Electricity: It All Starts With Electrons

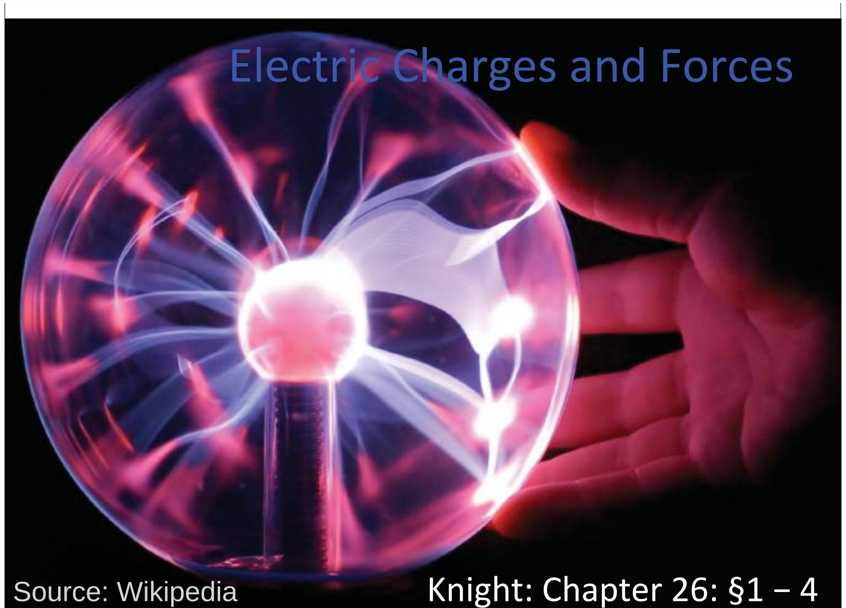
VCE Unit 1 Study 2
or thereabouts

Source: http://www.kfunigraz.ac.at/

bjectives:

- Charge, Electrostatics and Induction,
- Electric field and Forces on Charges,
- Conductors in Electric Fields,
- Lightning,
- Current, Resistance, Ohm’s Law,
- ower,
- Electrical Safety.

Electric Charges and Forces

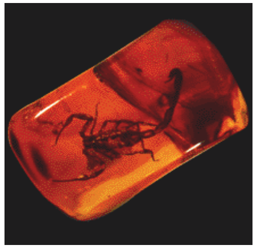


Source: Wikipedia

Knight: Chapter 26: §1 – 4

Electrostatics:

As early as 600 BC, Ancient Greeks discovered that lumps of amber charged by friction (rubbing) would pick up small pieces of straw.



Greek word for amber is "elektron"

agnetism discovered at about same time. Named after middle east region called Magnesia

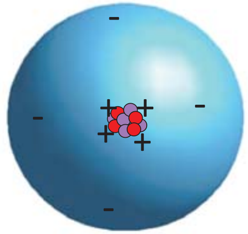
Electric Force and Electric Charge: §26.2

rdinary matter composed of neutral atoms (no net charge).

Particle scattering expts ⇒ atom

composed of:

- positively charged nucleus
  - protons (+ve)
  - neutrons (neutral)
- surrounded by "cloud" of electrons (negatively charge)



eutral atom : # of electrons = # of protons

on : imbalance in + and − charge due to excess or deficit of electrons (wrt # of protons)

Electric Force:

Force of attraction b/w protons and electrons due to their electric charge (holds atoms together).

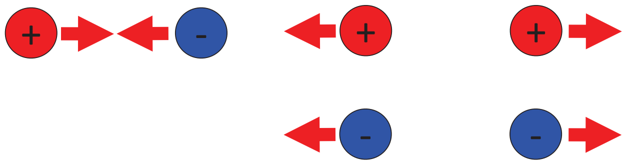
Electrostatics:

Deals with forces b/w charges at rest (or nearly at rest: quasistatic)

Direction of Electric Force:

pposite charges attract

ike charges repel



Unit of Electric Charge:

Electric force b/w objects depends on their net electric charge.

nimum unit of charge found in nature (thus far) is:

$-e$ charge on electron

$+e$ charge on proton

Unit of Electric Charge:

$$e = 1.60 \times 10^{-19}\ C\ (Coulomb)$$

= magnitude of charge on electron or proton

(Chosen so that current of 1 A (ampere) = 1 C.s^{-1})

Charge Quantization:

Electric charge is quantized (quantum unit is *e*)

Charge:	Particle:
-e	electron e^-, pion π^-, muon μ^-
+e	proton p^+, pion π^+, positron e^+
0	neutron n, neutr no ν, photon γ

(In particle theory, quarks postulated to have:

up (u)	+2/3 e	
down (d)	-1/3 e	(and antiparticles too)
strange (s)	-1/3 e	

These have not yet been observed.)

Conductors and Insulators:

Conductor:

uter shell electrons not involved in bonding $\Rightarrow$ free to travel through volume of conductor $\Rightarrow$ permits motion of electric charge through volume (In Cu ~10^{22} e's per cm^3 available for conduction).

Insulator:

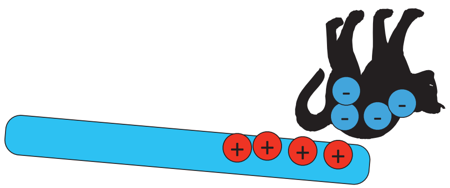
All electrons located in bonds b/w atoms $\Rightarrow$ none free to move charge. (e.g. glass, plastic, very pure water)

Semiconductor:

umber of free electrons strongly dependent on doping (purity) of material. (Si, Ge, GaAs...)

Charging:

A surface charge can be produced on insulators by rubbing (e.g. rubbing glass rod with cat's fur). This involves transfer of some surface electrons from one object to the other.



Aircraft can become charged due to electron transfer with air, dust + ice particles etc.

Charging:

urface charge can be produced on insulators through charge transfer by friction: weak molecular bonds are formed and roken during contact and sometimes when the bond breaks n electron ends up swapping from one material to the other.

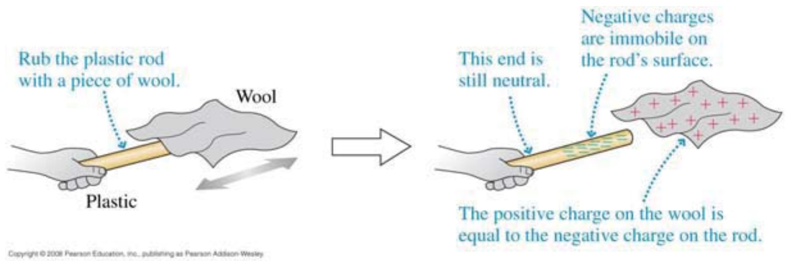
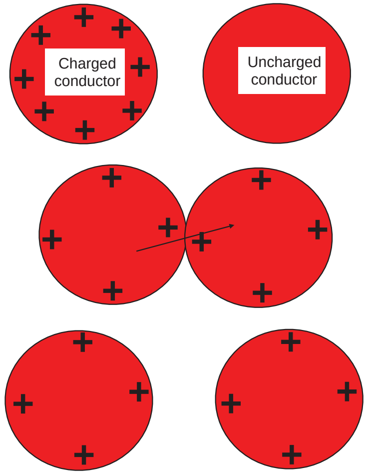


Fig.26.6 Knight, Physics for Scientists and Engineers, 2^{nd} Ed.

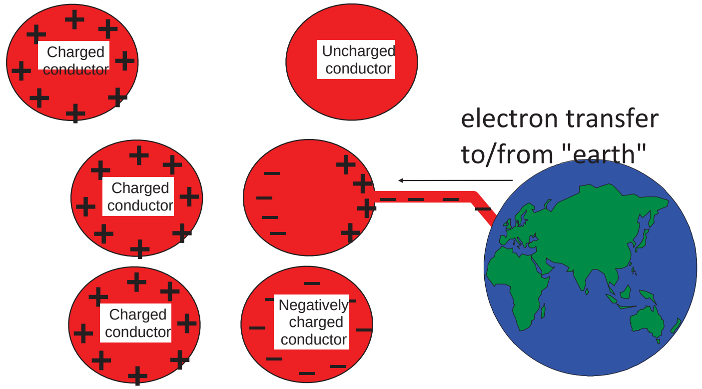
The surface charge is immobile on an insulator.

Conductors can share charge by contact:



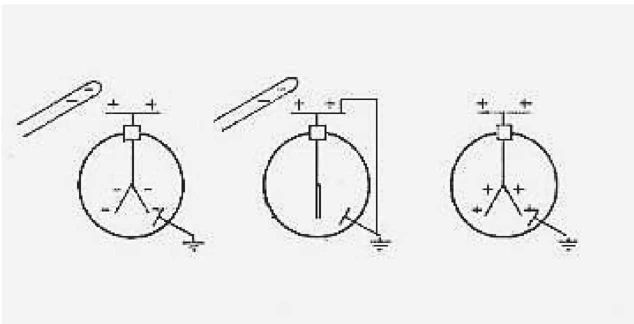
Equal charges on each.

… or charge can be induced:

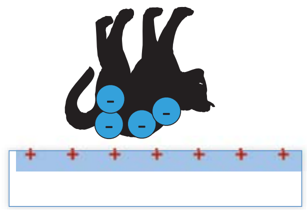


pposite charges on each.

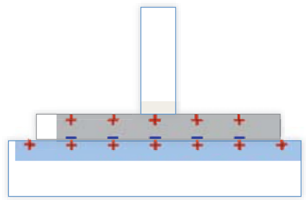
The Electroscope:



Charging by Induction: The Electrophorus

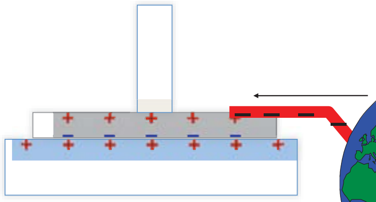


Fixed charge produced on paraffin surface.

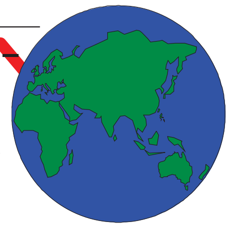


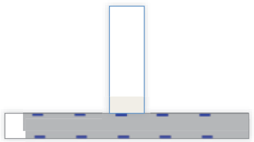
Charge separation induced between top and bottom surfaces of metal plate.

Charging by Induction: The Electrophorus



Charge transfer between top plate and “Earth”.

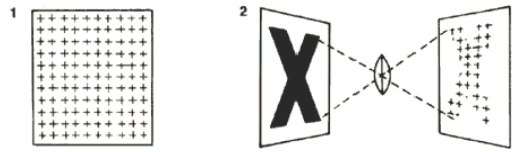




➔ Net charge on plate.

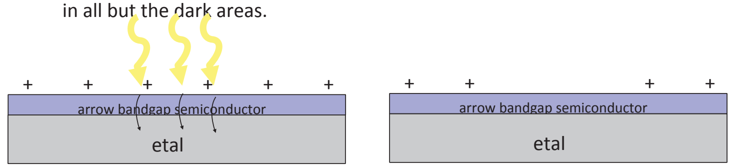
Photocopiers and Laser Printers

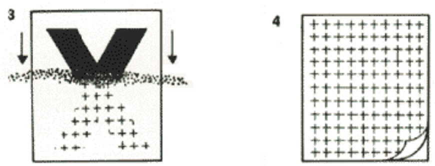
Electrostatics in action



(1) A photoconductive surface is given a positive charge (+).

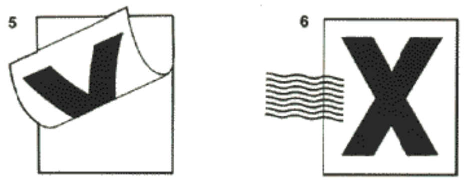
(2) The image of a document is exposed on the surface. This causes the charge to drain away from the surface in all but the dark areas.





(3) Negatively charged toner powder is cascaded over the surface. It **electrostatically** adheres to the positively charged image area making a visible image.

(4) A piece of plain paper is placed over the surface and given a positive charge.



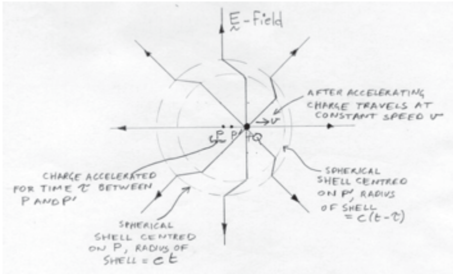
(5) The negatively charged powder image on the surface is **electrostatically** attracted to the positively charged paper.

(6) The powder image is fused to the paper by heat.

Electric Field:

Electric force is mediated by the **electric field**. Electric field is disturbance of space surrounding a charge due to its presence.

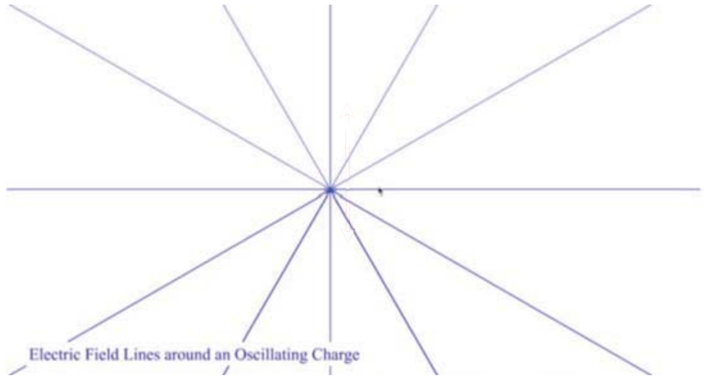
A second charge introduced into the space occupied by the electric field of the first charge experiences an electric force through an interaction with the field.



If a charge moves suddenly the change in the electric field propagates outward from the charge at the speed of light.

ght Propagation (Qualitative)

- Changing electric electric field associated with an oscillating charge:



http://www.cs.sbcc.cc.ca.us/~physics/flash/electricfieldwaves2.html

Electric Field

Electric field defined as force per unit positive charge, q:

$$\vec{E} = \frac{\vec{F}}{q} \quad (Units: N/C \text{ or } V/m)$$

$$\Rightarrow \vec{F} = \vec{E}\, q$$

$\Rightarrow$ find magnitude and direction of $\boldsymbol{E}$ at some point in space by placing small +ve test charge, q, at that point.

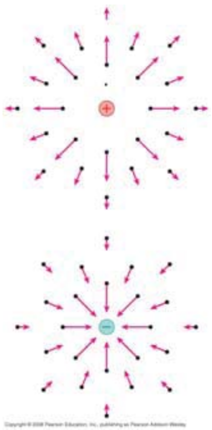


Fig.27.2 Knight, Physics for Scientists and Engineers, 2nd Ed.

Electric Dipole:

Many asymmetric molecules are electric dipoles e.g. H_2O molecule:

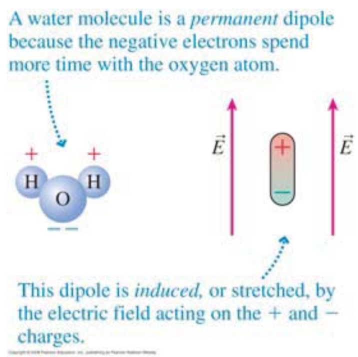


Fig.27.6 Knight, Physics for Scientists and Engineers, 2nd Ed.

Dipoles can also be induced by charge separation in an electric field e.g. on grass seeds or soot particles.

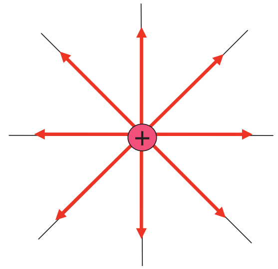
How big is the electric field?

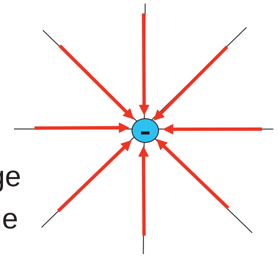
- Inside copper wire of household circuits — 10^{-2} N/C (or V/m)
- Charged plastic comb — 10^{3}
- Electron beam in TV; photocopier corona wire — 10^{5}
- Electric breakdown in air — 3×10^{6}
- Hydrogen atom, at electron orbit radius — 5×10^{11}
- At uranium nucleus — 3×10^{21}
  - Force holding nucleus together is ***very*** strong!

http://www.rakeshkapoor.us/ClassNotes/ElectricCharge.html

Electric Field Lines:

- give graphical representation of electric field
- tangent to field line gives direction of *E* at any point
- direction of arrows = direction +ve test charge would move if placed in field
- density of field lines proportional to field strength at any point (e.g. close to charge have high field density)

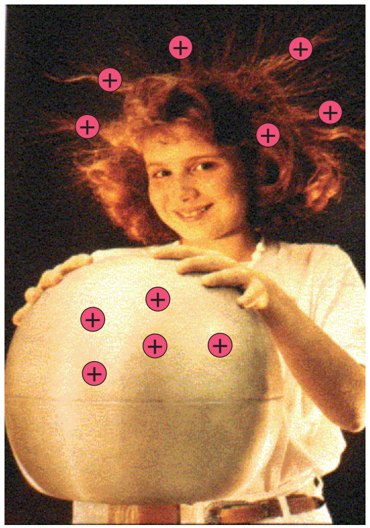




+ field lines originate on + charge

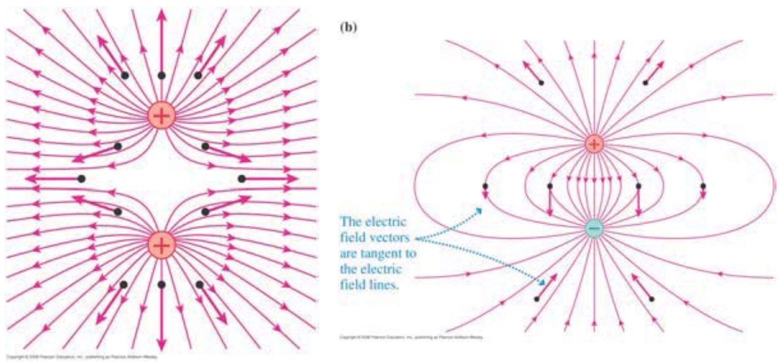
- field lines terminate on - charge

Visualising Field Lines:



van der Graaf generator

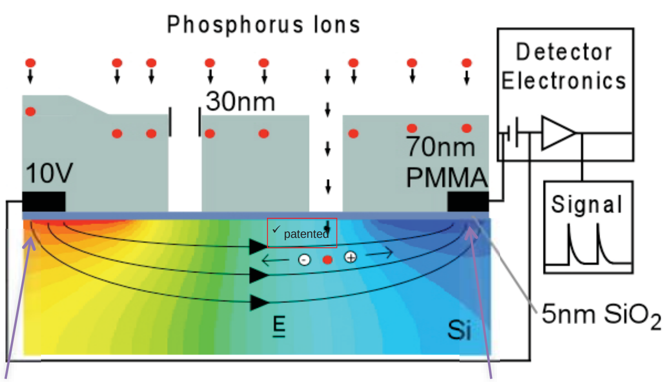
Field lines for pairs of point charges:



Pair of Like Charges — Pair of Opposite Charges

(Figs 27-10 and 27.9b, Knight, Physics for Scientists and Engineers, 2nd Ed.

Single Ion Implantation for Quantum Computer Fabrication:

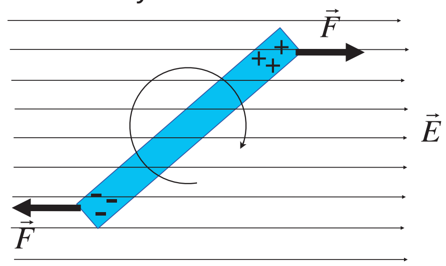


E-field established in substrate via metal contacts on silicon surface.

When ions enter silicon they lose energy and produce +ve and –ve charges that are separated by the E-field and transferred to the contacts where a current pulse is registered.

Induced Dipole Moment:

Separation of charges can occur in some molecules or bodies (e.g. metals) due to presence of $\boldsymbol{E}$ field. Charge separation ceases when field removed. Dipole moment is "induced" by field.



Charge separation in metal due to E field

(Also, small seeds, threads used to visualise field lines)

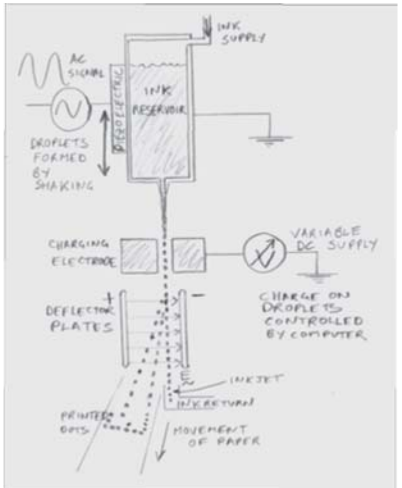
Electrostatics in Action – Continuous Inkjet Printer:

Ink droplets formed by shaking reservoir (piezoelectric crystal) or heating (microresistor).

Droplets charged by induction: charge separation along stream arising from E-field produced by charging electrode.

Charge on droplet selected by setting charging potential.

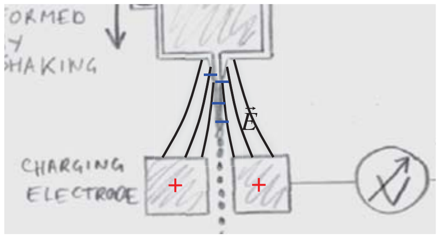
Fixed E-field between deflector plates: droplet steered according to its charge.



Electrostatics in Action – Continuous Inkjet Printer:

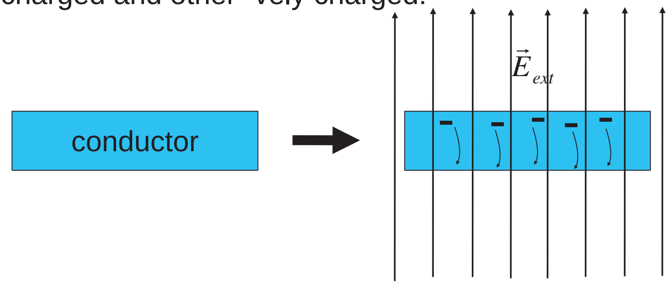
Droplets charged by induction: charge separation along stream arising from $\boldsymbol{E}$-field produced by charging electrode.

Charge on droplet selected by setting charging potential.



Conductors in Electric Fields:

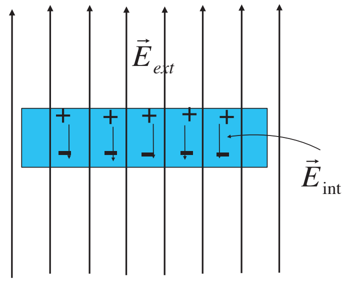
In conductor, large # of free electrons available ⇒ when conductor placed in $\boldsymbol{E}$-field, free electrons move in opposite direction to field leaving one surface +vely charged and other -vely charged:

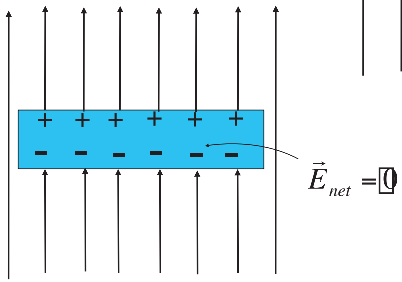


Charge separation generates internal $\boldsymbol{E}$-field $\boldsymbol{E}_{\text{int}}$ opposite in direction to the external field.

Separation of charge continues until:

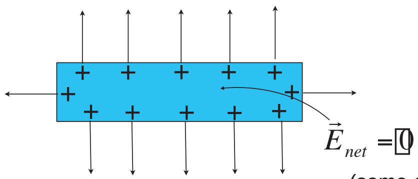
$$\left|\vec{E}_{\text{int}}\right| = \left|\vec{E}_{ext}\right|$$





At equilibrium $\boldsymbol{E}_{net} = 0$ everywhere inside conductor

Similarly, excess charge on conductor resides at the surface:

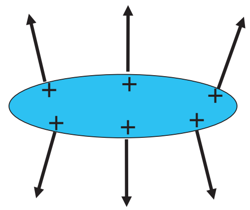


(same equilibrium condition applies)

This is also what we would expect based on charge repulsion and minimisation of potential energy (see later).

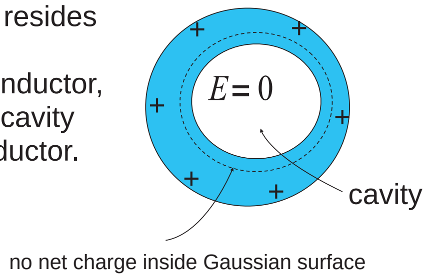
Also, at equilibrium, field lines at surface of conductor are perpendicular to the surface at every point

(otherwise there would be net lateral force on charges and they would move)



Hollow Conductor :

Since excess charge resides on surface and $\boldsymbol{E}$ =0 everywhere inside conductor, must also be true for cavity anywhere inside conductor.



⇒ metal shell or cage "shields" interior from electric field
⇒ Faraday Cage

NB. The electrostatic potential will give us a better way of arguing that there can be no electric field lines within an empty cavity in a conductor.

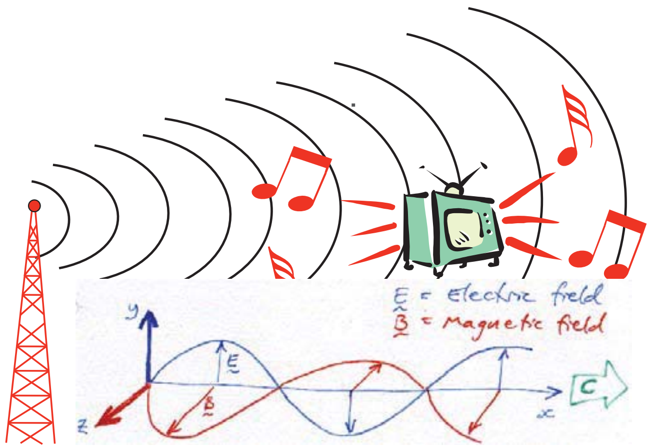
Faraday Cage:

Conductors shield their interior from *E*-field:

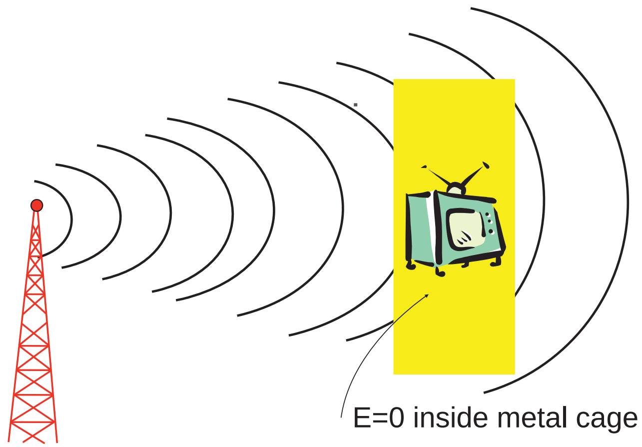
FIGURE 25-20 A large spark jumps to the car's body and then exits by moving across the insulated left front tire (note the flash there), leaving the person inside unharmed.

(Fig 25-19, Halliday, Resnick and Walker, Fundamentals Of Physics, Wiley 2001)

Conductors shield their interior from E-field:

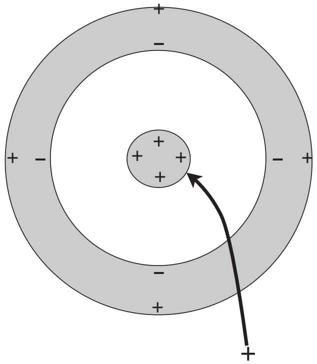


Conductors shield their interior from E-field:



Charge Transfer in van der Graaf generator

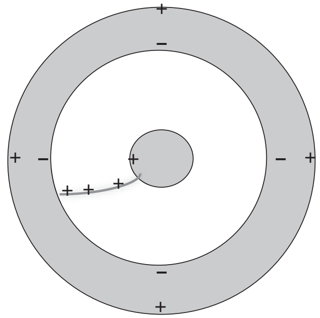
Introduce charge into cavity of conducting shell.



Charge Transfer in van der Graaf generator

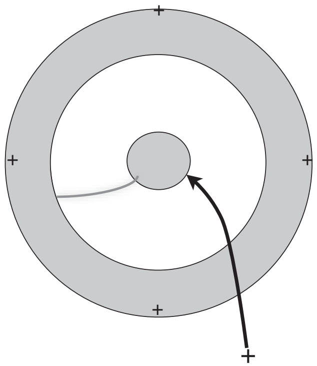
Connect inner conductor to shell.

Transfer charge to shell.

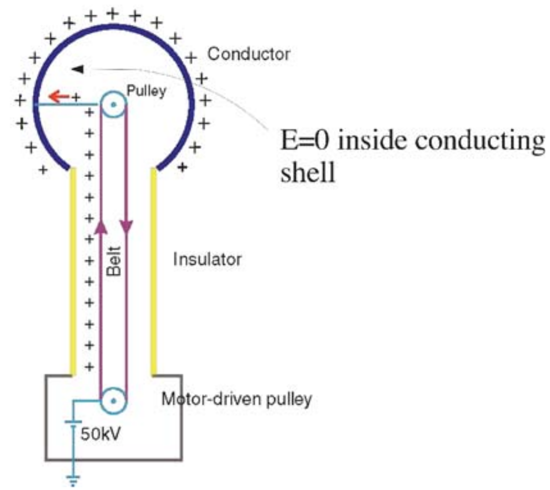


Charge Transfer in van der Graaf generator

To add more charge start the whole process over again.

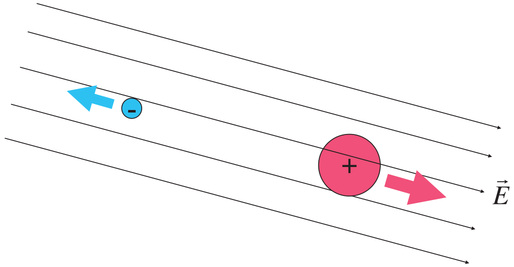


Charge Transfer in van der Graaf generator

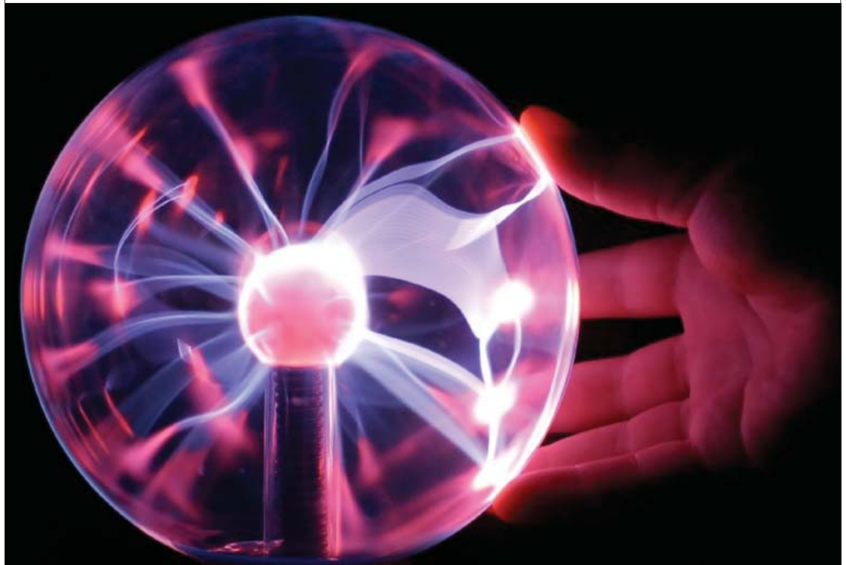


Lightning:

When E-field exceeds 3 x 10 ^{6} N/C (V/m) molecules in air can become ionised (neutral molecules broken into +vely and -vely charged ions):



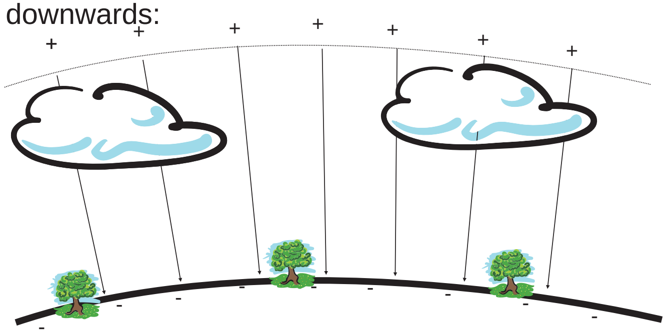
these ions collide with neutral molecules ⇒ more ions created ⇒ collision cascade ⇒ spark.



Source: Wikipedia

E-Field of Earth:

Dry air E-Field of Earth ~ 100-200 V/m (N/C) pointing downwards:



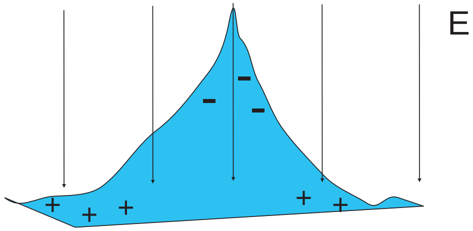
Earth = Giant Spherical Capacitor

Lightning = discharge through volume of capacitor

Sources of Mobile Charges:

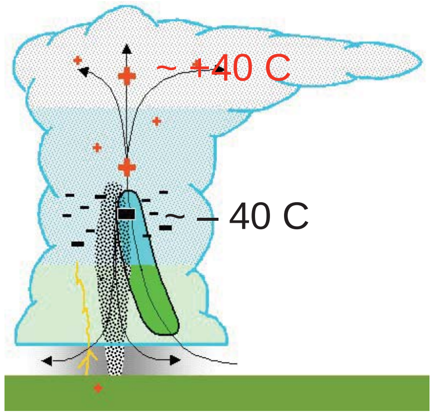
Upper Atmosphere: Cosmic Rays (very swift particles from space, mostly protons) enter atmosphere and produce dense collision cascades of charged particles (+ve and -ve).

Terrestrial: Ions produced by natural radioactive decay and other ionisation processes including induced charge on droplets of water spray:



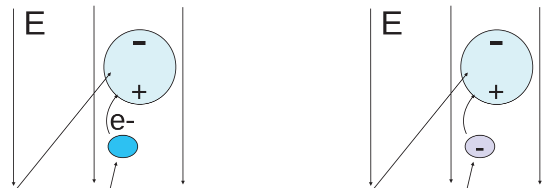
Thunder Clouds

Current understanding is that: Small ice particles are being charged positively and rapidly transported upward.



(From: http://littleswitzerlandweather.info/lightinfo/abtlightning.html)

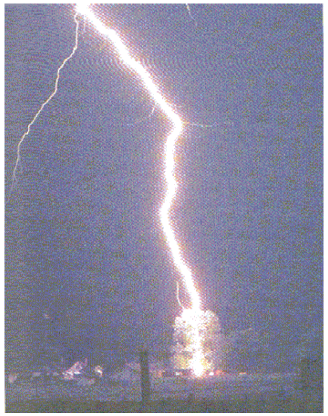
Possible Charging Mechanisms



Ice particle polarised in E-field + charge exchange with water droplet or another ice particle.

Or -ve ions attracted towards ice particle and captured.

Lightning Strike:



ground strike

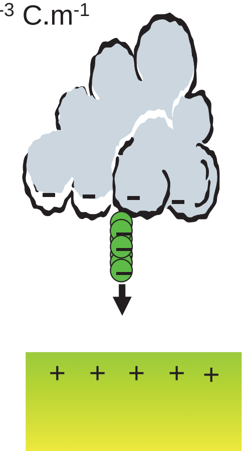
(Figs 24-13, 24-14, Halliday, Resnick and Walker, Fundamentals Of Physics, Wiley 2001)

Lightning:

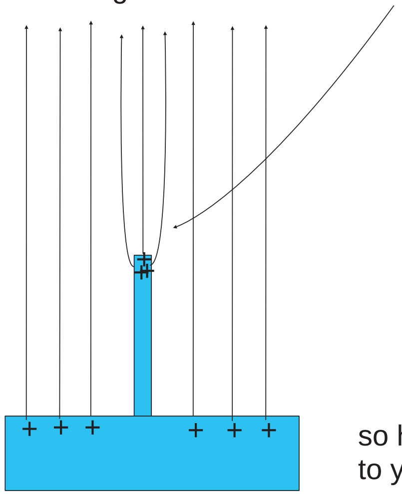
Just prior to flash, electron avalanche descends to ground
Charge density in column $\lambda \sim -1 \times 10^{-3}$ C.m^{-1}

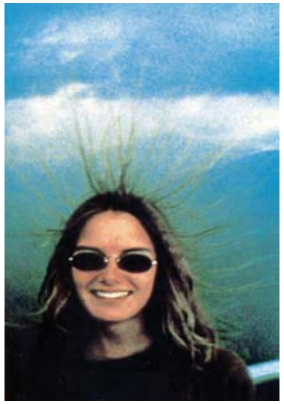
Once column bridges gap, e- rapidly

transported:
→ current
→e- collisions with air molecules
→ ionisation
→ further current
e- + air molecules
atom excitation
spontaneous decay
photons
flash



Discharge occurs first wherever E-field greatest:





so hit the deck if this happens to you!

(Fig 25-24, Halliday, Resnick and Walker, Fundamentals Of Physics, Wiley 2001)

Current, Resistance and Ohm's Law

Knight: Chapter 31: §1-5

i57.photobucket.com/.

Insulators:

- Electrons not free to move
- High resistance
- e.g. glasses, ceramics, most plastics, wood, pure water

Conductors:

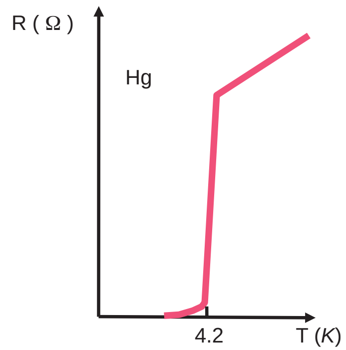
- Many free electrons
- Low resistance
- e.g. metals, impure water, humans, ionized gas

Semiconductors:

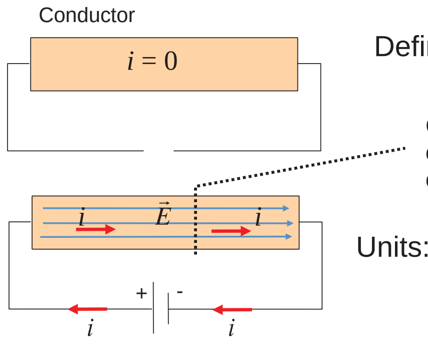
- Pure semiconductors ~ insulators, presence of certain impurities (dopants) provides free electrons (or holes (+))
- Resistance strongly dependent on presence of dopants
- e.g. Si, Ge, GaAs, GaN, …

Superconductors:

- Resistance becomes zero below some critical temperature
- e.g. Hg, Nb, $YBaCu_3O_7$



Electric Current i :



Define Current $i = \dfrac{dq}{dt}$

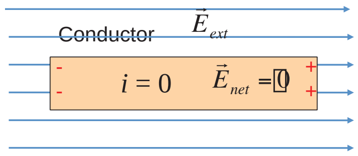
Charge dq passing through cross-sectional area of conductor in time dt

Units: 1 Ampere (A) = 1 C/s

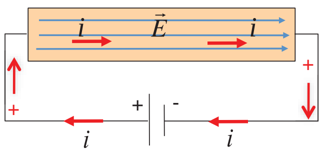
Direction of current: arrows drawn in direction +ve charge would move if it constituted the current.

Charge Carriers:

- In a metal the charge carriers are electrons (−).
- In a liquid, the charge carriers are positive (cations) and/ or negative ions (anions).
- In a semiconductor the charge carriers are (conduction band) electrons (−) and/or (valence band) holes (+) (bonds that are missing an electron).
- In a plasma (electrical discharge) both positive and negative charges can contribute to the current.
- In some solid-state materials such as those used in fuel cells or batteries both positive and negative charge carriers can contribute to the current.

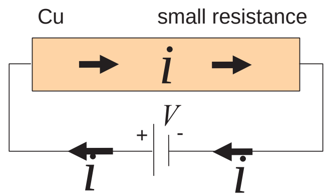


When an isolated conductor is immersed in an electric field a static charge distribution quickly establishes in the conductor, producing an internal electric field that exactly cancels the external field.



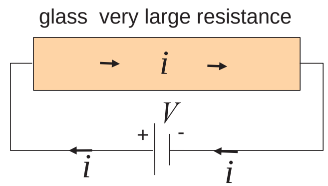
A battery establishes a non-equilibrium electric field in a conductor by expending chemical energy to continually replenish charge carriers at one end of the conductor as they are lost from the other.

Resistance:



Define resistance $R = \dfrac{V}{i}$

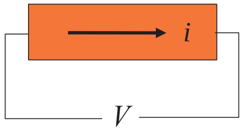
Units: 1 V/A = 1 Ω (ohm)



Resistors provide resistance values in circuits.

Resistance of a resistor depends on its geometry as well as characteristics of material used to make it.

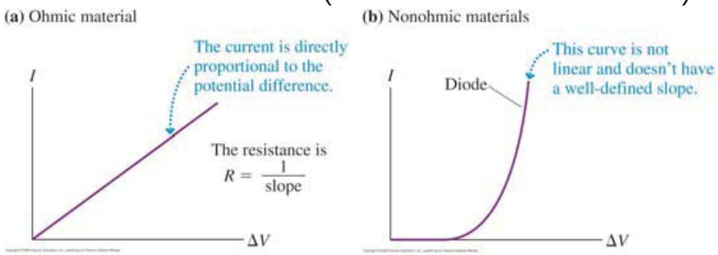
Ohm's Law:



Ohm's Law: $i = \dfrac{V}{R}$

where R = constant

(i.e. $i \propto V$ for all values of $\pm V$)

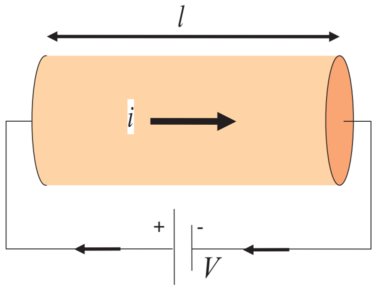


Ohmic device: one that obeys Ohm's Law (e.g. carbon film resistor)

Non-ohmic device: one that doesn't obey Ohm's Law (e.g. semiconductor diode)

Fig.31.22 Knight, Physics for Scientists and Engineers, 2nd Ed.

Relationship b/w R and ρ :



For homogeneous, isotropic conductor:

$$E = \frac{V}{l} \quad (V/m)$$

$$\Rightarrow J = \frac{i}{A} = \frac{E}{\rho} = \frac{V}{l\rho}$$

$$\Rightarrow R = \frac{V}{i} = \frac{\rho l}{A}$$

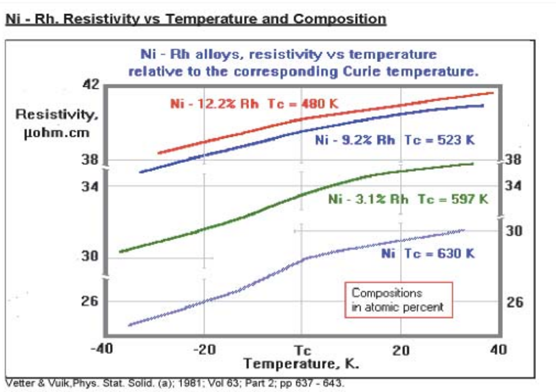
R depends directly on the resistivity of the material and the length of the conductor and inversely on the area through which the current is flowing. (Just as one would expect.)

Resistance (and resistivity ρ) vs temperature :

Resistance (and resistivity) of metal conductor increases with T since amplitude of vibration of lattice atoms increases ⇒ e's collide with lattice atoms more often.

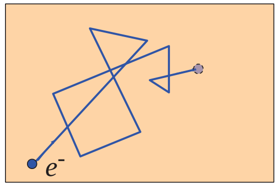
$$R = \rho \frac{l}{A}$$

Resistivity depends on the properties of the material but not its geometry.

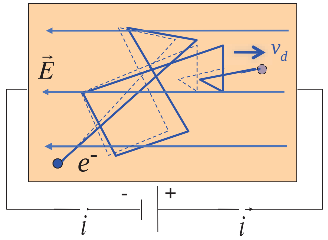


A model of conduction: Drift Speed v_d :

Without E-field:



With E-field:



Free-electron model of conductor ⇒ e's free to move throughout volume of solid (like molecules of gas in container). Thermal speed of electrons:

$$v \approx 10^6\, m.s^{-1}$$

Without E-field, motion is random, ~10^{14} collisions (with lattice atoms) per second (e in Cu) ⇒ direction constantly changing. No net movement of e's along conductor

With E-field:

- same random thermal motion
- drift speed $v_d \approx 10^{-4}$ m.s^{-1} superimposed on thermal motion
- Net movement of e's in direction opposite to E-field

A model of conduction:

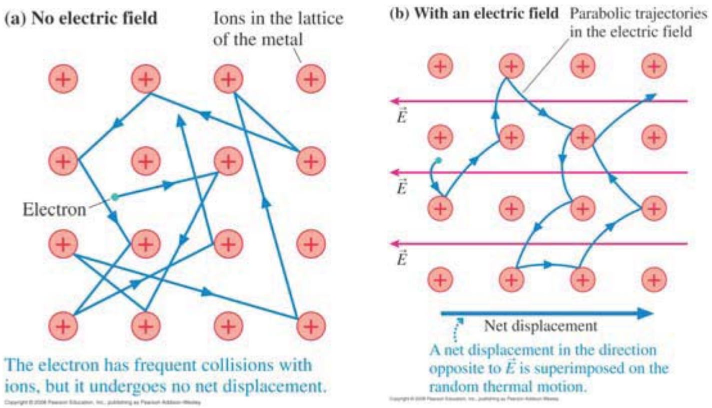


Fig.31.13 Knight, Physics for Scientists and Engineers, 2nd Ed.

Temperature dependence of resistance:

source: http://www.tracielee.com/

http://www.selfsufficientish.com/

Direct Current Circuits

Basic Circuit Elements: §32.1

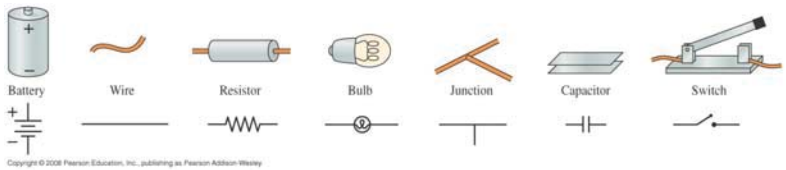
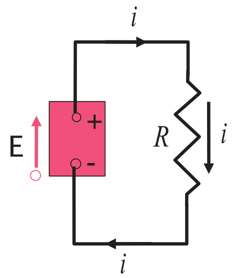


Fig.32.2 Knight, Physics for Scientists and Engineers, 2nd Ed.

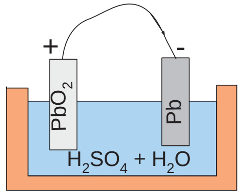
Batteries and Electromotive Force (EMF):

Battery = an example of a device which is a source of emf
(actually a source of energy rather than force)

- it is source of electric potential energy capable of pumping charge around an electric circuit while maintaining constant potential difference b/w its terminals .
- batteries convert chemical energy to electric energy.

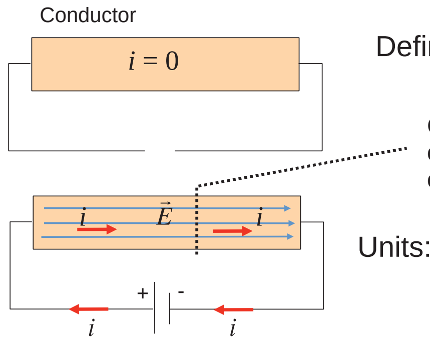


E.g lead acid battery:



$$-electrode: Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$$

$$+electrode: PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$$



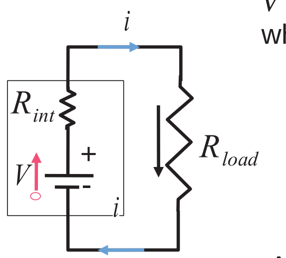
Define Current $i = \frac{dq}{dt}$

Charge dq passing through cross-sectional area of conductor in time dt

Units: 1 Ampere (A) = 1 C/s

Battery maintains electric field in conductor that keeps current flowing.

Equivalent Circuit of Battery:



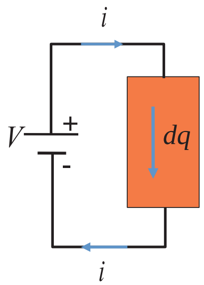
V = PD of battery under no load (i.e. when no current flows)

$$V = iR_{int} + iR_{load}$$

$$= V_{int} + V_{load}$$

As R_{int} increases, less emf available for external load.
In a battery, R_{int} tends to increase as the electrodes age i.e. with use.

Power in Electric Circuits:



Charge dq through device in time dt, potential difference V.

$\Rightarrow$ change in potential energy:

$$dU = dq\,V \quad and \quad i = \frac{dq}{dt}$$

$$\Rightarrow dU = i\,dt\,V \quad \Rightarrow power\ P = \frac{dU}{dt} = iV$$

$$\boxed{P = iV}$$

Power in Electric Circuits:

For an **ohmic conductor:**

$$i = \frac{V}{R} \Rightarrow P = \frac{V^2}{R} = i^2 R = iV$$

Power dissipated in resistors in form of heat: conduction e's lose energy to lattice atoms through collisions ⇒ lattice gains thermal energy.

$$P = iV \quad Units: 1A.V = 1\frac{C}{s}\frac{J}{C} = 1J/s = 1W$$

E.g. Power lines:

Electricity is transferred from power stations through transmission lines at very high voltages (e.g. 500 kV) and not at the 240 V used in houses. Why?

Power Lines

- 1 cm radius cable, 20 km long from LaTrobe valley to elbourne:

$$R = \rho\frac{l}{A} = 17 \times 10^{-9}\frac{20000}{\pi(0.01)^2} = 1\Omega$$

- Total power output of Loy Yang: 2200 x 10^6 W
- Transmission at 240 V:

$$i_{output} = \frac{P_{output}}{V} = \frac{2200 \times 10^6}{240} = 9.2 \times 10^6 A$$

ower Lines

- ower loss in transmission:
  $$P_{loss} = i^2 R = (9.2 \times 10^6)^2 \times 1 = 8.5 \times 10^{13} W$$
- which is far greater than the power output of the station!
- Alternatively, if we look at the current for transmission via a 1 ohm line at 240 V:

$$i_{transmission} = \frac{V}{R} = 240A$$

- and that ain't going to supply the needs of elbourne!

ower Lines

- So, let's try transmission at 500 kV:

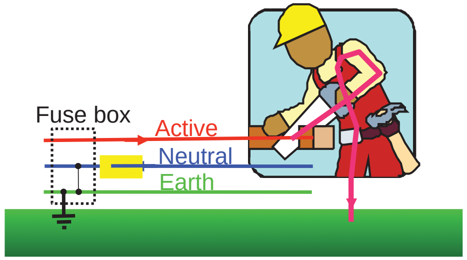
$$i_{output} = \frac{P_{output}}{V} = \frac{2200 \times 10^6}{5 \times 10^5} = 4,400A$$

$$P_{loss} = i^2 R = (4.4 \times 10^3)^2 \times 1 = 1.9 \times 10^7 W$$

- which is less than 1% of power output of the station. We can live with that!

Electrical Safety :

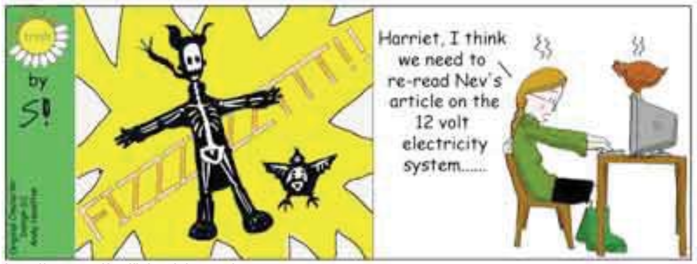
- ost electrical accidents involve AC (alternating current) rather than DC
- Current enters a house through the ACTIVE wire
- All current should return through NEUTRAL wire



- Any imbalance in ACTIVE/NEUTRAL indicates a fault!
- This “Earth Leakage” is detected by earth leakage protection circuitry and the ACTIVE is shut off

---

- Current of 1 mA causes tingling sensation.
- Higher currents ⇒ pain and strong muscle contraction.
- Above 10 mA : severe muscle contractions and victim may not be able to let go of current source.
- 20 mA through body from hands to feet produces contractions of chest muscles that halt breathing.
- 70-100 mA results in heart fibrillation (heart stops pumping blood).
- Many electrical appliances will leak 1 mA to EARTH wire by capacitive coupling.
- Earth leakage protection circuits typically set to trip at 20-30 mA.
- Patients fitted with implanted electrodes can die from as little as 0.02 mA. Electrical equipment for surgery/ monitoring must be well insulated.



http://www.selfsufficientish.com/

Be sure, Be safe!