Conceptual Physics

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Lesson V
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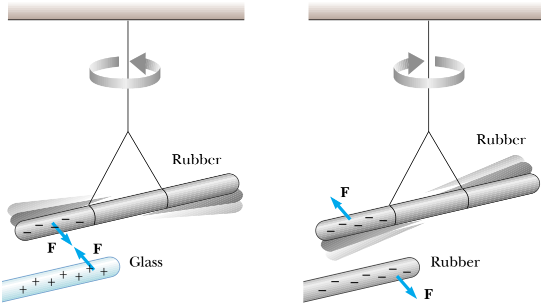
Table of Contents

- There are two types of observed electric charge which we designate as positive and negative
- Convention was derived from Franklin's experiments
- He rubbed a glass rod with silk and called charges on glass rod positive
- He rubbed sealing wax with fur and called charge on sealing wax negative
- Like charges repel and opposite charges attract each other



- Unit of charge ☞ Coulomb (C)
- Smallest unit of *free* charge known in nature ☞ charge of electron

$$e = 1.602 \times 10^{-19}\ \mathrm{C}$$

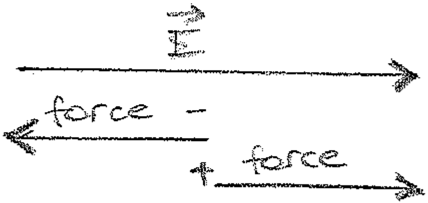
- Charge of ordinary matter is quantized in integral multiples of e
- An lectron carries one unit of negative charge $-e$ whereas a proton carries one unit of positive charge $+e$
- In closed system ☞ total amount of charge is conserved since charge can neither be created nor destroyed
- A charge can (however) be transferred from one body to another
- Consider system of two point charges q_1 and q_2 separated by distance r in vacuum

$$F_e = k_e \frac{q_1 q_2}{r^2}$$

$k_e = 8.9875 \times 10^9\ \mathrm{N\,m^2/C^2}$ ☞ Coulomb's constant

- Electric charge q ☞ produces electric field everywhere
- To quantify field strength ☞ measure force
  positive *test charge* q_0 experiences at some point
- We must take q_0 to be infinitesimally small
  so that field q_0 generates does not disturb "source charges"

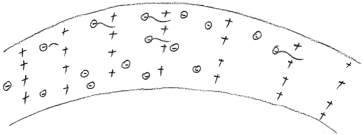
$$E = F/q_0$$



- Force direction ☞ along field if charge is positive (e.g. proton)
  and opposite to field if charge is negative (e.g. electron)

- Current i ☞ rate of flow of electric charge in wire
- Seen through some super-microscope

copper wire carrying electrical current looks like this



- $+$ charges are fixed atoms arranged on a regular array
- They vibrate in place ☞ but do not flow along wire
- $\ominus$ charges are electrons which flow along wire

bumping into fixed atoms losing their energy in this way

(i.e. “heating the wire”)

- We have seen that the electric charge is measured in coulombs
- A coulomb contains about 6 billion billion electrons
- More conveniently☞ we measure rate of flow of electric charge
- If one coulomb of charge past some point in circuit in one second

☞ current is one ampere (A)

- Electromotive force (emf) or voltage V
  energy given to each coulomb by power source
- If there are q coulombs ☞ total energy handed out $\propto V \times q$
- Then
$$\text{power} = \frac{\text{energy}}{\text{time}} \propto V \, \left(\frac{q}{t}\right) = \text{volts} \times \text{amperes}$$
- Units ☞ power (in watts) equals V (in volts) $\times$ i (in amperes)
- A watt is a small amount of power ☞ $1/1000$ of a kilowatt
- A *kilowatt* is power generated at rate of 1 kWh/hour

E.g. ☞ A light bulb rated at 100 W is connected to line voltage of 110 V

1. What is current through light bulb?

$$\text{power (watts)} = \text{voltage (volts)} \times \text{current (amperes)}$$

This implies that

$$100 \text{ watts} = 110 \text{ volts} \times \text{current}$$

and so

$$\text{current} = \frac{100 \text{ watts}}{110 \text{ volts}} = 0.9 \text{ amperes}$$

2. How much energy (in kWh) is used by light bulb in 24 hours?

$$\text{energy (kWh)} = \text{power (kilowatts)} \times \text{time (hours)}$$

since

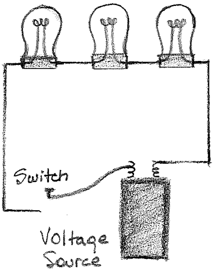
$$100 \text{ watts} = \frac{1}{10}(1{,}000 \text{ watts}) = \frac{1}{10} \text{ kilowatt}$$

we have

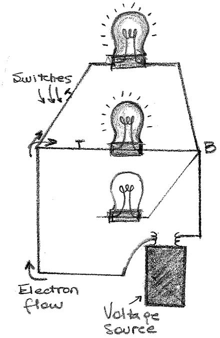
$$\text{energy} = \frac{1}{10} \text{ kW} \times 24 \text{ hours} = 2.4 \text{ kWh}$$

- *Circuit* ☞ any path along which electrons can flow
- For continuos flow of electrons ☞ there must be a complete circuit with no gaps
- Gap ☞ provided by electric switch that can be opened or closed to either cutoff or allow energy flow
- Most circuits have more than one device that receives energy
- Devices are connected in circuit in one of two ways $\left\{ \begin{array}{l} \text{series} \\ \text{parallel} \end{array} \right.$
- When connected in series ☞ form single pathway for electron flow
- When connected in parallel ☞ form branches each which is a separate path for flow of electrons

- *Series* circuit ☞ all lamps are connected end to end forming single path for electron flow
- Same current exists almost immediately in all three lamps and also in battery when switch is closed
- The greater the current in a lamp ☞ the brighter it glows
- A break anywhere in path results in open circuit and flow of electrons ceases
- Burning out one lamp filaments or simply opening switch could cause such break



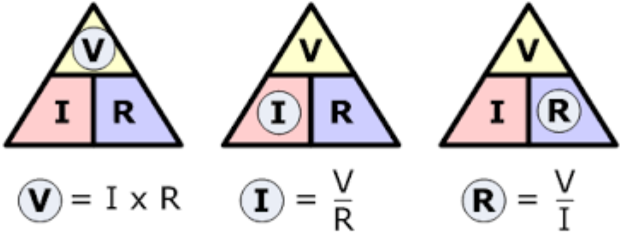
- *Parallel* circuit ☞ lamps connected to same two points: A and B
- Pathway from one terminal of battery to other
  is completed if only *one* lamp is lit
- E.g. ☞ circuit branches into 3 separate pathways from A to B
- Break in one path doesn't interrupt flow of charge in other paths
- Each device operates independently of other devices



- Relation among voltage and current is summarized by Ohm's law:
  At constant temperature
  electrical current flowing through a wire between two points
  is directly proportional to voltage across two points
- Constant of proportionality ☞ resistance R

$$i = \frac{V}{R}$$

i ☞ current through wire in units of amperes
V is voltage measured across wire in units of volts
R ☞ resistance of wire in units of ohms (Ω)



- If resistors are connected in series
  - each resistor has same current i
  - each resistor has voltage iR ☞ given by Ohm's law
  - total voltage drop across all three resistors in circuit

$$\begin{aligned} V_{\rm total} &= iR_1 + iR_2 + iR_3 \\ &= i(R_1 + R_2 + R_3) \end{aligned}$$

- When we look at all three resistors together as one unit
  we see that they have same i vs. V relation as one resistor
  whose value is sum of resistances

- So we can treat these resistors as just one equivalent resistance

$$R_{\rm eq} = R_1 + R_2 + R_3$$

  as long as we are not interested in individual voltages

- Effect on rest of circuit is same ☞ whether lumped together or not

- Resistors in parallel carry same voltage
- Current flowing through each resistor could definitely be different
- Although they have same voltage ☞ resistances could be different
- If we view three resistors as one unit ☞ with current i going in and a voltage V ☞ this unit has following i vs. V relation:

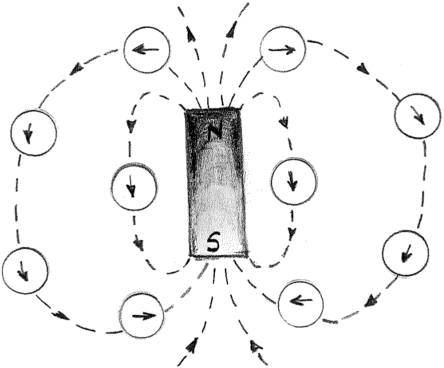
$$\begin{aligned} i &= i_1 + i_2 + i_3 \\ &= V\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) \end{aligned}$$

- To outside world ☞ parallel resistors look like one satisfying

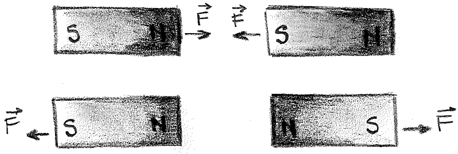
$$\frac{1}{R_{\rm eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

for equivalent resistance $R_{\rm eq}$

- Charged object produces electric field $\vec{E}$ at all points in space
- In similar fashion ☞ bar magnet is a source of magnetic field $\vec{B}$
- This can be demonstrated by moving compass near magnet
- Compass needle will line up along direction of magnetic field produced by magnet



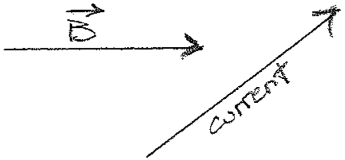
- Bar magnet consists of two poles ☞ designated N and S
- Magnetic fields are strongest at poles
- Magnetic field lines leave from N pole and enter S pole
- When holding two bar magnets close to each other
  like poles will repel each other while opposite poles attract



- Eelectric charges can be isolated but magnetic poles come in pair
- When you break bar magnet ☞ 2 new bar magnets are obtained
  each with N pole and S pole

- Magnetic *monopoles* have not been seen in isolation
  although they are of theoretical interest

- Magnetic field $\vec{B}$ exerts a force on a *moving* charge
- Direction of force ☞ perpendicular to field and motion of charge



- Magnitude of force depends on velocity of the charge v magnetic field strength B and angle between direction of $\vec{v}$ and $\vec{B}$

$$F_B = |q|\, v\, B\, \sin\theta$$

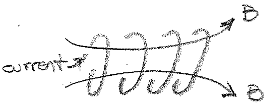
$|q|$ ☞ absolute value of charge
θ ☞ angle between $\vec{B}$ and $\vec{v}$

- Magnetic force F_B vanishes when $\vec{v}$ is parallel to $\vec{B}$

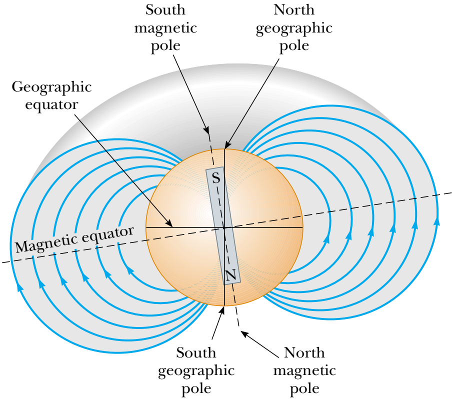
- Unit of magnetic field ☞ tesla (T)

$$\text{tesla} = \frac{\text{newton}}{(\text{coulomb})(\text{meter/second})} = \frac{\text{newton}}{(\text{ampere})(\text{meter})}$$

- We have seen that charged particle moving through B field experiences magnetic force $\vec{F}_B$
- Since electric current ☞ collection of charged particles in motion when current-carrying wire is placed in a magnetic field it will also experience a magnetic force
- Oersted noticed that electric current flowing through wire can cause a compass needle to deflect perpendicular to wire showing that current also creates magnetic field $\vec{B}$
- Lines of $\vec{B}$ surround current



- Configuration of Earth's magnetic field
  resembles gigantic bar magnet buried in interior of Earth



- When we speak of compass magnet having N and S poles
  we should say more properly it has N- and S-seeking poles
- Earth's south magnetic pole is located near north geographic pole
- Earth's north magnetic pole is located near south geographic pole