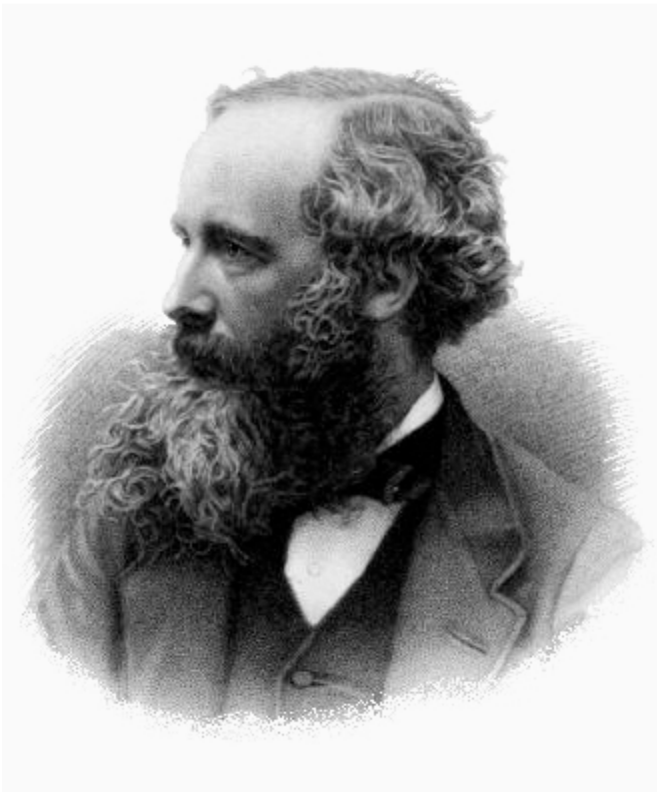
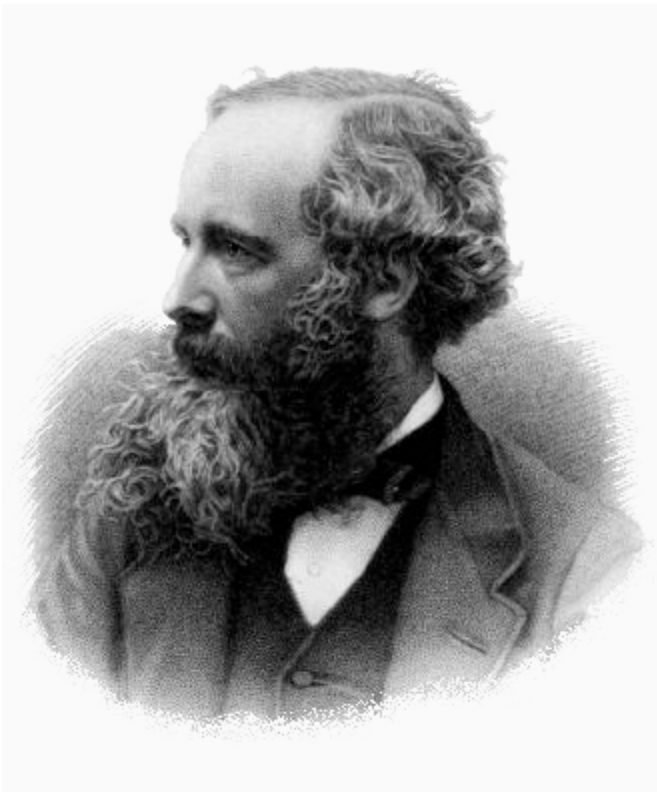
The Death of Classical Physics



The Rise of the Photon

A fundamental question: What is Light?



James Clerk Maxwell
1831-1879

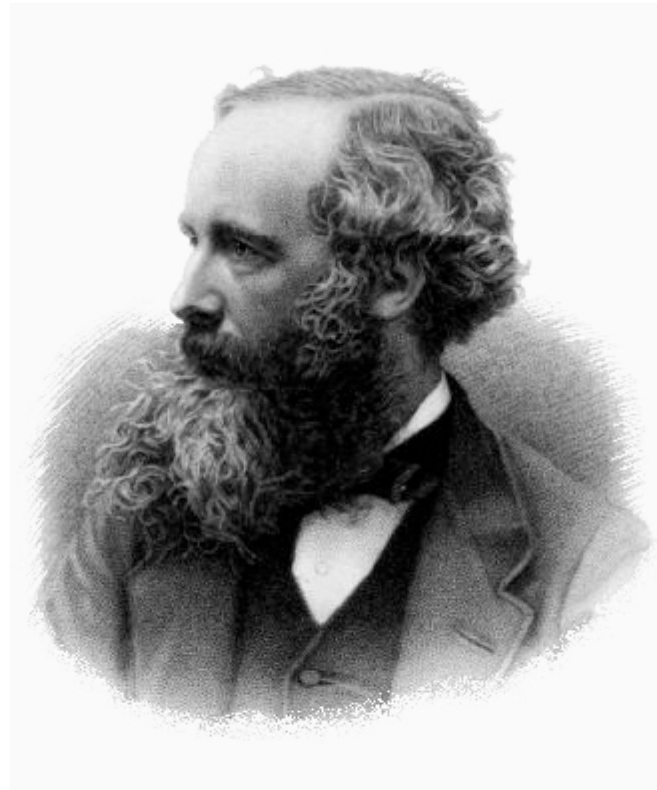
Electromagnetic Wave

Max Planck
1858-1947

Photon

Maxwell's Equations (1865)

Maxwell's equations are a set of four partial differential equations that describe the properties of the electric and magnetic fields and relate them to their sources, charge density and current density.



James Clerk Maxwell
1831-1879

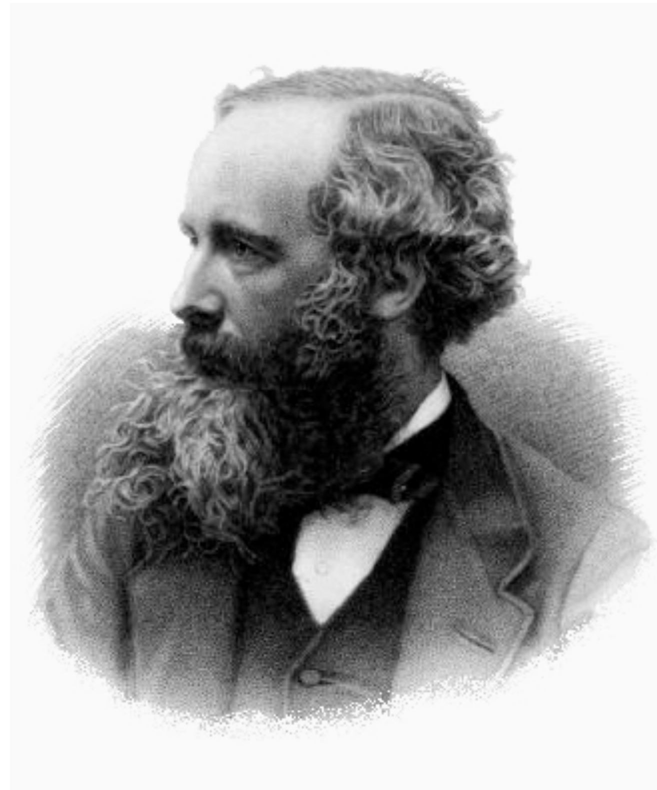
Maxwell's Equations (1865)

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$



James Clerk Maxwell
1831-1879

Electromagnetic Waves - Theory (1865)

$$\nabla^2 \mathbf{E} = \mu_0 \varepsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} = \frac{1}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

$$\nabla^2 \mathbf{B} = \mu_0 \varepsilon_0 \frac{\partial^2 \mathbf{B}}{\partial t^2} = \frac{1}{c^2} \frac{\partial^2 \mathbf{B}}{\partial t^2}$$

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

James Clerk Maxwell
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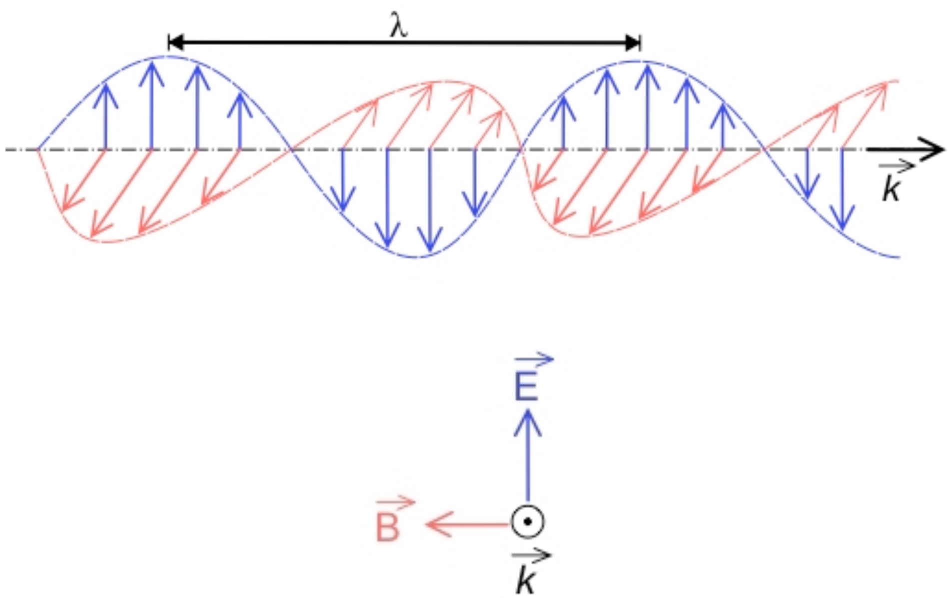
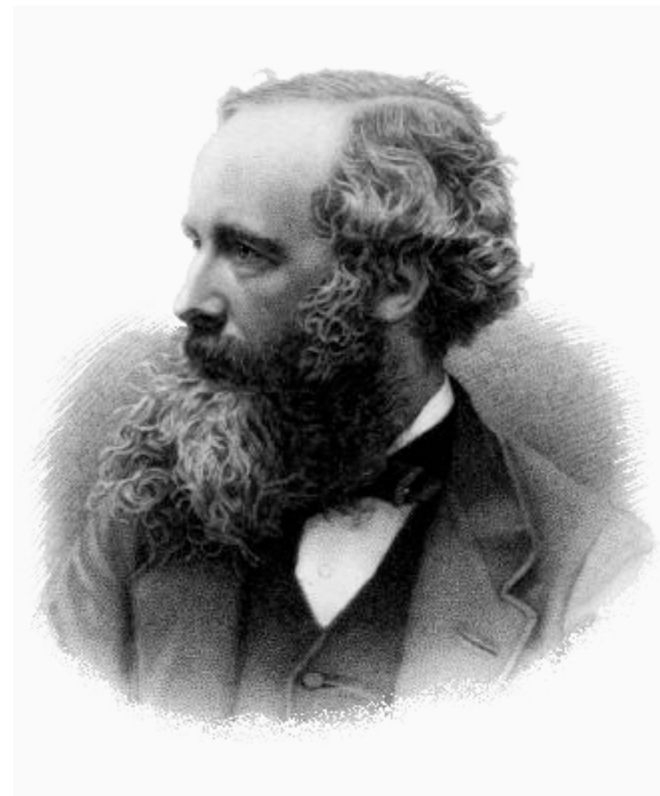
Electromagnetic Waves - Theory (1865)



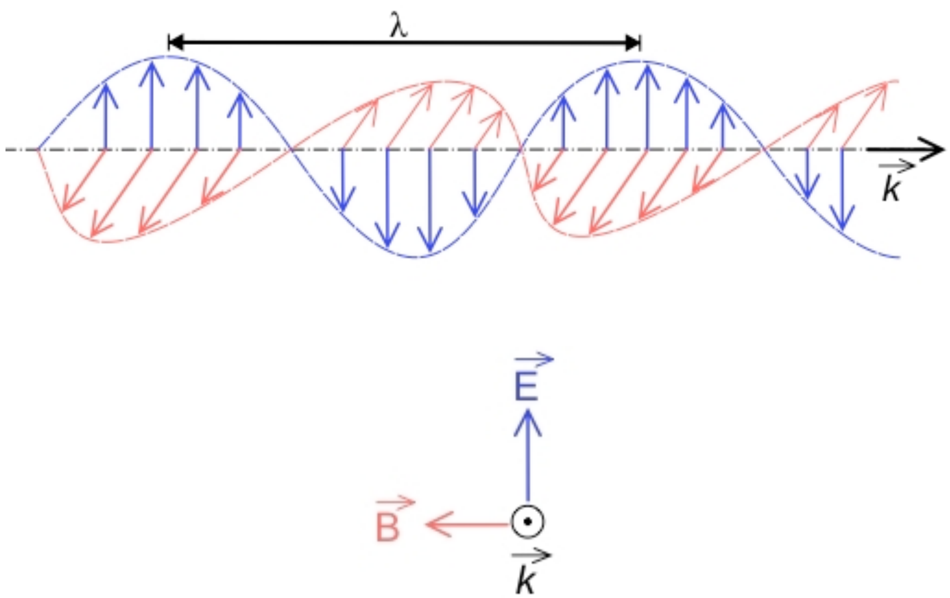


James Clerk Maxwell
1831-1879

E and B are "fields" that vary with time and space

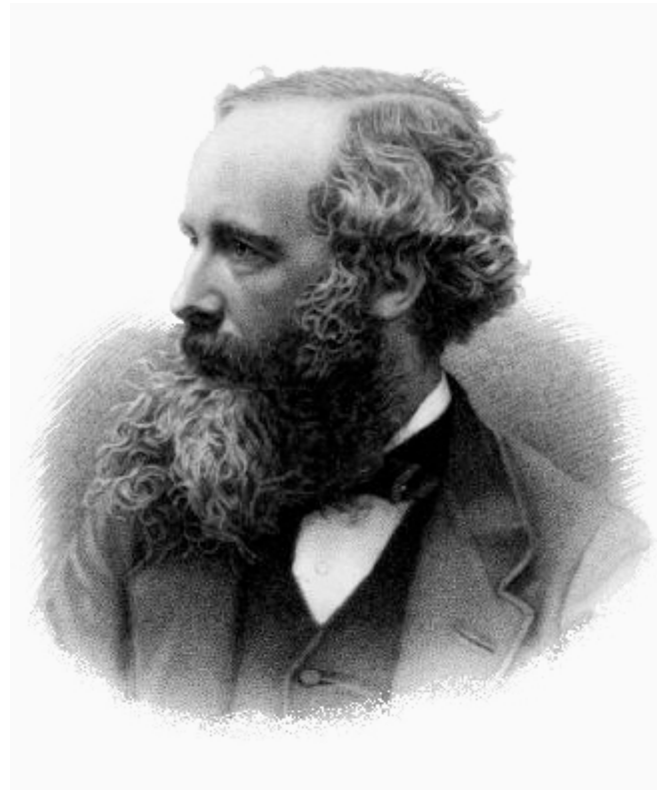
(k is the direction of the light wave)

Electromagnetic Waves - Theory (1865)



$$E(x,t) = E_0 \sin\left[\frac{2\pi}{\lambda}(x - ct)\right]$$

traveling wave equation in one dimension



James Clerk Maxwell
1831-1879

Electromagnetic Waves - Theory (1865)

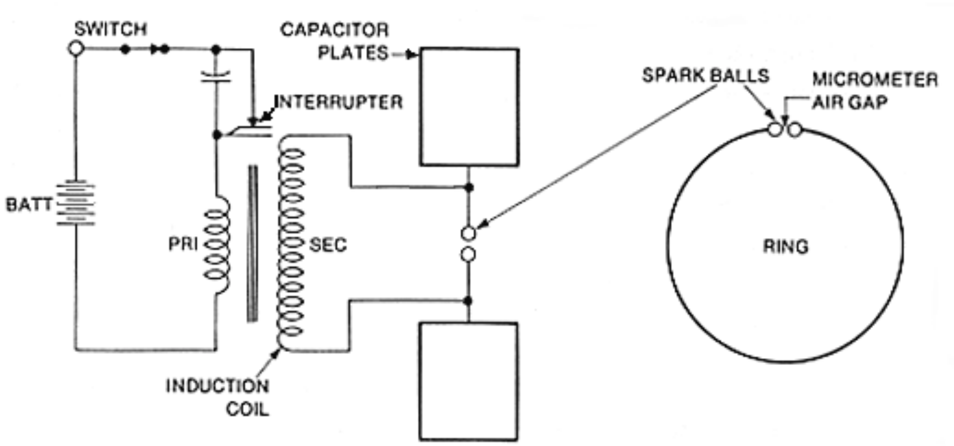
$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

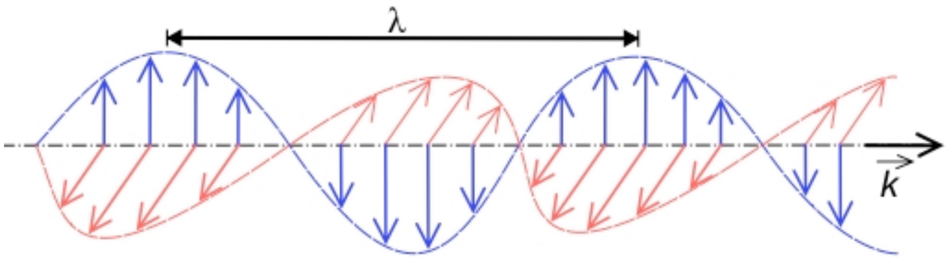
299,792,458 m/s

Electromagnetic Waves
are Light!!!

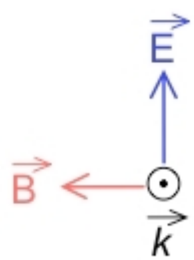
James Clerk Maxwell
1831-1879

Electromagnetic Waves - Experiment (1887)





Heinrich Hertz
1857-1894



E and B are fields that act on charged particles

Electromagnetic Waves - Experiment (1887)

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

299,792,458 m/s

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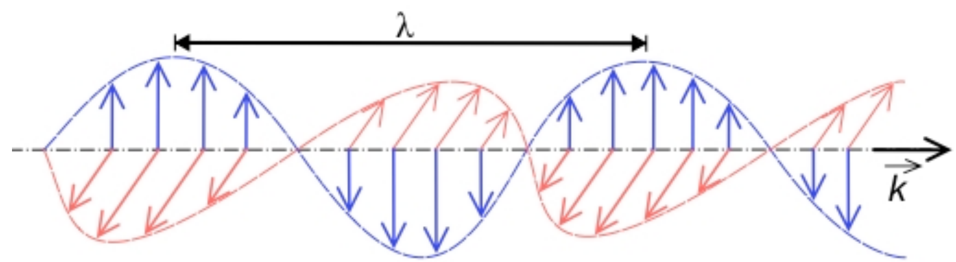
The Electromagnetic Spectrum

$$c = \lambda \nu$$

2.998×10^8 meters/sec

λ = the Greek letter lambda
ν = the Greek letter nu



velocity = wavelength x frequency

meters/sec = (meters) x $(\text{sec})^{-1}$

The units $(\text{sec})^{-1}$ are called Hertz (Hz)!

An example calculation of frequency

Question: Calculate the frequency of "typical" red light with a wavelength of 600.0 nm.

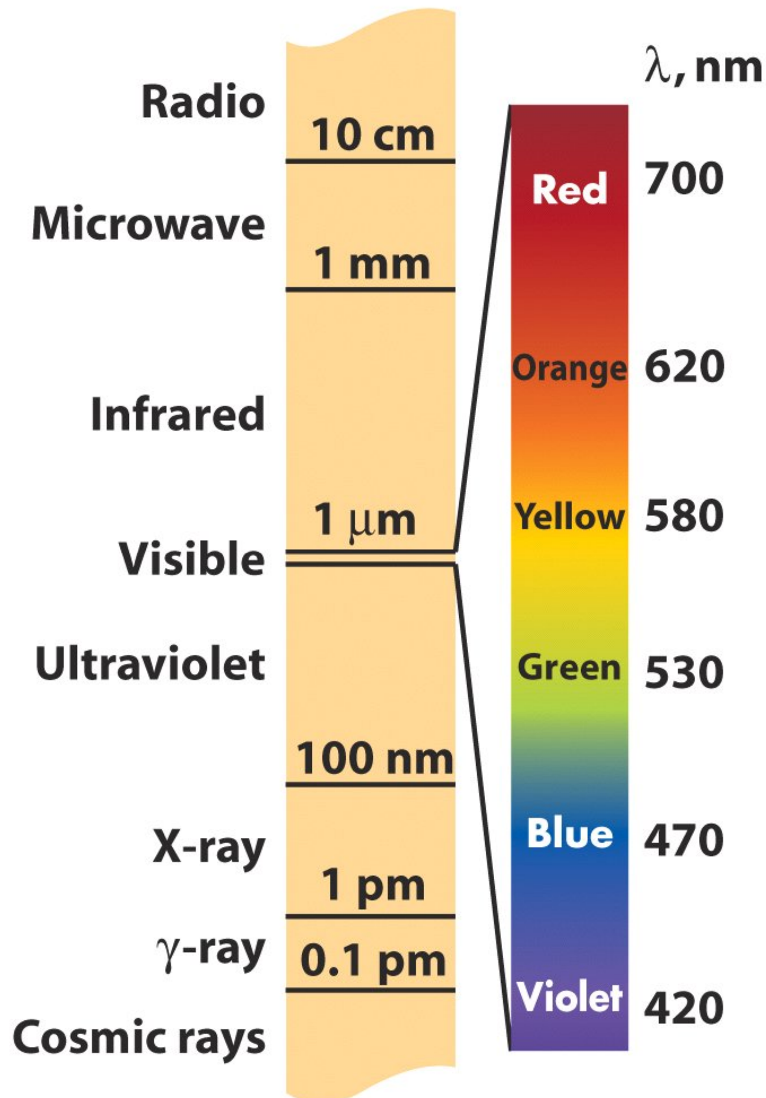
$c = 2.998 \times 10^8$ m/s $= \lambda\nu$
$\nu = (2.998 \times 10^8 \text{ m/s})/(600.0 \times 10^{-9} \text{ m})$
$4.997 \times 10^{14}\ \text{s}^{-1}$ or 4.997×10^{14} Hz.

(Note significant figures please!)

$$c = \lambda\nu$$

The Electromagnetic Spectrum

- light travels with a velocity of 3×10^8 m/s in vacuum.
- visible light ranges from 400 nm (violet) to 750 nm (red).
- Radio waves have lengths of cm - this is the reason antennae must be cm in length;
- X-rays have lengths of Angstroms - this is the reason we can use x-rays to elucidate the structure of matter composed of atoms (which are Angstroms in length).
  1 Å = 0.1 nm = 10^{-10} m



The Death of Classical Physics

"Experiments are the only means of knowledge at our disposal. The rest is poetry, imagination."

Max Planck
1858-1947

The Death of Classical Physics

Light energy is quantized.

$$E = h\nu = \frac{hc}{\lambda}$$

h = Planck's constant

6.626×10^{-34} Joule sec

Max Planck
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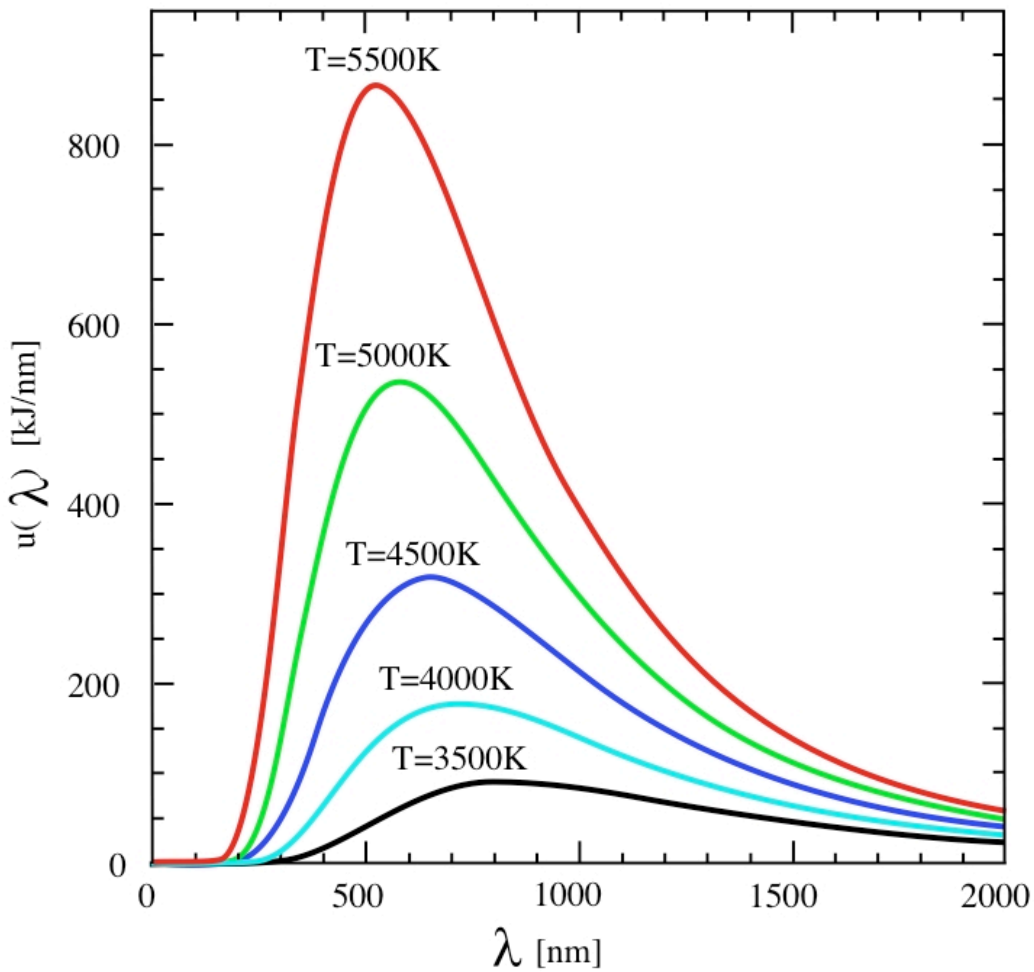
Blackbody Radiation

- Objects radiate light that has a spectrum based purely on the temperature of the object. We call this "blackbody radiation".

- The intensity increases with T, and the peak intensity is observed at shorter and shorter wavelengths as T increases. The threshold for light emission in λ also increases with T.

- The classical theories were insufficient to predict the intensity versus wavelength seen in the plot at right.



http://en.wikipedia.org/wiki/Image:Wiens_law.svg

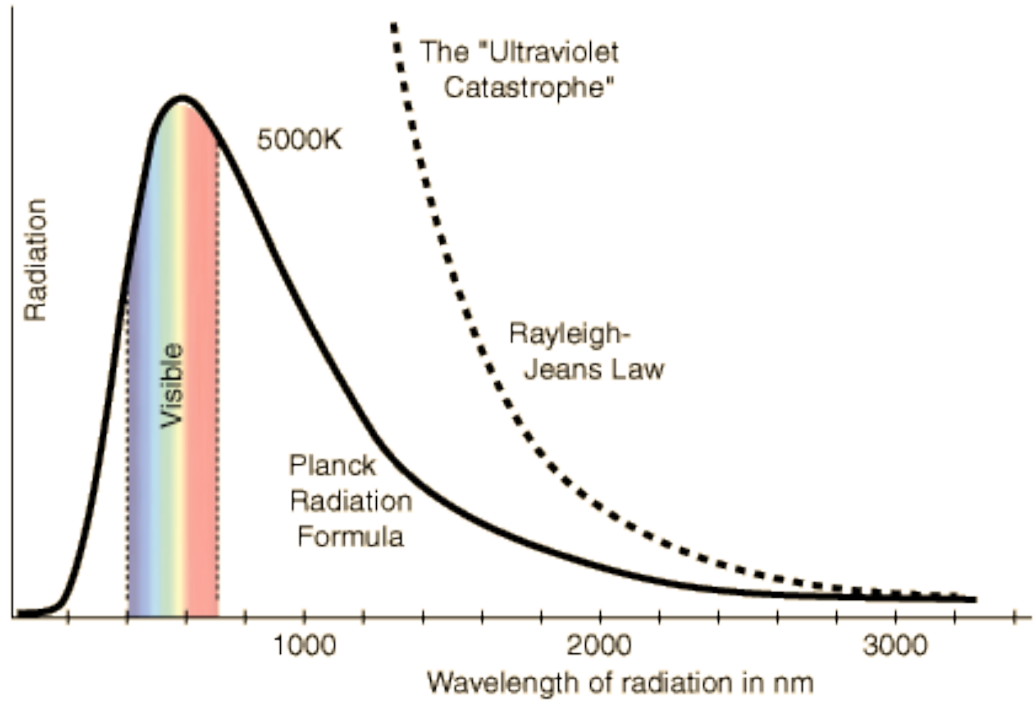
Blackbody Radiation

The "Ultraviolet Catastrophe"...

- The Rayleigh-Jeans law got the spectrum right at low ν, but it blew up as ν got larger.

wrong

$$\rho_\nu(T)d\nu = \frac{8\pi k_B T}{c^3}\nu^2 d\nu$$



http://hyperphysics.phy-astr.gsu.edu/hbase/mod6.html

Blackbody Radiation

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wrong

$$\rho_\nu(T)d\nu = \frac{8\pi k_B T}{c^3}\nu^2 d\nu$$

- Planck derived an equation based on a radical assumption: That the "generators" within the hot object could produce energy only in "packets" or "quanta" of *h*ν, where *h* was a fudge factor.

right

$$\rho_\nu(T)d\nu = \frac{8\pi h}{c^3}\frac{\nu^3 d\nu}{exp\left(\frac{h\nu}{k_B T}\right)-1}$$

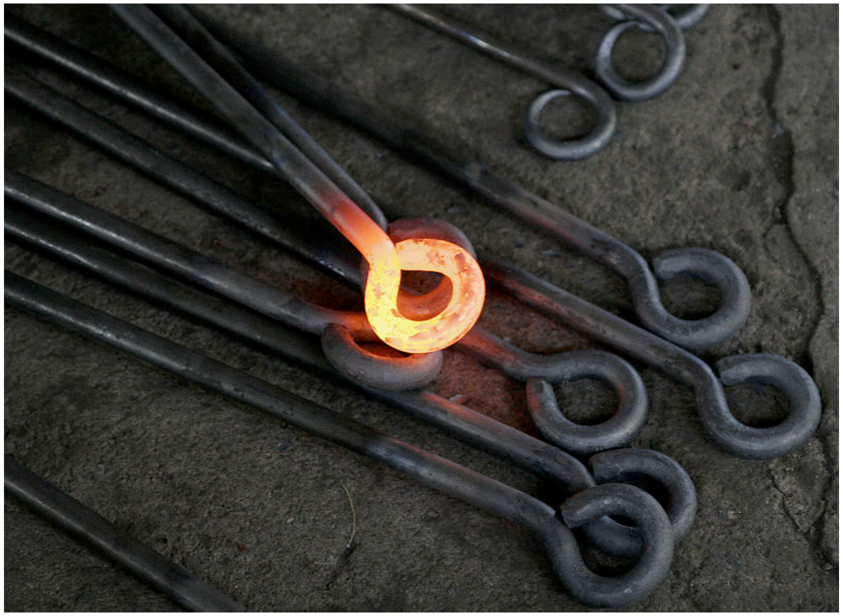
- Planck adjusted the value of h in his equation to fit the data at one temperature, and he found that, in fact, it then fit the data at all temperatures.

Blackbody Radiation

By differentiation, we can find the wavelength of maximum emission from a blackbody radiator. This is called:

Wien's Displacement Law

$$\lambda_{max} = \frac{2898.}{T}$$

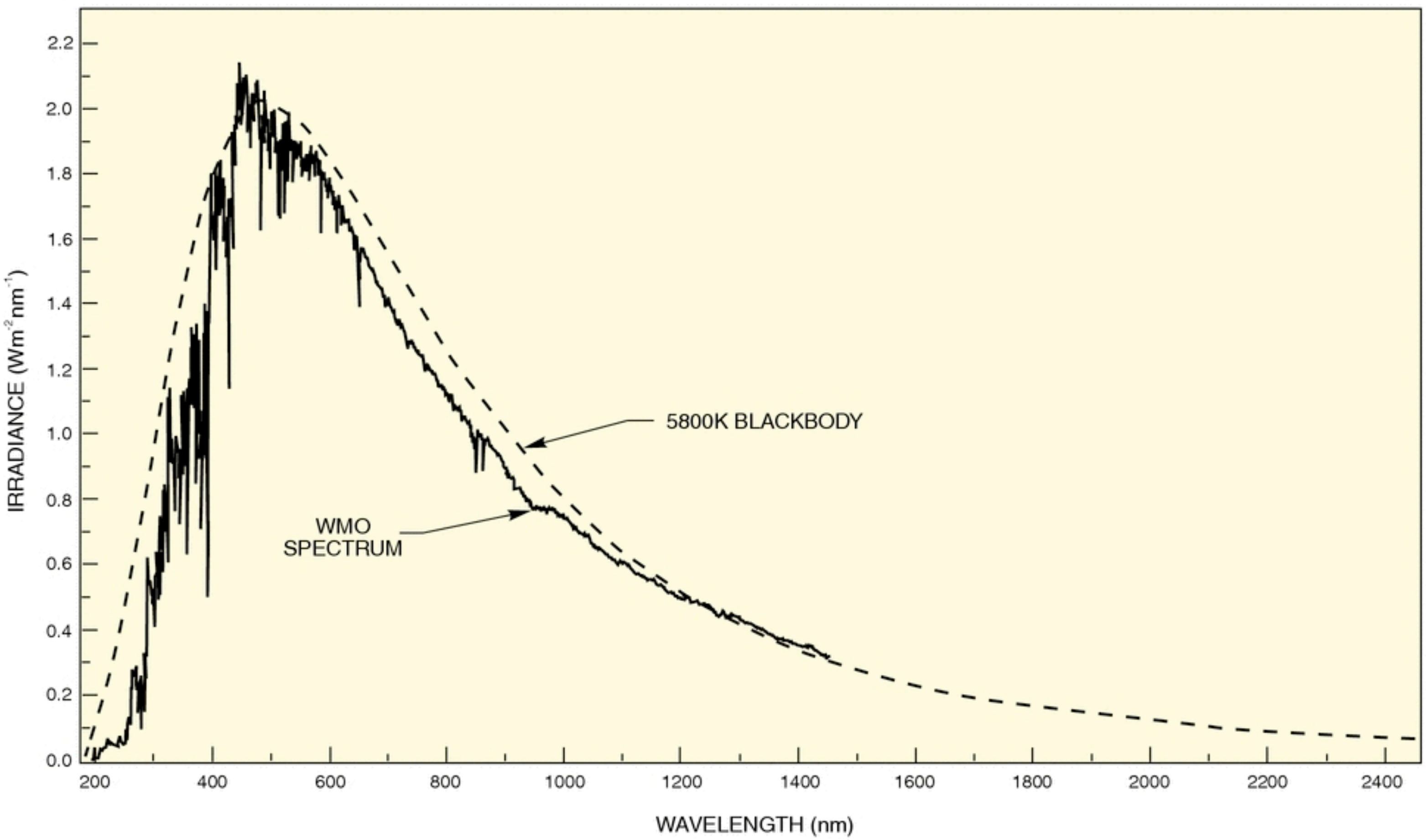


T is in Kelvin and Lambda is in microns in this equation. In SI units, the constant becomes:

2.898×10^{-3} m K

Blackbody Radiation

The spectrum of the sun (outside the atmosphere) has the shape of a blackbody radiator with a maximum irradiance at a wavelength of 500 nm. This corresponds to a temperature of 5800K.



Blackbody Radiation

Humans are blackbody radiators that emit light in the infrared.

$$\lambda_{max} = \frac{2898.}{T}$$

T = 37.0 C (310.K) corresponds to a λ_{max} = 9.35 microns.

Blackbody Radiation

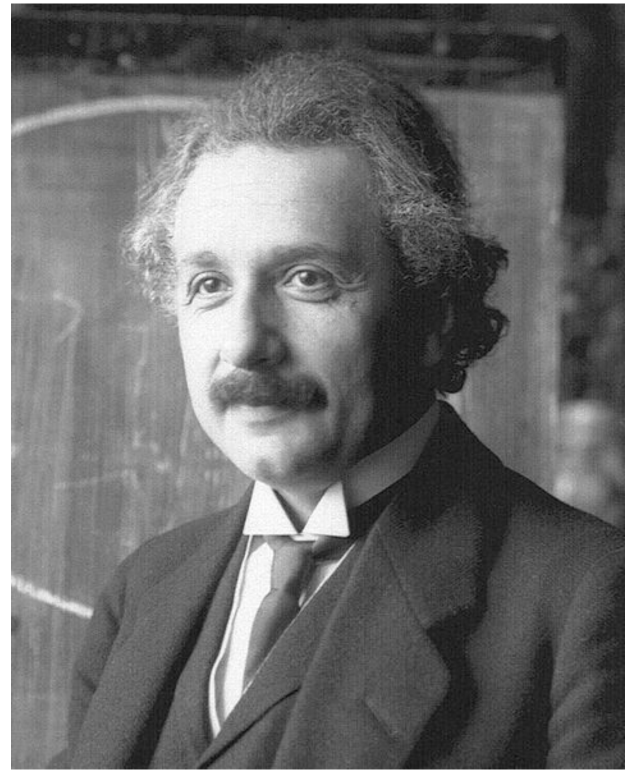
Humans are blackbody radiators that emit light in the infrared.

Ear thermometers measure the blackbody emission of infrared light from the eardrum to get a temperature.

T = 37.0 C (310.K) corresponds to a λ_{max} = 9.35 microns.

Photons and Electrons

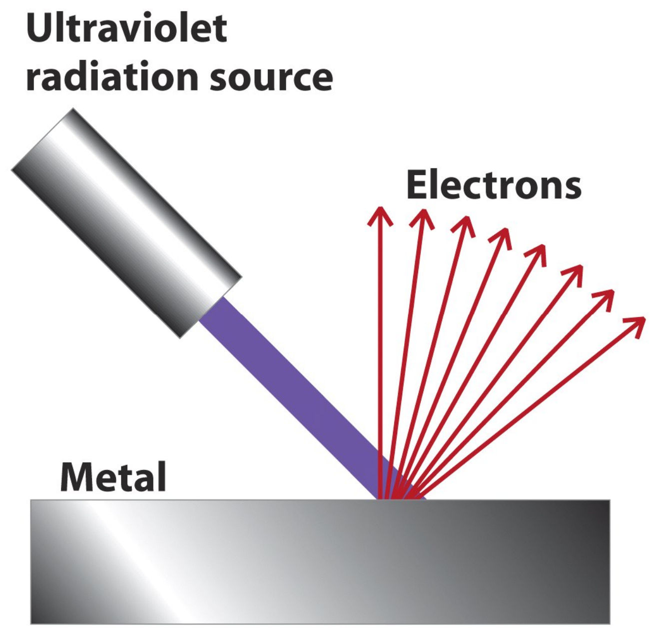
Heinrich Hertz
1857-1894



Albert Einstein
1879-1955

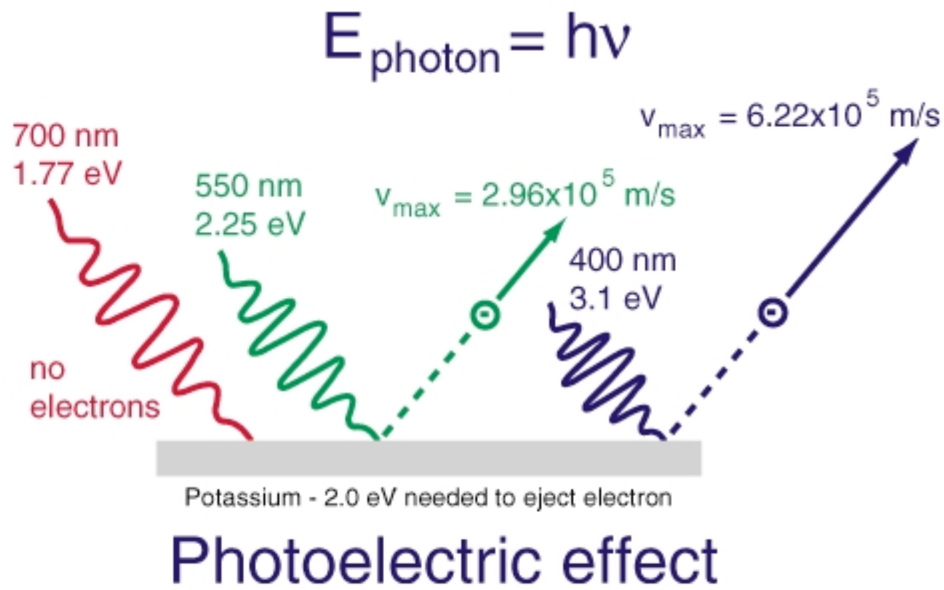
The Photoelectric Effect (1887)

Heinrich Hertz
1857-1894



aka "The Hertz Effect"

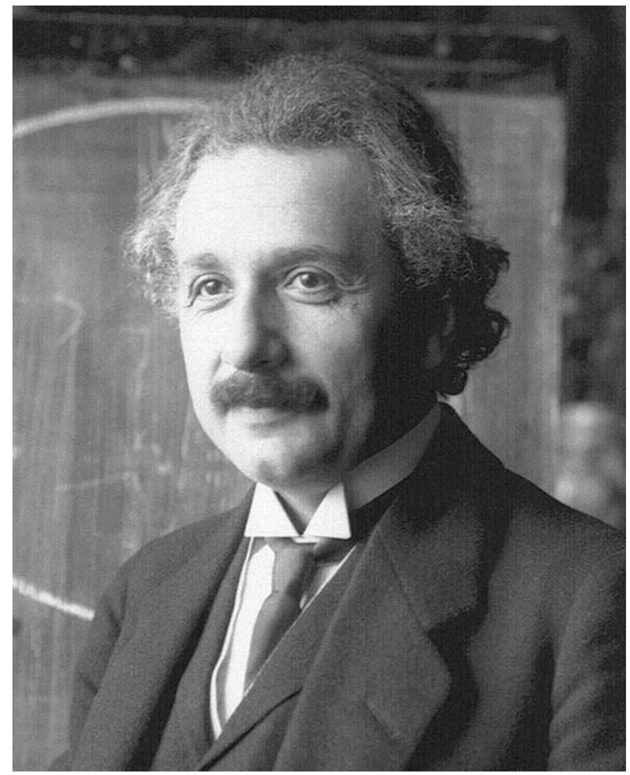
The Photoelectric Effect (1905)



$$h\nu = E_{kinetic} + \phi_{metal}$$

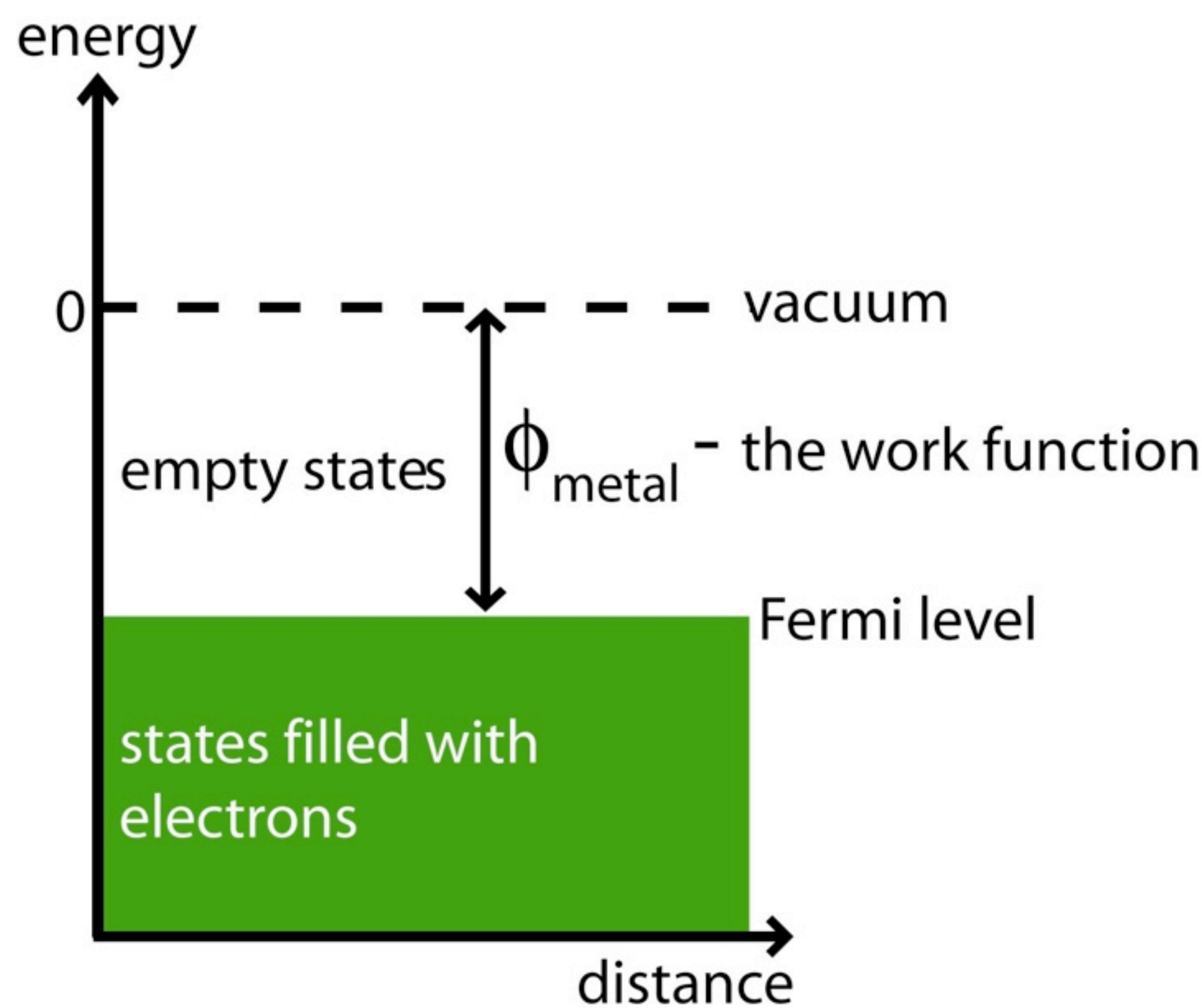
Wavelength dependence must be explained by the existence of quantized light.

Nobel Prize (his only one) awarded in 1921.

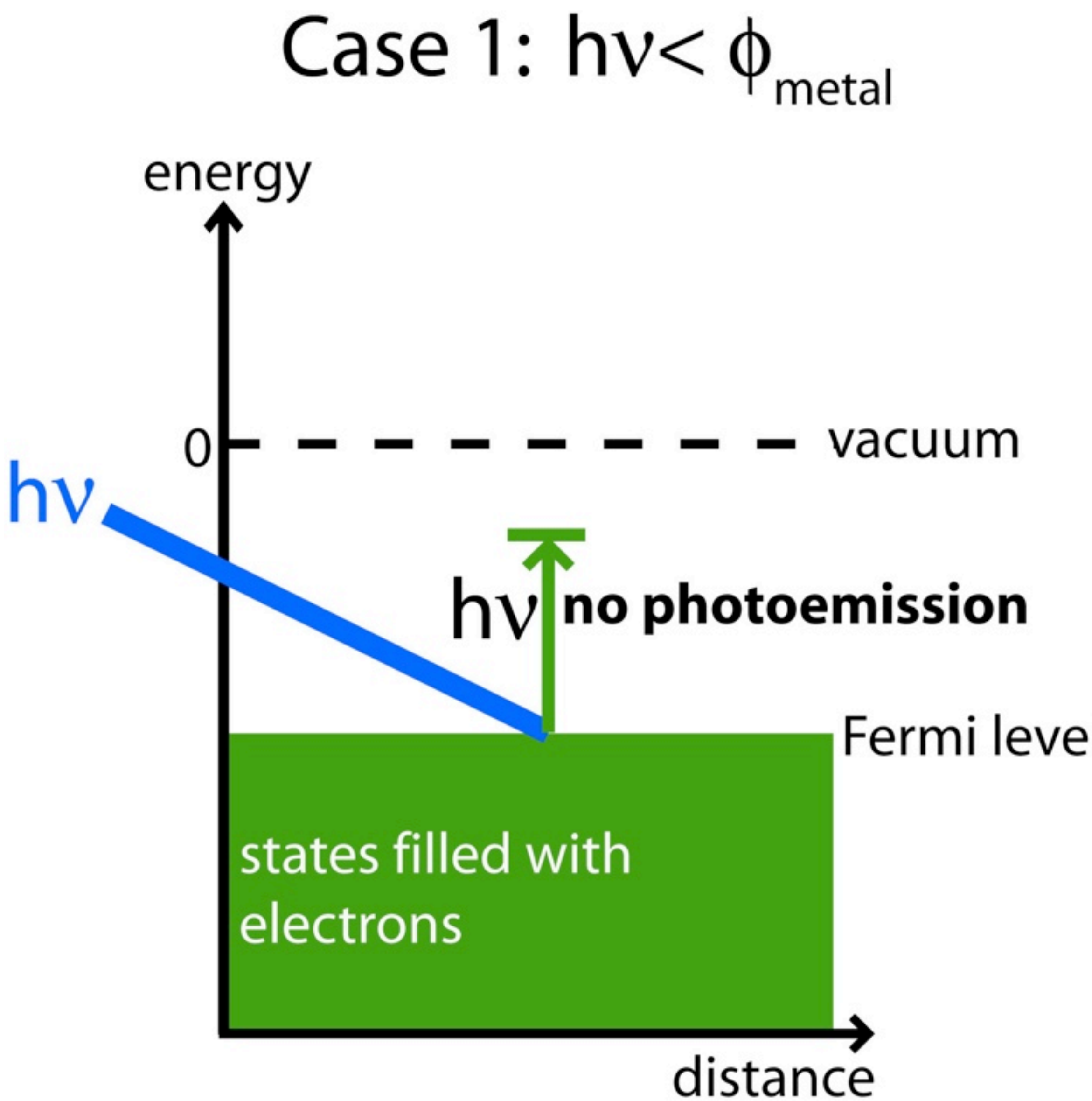


Albert Einstein
1879-1955

how does photoemission work at metals?



You shine light on a metal; **3 things can happen:**



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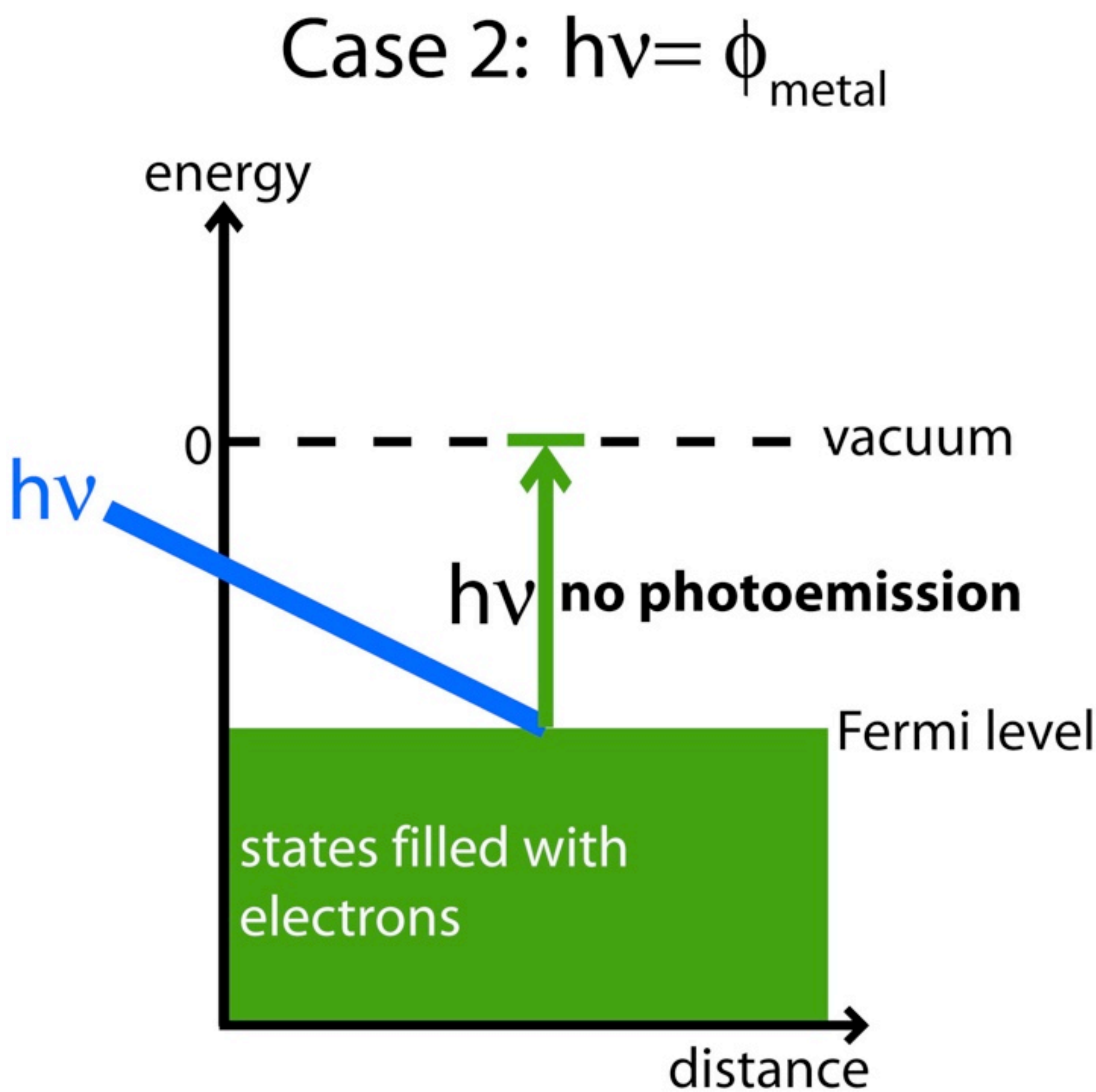
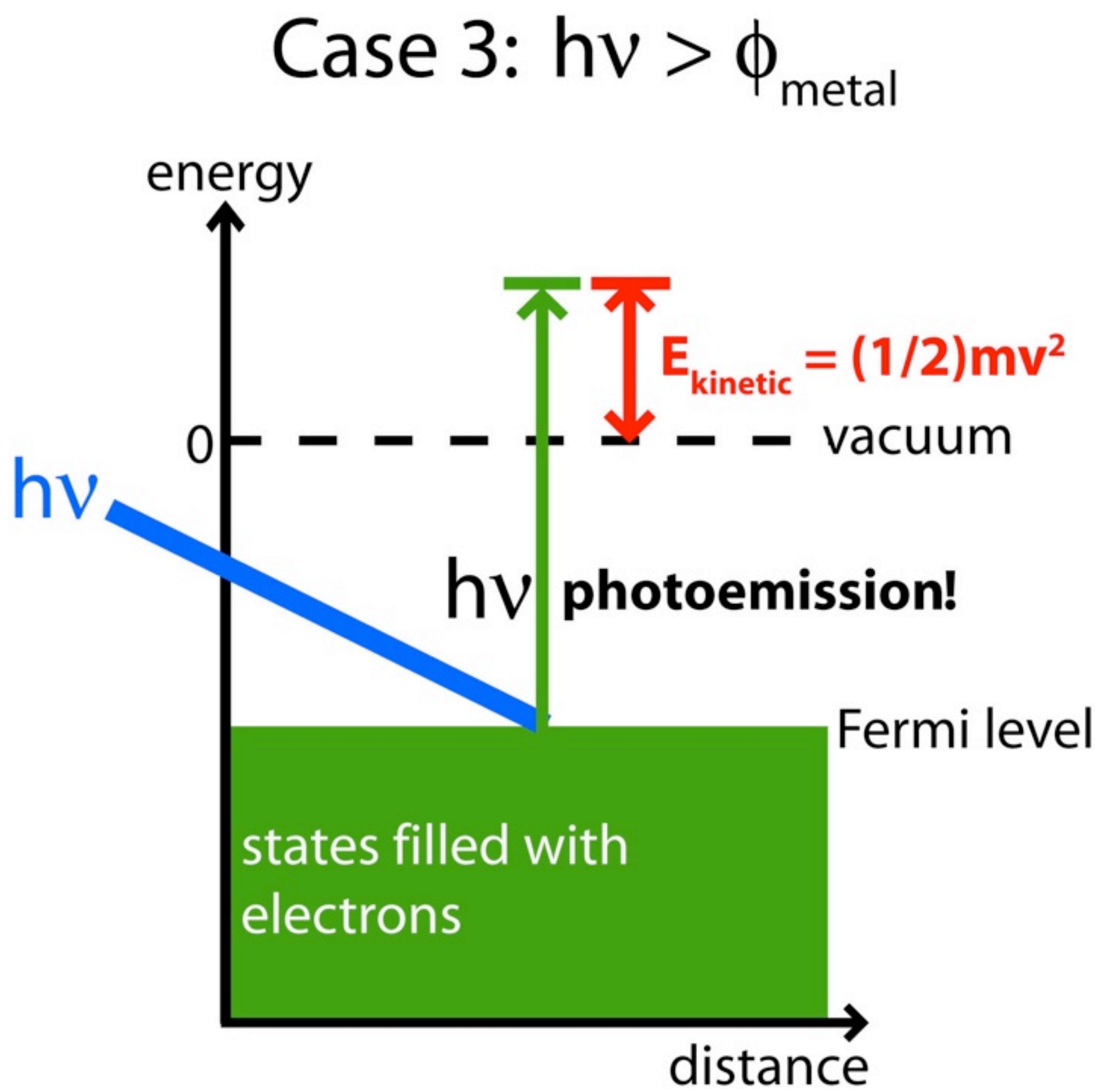
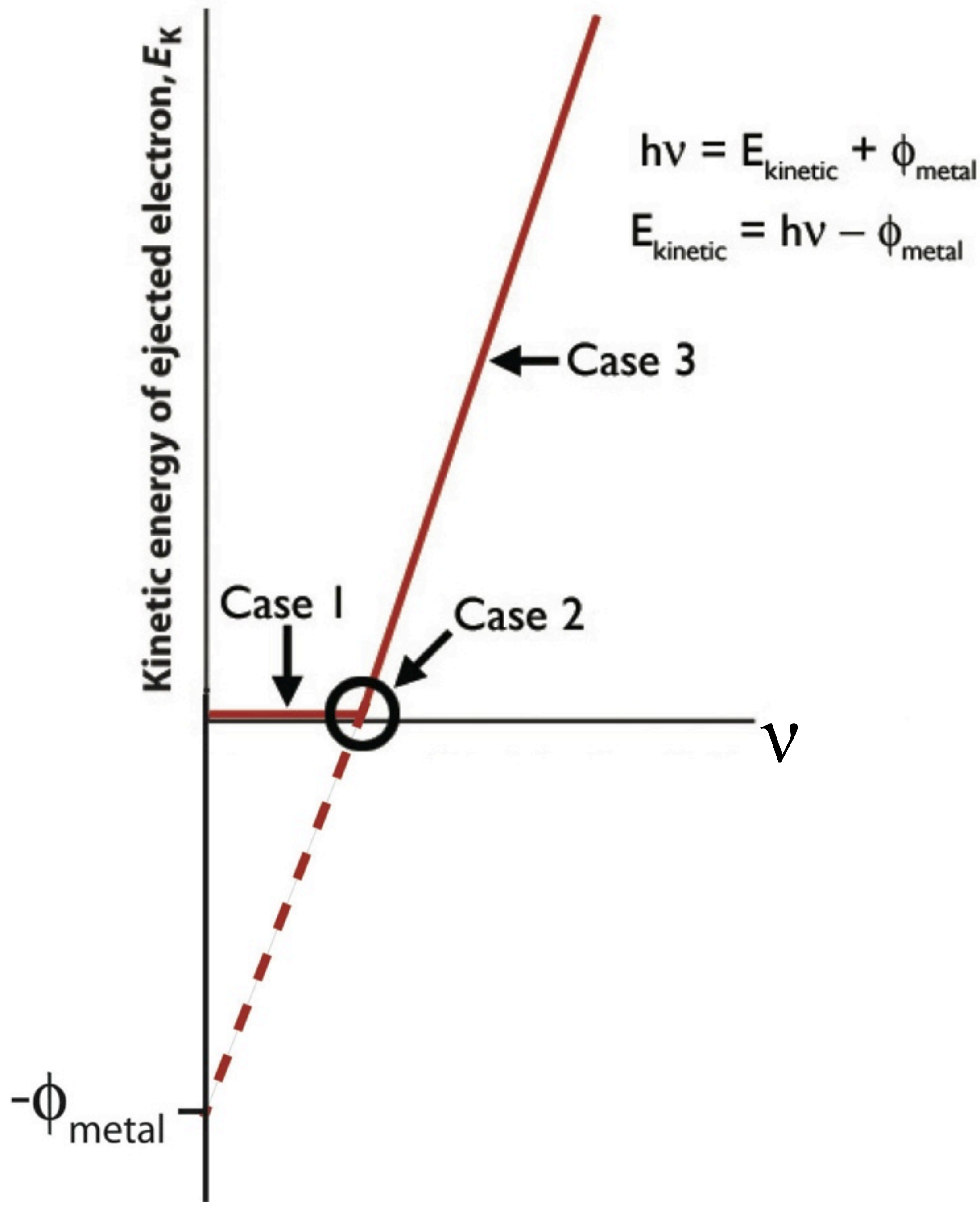


You shine light on a metal; **3 things can happen:**



what do we measure in the laboratory?



Actually...

The origin of the word "photon"

"I therefore take the liberty of proposing for this hypothetical new atom, which is not light but plays an essential part in every process of radiation, the name *photon.*"

-Gilbert N. Lewis, 1926

Although Planck and Einstein advanced the concept of quanta, Einstein did not use the word photon in his early writings and as far as my reading goes, he never did. The word "photon" originated from Gilbert N. Lewis years after Einstein's photoelectric paper and appeared in a letter to the editor of Nature magazine (Vol. 118, Part 2, December 18, 1926, page 874-875).

http://www.nobeliefs.com/photon.htm

The Death of Classical Physics

Light energy is quantized.

$$E = h\nu = \frac{hc}{\lambda}$$

h = Planck's constant

6.626×10^{-34} Joule sec

Max Planck
1858-1947

Question: Calculate the energy (in eV) of a "typical" red photon with a wavelength of 600.0 nm. (eV = electron volt)

Key equations: $c = \lambda\nu$ and $E = h\nu$

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Step 1 - Convert λ into ν:

$c = 2.998 \times 10^8$ m/s $= \lambda\nu$

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4.997×10^{14} s^{-1} or 4.997×10^{14} Hz.

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Step 2 - Multiply by h:

$E = (6.626 \times 10^{-34}\ \text{J s})(4.997 \times 10^{14}\ \text{s}^{-1})$

$E = 3.311 \times 10^{-19}$ J

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Step 2 - Multiply by h:

$E = (6.626 \times 10^{-34}$ J s$)(4.997 \times 10^{14}$ s$^{-1})$

$E = 3.311 \times 10^{-19}$ J

Step 3 - Convert to eV: 1eV $= 1.602 \times 10^{-19}$ J/eV

$E = (3.311 \times 10^{-19}$ J$)/(1.602 \times 10^{-19}$ J/eV$)$

$E = 2.067$ eV

Question: Calculate the energy (in eV) of a "typical" red photon with a wavelength of 600.0 nm. (eV = electron volt)

Key equations: $E = hc/\lambda$

Shortcut:

$c = 2.998 \times 10^{8}$ m/s

$h = (6.626 \times 10^{-34}$ J s$)/(1.602 \times 10^{-19}$ J/eV$)$

$E = (1.240 \times 10^{-6})/(\lambda \text{ in m})$

$E = 1240./(\lambda \text{ in nm})$

Calculation:

$E = 1240./600.0$

$E = 2.067$ eV

The Death of Classical Physics

from Planck, we have:

- the birth of quantum theory.
- h - Planck's constant. 6.626×10^{-34} J s.
- the quantization of energy - a concept underlying all of quantum mechanics.

We will use quantum mechanics to understand Chemistry!

Max Planck
1858-1947

De Broglie Wavelength (1924)

For photons:

Special Relativity and Planck

$$E = pc = \frac{hc}{\lambda}$$

momentum of a photon

$$p = \frac{h}{\lambda}$$

Louis de Broglie
1892-1987

De Broglie Wavelength (1924)

For photons:

Special Relativity and Planck

$$E = pc = \frac{hc}{\lambda}$$

momentum of a photon

$$p = \frac{h}{\lambda}$$

wavelength of a particle

$$\lambda = \frac{h}{p}$$

why not ALL particles?

Louis de Broglie
1892-1987

De Broglie Wavelength (1924)

6.626×10^{-34} J s

↓

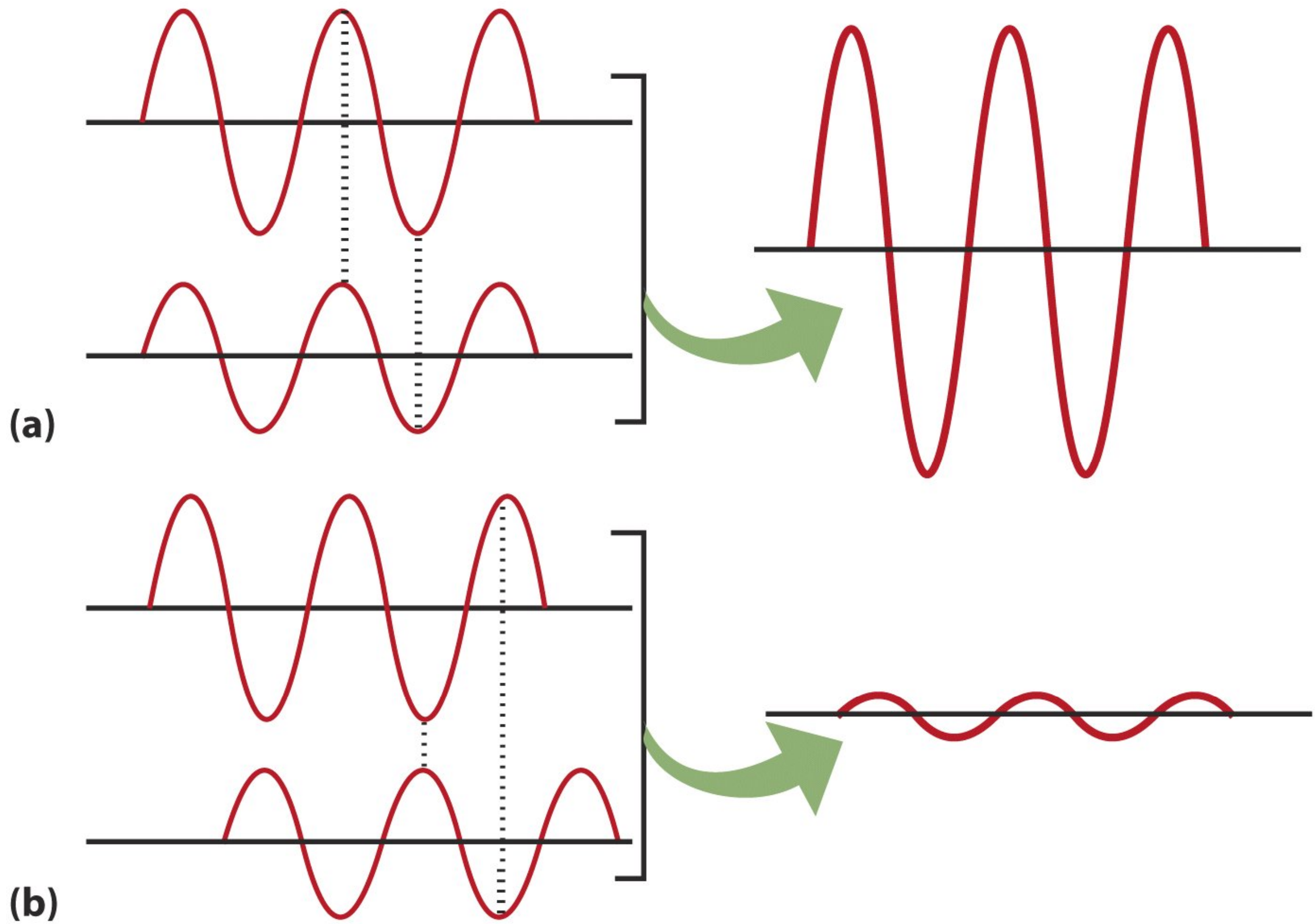
de Broglie wavelength → $$\lambda = \frac{h}{p}$$

↑

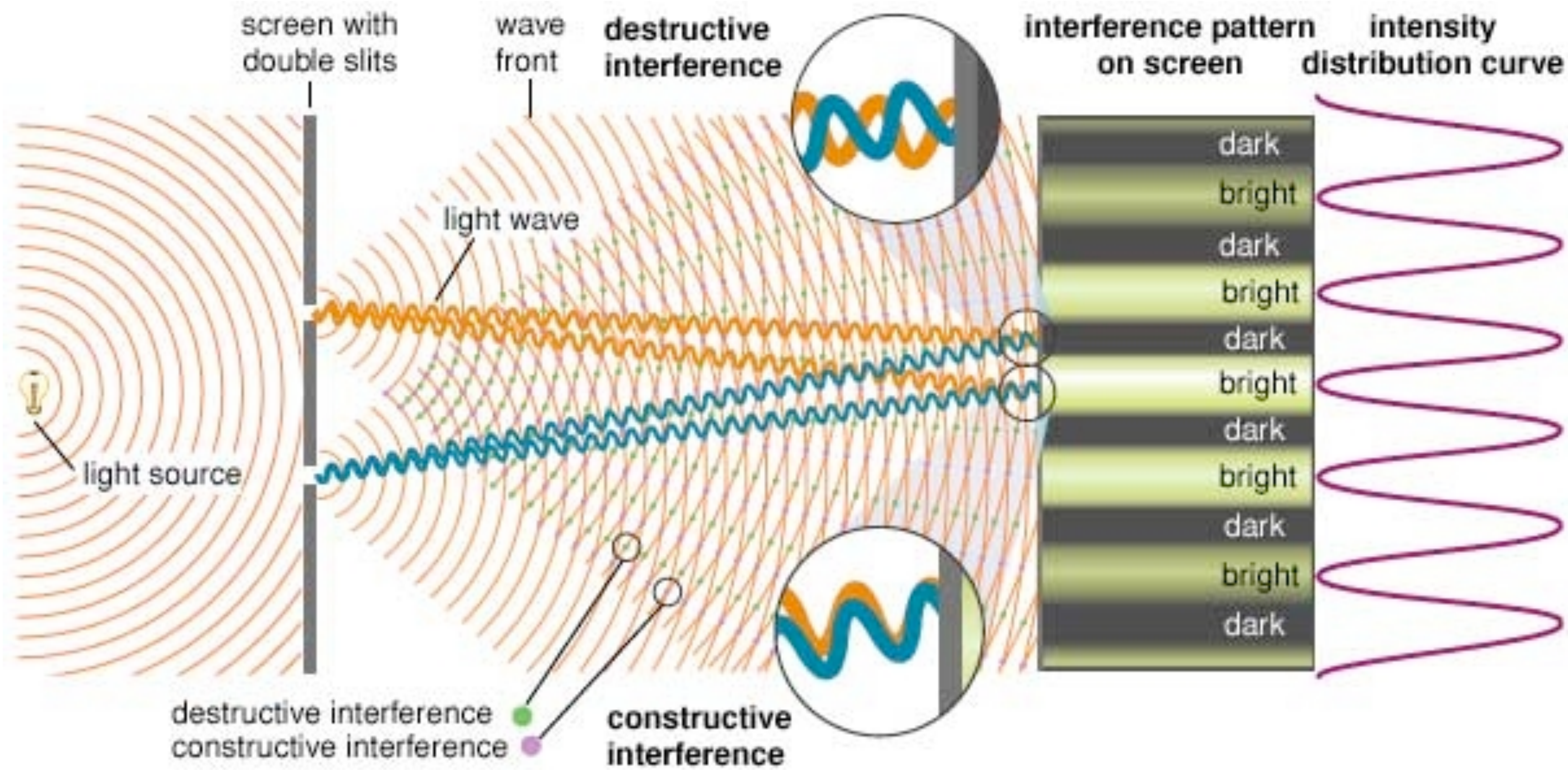
mass x velocity

Louis de Broglie
1892-1987

A signature property of waves is the phenomenon of interference: Waves can interfere either constructively (a) or destructively (b)...



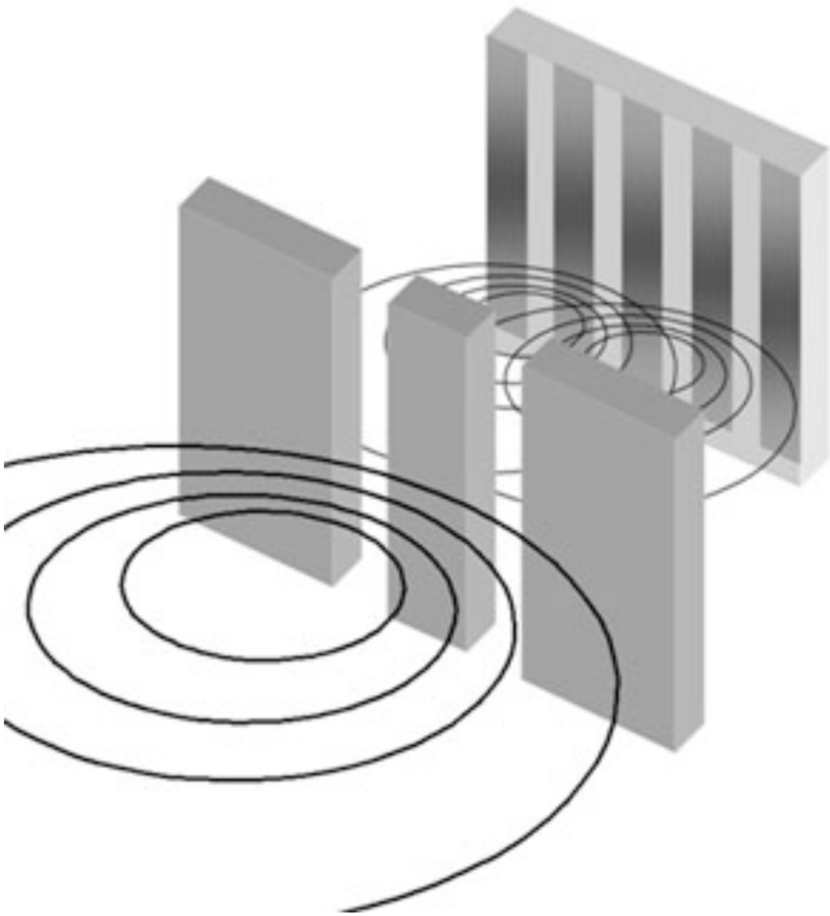
Thomas Young's two-slit experiment with light (1802).



Young's experiment convinced physicists that light was a wave.

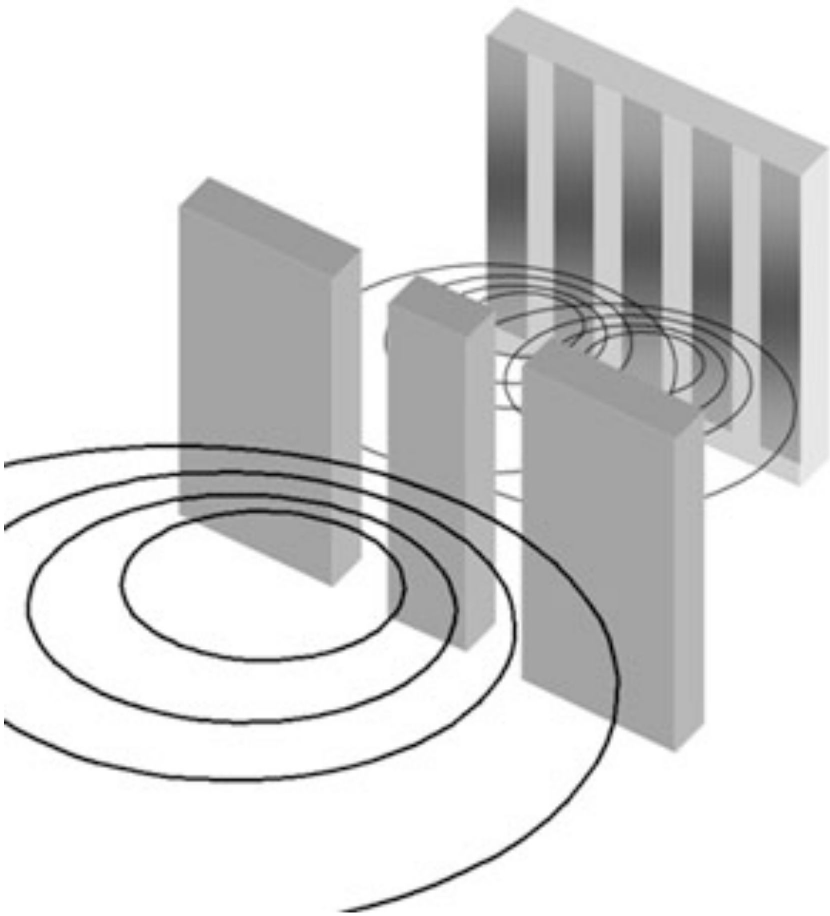
Light diffracts like waves:

Thomas Young's two-slit experiment with light (1802).

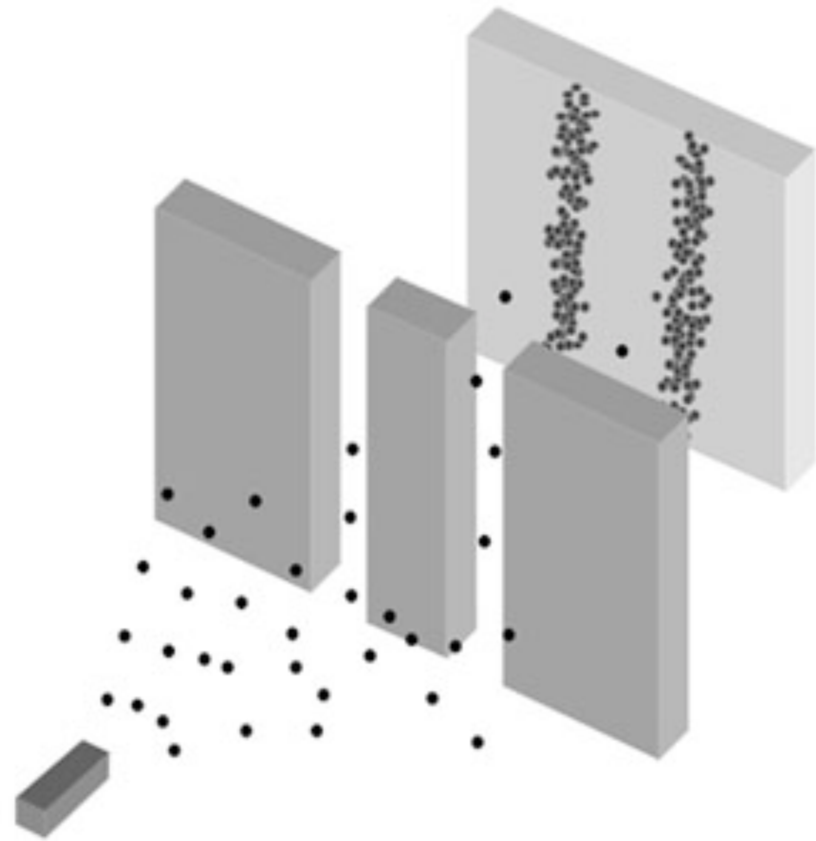


Electrons also diffract like waves!

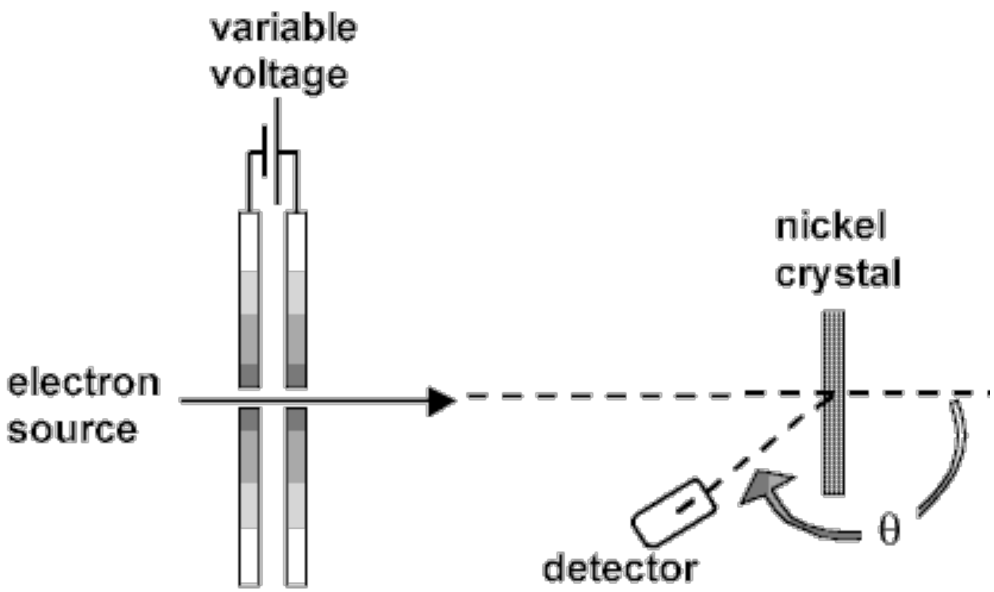
Thomas Young's two-slit experiment with light (1802).

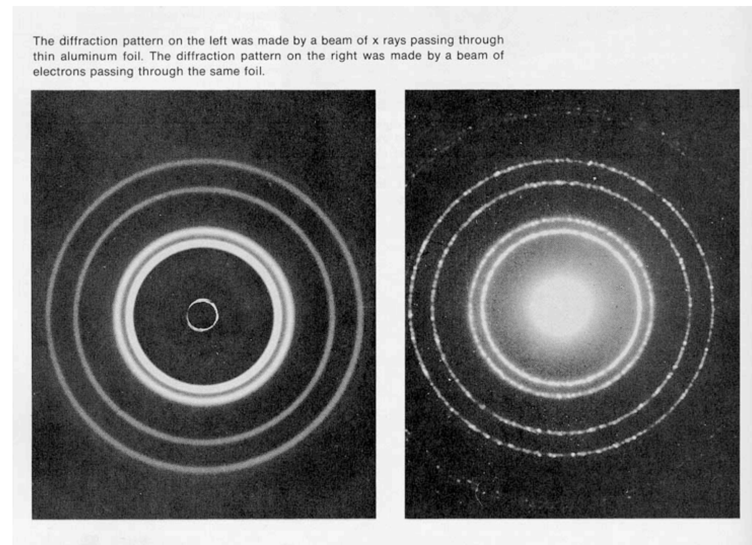


Davisson and Germer electron diffraction (1928).



Davission and Germer measured electron diffraction from a Nickel crystal in 1928.



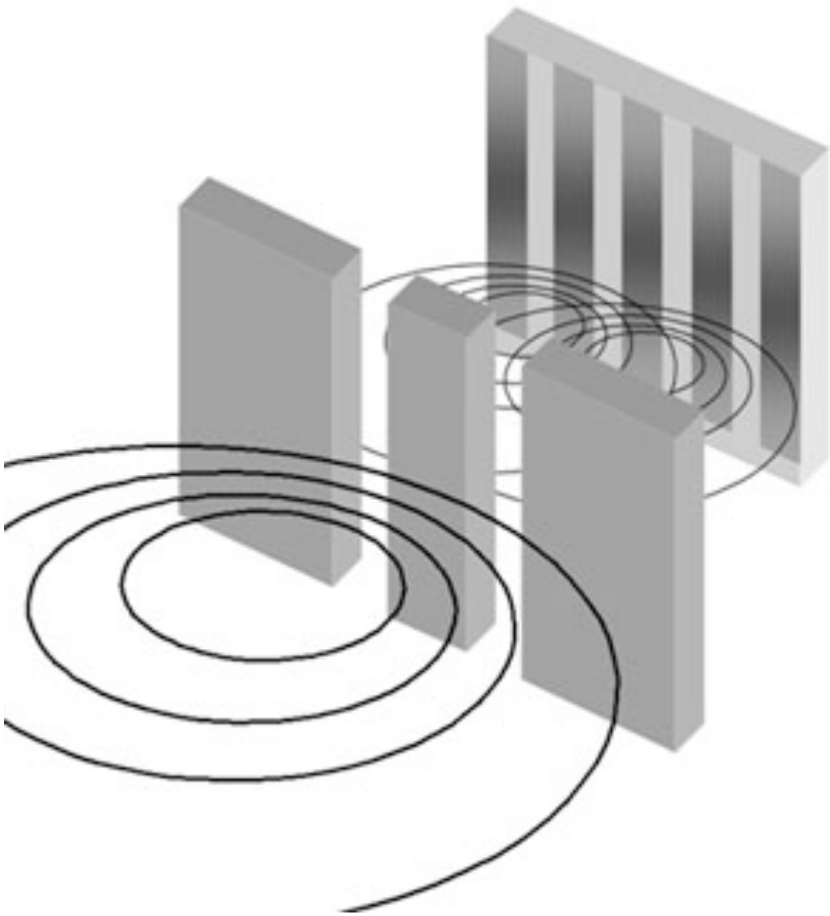

The diffraction pattern on the left was made by a beam of x rays passing through thin aluminum foil. The diffraction pattern on the right was made by a beam of electrons passing through the same foil.

X-rays electrons

The de Broglie wavelength of electrons in the lab is *Angstroms (10^{-10} m)*, so the "slits" have to be atomic scale - Davission and Germer used a Nickel crystal.

Electrons also diffract like waves!

Thomas Young's two-slit experiment with light (1802).



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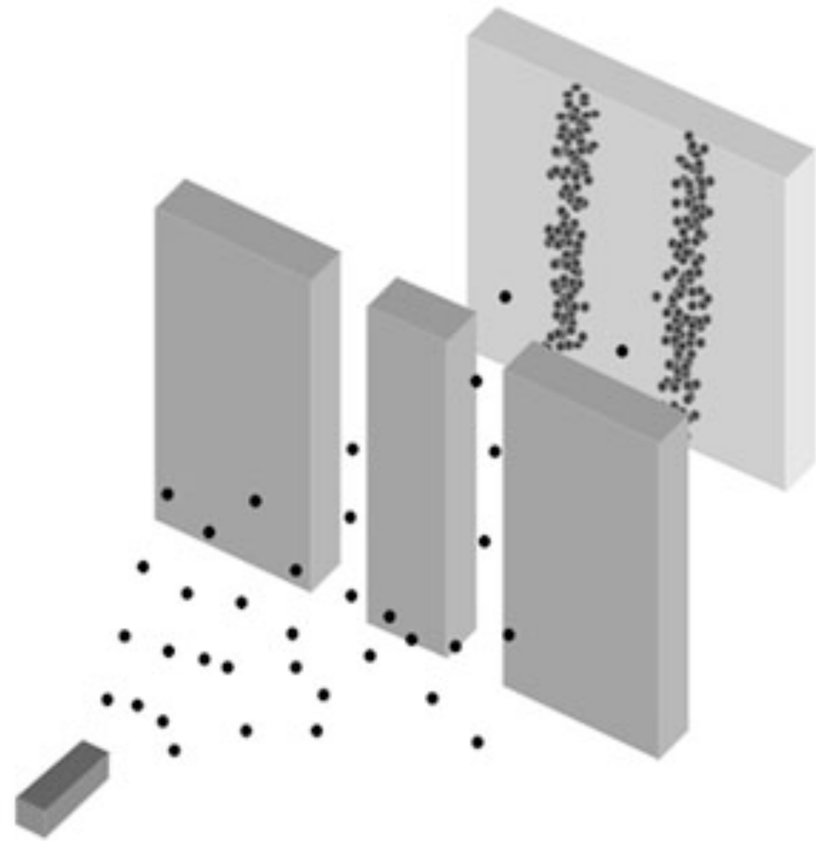
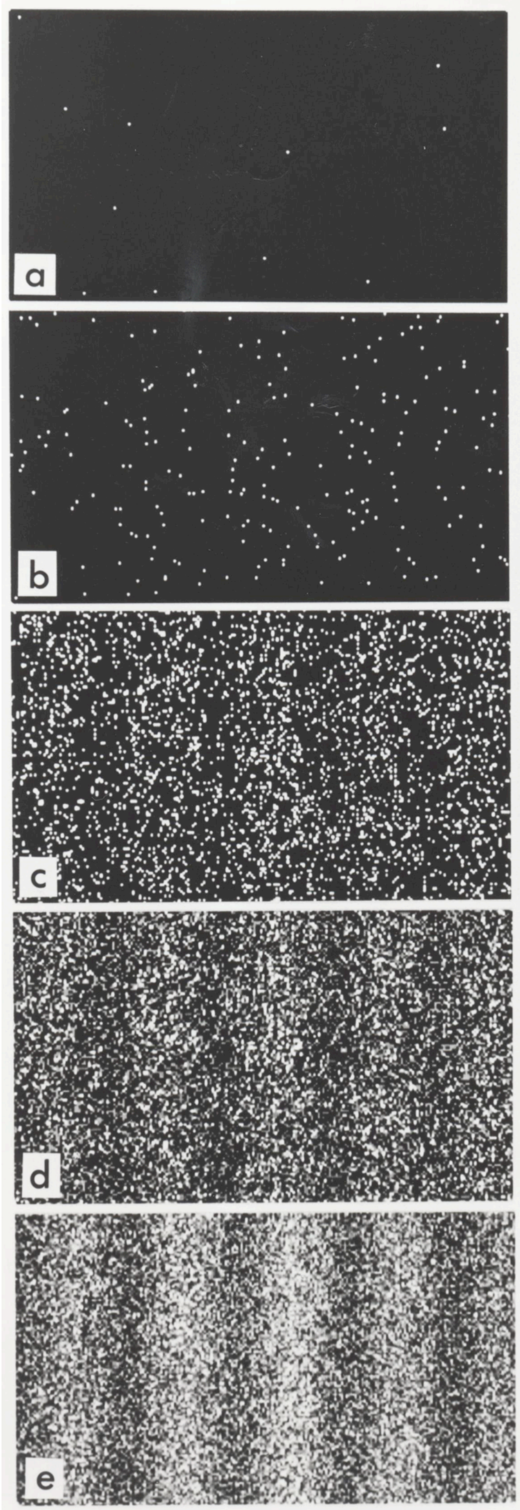


Question: How many electrons do we need to see interference?

Answer: one!

Modern version of Thomas Young's two-slit experiment performed with electrons.

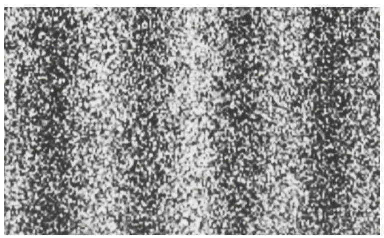
American Journal of Physics in 1974 (volume 42, pp4-11)



De Broglie Wavelength (1924)

All particles have a *wave* nature, just as electromagnetic *waves* have a *particle* nature.

$$\lambda = \frac{h}{p}$$



Electron diffraction is observed, even when the flux of electrons is so low, that *consecutive electrons encounter these slits one at a time.*

Louis de Broglie
1892-1987

Clearly, we need a way to predict the bizarre behavior of these particles.
Enter the New Wave Stars: Schrödinger, Heisenburg and Dirac!

The Birth of Quantum Mechanics

Louis de Broglie
1892-1987

Erwin Schrödinger
1887-1961

Paul Dirac
1902-1984

Werner Heisenberg
1901-1976

New Wave Rock Stars