Lecture 1: Electromagnetic Interactions

Electric Force (Coulombs Law)

$F = \frac{1}{4\pi\epsilon_0} \cdot \frac{|q_1||q_2|}{r^2}$, Newtons (N)

$\epsilon_0 = 8.85 \times 10^{-12}\ C^2/Nm^2$, Permittivity of free space.

$\frac{1}{4\pi\epsilon_0} = 8.99 \times 10^9 Nm^2/C^2$, Coulomb's Constant

Fundamentals of Charges

Fundament charge: $e = 1.60 \times 10^{-19}\ C$

$q = (N_p - N_e)e$

q : charge, N_p : No. of protons, N_e : No. of electrons

Lecture 2: Electric Force and Field

Electric Field

$E = \frac{1}{4\pi\epsilon_0} \cdot \frac{|q|}{r^2}$

S.I unit: Newtons/Coulombs (N/C)

*Direction of electric field: positive (outwards), negative (inwards)

Large charged plate

$E = \frac{\sigma}{2\epsilon_0}, \sigma = \frac{Q}{A}$.

σ is Surface Charge Density

Q is charge.

A is area of plate.

*No. of field lines entering/leaving the charge is proportional to the amount of charge.

Lecture 3: Electric Potential

Work done

$W_{a\to b} = -\Delta U = U_a - U_b$

Potential energy of charge q_0 in a uniform electric field

$U = q_0 E y$

y: distance from negative plate.

Electric potential energy between 2 point charges

$U = \frac{1}{4\pi\epsilon_0} \cdot \frac{q_1 \cdot q_2}{r}$

*For shells, r is distance between centers.

$U = \frac{1}{4\pi\epsilon_0} \cdot \sum_{i<j} \frac{q_i \cdot q_j}{r_{ij}}$

$U = q\Delta V = q(V_f - V_i)$

Electric Potential

$V = \frac{1}{4\pi\epsilon_0} \cdot \frac{q}{r}$

*Electric **force** on a charge is always in the direction of **lower** electric **potential energy**.

*Electric **field** is always in the direction of **lower potential**.

$V = \frac{1}{4\pi\epsilon_0} \cdot \sum_i \frac{q_i}{r_i}$ (scalar sum)

Total energy conservation

$K_i + qV_i = K_f + qV_f$

K: kinetic energy

qV: potential energy

V: potential

Kinetic Energy

$E_k = \frac{1}{2}mv^2$

*Mass of proton: $1.67 \times 10^{-27}\ kg$

*Mass of electron: $9.11 \times 10^{-31}\ kg$

Electric Field vs Potential

$E = \frac{\Delta V}{d}$

d: distance between 2 equipotential surfaces

Lecture 4: Capacitance

*Any 2 conductors (regardless of shape) separated by an insulator (or vacuum) form a Capacitor.

*The 2 conductors have charges with equal magnitude but opposite signs.

Capacitance

$C = \frac{Q}{\Delta V}$, Coulomb per Volt (C/V), Farad (F).

$C = \frac{\epsilon_0 A}{d}$, A: Area, d: distance between

Energy Storage in Capacitor

$U = \frac{1}{2}QV = \frac{Q^2}{2C} = \frac{1}{2}CV^2$, Joules (J)

Energy Density in Electric Field

$u = \frac{1}{2}\epsilon_0 E^2$, (J/m^3)

u: amount of energy per unit volume

Capacitors with Dielectrics

$C = \kappa C_0, \kappa > 1$

κ: dielectric constant

Inserting dielectric without battery

$\Rightarrow V = \frac{Q_0}{C} = \frac{Q_0}{\kappa C_0} = \frac{V_0}{\kappa}$

$\Rightarrow E = \frac{V}{d} = \frac{V_0}{\kappa d} = \frac{E_0}{\kappa}$

$\Rightarrow U = \frac{U_0}{\kappa} < U_0$

Inserting dielectric with battery

$\Rightarrow Q = CV_0 = (\kappa C_0)V_0 = \kappa Q_0$

$\Rightarrow U = \kappa U_0 > U_0$

*Dielectric strength of Dry Air $= 3 \times 10^6\ V/m$

Find Maximum Charge on Capacitor

*Given dielectric strength of medium:

$Q_{max} = \kappa \times \frac{\epsilon_0 A}{d} \times d$

Capacitor Network

In parallel: $C = C_1 + C_2$

In series: $\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$

Lecture 5: Current and Resistance

Ohm's Law

$I = \frac{\Delta V}{R}$

In series:

$V = V_1 + \ldots + V_n$

$I = I_1 = \ldots = I_n$

$R = R_1 + \ldots + R_n$

In parallel:

$V_1 = V_2 = \ldots = V_n$

$I = I_1 + \ldots + I_n$

$\frac{1}{R} = \frac{1}{R_1} + \ldots + \frac{1}{R_n}$

Currents and Charges

$I = \frac{\Delta Q}{\Delta t} = |q| n A v_d$

n: no. of charge carriers per unit volume

A: cross section area

v_d: drift speed of current

Resistance

$R = \frac{\rho L}{A}$, (Ohms, Ω)

ρ: resistivity, (Ohms meter, $\Omega \cdot m$)

L: length

A: cross section area

Resistance and Temperature

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

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

ρ_0: resistivity at T_0

T_0: usually $20°C$

α: temp. coefficient of resistivity $(°C)^{-1}$

Power

$P = \frac{\Delta Q \Delta V}{\Delta t} = \Delta V I = I^2 R = \frac{\Delta V^2}{R}$, (Watts, W).

Lecture 6: DC Circuits

$I = \frac{\varepsilon}{R+r}$

ε: EMF

R: external resistor

r: internal resistor (in battery)

Kirchhoff's Rules

*$\sum I_i$ into junction $= \sum I_i$ out of junction

*Sum of voltage drops around a loop is zero, $\varepsilon = Ir + IR$

*Intuition: Applying Kirchhoff is to form equations of $emf = 0$.

*Recall: Can use Row Operations from Linear Algebra to reduce to Reduced Row Echelon form.

RC Circuits

RC Circuit: Charging

$\varepsilon - I(t)R - \frac{q(t)}{c} = 0$

Just after switch closed:
$q(t) = q_0 = 0 \Rightarrow \varepsilon - I_0 R = 0 \Rightarrow I_0 = \frac{\varepsilon}{R}$
Long after switch closed:
$I(t) = I_\infty = 0 \Rightarrow \varepsilon - \frac{q_\infty}{C} = 0 \Rightarrow = q_\infty = C\varepsilon$
Intermediate:
$q(t) = q_\infty(1 - e^{-t/RC}),\ I(t) = I_0 e^{-t/RC}$
RC Circuit: Discharging
$\frac{q(t)}{C} + I(t)R = 0$
Just after switch closed:
$q(t) = q_0 \Rightarrow \frac{q_0}{C} + I_0 R = 0 \Rightarrow I_0 = -\frac{q_0}{RC}$
Long after switch closed:
$I(t) = I_\infty = 0 \Rightarrow \frac{q_\infty}{C} = 0 \Rightarrow q_\infty = 0$
Intermediate:
$q(t) = q_0 e^{-t/RC},\ I(t) = I_0 e^{-t/RC}$

Lecture 7: Magnetism

Magnetic Flux

$\Phi = BA\cos\theta$, SI unit: $Tm^2 \equiv Wb$
B: magnetic field strength (Teslas, T)
A: area of plane
θ: angle between B and normal to plane

Magnetic Force on ONE moving charge

$F = |q|vB\sin\theta$, Newtons
θ: angle between v and B.
(recall: $E = \frac{F}{q} \Rightarrow E = vB$, when $\theta = 90°$)

Right-hand Rule

Thumb: F, Index: v, Middle: B
*If negative charge, F is in opposite direction to thumb

Radius of circular orbit

$R = \frac{mv}{B|q|}$

Lecture 8: Currents and Magnetism

Magnetic Force on MANY moving charges

$F = ILB\sin\theta$
L: length of wire
θ: angle between I and B

Gravity Force

$F = mg$

Magnetic Field of a Long Straight Wire

$B = \frac{\mu_0 I}{2\pi r}$
μ_0: permeability of vacuum, $\mu_0 = 4\pi \times 10^{-7}\ Tm/A$
r: distance from wire
*Right-hand rule: Thumb: direction of I, fingers: direction of B.

Force between parallel wires with length L

*Consider I directed to the right, wire a is d meters from b.
Magnetic force on wire a and b:
$F_a = I_a L B_b = \frac{\mu_0 I_a I_b L}{2\pi d}$, (downward)
$F_b = I_b L B_a = \frac{\mu_0 I_a I_b L}{2\pi d}$, (upward)

Bar magnet vs Current Loop

*If wrap fingers around wire in loop, Thumb: I, fingers: B
*If put fingers on loop, Thumb:B, fingers: I, like inside of a Bar Magnet
*The side of the current loop from which B emerges is North pole.

Magnetic Field at CENTER of current loop

$B = \frac{\mu_0 N I}{2R}$
N: number of loops

Interaction between Current Loops

*Same I direction: attract
*Different I direction: repel

Magnetic Field INSIDE ideal solenoid

$B = \mu_0 n I$
n: no. of turns per unit length
*Solenoid becomes like a Bar Magnet

Cosine Rule

$c^2 = a^2 + b^2 - 2ab\cos C$, C is angle between a and b

Lecture 9: Electromagnetic Induction

$\Delta\Phi \to \varepsilon_{induced} \to I_{induced} \to B_{induced} \to \Phi_{induced}$

Len's Law

The direction of $I_{induced}$ is such that the $B_{induced}$ **opposes** the **change** in the flux that induces the current.

Faraday's Law of Induction

$|\varepsilon| = N\frac{|\Delta\Phi|}{\Delta t} = N\frac{|\Phi_f - \Phi_i|}{\Delta t}$, N is no. of loops

Motional Electromotive Force

$\Delta V = \varepsilon = vBL$, (recall $E = vB, E = \frac{\varepsilon}{L}$)
To have motional emf, conductor must **cut** through magnetic field

Induced Current

$I = \frac{\varepsilon}{R} = \frac{vBL}{R}$

Magnetic Force (magnitude) on bar

$F = ILB = \frac{vB^2L^2}{R}$

Lecture 10: Electromagnetic Waves (EM Waves)

Speed of EM Waves

$c = \frac{1}{\sqrt{\varepsilon_0\mu_0}}, E = cB$
Transverse wave: $\vec{E}$ and $\vec{B}$ fields are **perpendicular**.

Energy in EM Waves

$u_E = \frac{1}{2}\epsilon_0 E^2, u_B = \frac{1}{2}\frac{B^2}{\mu_0}, u_E = u_B$
So total, $u_{EM} = u_E + u_B = \epsilon_0 E^2 = \frac{B^2}{\mu_0}$

Intensity of EM Waves

$I = \frac{U}{A\Delta t} = \frac{P}{A} = u_{EM}c = c\varepsilon_0 E^2 = \frac{c}{\mu_0 B^2}$, (Watts/$m^2$ or W/m^2)
Here I is Intensity, not Current

EM Spectrum

$c = f\lambda$, f: frequency, λ: wavelength

Doppler Equation for EM Waves

$f_o = f_s(1 \pm \frac{u}{c})$, only valid for $u \ll c$
f_o : observed frequency
f_s : frequency emitted by the source
u : relative speed between source and observer
$u = |v_1 + v_2| \Rightarrow$ moving in opposite directions
$u = |v_1 - v_2| \Rightarrow$ moving in same directions
*Important intuition: As objects come closer, frequency increase

Polarization of EM Waves

*Direction of polarization of an EM wave is defined to be the **direction of $\vec{E}$ field**. A wave propagates with FIXED polarization $\to$ linearly polarized.

Unpolarized Light on Linear Polarizer

$I_{transmitted} = \frac{1}{2}I_{incident}$, here I is Intensity

Linearly Polarized Light on Linear Polarizer, Malus' Law

$E_{transmitted} = E_{incident}\cos\theta \Rightarrow I_{transmitted} = I_{incident}\cos^2\theta$
θ: angle between the incoming light's polarization and the transmission axis (TA)

Optical Activity

The ability of a substance to rotate the polarization direction of linearly polarization light. This ability depends on the molecular structure of the substance.

Lecture 11: Reflection Of Light

Law of Reflection

$\theta_i = \theta_r$
θ_i: Incident angle
θ_r: Reflected angle
Specular vs Diffuse reflection: one is smooth surface, one is rough surface. Diffuse makes dry road easy to see at night.
*For plane mirrors, basically it's all about similar triangles

Spherical Mirrors

C = center of curvature.

Focal Point for Concave/Convex Mirror

Concave: $f = \frac{R}{2}$, Convex: $f = -\frac{R}{2}$

Concave converges, Convex diverges

f: focal length, distance from Focal Point, F, to center of mirror

R: distance from C to center of mirror

*Flat/Plane mirror has $f = \infty, \because R \to \infty$

Ray tracing for Concave/Convex mirror (Find real/virtual image)

Ray#1: Parallel to principal axis, reflects through F.

Ray#2: Through C, center of curvature.

Ray#3: Through F, reflects parallel to principal axis.

*Intersection point is where the real/virtual image lies.

Spherical Mirror Equations

$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$, applies to concave/convex

d_o: object distance d_i: image distance f: focal length

Magnification

$m \equiv \frac{h_i}{h_o} = -\frac{d_i}{d_o}$

h_o: object height

h_i: image height, $(-ve) \to$ inverted image

m has same sign as h_i, $|m| < 1 \to$ reduced, $|m| > 1 \to$ enlarged.

Lecture 12: Refraction Of Light

Index of Refraction

$n \equiv \frac{c}{v}$, $n > 1, \because c > v$

c: speed of light in vacuum

v: speed of light in medium

Frequency between media

$v = f\lambda \Rightarrow \frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$

Snell's Law of Refraction

$n_1 \sin\theta_1 = n_2 \sin\theta_2$

θ: angle between light and normal of incidence

Apparent Depth

$\frac{d'}{d} = \frac{n_1}{n_2}$

d': apparent depth

d: actual depth

n_1: refraction index of medium 1 (before refraction)

n_2: refraction index of medium 2 (after refraction)

Total Internal Reflection

Critical angle: $n_1 \sin\theta_c = n_2 \sin 90° \Rightarrow \sin\theta_c = \frac{n_2}{n_1}$

Polarization by Reflection, Brewster's Angle

$\tan\theta_B = \frac{n_2}{n_1} \Rightarrow \theta_B$: Brewster's Angle

*When unpolarized light is reflected from a surface, it *can* get polarized at $0° < \theta_i < 90°$. At $0°/90°$, light remains unpolarized.

*Reflected light is **totally** polarized **parallel** to the surface when the reflected and refracted rays are at right angles.

**Dispersion* is the dependence of the index of refraction of a transparent medium on the wavelength of light.

Lecture 13: Optical Instruments

Thin Lenses

Principal Rays for Converging/Diverging lens

Ray#1: Parallel to principal axis, passes through F.

Ray#2: Through center of lens.

Ray#3: Through F, emerges parallel to principal axis.

Thin Lens Equation

$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$

d_o: object distance

Positive: real object (in front of lens)

Negative: virtual object (behind lens)

d_i: image distance

Positive: real image (behind lens)

Negative: virtual image (in front of lens)

f: focal length

Positive: convex (converging) lens

Negative: concave (diverging) lens

Magnification equation

$m \equiv \frac{h_i}{h_o} = -\frac{d_i}{d_o}$

h_o: object height

h_i: image height, $(-ve) \to$ inverted image

m has same sign as h_i, $|m| < 1 \to$ reduced, $|m| > 1 \to$ enlarged.

Combination of Lenses

$m_{total} = m_1 * m_2$

m_i: magnification by i-th lens

Human Eyes

Focal length of normal human eye $\approx$ 2.5cm

Near point of normal human eye $\approx$ 25cm

Far point of normal human eye : ∞

When you are **near-sighted**:

1. Far point is too close
2. Need concave (diverging) lens to create an virtual image at that abnormal far point (which is $< \infty$), which acts as new object for your eye

When you are **far-sighted**:

1. Near point is too far
2. Need convex (converging) lens to create an virtual image at that abnormal near point (which is $>$ 25cm), which acts as new object for your eye

Refractive Power of Lens

$P = \frac{1}{f}$, Unit: Diopter, (m^{-1})

f: focal length of lens

Magnifying Glass

Angular size,

$\tan\theta = \frac{h_o}{d_o} \Rightarrow \theta \approx \frac{h_o}{d_o}$ or $\theta \approx \frac{h_o}{N}$

h_o: object height

N: near point distance

As object is moved closer to eye, θ decreases.

Also,

$\theta \approx \frac{h_i}{d_i} \approx \frac{h_o}{d_o}$, (similar triangles)

Angular Magnification,

$M = \frac{\theta}{\theta_o}$

θ_o: angular size of object, (without magnifying glass)

θ: angular size of image, (with magnifying glass)

$M = N(\frac{1}{f} - \frac{1}{d_i})$

$\Rightarrow M = N(\frac{1}{f} - \frac{1}{-\infty})$ for virtual image at ∞

$\Rightarrow M = N(\frac{1}{f} - \frac{1}{-N})$ for virtual image at N

Lecture 14: Interference of Light

Principle of superposition

Constructive superposition: $\lambda_2 - \lambda_1 = m\lambda,\ m = 0, 1, 2, \ldots$

Destructive superposition: $\lambda_2 - \lambda_1 = (m + \frac{1}{2})\lambda,\ m = 0, 1, 2, \ldots$

Double Slit Interference

Optical Path Difference: $\delta = d\sin\theta$

Constructive Interference (Bright Fringes)

$\delta = d\sin\theta = m\lambda,\ m = 0, 1, 2, \ldots$

Destructive Interference (Dark Fringes)

$\delta = d\sin\theta = (m + \frac{1}{2})\lambda,\ m = 0, 1, 2, \ldots$

d: slit-spacing

θ: angle between ray and norm

***Center Bright** is $m = 0$, **1st Bright** usually means $m = 1$

***First Dark** from Center Bright is $m = 0$

Small Angle Approx. To Find Bright/Dark Fringes

Bright: $\theta \approx \frac{m\lambda}{d},\ y \approx \frac{m\lambda L}{d}$ | Dark: $\theta \approx (m + \frac{1}{2})\frac{\lambda}{d},\ y \approx (m + \frac{1}{2})\frac{\lambda L}{d}$

L: distance between slit and screen

Thin Film Interference

Reflection	Distance	Optical path diff
Ray 1 $0 (n_0 > n_1)$	0	$\delta_1 = 0 + 0 (n_0 > n_1)$
Ray 1 $\frac{\lambda}{2} (n_0 < n_1)$	0	$\delta_1 = \frac{\lambda}{2} + 0 (n_0 < n_1)$
Ray 2 $0 (n_1 > n_2)$	$2n_1t$	$\delta_1 = 0 + 2n_1t (n_1 > n_2)$
Ray 2 $\frac{\lambda}{2} (n_1 < n_2)$	$2n_1t$	$\delta_1 = \frac{\lambda}{2} + 2n_1t (n_1 < n_2)$

$\delta = |\delta_1 - \delta_2|$: optical path difference between Ray 1 and 2

δ_1: optical path difference between Ray 1 and incident ray

δ_2: optical path difference between Ray 2 and incident ray

Constructive: $\delta = m\lambda$, Destructive: $\delta = (m+\frac{1}{2})\lambda$, $m = 0, 1, \ldots$

Lecture 15: Diffraction and Grating

Single Slit Diffraction - Locating Minima (Dark Fringe)

$\sin\theta = \frac{m\lambda}{W},\ y = \frac{m\lambda L}{W},\ m = 1, 2, 3, \ldots$

*__First Dark__ is $m = 1$ (Notice the difference between Double Slit)

Diffraction from Circular Aperture

$\sin\theta = 1.22\frac{\lambda}{D}$

→**First minimum** of a circular diffraction pattern

D: diameter of circular aperture

Resolving Power (Rayleigh's Criterion)

$\theta_{min} = 1.22\frac{\lambda}{D}$, **NOTE**: θ_{min} will be in Radians

θ_{min}: angle between the 2 objects / light sources

λ: the wavelength *in* the region between the aperture and screen

Two point objects are *just resolved* when the 1st dark fringe in the diffraction pattern of one falls directly on the central bright fringe in the diffraction pattern of the other. So, to see 2 objects distinctively, we need:

$\theta_{objects} \geq \theta_{min}$, and $\theta_{objects} \approx \frac{d}{y}$

d: distance between objects

y: distance from objects to the aperture

Convert Radians to Degree

$\theta^\circ = \frac{\theta \text{ rad} \times 180^\circ}{\pi}$

Diffraction Grating

$d\sin\theta = m\lambda$

*Condition for constructive interference

$\theta = \sin^{-1}\frac{m\lambda}{d},\ y = L\tan\theta$

*__Center Bright__ fringe is $m = 0$

*As no. of slits per unit length of grating ↑, fringes get narrower and brighter

m: $m = 0, 1, 2, \ldots$

y: distance from center fringe to i-th fringe

L: distance from grating to screen

Lecture 16: Photoelectric Effect

Photoelectric Equation

$K_{max} = hf - W_0 \Rightarrow K_{max} = h\frac{c}{\lambda} - W_0$ (units: eV)

eV: electron volt, 1 electron charge times 1 V

K_{max}: max kinetic energy of released electrons

h: **Planck's constant** $= 6.63 \times 10^{-34} Js$ (Joules second)

f: frequency of light source

W_0: work function of the metal surface (minimum energy needed to free electron)

$f_0 = \frac{W_0}{h}, \lambda_0 = \frac{hc}{W_0}$

f_0, λ_0: cutoff frequency/wavelength (if $\lambda_0 \uparrow$ then $W_0 \downarrow$, no photoelectric)

*Remember: K_{max} depend **only** on frequency and work function, not intensity

*Photon energy $> W_0 \rightarrow$ electron freed

*Photon energy $< W_0 \rightarrow$ electron not freed regardless of intensity

Stopping Potential

$eV_0 = K_{max}, V_0 = \frac{h}{e}(f - f_0)$

de Broglie's Matter Wave

$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{h}{\sqrt{2meV}}$

p: momentum

m: mass

v: velocity

e: electron charge

V: potential

*Note: eV together may mean, for e.g. 10.2 eV. Need to multiply by electron charge

Finding No. of photons per second

$\frac{\#photons}{second} = \frac{energy/second}{energy/photon} = \frac{power}{energy/photon} = \frac{power}{hf}$

Lecture 17: Atomic Physics

Line Spectra

Absorption Spectrum:

Bright background with dark lines (Photons were absorbed)

Emission Spectrum:

Dark background with bright lines (Photons were emitted)

Balmer Series (Hydrogen)

$\frac{1}{\lambda} = R_H(\frac{1}{2^2} - \frac{1}{n^2}),\ n = 3, 4, 5, \ldots$

*When $n = 3$, λ is longest.

Lyman Series (Ultraviolet)

$\frac{1}{\lambda} = R_H(\frac{1}{1^2} - \frac{1}{n^2}),\ n = 2, 3, 4, \ldots$

Paschen Series (Infrared)

$\frac{1}{\lambda} = R_H(\frac{1}{3^2} - \frac{1}{n^2}),\ n = 4, 5, 6, \ldots$

Brackett Series (Infrared)

$\frac{1}{\lambda} = R_H(\frac{1}{4^2} - \frac{1}{n^2}),\ n = 5, 6, 7, \ldots$

Pfund Series (Infrared)

$\frac{1}{\lambda} = R_H(\frac{1}{5^2} - \frac{1}{n^2}),\ n = 6, 7, 8, \ldots$

In general... (for the spectral lines in Hydrogen atom)

$\frac{1}{\lambda} = R_H(\frac{1}{n_f^2} - \frac{1}{n_i^2}),\ n \in \mathbb{Z}^+, n_i > n_f$

R_H: Rydberg Constant, $1.097 \times 10^7 m^{-1}$

Bohr's Model of Atom

Intuition:

Electron jump from level $n = i$ to $n = i - 1 \rightarrow$ emits photons

Electron jump from level $n = i$ to $n = i + 1 \rightarrow$ absorbs photons

Bohr's Angular Momentum Quantization

$2\pi r = n\lambda$ & $\lambda = \frac{h}{p} \Rightarrow mrv = \frac{nh}{2\pi}$

Planck-Einstein / Planck's relation

$E = hf = h\frac{c}{\lambda} \Rightarrow \lambda = \frac{hc}{E}$

h: Planck's constant, $6.63 \times 10^{-34} Js$

f: frequency

E: energy, so can be in eV or J. (Recall equation in Lect 16)

Energy Levels of Hydrogen Atom

$E_n = -\frac{1}{2}\frac{1}{4\pi\epsilon_0}\frac{e^2}{n^2 a_0} = -\frac{13.6 \text{ eV}}{n^2},\ (a_0 = \epsilon_0\frac{h^2}{\pi m e^2},\ r_n = n^2 a_0)$

a_0: smallest orbit radius, *Bohr radius* $= 0.0529$nm

r_n: general expression for radius of any orbit

*Lowest energy level or *ground state* $\rightarrow n = 1$

**First excited state* $\rightarrow n = 2$, and so on...

*Highest level, electron removed $\rightarrow n = \infty, E = 0$

Some Intuition about Spectral Lines

When there is a transition from (e.g.) $n = 3$ to $n = 2$, then there is a wavelength for that photon(s). So for e.g. electron excited to $n = 3$. $(3 \rightarrow 2), (2 \rightarrow 1)$ & $(3 \rightarrow 1)$ are spectral lines.

Energy Levels and Spectrum

$\frac{1}{\lambda} = R_H|\frac{1}{n_f^2} - \frac{1}{n_i^2}|$

*Longest λ: e.g. $\lambda_{32} = \frac{hc}{E_3 - E_2}$ (Balmer series)

*Shortest λ: e.g. $\lambda_{\infty 2}$ (Balmer series)

In General, when there's Z/Protons involved..

$E_n = -\frac{1}{4\pi\epsilon_0}\frac{Z^2 e^2}{2n^2 a_0} = -\frac{Z^2(13.6 \text{ eV})}{n^2}, (r_n = \frac{n^2 a_0}{Z})$

Z: number of protons in nucleus

$\Rightarrow \frac{1}{\lambda} = Z^2 R_H|\frac{1}{n_f^2} - \frac{1}{n_i^2}|$

Converging lenses

$d_o < f$	Up.	Mag.	Virt.
$d_o = f$	–	–	–
$d_o = 2f$	Inv.	Same	Real
$d_o > f$	Inv.	Dim.	Real