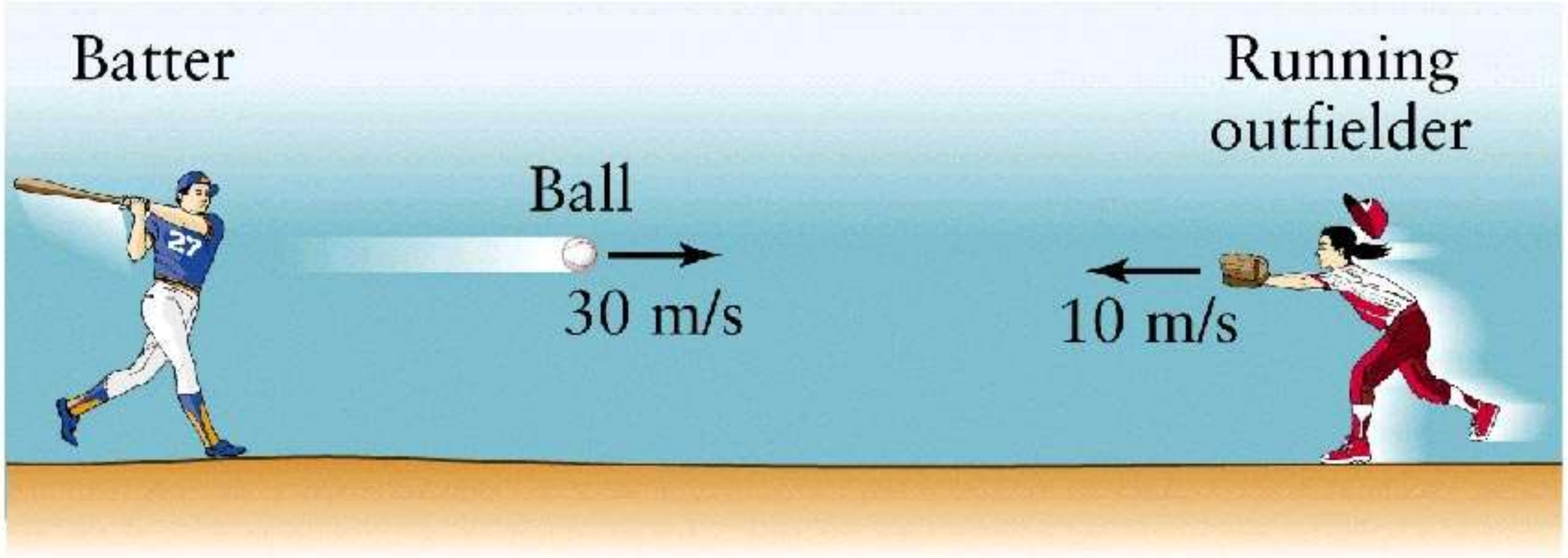
Modern Physics (Lec. 1)

Physics

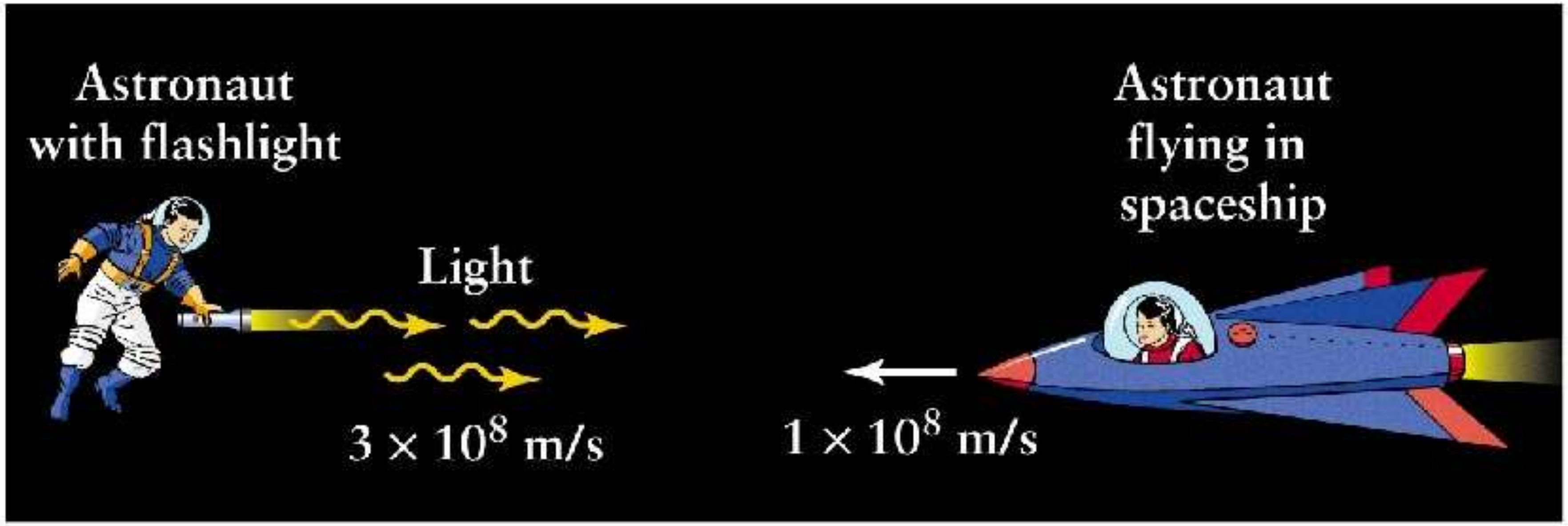
- Fundamental Science
  - Concerned with the fundamental principles of the Universe
  - Foundation of other physical sciences
  - Has simplicity of fundamental concepts
- Divided into five major areas
  - Classical Mechanics
  - Relativity
  - Thermodynamics
  - Electromagnetism
  - Optics
  - Quantum Mechanics



As seen by outfielder, ball is approaching her at
(30 m/s) + (10 m/s) = 40 m/s

a

Speed of light is constant



Incorrect Newtonian description:

As seen by astronaut in spaceship, light is approaching her at
$(3 \times 10^8 \text{ m/s}) + (1 \times 10^8 \text{ m/s}) = 4 \times 10^8 \text{ m/s}$

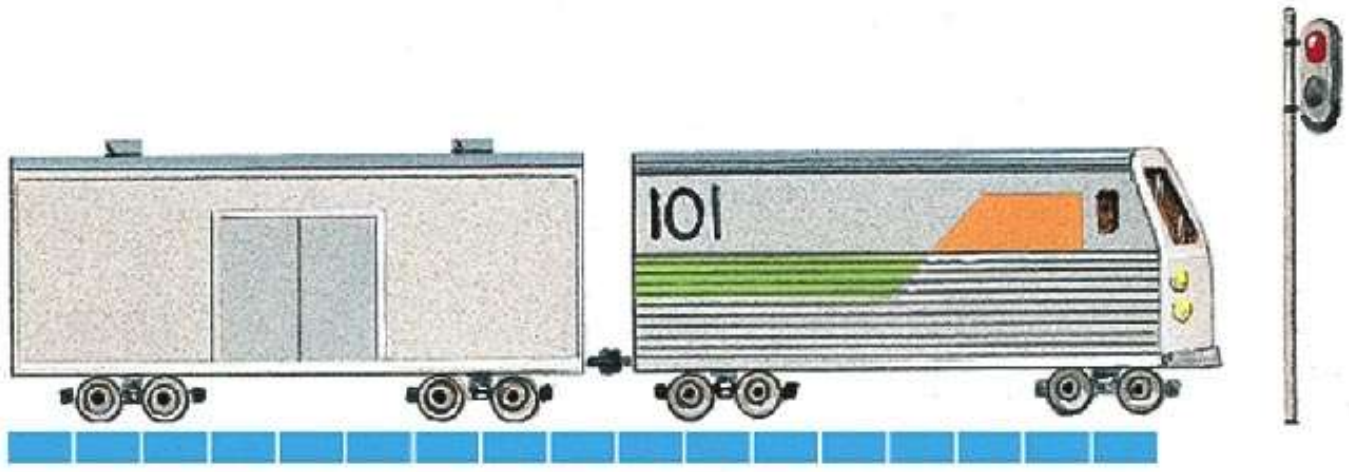
Correct Einsteinian description:

As seen by astronaut in spaceship, light is approaching her at
3×10^8 m/s

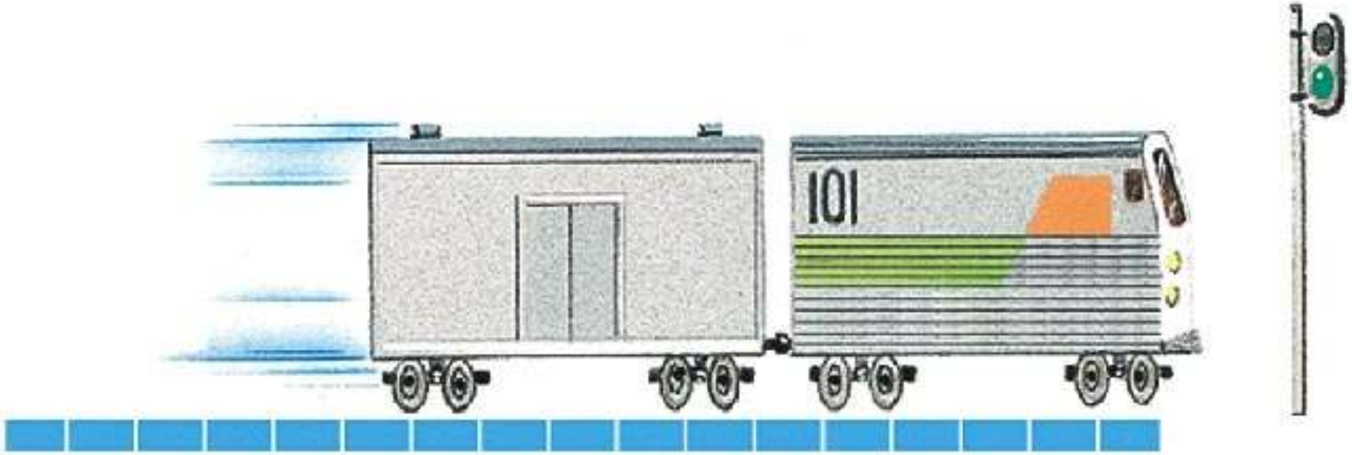
Our conceptions of space and time has to be changed.

- Facts:
  - Regardless of speed or direction, observers always measure the speed of light to be the same value.
  - Speed of light is maximum possible speed.
- Consequences:
  - The length of an object decreases as its speed increases
  - Clocks passing by you run more slowly than do clocks at rest

Special Relativity: Length Contraction

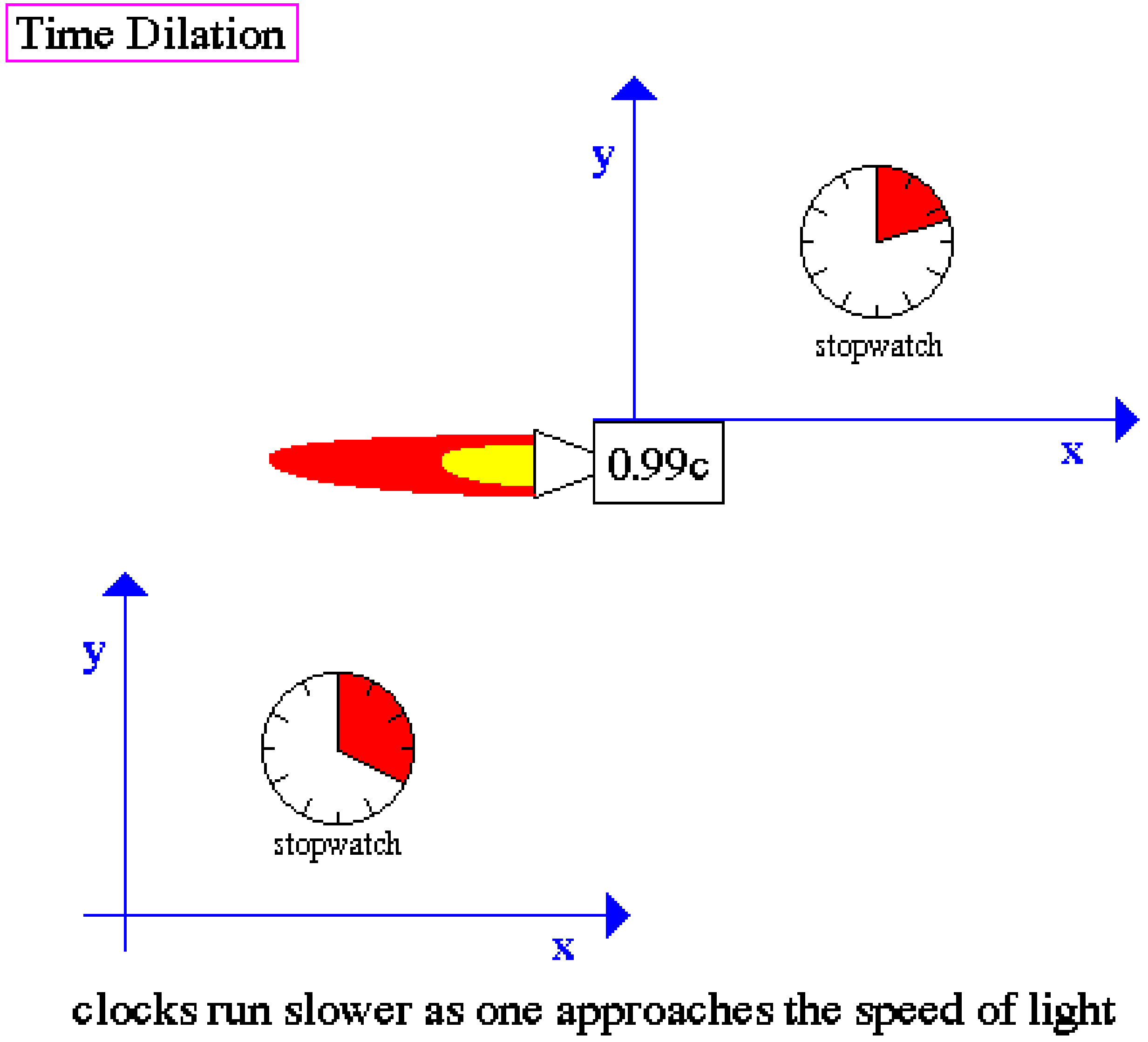


At rest



In motion

Time dilation



Classical Physics

- Mechanics and electromagnetism are basic to all other branches of classical and modern physics
- Classical physics
  - Developed before 1900
  - Our study will start with Classical Mechanics
    - Also called Newtonian Mechanics or Mechanics
- Modern physics
  - From about 1900 to the present

Theory and Experiments

- Should complement each other
- When a discrepancy occurs, theory may be modified
  - Theory may apply to limited conditions
    - Example: Newtonian Mechanics is confined to objects traveling slowly with respect to the speed of light
  - Try to develop a more general theory

Classical Physics Overview

- Classical physics includes principles in many branches developed before 1900
- Mechanics
  - Major developments by Newton, and continuing through the 18th century
- Thermodynamics, optics and electromagnetism
  - Developed in the latter part of the 19th century
  - Apparatus for controlled experiments became available

Modern Physics

- Began near the end of the 19^{th} century
- Phenomena that could not be explained by classical physics
- Includes theories of relativity and quantum mechanics

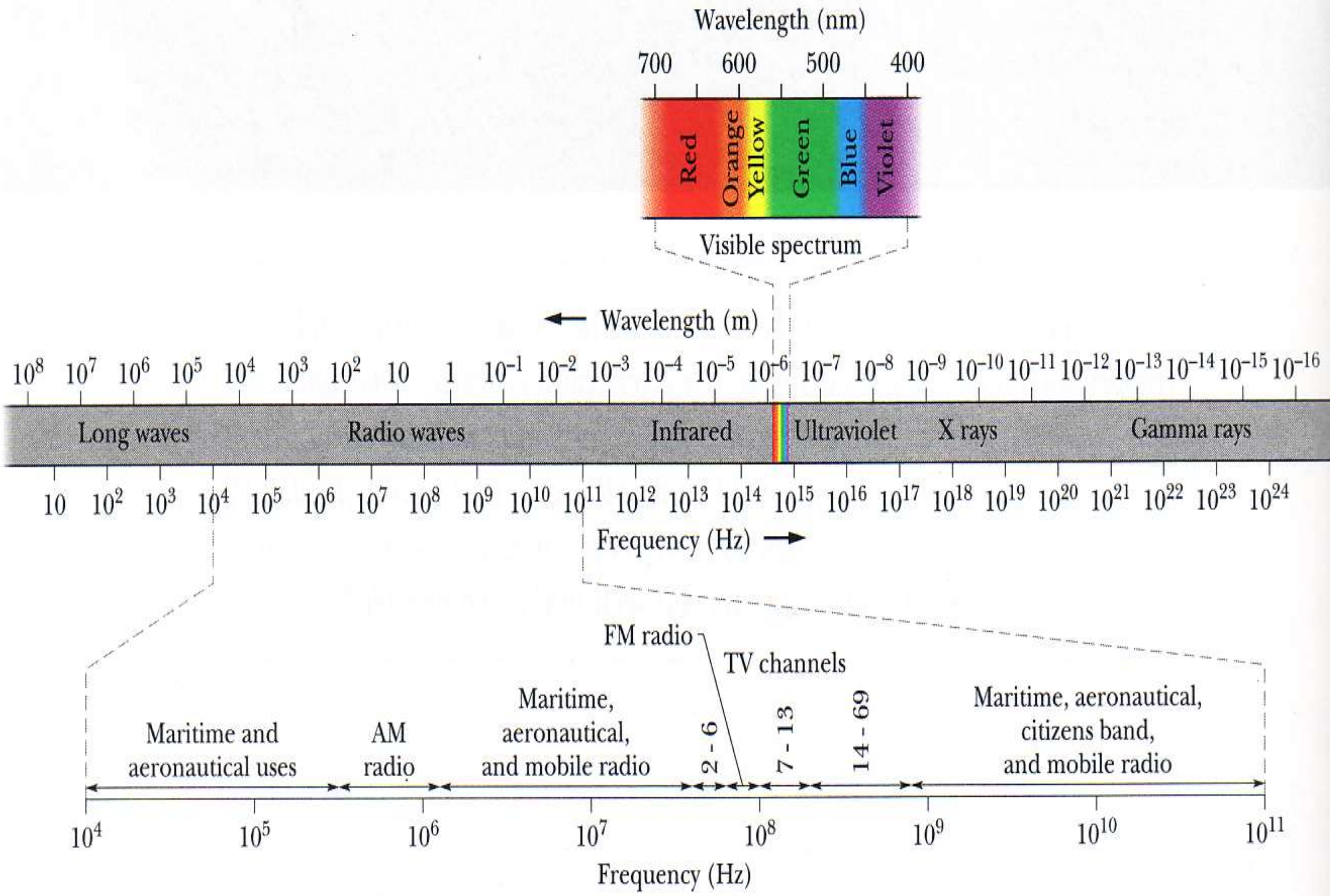
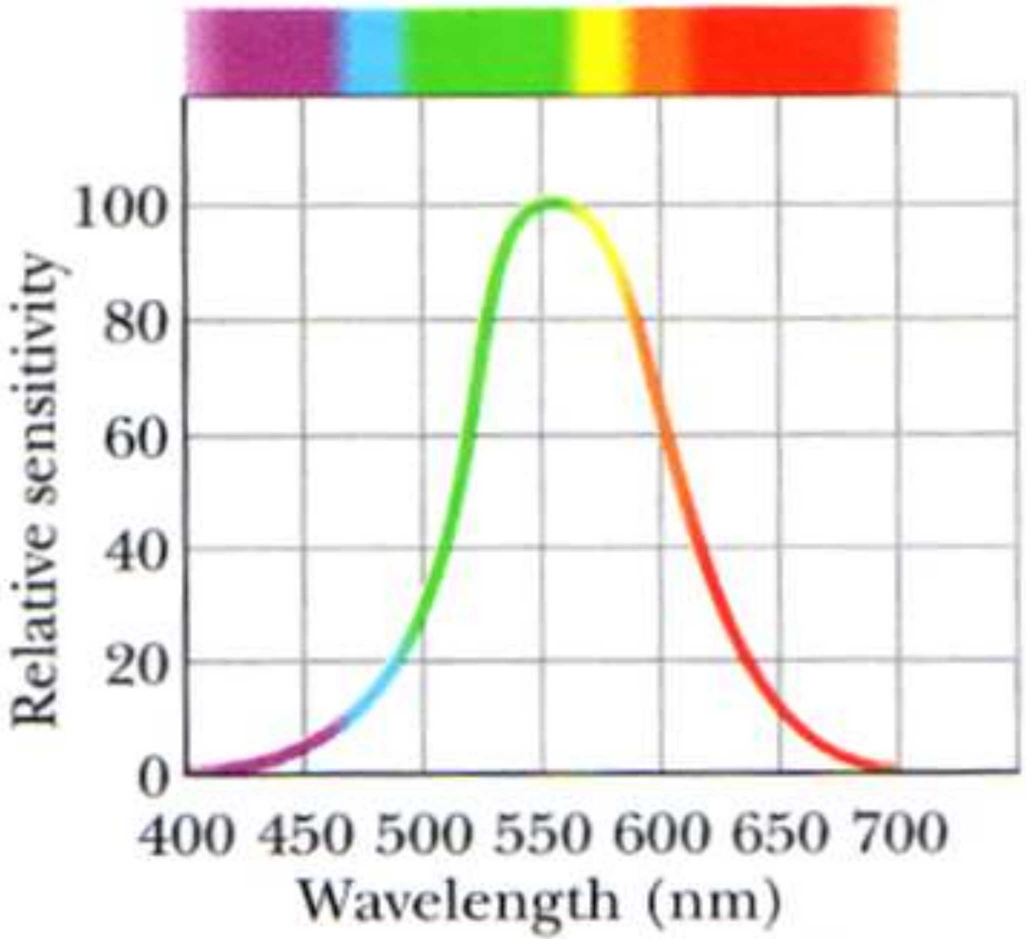


FIGURE 34-1 The electromagnetic spectrum.



URE 34-2 The relative sensitivity of the eye to electromag- waves at different wavelengths. This portion of the electro- netic spectrum consists of *visible light*.

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MAXWELL'S EQUATIONS

$$\oint \mathbf{E} \cdot d\mathbf{A} = \frac{q}{\varepsilon_0}$$

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

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

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 \left(i + \varepsilon_0 \frac{d\Phi_E}{dt} \right)$$

ELECTROMAGNETIC WAVES

Maxwell's Equations in Free Space

$$q = 0 \qquad\qquad i = 0$$

$$\oint \mathbf{E} \cdot d\mathbf{A} = 0 \qquad\qquad \oint \mathbf{E} \cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$$

$$\oint \mathbf{B} \cdot d\mathbf{A} = 0 \qquad\qquad \oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}$$

Maxwell's Equations – Differential Form

$$\nabla \cdot E = \frac{\rho}{\varepsilon_o} \qquad \nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \cdot B = 0 \qquad \nabla \times B = \mu_o \varepsilon_o \frac{\partial E}{\partial t}$$

Derivation of the Wave Equation from Maxwell's Equations (cont'd)

But:

$$\vec{\nabla} \times \vec{B} = \mu\varepsilon \frac{\partial \vec{E}}{\partial t}$$

Substituting for $\vec{\nabla} \times \vec{B}$, we have:

$$\vec{\nabla} \times [\vec{\nabla} \times \vec{E}] = -\frac{\partial}{\partial t}[\vec{\nabla} \times \vec{B}] \Rightarrow \vec{\nabla} \times [\vec{\nabla} \times \vec{E}] = -\frac{\partial}{\partial t}[\mu\varepsilon \frac{\partial \vec{E}}{\partial t}]$$

Or:

$$\vec{\nabla} \times [\vec{\nabla} \times \vec{E}] = -\mu\varepsilon \frac{\partial^2 \vec{E}}{\partial t^2}$$

assuming that μ and ε are constant in time.

Derivation of the Wave Equation from Maxwell's Equations (cont'd)

Identity: $\vec{\nabla} \times [\vec{\nabla} \times \vec{f}\,] \equiv \vec{\nabla}(\vec{\nabla} \cdot \vec{f}\,) - \nabla^2 \vec{f}$

Using the identity, $\vec{\nabla}\times[\vec{\nabla}\times\vec{E}] = -\mu\varepsilon\dfrac{\partial^2\vec{E}}{\partial t^2}$

becomes: $\vec{\nabla}(\vec{\nabla}\cdot\vec{E}) - \nabla^2\vec{E} = -\mu\varepsilon\dfrac{\partial^2\vec{E}}{\partial t^2}$

If we now assume zero charge density: $\rho = 0$, then

$$\vec{\nabla}\cdot\vec{E} = 0$$

and we're left with the Wave Equation!

$$\nabla^2\vec{E} = \mu\varepsilon\frac{\partial^2\vec{E}}{\partial t^2} \qquad \text{where } \mu\varepsilon \equiv 1/c^2$$

It's Alive!

- Well, at least it's a wave! Combining the last two equations leads us to:

$$\frac{\partial^2 E_y}{\partial x^2} = \mu_o \varepsilon_o \frac{\partial^2 E_y}{\partial t^2}$$

- example - consider the electric field part of an electromagnetic wave described by:

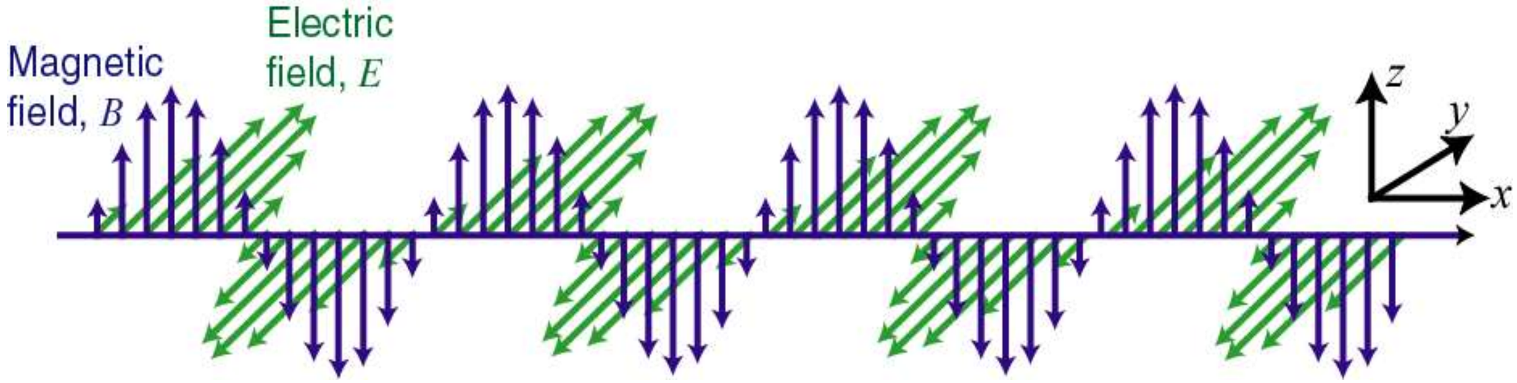
$$E(x,t) = E_o \sin(kx - \omega t)\, j + E_o \cos(kx - \omega t) k$$

POYNTING VECTOR

$$\mathbf{S} = \frac{1}{\mu_0}\mathbf{E} \times \mathbf{B}$$

- This is a measure of power per area. Units are watts per meter^2.
- Direction is the direction in which the wave is moving.

Maxwell's Equations and Light Waves



Longitudinal vs. transverse waves

Derivation of wave equation from Maxwell's Equations

Why light waves are transverse waves

Why we neglect the magnetic field

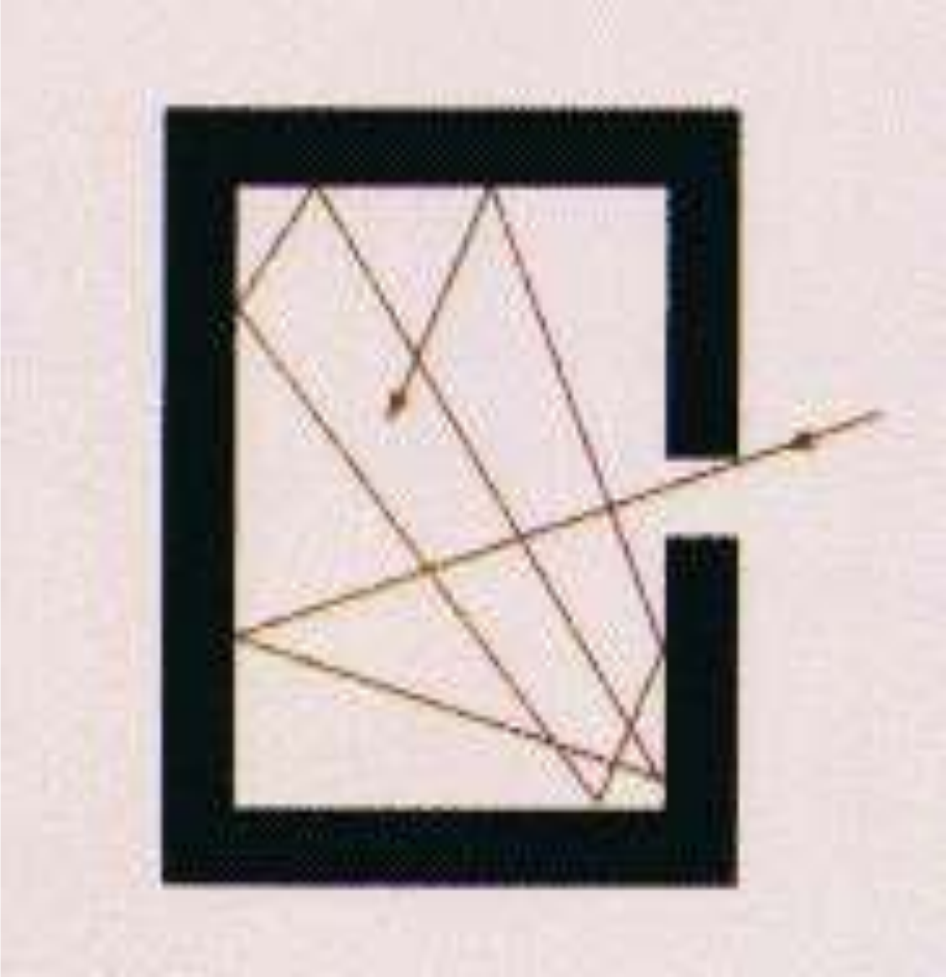
Photons and photon statistics

Motivation

- The black body is importance in thermal radiation theory and practice.
- The ideal black body notion is importance in studying thermal radiation and electromagnetic radiation transfer in all wavelength bands.
- The black body is used as a standard with which the absorption of real bodies is compared.

Definition of a black body

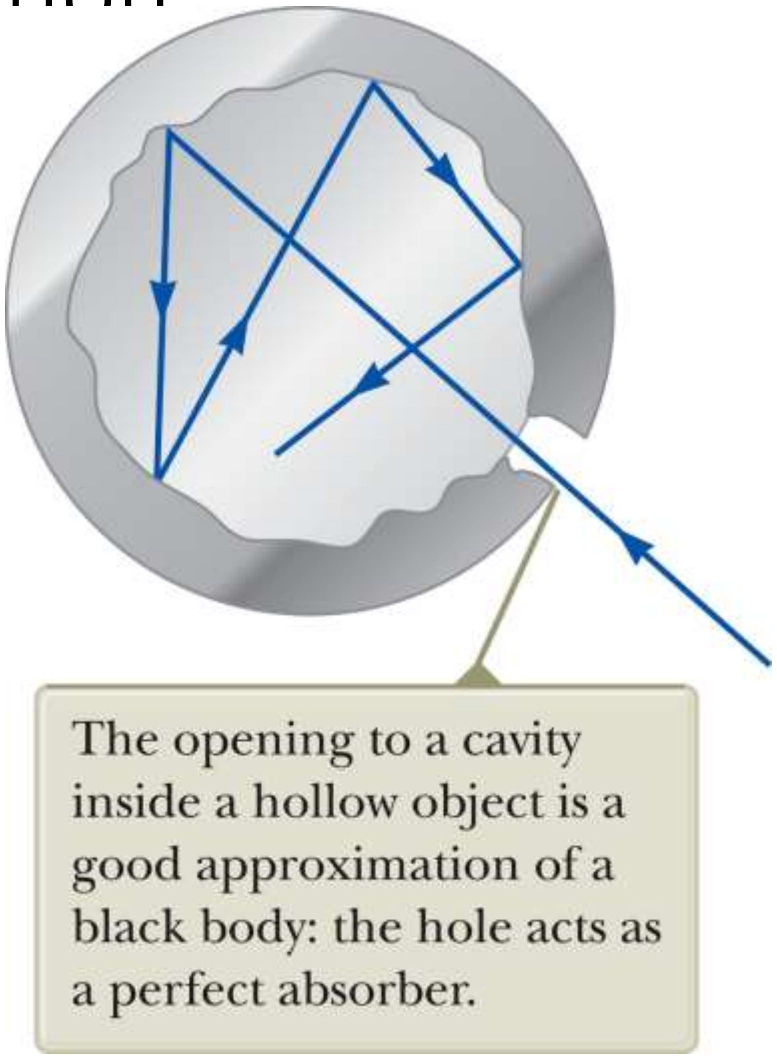
A black body is an ideal body which allows the whole of the incident radiation to pass into itself (without reflecting the energy) and absorbs within itself this whole incident radiation (without passing on the energy). This propety is valid for radiation corresponding to all wavelengths and to all angels of incidence. Therefore, the black body is an ideal absorber of incident radaition.



Univ. of Oregon web site

Blackbody Approximation

- A good approximation of a black body is a small hole leading to the inside of a hollow object.
- The hole acts as a perfect absorber.
- The nature of the radiation leaving the cavity through the hole depends only on the temperature of the cavity.



Black-Body Radiation Laws (1)

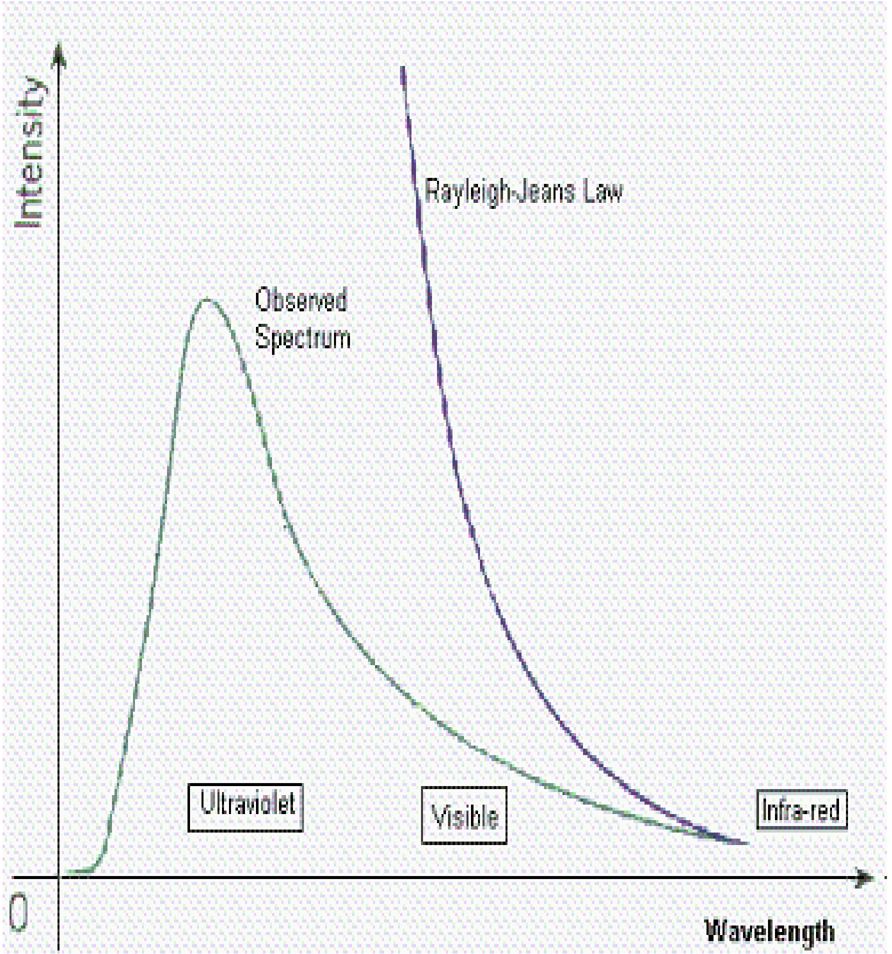
$$I(\lambda, T) = \frac{2\pi ckT}{\lambda^4}$$

1- The Rayleigh-Jeans Law.

* It agrees with experimental measurements for long wavelengths.

* It predicts an energy output that diverges towards infinity as wavelengths grow smaller.

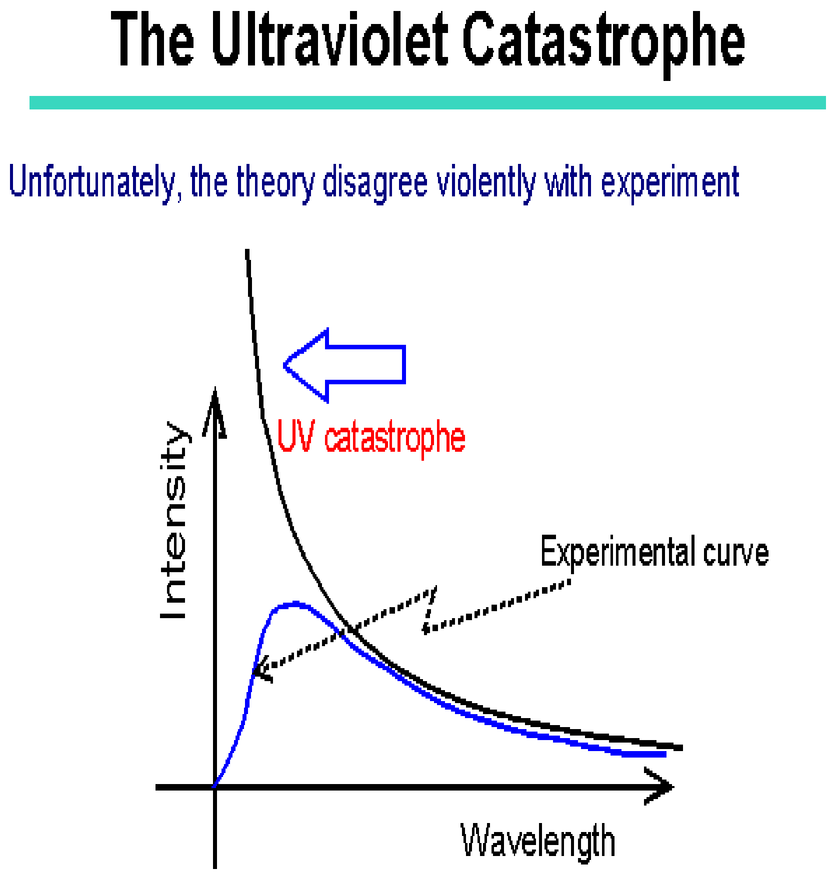
* The failure has become known as the ultraviolet catastrophe.



http://www.egglescliffe.org.uk/physics/astronomy/blackbody/Image22c.gif

Ultraviolet Catastrophe

$$I(\lambda,T)=\frac{2\pi ckT}{\lambda^4}$$



- This formula also had a problem. The problem was the term in the denominator.
- For large wavelengths it fitted the experimental data but it had major problems at shorter wavelengths.

http://theory.uwinnipeg.ca/users/gabor/foundations/quantum/images/slide5.gif

Blackbody Experiment Results

- The total power of the emitted radiation increases with temperature.
  - Stefan's law (from Chapter 20):

    $P = \sigma A e T^4$
  - The emissivity, e, of a black body is 1, exactly
- The peak of the wavelength distribution shifts to shorter wavelengths as the temperature increases.
  - Wien's displacement law
  - $\lambda_{max}T = 2.898 \times 10^{-3}\ \mathrm{m \cdot K}$

Black-Body Radiation Laws (2)

2- Planck Law

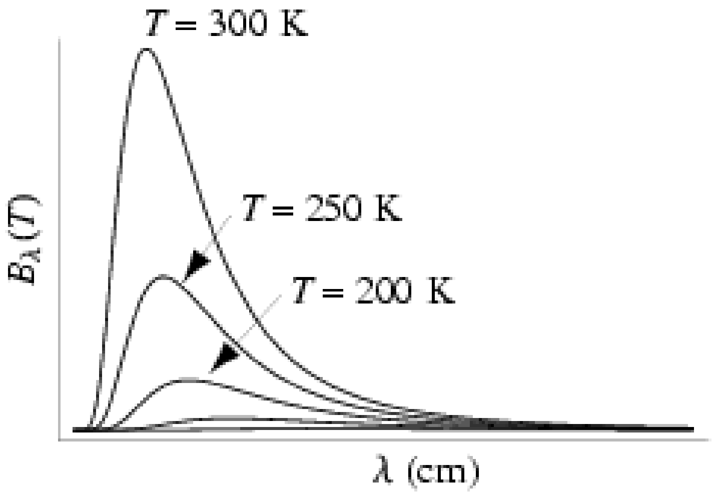
- We have two forms. As a function of wavelength.

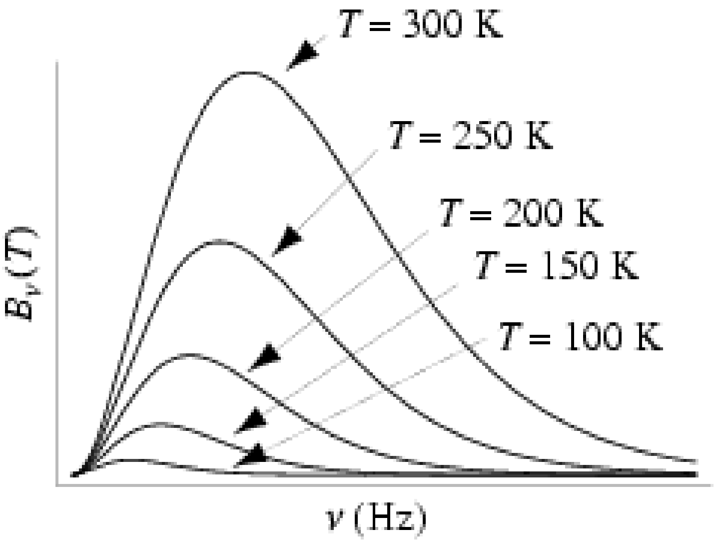
$$I(\lambda,T)=\frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}}-1}$$

And as a function of frequency

$$I(\nu,T)=\frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}$$

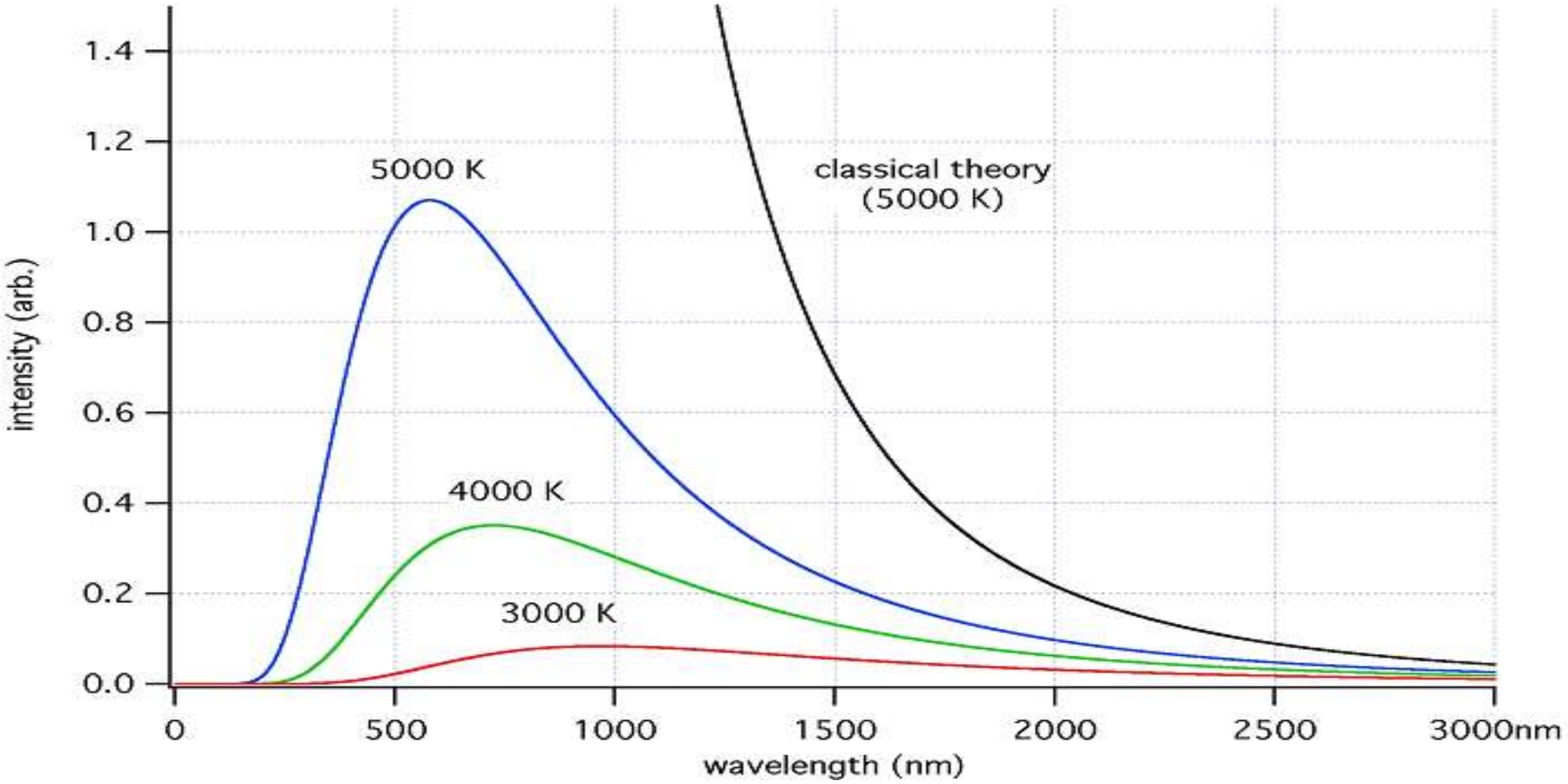
The Planck Law gives a distribution that peaks at a certain wavelength, the peak shifts to shorter wavelengths for higher temperatures, and the area under the curve grows rapidly with increasing temperature.





http://scienceworld.wolfram.com/physics/PlanckLaw.html

Comparison between Classical and Quantum viewpoint



http://upload.wikimedia.org/wikipedia/commons/a/a1/Blackbody-lg.png

Summary

- A black body is a theoretical object that absorbs 100% of the radiation that hits it. Therefore it reflects no radiation and appears perfectly black.
- Roughly we can say that the stars radiate like blackbody radiators. This is important because it means that we can use the theory for blackbody radiators to infer things about stars.
- At a particular temperature the black body would emit the maximum amount of energy possible for that temperature.
- Blackbody radiation does not depend on the type of object emitting it. Entire spectrum of blackbody radiation depends on only one parameter, the temperature, T.

The Birth of the Quantum

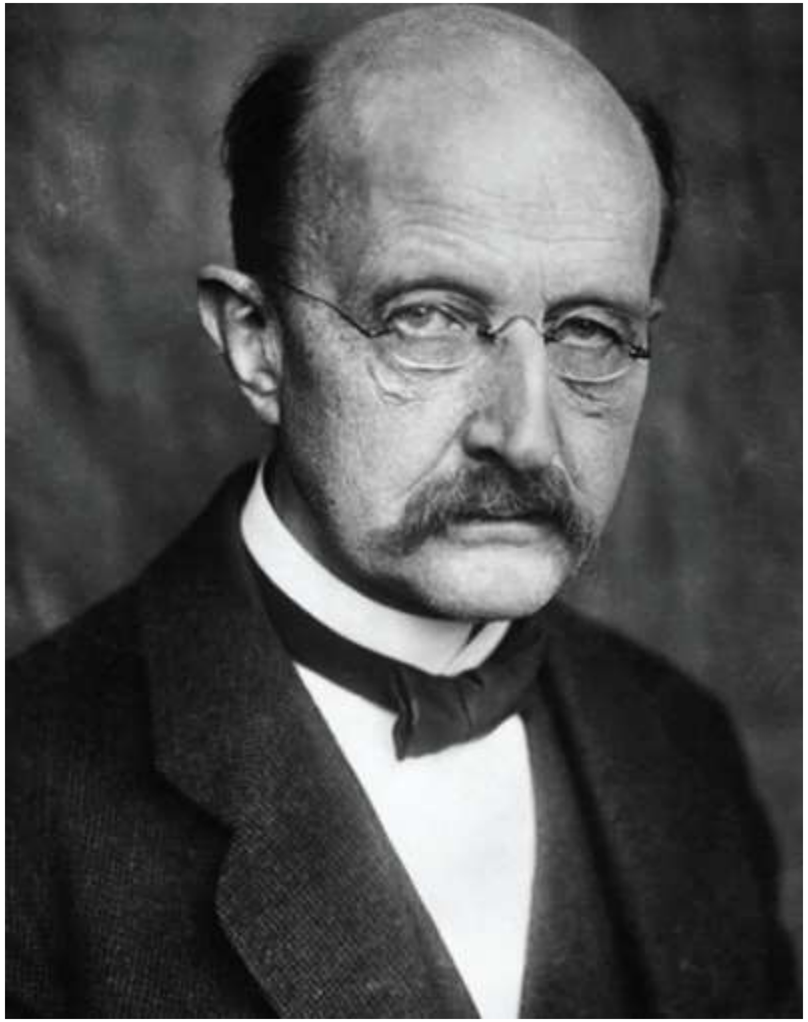
- Max Planck
  - The energy contained in radiation is related to the frequency of the radiation by the relationship

$$E = nhf$$

    - n is a positive integer called the *quantum number*
    - f is the frequency of the oscillation
  - A discreet packet of energy, later to become known as "a photon"

Max Planck

- 1858 – 1847
- German physicist
- Introduced the concept of "quantum of action"
- In 1918 he was awarded the Nobel Prize for the discovery of the quantized nature of energy.



Planck's Theory of Blackbody Radiation

- In 1900 Planck developed a theory of blackbody radiation that leads to an equation for the intensity of the radiation.
- This equation is in complete agreement with experimental observations.
- He assumed the cavity radiation came from atomic oscillations in the cavity walls.
- Planck made two assumptions about the nature of the oscillators in the cavity walls.

Planck’s Assumption, 1

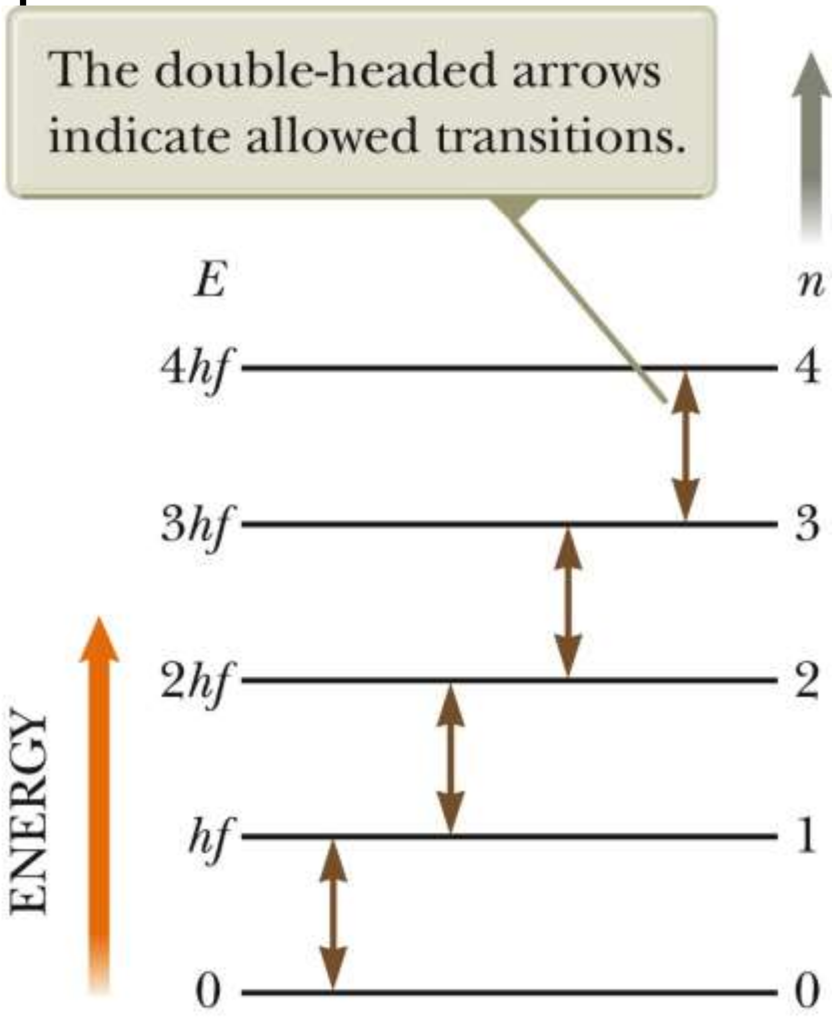
- The energy of an oscillator can have only certain discrete values E_n.
  - $E_n = n\,h\,f$
    - n is a positive integer called the quantum number
    - ƒ is the frequency of oscillation
    - h is Planck’s constant
  - This says the energy is quantized.
  - Each discrete energy value corresponds to a different quantum state.
    - Each quantum state is represented by the quantum number, *n.*

Planck's Assumption, 2

- The oscillators emit or absorb energy when making a transition from one quantum state to another.
    - The entire energy difference between the initial and final states in the transition is emitted or absorbed as a single quantum of radiation.
    - An oscillator emits or absorbs energy only when it changes quantum states.
    - The energy carried by the quantum of radiation is $E = h f$.

Energy-Level Diagram

- An **energy-level diagram** shows the quantized energy levels and allowed transitions.
- Energy is on the vertical axis.
- Horizontal lines represent the allowed energy levels.
- The double-headed arrows indicate allowed transitions.



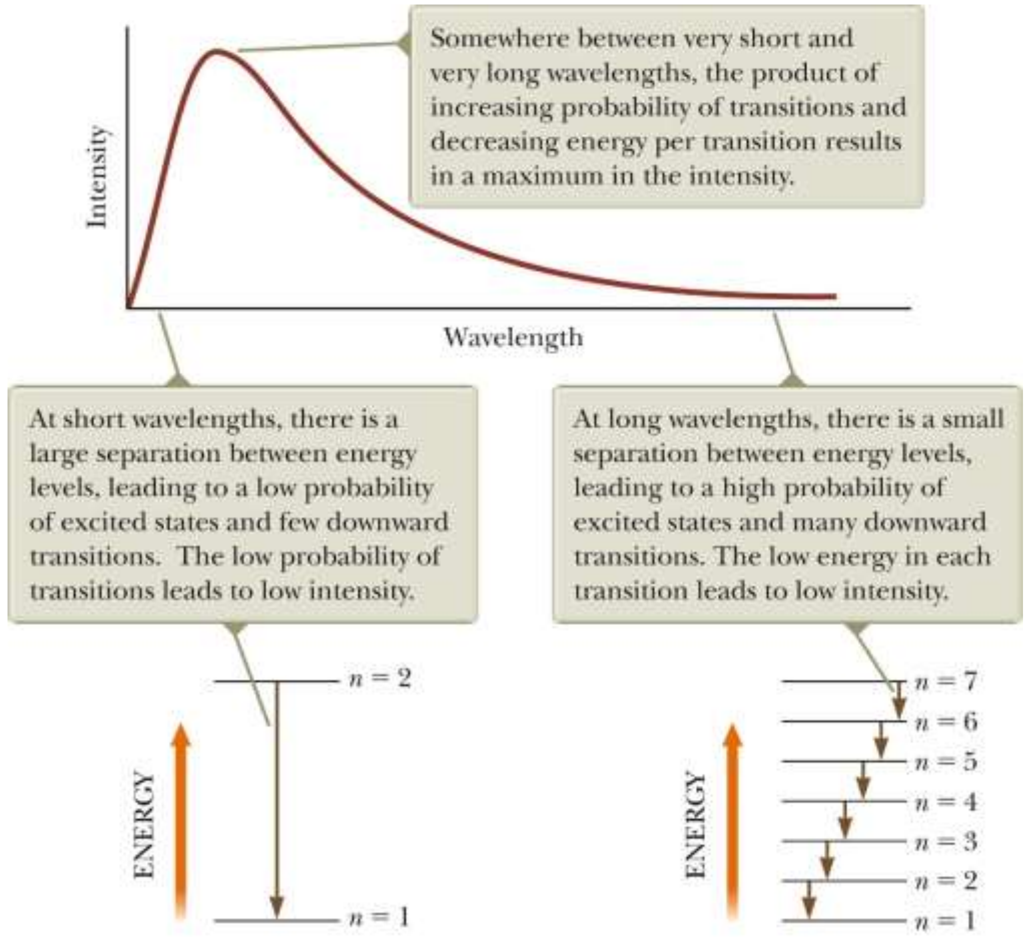
More About Planck’s Model

- The average energy of a wave is the average energy difference between levels of the oscillator, *weighted according to the probability of the wave being emitted.*
- This weighting is described by the Boltzmann distribution law and gives the probability of a state being occupied as being proportional to

$$e^{-E/k_BT}$$

where *E* is the energy of the state.

Planck’s Model, Graph



Planck's Wavelength Distribution Function

- Planck generated a theoretical expression for the wavelength distribution.

$$I(\lambda,T)=\frac{2\pi hc^2}{\lambda^5\left(e^{hc/\lambda k_B T}-1\right)}$$

  - h = 6.626 x 10^{-34} J·s
  - h is a fundamental constant of nature.
- At long wavelengths, Planck's equation reduces to the Rayleigh-Jeans expression.
- At short wavelengths, it predicts an exponential decrease in intensity with decreasing wavelength.
  - This is in agreement with experimental results.

Einstein and Planck’s Results

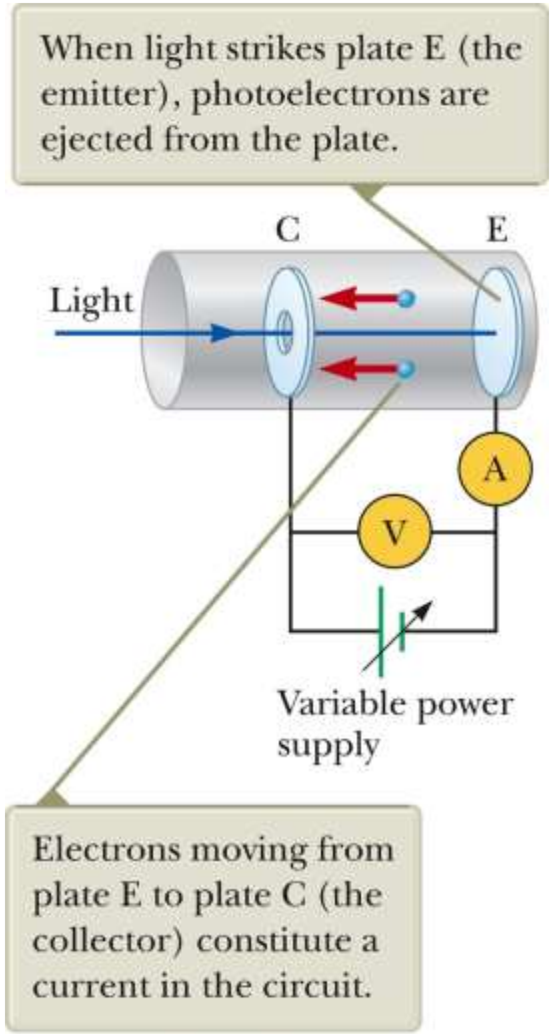
- Einstein rederived Planck’s results by assuming the oscillations of the electromagnetic field were themselves quantized.
- In other words, Einstein proposed that quantization is a fundamental property of light and other electromagnetic radiation.
- This led to the concept of photons.

Photoelectric Effect

- The **photoelectric effect** occurs when light incident on certain metallic surfaces causes electrons to be emitted from those surfaces.
  - The emitted electrons are called **photoelectrons.**
    - They are no different than other electrons.
    - The name is given because of their ejection from a metal by light in the photoelectric effect

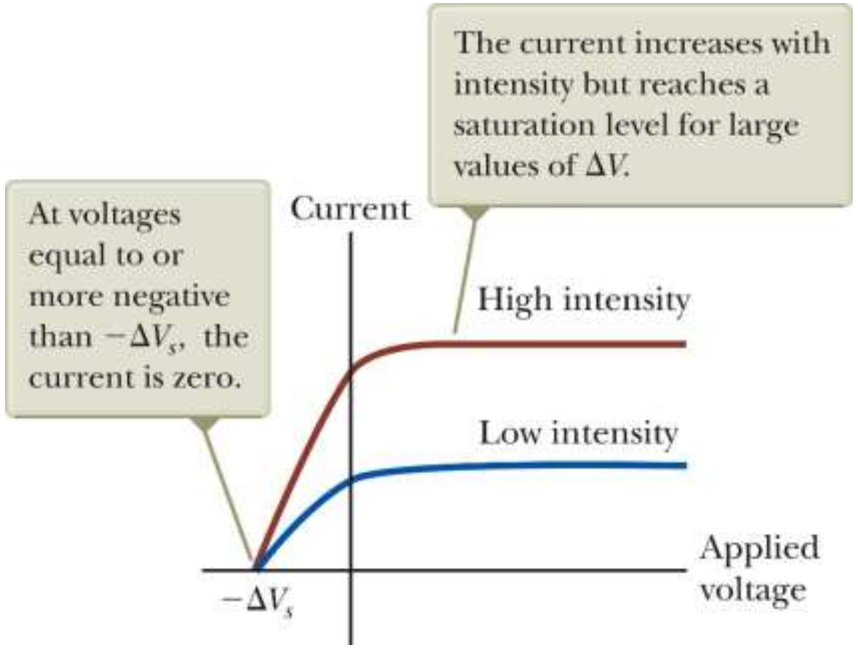
Photoelectric Effect Apparatus

- When the tube is kept in the dark, the ammeter reads zero.
- When plate E is illuminated by light having an appropriate wavelength, a current is detected by the ammeter.
- The current arises from photoelectrons emitted from the negative plate and collected at the positive plate.



Photoelectric Effect, Results

- At large values of ΔV, the current reaches a maximum value.
  - All the electrons emitted at *E* are collected at *C.*
- The maximum current increases as the intensity of the incident light increases.
- When ΔV is negative, the current drops.
- When ΔV is equal to or more negative than ΔV_s, the current is zero.



Photoelectric Effect Feature 1

- Dependence of photoelectron kinetic energy on light intensity
  - *Classical Prediction*
    - Electrons should absorb energy continually from the electromagnetic waves.
    - As the light intensity incident on the metal is increased, the electrons should be ejected with more kinetic energy.
  - *Experimental Result*
    - The maximum kinetic energy is independent of light intensity.
    - The maximum kinetic energy is proportional to the stopping potential (ΔV_s).

Photoelectric Effect Feature 2

- Time interval between incidence of light and ejection of photoelectrons
  - *Classical Prediction*
    - At low light intensities, a measurable time interval should pass between the instant the light is turned on and the time an electron is ejected from the metal.
    - This time interval is required for the electron to absorb the incident radiation before it acquires enough energy to escape from the metal.
  - *Experimental Result*
    - Electrons are emitted almost instantaneously, even at very low light intensities.

Photoelectric Effect Feature 3

- Dependence of ejection of electrons on light frequency
  - *Classical Prediction*
    - Electrons should be ejected at any frequency as long as the light intensity is high enough.
  - *Experimental Result*
    - No electrons are emitted if the incident light falls below some **cutoff frequency, f_c.**
    - The cutoff frequency is characteristic of the material being illuminated.
    - No electrons are ejected below the cutoff frequency regardless of intensity.

Photoelectric Effect Feature 4

- Dependence of photoelectron kinetic energy on light frequency
  - *Classical Prediction*
    - There should be no relationship between the frequency of the light and the electric kinetic energy.
    - The kinetic energy should be related to the intensity of the light.
  - *Experimental Result*
    - The maximum kinetic energy of the photoelectrons increases with increasing light frequency.

Photoelectric Effect Features, Summary

- The experimental results contradict all four classical predictions.
- Einstein extended Planck's concept of quantization to electromagnetic waves.
- All electromagnetic radiation of frequency f from any source can be considered a stream of quanta, now called *photons.*
- Each photon has an energy *E* and moves at the speed of light in a vacuum.
    - $E = hf$
- A photon of incident light gives all its energy to a single electron in the metal.

Photoelectric Effect, Work Function

- Electrons ejected from the surface of the metal and not making collisions with other metal atoms before escaping possess the maximum kinetic energy $K_{max.}$
- $K_{max} = hf - \varphi$
  - φ is called the work function of the metal.
  - The work function represents the minimum energy with which an electron is bound in the metal.

Some Work Function Values

TABLE 40.1

Work Functions of Selected Metals

Metal	ϕ (eV)
Na	2.46
Al	4.08
Fe	4.50
Cu	4.70
Zn	4.31
Ag	4.73
Pt	6.35
Pb	4.14

Note: Values are typical for metals listed. Actual values may vary depending on whether the metal is a single crystal or polycrystalline. Values may also depend on the face from which electrons are ejected from crystalline metals. Furthermore, different experimental procedures may produce differing values.

Photon Model Explanation of the Photoelectric Effect

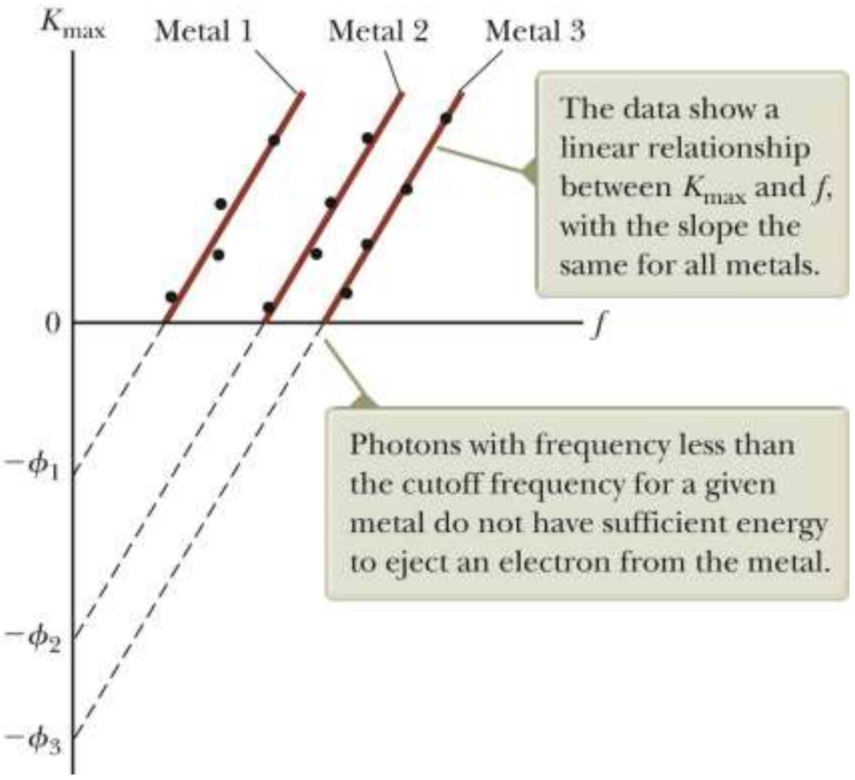
- Dependence of photoelectron kinetic energy on light intensity
  - K_{max} is independent of light intensity.
  - K depends on the light frequency and the work function.
- Time interval between incidence of light and ejection of the photoelectron
  - Each photon can have enough energy to eject an electron immediately.
- Dependence of ejection of electrons on light frequency
  - There is a failure to observe photoelectric effect below a certain cutoff frequency, which indicates the photon must have more energy than the work function in order to eject an electron.
  - Without enough energy, an electron cannot be ejected, regardless of the fact that many photons per unit time are incident on the metal in a very intense light beam.

Photon Model Explanation of the Photoelectric Effect, cont.

- Dependence of photoelectron kinetic energy on light frequency
  - Since $K_{max} = hf - \varphi$
  - A photon of higher frequency carries more energy.
    - A photoelectron is ejected with higher kinetic energy.
    - Once the energy of the work function is exceeded
  - There is a linear relationship between the maximum electron kinetic energy and the frequency.

Cutoff Frequency

- The lines show the linear relationship between *K* and ƒ.
- The slope of each line is *h.*
- The *x*-intercept is the **cutoff frequency.**
  - This is the frequency below which no photoelectrons are emitted.



Cutoff Frequency and Wavelength

- The cutoff frequency is related to the work function through $f_c = \varphi / h$.
- The cutoff frequency corresponds to a **cutoff wavelength.**

$$\lambda_c = \frac{c}{f_c} = \frac{hc}{\varphi}$$

- Wavelengths greater than λ_c incident on a material having a work function φ do not result in the emission of photoelectrons.

Arthur Holly Compton

- 1892 – 1962
- American physicist
- Director of the lab at the University of Chicago
- Discovered the Compton Effect
- Shared the Nobel Prize in 1927