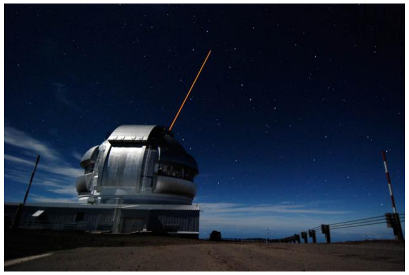
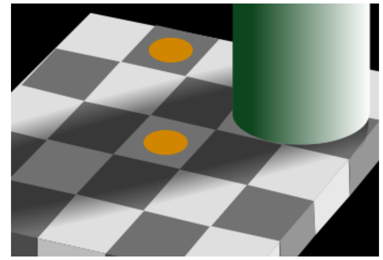
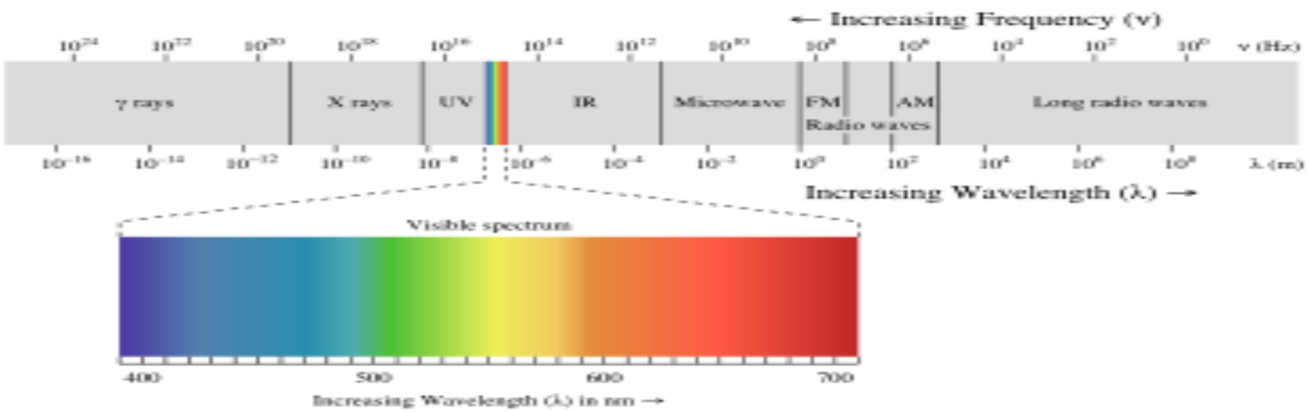
Physics 1230: Light and Color



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http://www.colorado.edu/physics/phys1230/

Fundamental properties of light

Announcements:

- lecture 2 is posted on the class website
- homework 2 is posted on D2L
  - due Tuesday, Jan 28 in homework box in Help Room
  - solutions will be posted on D2L
- reading for this week is:
  - Ch. 2 in SL
- remember to bring your clicker to every class
  - register it (once)
  - set it to frequency BA

Fire up the iClickers

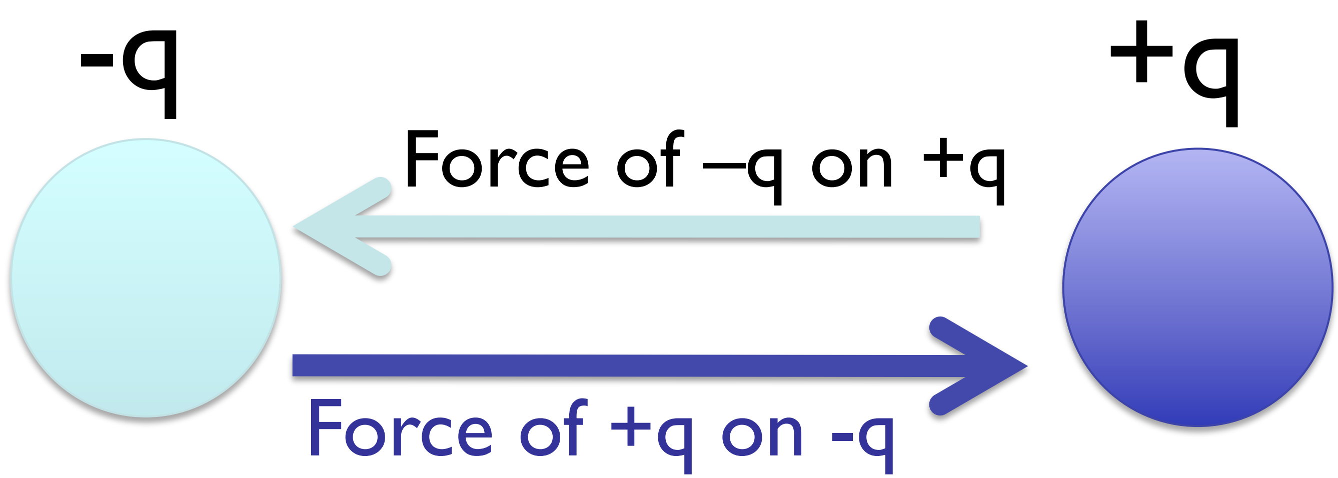
- swap clicker code to BA
- hold down on/off switch for 4 seconds
- flashing blue light: hit BA
- should see GREEN light and you're ready to go

clicker question

Coulomb force between charges

Q: *What's the direction of the force between the charges?*

a) to the left
b) to the right
c) depends on which charge you're talking about



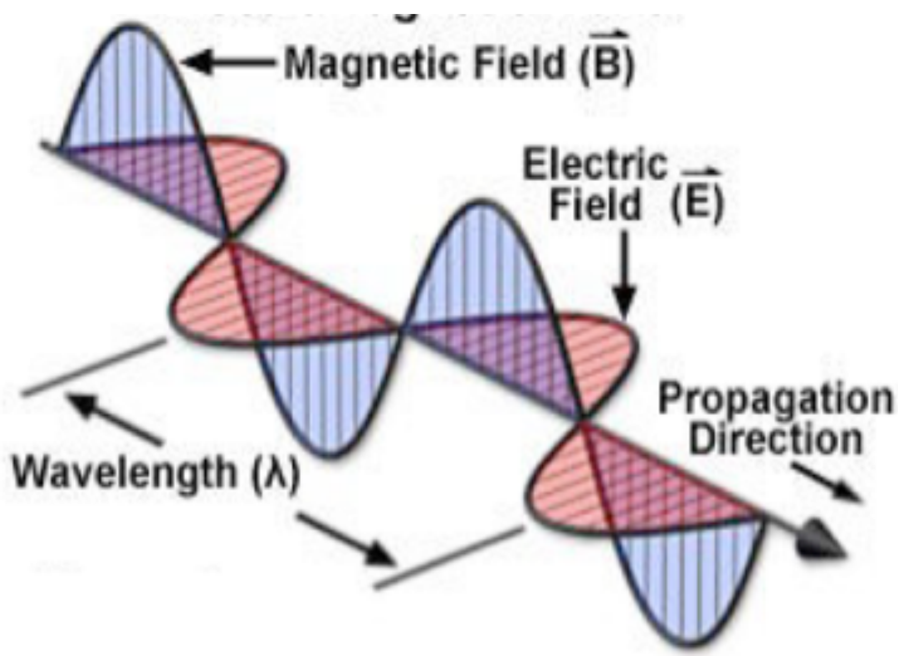
A: *c) The force on +q due to –q is to the left.*
The force on -q due to +q is to the right.

Last Time

recall lecture 2:

What is light?

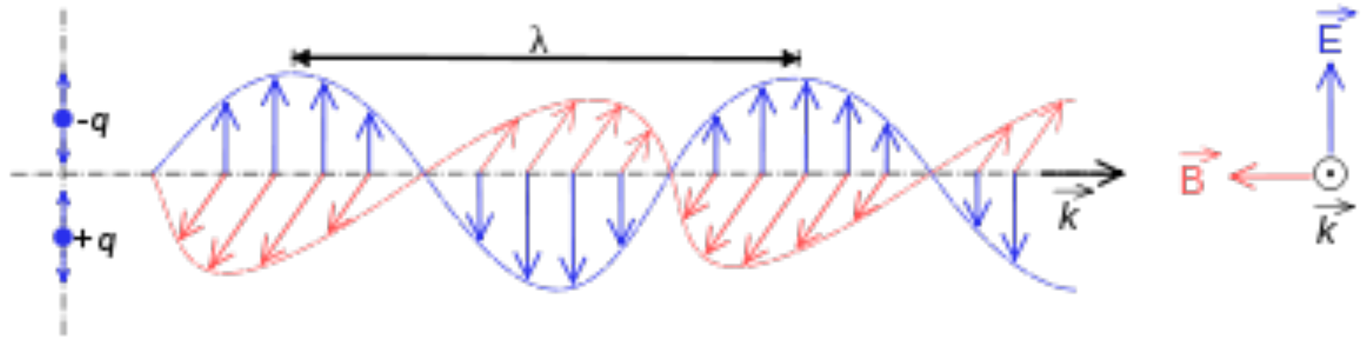
- charges -> electric and magnetic fields
- accelerating charges -> electromagnetic waves
- electromagnetic spectrum
- generating different types of EM radiation



Recall

Electromagnetic radiation generators

- EM wave generated by oscillating electrical currents -> send signal (radio antenna, garage door opener, remote control, ...)



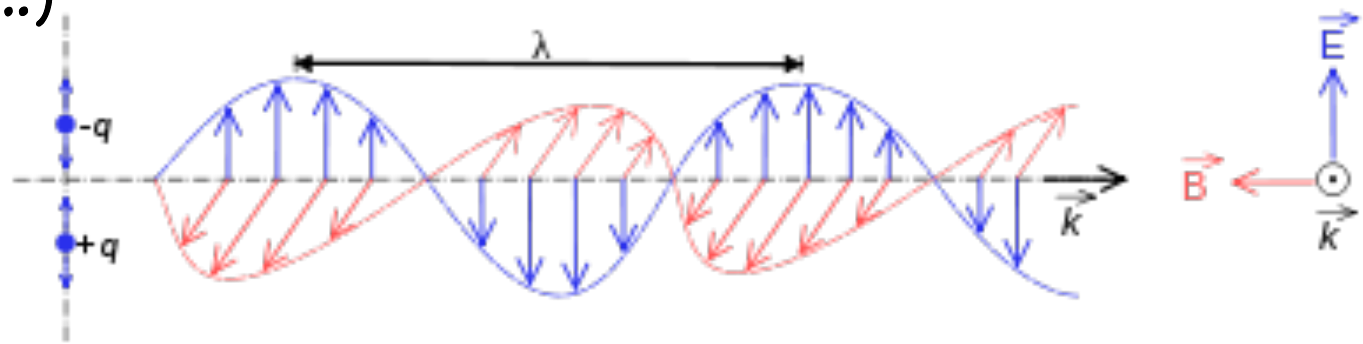
tv, radio antennas

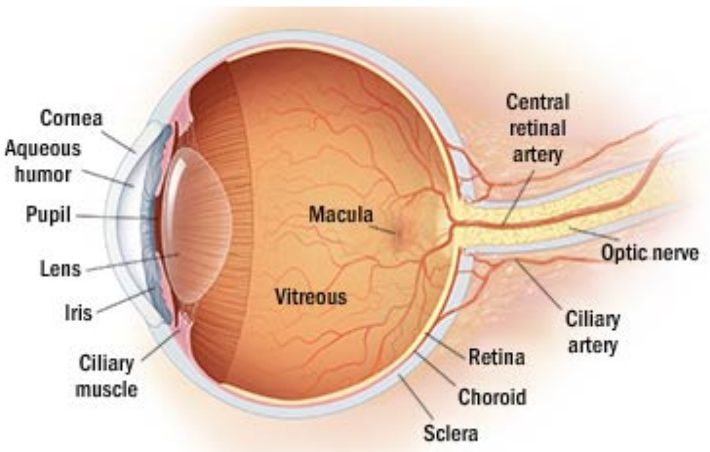
Atacama Large Millimeter Array

Recall

Electromagnetic radiation sensors

- EM wave exerts oscillating force on charges (electrons) in matter (radio antenna, your eyes, ...) -> ac current -> image (speaker sound, brain, tv, lcd,...)





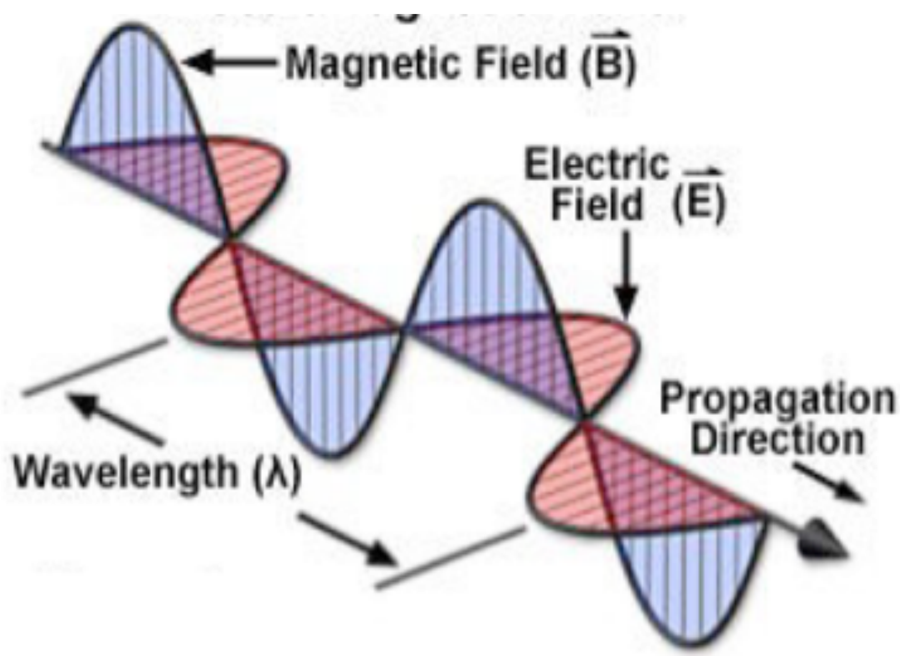
Atacama Large Millimeter Array

tv, radio antennas

Today

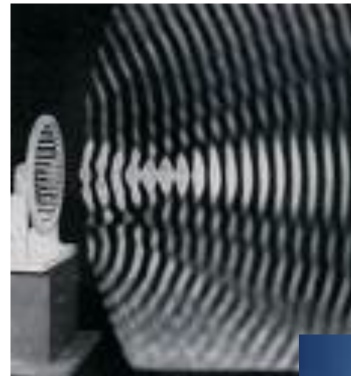
Fundamentals of EM waves

- EM waves in vacuum
- properties of light: wavelength, frequency, speed,...
- electromagnetic spectrum
- blackbody radiation
- color
- quantum picture of light: photons



EM-waves in what?

- *Sound wave* propagates through air, with velocity (330 m/sec) relative to *air*

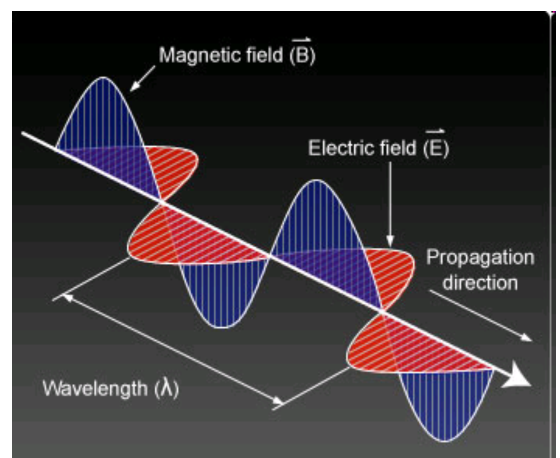


- *Water waves* propagates through water, with velocity relative to *water*

- *"The wave"* propagates through a crowd in a stadium, with velocity relative to the *crowd*

- *Electromagnetic wave* propagates through what??? What is "moving"/oscillating?

~~Ether~~...so it was (incorrectly) thought in 19th century before Einstein



Michelson & Morley (1887): there is no Ether!

clicker question

Distance, speed, time

Q: *It takes 4 hours going at 50 miles/hr to get to Aspen from Boulder. How far is Aspen?*

a) 10 miles away

b) 150 miles away

c) 200 miles away

d) Not enough information

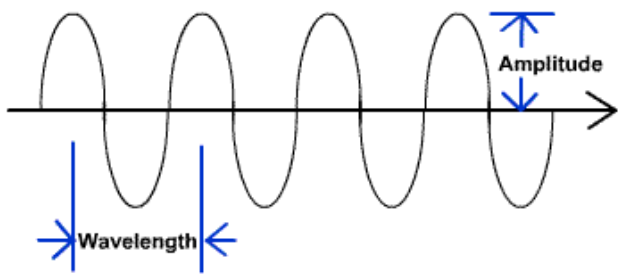
A: *c) distance = speed x time, i.e., $d = v\,t$*

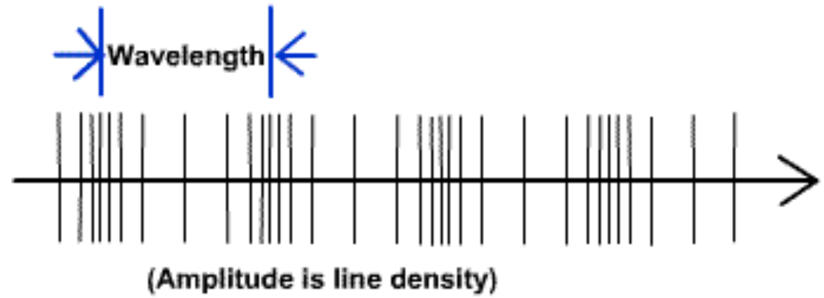
$d = 50$ mi/hr x 4 hrs = 200 miles

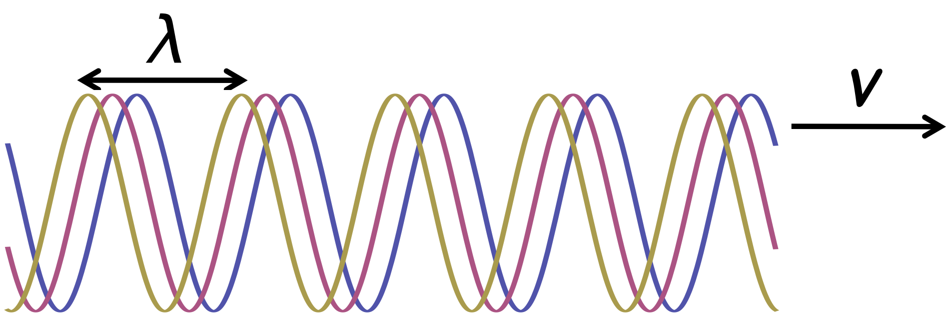
Waves primer: basics

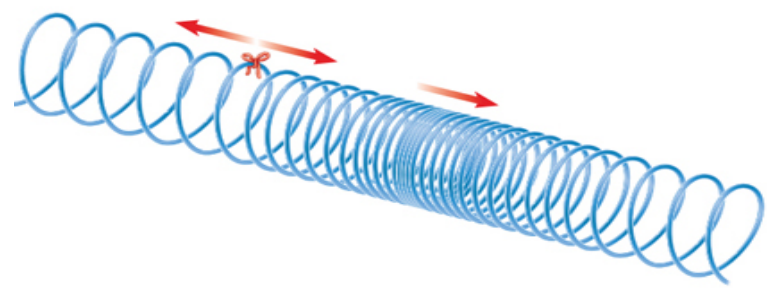
- periodic *(spatially-temporally extended)* disturbance

  e.g., sound, water, stadium, EM waves (in gas, liquid, solid, people, vacuum)









  - *frequency: f (Hz) <-> period in* ***time*** *T = 1/f* (seconds)
  - *wavelength: λ (meters) period is* ***space***
  - *phase speed (velocity):* $v_p = f\lambda$ *(meters/second)*

Waves primer: basics

- periodic *(spatially-temporally extended)* disturbance

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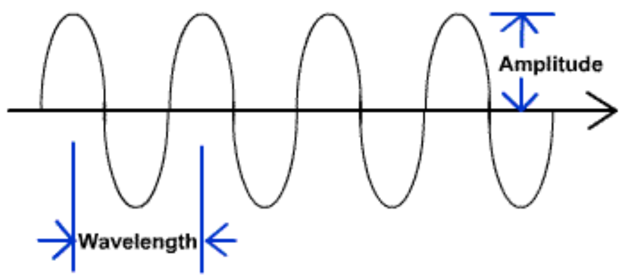
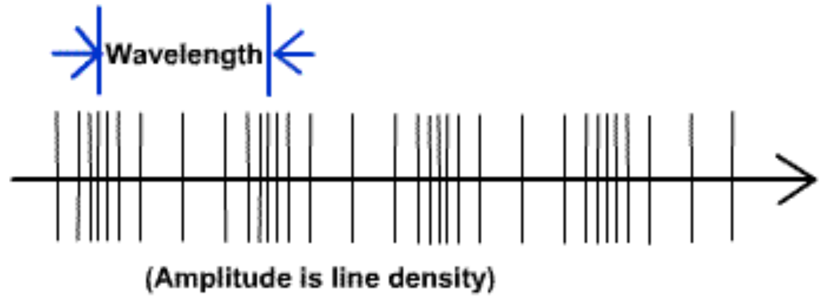
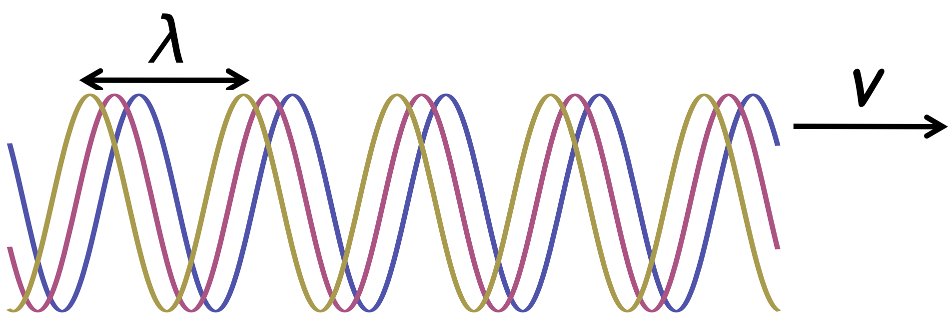
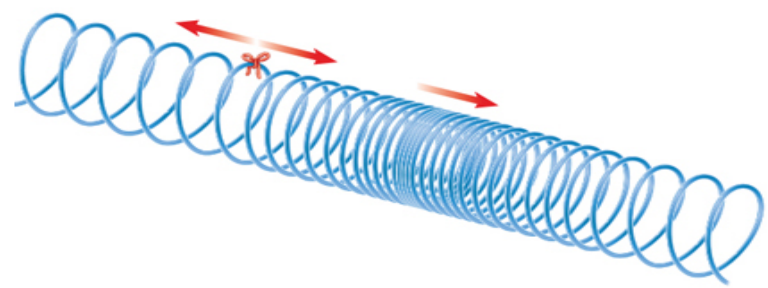






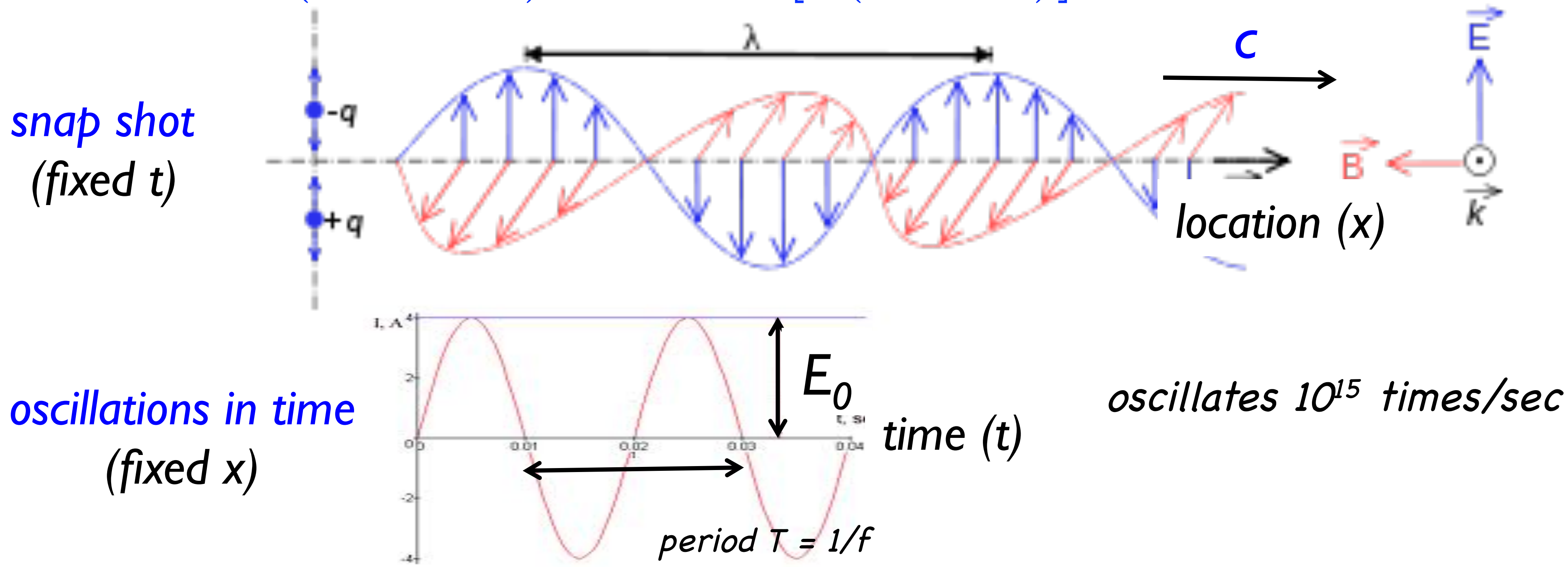


$$\mathcal{E} = \mathcal{E}_0 \cos(kx - \omega t) = \mathcal{E}_0 \cos[k(x - vt)]$$

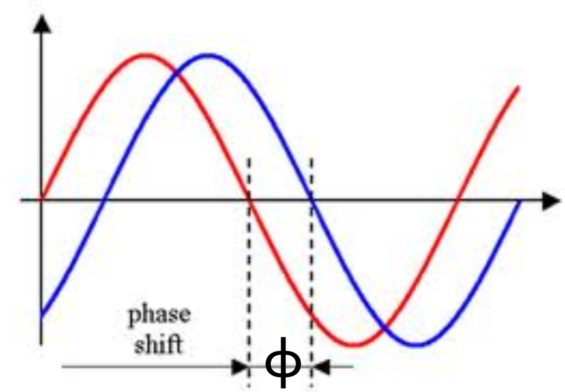
- *frequency:* $\omega = 2\pi f$ ($f = \nu$)
- *wavevector:* $k = 2\pi/\lambda$
- *phase velocity:* $\omega = v_p\, k$

Properties of EM waves

$$\mathcal{E} = \mathcal{E}_0 \cos(kx - \omega t) = \mathcal{E}_0 \cos[k(x - vt)]$$



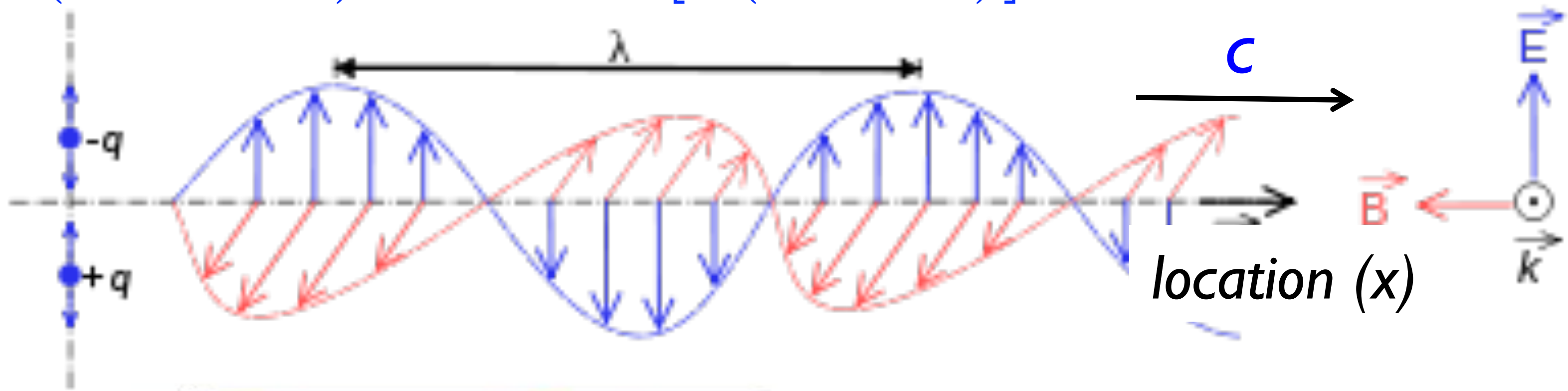
- wavelength (color): λ (m), $2\pi/\lambda = k$ *(wavevector)*
- frequency (color): $f = \nu$ (Hz), $2\pi f = \omega$ *(angular frequency)*
- speed c (3×10^8 m/s): $c = f\lambda \iff \omega = ck$
- amplitude (brightness): Intensity $I = E^2$
- phase (position): ϕ



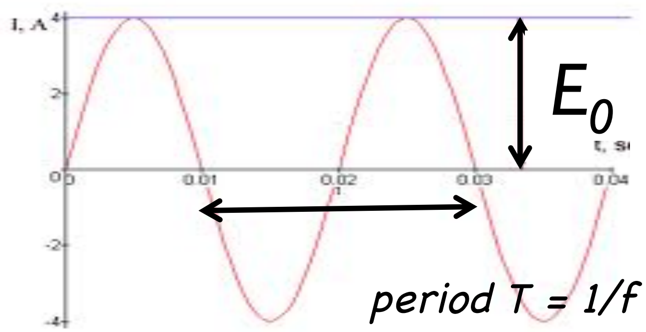
Properties of EM waves

$$\mathcal{E} = \mathcal{E}_0 \cos(kx - \omega t) = \mathcal{E}_0 \cos[k(x - vt)]$$

snap shot
(fixed t)



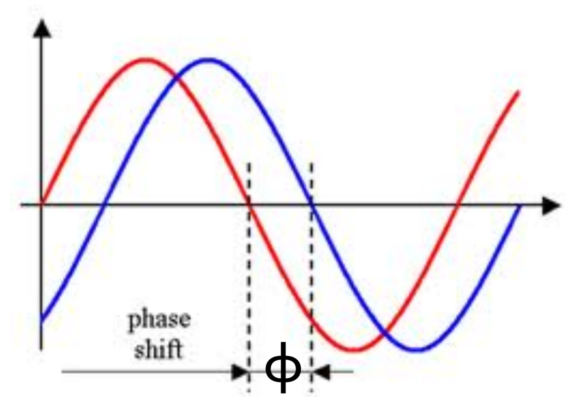
oscillations in time
(fixed x)



time (t)

oscillates 10^{15} times/sec

- wavelength (color): λ (m)
- frequency (color): f = ν (Hz)
- speed c (3×10^8 m/s): c = f λ
- amplitude (brightness): Intensity I = E^2
- phase (position): ϕ

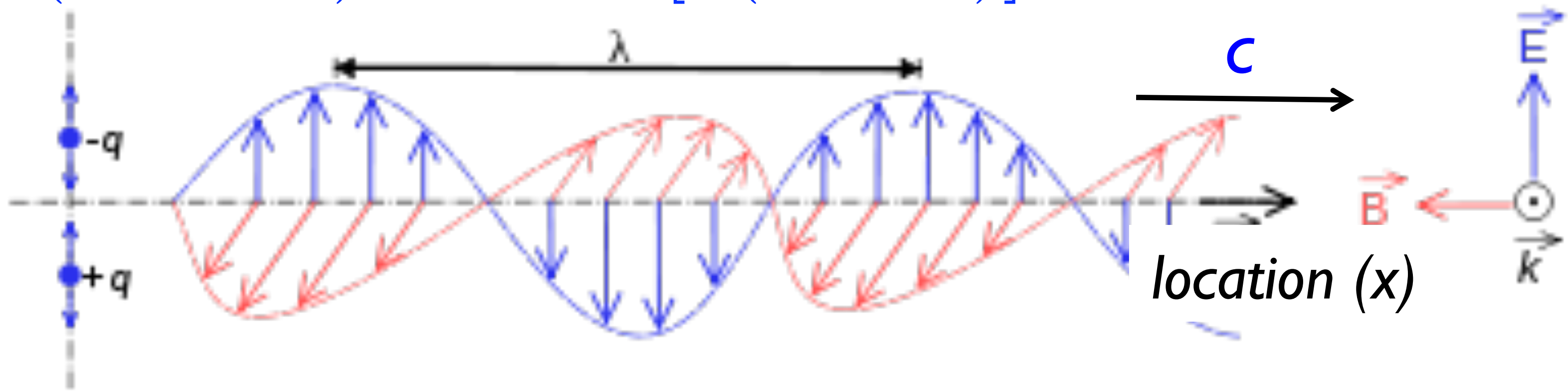


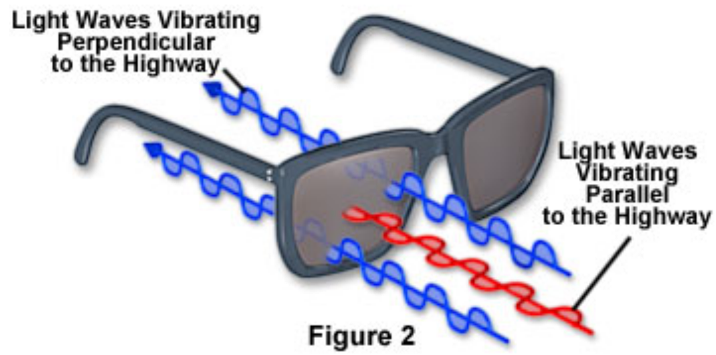
Properties of EM waves

$$\mathcal{E} = \mathcal{E}_0 \cos(kx - \omega t) = \mathcal{E}_0 \cos[k(x - vt)]$$

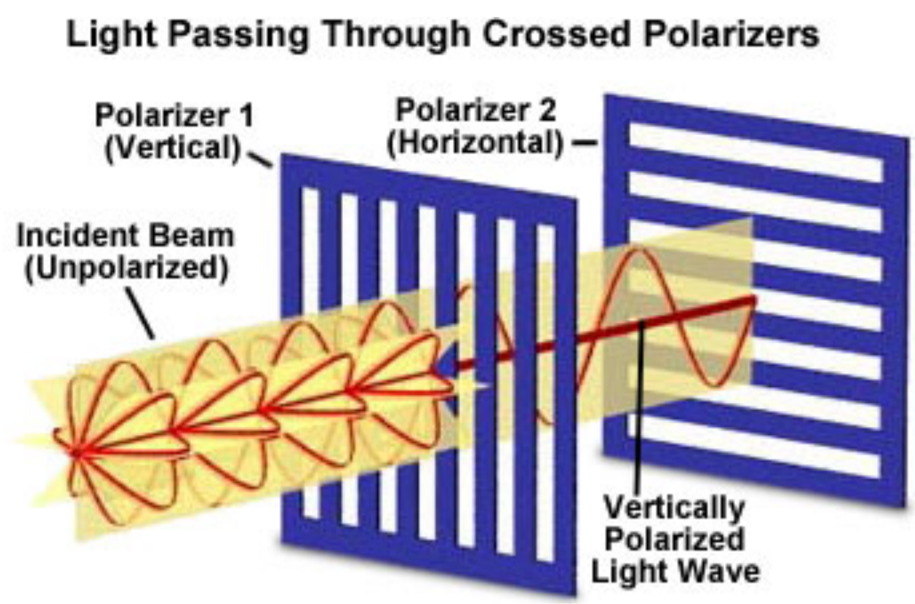
snap shot

(fixed t)

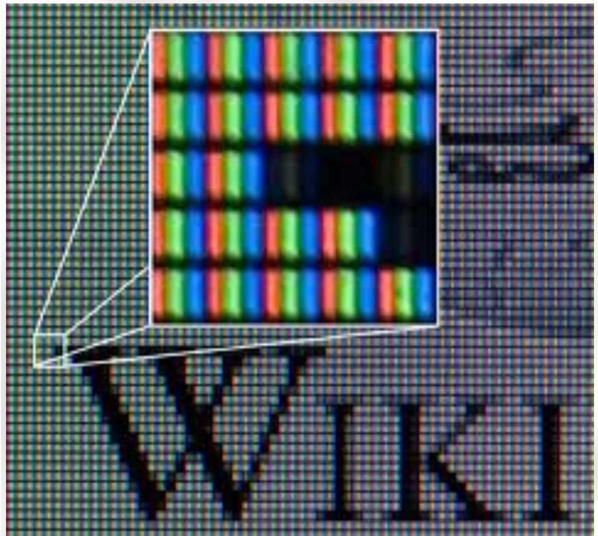


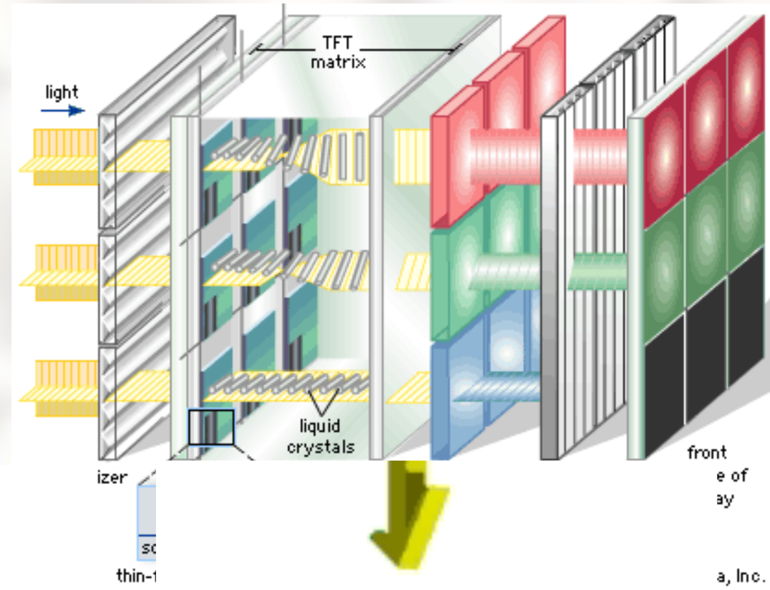


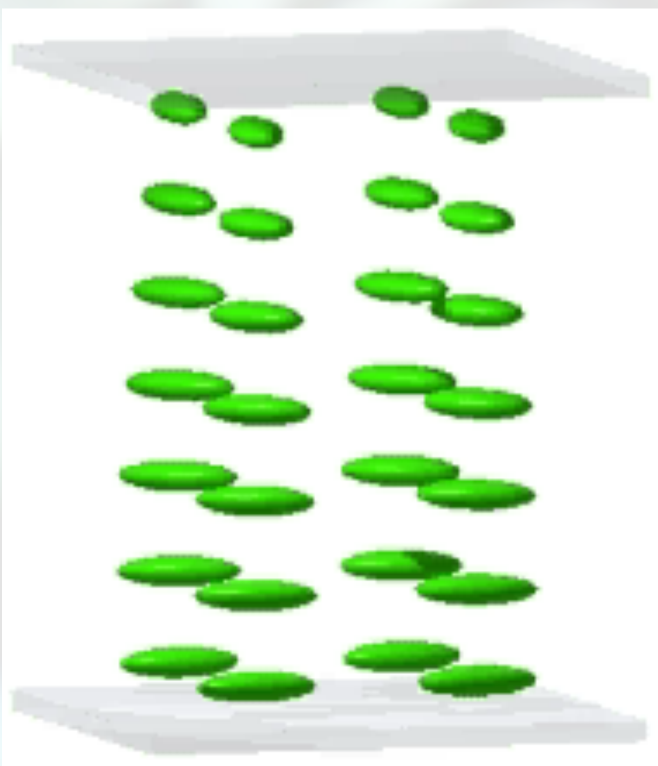
- wavelength (color): λ (m)
- frequency (color): f = ν (Hz)
- speed c (3×10^8 m/s): c = f λ
- amplitude (brightness): $I=E^2$
- phase (position): ϕ
- polarization

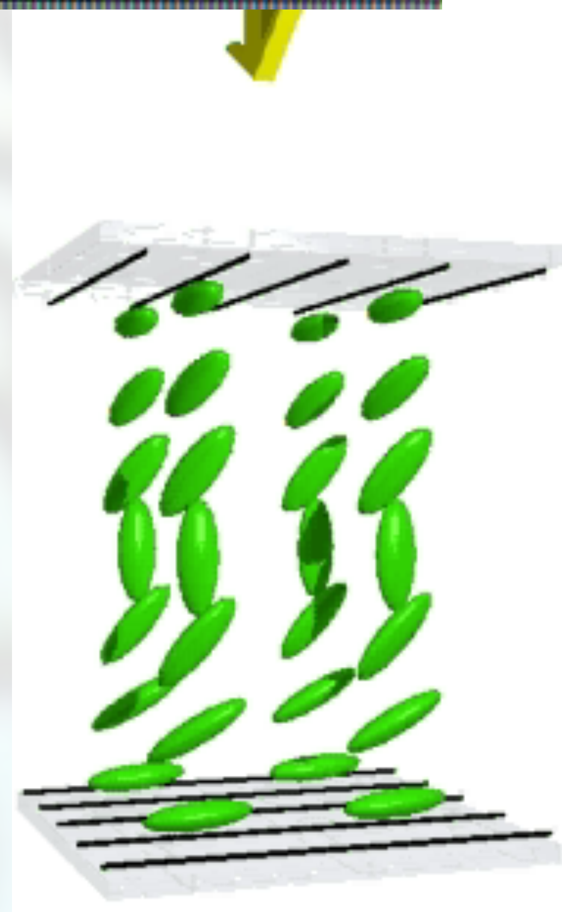


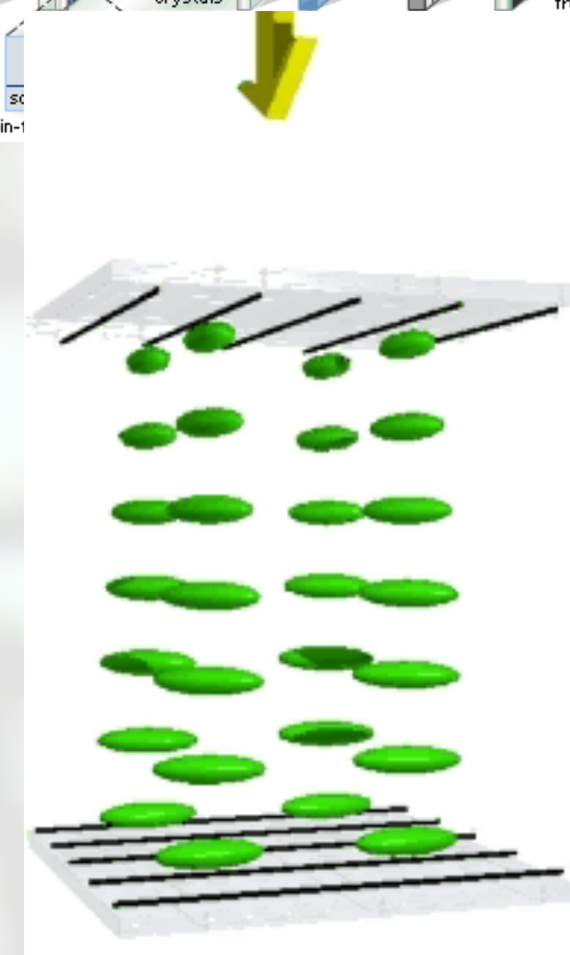
Liquid-crystal display applications











Properties of EM waves

For *periodic* waves, we can identify a *speed*, v, by

Speed = distance/time

Speed = Wavelength/Period

Speed = Wavelength x frequency

$$v = f\,\lambda$$

$$c = f\,\lambda \text{ or } f = c/\lambda \text{ or } \lambda = c/f$$

So knowing the **frequency**, we can calculate the **wavelength**

Or knowing the **wavelength**, we can calculate the **frequency**

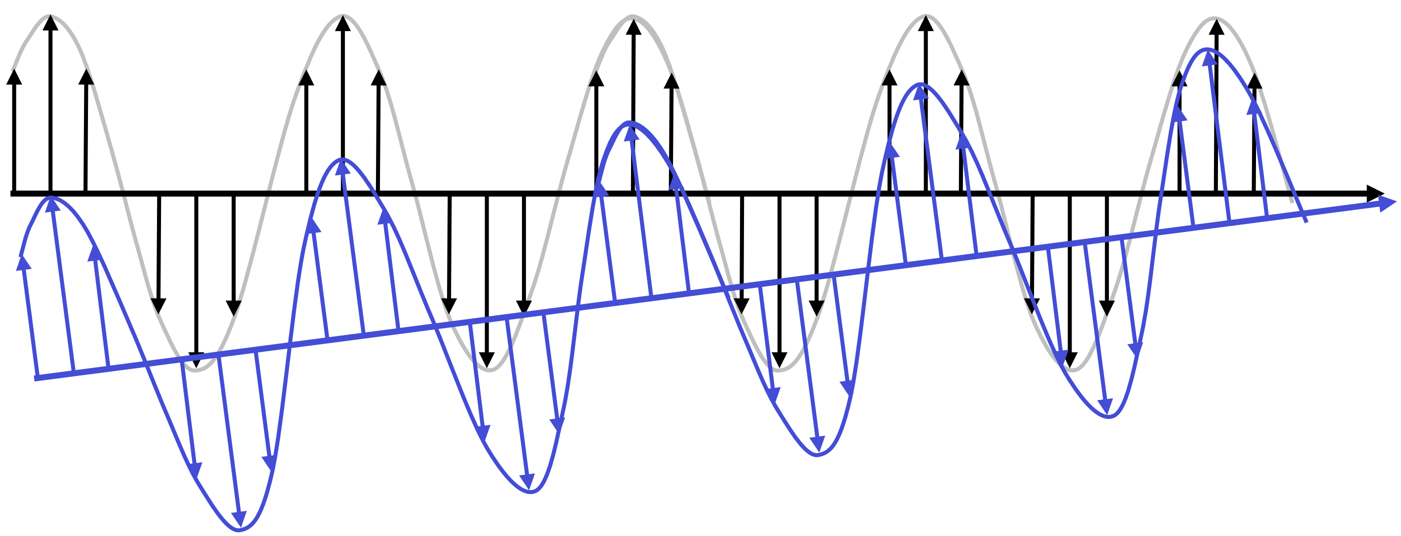
For light waves, the speed in air or vacuum is 3×10^8 meters/sec

inside medium n: $c \rightarrow v = c/n$, $\lambda_n = \lambda/n$ $(n > 1)$

Interference

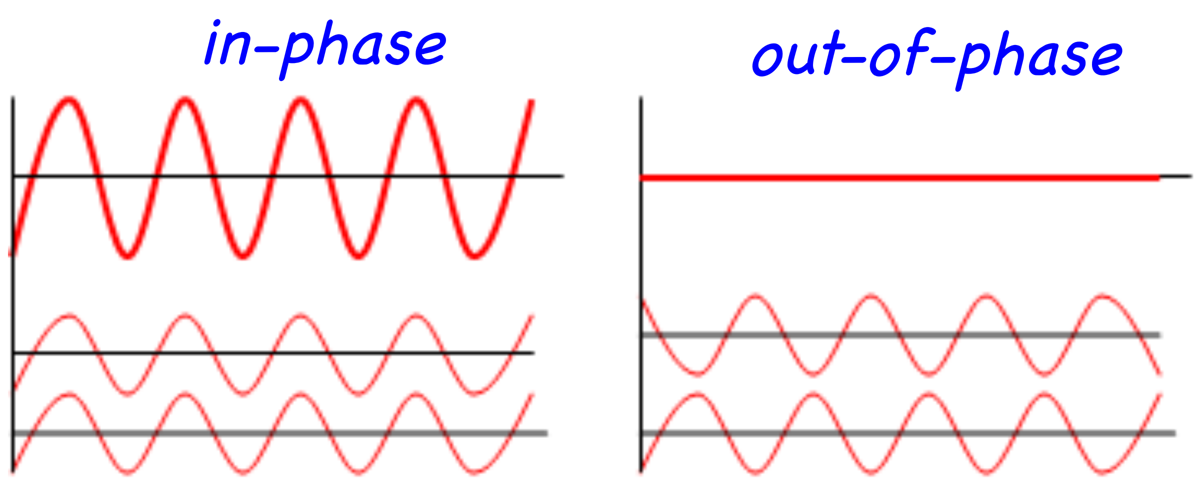
- key wave property: *interference*

- constructive
  destructive



Mathematics of interference (I)

- wave interference: $$\begin{aligned} I_{12} &= \mathcal{E}_{12}^2 = (\mathcal{E}_1 + \mathcal{E}_2)^2 \\ &= \mathcal{E}_1^2 + \mathcal{E}_2^2 + 2\mathcal{E}_1\mathcal{E}_2 \\ &= I_1 + I_2 + 2\mathcal{E}_1\mathcal{E}_2 \neq I_1 + I_2 \end{aligned}$$
  - adding two phase-shifted waves:



constructive interference

destructive interference

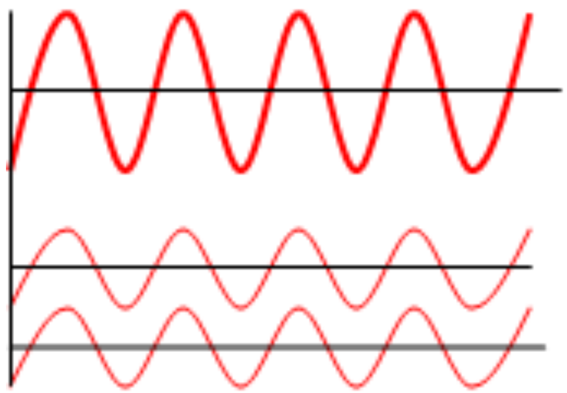
Mathematics of interference (I)

- wave interference: $$I_{12} = \mathcal{E}_{12}^2 = (\mathcal{E}_1 + \mathcal{E}_2)^2 = \mathcal{E}_1^2 + \mathcal{E}_2^2 + 2\mathcal{E}_1\mathcal{E}_2 = I_1 + I_2 + 2\mathcal{E}_1\mathcal{E}_2 \neq I_1 + I_2$$

  - adding two phase-shifted waves:

in-phase

$\mathcal{E}_{12} = 2\cos(kx)$



$\mathcal{E}_1 = \cos(kx)$

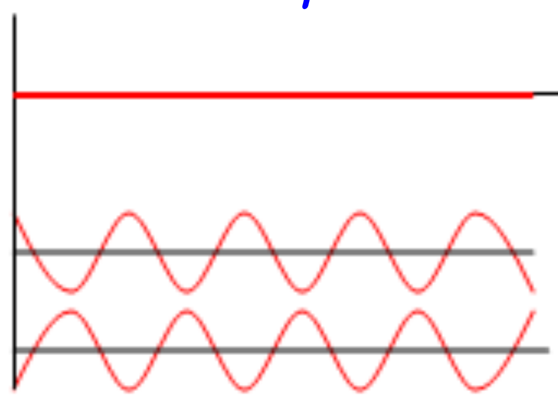
$\mathcal{E}_2 = \cos(kx)$

$$I_{12} = 4\cos^2 kx = \cos^2 kx + \cos^2 kx + 2\cos^2 kx$$

constructive interference

out-of-phase

$\mathcal{E}_{12} = 0$



$\mathcal{E}_1 = \cos(kx + \pi)$

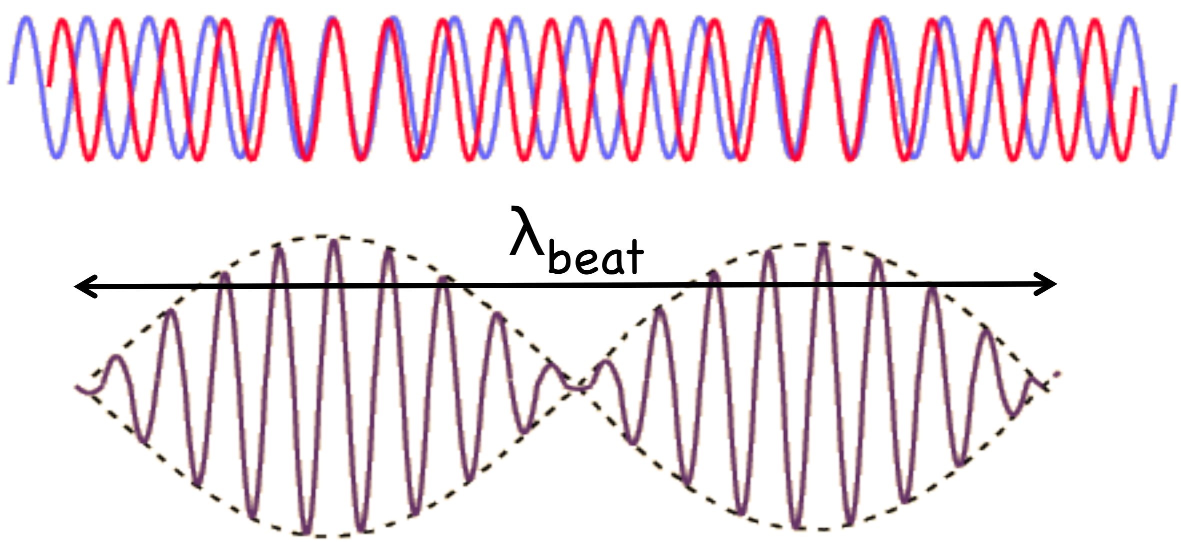
$\mathcal{E}_2 = \cos(kx)$

$$I_{12} = 0 = \cos^2 kx + \cos^2 kx - 2\cos^2 kx$$

destructive interference

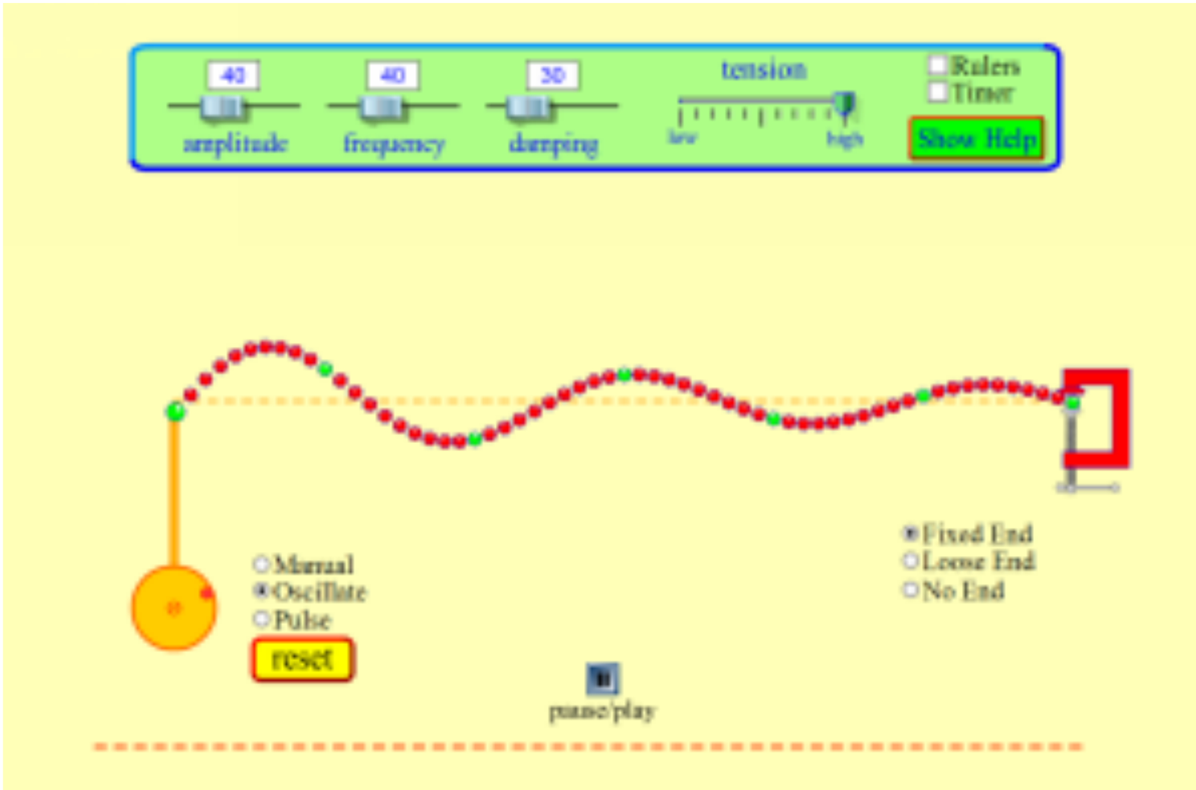
Mathematics of interference (II)

- wave interference: $$I_{12} = \mathcal{E}_{12}^2 = (\mathcal{E}_1 + \mathcal{E}_2)^2 = \mathcal{E}_1^2 + \mathcal{E}_2^2 + 2\mathcal{E}_1\mathcal{E}_2 = I_1 + I_2 + 2\mathcal{E}_1\mathcal{E}_2 \neq I_1 + I_2$$
  - adding two different wavelengths, λ_1, λ_2 waves:



beating phenomena (tuning piano, FM modulation,...)

Phet simulations

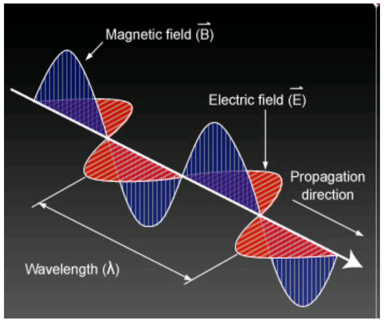


http://phet.colorado.edu/sims/wave-on-a-string/wave-on-a-string_en.html

Electromagnetic radiation and speed of light

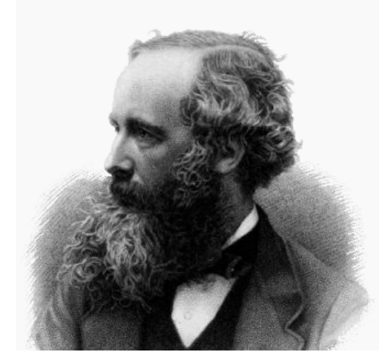
E&M waves:

$$\partial_t^2 \mathbf{E} - c^2 \partial_x^2 \mathbf{E} = 0$$

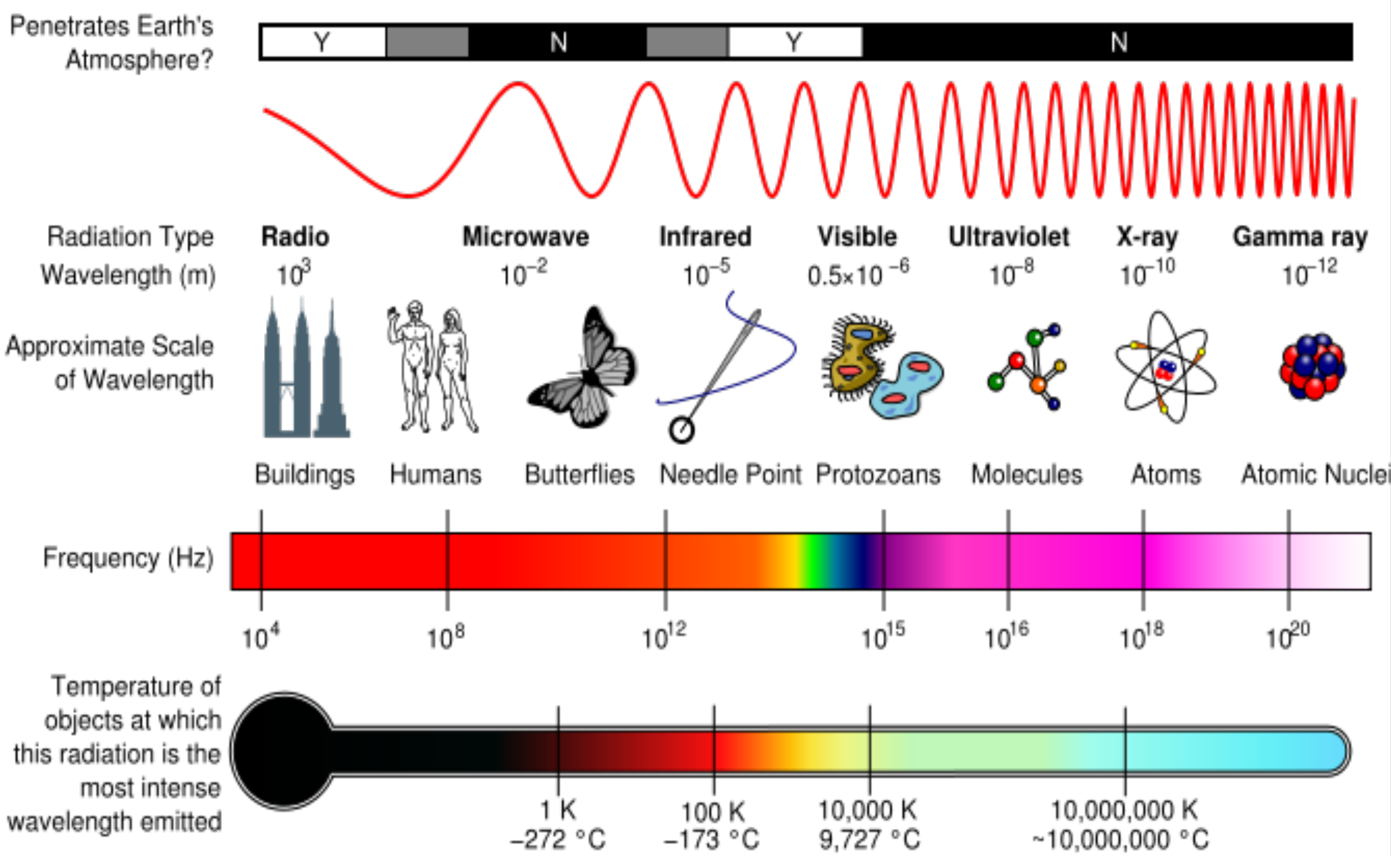


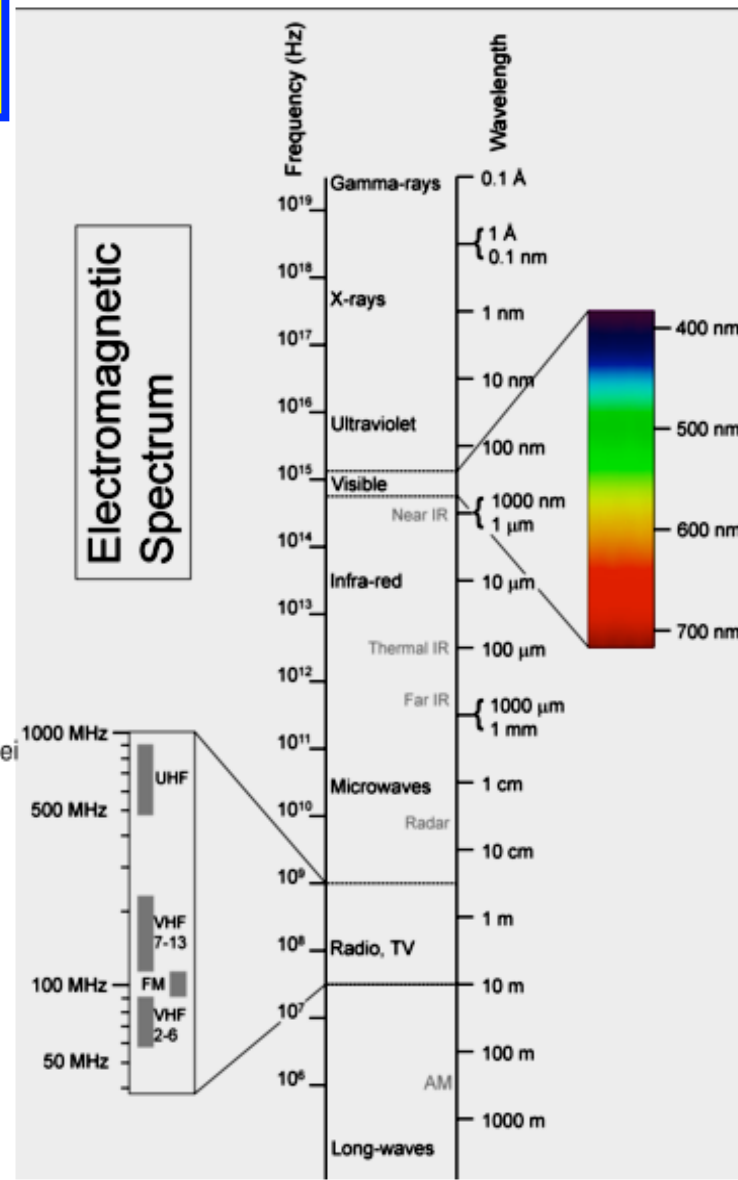
oscillating E and B fields

c = 300,000 km/s
= 186,000 mi/s
= 3 x 10^8 m/s
≈ 1 ft/nanosec



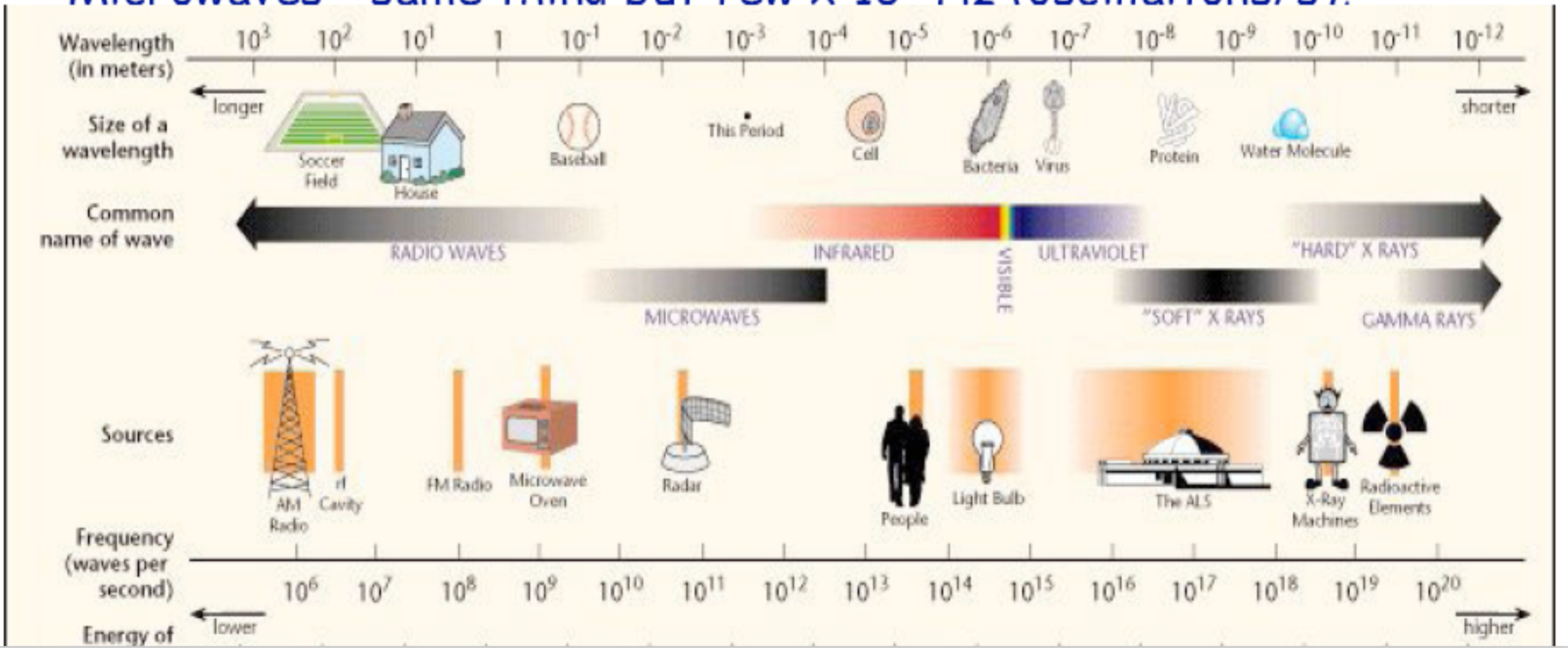
James Clerk Maxwell
1831-1879





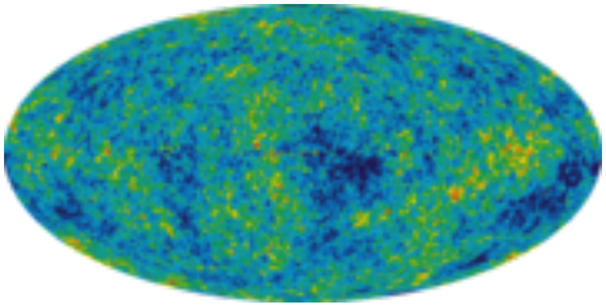
Electromagnetic waves critical to life as we know it!

- Communications – radio, TV, cell phones, portable phones
- Food prep - microwaves
- Vision – visible light
- AM radio 530 to 1600 kHz.
- FM is 88 to 108 MHz.
- TV is 54-206 MHz (each station gets 6 MHz band (Station 1, 54-60 MHz))
- Microwaves - same thing but few x 10^9 Hz (oscillaitons/s).

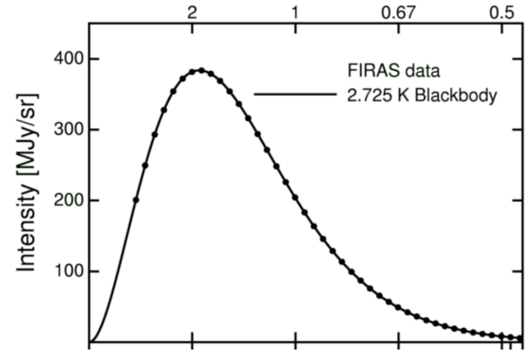


Blackbody radiation

- "black" body radiates: *hot oven, poker, Sun, glowing coal, CMB,...*

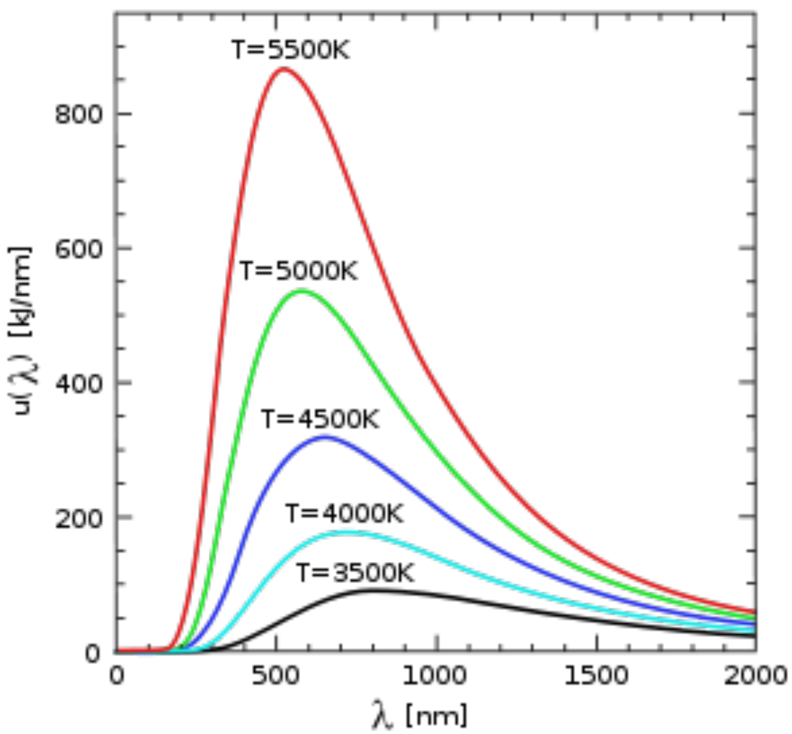


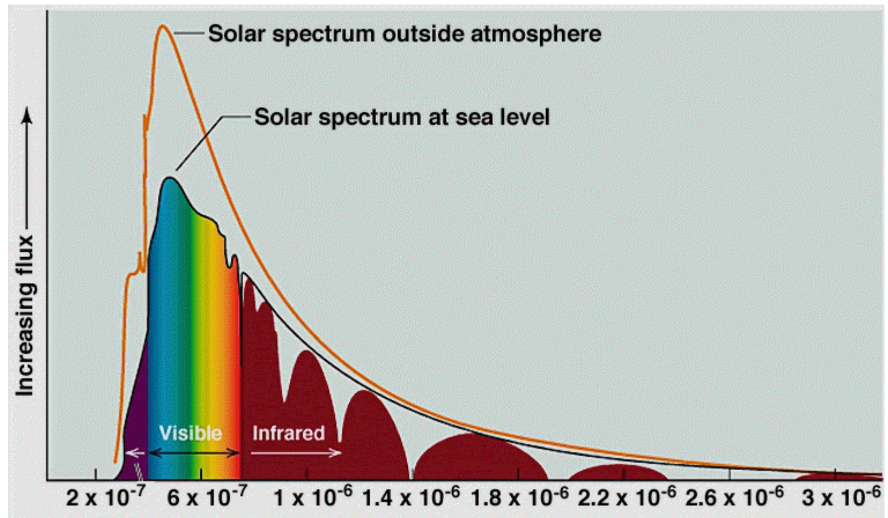
$\lambda T = 3\times10^{-3}$

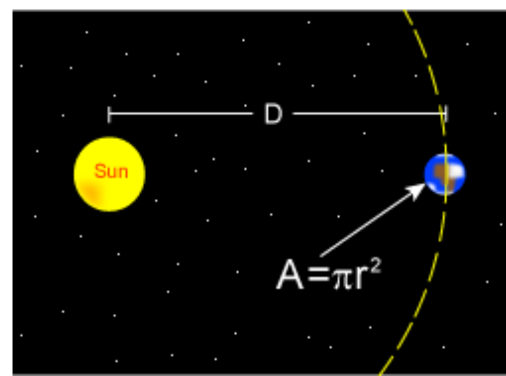


T_{CMB} = 3K, Big Bang, 13.3 billion years ago, cooled from 3000K

- independent of material, just T: *shorter λ higher T*





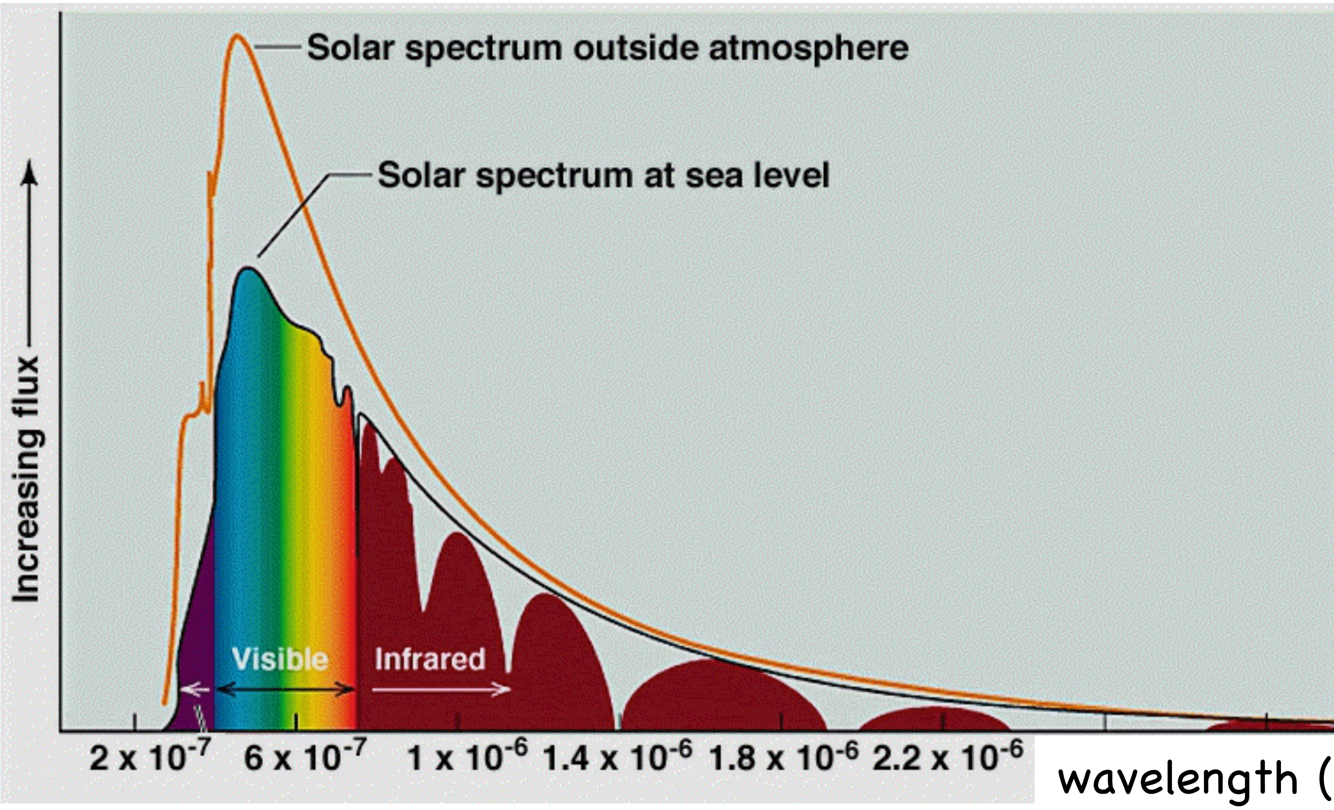


- determines Earth's average temperature: 100 W/ft^2

clicker question

Blackbody radiation of the Sun

Q: *The Sun is approximately a blackbody radiator as can be seen from its emitted spectrum below. Estimate Sun's T from its spectrum below*



wavelength (meters)

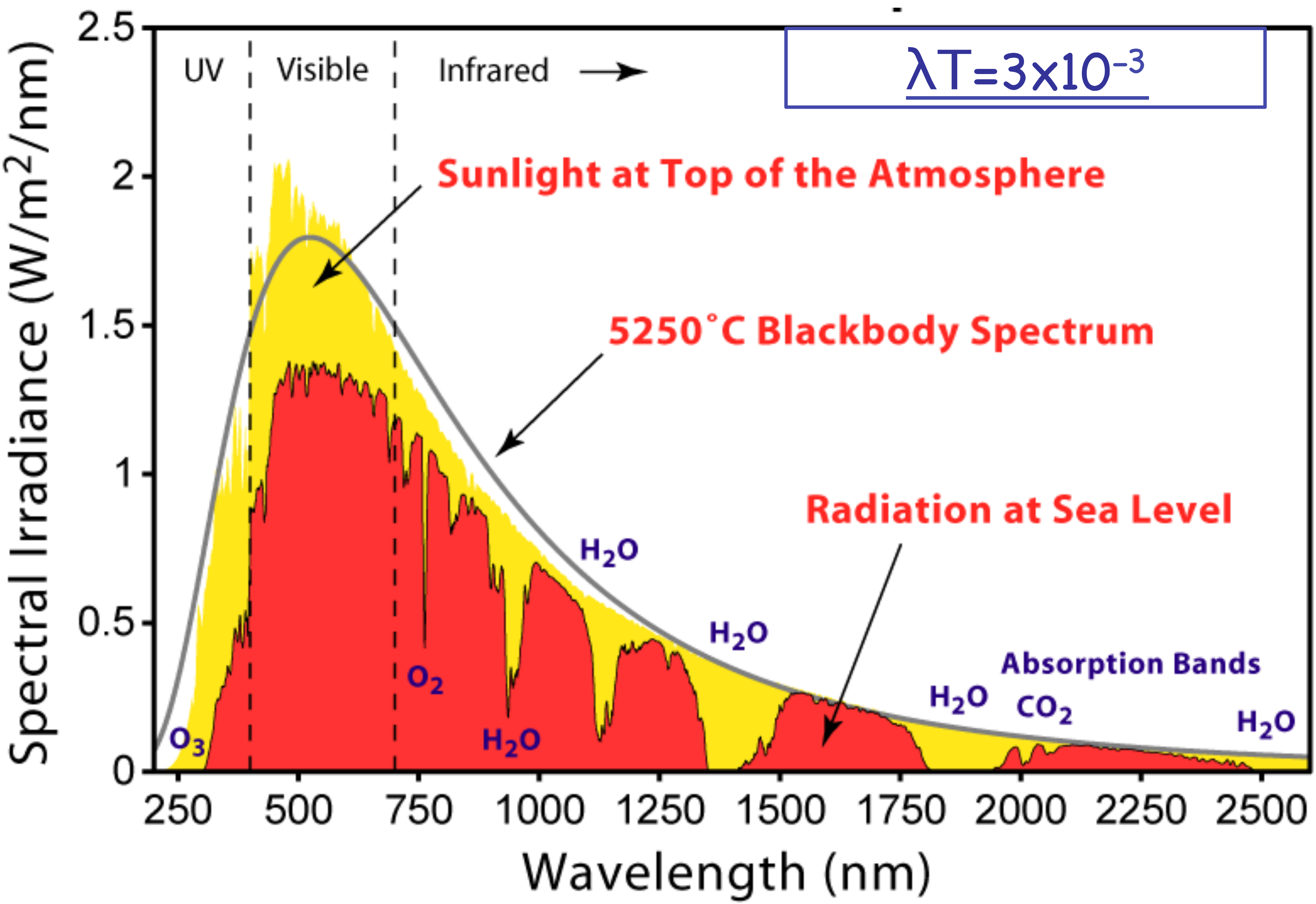
$\lambda T = 3\times10^{-3}$

a) 100 K, b) 10^{10} C, c) 5000 K, d) 2 trillion degrees

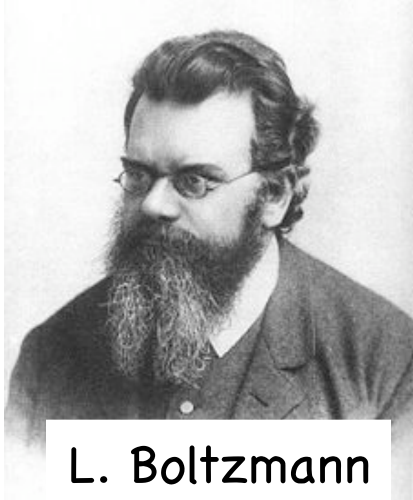
A: *The peak is roughly at around 6×10^{-7} m, which using $\lambda T=3\times10^{-3}$ -> $T_{sun} \approx 5000$ Kelvin*

Solar radiation spectrum

100 Watts/ft²

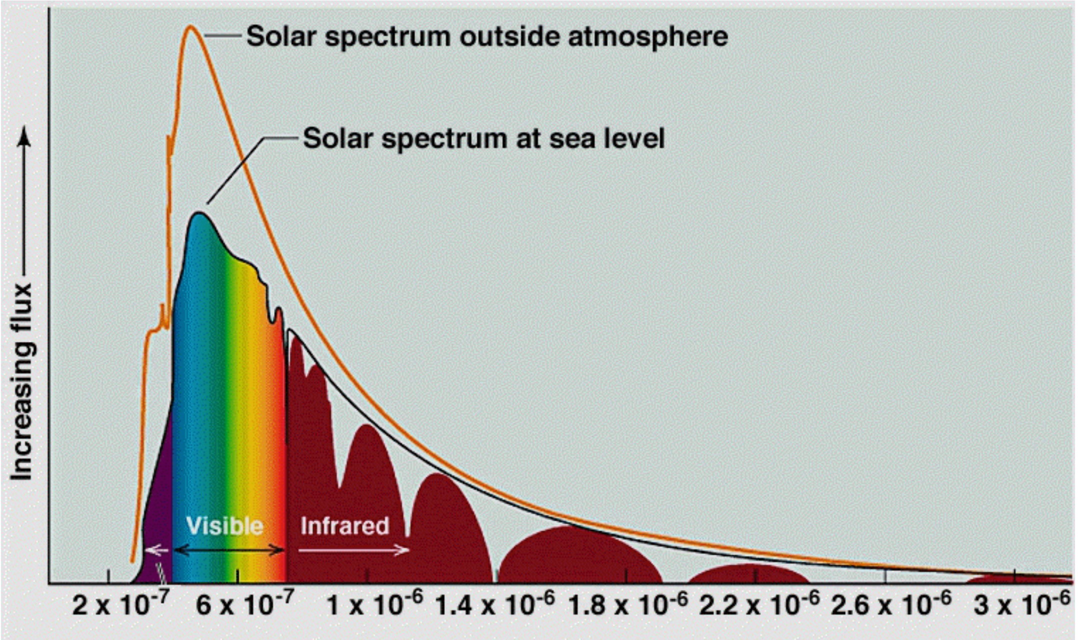


Temperature - energy



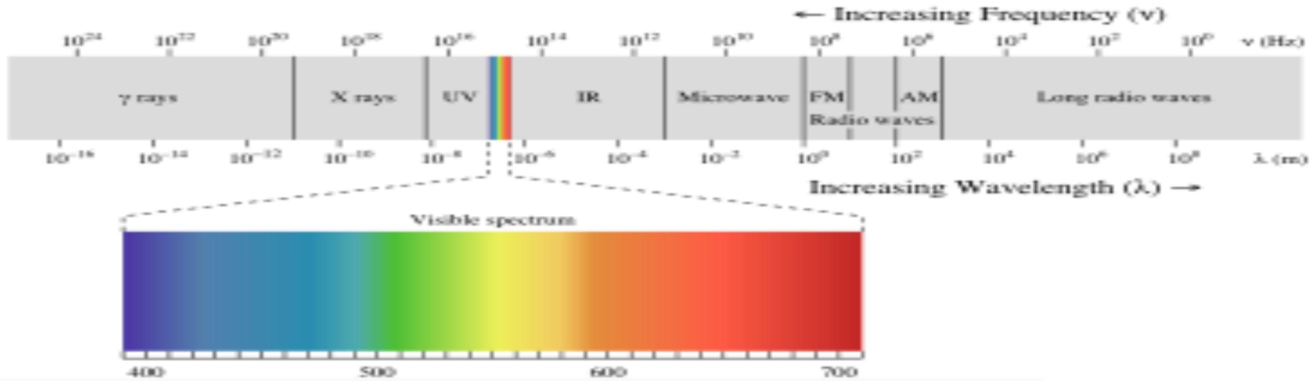
L. Boltzmann
1844-1906

- Thermal energy = k_BT
- Boltzmann constant $k_B = 1.38 \times 10^{-23}$ J/K $= 8.6 \times 10^{-5}$ eV/K
- 1 eV = 12000 Kelvin



$$k_BT \approx E_{peak}/3$$

What we see: eye is a band-pass filter



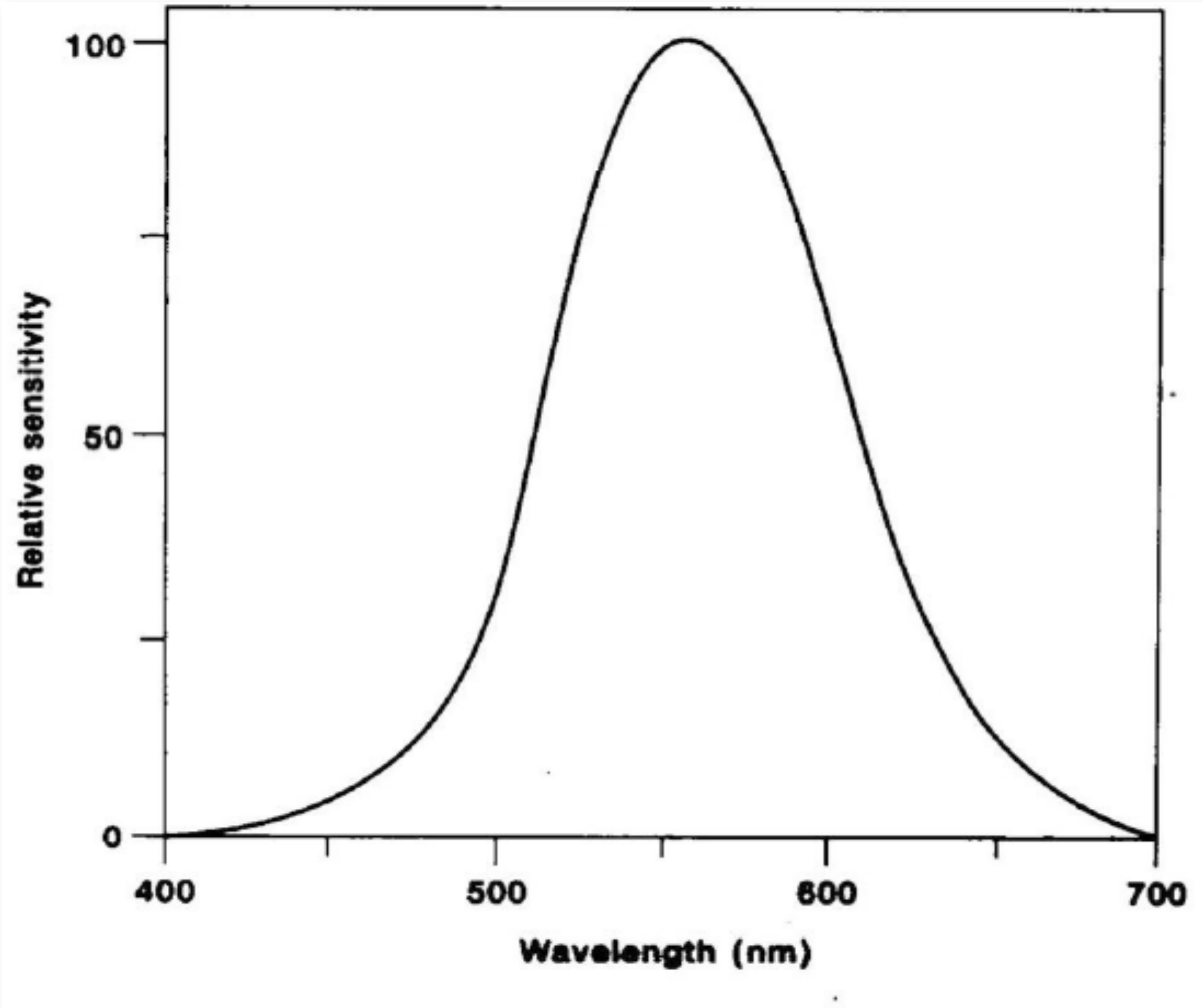
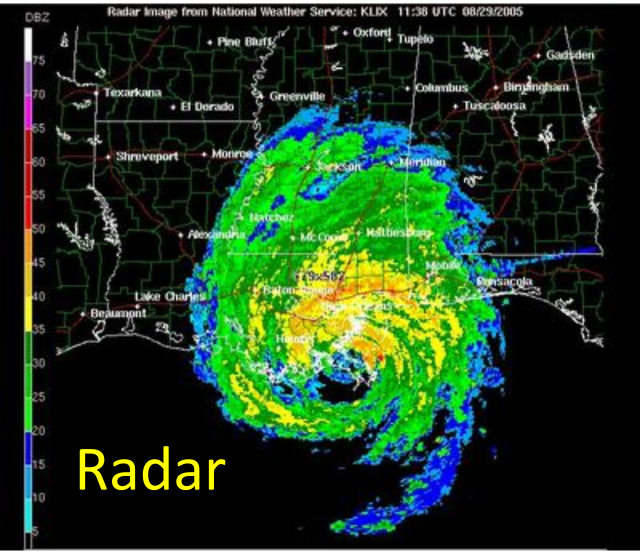
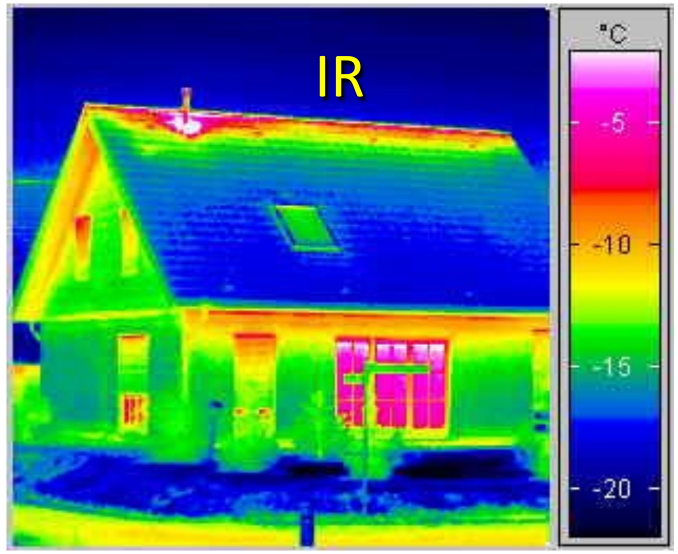
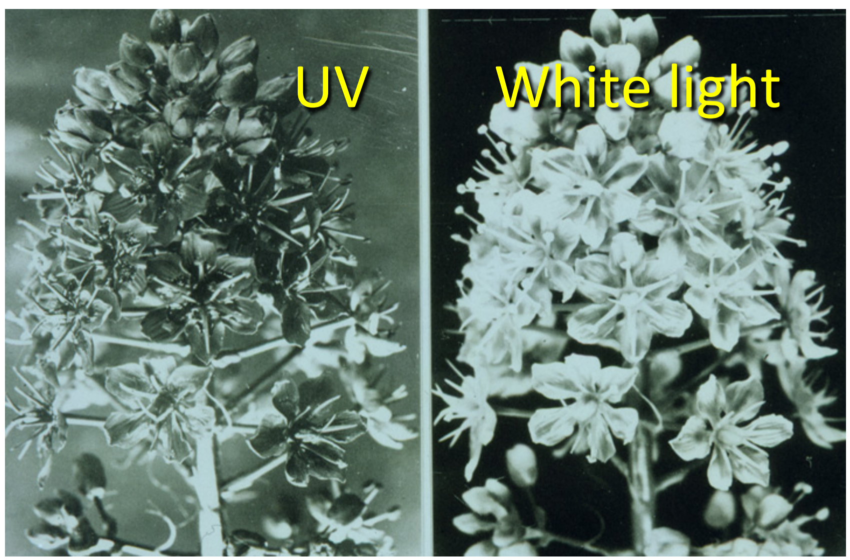


FIGURE 2-3. Sensitivity of the human eye to visible light.

Images at different frequencies

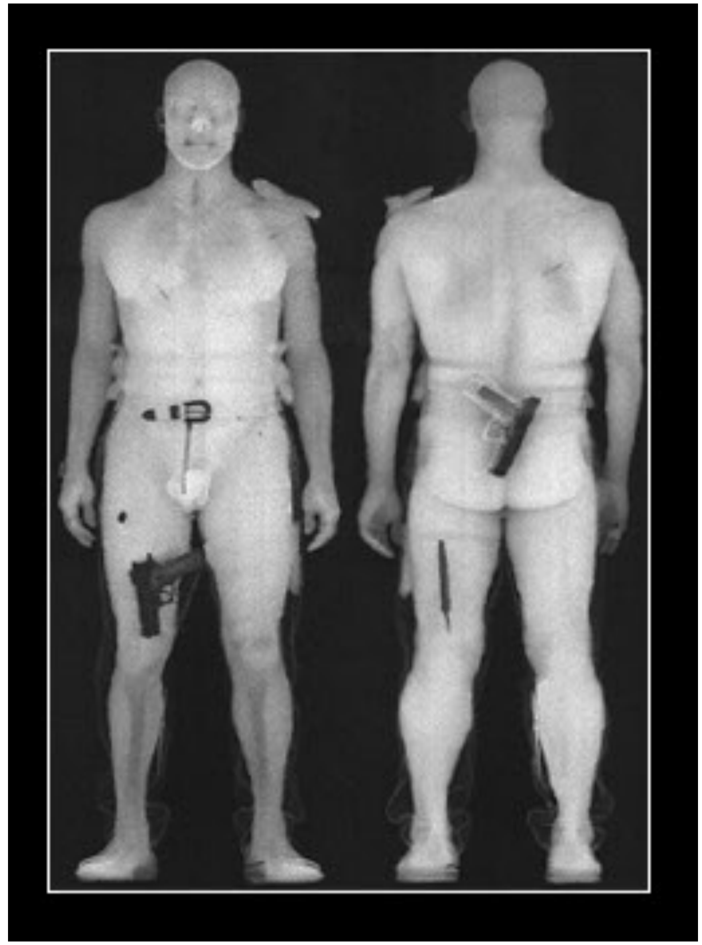






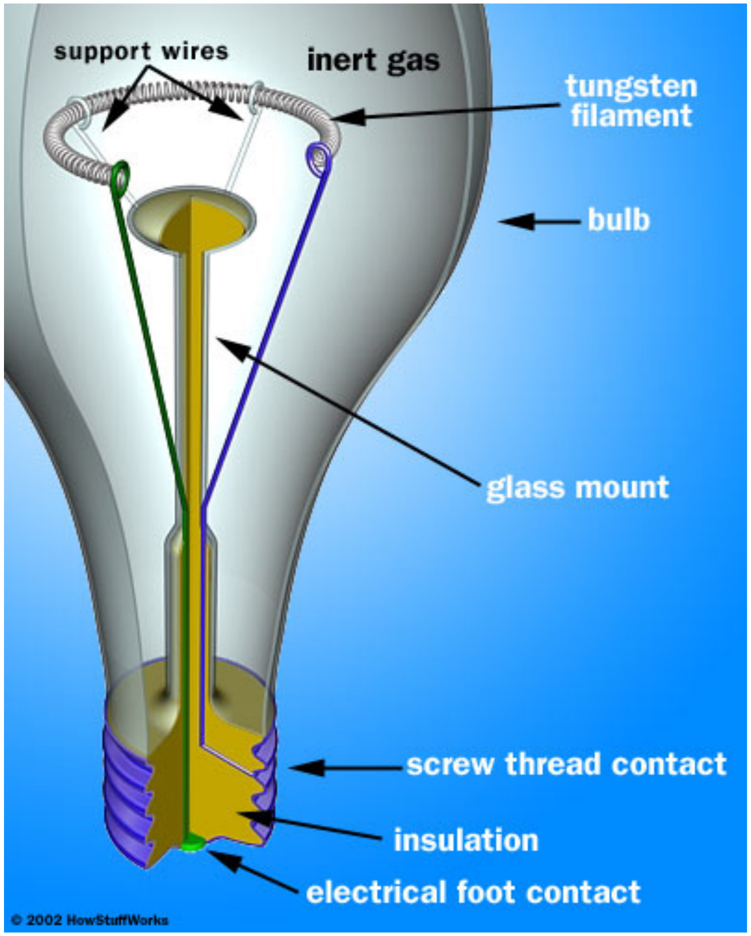
Images at different frequencies

Millimeter Wave Scanning

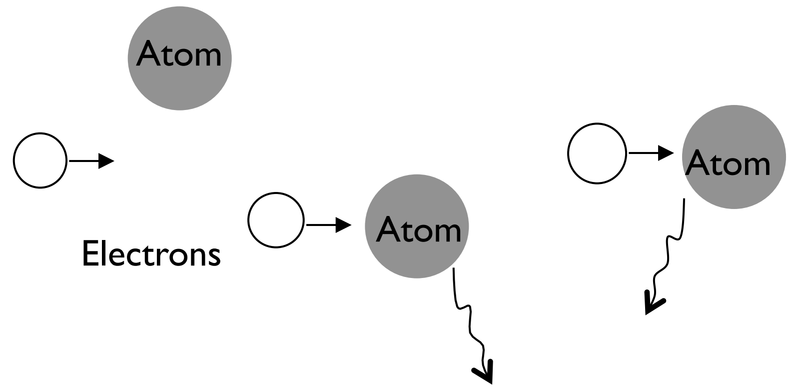


Incandescent light bulbs

Incandescent light bulbs

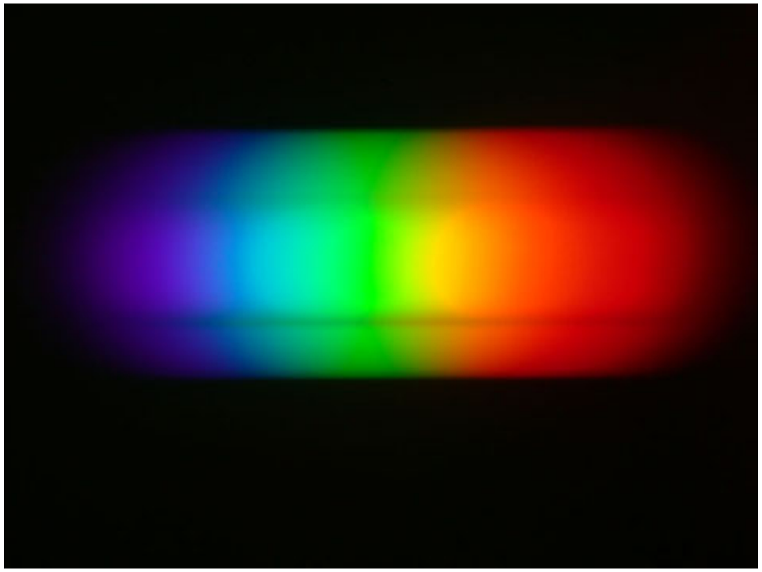


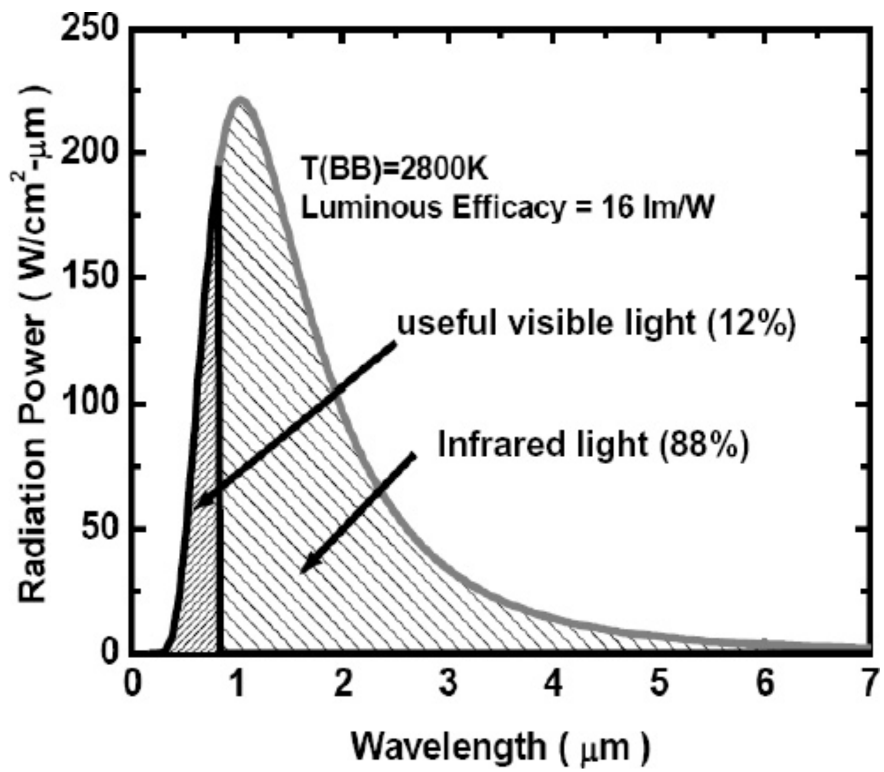
Filament with *current* of electrons which hit into atoms causing light to be emitted



Light emitted at many different **resonance** frequencies of atoms appears as white light

Incandescent light bulbs





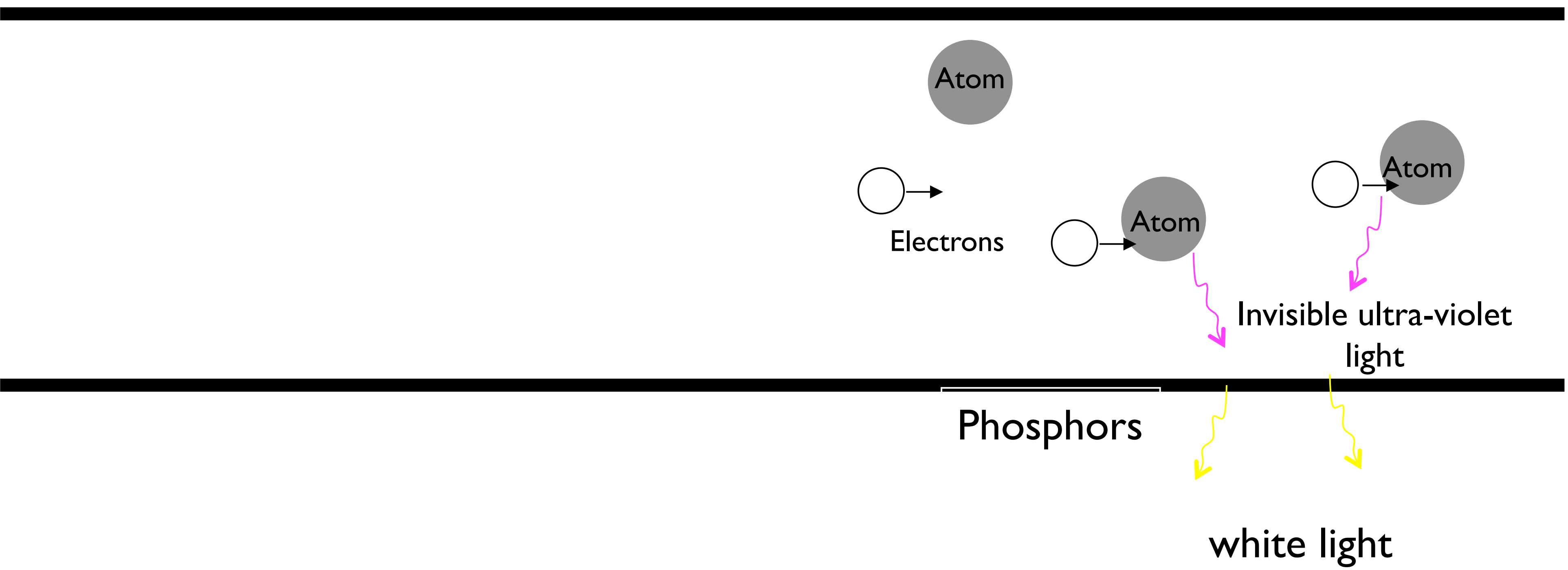
- A *continuous* light source
- Almost 90% of its emission is invisible to the human eye, producing heat and wasting energy

Fluorescent light bulbs

Fluorescent bulbs have a lower current and power usage for the same light output in the visible range. How do they do this?

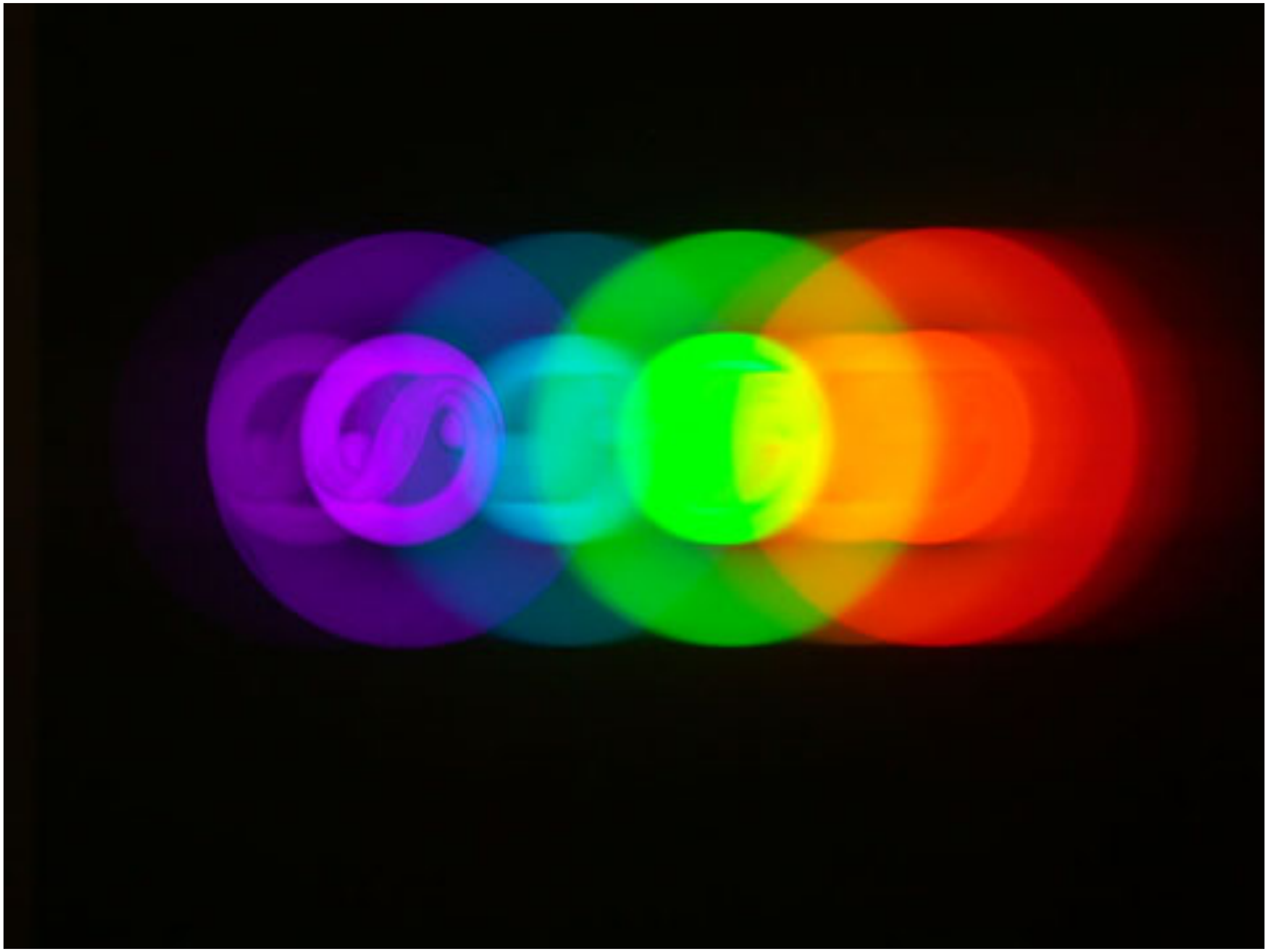
Fluorescent light bulbs

The atoms inside a fluorescent bulb have *ultraviolet* resonant frequencies



Fluorescent light bulbs

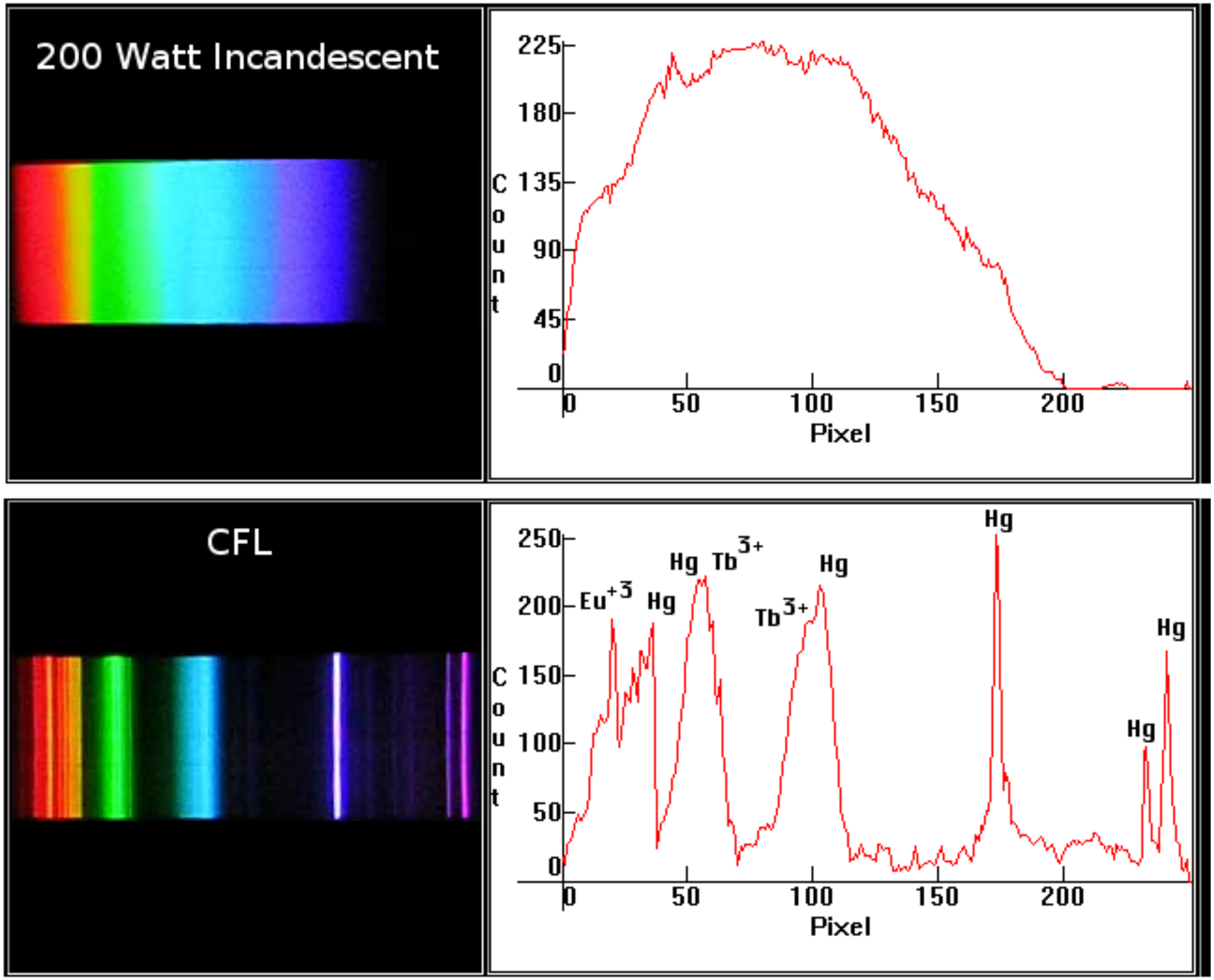
Because the phosphors emit at very specific resonant frequencies, the spectrum is not continuous



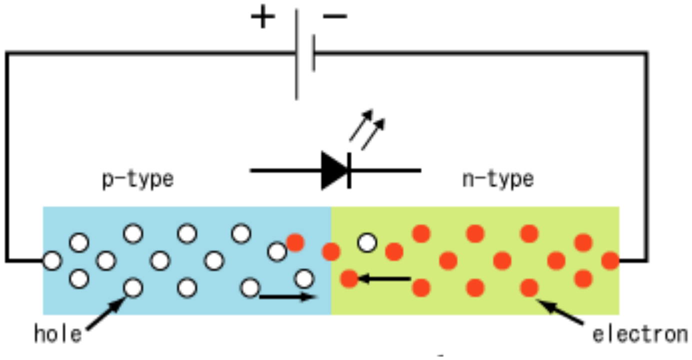
Fluorescent light bulbs: neon lights

Produced the same way, but with a different set of atoms in the tube to produce the different colors

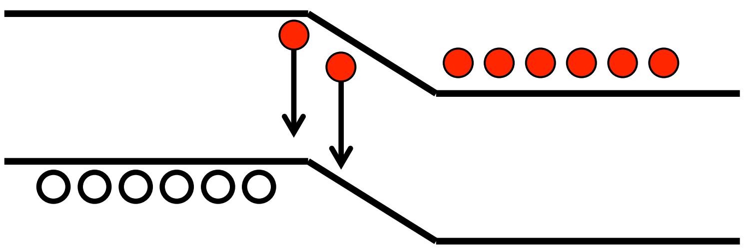
Incandescent vs fluorescent light bulbs



Light emitting diodes (LEDs)

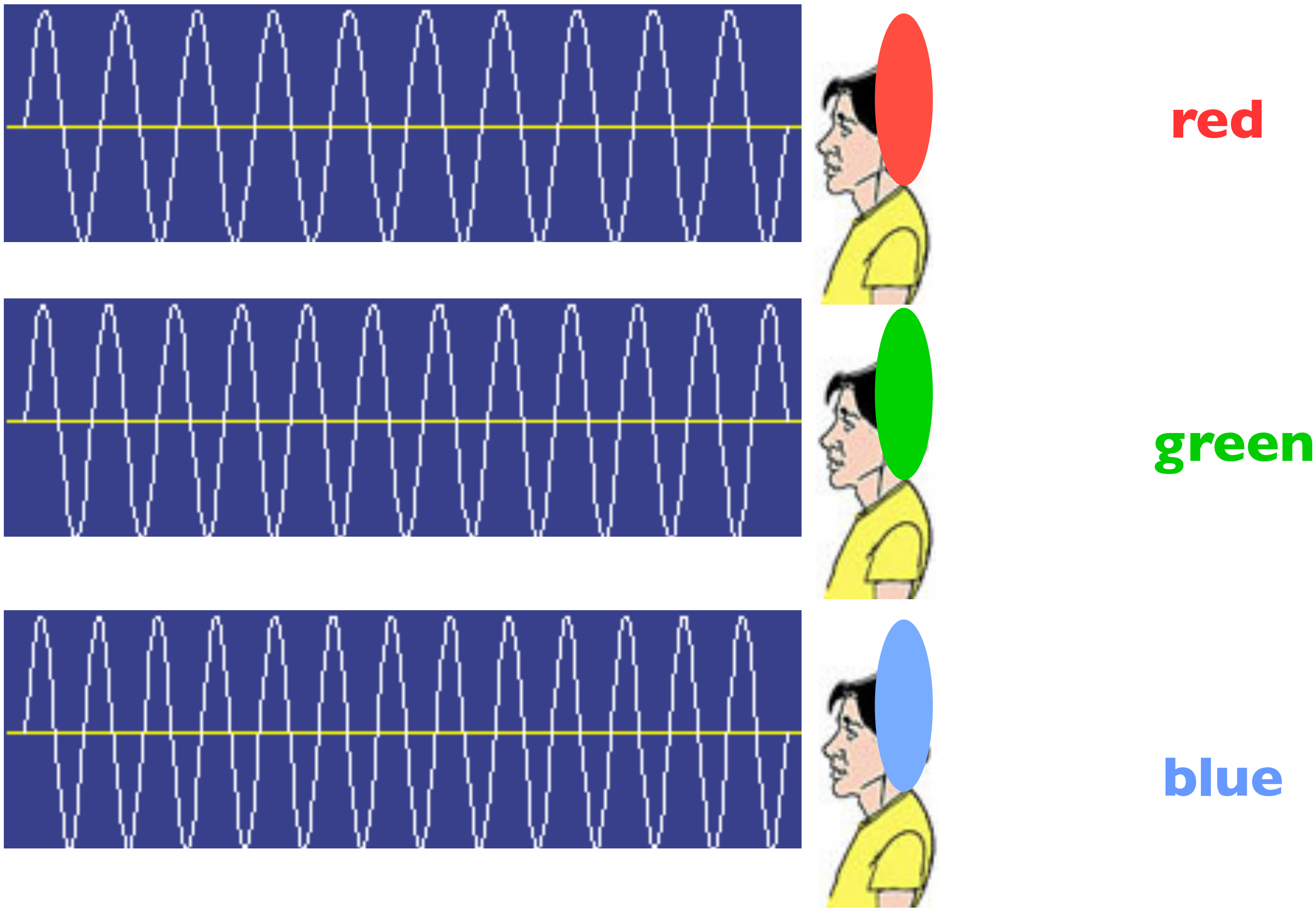


- A semiconductor system
- Charges are initially separated
- An applied current pushes them "up the hill", where they can recombine and emit light



What is color?

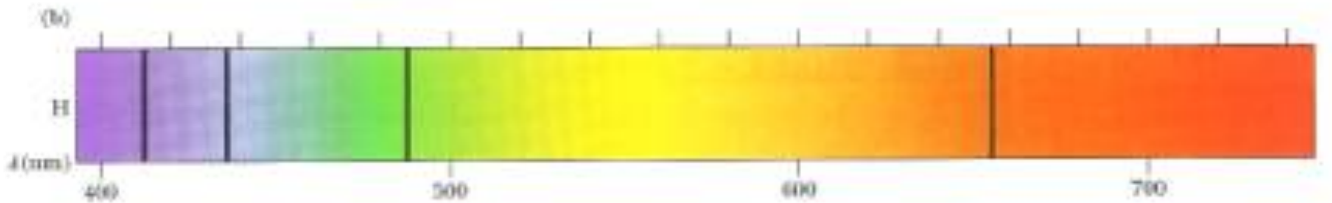
Color is our brain's interpretation of light of different wavelengths/frequencies entering our eyes



The speed of light in <u>empty</u> space is the *same* for all wavelengths

Atomic spectra

- observed emission/absorption spectra for Hydrogen:



- Balmer-Rydberg formula (n′ -> n=2):

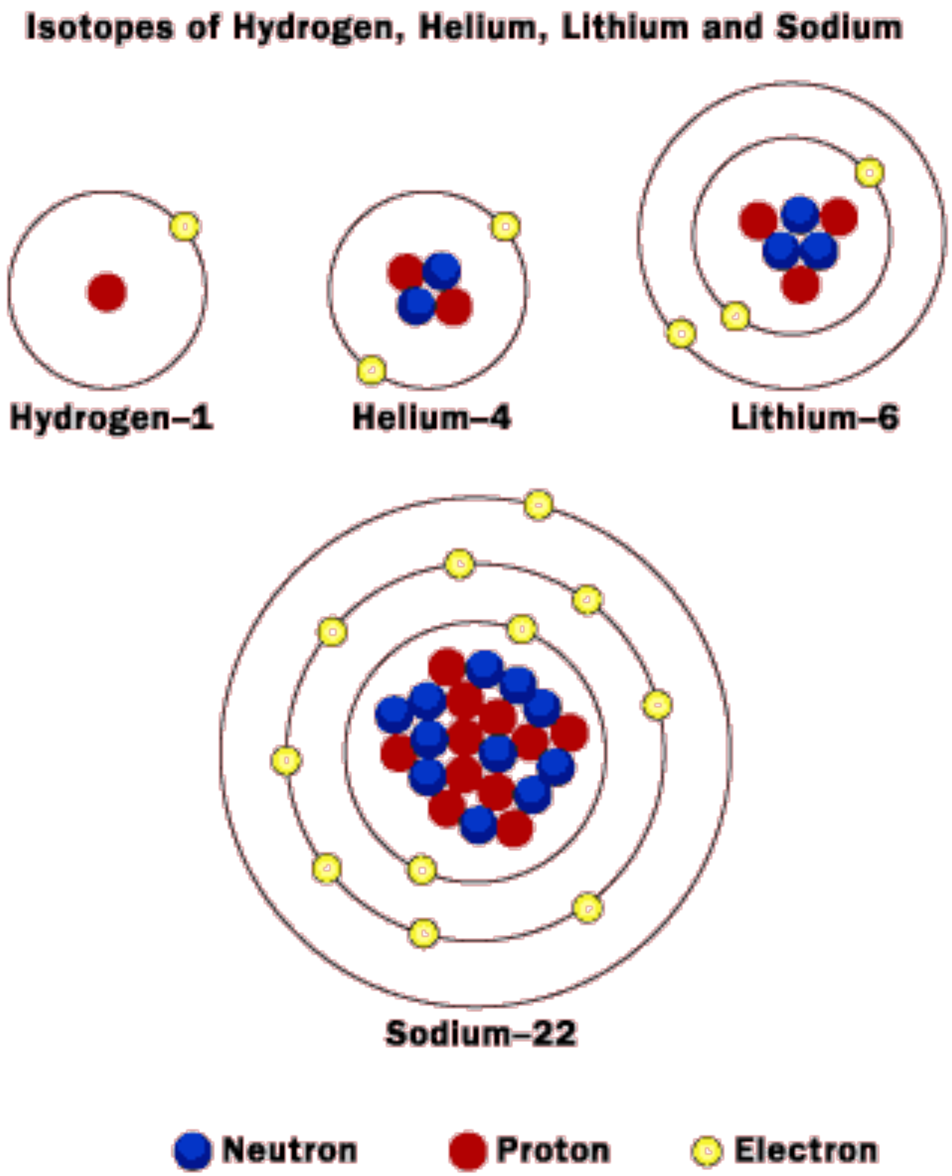
$$\frac{1}{\lambda} = R\left(\frac{1}{n'^2} - \frac{1}{n^2}\right), \quad n > n', \text{both integers}$$

Rydberg constant R = 0.001 Å^{-1}

light emission due to de-excitation from n′ -> n=2

Bohr-Rutherford's picture of atoms

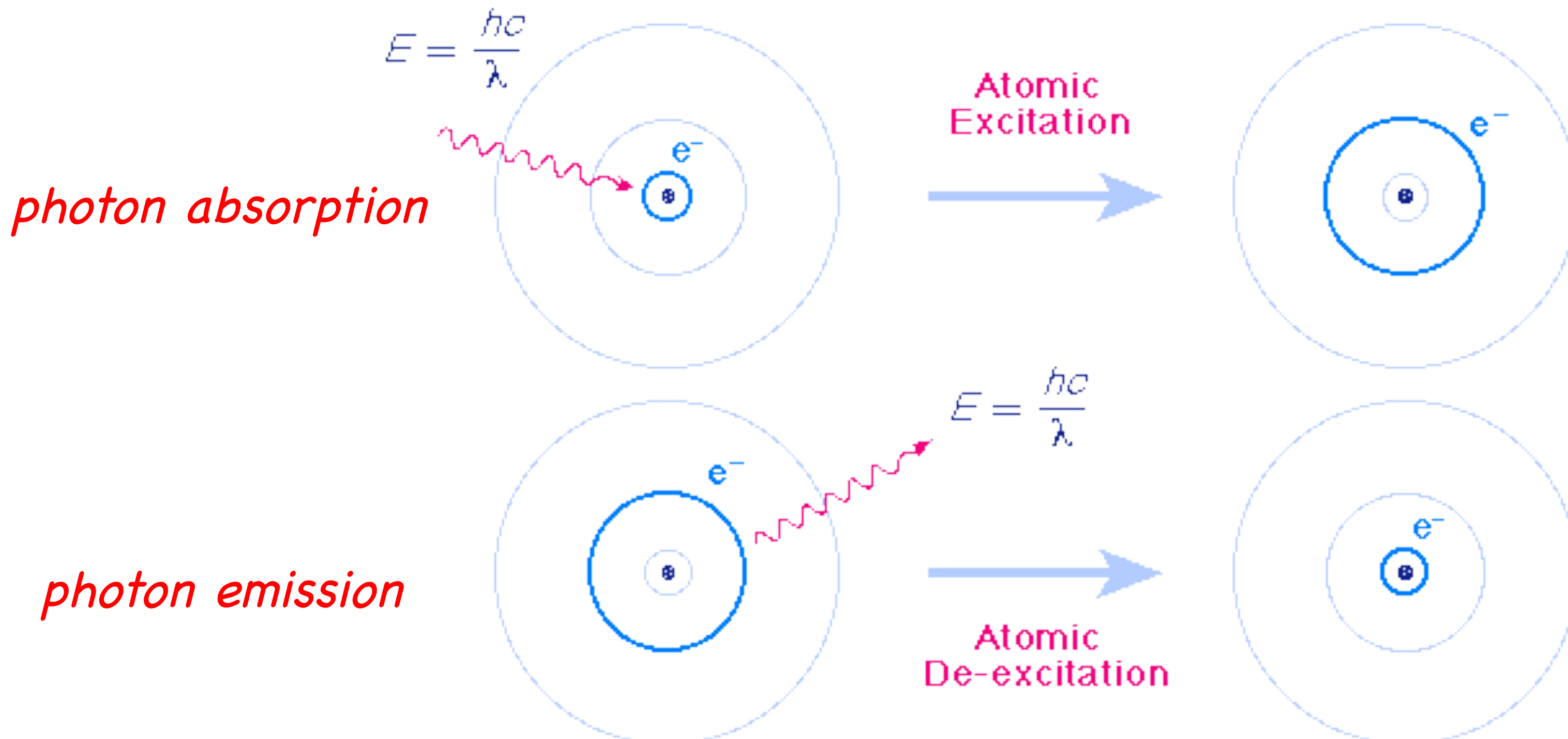
- planetary semi-classical model (1913) inspired by Rutherford's scattering



Niels Bohr
1885-1962

Bohr's picture of atomic emission/absorption (1)

- electron's discrete transition between a set of allowed "orbits":

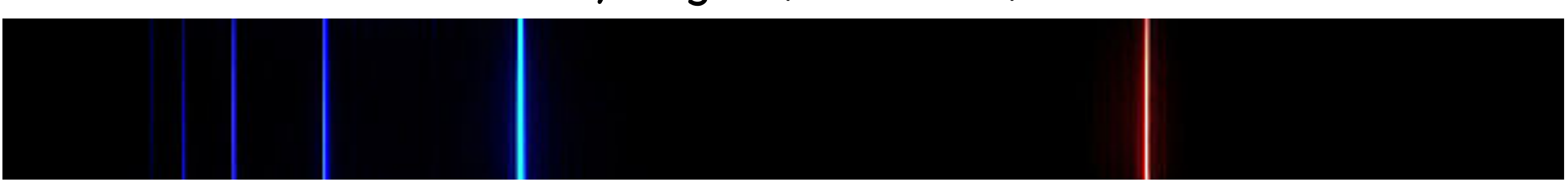


- energies of emitted/absorbed photon:

$$\frac{1}{\lambda} = R\left(\frac{1}{n'^2} - \frac{1}{n^2}\right), \quad n > n', \text{both integers}$$

Rydberg constant R = 0.001 Å^{-1}

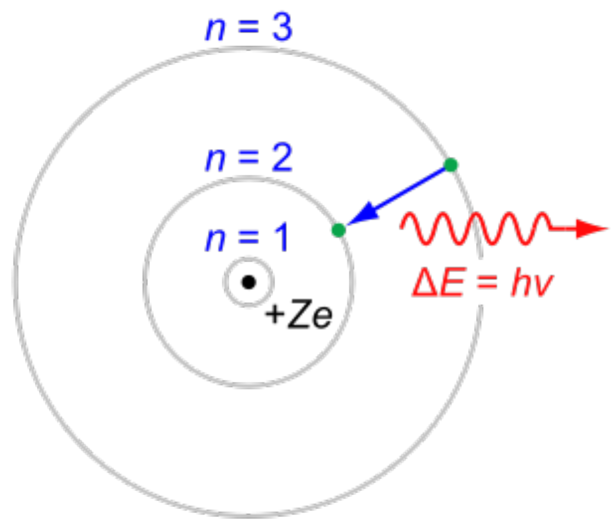
Balmer series of Hydrogen (n' -> n = 2):

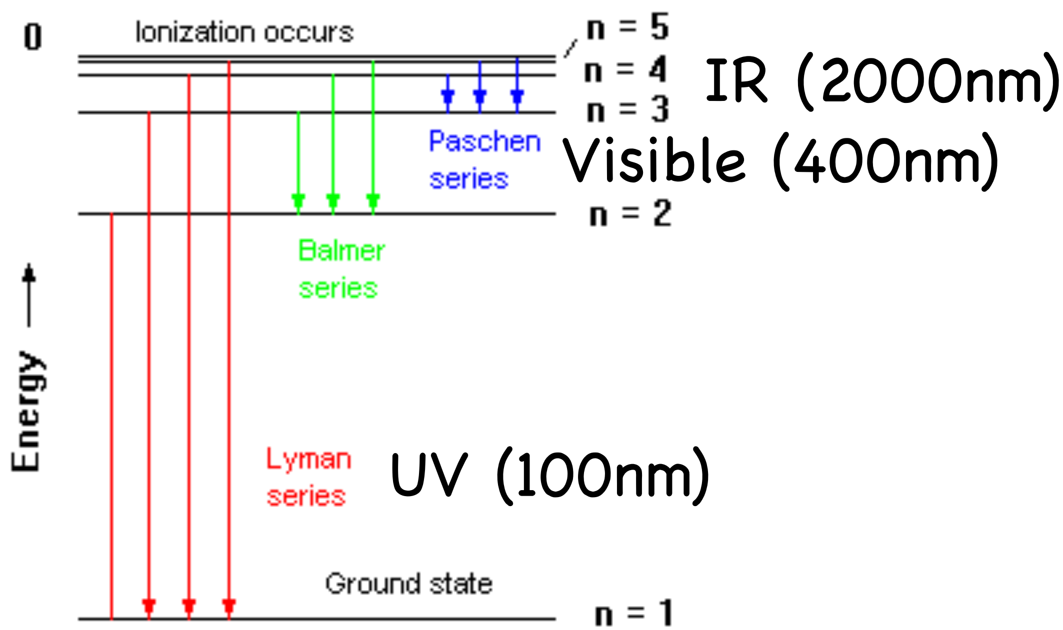


Bohr's picture of atomic emission/absorption (2)

- electron's discrete transition between a set of allowed "orbits":

$$\Delta E_{n,n'} = hcR\left(\frac{1}{n'^2} - \frac{1}{n^2}\right)$$





Balmer series of Hydrogen (n' -> n=2 transitions):