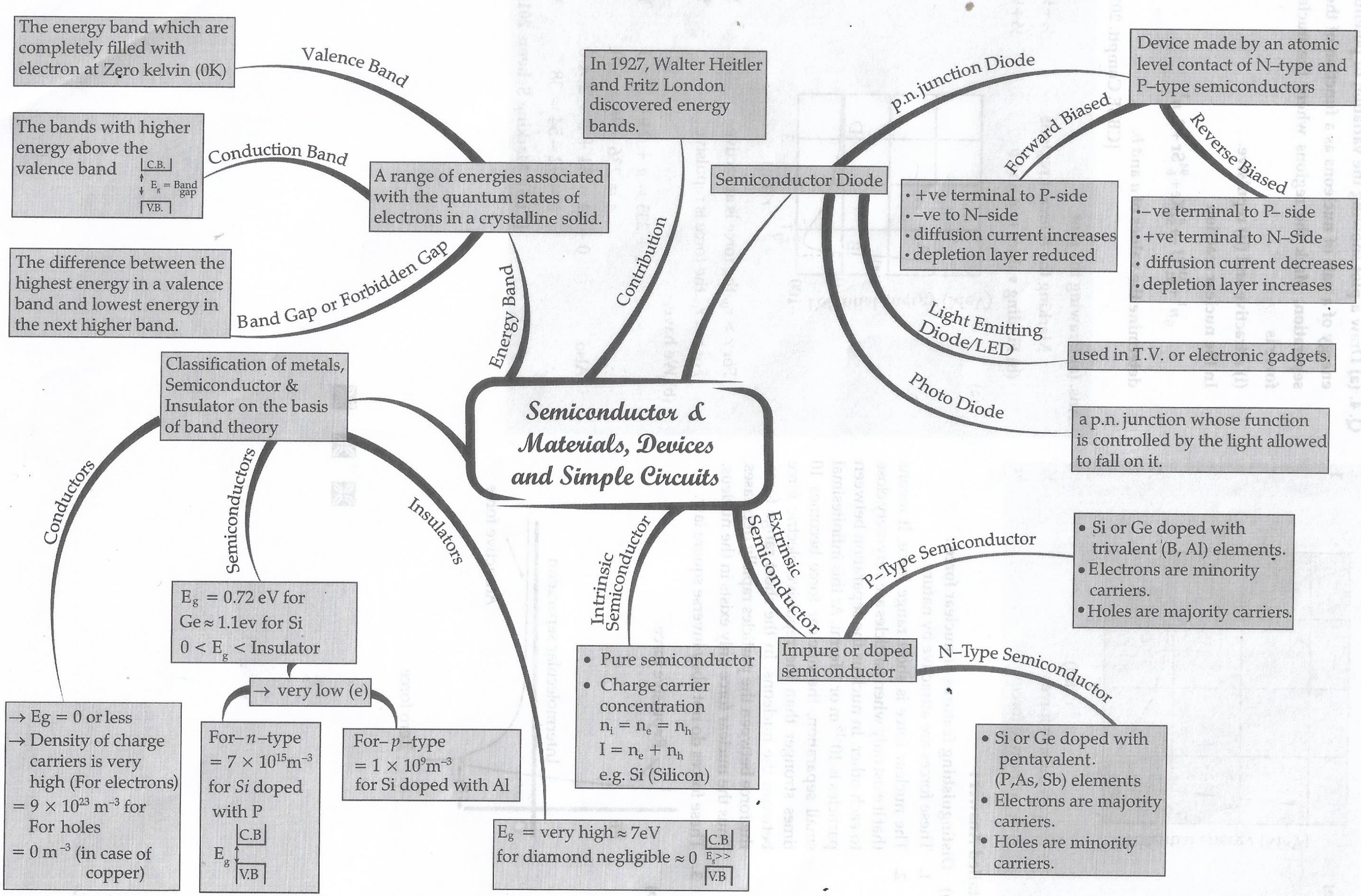


Semiconductor & Materials, Devices and Simple Circuits
Energy Band
A range of energies associated with the quantum states of electrons in a crystalline solid.
Valence Band
The energy band which are completely filled with electron at Zero kelvin (0K)
Conduction Band
The bands with higher energy above the valence band
C.B.
E_g = Band gap
V.B.
Band Gap or Forbidden Gap
The difference between the highest energy in a valence band and lowest energy in the next higher band.
Contribution
In 1927, Walter Heitler and Fritz London discovered energy bands.
Semiconductor Diode
p.n.junction Diode
Device made by an atomic level contact of N–type and P–type semiconductors
Forward Biased
• +ve terminal to P-side
• –ve to N–side
• diffusion current increases
• depletion layer reduced
Reverse Biased
• –ve terminal to P– side
• +ve terminal to N–Side
• diffusion current decreases
• depletion layer increases
Light Emitting Diode/LED
used in T.V. or electronic gadgets.
Photo Diode
a p.n. junction whose function is controlled by the light allowed to fall on it.
Classification of metals, Semiconductor & Insulator on the basis of band theory
Conductors
→ Eg = 0 or less
→ Density of charge carriers is very high (For electrons) $= 9 \times 10^{23}\ m^{-3}$ for For holes $= 0\ m^{-3}$ (in case of copper)
Semiconductors
$E_g = 0.72$ eV for Ge ≈ 1.1ev for Si
$0 < E_g <$ Insulator
→ very low (e)
For–n–type $= 7 \times 10^{15} m^{-3}$ for Si doped with P
C.B
E_g
V.B
For–p–type $= 1 \times 10^{9} m^{-3}$ for Si doped with Al
Insulators
E_g = very high ≈ 7eV for diamond negligible ≈ 0
C.B
E_g>>
V.B
Intrinsic Semiconductor
• Pure semiconductor
• Charge carrier concentration
$n_i = n_e = n_h$
$I = n_e + n_h$
e.g. Si (Silicon)
Extrinsic Semiconductor
Impure or doped semiconductor
P–Type Semiconductor
• Si or Ge doped with trivalent (B, Al) elements.
• Electrons are minority carriers.
• Holes are majority carriers.
N–Type Semiconductor
• Si or Ge doped with pentavalent. (P,As, Sb) elements
• Electrons are majority carriers.
• Holes are minority carriers.

Nuclei

- **Composition**
  - Nuclei consist of protons and neutrons.
  - Total No. of protons & neutrons in the nucleus is called nucleons
  - ${}_{Z}X^{A}$, $A = Z + N$ = Mass Number
    - A = Atomic Number
    - N = No. of neutrons
- **Contribution**
  - In 1896, Henri Becquerel discovers Radioactivity
- **Mass-Energy Relation**
  - Einstein showed that mass is an another form of energy and gave a relation $E = mc^2$
- **Mass Defect**
  - $\Delta M = [Z m_p + (A - Z)m_n] - M$
  - m_p = mass of proton, m_n = mass of neutron
  - M = mass of nucleus
- **Nuclear Fission**
  - Splitting of a heavy nucleus into two or more lighter nuclei.
  - *e.g.,* ${}_{92}U^{235} + {}_{0}n^{1} \rightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3{}_{0}n^{1}$ +200 mev
- **Nuclear Fusion**
  - Combining two lighter nuclei to form a heavy nucleus
  - *e.g.,* ${}_{1}^{1}H + {}_{1}^{1}H \rightarrow {}_{1}^{2}H + e^{+} + \nu + 0.42$ MeV (energy)
- **Types of Nuclei**
  - **Isotopes**
    - Same atomic No.(Z)
    - Different mass No.(A)
    - e.g. ${}_{6}C^{12}, {}_{6}C^{14}$
  - **Isobars**
    - Same mass No.(A)
    - Different atomic No.(Z)
    - e.g. ${}_{6}C^{14}, {}_{7}N^{14}$
  - **Isotone**
    - Atoms whose nuclei having same number of neutrons(N)
    - e.g. ${}_{11}Na^{23}, {}_{12}Mg^{24}$
- **Size of Nucleus**
  - **Nuclear Radius**
    - $R = R_0 A^{1/3}$
    - $R_0 = 1.2 \times 10^{-15}$ m
    - A = Mass No.
  - **Nuclear Volume**
    - $V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi R_0^3 A$
    - $V \propto A$ (mass no.)
  - **Nuclear Density**
    - $\rho = \frac{\text{mass of nucleus}}{\text{volume of nucleus}} = \frac{A \times 1.67 \times 10^{-27}}{\frac{4}{3}\pi \times (1.2 \times 10^{-15})^3 \times A}$
    - $\approx 2.9 \times 10^{17}$ kgm^{-3} (independent of A)

Atoms

Contribution

In 1898, J.J Thomson proposed the first model of atom known as plum-pudding model.

α – particle scattering experiment

- α- particle bombarded on thin gold foil
- Most of α– particles passed undeviated or with a small angle
- 1 out of 8000 α– particles were deflected by scattering angle

Impact parameter

$$b = \frac{Ze^2 \cot\theta/2}{4\pi\varepsilon_0\left(\frac{1}{2}mv^2\right)}$$

Rutherford's Model

Postulates

- Atoms have a central, massive, positively charged core called nucleus around which electrons revolve.
- Size of nucleus ≈ 1 fermi = 10^{-15} m

Drawbacks

- Doesn't explain the stability of atom
- Doesn't explain the atomic spectra

Energy Level

Energy of electron in each stationary orbits is

Given by $E_n = -13.6\,\frac{Z^2}{n^2}$ eV

Where $n = 1,2,3....$

Z = atomic number of atom

- These stationary energy orbits are also called energy levels.
- When electron jumps from higher energy level to lower energy level, it releases energy.

$$\Delta E = E_f - E_i = 13.6\left[\frac{1}{n_i^2} - \frac{1}{n_f^2}\right]Z^2 \text{eV}$$

Hydrogen Spectrum

- Hydrogen gas heated in a sealed tube emits radiation which passes through prism components of different wavelength appear.
- Wavelength in each series given by

$$\bar{v} = \frac{1}{\lambda} = R\left[\frac{1}{n_i^2} - \frac{1}{n_f^2}\right]$$

$n_f > n_i$

- Lyman series [U.V. region]
  $n_i = 1$, $n_f = 2,3,4....$
  $\lambda_{min} = 912$ Å , $\lambda_{max} = 1216$ Å
- Balmer series [visible region]
  $n_i = 2$ $n_f = 3, 4, 5.....$
  $\lambda_{min} = 3648$ Å , $\lambda_{max} = 6563$ Å
- Paschan series [I–R region]
  $n_i = 3$ $n_f = 4, 5, 6.....$
  $\lambda_{min} = 8208$ Å , $\lambda_{max} = 18761$ Å
- Brackett series [I R region]
  $n_i = 4$ $n_f = 5, 6, 7...$
  $\lambda_{min} = 14592$ Å $\lambda_{max} = 40533$ Å
- P –fund [I R region]
  $n_i = 5$ $n_f = 6, 7, 8......$
  $\lambda_{min} = 23850$ Å $\lambda_{max} = 74618$ Å

Bohr Model

Postulates

- Electron revolves around the nucleus in stationary orbits.
- Angular momentum of electron
  $mvr_n = n \times \frac{h}{2\pi}$ where n is an integer
  It is also known as principle Quantum Number.
- It explains spectrums of hydrogen or hydrogen like [He^+, Li^{++}] atoms.

Limitations

- Fails to explain spectrum of complex atoms/ions of multi electron system.
- Doesn't explain Zeeman's and Stark's effect.

Radius of nth Bohr's orbit

$$R_n = \frac{\varepsilon_0 h^2}{\pi me^2}\left(\frac{n^2}{Z}\right) = 0.53\,\frac{n^2}{Z}\,\text{Å}$$

Velocity of electron in nth Bohr's orbit

$$v_n = \frac{e^2}{2\varepsilon_0 h}\left(\frac{Z}{n}\right) = 2.2 \times 10^6\,\frac{Z}{n}\ \text{m/s}$$

Potential Energy

$$U_n = -\frac{KZe^2}{r_n} = \frac{-me^4}{4\varepsilon_0^2 h^2}\left(\frac{Z^2}{n^2}\right) = \frac{-27.2\,Z^2}{n^2}\text{eV}$$

Kinetic Energy

$$E_k = \frac{KZe^2}{2r_n} = \frac{me^4}{8\varepsilon_0^2 h^2}\frac{Z^2}{n^2} = \frac{13.6^2}{n^2}Z^2\text{eV}$$

Total Energy

$$E = U_n + E_k = -\frac{KZe^2}{2r_n} = \frac{-13.6\,Z^2}{n^2}\text{eV} = \frac{U_n}{2} = -E_K$$

Dual Nature of Radiation & Matter

Dual Nature of Radiation

- Light has both wave character as well as particle nature
- Interference can be explained by wave nature
- When light is of sufficiently low wavelength, it behaves as particle
- Light particles having definite energy and definite linear momentum are called "photons"
  Energy of each photon $= h\nu = hc/\lambda$
  Momentum of each photon $= h/\lambda = E/c$

Contribution

Einstein, after an average academic career put forward quantum theory of light in 1905 while working as a grade III technical officer in a patent office.

Matter waves

All matter can exhibit wave–like behaviour e.g. beam of electrons can be diffracted like a water wave

de - Broglie relation

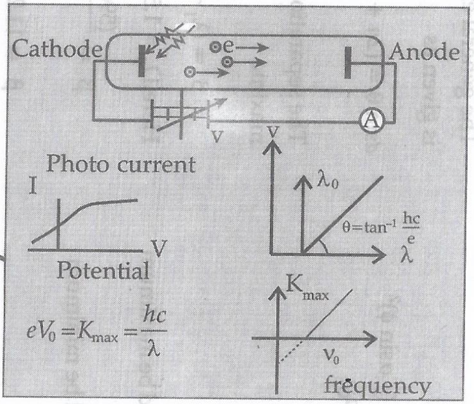
$\lambda = h/p$

λ = wavelength associated with particle or de-Broglie wavelength

p = momentum

$$\lambda = \frac{h}{mv} = \frac{h}{\sqrt{2\,m\,K_{max}}}$$

Hertz and Lenard's Observation



$$eV_0 = K_{max} = \frac{hc}{\lambda}$$

Photoelectric Effect

- When light of sufficient small wavelength is incident on metal surface, electrons are ejected from the metal, the phenomenon is called photoelectric effect.
- Ejected electrons are called photoelectrons
- Minimum energy equal to work function (ϕ) must be given to an electron so as to bring it out of the metal

Einstein's Photoelectric equation

- $K_{max} = E - \phi = eV_0$
  $= \frac{hc}{\lambda} - \phi$, V_0 = stopping potential
  K_{max} = maximum kinetic energy of elected electrons

Here, $\lambda_0 = hc/\phi$

λ_0 = Threshold Wavelength

$\lambda_0 = c/\nu_0 = \phi/h$

ν_0 = Threshold frequency

$K_{max} = \lambda(\nu - \nu_0)$

- If $\lambda = \lambda_0 = hc/\phi$
  $K_{max} = 0$, *i.e.*
  Electron may just come out onto the surface
- If $\lambda > \lambda_0$
  i.e. $E < \phi$
  no electron will come out
- If $\lambda \leq \lambda_0$.
  Photoelectric effect takes place this λ_0
- λ_0 = depends on metal used

Wave Optics

- **Wave front**
  - •Locus of all particles vibrating in some phase
    - For spherical wavefront
      $I \propto \frac{1}{r^2}$
      $A \propto \frac{1}{r}$
  - Each point on the primary wavefront is the source of a secondary wavelets
- **Huygens' Principle**
  - Each point on the primary wavefront is the source of a secondary wavelets
- **Interference of Light**
  - Two waves superimpose to form a resultant wave of greater or lower or same amplitude.
    $I = \left(\sqrt{I_1} + \sqrt{I_2}\right)^2 = \beta\left(A_1 + A_2\right)^2$
    - •For constructive Interference,
      $A = A_1 + A_2$
    - •For destructive interference, $A = \left(A_1 - A_2\right)$
- **Diffraction of light by single slit**
  - $b\sin\theta = \eta\lambda$ (dark fringe)
  - Linear width of central maxima
  - Width of central maxima $= \frac{2\lambda}{b}$
  - Angular width $= \frac{2D\lambda}{b}$
  - $b\sin\theta = (2n+1)\,\frac{\lambda}{2}$
  - (for maxima bright fringe)
- **Coherent source**
  - Two sources of light are said to be coherent if the initial phase difference between the waves emitted by the sources remains constant in time, otherwise they are called Incoherent source of light.
- **Young's Double Slit Experiment**
  - **Fringe-width**
    - $\beta = \frac{D}{d}\lambda$
    - It is the distance between two consecutive, bright or dark fringes.
  - **Based on interference of light**
    - Distance between nth bright fringe and central fringe
      $x_n = \frac{n\lambda D}{d}$
      D= distance between source and screen
    - Distance between nth dark fringe and central fringe
      $x_n = \frac{(2n-1)\lambda D}{2d}$
      d = distance between slits
  - **Path difference**
    - • For bright fringe
      $\Delta\phi = n\lambda$
    - • For dark fringe
      $\Delta\phi = \left(n + \frac{1}{2}\right)\lambda$

Ray Optics & Optical Instruments

Sign Conventions

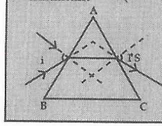
- Pole is taken as origin
- Principle axis as the X-axis
- All distances are measured from origin (or pole)
- All distances measured in the direction of incident ray are taken + ve.
- All distances measured in the direction opposite to the incident ray are taken - ve.

Prism

Angle of deviation $\delta = i - i' - A$

$\delta_{minimum} = 2i - A \quad [i = i']$

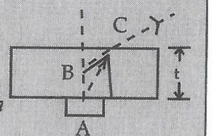
$\delta_{minimum} = (\mu - 1)A$, if A is small



Refraction of light

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\mu_2}{\mu_1}$$

$$\mu = \frac{real\ depth}{apparent\ depth}$$



$$\Delta t = \left(1 - \frac{1}{\mu}\right)t = \text{image shift}$$

Total internal reflection

When ray passes from optically denser to rarer medium, if incident angle (i) further increased till $(\theta)_c$ critical angle, entire light is then reflected back to the denser medium again, this process is called T.I.R. It is used in optical fibre.

Critical Angle

- Incident angle (θ_c) for which angle of refraction is 90°

i.e. $\sin\theta_c = 1/\mu$

$$\theta_c = \sin^{-1}\left(\frac{1}{\mu}\right)$$

When ray passes from optically denser to rarer medium.

Refraction on Spherical surface

$$\frac{\mu_2}{v} - \frac{\mu_1}{u} = \frac{\mu_2 - \mu_1}{R}$$

Lateral Magnification

$$m = \frac{h_2}{h_1} = \frac{\mu_1 v}{\mu_2 u} = \frac{R - v}{R - u}$$

Lens Maker's Formula

$$\frac{1}{v} - \frac{1}{u} = \frac{\mu_2 - \mu_1}{\mu_1}\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

$$\frac{1}{f} = \left(\frac{\mu_2}{\mu_1} - 1\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

$$\frac{1}{f} = (\mu - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \quad [If\ \mu_2 = \mu, \mu_1 = 1\ (air)]$$

$$\frac{1}{f} = \frac{1}{v} - \frac{1}{u} \quad \text{(lens formula)}$$

Lateral Magnification $= \dfrac{h_2}{h_1} = \dfrac{v}{u}$

Power of a lens

$$P = \frac{1}{f}$$

[For combination of lens]

$$P = \frac{1}{f_1} + \frac{1}{f_2}$$

Optical Instruments

Microscope

$M = 1 + \dfrac{D}{f}$ [image at near point]

$M = D/f$ [image at infinity]

Compound Microscope

$M = \dfrac{v}{u}\left[\dfrac{D}{f_e}\right]$ [normal adjustment]

$$M = \frac{v}{u}\left(1 + \frac{D}{f_e}\right) = -\frac{1}{f_o}\left(1 + \frac{D}{f_e}\right)$$

For final image at least distance

Telescope

$M = \dfrac{f_o}{f_e}\left(1 + \dfrac{f_e}{D}\right)$ [image at near point]

$M = -\dfrac{fo}{fe}$ [image at infinite].

Electromagnetic Waves

History

In 1886 Heinrich Hertz became the first person to transmit and receive controlled radio waves

Conduction Current

The current due to flow of charge is often called conduction current

$$i_c = \frac{dq}{dt}$$

Electromagnetic spectrum

- Radio waves $\lambda > 10^8$nm
  Use : radio, TV signal
- Micro waves $10^8 > \lambda > 10^5$nm
  Use : micro wave oven, radar
- Infrared $10^5 > \lambda > 700$ nm
  Use : night vision
- Visible light $700 > \lambda > 400$ nm
  Use : to observe world
- UV rays $400 > \lambda > 10$nm
  Use : destroying bacteria
- X-rays $10 > \lambda > 0.01$ nm
  Use : detect bone break
- γ rays $0.01\text{nm} > \lambda$
  Use : to treat cancer

Maxwell's Equations

Gauss's Law (electricity)

$$\oint \vec{E}.\vec{ds} = \frac{q_{in}}{\varepsilon_0}$$

Gauss's Law (magnetism)

$$\oint \vec{B}.\vec{ds} = 0$$

Faraday's Law

$$\oint \vec{E}.\vec{dl} = \frac{-d\phi_B}{dt}$$

Ampere's Law

$$\oint \vec{B}.\vec{dl} = \mu_0 i + \mu_0\varepsilon_0 \frac{-d\phi_E}{dt}$$

Energy density

- $U = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2}\frac{B^2}{\mu_0}$ =Total energy per unit volume
- U_{av} over a long time
  $= \frac{1}{4}\varepsilon_0 E_0^2 + \frac{1}{4}\frac{B_0}{\mu_0}$
  $= \frac{1}{2}\varepsilon_0 E_0^2$ [as $c = B/E_0$ & $\mu_0\varepsilon_0 = \frac{1}{c^2}$]
  $= \frac{1}{2}\frac{B_0^2}{\mu_0}$

Characteristics of Electromagnetic waves

- Do not need any material medium for propagation
- Travel with speed of light $(c) = \frac{1}{\sqrt{\mu_0\varepsilon_0}}$
- Produced be accelerated charged particle
- Transverse in nature
- Oscillating electric & magnetic fields are in phase and their ratio is contant $(c)=E_0/B_0$

Combination of mutually perpendicular electric & magnetic fields is referred to as an electromagnetic wave

Alternating Current

AC Current

Direction of current changes alternatively
$i = i_0 \sin\omega t$
$v = v_0 \sin\omega t$

- **RMS value or root mean square value**
  $i_{rms} = i_0/\sqrt{2}$
  $v_{rms} = v_0/\sqrt{2}$
- **Mean value or Average value**
  $i_{mean} = 2i_0/\pi$
  $v_{rms} = 2v_0/\pi$
- **Peak value or Max^m value**
  $i_0 = \sqrt{2}\, i_{rms}$
  $v_0 = \sqrt{2}\, v_{rms}$

Impedance

The ratio of emf applied and the current produced in an AC circuit
$Z = E_0/i_0$ Ohm

Reactance

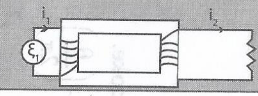
The hindrance offered by inductor or capacitor or both to the flow of AC (χ)

Contribution

In 1883, Nikola Tesla constructed the first induction motor at the age of 27 years only.

A C Generator

A device generating alternating current having elements magnet, Armature and graphite Brushes
emf induced through coil
$E = NBA\,\omega \sin\omega t$
$i = E/R = NBA\,\omega \sin \omega t/R$



$E_2 = N_2E_1/N_1$
$i_2 = N_1E_1/N_2$
If $N_2 > N_1$ it is called step–up Transfomer
If $N_1 > N_2$, it is called step–down

Transformer

It is used to obtain a high AC voltage from a Low–voltage AC source or vice–versa

- **Efficiency of a transformer**
  η = output power/Input power
  99% efficiency can easily achieved

Power in AC Circuit

$P = E_{rms}\, i_{rms} \cos\phi = \frac{E_0}{\sqrt{2}} \times \frac{i_0}{\sqrt{2}} \cos\phi = \frac{1}{2} E_0 i_0 \cos\phi$

A C Circuits

Inductive (L) circuit

$i = i_0 \sin\left(\omega t - \frac{\pi}{2}\right)$
Phase difference b/w V& I, $\phi = \pi/2$
Power factor $\cos(\phi) = 0$
Voltage leads current by $\pi/2$
$P = 0$

Capacitive (C) circuit

$i = i_0 \sin\left(\omega t + \frac{\pi}{2}\right)$
$\phi = \pi/2$ or $-\pi/2$
$\cos\phi = 0$
Power(P) $= 0$
Current leads the voltage by $\pi/2$

Resistive (R) circuit

$i = i_0 \sin(\omega t)$
$\phi = 0°$
$\cos\phi = 1$
$P = V_0 I_0/2$
Current & voltage both are in same phase

R–C circuit

$i = i_0 \sin(\omega t + \phi)$
$Z = \sqrt{R^2 + X_c^2}$
$X_c = 1/\omega C$
$\tan\phi = 1/\omega CR$
$i_0 = E_0/Z$
- Power factor $\cos\phi = \frac{R^2}{\sqrt{R^2 + X_c^2}}$
- current leading.

L–C circuit

$i = i_0 \sin\left(\omega t \pm \frac{\pi}{2}\right)$
$X = X_L - X_C$
$\phi = \pi/2$
- Power factor = 0, Either voltage or current leading

L–R circuit

$i = i_0 \sin(\omega t + \phi)$
$Z = \sqrt{R^2 + X_L^2}$
$X_L = \omega L$
$\tan\phi = \omega L/R$
$i_0 = E_0/Z$
- power factor = R/Z
- voltage is leading

L–C–R circuit

$i = i_0 \sin(\omega t \pm \phi)$
$Z = \sqrt{R^2 + (X_c - X_L)^2}$
$X = X_c - X_L$
$= \left(\frac{1}{\omega c} - \omega L\right)$
$\tan\phi = \left(\frac{1}{\omega c} - \omega L\right) / R$, $i_0 = \frac{E_0}{Z}$

Electromagnetic Induction

Faraday's Law of Electromagnetic Induction

1- Whenever magnetic flux through an area bounded by a closed conducting loop changes, an emf is produced in the loop.

2- The emf is given by $E = -d\phi/dt$ where $\phi = \int \vec{B}.\vec{ds}$ is the magnetic flux through the area.

In 1831, Michael Faraday discovered electromagnetic induction and James Clerk Maxwell mathematically described it.

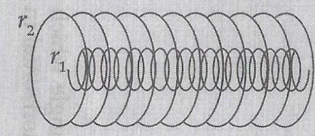
Mutual Inductance

$\phi = Mi$

$\frac{d\phi}{dt} = -M\frac{di}{dt}$

$M_{12} = \mu_0 n_1 n_2 \pi r_1^2 l$

$M_{21} = \mu_0 n_1 n_2 \pi r_2^2 l$



Emf induced in an AC generator, $E = NBA\omega \sin \omega t$

Lenz's Law

The direction of the induced current is such that it opposes the change that has induced it.

Self Induction

If we consider a solenoid of N turns, the flux through each each turn $= \phi = \int \vec{B}.\vec{ds}$

emf induced between the ends of coil $= E = -N\frac{d}{dt}\int \vec{B}.\vec{ds}$

Self Inductance of long Solenoid

$L = \mu_0 n^2 \pi r^2 l$

n = no. of turns per unit length.

ϕ = flux $= (\mu_0 n i)\, \pi r^2$

r = radius of each loop of solenoid

- **Growth of current in LR Circuit**

  $i = \frac{E}{R}(1 - e^{tR/L}) = i_0(1 - e^{-t/\tau})$

- **Decay of current**

  $i = i_0 e^{-t/\tau}$

- **Energy stored in an Inductor**

  $U = \frac{1}{2}Li^2$

Eddy Current

It is induced when magnetic flux linked with the conductor changes.

Induced current

$I = \frac{E}{R} = -\frac{1}{R}\frac{d\phi}{dt}$

Induced EMF

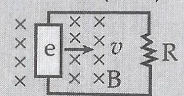
$E = \frac{-d\phi}{dt}$

Motional EMF

$E = \left|\frac{d\phi}{dt}\right| = \left|Bl\frac{dx}{dt}\right|$

$= Blv$

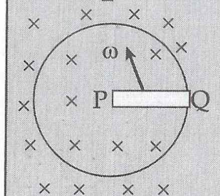
$i = Blv/(R+r)$



r = resistance of rod moving with velocity v in uniform magnetic field $\vec{B}$

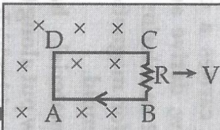
EMF induced in a rotating conductor

$E = \frac{1}{2}B\omega l^2$



Where l = length of rod

Rectangular loop



emf induced

$E = vBl$

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

Magnetic force on the loop

$F = B^2 l^2 v/R$

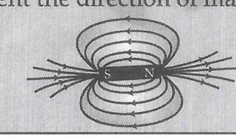
= force required to move the loop with constant velocity (v)

Thermal power developed in the loop is

$P = \frac{v^2 B^2 l^2}{R}$

Magnetism & Matter

- **Earth's Magnetic field**
  - Earth is a natural source of magnetic field having geometric north and geometric south pole
    - **Declination**: Angle b/w magnetic meridian and geographical meridian.
    - **Inclination or dip (δ)**: Angle made by earth's magnetic field with horizontal in the magnetic direction $\delta_{equator} = 0, \delta_{pole} = 90°$
    - **Horizontal component**: $B_H = B\cos\theta$; B_H (at pole) $= 0$; B_H(at equator) is maximum
- **Magnetic field Lines**
  - Continuous imaginary lines which represent the direction of magnetic field.



- **Electromagnets**
  - Magnet in which the magnetic field is produced by an electric current. Magnetic field disappears when current is turned off.
- **Megenetic Terms**
  - Magnetic Intensity: $H = \frac{B_0}{\mu}$
  - Magnetic permeability: $\mu = \mu_0(1+\chi_m)$
  - Magnetic susceptibility: $\chi = \frac{I}{H}$
  - Intensity of magnetization: $I = \frac{M}{V}$
  - Time period oscillating bar magnet: $T = 2\pi\sqrt{\frac{I}{MB}}$
- **Bar Magnet**
  - **Potential Energy of a Field-Magnet System**: $U_\theta = U_\theta - U_{90°} = -MB\cos\theta = -\vec{M}.\vec{B}$ we take P.E. at $\theta = 90°$ to be zero
- **Dipole moment**
  - **Circular Loop**: Current loop of area $A = \pi r^2$ carrying current i may be replaced by a magnetic dipole of dipole moment $\mu = md = iA$
  - **Revolving Electron**:
    - $|\vec{\mu}| = iA = \frac{ev}{2\pi r} \times \pi r^2$
    - $= evr/2$
    - $\vec{\mu} = \frac{-e}{2m_e}\vec{L}$
    - $\mu = md$
    - m = magnetic charge or pole strength
    - d = separation between poles
    - r = radius of circular orbit
    - e = charge on electron
    - v = speed of electron;
    - L = angular momentum
    - m_e = mass of electron
  - **Solenoid**: $\mu = NIA$, N = no. of turns, I = current, A = area

Moving Charges & Magnetism

Magnetic Field $(\vec{B})$

- It is a region around a magnet or current carrying conductor or a moving charge in which its magnetic effect can be felt
- SI unit is Tesla(T) = weber/m^2
- 1 Gauss = 10^{-4} Tesla where gauss is the CGS unit

Magnetic Force on a moving charge

$\vec{F} = q(\vec{v}\times\vec{B})$

$= qvB\sin\theta$

- For $\theta = 0$, $\vec{F} = 0$ along the magnetic field
- For $\theta = 90°$, *i.e.* if charge's velocity is perpendicular to field direction, Force is perpendicular to both field & velocity

$F = qvB = \dfrac{mv^2}{r}$

$r = \dfrac{mv}{qB}$ = radius of the circle in which charge rotates

Time period (T) $= \dfrac{2\pi m}{qB}$

ν(frequency) $= \dfrac{1}{T} = \dfrac{qB}{2\pi m}$

If $\theta \neq 0, 180°, 90°$

Then, $F = qvB\sin\theta$

And the charge particle will follow helical path whose

$r = \dfrac{m v_{\perp}}{q B}$ and pitch $= V_{\parallel} \times T = V_{\parallel} \times \dfrac{2\pi m}{qB}$

Oersted's Law

In April 1820, Hans Christian Oersted discovered that flow of current in a wire can deflect a nearby magnetic compass needle.

Biot-Savart Law

$\odot$ $\otimes$

$d\vec{B} = \dfrac{1}{4\pi\varepsilon_0 c^2}\dfrac{i d\vec{l}\times\vec{r}}{r^3}$

$d\vec{B} = \dfrac{\mu_0}{4\pi}\dfrac{i d\vec{l}\times\vec{r}}{r^3}$ [θ = angle between $d\vec{l}$ and $\vec{r}$]

$dB = \dfrac{\mu_0}{4\pi}\dfrac{i dl\sin\theta}{r^2}$ [Direction of field will be perpendicular to plane containing current element and the point of observation]

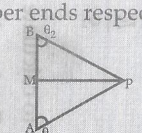
where $\mu_0 = \dfrac{1}{\varepsilon_0 c^2}$

$= 4\pi \times 10^{-7}$ TmA^{-1}

Magnetic field due to straight wire current

$B = \dfrac{\mu_0 i}{4\pi d}(\sin\theta_1 + \sin\theta_2)$

where θ_1 and θ_2 are the angle corresponding to the lower and upper ends respectively



Field due to a long straight current carrying wire

i.e $\theta_1 = 0$

$\theta_2 = \pi$

$B = \dfrac{\mu_0 i}{2\pi d}$

Ampere's Law

$\oint \vec{B}.d\vec{l} = \mu_0 i$

where i = total current crossing the area bounded by closed curve.

Solenoid

- Magnetic field at a point inside due to a long solenoid $B = \mu_0 ni$
- At a point on one end $B = \dfrac{\mu_0 n i}{2}$

where n = no. of turns per unit length along the length of solenoid.

Magnetic field due to Toroid

$B = \dfrac{\mu_0 Ni}{2\pi r}$, N = total no. of turns, i = current in toroid

Force on a current carrying conductor

$d\vec{F} = i(d\vec{l}\times\vec{B})$, $F = ilB$

Force between parallel current carrying wires

$F = \dfrac{\mu_0 i_1 i_2}{2\pi d}$

Torque experienced by a loop in uniform magnetic field

$\vec{\tau} = MB\sin\theta\,\hat{n} = \vec{M}\times\vec{B}$ carrying wires

Definition of Ampere

If two parallel wire kept 1 m apart, if and $F = 2 \times 10^{-7}$, then current = 1A in each wire.

Sensitivity

Sensitivity of moving coil galvanometer is nBA/k

Galvanometer

- Ammeter: $S = \dfrac{I_g}{I_T - I_g}G$
- Voltmeter: $R = \dfrac{V}{I_g} - G$

Field due to a current carrying circular ring $\odot$

- Field at the centre: $B = \dfrac{\mu_0 i}{2a}$ $\otimes$ $\odot$
- Field at an axial point: $B = \dfrac{\mu_0 i a^2}{2(a^2+d^2)^{3/2}}$
- Field at a point far away from the centre: i.e. for $d >>> a$, $B = \dfrac{\mu_0 i a^2}{2d^3}$

Current Electricity

Current density

$\vec{J} = \dfrac{\Delta i}{\Delta s \cos\theta} = \sigma E$

Δs = area of cross-section

θ = angle between Area vector & current flow

σ = conductivity

Drift velocity

$V_d = \dfrac{i}{neA} = \dfrac{J}{ne}$

Mobility

$\mu = \dfrac{V_d}{E} = \dfrac{e\tau}{m}$

τ = average collision time

Ohm's Law

$J = \sigma E$
or
$V = IR$

Resistance

$R = \rho \dfrac{l}{A} \tau$

Resistivity

$\rho = \dfrac{1}{\sigma} \Omega\, m$

conductivity

$\sigma = J/E$

Temperature Dependence of Resistance

$R = R_0[1 + \alpha (T - T_0)]$

$\rho = \rho_0 \int [1 + \alpha (T - T_0)]$

R = resistance at temperature T

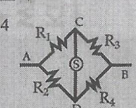
R_0 = resistance at temperature T_0

α = coefficient of resistivity

Wheatstone Bridge

- Condition for balanced

If $\dfrac{R_1}{R_2} = \dfrac{R_3}{R_4}$



- $V_c = V_D$

No current through G

Electric Current

Rate of flow of charge through an area.

$i = \dfrac{Q}{t}$

$i = \int \vec{J}.\vec{ds}$

Meter Bridge

Unknown resistance

$S = \dfrac{R(100-l)}{l}$

l = balancing length

R = known resistance

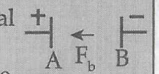
Electric cell

It is a device which maintains a potential difference between its two terminals.

E MF

$emf = E = \dfrac{W}{q} = \dfrac{F_b}{d}$

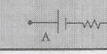
It is equal to the potential difference between the terminals when the terminals are not connected externally.



Internal Resistance

$V_A - V_B = E - ir$

r = internal resistance of the cell



Grouping of Cell

Parallel grouping

$E_{eq} = \dfrac{E_1 r_2 + E_2 r_1}{r_1 + r_2}, \; i = \dfrac{E_{eq}}{R + \dfrac{r_1 r_2}{r_1 + r_2}}$

Series grouping

$i = \dfrac{E_1 + E_2}{R + (r_1 + r_2)} = \dfrac{E_0}{R_1 + R_2}$

$E_0 = E_1 + E_2, \quad R_2 = r_1 + r_2$

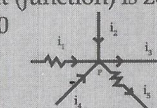
Kirchhoff's Law

Junction Law

$i_1 + i_2 + i_4 = i_3 + i_5$

The algebraic sum of all currents directed towards a point (junction) is zero.

$\Sigma I_P = 0$



Loop Law

The algebraic sum of all the potential difference along a closed loop is zero.

Potentiometer

$P = \dfrac{V_A - V_B}{l} = \dfrac{\text{potential difference}}{\text{length of wire}}$

Comparison of emf, $\dfrac{E_1}{E_2} = \dfrac{l_1}{l_2}$

Internal Resistance (r) $= R\left(\dfrac{l_1}{l_2} - 1\right)$

l_1 and l_2 are lengths of null point

Electrostatic Potential & Capacitance

Electric Potential

- Work done per unit test charge by an external agent in moving the test charge from reference point to the desired point. Its SI unit is J/C

  V_0 = Work. Its SI Unit charge

Electric potential due to a point charge

$V_P = Q/4\pi\varepsilon_0 r$

Potential due to a system of charges

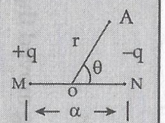
$$V = \frac{1}{4\pi\varepsilon_0}\sum \frac{Q_i}{r_i}$$

Potential due to a dipole

$$V = \frac{1}{4\pi\varepsilon_0}\frac{p\cos\theta}{r^2}$$

Where $p = qd$

$\theta = \angle AON$



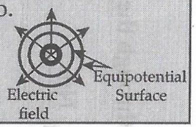
At $\theta = 0$, $V = \frac{1}{4\pi\varepsilon_0}\frac{p}{r^2}$ [axial position]

At, $\theta = 90°$, $V = 0$ [equitorial position]

In 1774, Alessandro Volta wrote treatise"on the forces of attraction of electric fire".

Equipotential Surface

- Potential is same at all the points of the surface.
- Component of electric field parallel to an equipotential surface is zero.



Electric Potential Energy

- It is negative count of work done by the electric force as the configuration of the system changes.
- $Ur_2 - Ur_1 = -W = \frac{q_1 \cdot q_2}{4\pi\varepsilon_0}\left(\frac{1}{r_2} - \frac{1}{r_1}\right)$
- If the separation between charges is 'r' then $U_{(r)} = \frac{q_1 \cdot q_2}{4\pi\varepsilon_0 r}$
- Potential Difference,

  $V_B - V_A = \frac{U_B - U_A}{q}$

  $U_B - U_A$ = change in Potential Energy

  q = test charge

Potential Energy of a dipole

$dU = pE\sin\theta d\theta$

If we choose P.E. of dipole to be zero when $\theta = 90°$ then

$$U_\theta - U_{90°} = \int_{90°}^{\theta} pE\sin\theta\, d\theta$$

$U_\theta = -pE\cos\theta = -\vec{p}\cdot\vec{E}$

If it is rotated through angle θ against the torque

Conductors & Insulators

Conductors	Insulators
Such a material which when placed in an electric field, the free electrons move in a direction opposite to the field.	Such a material in which electrons are tightly bound, & when exposed in an electric field, electrons do not move *i.e.* having no free electrons.

- Electric field inside a conductor is zero.
- Electric field is always perpendicular to the charged surface.
- In static state, there will be no additional charge in a conductor.

Dielectric

- $F = \frac{q_1 q_2}{4\pi K\varepsilon_0 r^2}$, K = dielectric constant of medium
- A dielectric is an electrical insulator that can be polarized by "application of" electric field.

Capacitance, $C = \frac{Q}{V}$

Capacitance of a parallel plate capacitor

$C = K\varepsilon_0 A/d$, K = dielectric constant

Capacitance when material slab is inserted between the plates

$C = K\varepsilon_0 A/[Kd - x(K-1)]$

where x = thickness of the slab inserted

Capacitance of a spherical capacitor

$$C = 4\pi\varepsilon_0 / \left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

For isolated sphere

$C = 4\pi\varepsilon_0 R$

Parallel grouping of capacitors

$C = C_1 + C_2 + C_3 + \cdots + C_n$

for two, $C = C_1 + C_2$

Series grouping of capacitors

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots + \frac{1}{C_n}$$

For two, $C = \frac{C_1 C_2}{C_1 + C_2}$

Energy stored in a capacitor

$$U = \frac{1}{2}CV^2 = \frac{Q^2}{2C} = 1/2\, QV$$

Electric Charges & Fields

Electric charges

- Two kinds of charges + ve and – ve
- S.I unit is coulomb (C)
  1 C = charge flowing through a wire in 1 sec if current in it is 1A
  1e = 1.602×10^{-19}C

In 1985, Charles Augustin de Coulomb gave Coulomb's law

Quantization of charge

All charges must be a multiple of charge (e)
Q = ne
Where *n* is an integer

Conservation of charge

It is not possible to create or destroy net charge of an isolated system.

Coulomb's Law

- Force between two charged particles

$$\vec{F} = \frac{k\, q_1\, q_2 \vec{r}}{r^3} = \frac{k q_1\, q_2 \hat{r}}{r^2}$$
, force is attractive when q_1 and q_2 are of opposite sign, with else repulsive

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

$$k = \frac{1}{4\pi\varepsilon_0} \approx 9\times10^9\,\text{Nm}^2\text{C}^{-2}$$

- Force between multiple charges

$$\vec{F}_1 = \vec{F}_{12} + \vec{F}_{13} + \vec{F}_{14} + \vec{F}_{15} + \ldots\ldots = \frac{q_1}{4\pi\varepsilon_0}\sum_{i=2}^{n}\frac{q_i}{r_{1i}^2}\,\hat{r}_{1i}$$

where $\hat{r}_{1i}$ is the unit vector along charge particle under consideration
$\hat{r}_{1i}$ = distance between I and i^{th} particle

"The electric force with which two charges attract or repel one another are not affected by the presence of other charges". It is known as Superposition Principle.

Electric Dipole moment, $\vec{p} = q\vec{d}$

Electric field due to dipole at axial position

$$\vec{E} = \frac{1}{4\pi\,\varepsilon_0}\left(\frac{2p}{r^3}\right)\hat{r}$$

Electric field due to dipole at equatorial position

$$|E| = \frac{1}{4\pi\,\varepsilon_0}\left(\frac{p}{r^3}\right)$$

Torque on an electric dipole placed in an electric field $(\vec{E})$

$$\vec{\tau} = \vec{p}\times\vec{E} = p\,E\,\sin\theta$$

Electric Field

Electric field due to point charge

$$\vec{E} = \frac{\vec{F}}{q} = k\,\frac{Q}{r^2}\ \text{(N/C)}$$

$\because$ unit = N/C

- Due to discrete distribution of charges

$$\vec{E} = \sum_{i}^{n}\vec{E_i}$$

- Due to continuous distribution of charges

$$\vec{E} = k\int\frac{dQ}{r^3}\vec{r}$$

$$|\vec{E}| = k\int\frac{dQ}{r^2}$$

Electric field lines

- Always normal to conducting surface
- Lines originating from +ve charge
- Terminating at –ve charge
- Never intersect each other
- Do not form closed loop
- Are imaginary lines.

Electric flux

$\Delta\phi = \vec{E}.\Delta\vec{S}$, $\Delta\vec{S}$ = area vector
$\vec{E}$ = electric field

$\phi = \int\vec{E}.\vec{ds}$

Gauss's Theorem

$\oint\vec{E}.\vec{ds} = q_{in}/\varepsilon_0 = \phi$

where, q_{in} = net charge enclosed
ϕ = flux through a closed surface

Applications of Gauss's Law

- Field due to linear charge distribution
  $E = \lambda/2\pi\,\varepsilon_0 r$,
  λ= linear charge density
- Field due to a plane sheet of charge
  $E = \sigma/2\varepsilon_0$,
  σ = charge per unit area
- Field due to a charged conducting plate
  $E = \sigma/\varepsilon_0$,
  σ = charge per unit area
- Field inside a conductor = 0

Electric field due to uniformly charged sphere at

- Outside point
  $E = Q/4\pi\varepsilon_0 r^2$
- Internal point
  $E = Q/4\pi\varepsilon_0 R^3$
- The surface
  $E = Q/4\pi\varepsilon_0 R^2$