Quiz 1 Blue Books will be returned to Student Affairs office
(Ground Floor, Urey Hall Extension)
this Wednesday by 10am
(usually you can pick it up Tuesday 2pm)

Regrade Requests must get to TA within 7 days
Frivolous regrade requests will lead to loss of points

Quiz 2 is This Friday
Quiz 2 will emphasize Sections 1.6-1.10 (inclusive)
[But you will need to know concepts from earlier sections]

Physics 2D Lecture Slides
Lecture 9: Jan 21st 2004

Vivek Sharma
UCSD Physics

Ch 2 : Quantum Theory Of Light

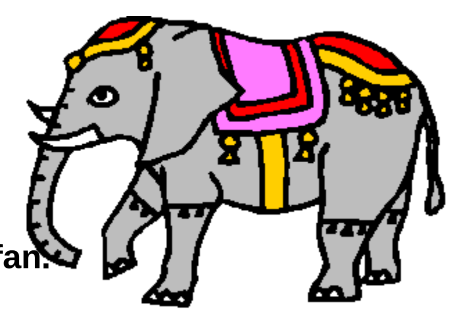
- What is the nature of light ?
  - When it propagates ?
  - When it interacts with Matter?
- What is Nature of Matter ?
  - When it interacts with light ?
  - As it propagates ?

- Revolution in Scientific Thought
  - Like a firestorm of new ideas (every body goes nuts!..not like Evolution)
    - Old concepts violently demolished , new ideas born
      - Interplay of experimental findings & scientific reason
- One such revolution happened at the turn of 20^{th} Century
  - Led to the birth of Quantum Theory & Modern Physics

Blindmen & an Elephant


touched the trunk of the elephant, said elephant was like a **branch of a tree**.


touched the tail of the elephant, said elephant was like a **snake.**




touched an ear. He said elephant was a **huge fan.**


felt a leg of the elephant., elephant was like a **pillar**.


touched the side of the elephant, said the elephant was like a **wall**


The Physicist: Gentlemen, all five of you have touched only one part of the Elephant......elephant **is all of above**

LIKEWISE WITH LIGHT !

Classical Picture of Light : Maxwell's Equations

- Maxwell's Equations:

$$\oint_S \mathbf{E}\cdot d\mathbf{A} = \frac{Q}{\epsilon_0}$$

$$\oint_S \mathbf{B}\cdot d\mathbf{A} = 0$$

$$\oint \mathbf{E}\cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$$

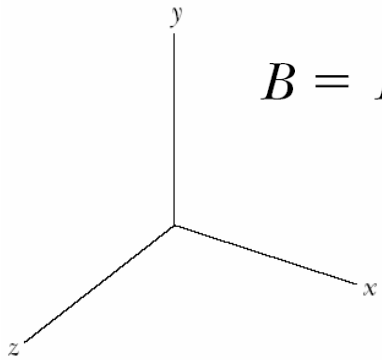
$$\oint \mathbf{B}\cdot d\mathbf{s} = \mu_0 I + \mu_0\epsilon_0\frac{d\Phi_E}{dt}$$

$$\frac{\partial^2 E}{\partial x^2} = \mu_0\epsilon_0\frac{\partial^2 E}{\partial t^2}$$

$$\frac{\partial^2 B}{\partial x^2} = \mu_0\epsilon_0\frac{\partial^2 B}{\partial t^2}$$

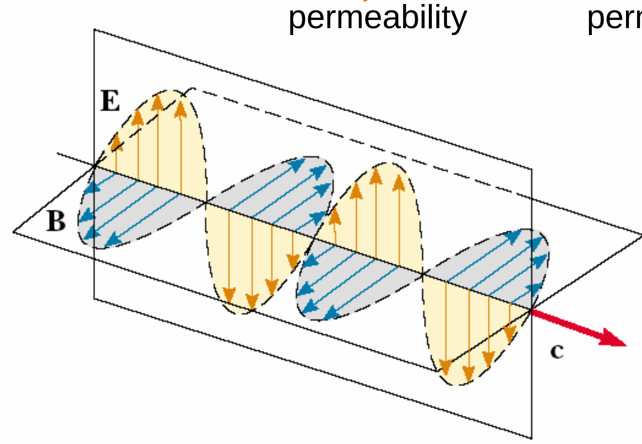
$$E = E_{\max}\cos(kx - \omega t)$$

$$B = B_{\max}\cos(kx - \omega t)$$

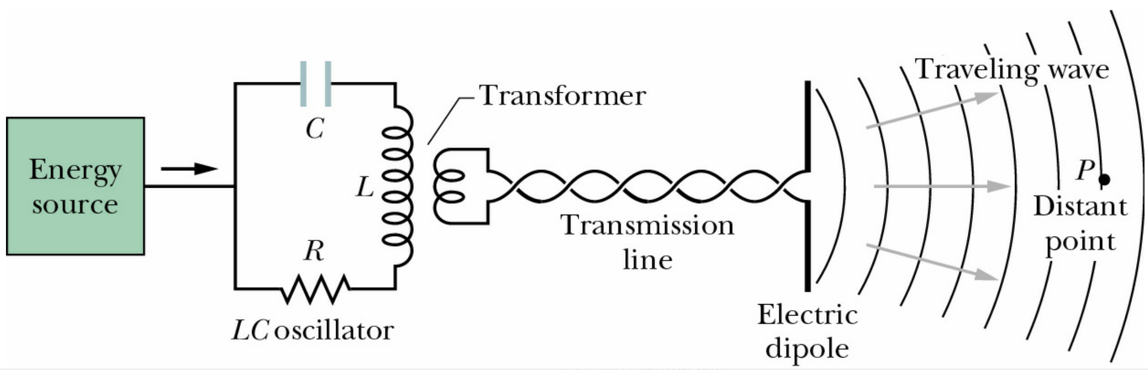


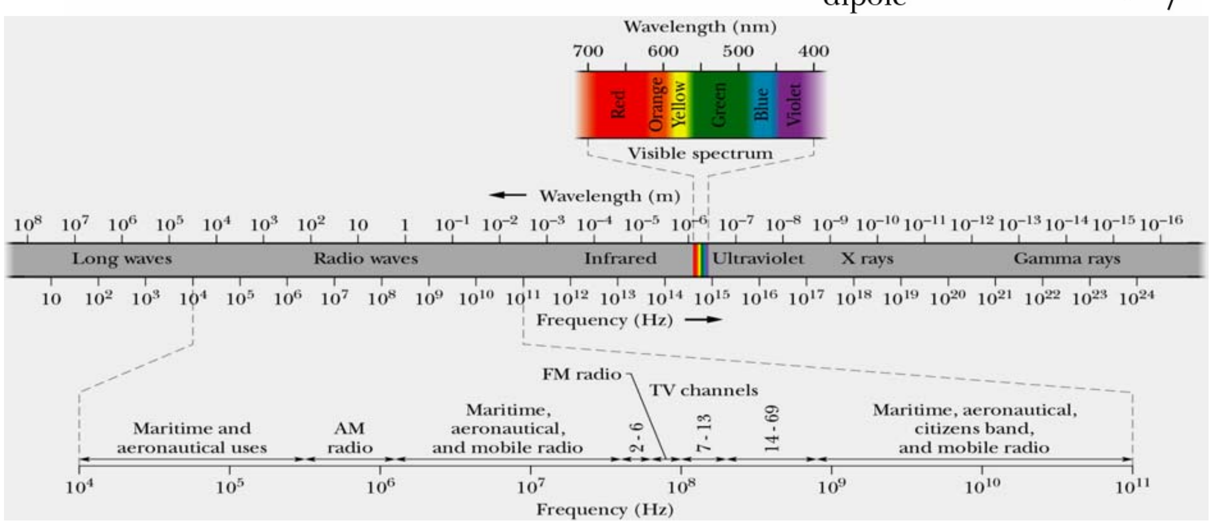
$$c = \frac{1}{\sqrt{\mu_0\epsilon_0}}$$

permeability permittivity

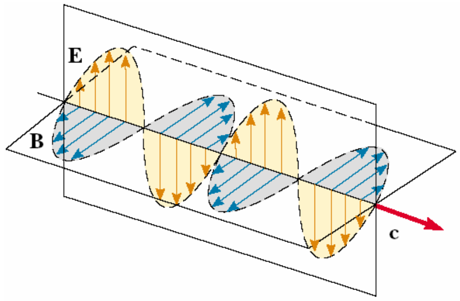


Hertz & Experimental Demo of Light as EM Wave





Properties of EM Waves: Maxwell's Equations



Energy Flow in EM Waves :

Poynting Vector $\vec{S} = \frac{1}{\mu_0}(\vec{E} \times \vec{B})$

Power incident on an area A $= \vec{S}.\vec{A} = \frac{1}{\mu_0}\left(AE_0B_0Sin^2(kx - \omega t)\right)$

Intensity of Radiation $I = \frac{1}{2\mu_0 c}E_0^2$

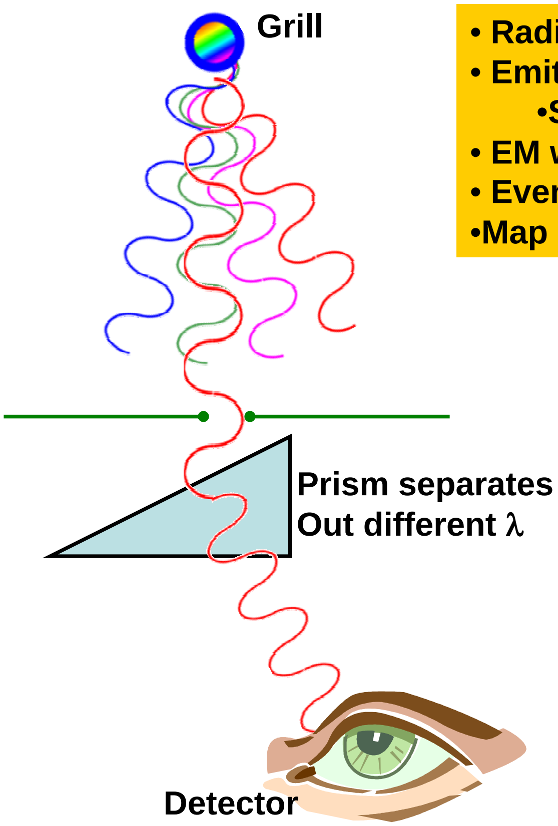
Larger the amplitude of Oscillation
More intense is the radiation

Disasters in Classical Physics (1899-1922)

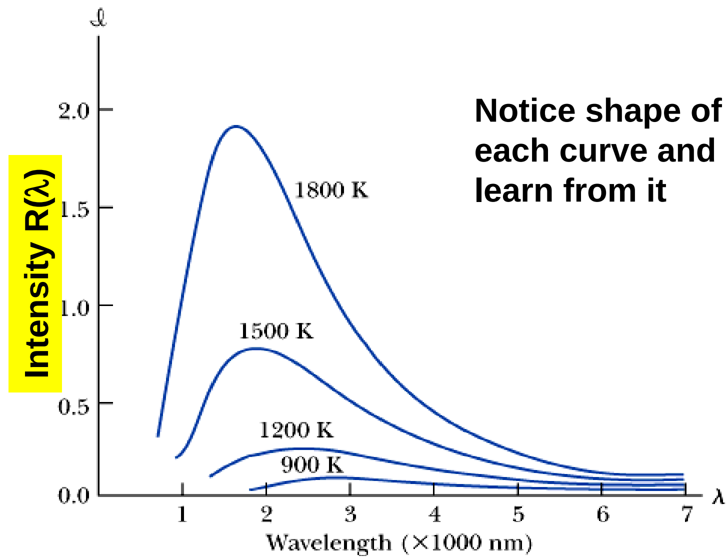
- Disaster → Experimental observation that could not be explained by Classical theory (Phys 2A, 2B, 2C)
  - Disaster # 1 : Nature of Blackbody Radiation from your BBQ grill
  - Disaster # 2: Photo Electric Effect
  - Disaster # 3: Scattering light off electrons (Compton Effect)
- Resolution of Experimental Observation will require radical changes in how we think about nature
  - → QUANTUM MECHANICS
    - The Art of Conversation with Subatomic Particles

Nature of Radiation: An Expt with BBQ Grill

Question : Distribution of Intensity of EM radiation Vs T & λ

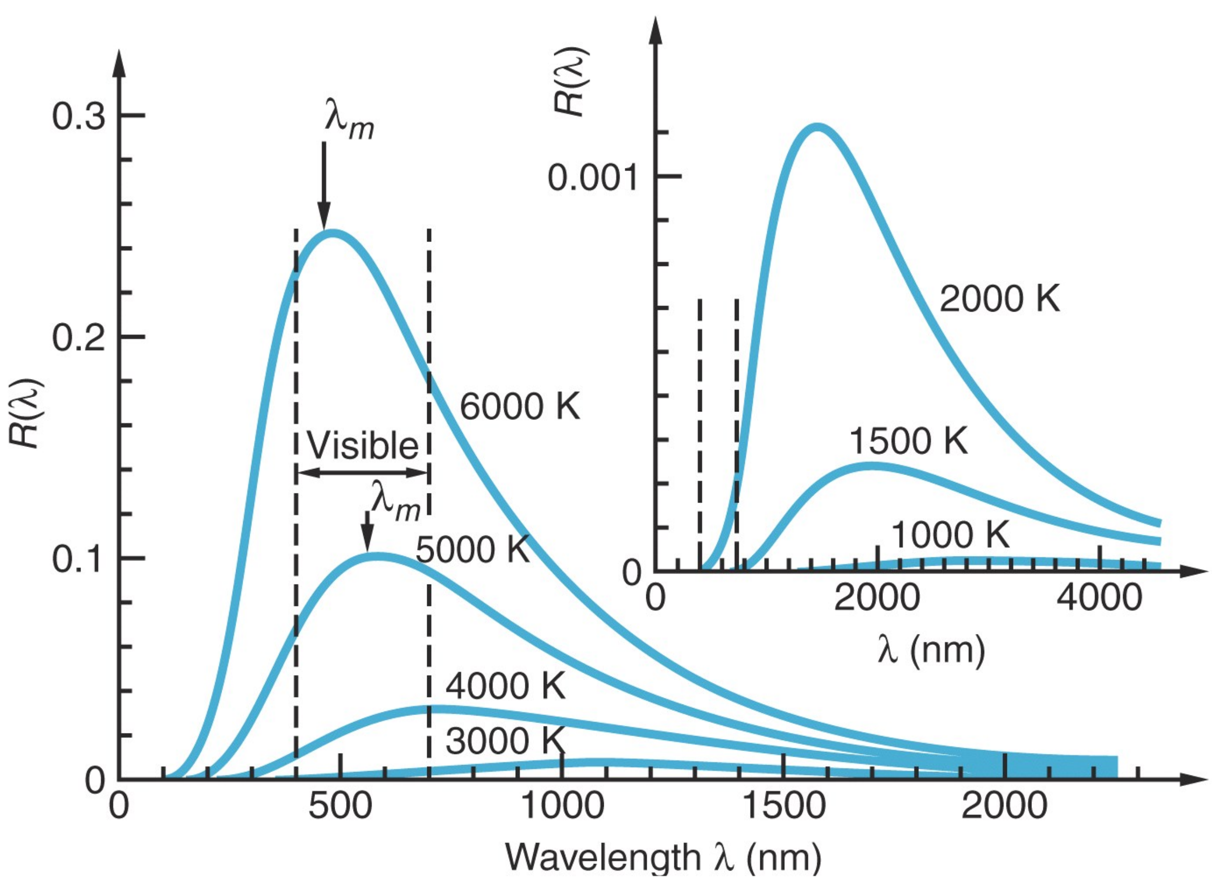


- **Radiator (grill) at some temp T**
- **Emits variety of wavelengths**
  - **Some with more intensity than others**
- **EM waves of diff. λ bend differently within prism**
- **Eventually recorded by a detector (eye)**
- **Map out emitted Power / area Vs λ**



Notice shape of each curve and learn from it

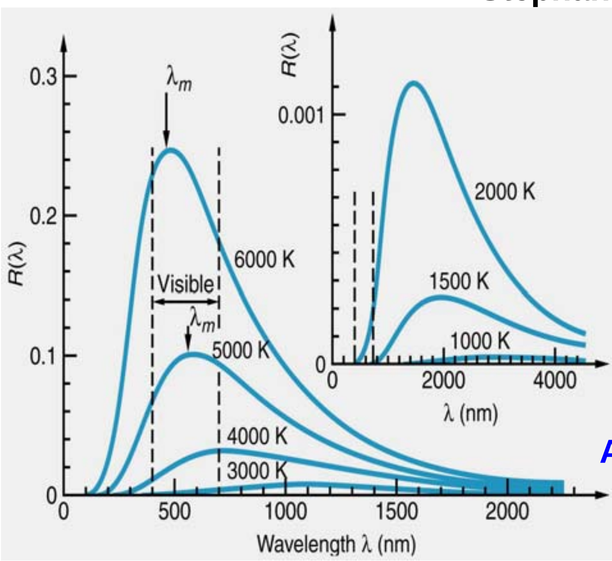
Radiation from A Blackbody



(a) Intensity of Radiation $I = \int R(\lambda)d\lambda \propto T^4$

$$I = \sigma T^4 \text{(Area under curve)}$$

Stephan-Boltzmann Constant σ = 5.67 10^{-8} W / $m^2 K^4$



(b) Higher the temperature of BBQ Lower is the λ of PEAK intensity

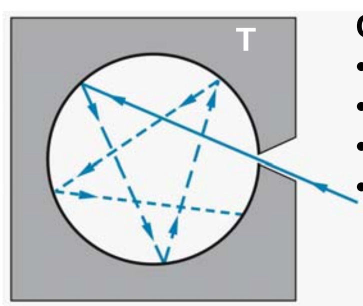
$$\lambda_{MAX} \propto 1 / T$$

Wein's Law λ_{MAX} T = const = 2.898 10^{-3} mK

As a body gets hotter it gets more RED then White

Reason for different shape of R(λ) Vs λ for different temperature?
Can one explain in on basis of Classical Physics (2A,2B,2C) ??

Blackbody Radiator: An Idealization



Classical Analysis:

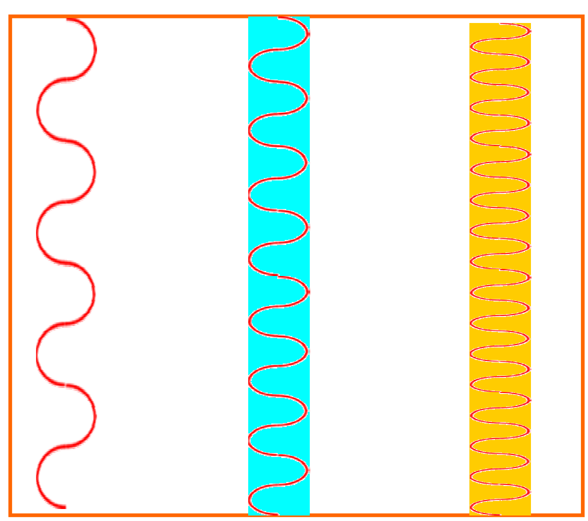
- **Box is filled with EM standing waves**
- **Radiation reflected back-and-forth between walls**
- **Radiation in thermal equilibrium with walls of Box**
- **How may waves of wavelength λ can fit inside the box ?**

Blackbody Absorbs everything
Reflects nothing
All light entering opening gets absorbed (ultimately) by the cavity wall

Cavity in equilibrium T w.r.t. surrounding. So it radiates everything It absorbs

Emerging radiation is a sample of radiation inside box at temp T

Predict nature of radiation inside Box ?



less **more** **Even more**

The Beginning of The End ! How BBQ Broke Physics

Classical Calculation

# of standing waves between Wavelengths λ and $\lambda + d\lambda$ are

$$N(\lambda)d\lambda = \frac{8\pi V}{\lambda^4} \bullet d\lambda \; ; \; V = \text{Volume of box} = L^3$$

Each standing wave contributes energy E= kT to radiation in Box

Energy density $u(\lambda)$= [# of standing waves/volume] × Energy/Standing Wave

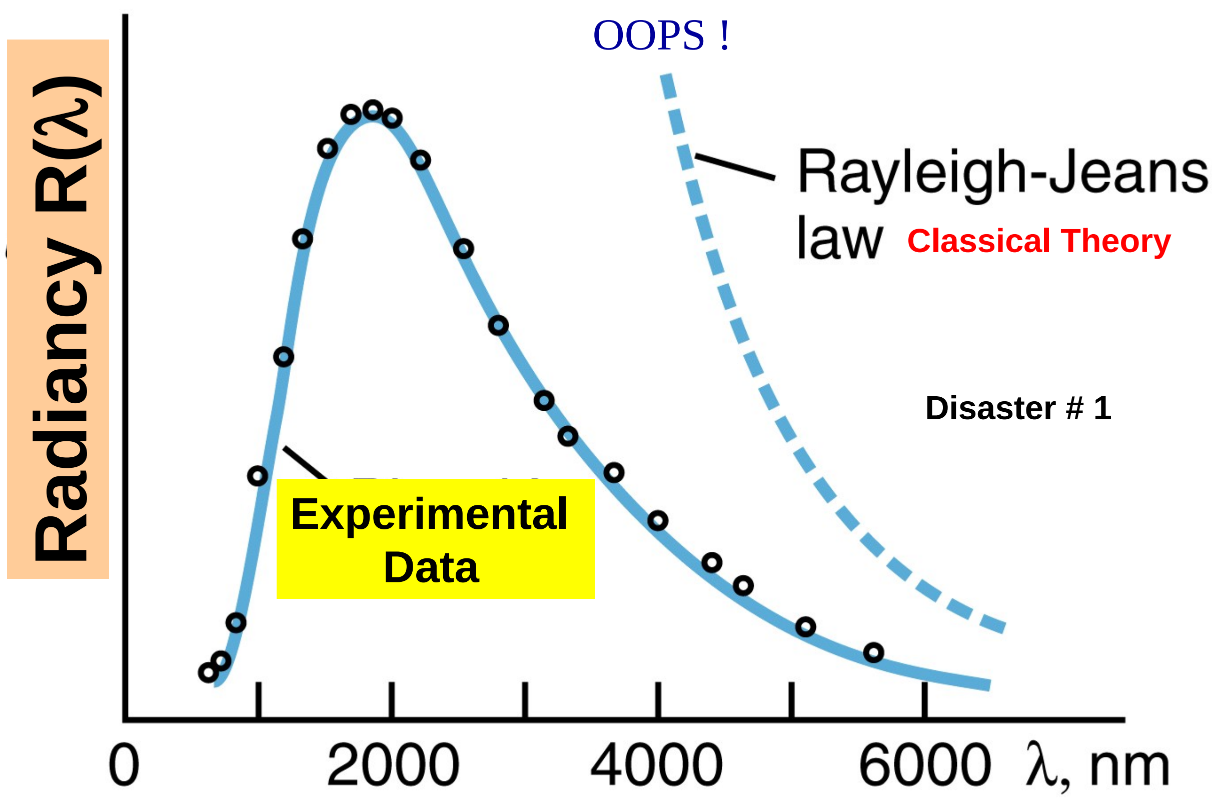
$$= \frac{8\pi V}{\lambda^4} \times \frac{1}{V} \times kT = \frac{8\pi}{\lambda^4} kT$$

$$\text{Radiancy } R(\lambda) = \frac{c}{4} u(\lambda) = \frac{c}{4}\frac{8\pi}{\lambda^4} kT = \frac{2\pi c}{\lambda^4} kT$$

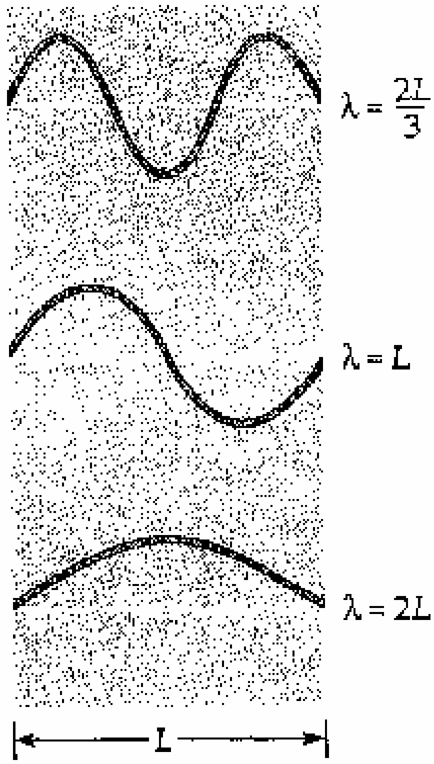
Radiancy is Radiation intensity per unit λ interval: Lets plot it

Prediction : as $\lambda \rightarrow 0$ (high frequency) ⇒ $R(\lambda) \rightarrow$ Infinity !
Oops !

Ultra Violet (Frequency) Catastrophe

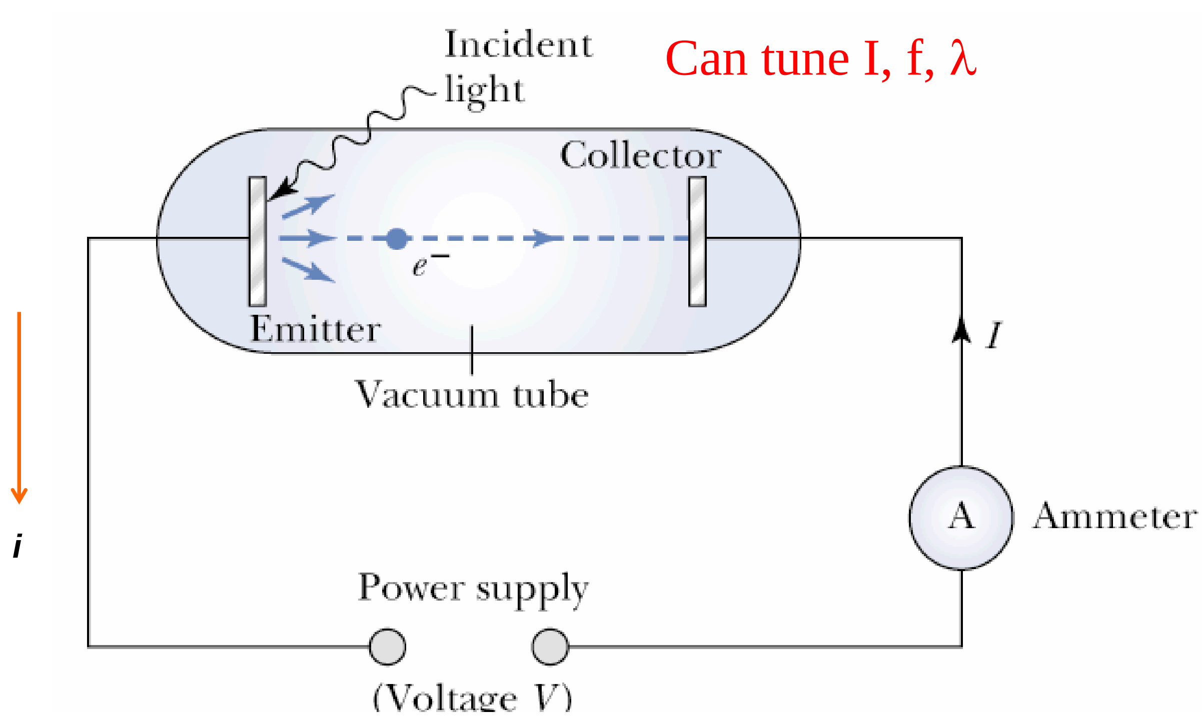


Standing Waves



Disaster # 2 : Photo-Electric Effect

Light of intensity I, wavelength λ and frequency ν incident on a photo-cathode

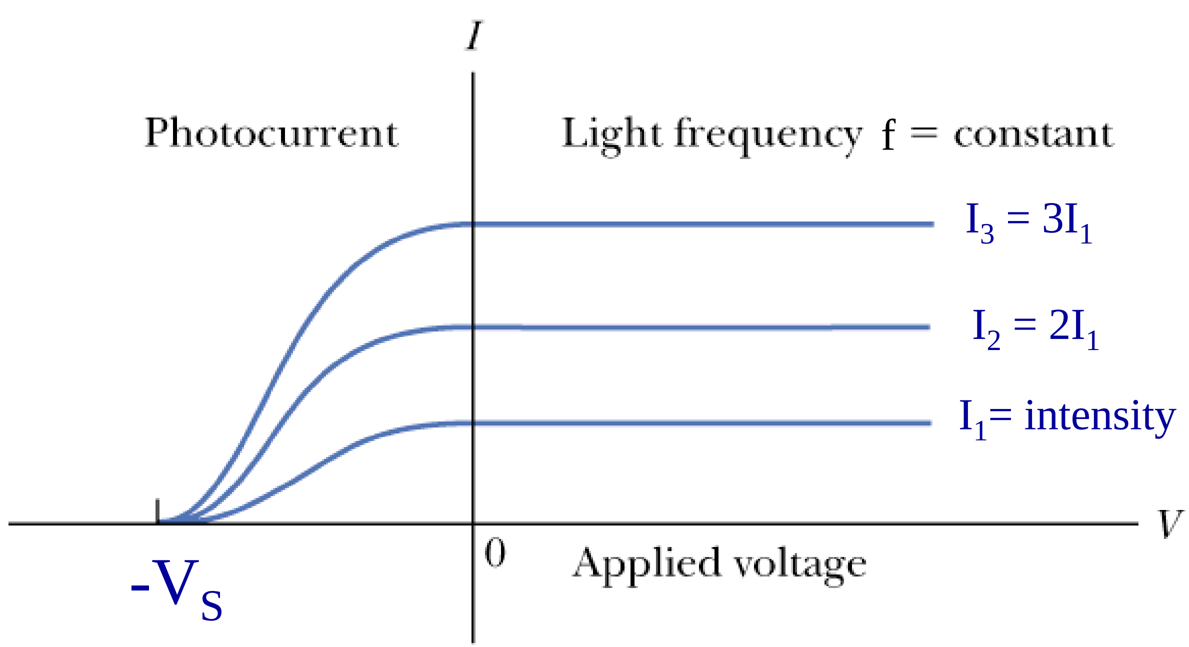


Measure characteristics of current in the circuit as a fn of I, f, λ

Photo Electric Effect: Measurable Properties

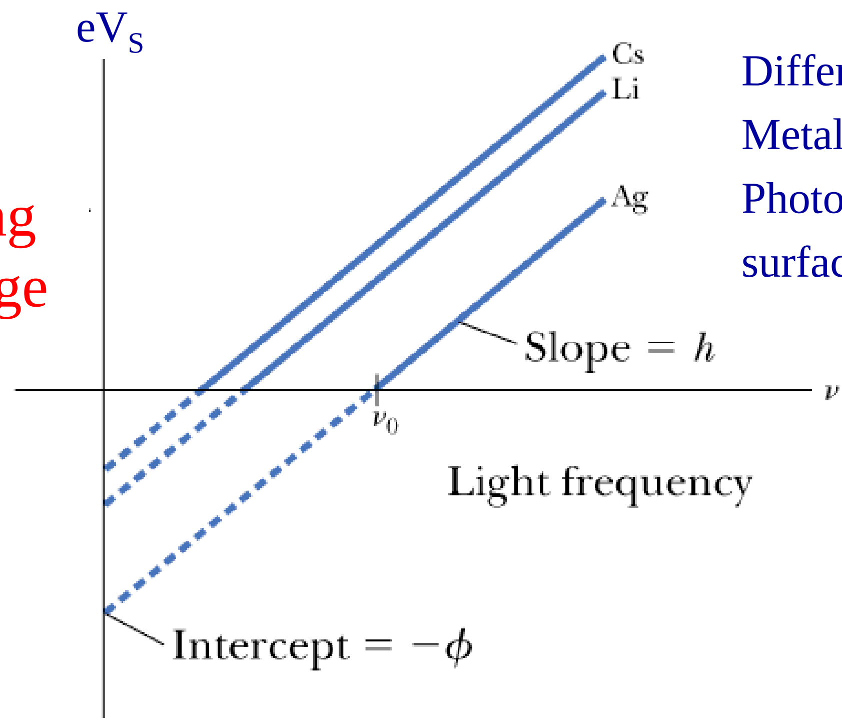
- Rate of electron emission from cathode
  - From current *i* seen in ammeter
- Maximum kinetic energy of emitted electron
  - By applying retarding potential on electron moving towards Collector plate
    - » $K_{MAX} = eV_S$ (V_S = Stopping voltage)
    - » Stopping voltage → no current flows
- Effect of different types of photo-cathode metal
- Time between shining light and first sign of photo-current in the circuit

Observations : Current Vs Frequency of Incident Light



Stopping Voltage V_s Vs Incident Light Frequency

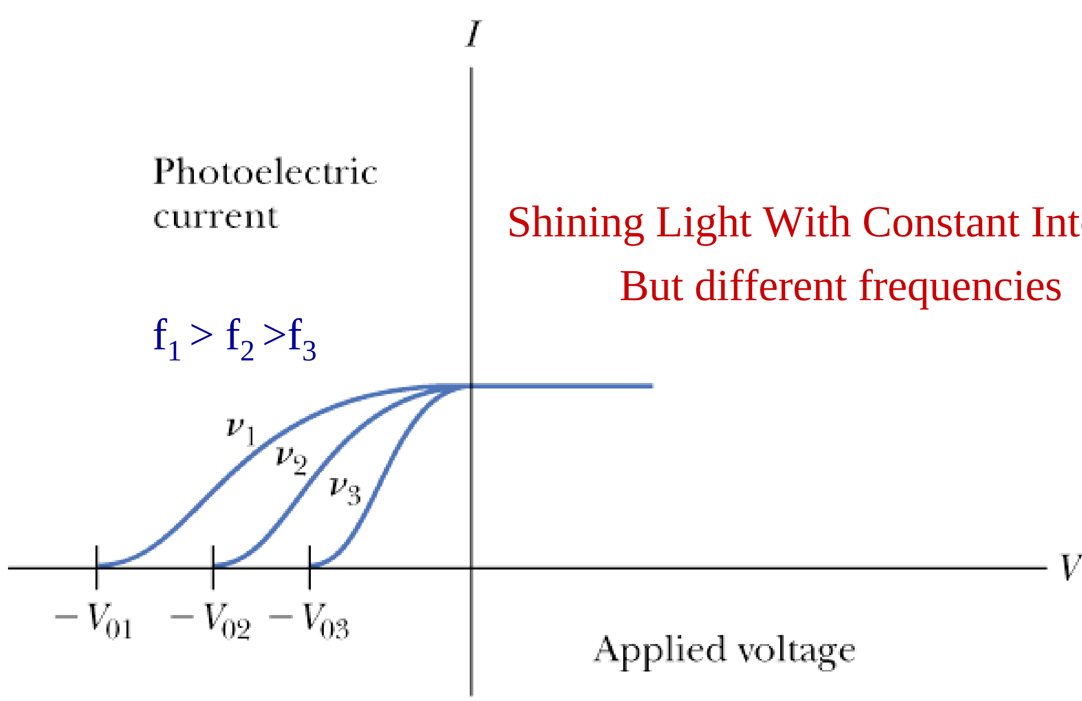
Stopping Voltage



Different Metal Photocathode surfaces

Retarding Potential Vs Light Frequency

Shining Light With Constant Intensity But different frequencies



Conclusions from the Experimental Observation

- Max Kinetic energy K_{MAX} independent of Intensity I for light of same frequency
- No photoelectric effect occurs if light frequency f is below a threshold no matter how high the intensity of light
- For a particular metal, light with $f > f_0$ causes photoelectric effect IRRESPECTIVE of light intensity.
  - f_0 is characteristic of that metal
- Photoelectric effect is instantaneous !...not time delay

Can one Explain all this Classically !

Classical Explanation of Photo Electric Effect

- As light Intensity increased $\Rightarrow$ $\vec{E}$ field amplitude larger
  - E field and electrical force seen by the "charged subatomic oscillators" Larger
    - $\vec{F} = e\vec{E}$
    - More force acting on the subatomic charged oscillator
    - $\Rightarrow$ More energy transferred to it
    - $\Rightarrow$ Charged particle "hooked to the atom" should leave the surface with more Kinetic Energy KE !! The intensity of light shining rules !
- As long as light is <u>intense enough</u> , light of ANY frequency f should cause photoelectric effect
- Because the Energy in a Wave is uniformly distributed over the Spherical wavefront incident on cathode, thould be a noticeable time lag ΔT between time is incident & the time a photo-electron is ejected : Energy absorption time
  - How much time ? Lets calculate it classically.

Classical Physics: Time Lag in Photo-Electric Effect

- Electron absorbs energy incident on a surface area where the electron is confined ≅ size of atom in cathode metal
- Electron is "bound" by attractive Coulomb force in the atom, so it must absorb a minimum amount of radiation before its stripped off
- Example : Laser light Intensity I = $120 W/m^2$ on Na metal
  - Binding energy = 2.3 eV= "Work Function"
  - Electron confined in Na atom, size ≅ 0.1nm ..how long before ejection ?
  - Average Power Delivered P_{AV} = **I . A**, $A = \pi r^2 \cong 3.1 \times 10^{-20}\ m^2$
  - If all energy absorbed then $\Delta E = P_{AV} \cdot \Delta T \Rightarrow \Delta T = \Delta E / P_{AV}$

$$\Delta T = \frac{(2.3eV)(1.6\times10^{-19}\ J/eV)}{(120W/m^2)(3.1\times10^{-20}\ m^2)} = 0.10\ S$$

  - Classical Physics predicts Measurable delay even by the primitive clocks of 1900
  - But in experiment, the effect was observed to be instantaneous !!
  - Classical Physics fails in explaining all results & goes to DOGHOUSE !