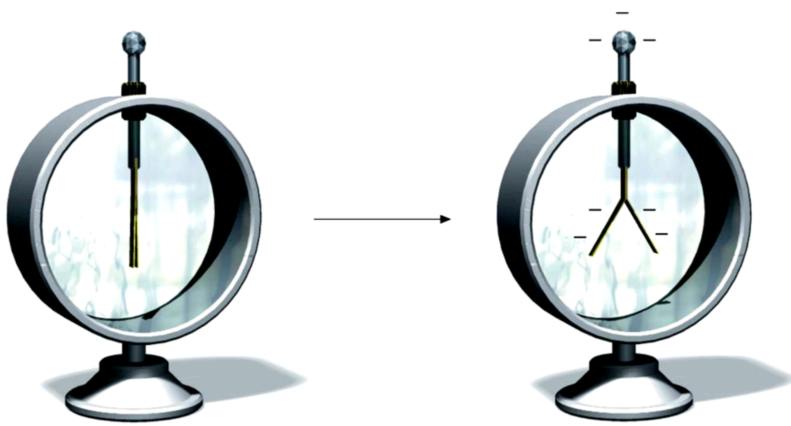
Physics 115
General Physics II

Session 15



Electric Charge
Coulomb's Law

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Lecture Schedule
(up to exam 2)

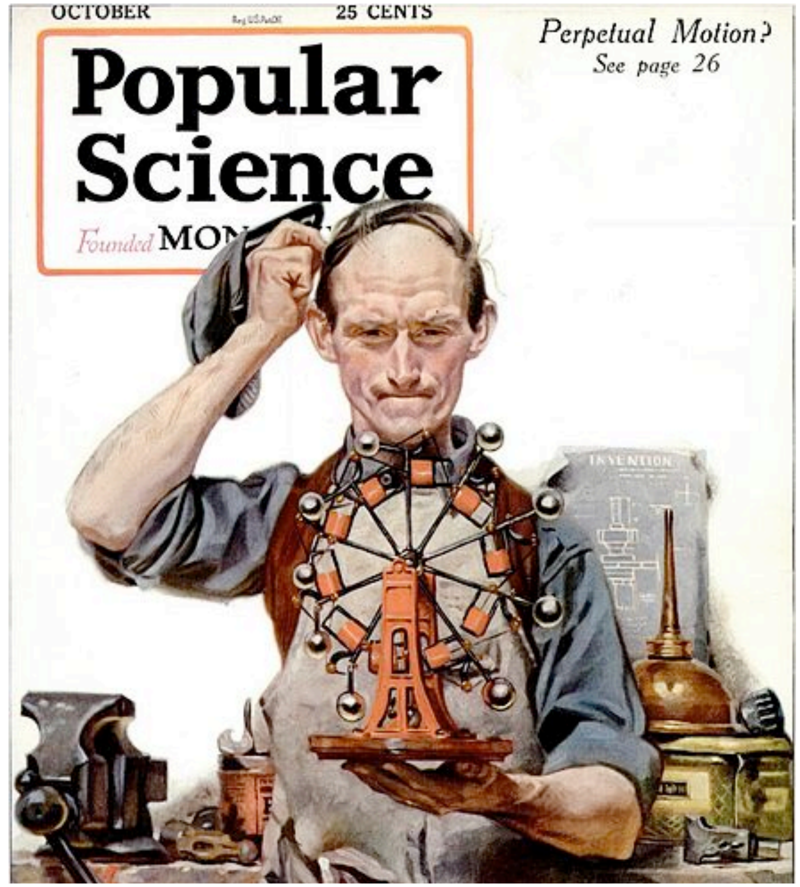
21-Apr	Mon	12	Specific Heats	18.4-18.6
22-Apr	Tues	13	Second Law	18.7-18.10
24-Apr	Thurs	14	Entropy	18.8-18.10
25-Apr	Fri	15	Charges	19.1-19.4
28-Apr	Mon	16	E field	19.5-19.66
29-Apr	Tues	17	Gauss law	19.7
1-May	Thurs	18	Electrical potential	20.1-20.3
2-May	Fri	19	Potential, conductors	20.4
5-May	Mon	20	Capacitors	20.5-20.6
6-May	Tues	21	Current	21.1-21.2
8-May	Thurs	22	Power, Series & Parallel Circuits	21.3-21.4
9-May	**Fri**		**EXAM 2 - Ch. 18,19,20**	

Today

Minor revisions to calendar – almost caught up...

About 'Perpetual Motion' Machines

People are constantly proposing "perpetual motion" machines that do useful work with no net energy consumed.



Inventors (whether innocent or charlatans) claim their devices

- Create energy, violating the 1st Law.
- "Completely eliminate" friction, so are 100% efficient, which violates the 2nd Law.

The 2nd Law means no engine can be 100% efficient converting energy flow to work.

Investment advice: don't

3rd Law of thermodynamics

- Notice that as we get close to 0 K, any heat removal requires enormous entropy change:

$$\Delta S = \frac{\Delta Q_T}{T}, \quad \Delta S \rightarrow \infty \text{ as } T \rightarrow 0$$

- 3rd Law: "It is impossible to cool an object to 0 K"
  - Lowest temperature so far achieved in lab is quite close! <100 pK (10^{-10} K) at Helsinki Technical U., Finland

BTW #1: what of news items about "negative absolute T" ?

This is about atomic spin population inversions, which are actually "hotter" than 0 K

See http://math.ucr.edu/home/baez/physics/ParticleAndNuclear/neg_temperature.html

BTW #2: Why you should be cautious using internet info sources:

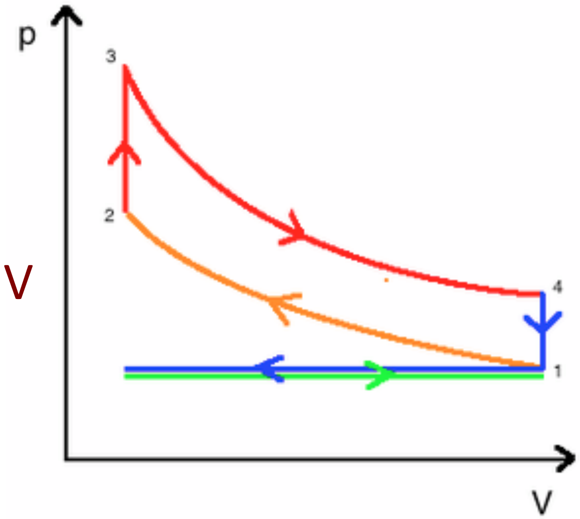
http://wiki.answers.com/Q/What_is_the_coldest_temperature_ever_achieved

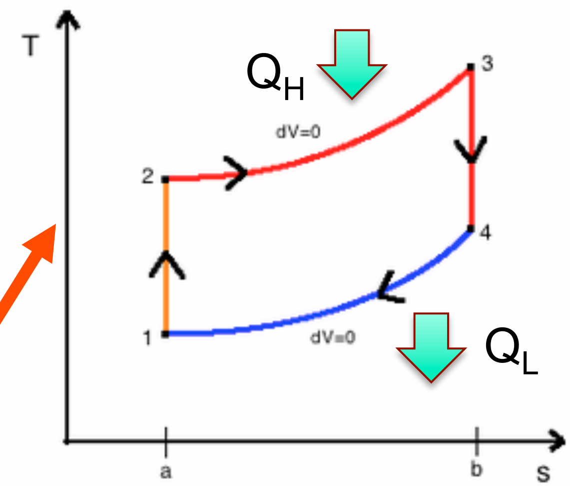
"Some scientist think it may be impossible here on earth due to the fact that heat from the earth will always permeate even the thickest insulation. That being the case the coldest man has ever achieved is 4 Kelvin, or -269.15 Celsius, or -452.47 Fahrenheit. When trying to go colder than that the object being cooled would literally shatter into millions of pieces!"

Everyday heat engine: Otto cycle

"Cultural supplement" (not on test)

- Model for real internal combustion engines
- Describes 4-stroke gas engines:
  - 0-1: constant P fuel-air intake stroke
  - 1-2: adiabatic compression stroke
  - 2-3: add fuel + spark = combustion at constant V
  - 3-4: adiabatic expansion = power stroke
  - 4-1: constant V cooling followed by
  - 1-0: exhaust stroke: constant P compression
- Typical T's: 300K/580K, so ideal eff = 48%
- Friction, turbulence, heat conduction through cylinder walls, etc, make actual efficiency ~ 25% at best



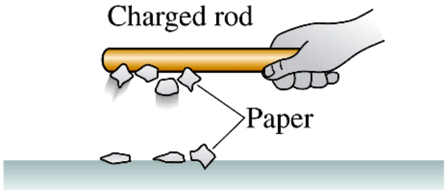


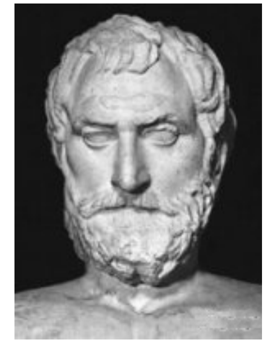
Notice: S is a state variable, so we can plot processes on T vs S axes, as well as P vs V axes

Electricity

"Rub amber with wool, and it will pick up bits of wood, feathers, straw …"

Thales of Miletus
(640-546 BC)





elektron = Greek word for amber

c. 1736: Charles Francois du Fay (1698-1739)

- rubbing glass or resins (e.g., amber) creates electric charges of 2 kinds
- charges of the same kind repel each other, unlike kinds attract
- Named the 2 charges ***"vitreous"*** and ***"resinous"*** electricity.

c. 1746: William Watson (1715-1790)

- Electricity is a fluid
- One of Du Fay's two charge types is an excess (+) of the fluid and the other a deficiency of it (-).
- Flow from + to – (fluid current) explains electrical sparks.

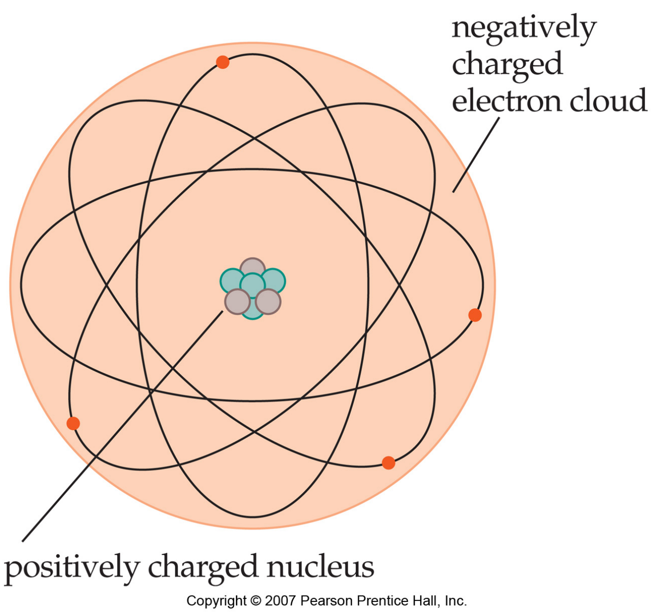
1747: Benjamin Franklin (1706-1790)

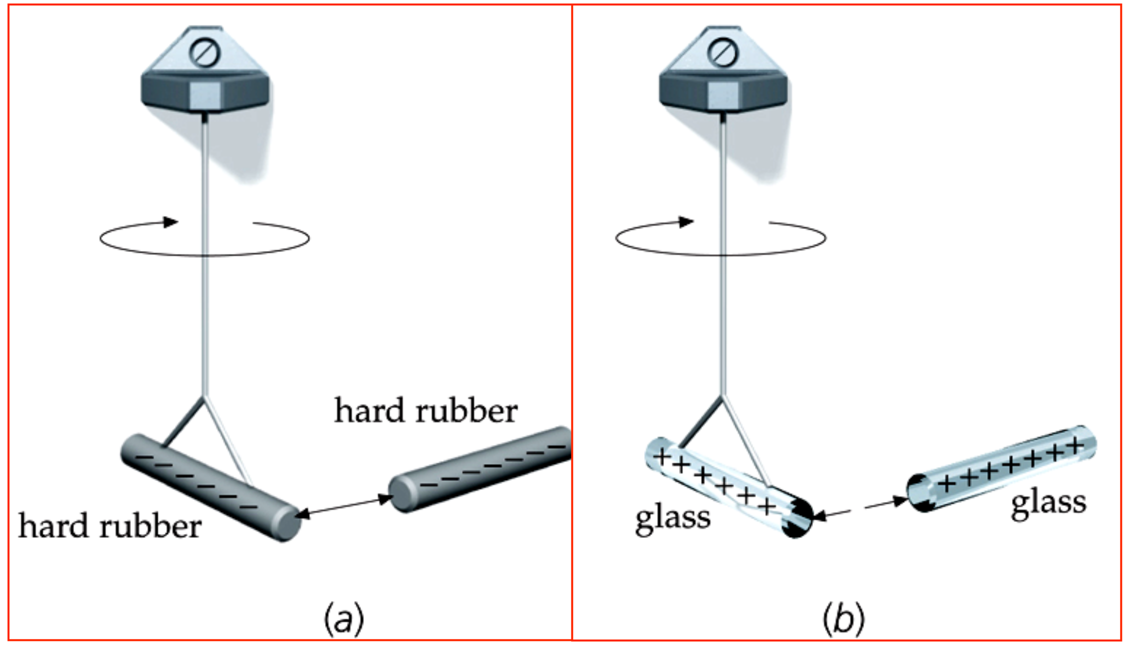
- Popularized Watson's "one fluid" theory
- chose *vitreous* electricity to be the positive type

  SO: electrons are negative.

Franklin's great reputation (later in life) won universal acceptance for his choice

Electric Charge





Today's understanding:

Atoms have heavy positively charged nuclei, surrounded by electrons

By Franklin's convention (now universal): electrons have ***negative charge***, are very light and more mobile than nuclei

- Rub glass with silk: electrons are transferred to the cloth
- Rub hard rubber (or plastic) with wool: electrons are transferred to the rod.

Who gains, who loses?

The ***triboelectric series***:

(Greek: *tribos* = "rubbing.")

If two of these materials are rubbed together, electrons are transferred from the material higher in the table to the one lower in the table

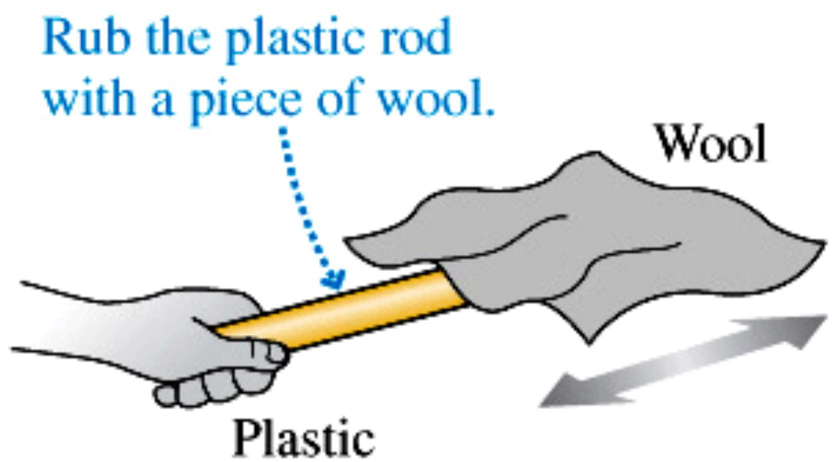
TABLE 19–1 Triboelectric charging

Material	Relative charging with rubbing
Rabbit fur	+ + + + + + +
Glass	+ + + + + +
Human hair	+ + + + +
Nylon	+ + + +
Silk	+ +
Paper	+
Cotton	−
Wood	− −
Amber	− − −
Rubber	− − − −
PVC	− − − − −
Teflon	− − − − − −

Conservation of Charge

Electrical charge can be neither created or destroyed. It can be separated and moved around, but the net charge of an isolated system must remain constant. $q_{initial} = q_{final}$

Example: A plastic rod is rubbed with wool, both initially neutral. Then $q_{wool} = -q_{rod.}$



Electric Charge is Quantized

- No charge smaller than one electron-charge (- *e*) can be isolated*
  - Charge q is *not* represented by real numbers, but by integers
  - "Looks like" a continuously variable quantity because numbers of electrons involved are always large (in everyday life): Q=Ne, where N is huge
  - Protons have q = +e
  - Atoms have nuclei with Z protons, surrounded by Z electrons
    - Net q = 0, viewed from outside atom
    - Z=atomic number (eg, carbon has Z=6)

*Fundamental particles called quarks have fractional charge, but it is impossible to isolate them, they always couple into pairs or triplets. Observable elementary particles always have q = N e.

TABLE 25.1 Protons and electrons

Particle	Mass (kg)	Charge
Proton	1.67×10^{-27}	$+e$
Electron	9.11×10^{-31}	$-e$

Example: How many e's in a penny?

A copper (Z = 29) penny has mass = 3.10 grams.

What is the total charge of all the electrons in the coin?

$Q = N_e(-e)$ Element of atomic number Z has Z electrons: $N_e = ZN_{at}$

$$N_{at} = (3.10g)\frac{6.02\times10^{23}\ \text{atoms/mol}}{63.5\ \text{g/mol}} = 2.94\times10^{22}\ \text{atoms}$$

$$N_e = ZN_{at} = (29\ \text{electrons/atom})(2.94\times10^{22}\ \text{atoms}) = 8.53\times10^{23}\ \text{electrons}$$

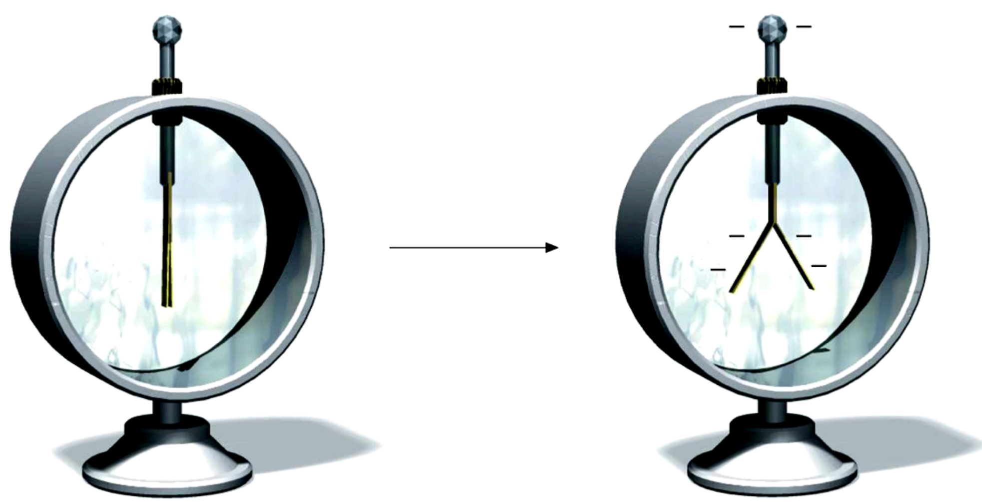
$$Q = N_e(-e) = (8.53\times10^{23}\ \text{electrons})(-1.60\times10^{-19}\ \text{C/electron}) = -1.37\times10^{5}\ \text{C}$$

As we'll see, this is an **enormous** charge!
Why don't pennies emit sparks?

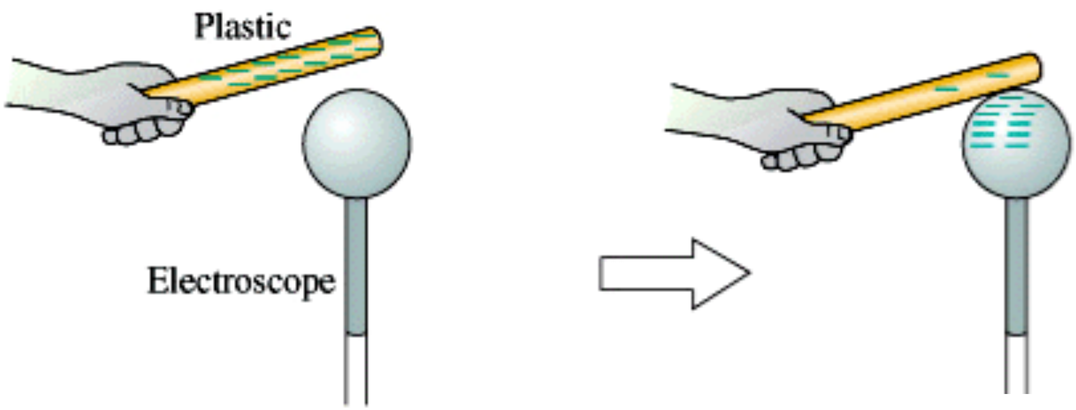
Detecting charge: the Electroscope

Device used in the 18th and 19th centuries:

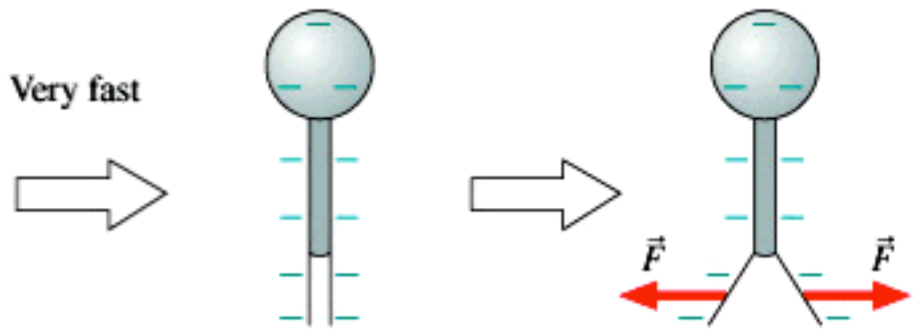
- Metal-foil leaves attached to a conducting post
  - Post and foils are insulated from the container
  - Container isolates leaves so they aren't disturbed
- Uncharged: the leaves hang together
- Touch with a charged object:
  - some charge is transferred to leaves
  - They spread apart: same sign q on each → repel each other



Charging an Electroscope

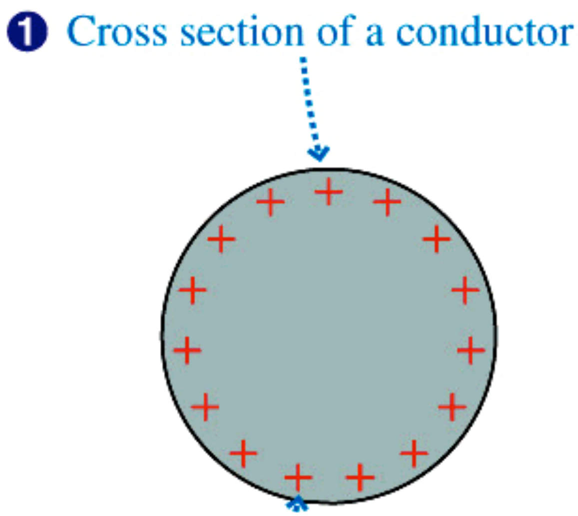


The deflection of the leaves gives a rough measure of the charge deposited on the electroscope.



Insulators and Conductors

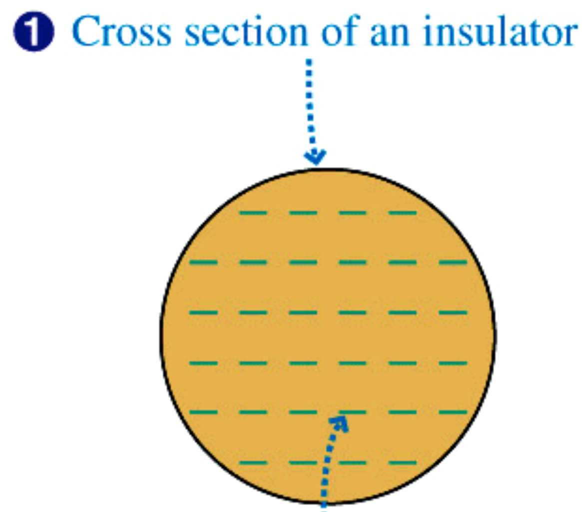
Materials with mobile electrons = conductors (most metals, for example)
Materials with tightly bound electrons = insulators
Typically, a good electrical conductor is also a good heat conductor



If a conductor is charged, ***all*** charge quickly moves to the outer surface (none stays in the interior.)

- Conductor = mobile charge

  Like charges repel !



If an insulator is charged, charge may (or may not) be present in the interior, depending on material.

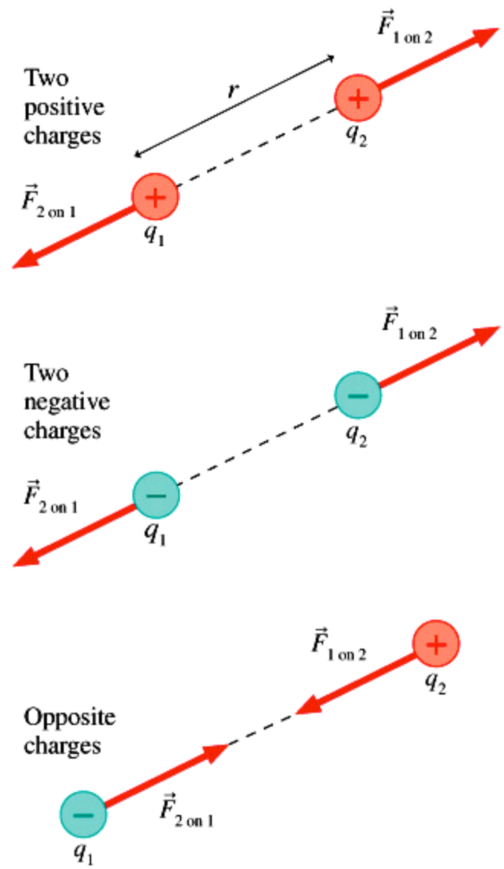
- Insulator = immobile charge

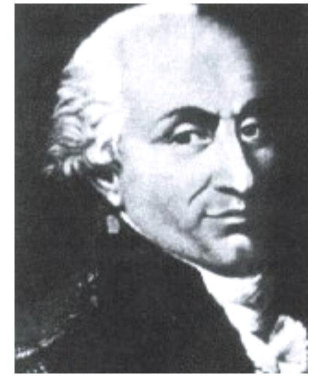
Coulomb's Law

Like charges repel,
Unlike charges attract

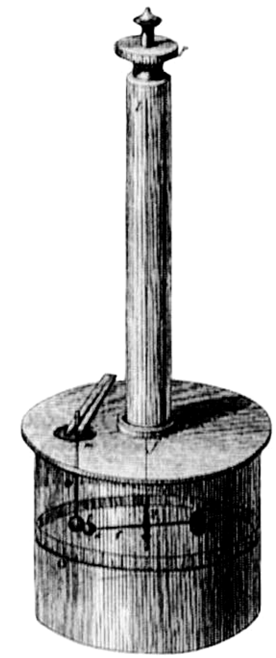
The electrostatic force between charges is:
1) Proportional* to each q, and
2) Inversely proportional to the distance r between them

* "Proportional to A" means B = (constant) x A





Charles Augustine de Coulomb (1736-1806).



Coulomb's torsion balance

Coulomb's Law:

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

15

Units of Charge

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

Coulomb's Law

$$k = 8.99\times10^{9}\ \mathrm{N\ m^2/C^2} \cong 9.0\times10^{9}\ \mathrm{N\ m^2/C^2}$$

C = coulomb = SI unit of charge;

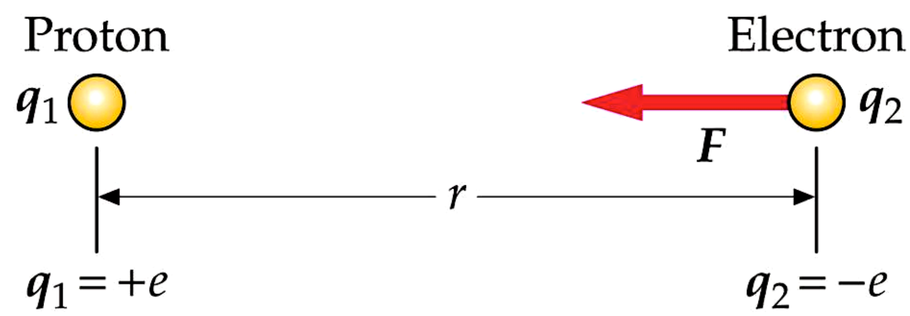
$$1.0\ nC = 1.0\times10^{-9}\ C$$

SI units are "everyday physics" in size

Notice: Newton's gravitational constant, G (which plays a role similar to k) is
$G = 6.67 \times 10^{-11}\ \mathrm{N\ m^2/kg^2}$ – much weaker!

Example:
Electric Force in Hydrogen

Hydrogen atom: electron is (on average) about 5.3 x 10^{-11} m away from proton



Magnitude of the electrostatic force of attraction exerted by the proton on the electron?

$$F = \frac{k|q_1 q_2|}{r^2} = \frac{ke^2}{r^2}$$

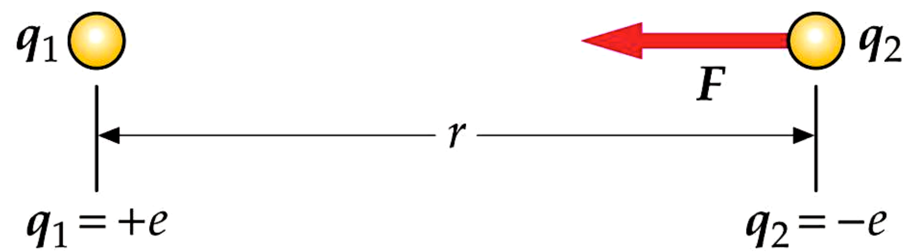
$$= \frac{(8.99\times10^{9}\ \mathrm{N\cdot m^2/C^2})(1.60\times10^{-19}\ \mathrm{C})^2}{(5.3\times10^{-11}\ \mathrm{m})^2}$$

$$= 8.2\times10^{-8}\ \mathrm{N}$$

Example: macroscopic charges

Suppose instead, the previous example had Q = $\pm$1 C and r = 1 m

Now what is the magnitude of the electrostatic force of attraction ?



$$F = \frac{k|q_1 q_2|}{r^2} = \frac{ke^2}{r^2}$$

$$= \frac{(8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2)(1.0 \text{ C})^2}{(1.0 \text{ m})^2}$$

$$= 9 \times 10^9 \text{ N}$$

Huge electrostatic force:
10 billion N ~ 1 million tons
1 coulomb is a lot of charge!

Example: Ratio of Electric & Gravitational Forces

Compare the electric force and gravitational forces between proton and electron in a hydrogen atom.

$$F_\mathrm{e} = \frac{ke^2}{r^2} \qquad F_\mathrm{g} = \frac{Gm_p m_e}{r^2}$$

$$R = \frac{F_\mathrm{e}}{F_\mathrm{g}} = \frac{ke^2 / r^2}{Gm_p m_e / r^2} = \frac{ke^2}{Gm_p m_e}$$

$$= \frac{(8.99\times10^9\ \mathrm{N\cdot m^2/C^2})(1.60\times10^{-19}\ \mathrm{C})^2}{(6.67\times10^{-11}\ \mathrm{N\cdot m^2/kg^2})(1.67\times10^{-27}\ \mathrm{kg})(9.11\times10^{-31}\ \mathrm{kg})}$$

$$= \boxed{2.27\times10^{39}}$$

How to use Coulomb's Law

1. Coulomb's Law applies ***only*** to point charges
   - Any charge distribution = sum of point charges

   (But usually have to use calculus)

2. Strictly speaking, Coulomb's Law applies only to electrostatics (stationary charges).
   - However, it is usually a good approx *if* v << c

   (v = speed of moving charge, c = speed of light)

3. Electrostatic forces, like other forces, obey the superposition principle:

$$\vec{F}_{\text{net}} = \vec{F}_{\text{1 on j}} + \vec{F}_{\text{2 on j}} + \vec{F}_{\text{3 on j}} + \cdots$$

F_{net} = vector sum of individual contributions

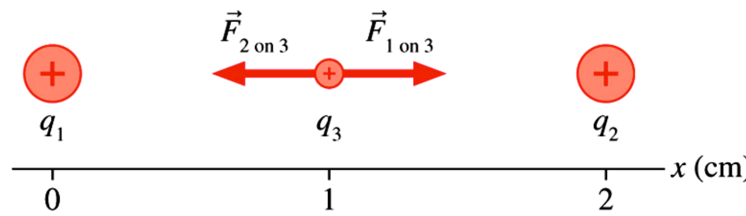
Each charge contributes as if others were not present

Example: Sum of Two Forces

Two +10 nC charged particles are 10 cm apart on the x axis.

(1) What is the net force on a +1.0 nC particle midway between them?

(2) What is the net force if the + charged particle on the right is replaced by a -10 nC charge?



$$\vec{F}_{(++)net} = \vec{F}_{1\text{ on }3} + \vec{F}_{2\text{ on }3} = |F|\hat{i} - |F|\hat{i} = 0$$

$$\vec{F}_{(+-)net} = F_{1\text{ on }3} + F_{2\text{ on }3} = |F|i + |F|i$$

$$= 2|F|\hat{i} = 1.8 \times 10^{-3}\ \text{N}$$

$$F = K\frac{q_1 q_2}{r^2} = (9.0 \times 10^9\ \text{N m}^2/\text{C}^2)\frac{(1.0\times10^{-8}C)(1.0\times10^{-8}C)}{(1.0\times10^{-2}m)^2}$$

$$= 9.0 \times 10^{-4}\ \text{N}$$