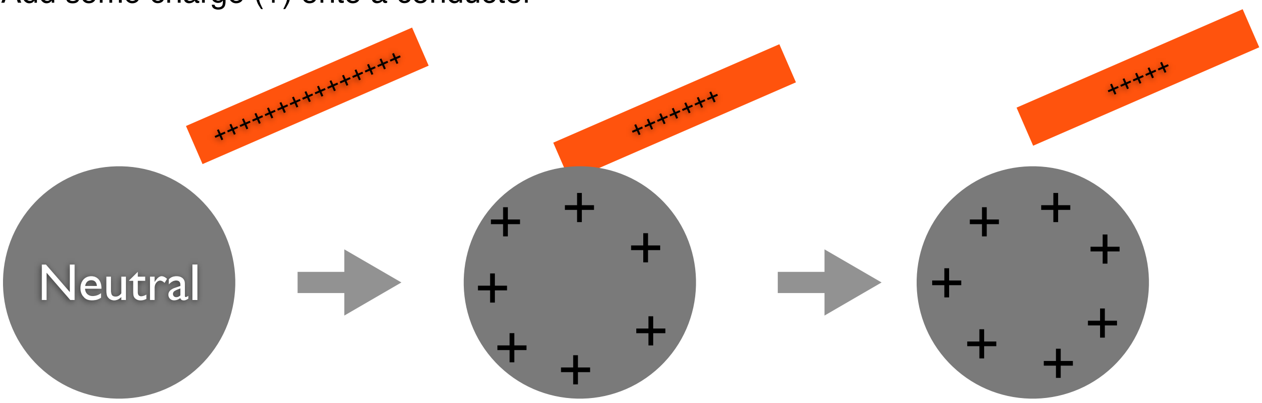
Conductors & Insulators

- Materials can be divided into 4 categories depending on how easily charges move:

Conductors: Charges move easily. i.e. metals, saltwater, people,...
Insulators: Charges cannot move. i.e. rubber, glass, plastics, pure H2O
Semiconductors: In between conductors and insulators. i.e. silicon, germanium
Superconductors: Charges move perfectly. i.e mercury@2k, <u>aluminum@1.2k</u>

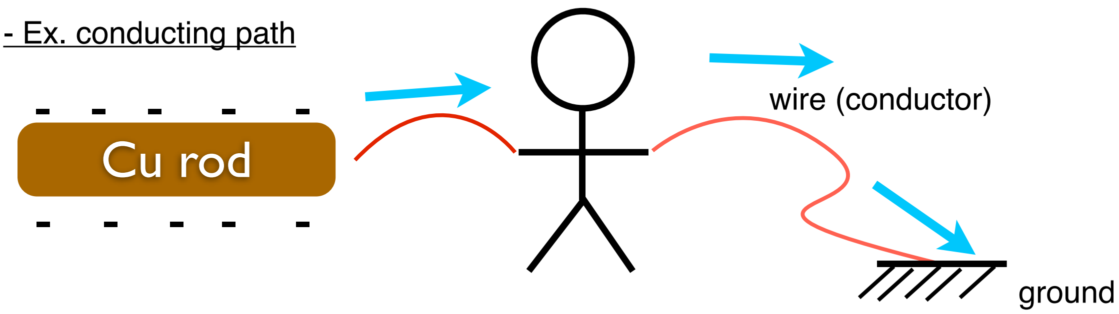
Conductors

- Charges move freely + like charges repel.
- Add some charge (+) onto a conductor



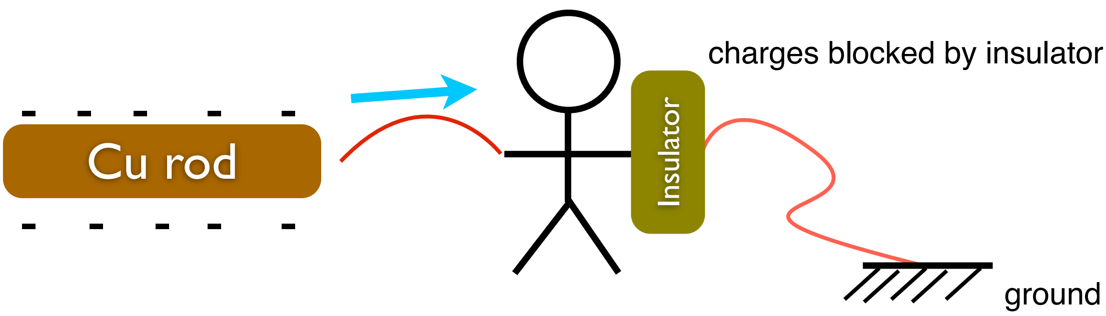
Charge spreads out over conductor to reach equilibrium

<u>- Ex. conducting path</u>

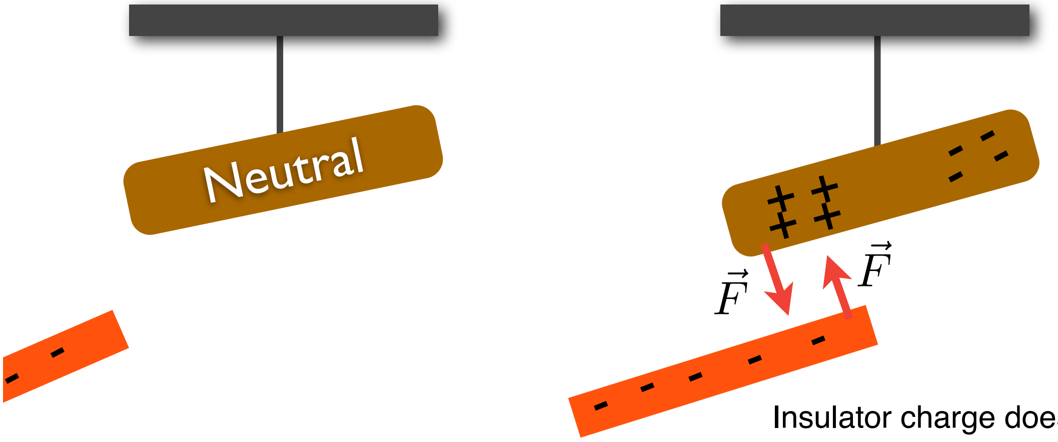


- Charge moves through conductors due to repelling force to ground
- Earth is a huge conductor... can always dump charge there.
    - Any conducting path connected to the Earth is called **grounded**

<u>- Ex. conducting path + insulator</u>



- Since charges move freely, can **induce** a charge on a conductor:

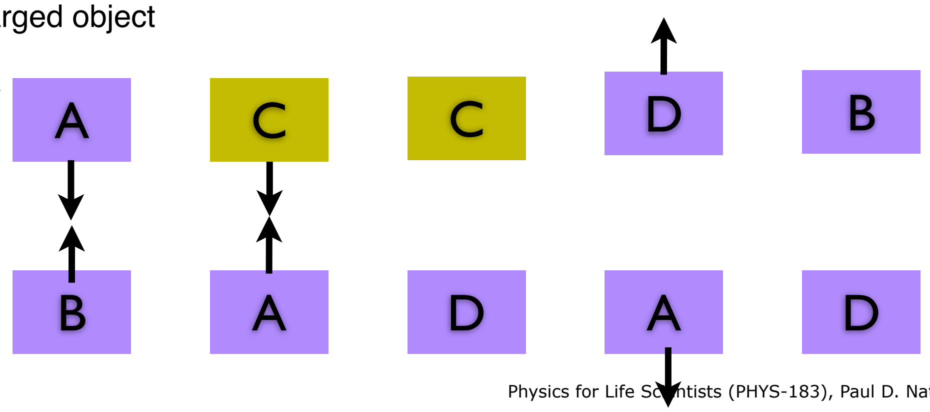


- Copper rod is neutral but had induced charge; positive and negative charges separated due to force from nearby charged object

<u>Conceptual Question:</u>

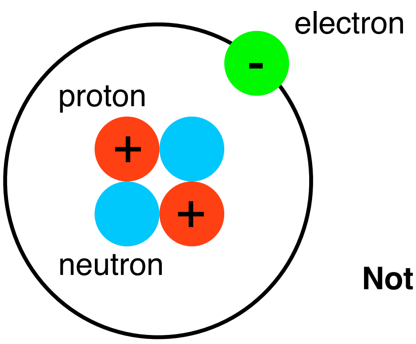
A,B,D charged plastic

C is neutral metal



<u>Where do charges come from?</u>

- Recall that charge is a fundamental property of matter.



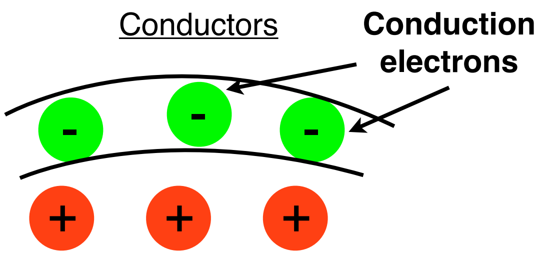
+ charges = protons

- charges = electrons

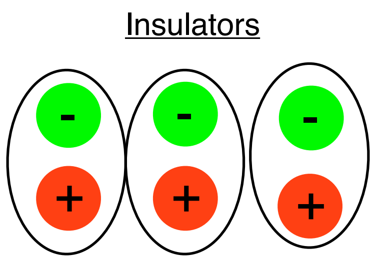
<u>1st guess:</u>

- Protons are the charges that move around

Not True! Only electrons are free to move in most materials



Electrons do not belong to single atom, spread out over surface



- Electrons tightly bound to nucleus, cannot move.

- None or few conduction electrons

Only way to get positive charge is to remove electrons such that:

\# of protons > # of electrons

$\boxed{\text{Positive charge implies deficit of electrons}}$

- Electrons are fundamental particles; they can not be subdivided (Thompson 1897)

Charge comes only in discrete units

charge → $q = n \cdot e \qquad n = \pm 1, 2, 3 \ldots$

"elementary charge" $e = 1.602 \times 10^{19}\mathrm{C}$ Coulombs

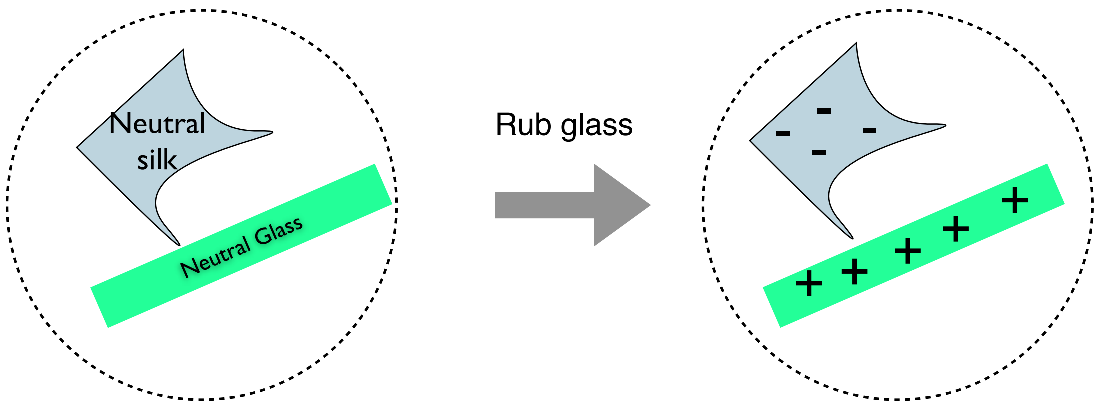
- Elementary charge e is a fundamental constant

$$e = 1.602 \times 10^{-19}\mathrm{C} \quad \Rightarrow \quad 1\mathrm{C} \approx 6.25 \times 10^{18}\mathrm{e}$$

7.5×10^{18} Grains of sand on the entire Earth!

Charge is a conserved quantity.

- Let's return to the silk + glass example.



No **net** charge | No **net** charge

- Charge is **not** created, just moved around
- True for any physical process.

Conservation of charge: The **net** charge of <u>any</u> isolated system cannot change.

- 4th conservation law encountered: Energy, Momentum, Angular Momentum, Charge
- Key word here is "net": Can create +/- charges in pairs; net charge is still zero.

Coulombs Law:

- We know everything there is to know about individual charges
- How do charges interact?
- Saw that charges exert forces on each other:

Opposite charges attract
Like charges repel

- Force between non-moving charges is called **Electrostatic Force.**
- Determined experimentally (like most of EM) by Coulomb (1785)

Coulomb's Law: Given two particles with charges q_1 and q_2, the resulting force is:

$$\vec{F} = k\frac{q_1 q_2}{r^2}\hat{r}$$

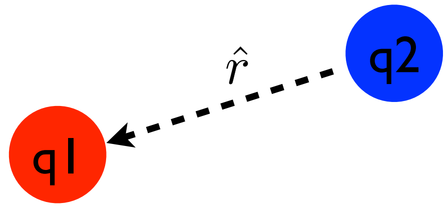
in radial direction

"electrostatic constant"

$$k = 9\times 10^9 \mathrm{C}^2/\mathrm{N}-\mathrm{m}^2$$

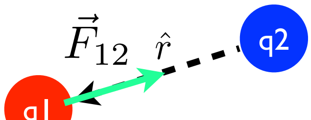
How to determine "radial direction"

Force of q2 on q1: $\vec{F}_{12}$



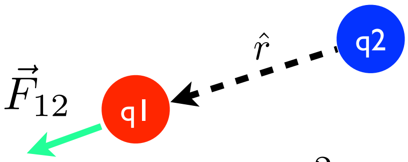
- Check for consistency:

$$q_1 = e \quad ; \quad q_2 = -e$$



$$\vec{F}_{12} = \frac{-ke^2}{r^2}\hat{r}$$

$$q_1 = e \quad ; \quad q_2 = e$$



$$\vec{F}_{12} = \frac{ke^2}{r^2}\hat{r}$$

Connection between EM and Gravity:

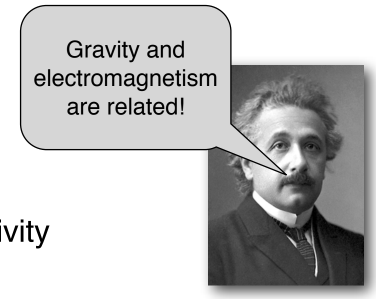
$$\vec{F}_{\mathrm{EM}} = k\frac{q_1 q_2}{r^2}\hat{r}$$ Coulomb's Law

$$\vec{F}_{\mathrm{G}} = G\frac{m_1 m_2}{r^2}\hat{r}$$ Newton's Law

-Both equations have same form:

- 1/r^2 spatial dependence
- interactions correspond to products of particle properties; charges for Coulomb, and masses for Newton's law.
- Both laws has a fundamental constant

- Amazing! Why should Gravity and EM follow same force law?
  - Hints at a deeper connection
  - This connection used by Einstein in formulating relativity



<u>- Ex. force of gravity vs. EM force:</u>

- Let us compare the force of gravity between an electron and a proton to the EM force.

- What is your guess? Which is stronger?

$$m_p = 1.67\times 10^{-27}\mathrm{Kg}$$
$$m_e = 9.11\times 10^{-31}\mathrm{Kg}$$
$$G = 6.67\times 10^{-11}\mathrm{m}^3/\mathrm{Kg}-\mathrm{s}^2$$

$$\frac{|F_{EM}|}{|F_G|} = \frac{k}{G}\frac{q_1 q_2}{m_1 m_2} = \frac{k}{G}\frac{e^2}{m_p m_e}$$

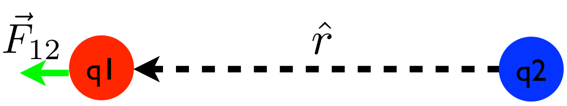
$$\frac{|F_{EM}|}{|F_G|} \approx \frac{9\cdot 10^{9} * 2\cdot 10^{-38}}{7\cdot 10^{-11}\times 2\cdot 10^{-27}\times 9\cdot 10^{-31}} = \frac{1}{7}\frac{10^{-29}}{10^{-68}} \approx \boxed{10^{39}}$$

- EM force is huge compared to gravity!

- As mentioned, objects nearly neutral, and mass of Earth is huge -> not noticed so much.

<u>Ex. force of between two charges</u>

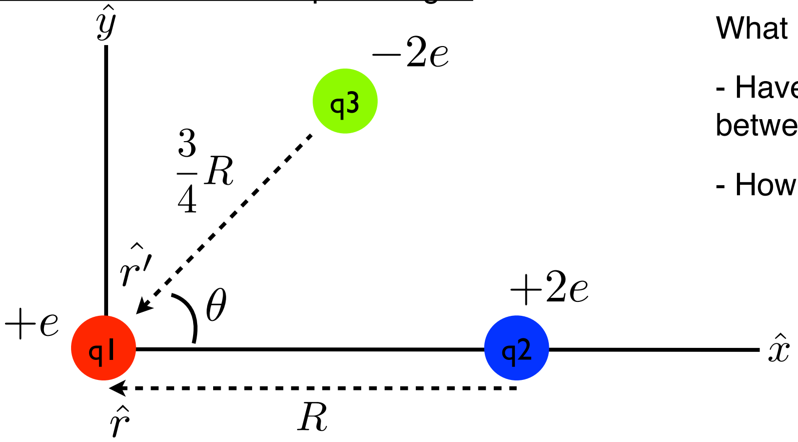
What is force on q1 from q2 when q1=e and q2=2e and separated by a distance of 4m?



$$\vec{F}_{12} = k\frac{q_1 q_2}{r^2}\hat{r} = k\frac{2e^2}{4}\hat{r} = \frac{ke^2}{2}\hat{r}$$

in $\hat{r}$ direction since both charges same sign

Ex. force between multiple charges



What is the **net** force on q1?

- Have only considered force between two charges

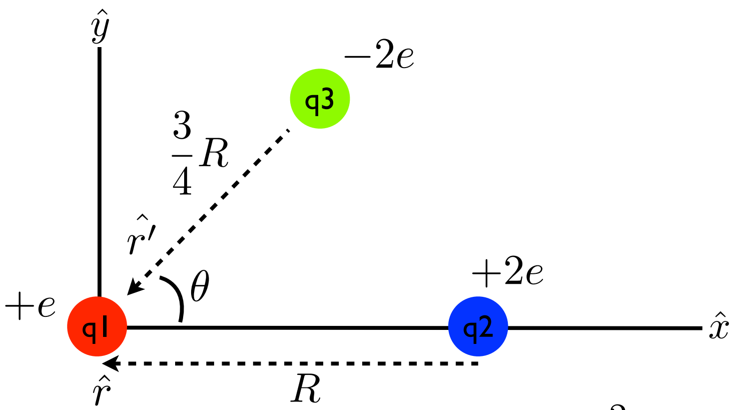
- How do we handle multiple particles?

- Because we know that $\vec{F}_{EM}$ has the same form as $\vec{F}_G$ we can borrow the concept of **superposition**:

The **net** force from a collection of charges on charge q1 is given by:

$$\vec{F}_{1,\text{net}} = \sum_{i=2}^{N} F_{1i}$$

Superposition principle is not obvious. But it is confirmed by experiments.



$$\vec{F}_{1,\text{net}} = \vec{F}_{12} + \vec{F}_{13}$$

- Find F12 (easy part first): $\vec{F}_{12} = k\frac{2e^2}{R^2}\hat{r} = -k\frac{2e^2}{R^2}\hat{x}$

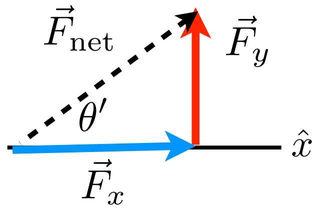
- F13: $\vec{F}_{13} = -k\frac{2e^2}{\left(\frac{3}{4}R\right)^2}\hat{r}'$

r' is not along x or y directions; must decompose into x and y pieces

$$\vec{F}_{13} = k\frac{16(2e^2)}{9R^2}\cos\theta\hat{x} + k\frac{16(2e^2)}{9R^2}\sin\theta\hat{y}$$

$$\boxed{\vec{F}_{1,\text{net}} = k\frac{(2e^2)}{R^2}\left[\frac{16}{9}\cos\theta - 1\right]\hat{x} + k\frac{16(2e^2)}{9R^2}\sin\theta\hat{y}}$$

-What is the angle θ' of the resulting force?



$$\tan\theta' = \frac{F_y}{F_x} \quad \Rightarrow \quad \theta' = \arctan\frac{F_y}{F_x}$$

$$\frac{F_y}{F_x} = \frac{16\sin\theta}{9\left(16/9\cos\theta - 1\right)}$$

$$\frac{F_y}{F_x} = \frac{\sin\theta}{\cos\theta - \frac{9}{16}}$$