Today:

Finish Chapter 20 (Sound)

Chapter 22 (Electrostatics)

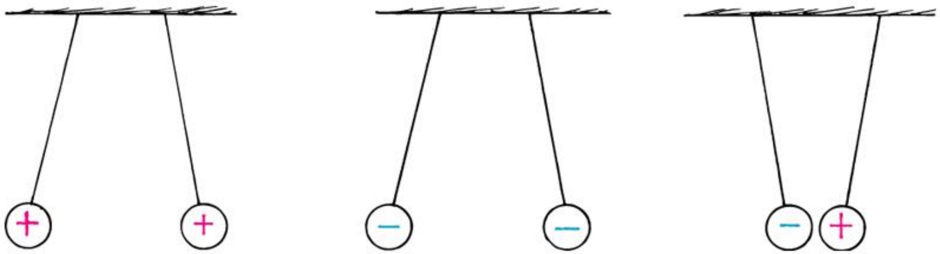
Reminder: Nov 18th is 2nd midterm, Chs. 9, 11, 13, 14, 15, 19, 20, 22

Electrical Force: Coulomb's Law

- Charged particles exert forces on one another :

Like charges repel each other

Unlike charges attract



- Acts along a line connecting the charges
- Determined by **Coulomb's Law** (18th century):

C = Coulomb, unit of charge q (more next slide)

$$\boxed{F = k\frac{q_1 q_2}{d^2}}$$

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

d = separation

- *c.f.* Newton's gravitational law

-- Inverse-square dependence on separation

-- proportional to size of each charge - *c.f.* grav. law (prop to each mass)

-- BUT k >> G; the electrical force is much stronger than gravitational force

--- Also, elec. force can be either attractive or repulsive, grav. force always attractive

Charge

- Fundamental quantity in all electrical phenomena: positive and negative particles carry "charge"

Recall, protons

electrons

• Attractive force btn protons and electrons cause them to form atoms, as we saw in Ch.11.

• Electrical force is behind all of how atoms bond i.e. behind chemistry…

• Every electron has charge -1.6×10^{-19} C, and every proton 1.6×10^{-19} C

i.e. -1 C represents the charge of 6.25 billion billion electrons !

Yet 1C is the amount of charge passing through a 100-W light bulb in just over a second. A lot of electrons!

• **Charge is always conserved:** charge cannot be created or destroyed, but can be transferred from one object to another.

Eg. Rubbing a rod with fur – electrons transfer from fur to rod, leaving rod negatively charged, and fur with exactly same magnitude of positive charge.

More on charge

- Note that in everyday charging processes (like rubbing objects), it is the *electrons* that transfer (not the protons). A negatively charged object has an excess of e's, whereas positively charged one has deficiency (by same amount)
- Which object gains the electrons depends on their ***electron affinity:***

Eg. Rod has greater affinity than fur, so rod becomes –, fur +

Eg. Silk has greater affinity than rod → when rubbed together, rod becomes +, silk -

Eg. Combing hair → Comb becomes –, hair + (e's go from hair to comb)

- Charge is **quantized:** cannot divide up charge into smaller units than that of electron (or proton) i.e. all objects have a charge that is a whole-number multiple of charge of a single e.

Question

Compare the gravitational force between an electron and proton in an H atom with the electrical force between them. Use:

Average radius of H atom = 0.5×10^{-10} m

Mass of proton = 1.67×10^{-27} kg

Mass of electron = proton mass/2000 = 8.35×10^{-31} kg

Felec = kq_eq_p/d^2

$= (9\mathrm{x}10^9)(1.6 \times 10^{-19})(1.6 \times 10^{-19})/(0.5\mathrm{x}10^{-10})^2$

= $\underline{9.2 \times 10^{-8}\ \mathrm{N}}$

Fgrav = Gm_1m_2/d^2

$=(6.67 \times 10^{-11})(1.67 \times 10^{-27})(8.35 \times 10^{-31}\ \mathrm{kg})/(0.5\mathrm{x}10^{-10})^2$

= $\underline{3.7 \times 10^{-47}\ \mathrm{N}}$ -- *far smaller!*

Clicker Question

So the electrical attraction is by far dominant in providing the centripetal force that keeps the electron in orbit around the proton. How about the force the electron exerts on the proton?

A) it's larger than the force on the electron

B) It's the same

C) It's smaller

D) It depends

Answer: B, Newton's 3rd law

The electrical force is an interaction (as any force is) and each pulls on the other equally. As always, distinguish the effect of the force from the force itself: due to the proton's mass being 2000 x that of the electron's it is the electron that rotates around the proton due to this force, rather then both of them rotating about each other…

Clicker Question

What is the ratio of the force on the electron in an ionized He atom, i.e. He^+, to that on the electron in a H atom, if the average distance to the nucleus in He ion is ¾ of that in the H atom?

(Note that He has atomic number of 2)

A) 32/9
B) 8/3
C) 4/3
D) 16/9
E) None of the above

Answer: A

Force = kq_1q_2/d^2

For He^+ one of the charges is doubled compared with H atom, while d is ¾ as much. So Force is $\frac{2}{(3/4)^2}$ = 2*16/9 = 32/9 as much.

Conductors and Insulators

- How easy is it to get an electric current to flow across a material? Property called **electrical conductivity**.
- Depends on how strongly the electrons are anchored to the nuclei:

Good **conductor**: e.g. metal. Electrons freely wander in the material, they are “loose”. Good conductors of electrical current are also good heat conductors.

Good **insulator**: e.g. rubber, glass, wood. Electrons tightly bound to nuclei, so hard to make them flow. Hence, poor conductors of current and of heat.

- **Electrical resistivity –** quantifies how much a material resists current flow.

Insulator has very high resistance (or resistivity), conductor very low. There is a range, depending on the material.

(More on this in Ch 23)

Semiconductors

- **Materials that can be made to behave sometimes as insulators, sometimes as conductors.**

E.g. Germanium, silicon. In pure crystalline form, are insulators. But if replace even one atom in 10 million with an impurity atom (i.e. a different type of atom that has a different # of electrons in their outer shell), it becomes an excellent conductor.

- **Transistors**: thin layers of semiconducting materials joined together.

Used to control flow of currents, detect and amplify radio signals, act as digital switches…An integrated circuit contains many transistors.

- **Light can cause conduction in semiconductors**:

E.g. In the dark, selenium is a good insulator, can hold electric charge for long time. But if shine light on it, charge quickly leaks away to surroundings.

This is the basis of xerox machines! Black plastic powder sticks only to the charged areas which have *not* been exposed to light – hence reproduces pattern of the light.

Superconductors

- Have **zero resistance, infinite conductivity** below a critical temperature
- Not common! Have to cool to very very low temperatures.
- Current passes without losing energy, no heat loss.
- Discovered in 1911 in metals near absolute zero (recall this is 0^{o}K, -273^{o}C)
- Discovered in 1987 in non-metallic compound (ceramic) at “high” temperature around 100 K, (-173^{o}C)
- Under intense research! Many useful applications eg transmission of power without loss, magnetically-levitated trains…

Charging

(1) Charging by friction and contact

Already discussed (rubbing materials together, see earlier slide on charge).

Often can see or hear the sparks when the charges move.

eg. Walk across a rug – feel tingle when touch door knob: electrons transferred from rug to your feet, then to the door knob.

charging by friction

charging by contact – simply touch

Clicker Question

Consider a negatively charged rod that touches a long conductor, transferring its charge to the conductor. What is the difference between how the electrons become arranged on the conductor, versus how they would be arranged if it had been an insulator?

A) There is no difference – evenly distributed on both
B) There is no difference – localized on both, near the contact point with the rod.
C) They are evenly distributed on the conductor, but localized on the insulator near the contact point with the rod
D) They are evenly distributed on the insulator, but localized on the conductor near the contact point with the rod

Answer: C

Would spread out evenly on a good conductor, because the transferred e's repel each other. But on insulator, or poor conductor, would be more localized at where the rod touched.

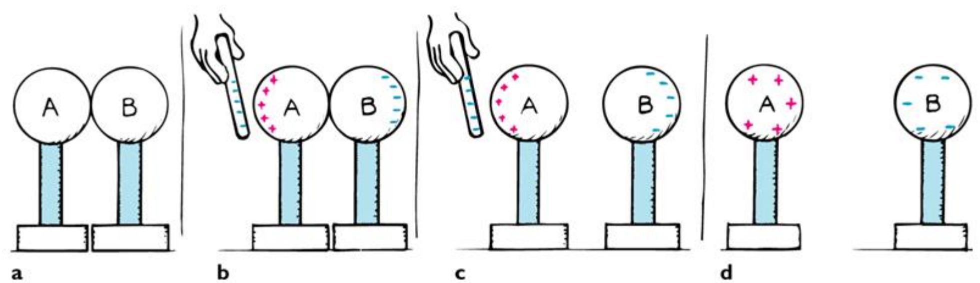
(2) Charging by induction

Bring a charged object *near* a conducting surface, electrons will move in conductor even though *no physical contact*: Due to attraction or repulsion of electrons in conductor to the charged object – since free to move, they will!

Charge redistribution until forces between all charges balance to 0.

Then if you separate parts of conductor – they will be charged.

Eg. Here, in (b), e's in A-B repelled away from rod, so get excess on B, leaving A positively charged:



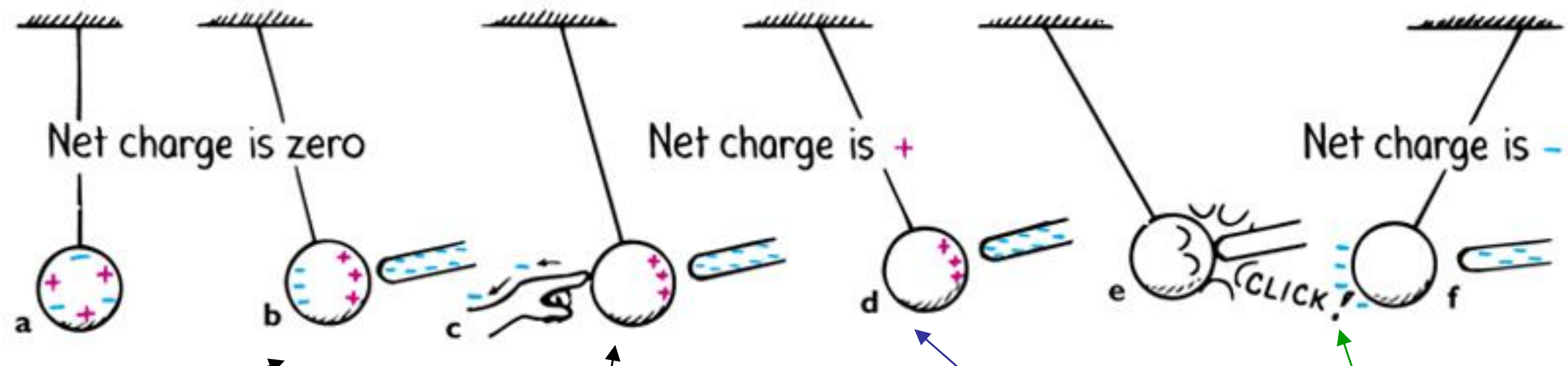
Note, the charged rod never touched them, and retains its original charge.

Question: Must the resulting charges on spheres A and B be equal and opposite?

Yes, because each + charge on A is from an electron leaving it and moving to B. Charge is conserved – no charge is added from rod as no contact.

Charging by induction continued…

• Charge induction by **grounding**: Here, can induce charge on a *single* neutral sphere hanging from a non-conducting string:



Here, charge redistributes, but net charge on sphere still 0

When touch with finger, **electrons flow from your finger, through you, to the ground**. The earth is a huge reservoir of charge... *(More in Ch 23)*

…so that here, sphere is left +.

Remove rod:

Steps a-d yield a +charged sphere.

If touch rod to sphere, get charging by contact – electrons flow onto sphere.

Remove rod:

Steps a-f yield a -charged sphere.

Eg Thunderstorms

Negative charge at bottom of cloud induces positive charge on ground below.

Charge flows most readily to and fro sharp metal points - hence **lightning rods**.

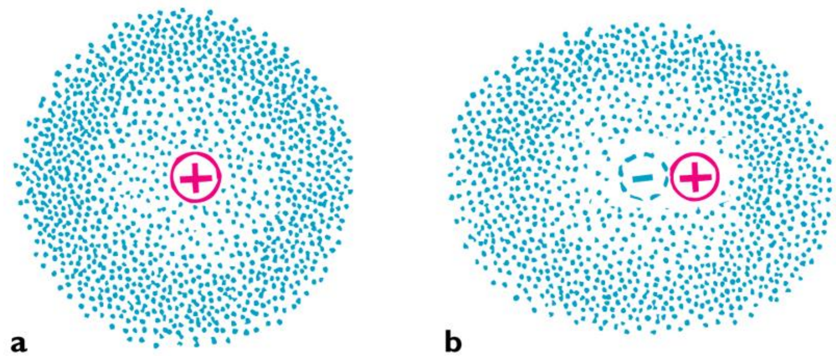
Place rod above a building, and connect it to ground. Then the point of the rod picks up e's from the air, so prevents large build up of + on the building, hence decreasing chance of a lightning strike.

But even if there is a lightning strike, the electricity goes through rod to ground, rather than through building.

Charge polarization

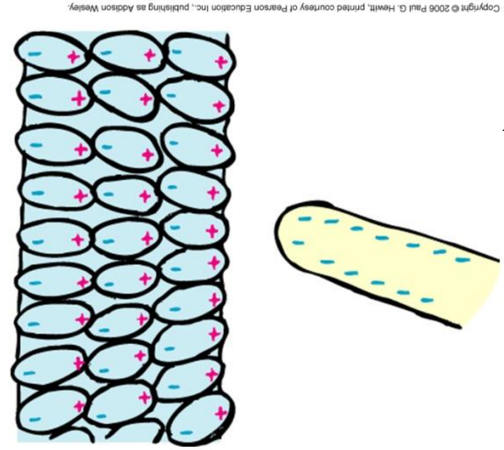
Instead, if bring a charged object near an insulator, electrons are not free to migrate throughout material. Instead, they redistribute **within** the atoms/molecules themselves: their "centers of charge" move

Here, usual atom, with center of electron cloud at positive nucleus



When a –ve charge is brought near the right, electron cloud shifts to the left. Centers of + and – charges no longer coincide.

Atom is ***electrically polarized***

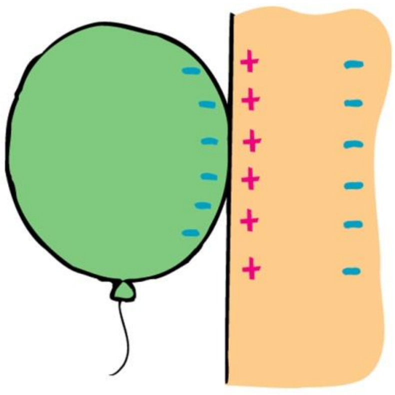


Surfaces of material look like this. A – charge induced on left, and + on the right.

(Zero net charge on whole object)

Charge polarization continued

- Charge polarization is why **a charged object can attract a *neutral* one** :



- **DEMO:** Rub balloon on your hair – it will then stick to the wall !

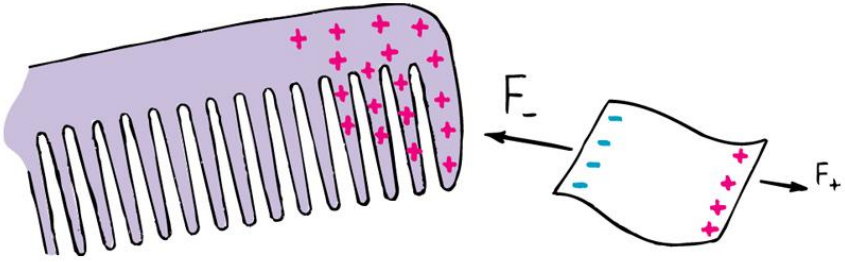
Why?

Balloon becomes charged (by friction) when rub on hair, picking up electrons. It then induces opposite charge on the wall's surface closest to it (+ve), and the same charge as itself (-) on side of wall furthest away.

So balloon is attracted to + charges and repelled by – charges in wall – but the – charges are further away so repulsive force is weaker and attraction wins.

(Argument applies generally – key thing is difference in distance btn + and -)

- Eg. Charge a comb by rubbing it through your hair, and then see it attracts bits of paper and fluff…



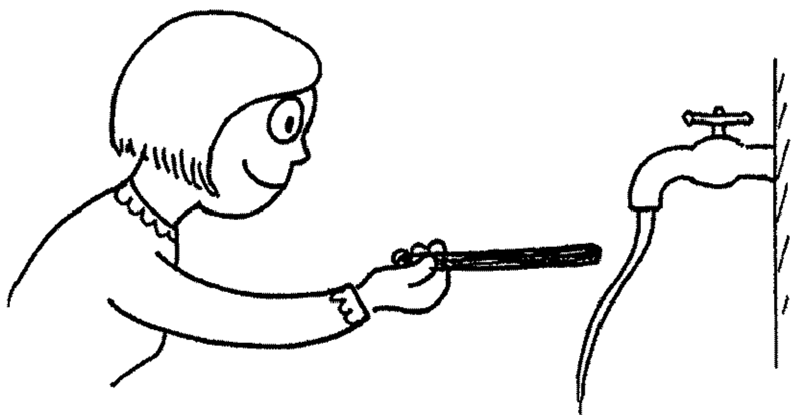
Clicker question

Which of the following is true?

A) A positively charged object can attract only a negatively charged object
B) A positively charged object can attract a negatively charged object or a neutral object
C) A positively charged object can attract a negatively charged object, a positively charged object, or a neutral object.
D) A positively charged object can attract a negatively charged object, but can repel or attract a neutral object.

Answer: B
Unlike charges attract, but a charged object can attract a neutral one due to polarization

Clicker Question



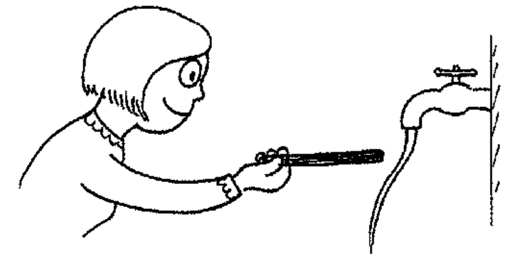
A thin stream of water bends toward a negatively charged rod. When a positively charged rod is placed near the stream, it will bend in the

1. opposite direction.
2. same direction.
3. … but it won’t bend at all.

Answer: 2

If you answered 1, you likely thought the bending was due to positively charged water. But the water normally has no appreciable net charge. The interaction between the charged rod and the water stream is mainly due to the dipole nature of water molecules. H_2O molecules are electric dipoles, positive on the hydrogen side and negative on the oxygen side.

Like compasses that align along a magnetic field, H_2Os align along the electric field of the nearby rod—whether the rod is positive or negative. For both magnets and charges, the closest aligned pole or charge is always opposite in sign. Opposites attract, so net attraction is the result.



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2. **same direction.**
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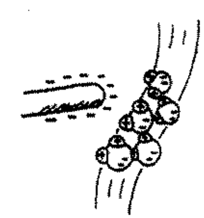
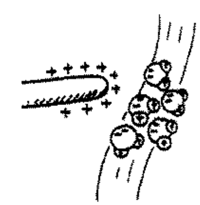
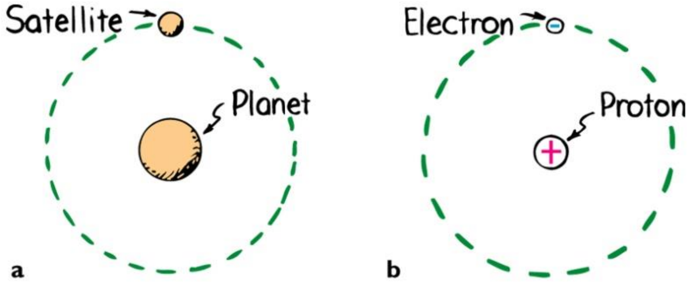




Electric Field

- Just like we defined grav field, we'll define electric field: both forces act on objects they are not in contact with.

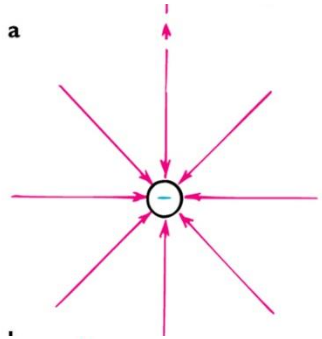
The orbiting bodies interact with the force fields (grav for planet, electric for proton).



i.e. think of the force as interaction between one body and field set up by the other.

Electric field, $\boxed{\boldsymbol{E} = \dfrac{\boldsymbol{F}}{\boldsymbol{q}}}$

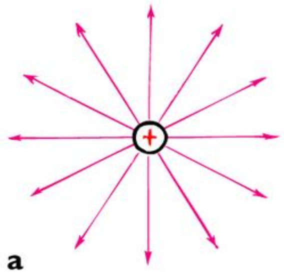
Eg. For a – charge: →



And field lines have arrow indicating direction a *positive test charge* would be pushed.

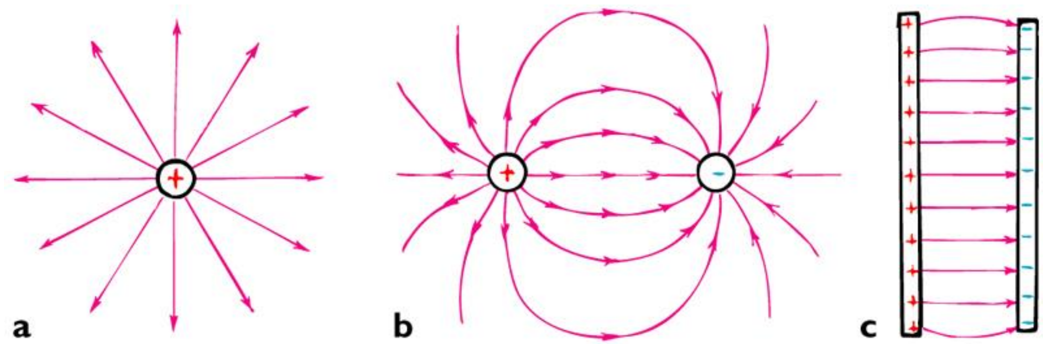
So always point away from +charges, towards – charges…

and for a (larger) + charge:



Electric field cont.

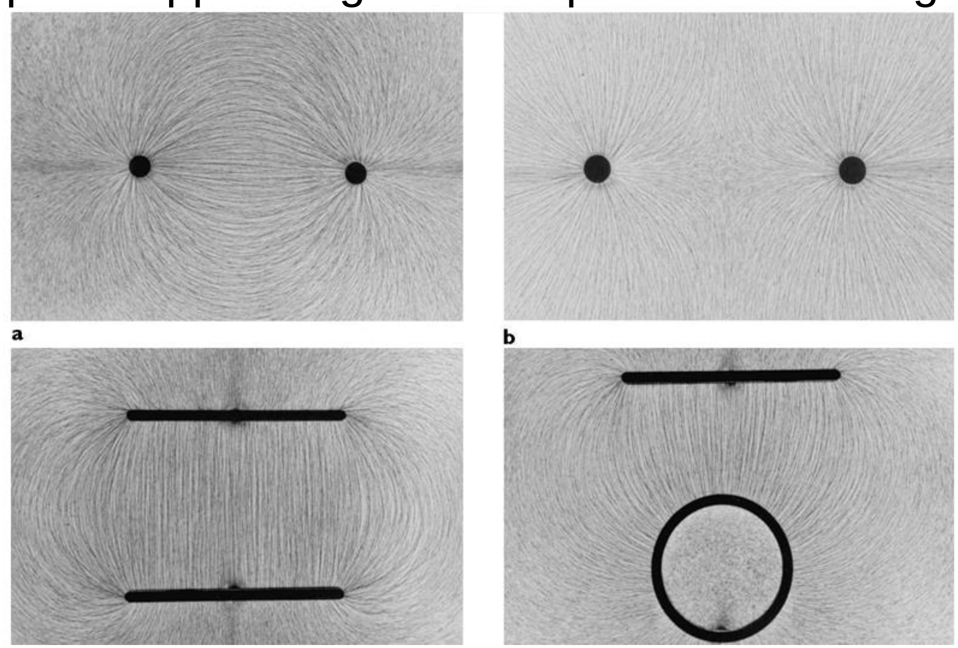
Eg. Field for some other charge configurations:



(non-examinable) EXTRA READING:

Eg. Field lines shown by small pieces of thread in an oil bath surrounding charged objects:

Equal & opp. charges | Equal and same sign



Opp. charged plates | Opp charged cyl & plate

• *Note:* Field concept useful when dealing with motion of charges – creates a disturbance of the field that propagates at the speed of light, affecting other charges via this wave (more later..)

Clicker Question

Say the electric field from an isolated point charge has a certain value at a distance of 1m. How will the electric field strength compare at a distance of 2 m from the charge?

A) It's the same

B) It is half as much at a distance 2 m compared to at 1m.

C) It is ¼ as much

D) It is twice as much

E) It is 4x as much

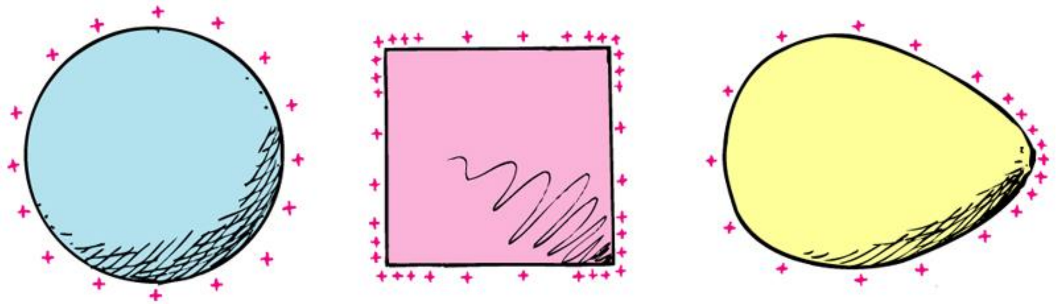
Answer: C

It will be ¼ as much – inverse square law for force between two charges carries over to the electric field from a point charge.

Electrical Shielding

- **The electric field inside *any* charged conductor is zero.**
- The exact charge distribution over the surface is such that E-field inside is 0. If it weren't, then the free electrons inside would move under the net force, until they feel 0 net force i.e until E-field was 0.

Note, can read in your book for a mathematical explanation of 0 E-field for case of sphere –but actually 0 E-field inside is true generally.



- True also for metal cavities - so put electrical equipment in metal boxes. Outside may be very strong fields and high charges, but the charges on the metal surface rearrange to give 0 inside.

- More general concept of shielding – air, oil etc makes field between two charges weaker than in vacuum.

- Grav fields cannot be shielded (due it purely attractive nature – no repulsion that can cancel fields)

Clicker Question

When lightning strikes a car, it is safe to sit inside it, because

A) The electric field is zero inside

B) The electric field is huge but only for a brief time

C) Nonsense! It is not safe – the electric field is huge inside the car

Answer: A

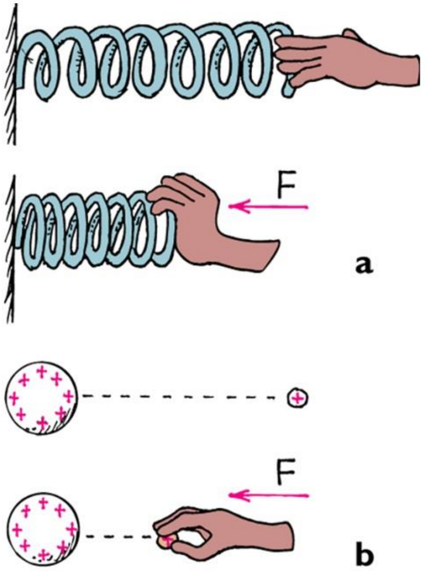
Electrical shielding…

Electric Potential

- A charged object has **potential energy (PE)** from its location in E-field (c.f. grav. PE in Ch. 9)
- Work is required to push charge against an E-field – this work changes the electric PE of the charged particle.

• Compare with a spring: Do work in pushing it in, this work is stored as mechanical PE of spring.

• Similarly, push two like charges together, working against the electrical force, increasing its energy. This work is stored as electrical PE.



If push a particle with twice the charge, do twice as much work.

So, define $\boxed{\textbf{electric potential} = \dfrac{\textbf{electric potential energy}}{\textbf{charge}}}$

Electric potential cont.

$$\text{electric potential} = \frac{\text{electric potential energy}}{\text{charge}}$$

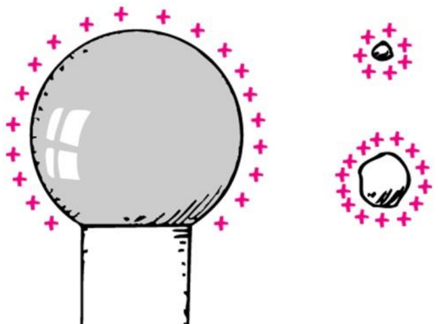
Units: potential is measured in *voltage,* or *volts, V.*

1 volt = 1 Joule/Coulomb

Eg. 12-V battery in your car, means that one terminal is 12 V higher in potential than the other.

Will use terms "electric potential" and "voltage" interchangeably.

- Often useful to think of what the electric potential is at various locations without actually having charge there. (See also Ch 23)
- Note important difference between energy and potential:



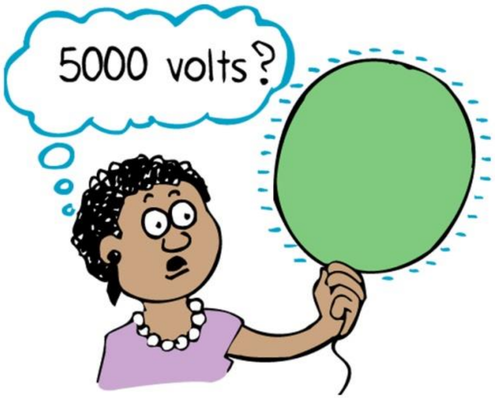
Both the small charged objects are at the *same electric potential*, but the one with more charge on it has *higher electric potential energy*.

Clicker Question

When you rub a balloon on your hair, the balloon can get charged to about -5000 V. The charge on it is less than a millionth of a Coulomb. Should you be worried about touching it?

A) yes

B) no



Answer: B

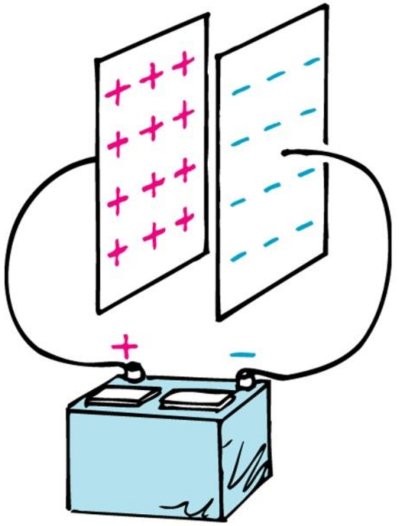
No, since very little energy is involved, despite the high voltage.

(If, instead the charge was 1 Coulomb, then it would be 5000J of energy, dangerous)

Electrical Energy Storage

• Can store electric energy in a **capacitor** :

• Found in nearly all electronic circuits eg in photo-flash units.



• Simplest is two close but separated parallel plates. When connected to a battery electrons get transferred from one plate to the other until the potential difference between them = voltage of battery.

• (How? Positive battery terminal attracts electrons from LH plate; these are then pumped through battery, through the – terminal to the opposite plate. Process continues until no more pot. diff. btn plate and connected terminal.)

• Discharging: when conducting path links the two charged plates. If very high voltages (eg capacitors in tv), its dangerous if you are this path!

e.g. Discharging is what creates the flash in a camera.

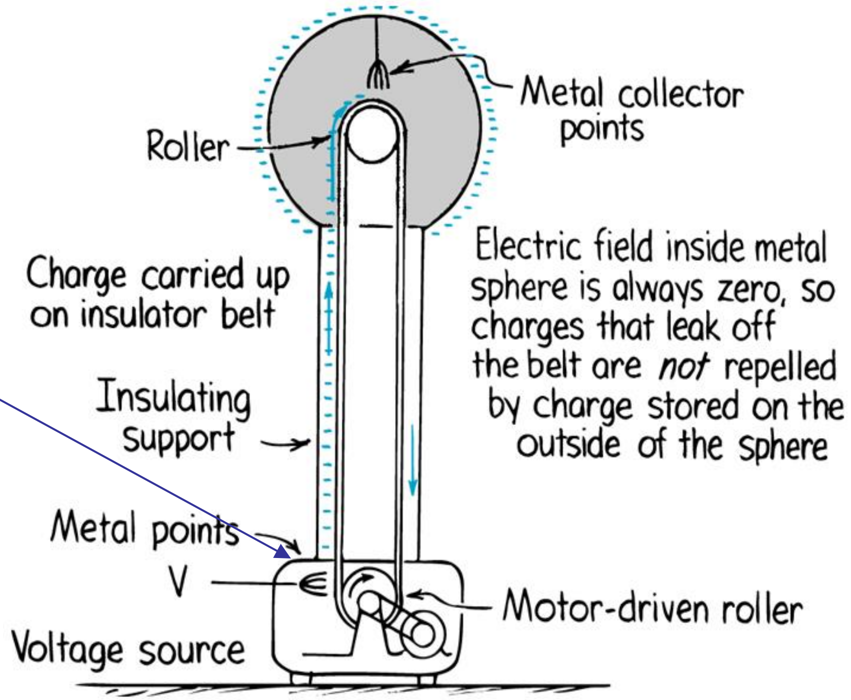
Van de Graaff generator

Is a common device for building up high voltages:

EXTRA READING:

Needles maintained at large negative potential w.r.t. ground. They discharge electrons continuously onto the rubber belt which then carry them up into hollow conductor.

Electrons end up on the outer sphere because there has to be 0 E-field inside – picked up by metal points (acting like lightning rods). Inside remains uncharged so more electrons keep coming up – end up with huge voltage on the dome. Can get as high as 20 million volts!

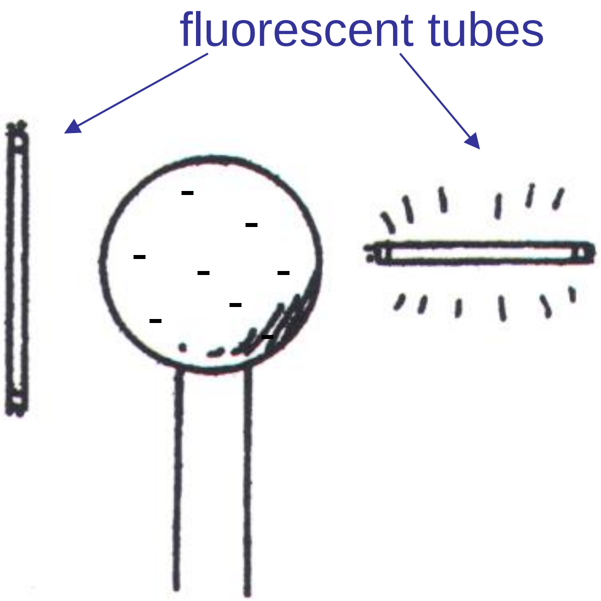


Can raise your hair with this !! Charges go into your hair, causing hairs to repel each other.

Clicker Question

In next chapter we'll study how charges tend to move from regions of high potential to low potential.

In which case here does current flow?



A) In tube on the right: when one end of the fluorescent tube is held closer to the charged Van de Graaff generator

B) In the tube on the left: when both ends are equidistant

C) In both tubes

D) In neither tube

.

Answer: A

The close end is in a stronger part of the field than the far end. More energy per charge means more voltage at the near end. With a voltage difference across the tube, you get a current. When both ends are equidistant, there is no voltage difference across the tube, and no current