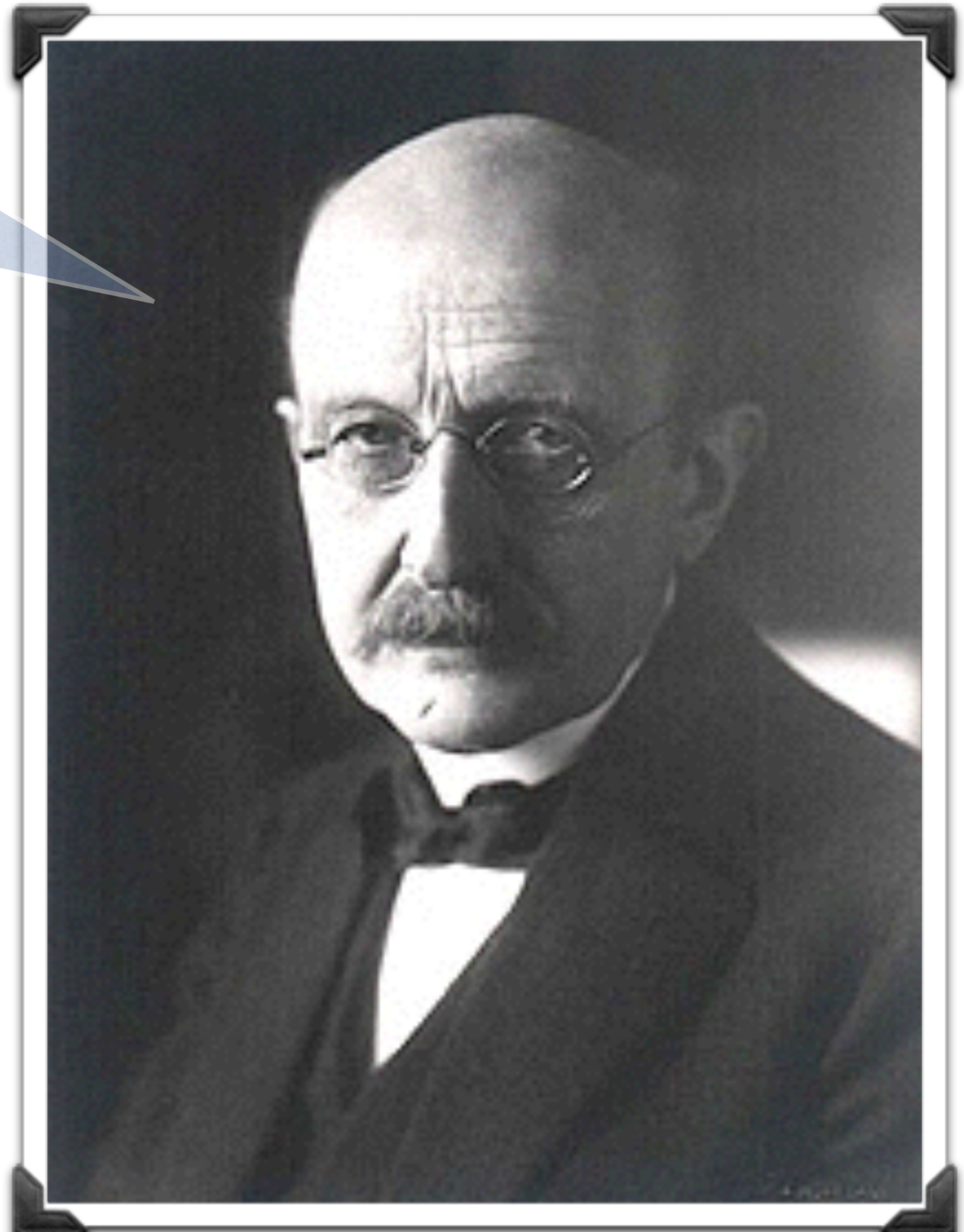
Welcome back to PHY 3305



Today's Lecture:

Blackbody Radiation

Photoelectric Effect

Max Plank

1858 - 1947

Professor Jodi Cooley

PARALLEL REVOLUTION: THE QUANTIZATION OF ENERGY

- In parallel with the realizations of Lorentz, Einstein and others regarding space and time were developments in energy and matter.
- Max Planck initiated these developments with his studies of the "blackbody problem".
  - His hypothesis, which resolved the problem, had stunning implications for the nature of energy and matter.

What is a blackbody?

A blackbody is any object whose emitted electromagnetic radiation results slowly from thermal motion of its electric charges.

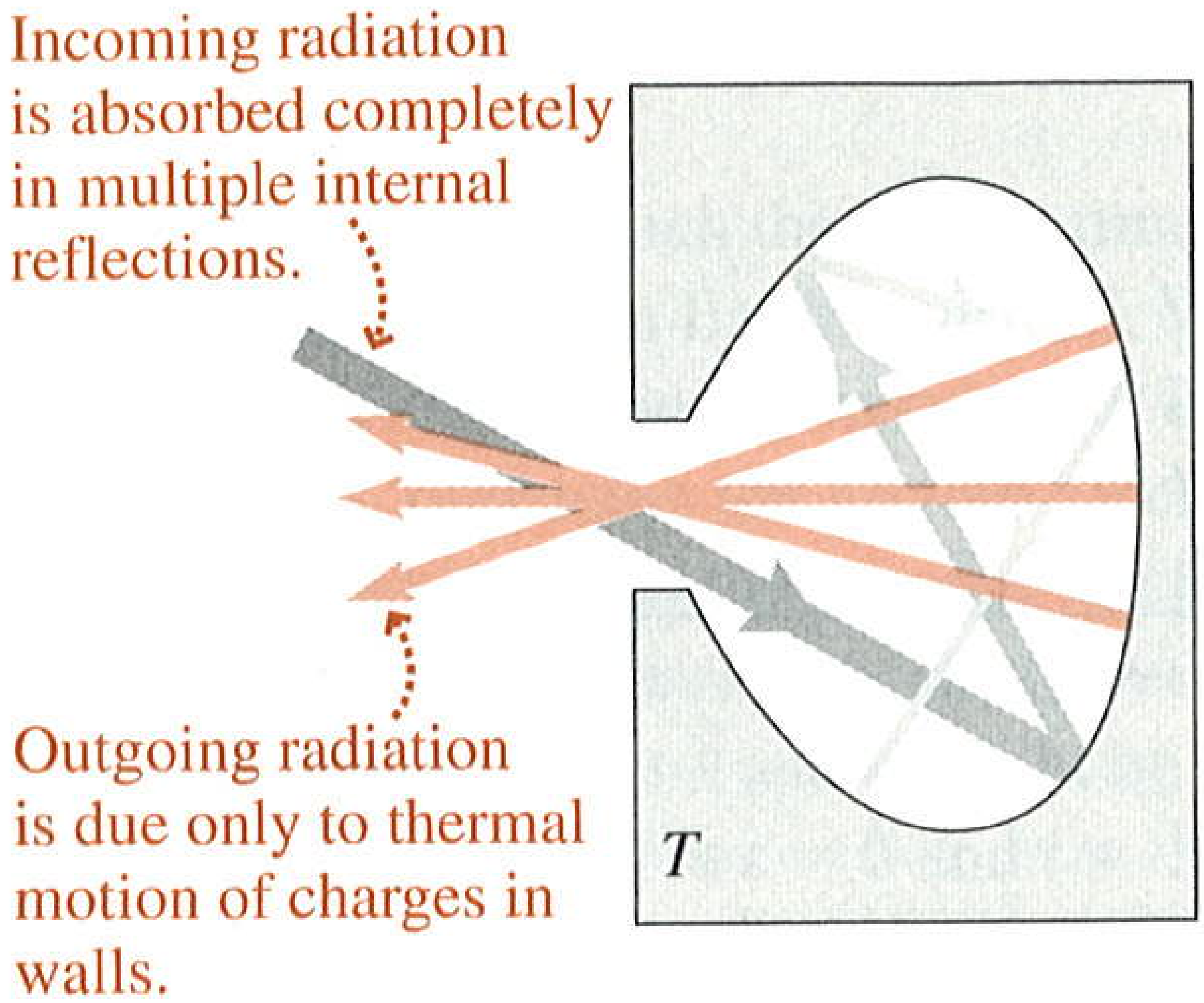
A blackbody is an ideal emitter. It absorbs all of the light energy incident upon it and radiates this energy with a characteristic spectrum.

An ideal emitter reflects no light.

Examples of blackbodies:

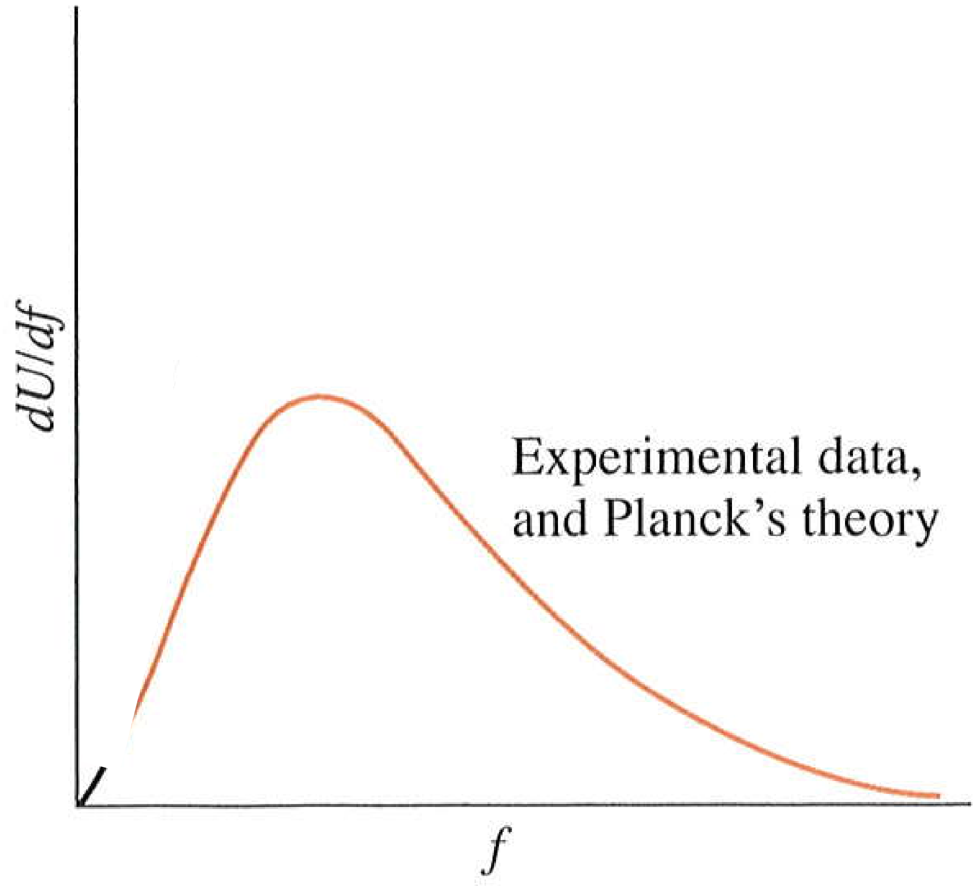
- coal, tar, oil (anything painted black)
- an oven
- the sun (stars and planets)
- the cosmic microwave background

CONSTRUCT A BLACKBODY



spectral energy density

The electromagnetic energy (dU) per frequency range (df).



Experiments demonstrate that energy emitted by blackbodies follow a characteristic pattern.

Let's try to calculate the spectral density of a blackbody.

Think of the radiation trapped in the cavity as sinusoidal waves resonating in the cavity. Classical thermodynamics tells us the average energy of any wave of a given frequency (f) is

$$\overline{E(f)} = k_B T$$

k_B = Boltzman Constant

$k_B = 1.380... \times 10^{-23}$ J/K

T = temperature of cavity

The total energy in the range of frequencies around f is

$$dU(f) = \overline{E(f)} dN(f)$$

$$dU(f) = k_B T \times dN(f)$$

dU(f) = energy in frequency range f to f + df

dN(f) = number of waves in frequency range f to df

$$dU(f) = k_B T \times dN(f)$$

The number of waves in a given frequency range in a cavity of volume V.

$$dN(f) = \frac{8\pi V}{c^3} f^2 df$$

Substituting into dU(f)

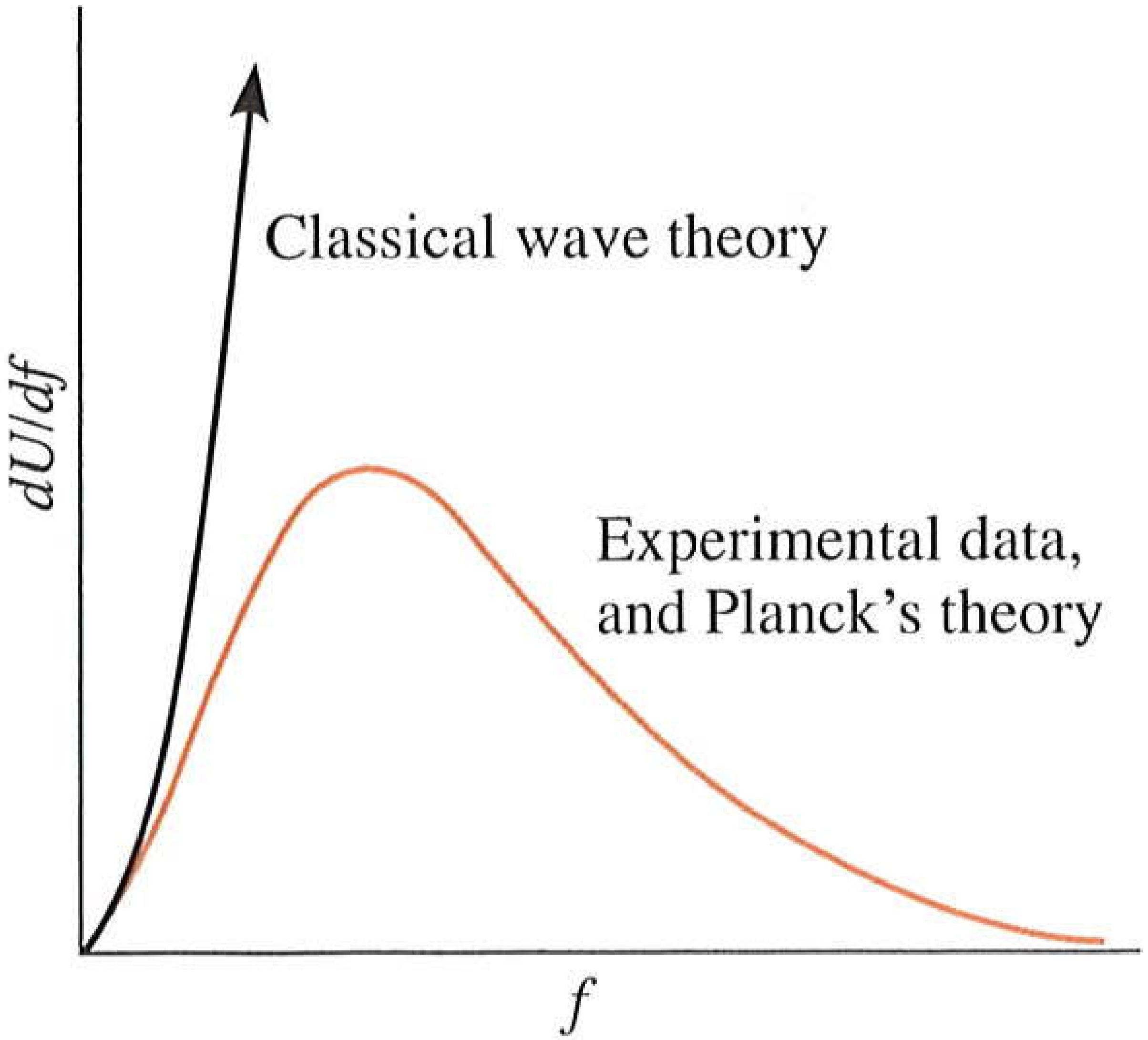
$$\frac{dU}{df} = k_B T \times \frac{8\pi V}{c^3} f^2$$

Details of this calculation are in Appendix C of your textbook.

$$\frac{dU}{df} = k_B T \times \frac{8\pi V}{c^3} f^2$$

How did this compare with experimental observation?

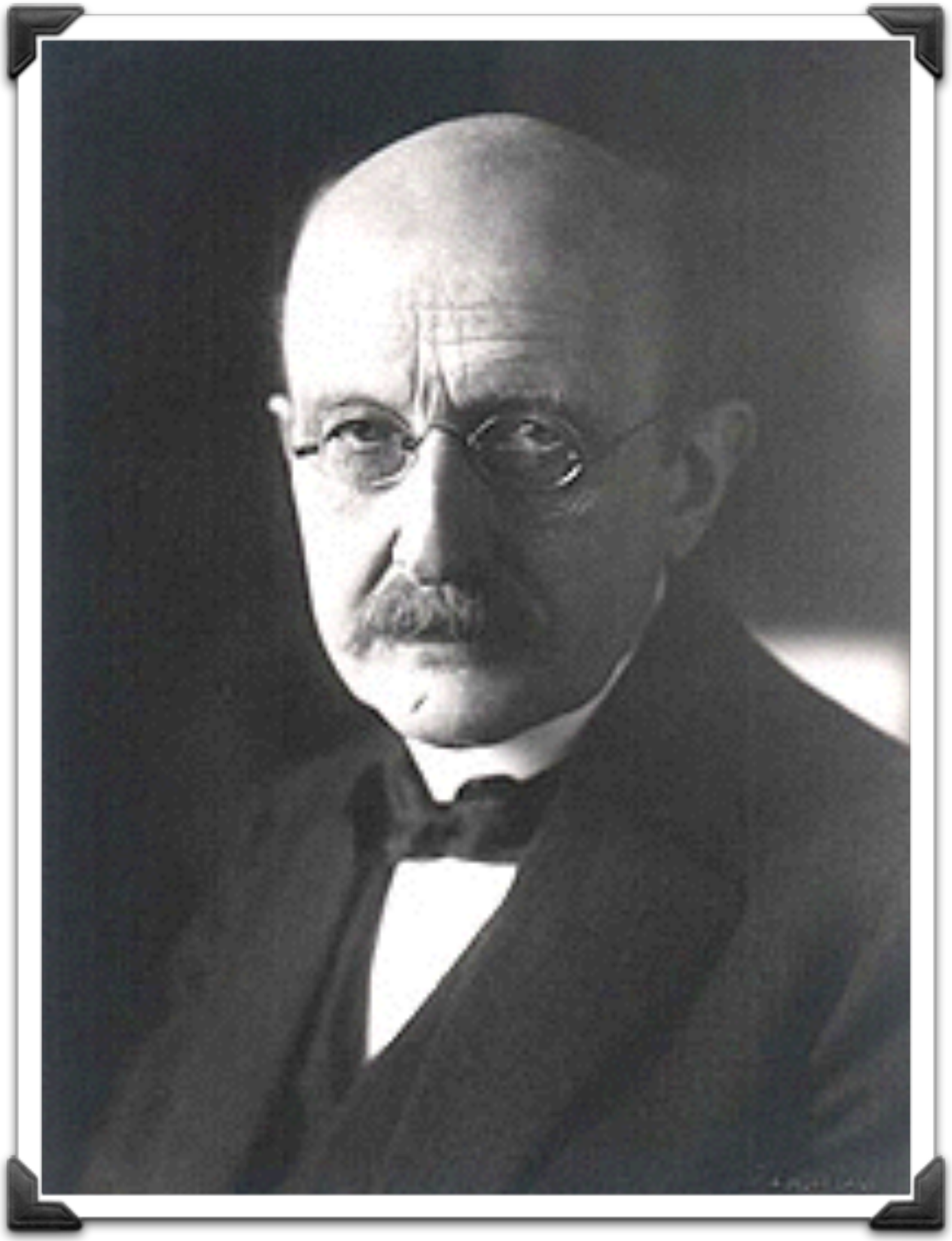
Poorly!



- At high frequency, the energy diverges.
- Known as the "Ultraviolet Catastrophe".

Plank made a hypothesis that changed our understanding of the universe.

- Classical assumption: waves of any energy were allowed for a frequency range (df).
- Plank assumption: energy emitted was restricted for a frequency range (df). The energy of the waves was discrete rather than continuously distributed



Max Plank
1858 - 1947

So if,

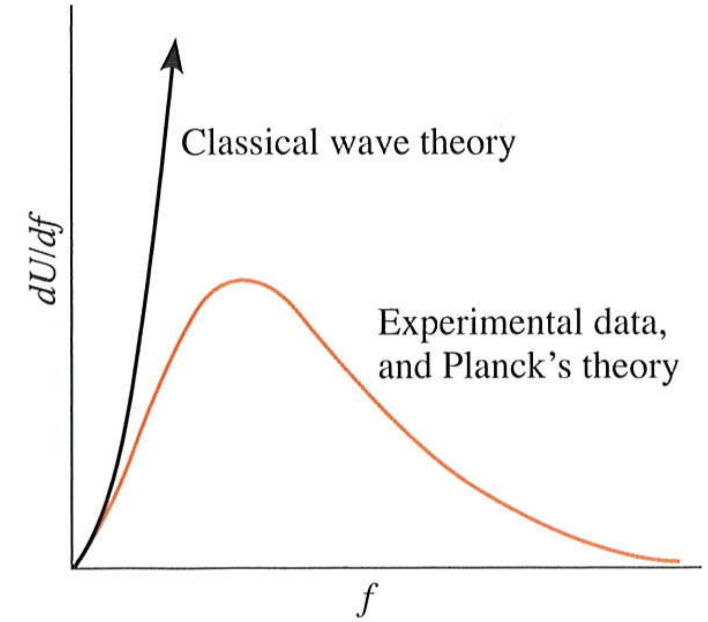
$$E = nhf$$

n is an integer
h is a constant

$$\frac{dU}{df} = k_B T \times \frac{8\pi V}{c^3} f^2$$

Then,

$$\frac{dU}{df} = \frac{hf}{e^{\frac{hf}{k_B T}} - 1} \times \frac{8\pi V}{c^3} f^2$$



What happens as f approaches infinity?

The first term in the equation forces the spectral energy density to turn over and fall as f increases.

Matches experimental results.

$$h = 6.63 \times 10^{-34} J \cdot s$$

Plank's Constant

A few words about Plank's Constant, h.

- It has units that are the same as momentum.
- It is believed to be one of the fundamental constants of nature.
- Its value can only be determined by extraction from experimental data.

Plank in a letter to R.W. Wood called this hypothesis "an act of desperation".

"... a theoretical interpretation [of the blackbody spectrum] had to be found at any cost, no matter how high."

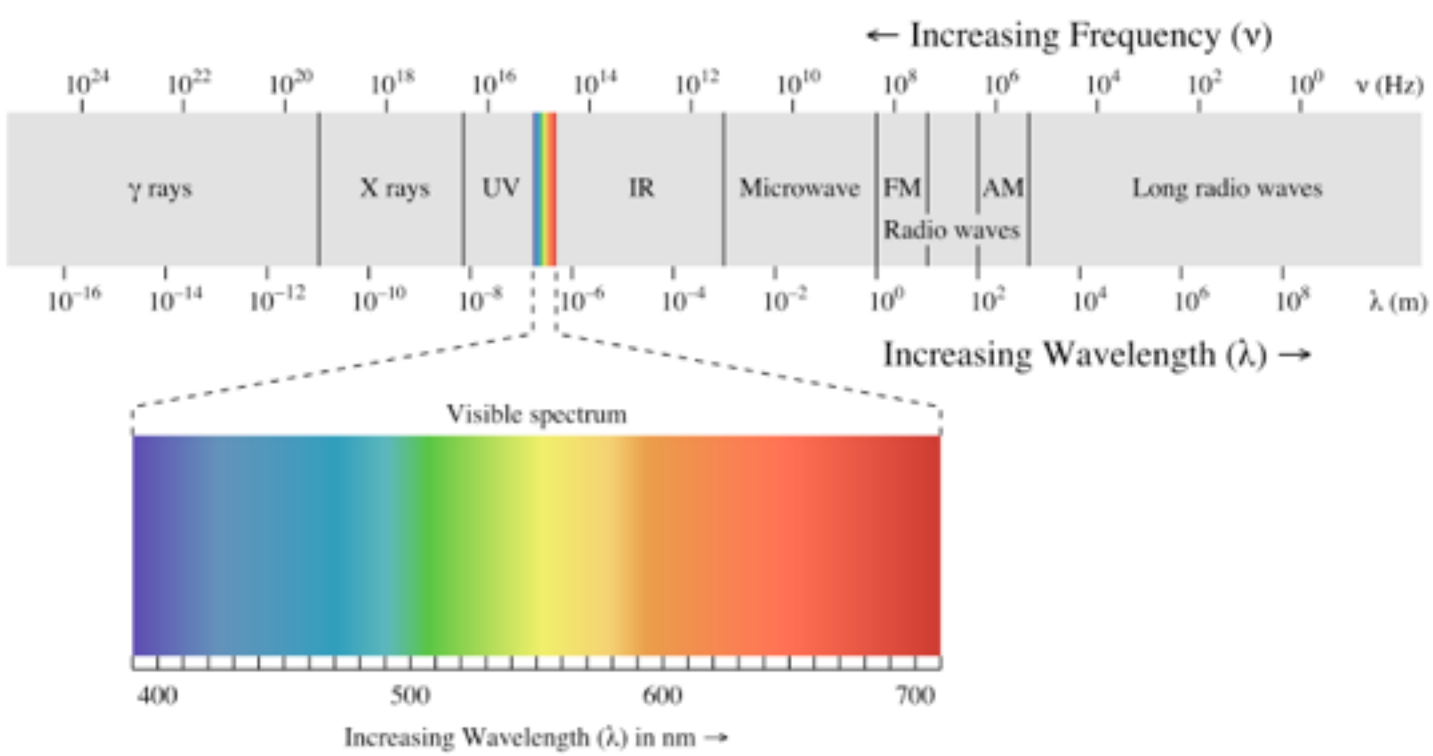
MORE ON BLACKBODY RADIATION

thermal radiation

- There is a connection between color of light emitted by a hot object and its temperature.
  - First observed in 1792 by Thomas Wedgewood, porcelain maker.
- Dark objects absorb radiation.
  - Increase in the KE of the constituent atoms.
  - Charges (e^-) in the atoms are accelerated by the oscillations
  - Theory of E&M requires that the electrons emit electromagnetic radiation, which reduces the temperature.
- Equilibrium occurs when the rate of absorption equals the rate of emission.

THERMAL RADIATION

- At temperatures below ~600 C the thermal radiation emitted by an object is not visible.
  - i.e. Coal - emits radiation (longer wavelength than visible light) even when it is cold.
- As the temperature of an object rises, energy is radiated at shorter wavelengths.
  - At ~600 - 700 C there is enough energy in the visible spectrum that the body glows red.



STEFAN-BOLTZMAN LAW

A body that absorbs all radiation incident on it is called an **ideal blackbody**.

The empirical relationship between the power radiated by an ideal blackbody and the temperature was found in 1879 by Josef Stefan.

$$I = \varepsilon \sigma T^4 \qquad \text{Stefan-Boltzman law}$$

$\sigma = 5.67 \times 10^{-8}$ W/m^2 K^4, I = intensity = power/surface area
ε = emissivity = 1 for an ideal blackbody

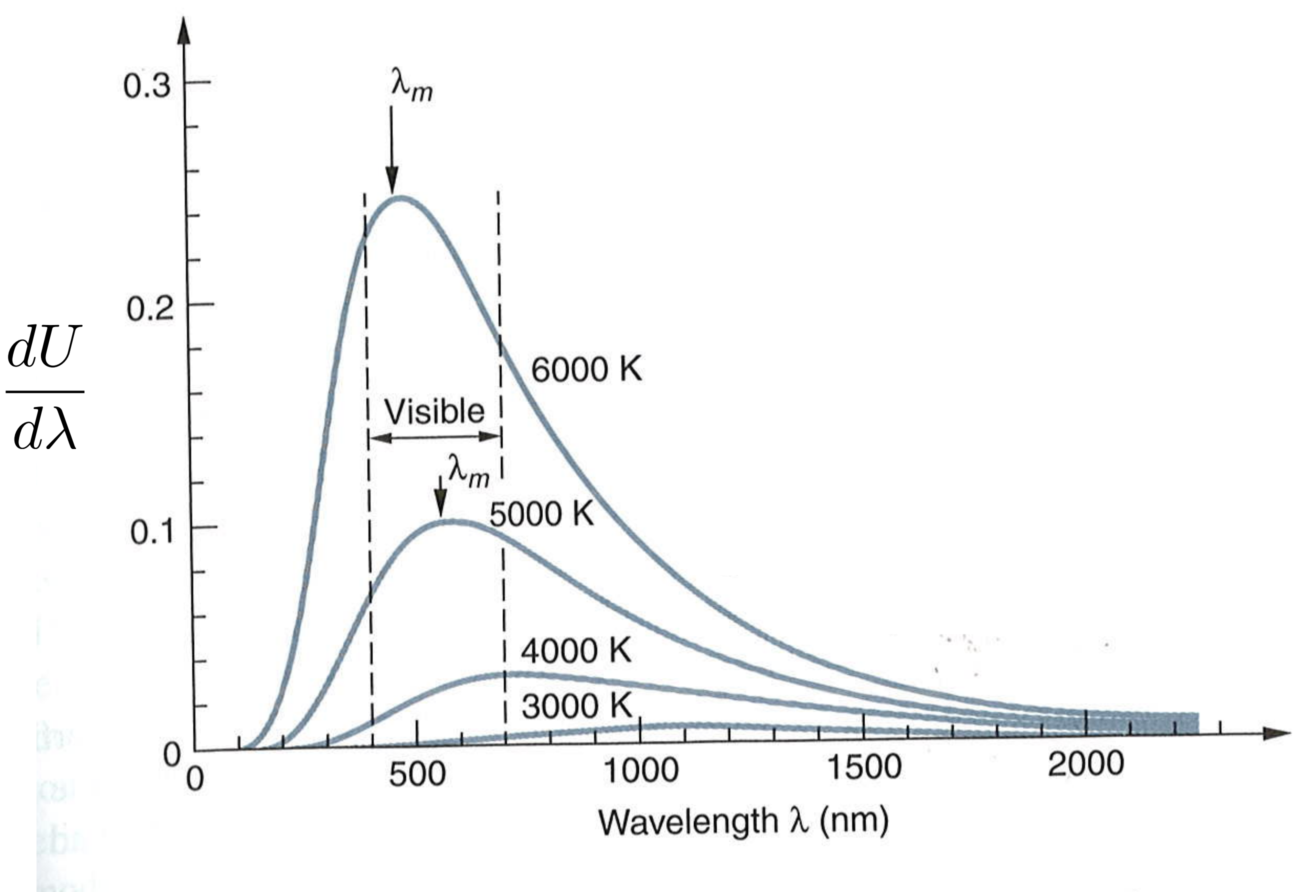
This law was derived by Ludwig Boltzman in 1874. The derivation is problem 3.15 in your textbook.

Wien's Law:

The wavelength at which the blackbody distribution has its maximum value varies inversely as temperature.

$$\lambda_{max} \propto \frac{1}{T}$$

$$\lambda T = 2.898 \times 10^{-3} m \cdot K$$



The derivation of Wien's Law is problem 3.14 in your textbook.

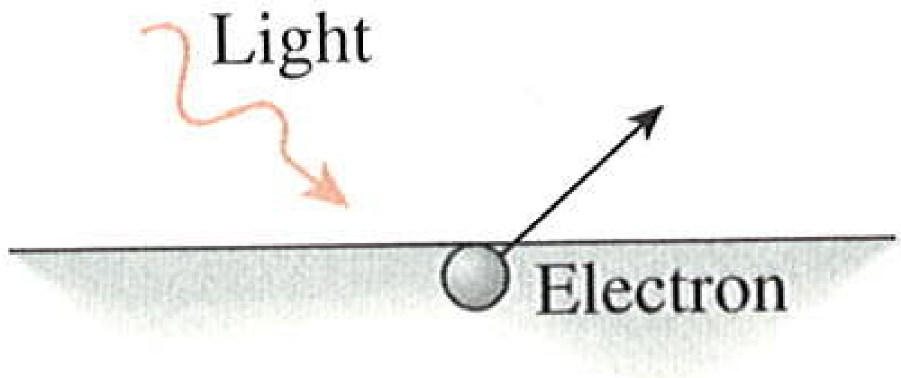
Also, the derivation of dU/dλ from dU/df is problem 3.13 in your textbook.

LIGHT AS PARTICLES

- Blackbody Radiation
  - If light were a wave, we would expect the spectral density to continuously increase as a function of frequency.
  - Plank proposes that the average energy of a given wave is discrete - not continuous as in classical theory.

THE QUANTIZATION OF RADIATION: PHOTOELECTRIC EFFECT

What is the photoelectric effect?



Electrons are emitted from matter as a consequence of their absorption of energy from visible or ultraviolet radiation.

First observed by Heinrich Hertz in the 1880s.

"light producing a flow of electricity"

Heinrich Hertz
1857-1894 (yes, that Hz!)

THE QUANTIZATION OF RADIATION: PHOTOELECTRIC EFFECT

Example: Ball on a Pond

Say you wanted to knock-free a floating ball that had become entangled in lilypads in the middle of a lake. How would you do it?

You could knock it free if you can hit it with waves.

Result: The wave momentarily strains the hold the lilypad has but does not free the ball. Now what?

Crank up the intensity.

increase frequency and amplitude of waves

friend sends the same wave packets at the same time as you do

Can you knock the ball free with very long waves?

Yes, intensity is the key. The long wavelength delivers energy to the ball slowly, but if you have 100 friends on one side of the pond, the combine energy of the waves could knock the ball free.

Originally this is how it was assumed the photoelectric effect worked.

- Negative and positive charges bound together in metal
- Hitting the negative charge with light (a wave) momentarily stretches the the bond between +/- charges - no break
- Increasing the intensity enough should strain the bond until it breaks and the negative charge is free to move on its own.
- If the wavelength is long, it should still eject electrons so long as the intensity is increased.

What's going on in the photoelectric effect?

- The energy required to stop the photoelectrons (bring the current in the circuit to zero) is given by the kinetic energy of the highest-energy photoelectron.

$$KE = eV_0$$

V_0 = stopping potential

- Changing the intensity for a fixed frequency of light does not change the stopping potential. Intensity does not affect the maximum energy that photoelectrons have as they leave the cathode.

- Changing the frequency of the light for a fixed intensity does change the stopping potential. The energy of the photoelectrons depends on frequency.

- There is a minimum frequency of the light at which no photoelectrons are free of the material, no matter how strong a positive potential we apply.

In 1905 Einstein tried to resolve the mystery with the following hypothesis.

Light is transmitted not as a wave but rather in smaller units (quanta) which he called photons. The energy of the photons is given as

$$E = hf \qquad h = \text{Plank's Constant}$$

Better analogy: The small ball is in a tree. You have to knock it down. You throwing baseballs would eventually knock it down (chances of hitting it are small, but lots of energy is transferred) so long as the energy of the baseball is sufficient.
If you have 10 friends helping you (all throwing at once), the chance of a baseball striking the small ball is greater. However, if they all have weak pitching arms, it doesn't matter how many people you have helping. The small ball will not make it out of the tree.

Work Function:

The work function (φ) is the minimum amount of energy needed to strip the electron from the metal.

$$KE_{max} = hf - \phi$$

Kinetic energy of the electron.

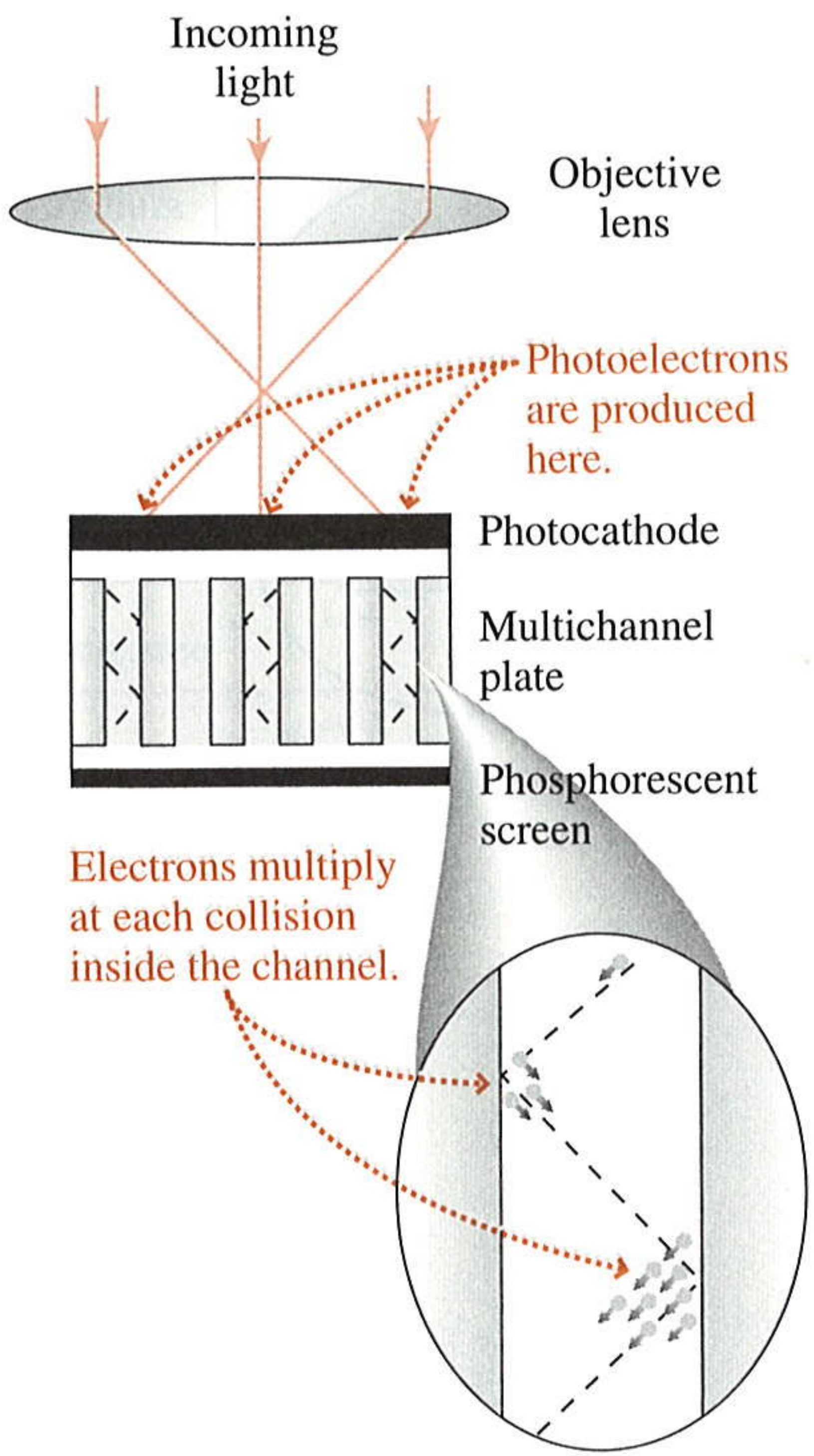
Experimentally, we can determine φ of a metal by setting the voltage such that the current just drops to zero.

$$KE_{max} = eV_0$$

Thus, the work function can be determined by

$$\phi = hf - eV_0$$

APPLICATION: NIGHT VISION



"Replace" photon with electron whose charge is easier to amplify.

Optical lens focuses an image onto a thin piece of of material, where the photoelectric effect transforms it into an image of freed electrons.

A multichannel plate amplifies the image.

Amplified image strikes a phosphorescent screen to produce the final visible image.

Why is zinc a poor choice if we wish to have a light-sensing device sensitive to the visible spectrum?

TABLE 3.1

Metal	Work Function ϕ (in eV)
Cesium	1.9
Potassium	2.2
Sodium	2.3
Magnesium	3.7
Zinc	4.3
Chromium	4.4
Tungsten	4.5

Energy of a photon

- From table 3.1 we see that zinc has a work function of 4.3 eV.
- The limit for ejecting electrons is when the incoming photon has only enough energy to free an electron from the material with none left for kinetic energy.

$$KE_{max} = hf - \phi$$

$$0 = hf - \phi$$

$$\phi = hf = h\frac{c}{\lambda}$$

$$\lambda = \frac{hc}{\phi} = \frac{(1.6 \times 10^{-34} J \cdot s)(3 \times 10^{8} \frac{m}{s})}{4.3eV \times \frac{1.6\times10^{-19} J}{1eV}}$$

recall:
$1 \text{ eV} = 1.6 \times 10^{-19}$ J
energy gained by one electron moving across an electric potential difference of 1 V

$$\lambda = 289nm$$

visible spectrum
~400 to 700 nm

What would be the work function of a metal that could see wavelengths in the visible spectrum?

$$\phi = h\frac{c}{\lambda} = (6.63 \times 10^{-34} J \cdot s)\frac{3 \times 10^{8} \frac{m}{s}}{700 \times 10^{-9} m}$$

$$\phi = 2.84 \times 10^{-19} J$$

$$\phi = 2.84 \times 10^{-19} J \times \frac{1eV}{1.6 \times 10^{-19} J}$$

$$\phi = 1.8eV$$

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Energy of a photon

LIGHT AS PARTICLES

- Blackbody Radiation
  - If light were a wave, we would expect the spectral density to continuously increase as a function of frequency.
  - Plank proposes that the average energy of a given wave is discrete - not continuous as in classical theory.
- Photoelectric Effect
  - If light were a wave, it should be able to eject electrons at any wavelength. There should be considerable lag time between the wave hitting the metal and the ejection of electrons. Also, increasing the intensity at any frequency should make the electrons more energetic.
  - Einstein proposes that light behaves as a collection of particles called photons.

THE END
(FOR TODAY)