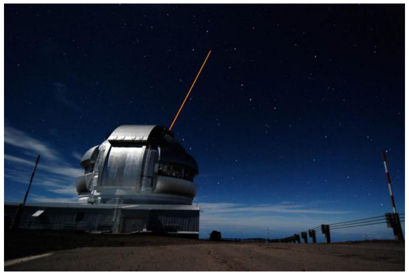
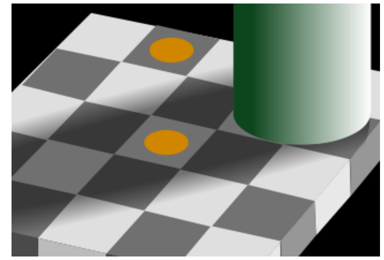
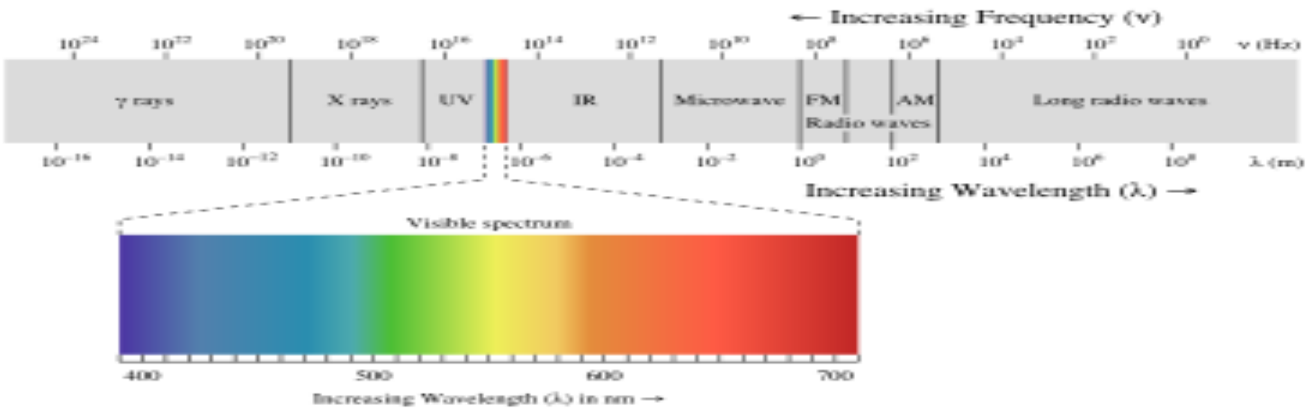
Physics 1230: Light and Color



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

clicker question

Light vs EM radiation

Q: *What is the relation of light and EM radiation*

a) Light and EM radiation are the same thing

b) Light is EM radiation in a frequency range that human eye can see, from 400nm – 700nm

c) They have nothing to do with each other

A:

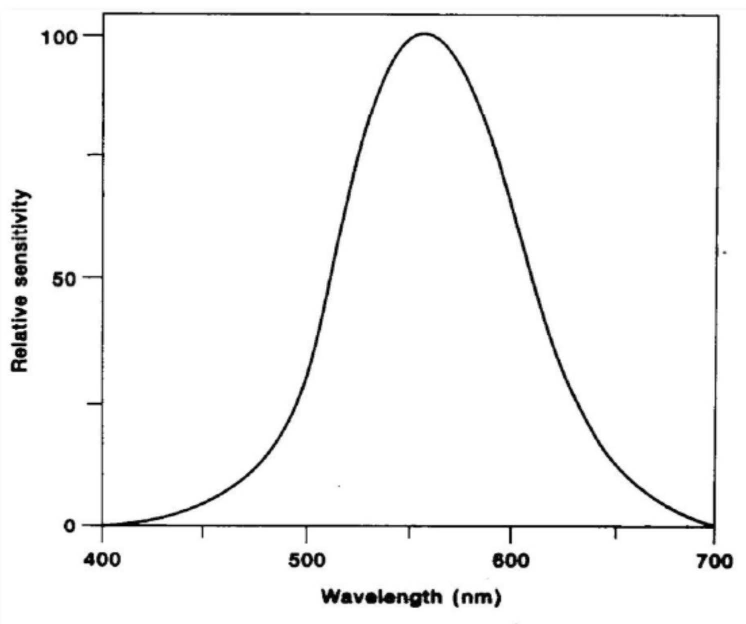
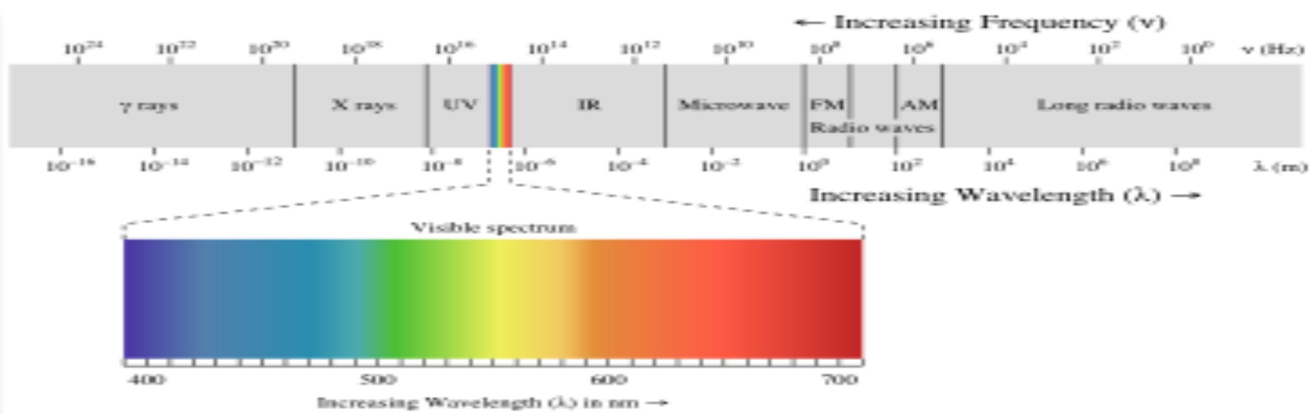


FIGURE 2-3. Sensitivity of the human eye to visible light.



clicker question

Interference

Q: *When two identical waves with intensity, I, added in-phase, what is the intensity?*

a) the same, I
b) double, 2I
c) 4 times as big, 4I

A: *The amplitude is twice as big, but the intensity (which is a square of the amplitude,* $I_{tot} = E_{tot}^2 = (2E)^2 = 4E^2 = 4I$

Light propagation: ray optics

Announcements:

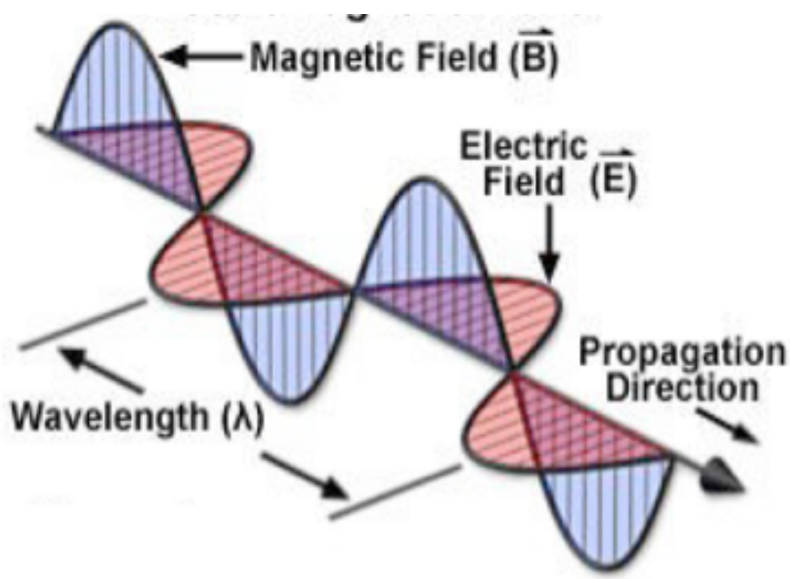
- lecture 3 is posted on the class website
- homework 3 is posted on D2L
  - due Tuesday, Feb 5 in homework box in Help Room
  - solutions will be posted on D2L
- reading for this week is:
  - Ch. 2 in SL
- remember to bring your clicker to every class
  - register it (once)
  - set it to frequency BA

Last Time

recall lecture 3:

Fundamentals of EM waves

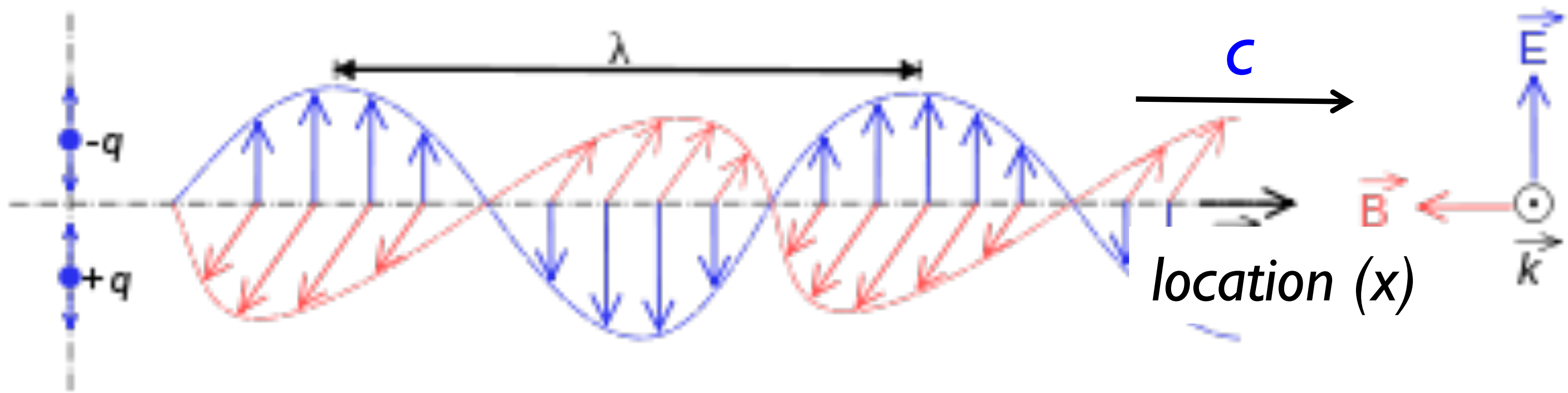
- EM waves in vacuum
- properties of light: wavelength, frequency, speed,...
- electromagnetic spectrum
- blackbody radiation
- color
- quantum picture of light: photons



Recall

Properties of EM waves

snap shot
(fixed t)



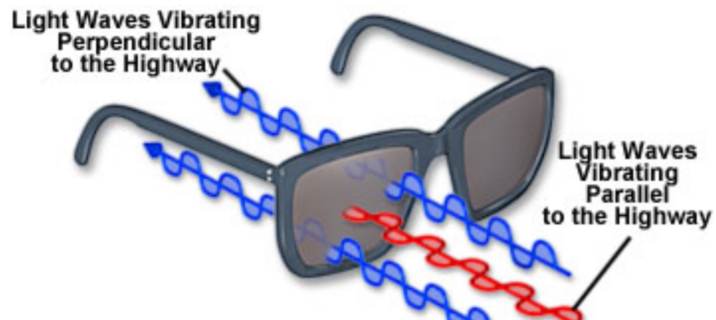
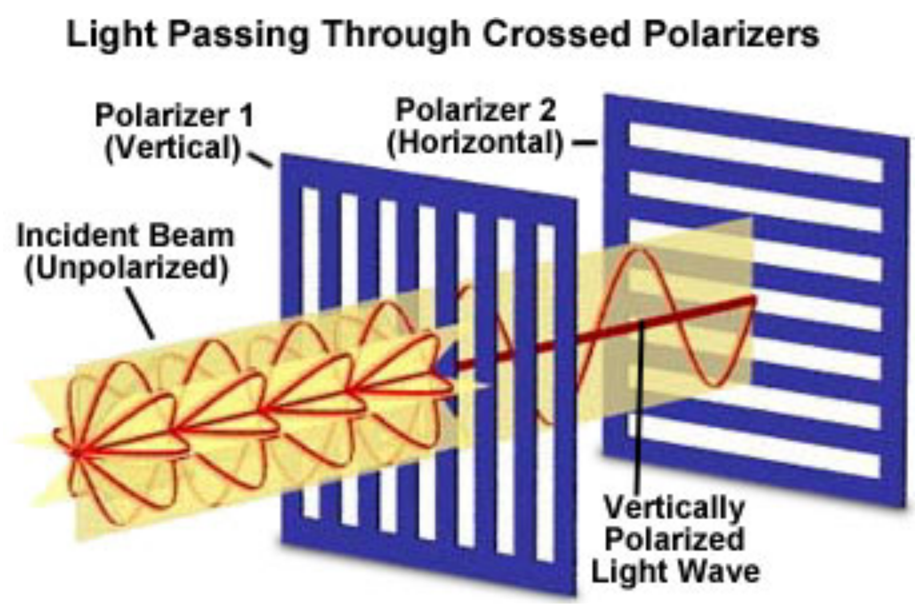


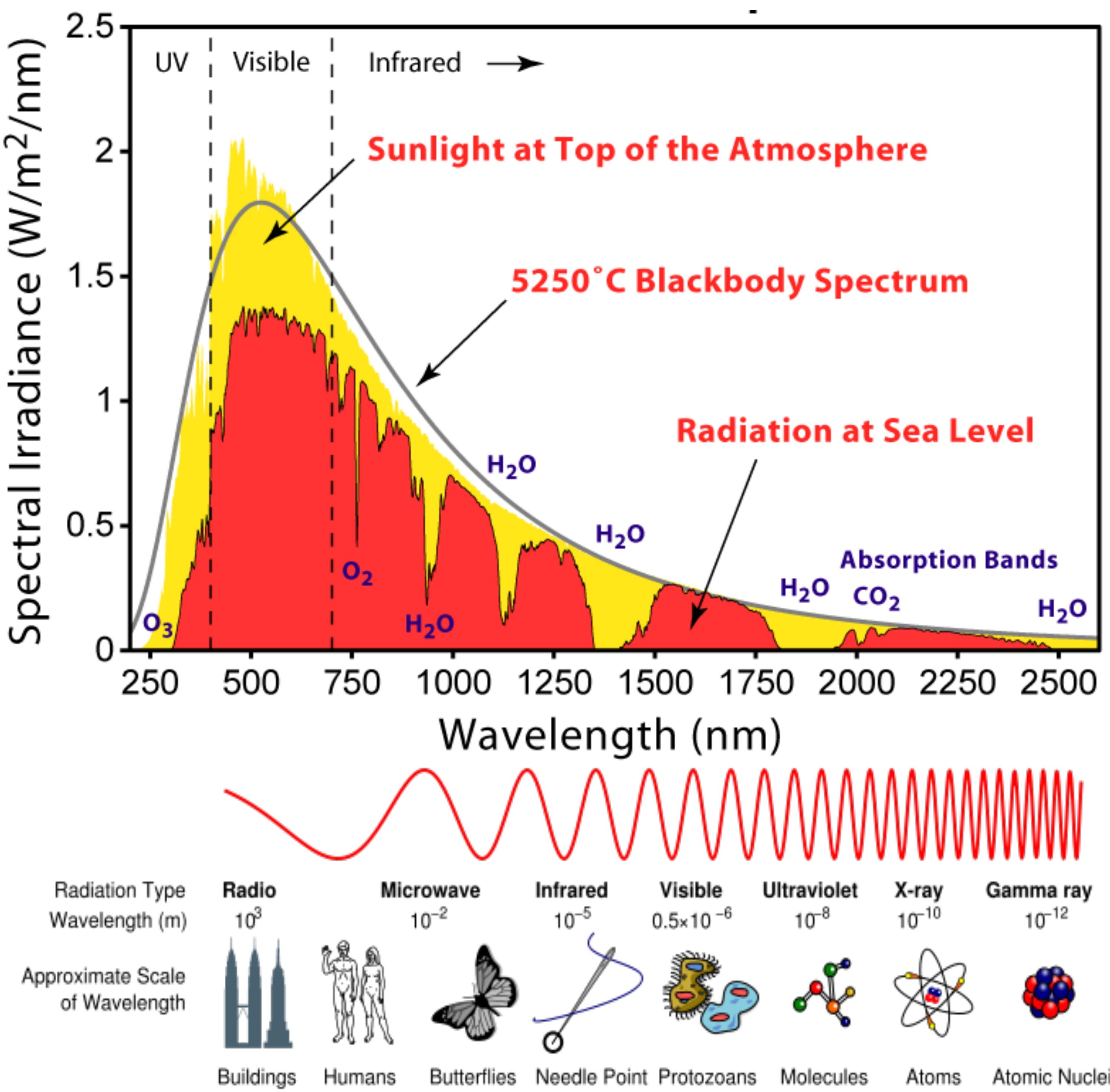
Figure 2

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



Recall

Solar radiation spectrum



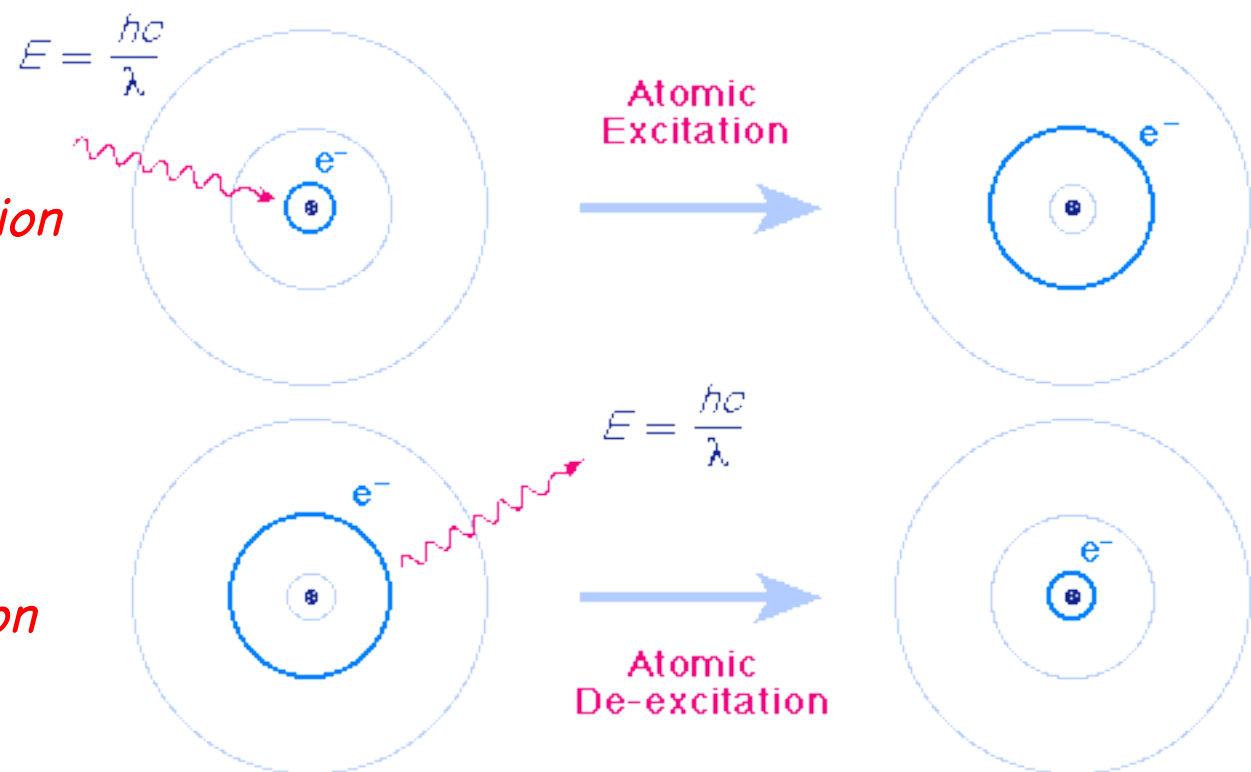
Recall

Bohr's picture of atomic emission/absorption

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

photon absorption

photon emission



- wavelength 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):

clicker question

Preparation for class

Q: *Before today's class I have*

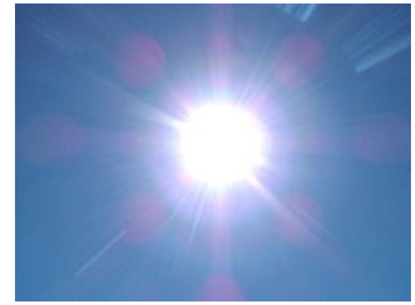
a) not prepared at all, didn't read the text nor notes
b) not prepared at all, but last time I read Ch.1
c) read Ch.2, and last time read Ch.1, but not the notes
d) read Ch.2 and the notes and last time read Ch.1
e) not prepared at all, but wanted to and will start now

A: *read Ch.2, the notes and last time read Ch.1*

Today

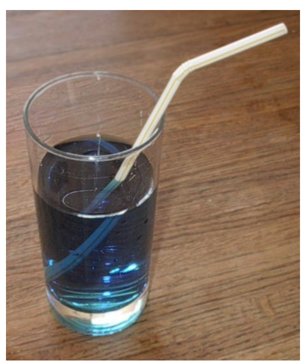
Light propagation: ray optics

- from wave to ray picture

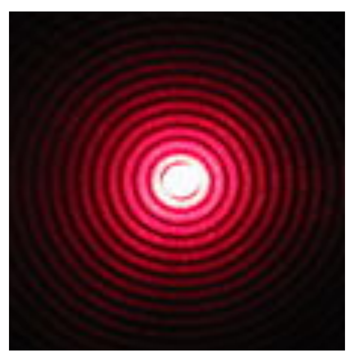


- shadows and apertures

- scattering
- reflection

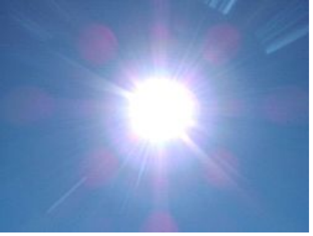


- refraction



- diffraction

- absorption

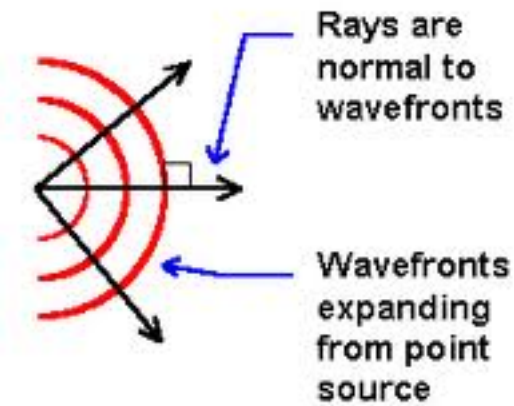


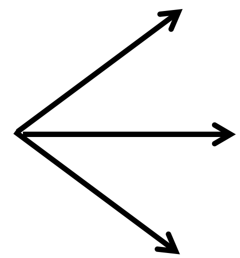
Ray picture of light: geometric optics

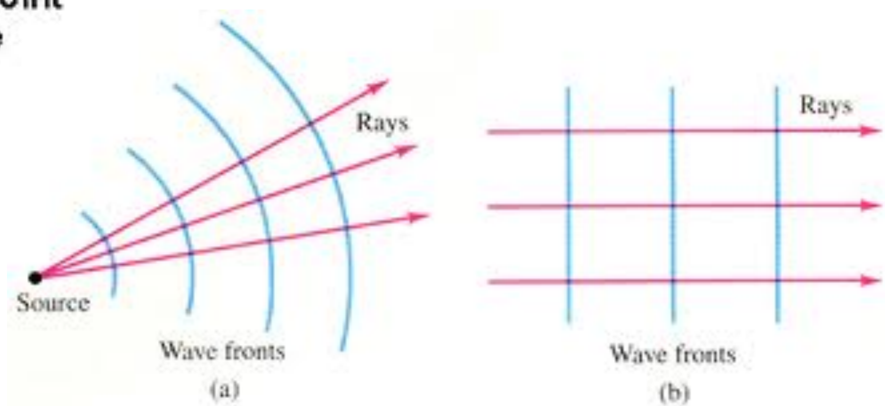
wave:

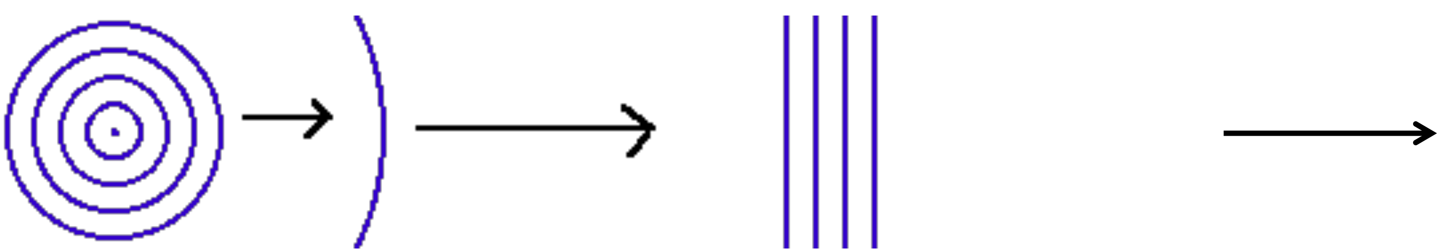
ray:

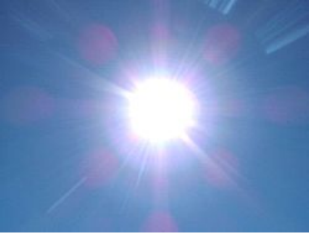
OK if $d \gg \lambda$





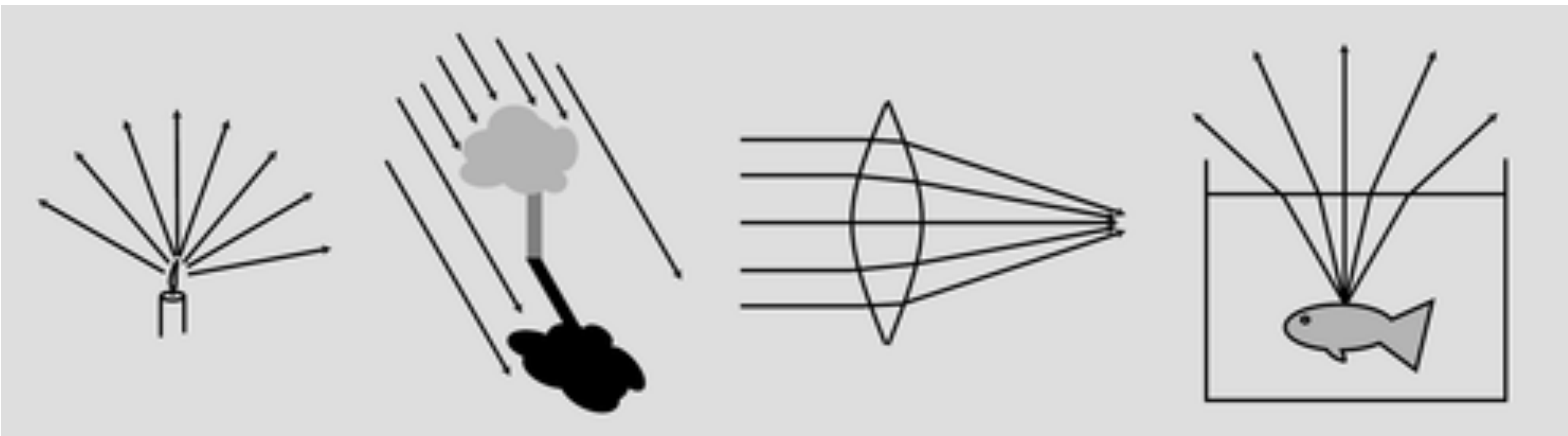






Ray picture of light: geometric optics

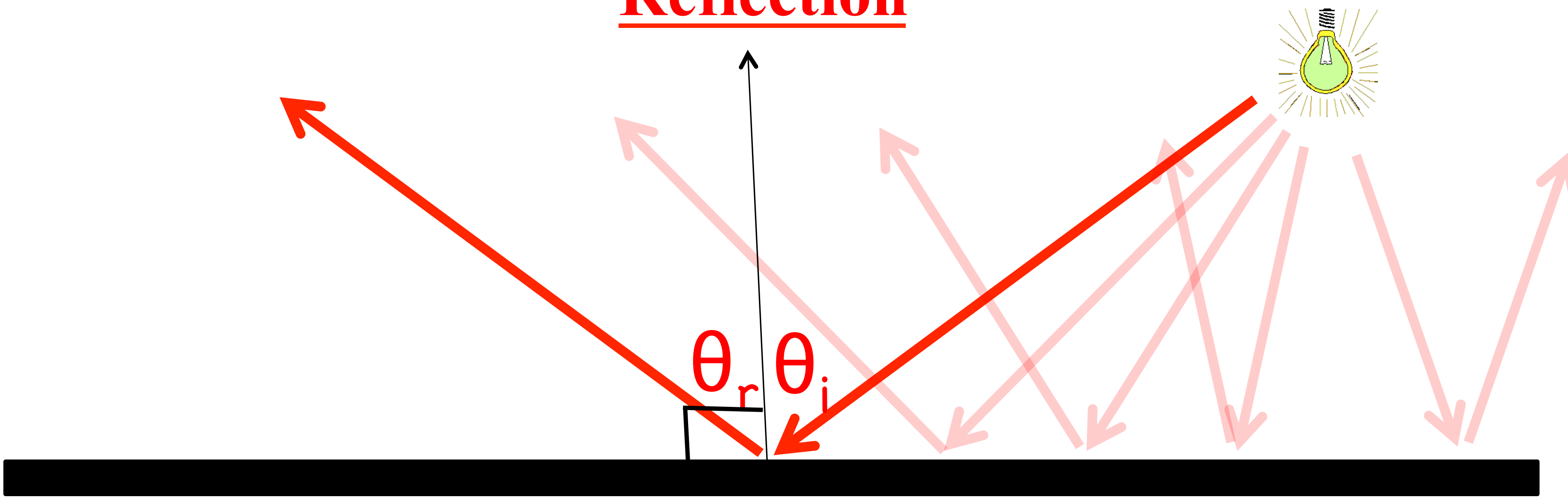
OK only if d >> λ



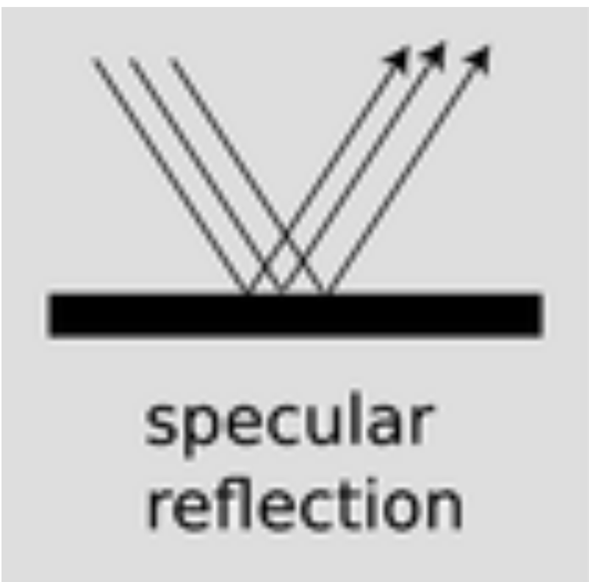
point source | shadow | lens | refraction

Light travels in straight line through homogeneous medium

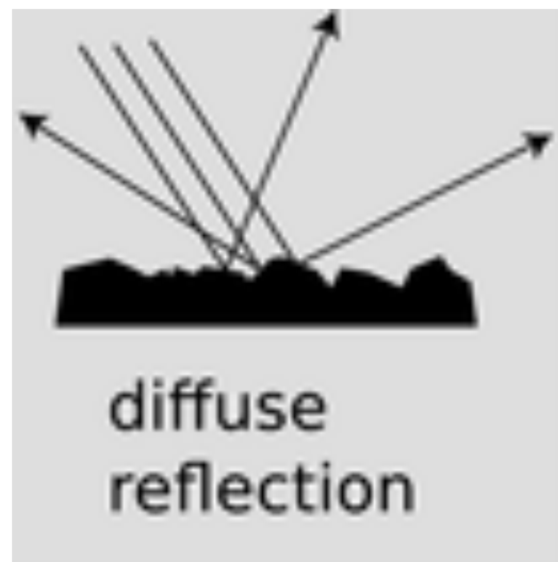
Reflection



smooth surface -> specular reflection: $\theta_{incident} = \theta_{reflection}$

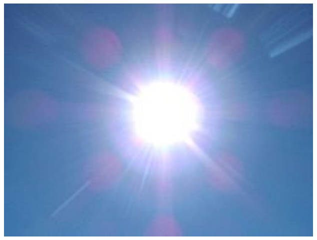


angle of reflection =
angle of incidence
mirror



random angle of reflection
paper

Luminous sources of light



A shadow from each light source

Shadows and Eclipses

shadows from two light sources:

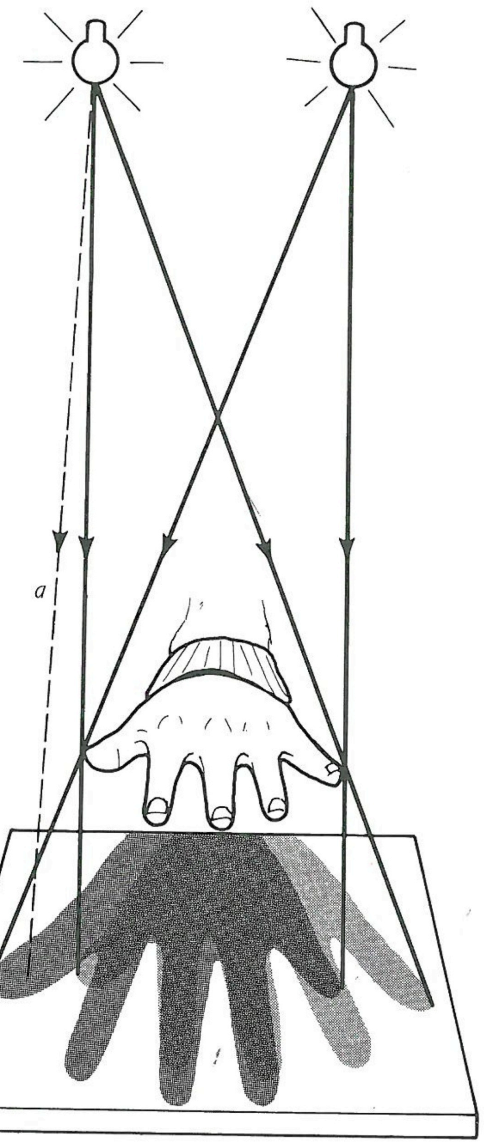


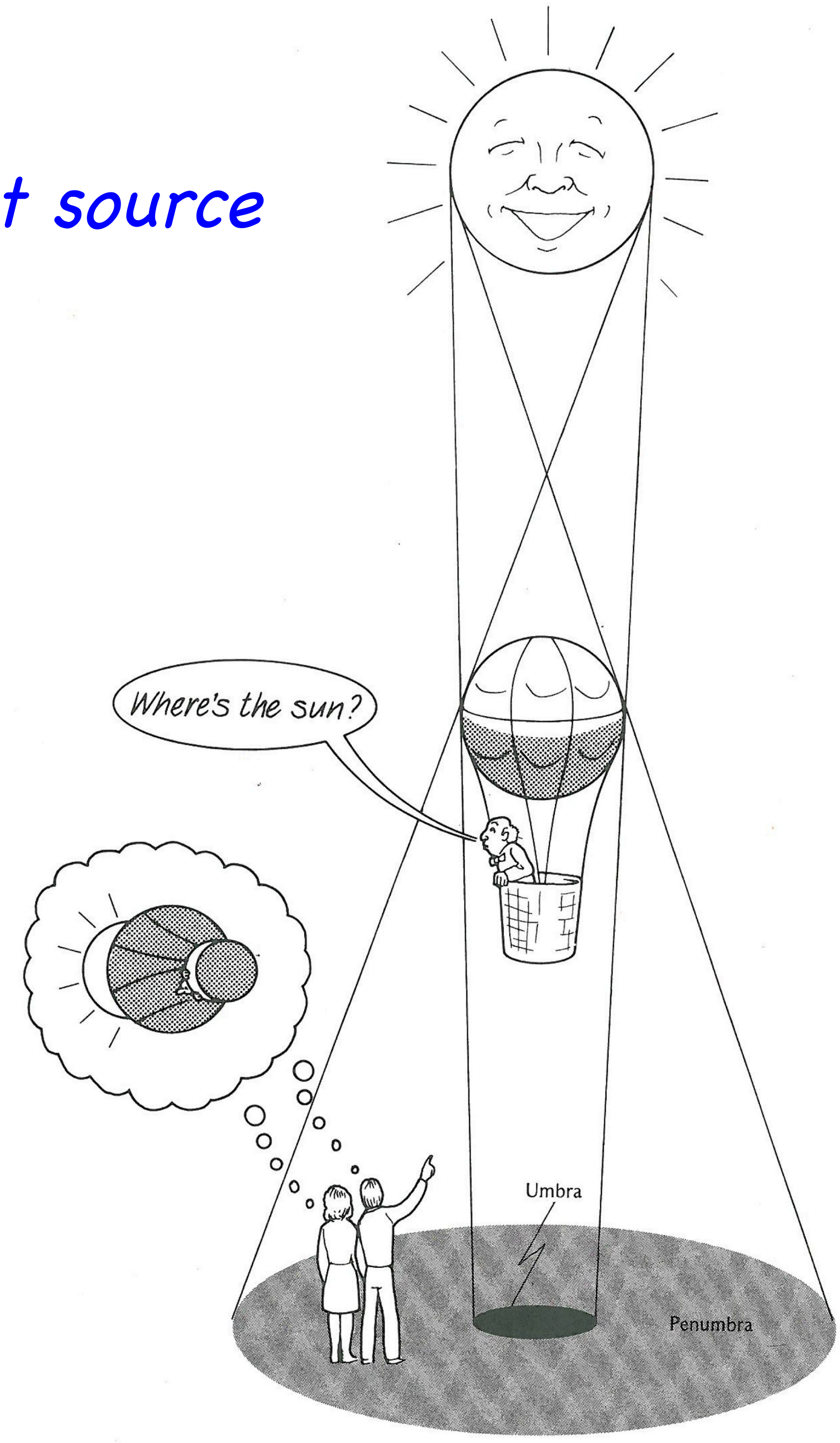
FIGURE 2.2

Two light sources throw two shadows. Their overlap, reached by no ray from either source, is the umbra. The penumbra is illuminated by rays, such as ray *a*, from only one of the sources.

Shadows and Eclipses

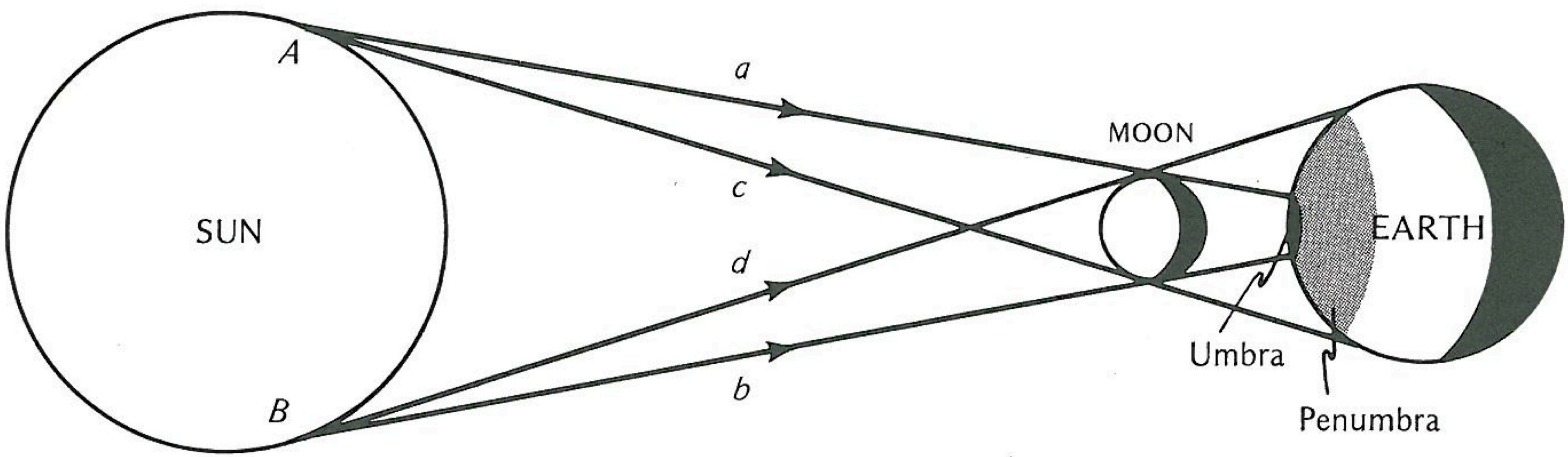
shadows from extended light source

"solar eclipse":



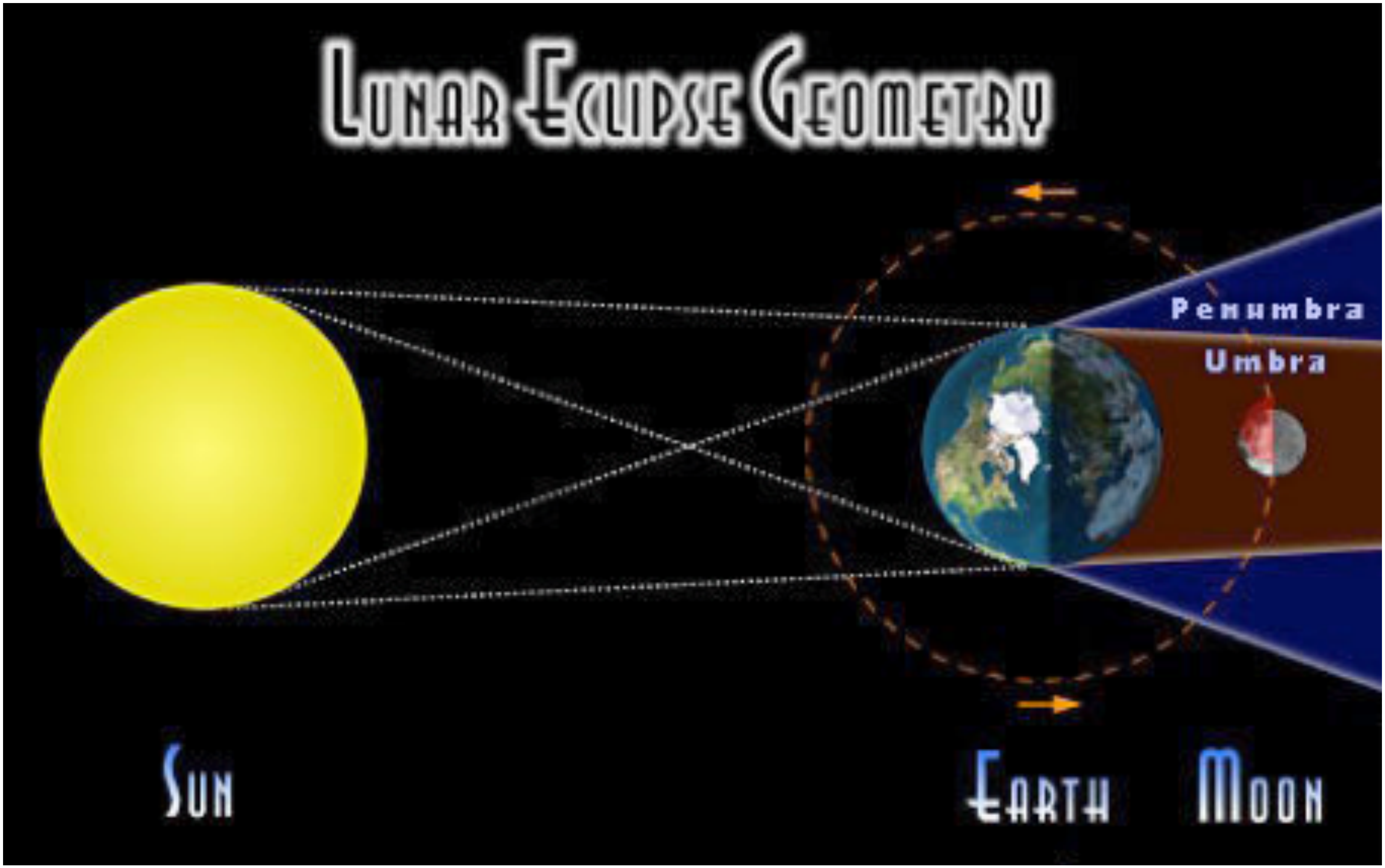
Shadows and Eclipses

Solar eclipse (Moon shadowing the Sun):



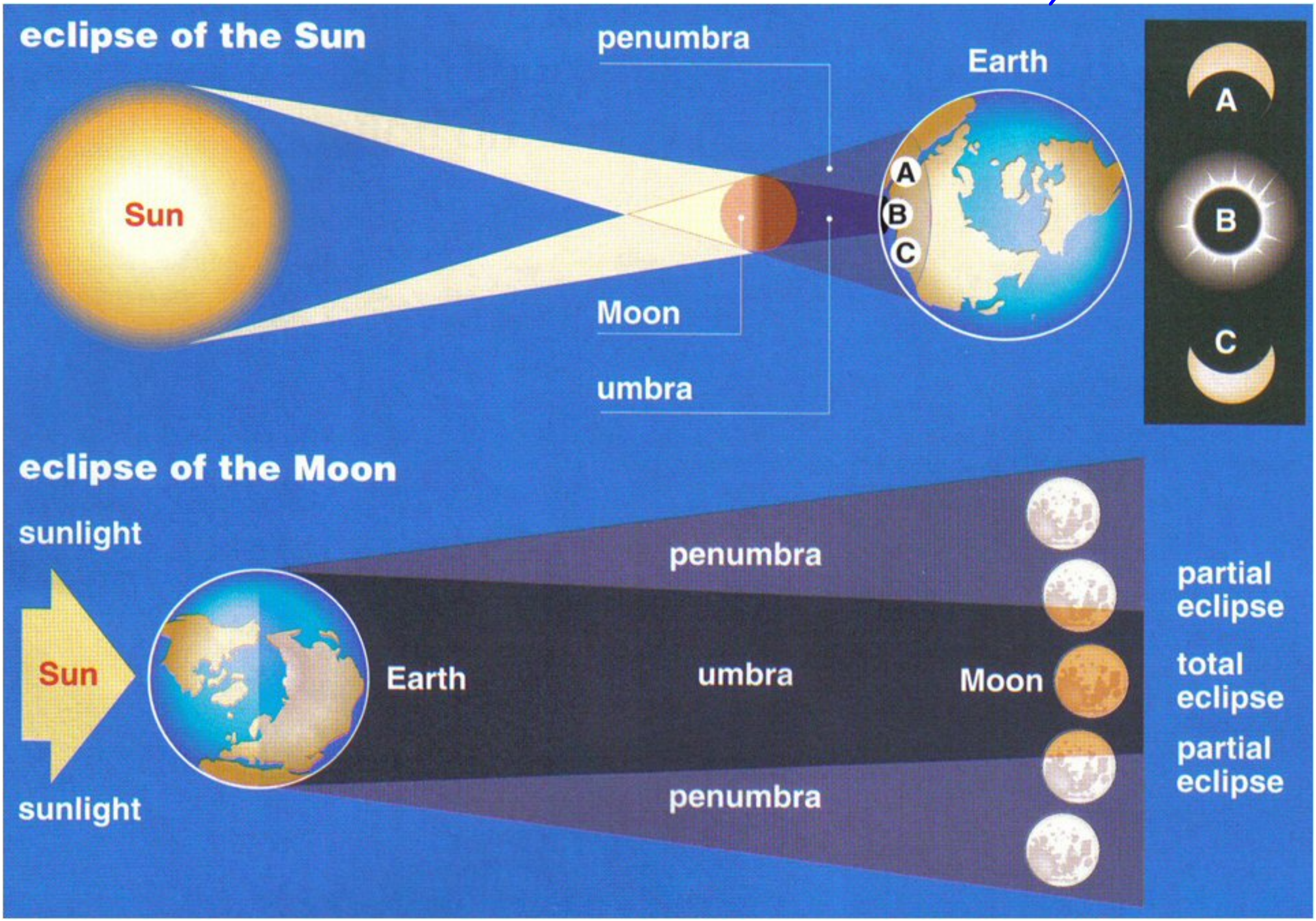
Shadows and Eclipses

Lunar eclipse (Earth shadowing the Moon):

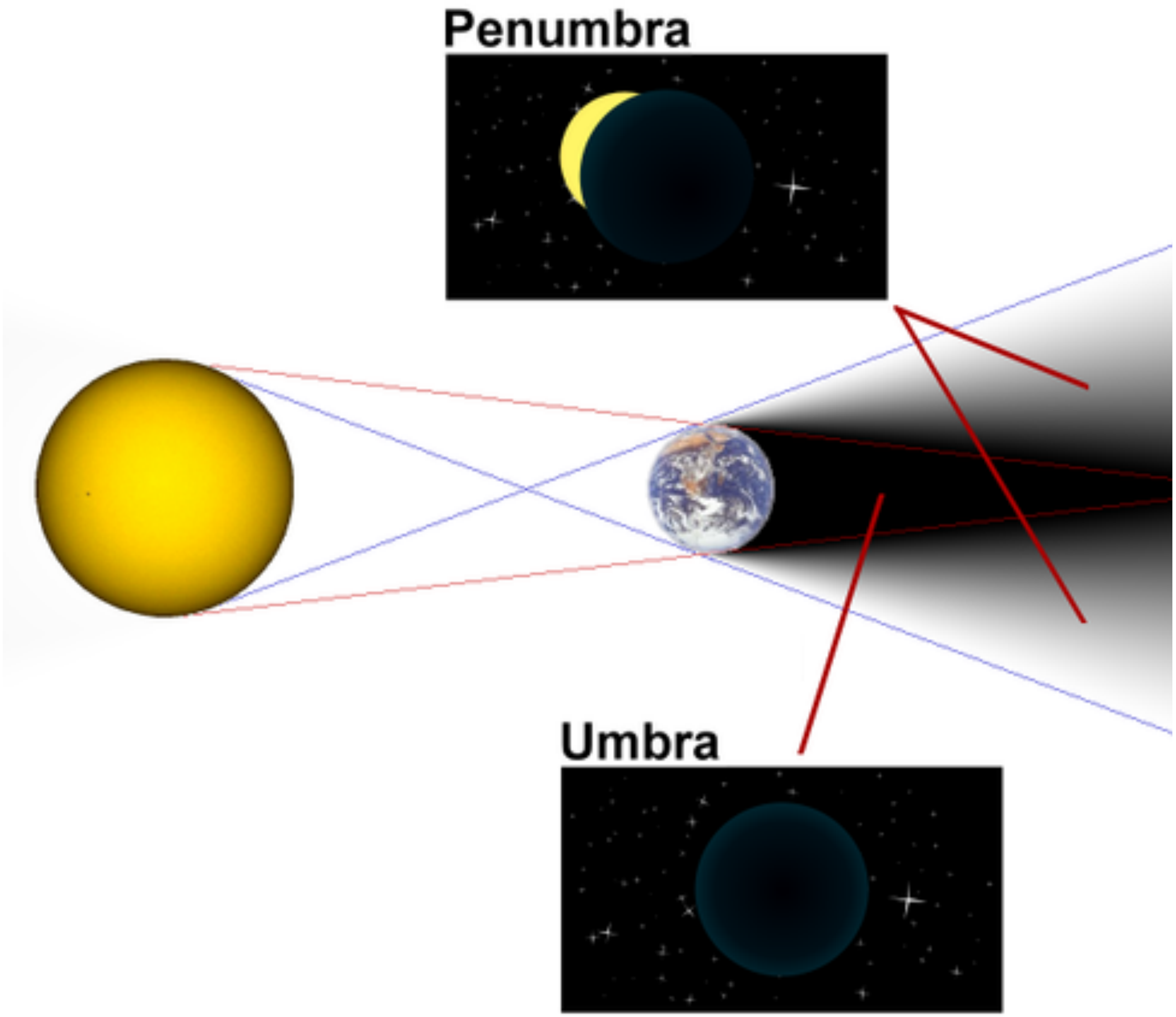


Shadows and Eclipses

umbra only few 100 km

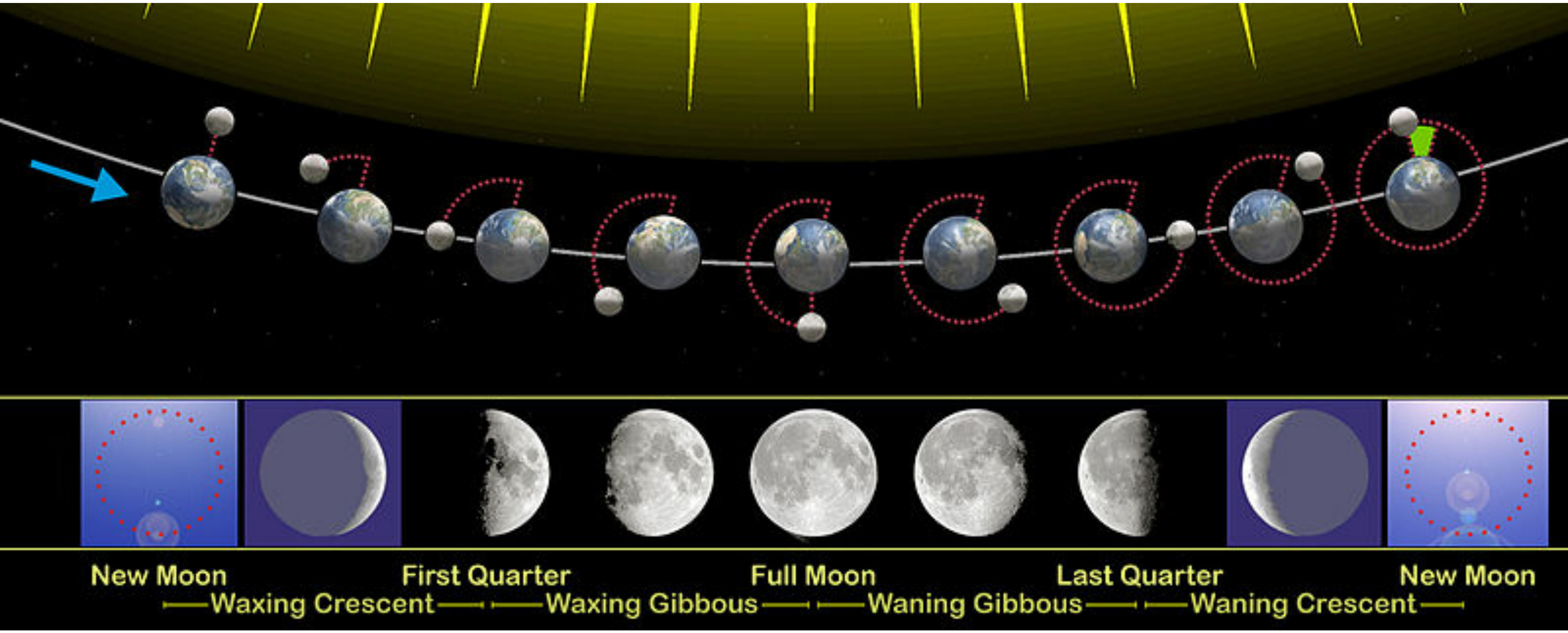


Shadows and Eclipses



Phases of the moon vs lunar eclipse

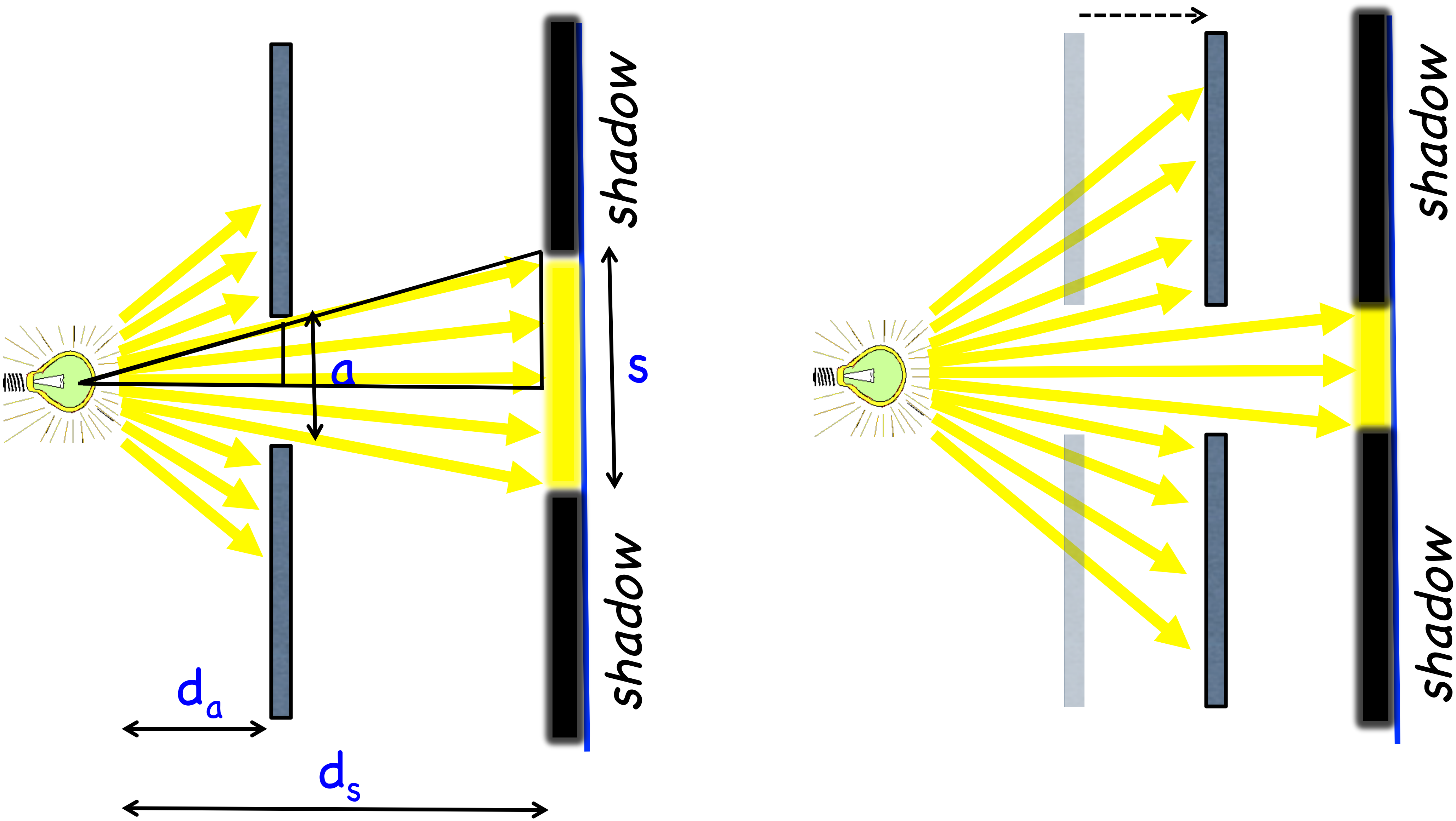
Phases repeat every month (29 days) due to looking at the sun-illuminated half of the moon from different angles



Lunar eclipse (earth shadowing the moon) is rare because moon's orbit is tilted by 5° relative to earth's, so most of the time moon, earth and sun are not lined up

OK only if $d \gg \lambda$

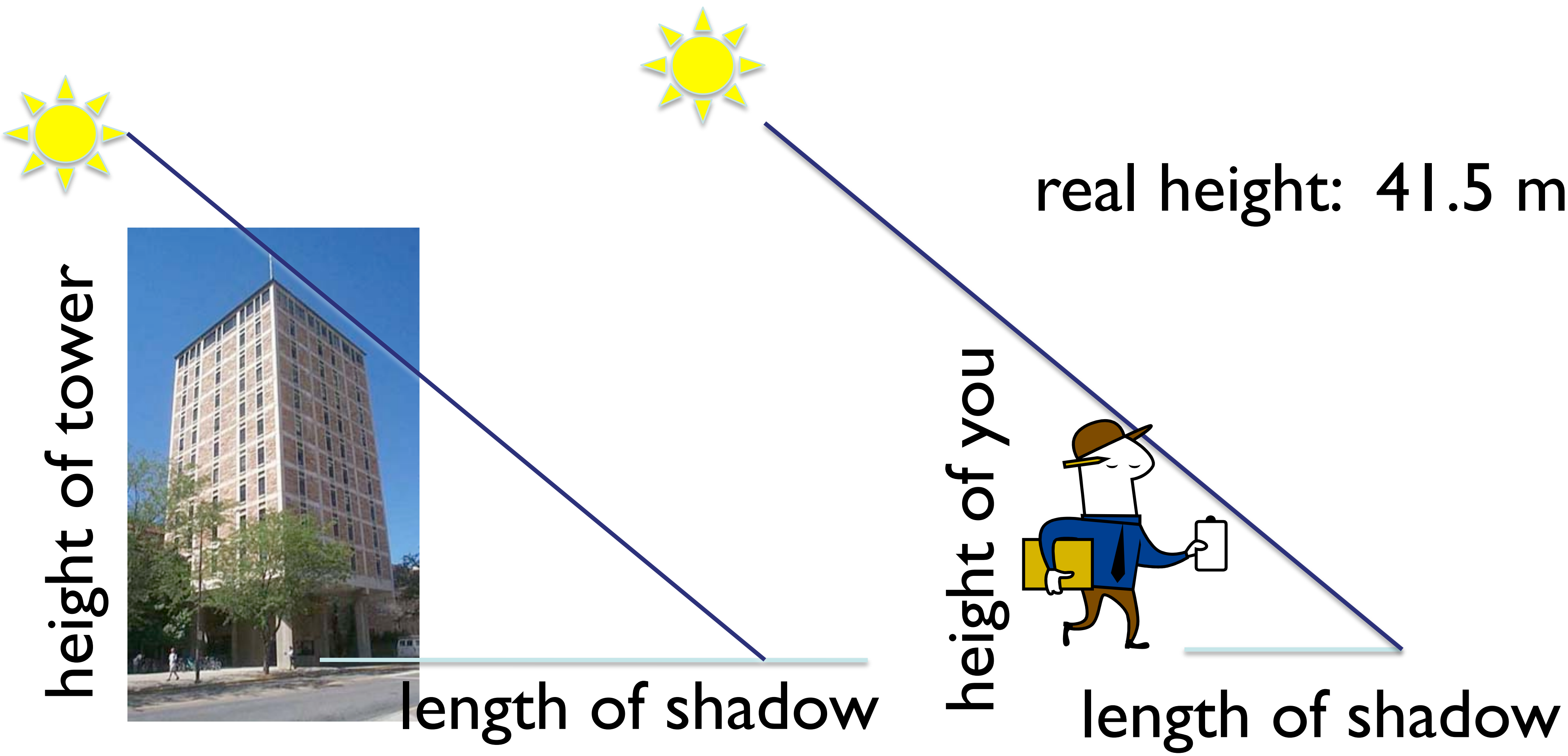
Aperture



similar triangles: $a/d_a = s/d_s \rightarrow s = d_s(a/d_a)$

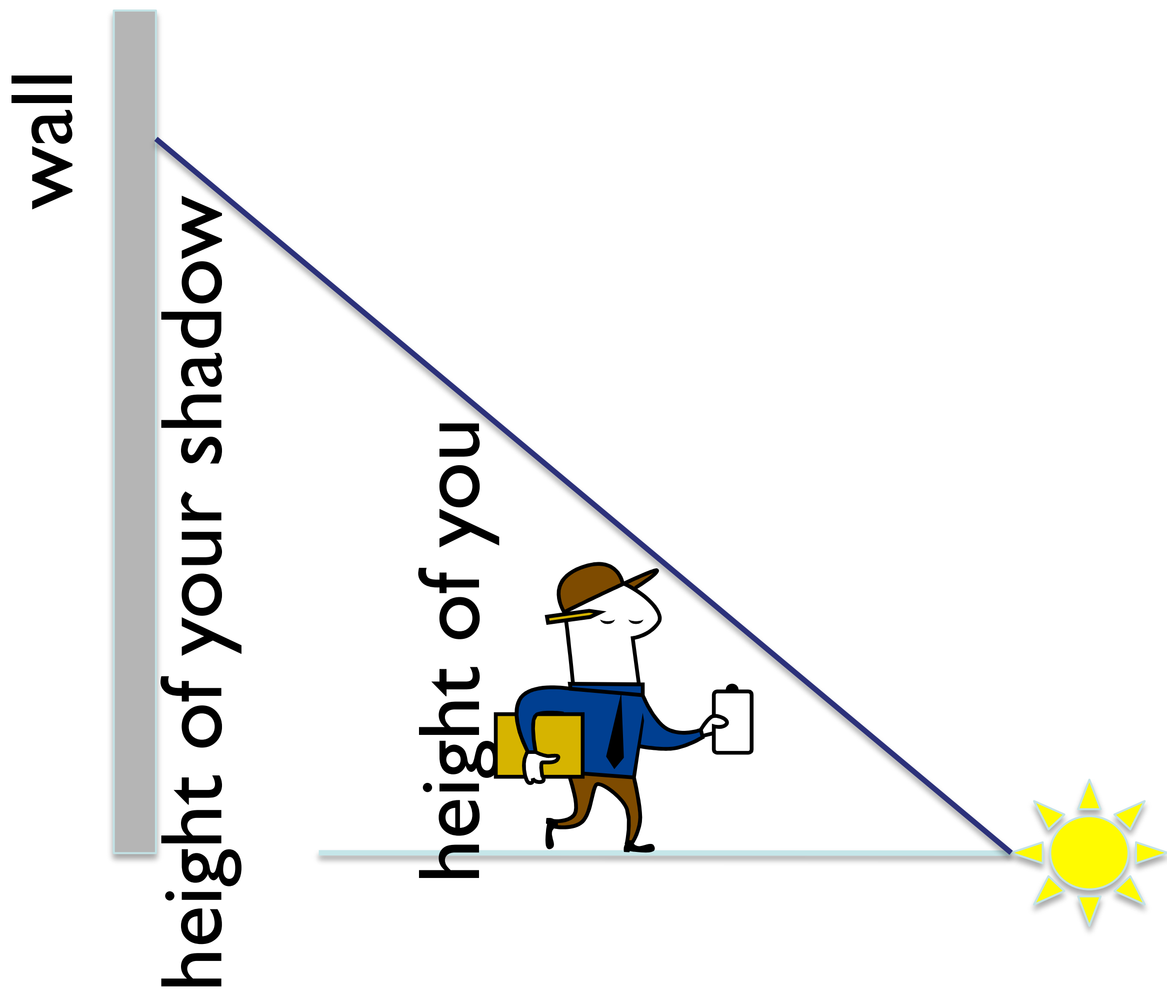
Shadows

$$\frac{\text{Height of you}}{\text{Height of tower}} = \frac{\text{length of your shadow}}{\text{length of tower shadow}}$$



Shadows

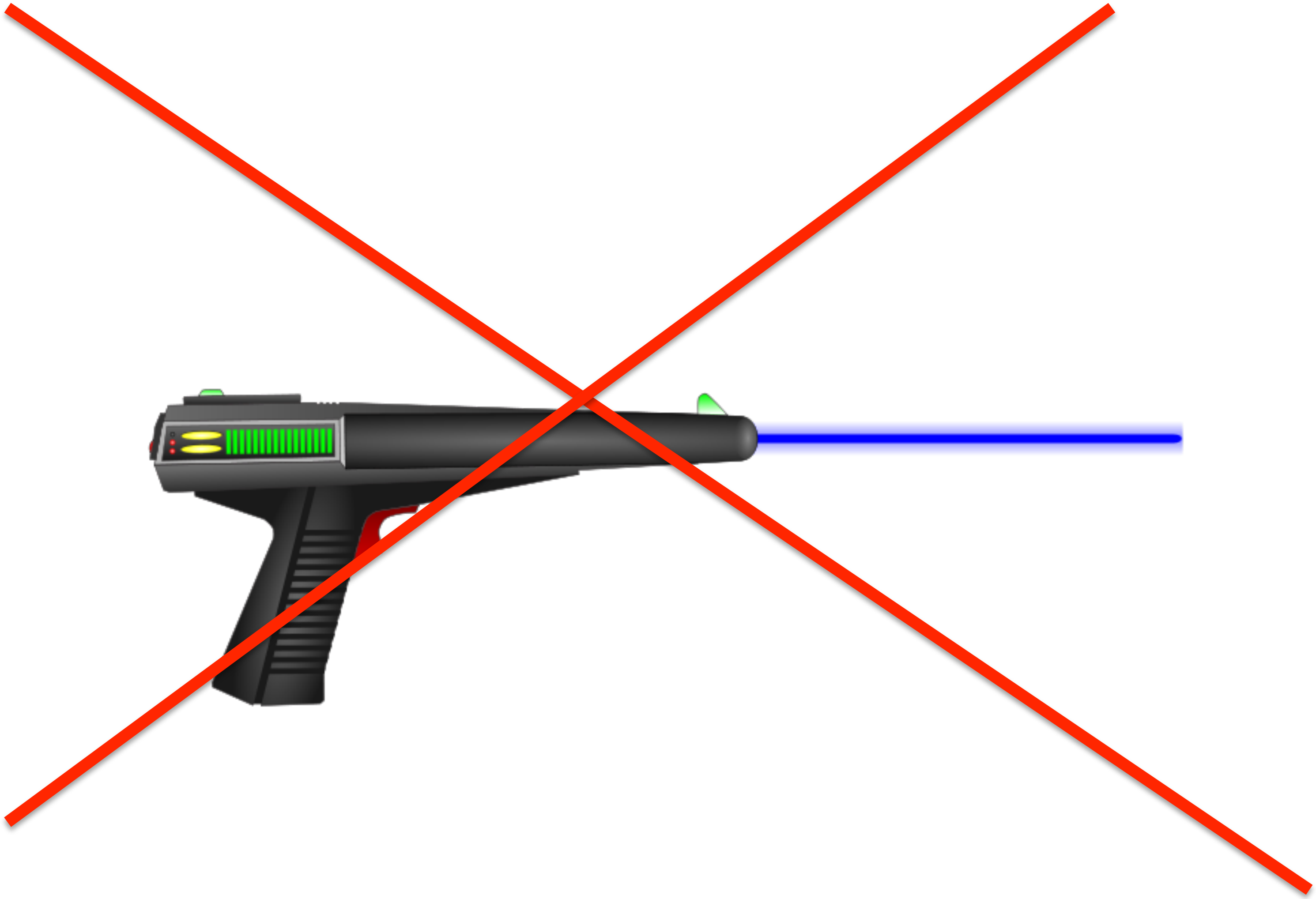
Notice that a shadow on the wall is the same situation, flipped



How do you see this?

300,000 km/sec = 186,000 mi/sec = 1 foot/nanosec
(sound is 343 m/s = 1,126 feet/second)

How do you see this?



Light needs to bounce off something to get to your eye e.g., fog, dust, an object, etc.

clicker question

Specular and diffuse reflections

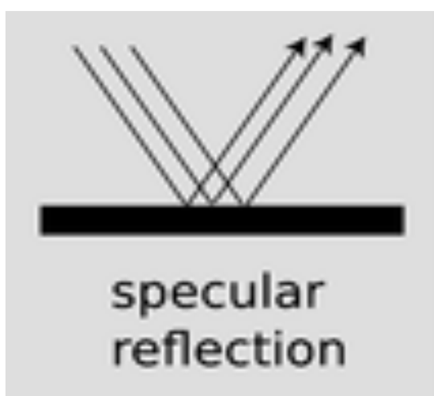
Q: *What is the difference between a reflection by a white piece of paper and a mirror?*

a) A white piece of paper does not reflect light

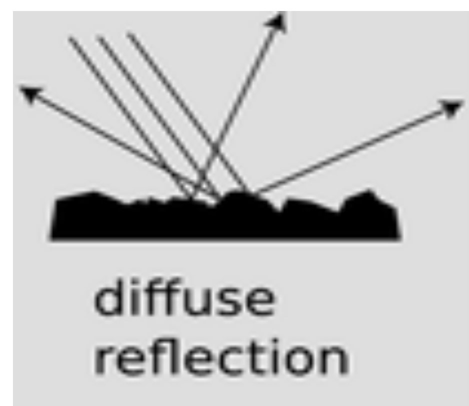
b) A mirror is smooth and so reflects specularly, at a single angle. A paper is rough and so reflects at many angles in all directions

c) They reflect the same way

A: *specular reflection by mirror and diffuse reflection by piece of paper*

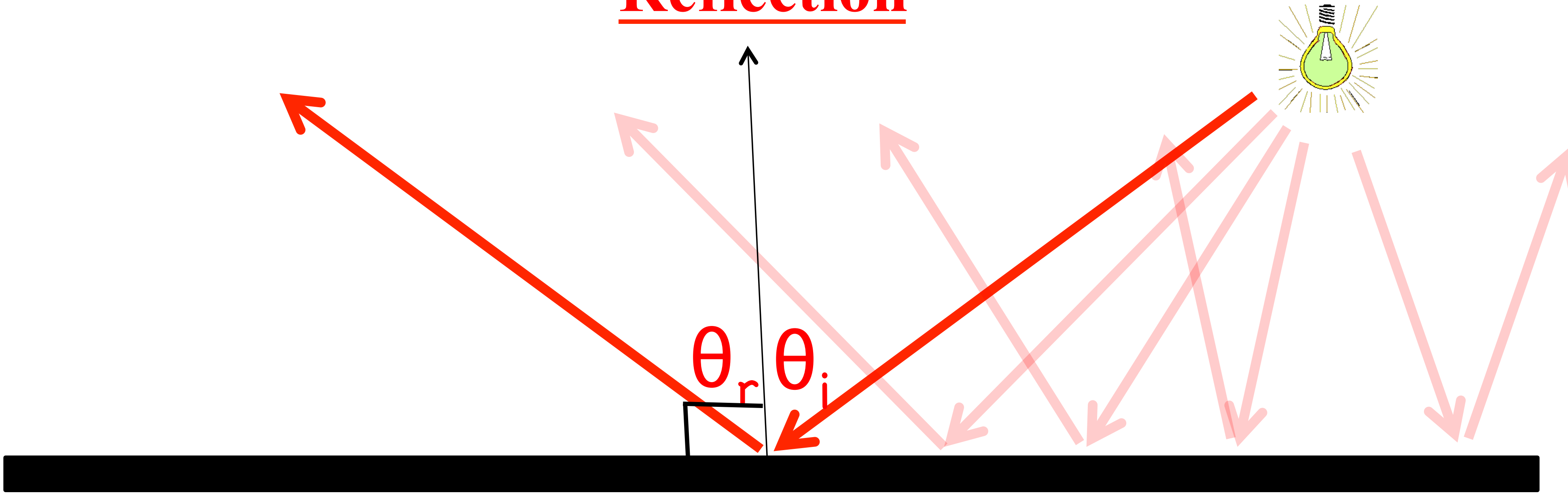


mirror

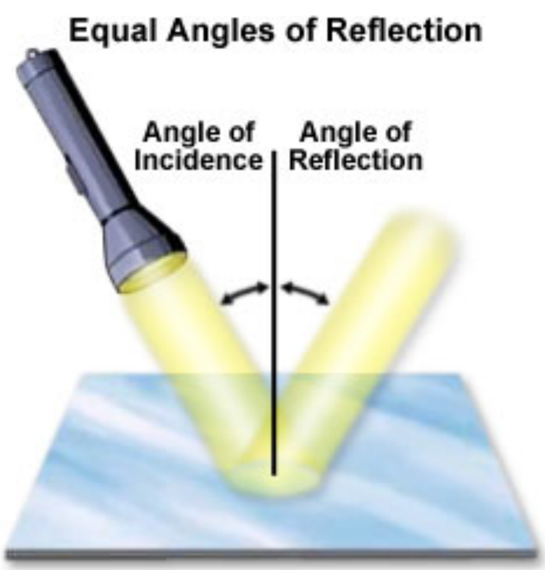


paper

Reflection



smooth surface -> specular reflection: $\theta_{incident} = \theta_{reflection}$

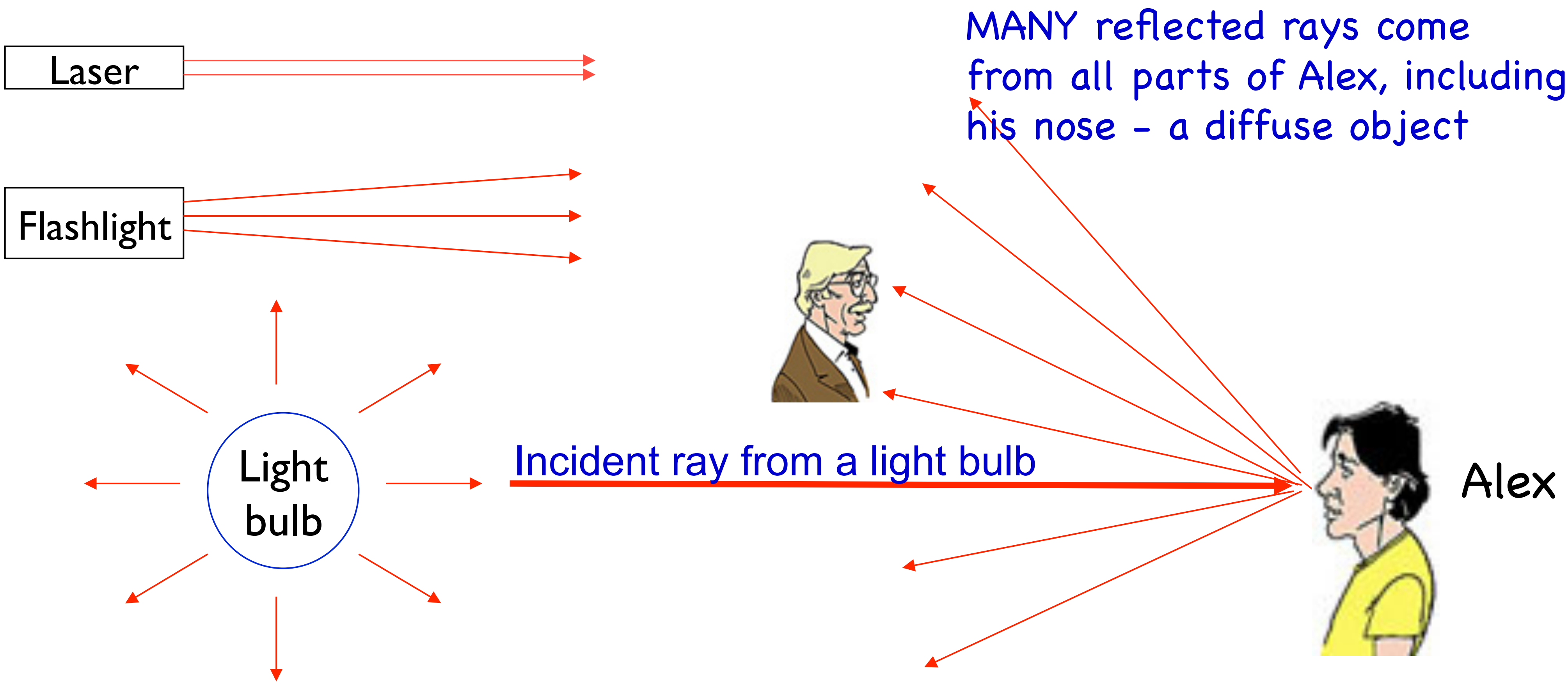


Smooth Water Surface

Wavy Water Surface

Scattering of light to see it

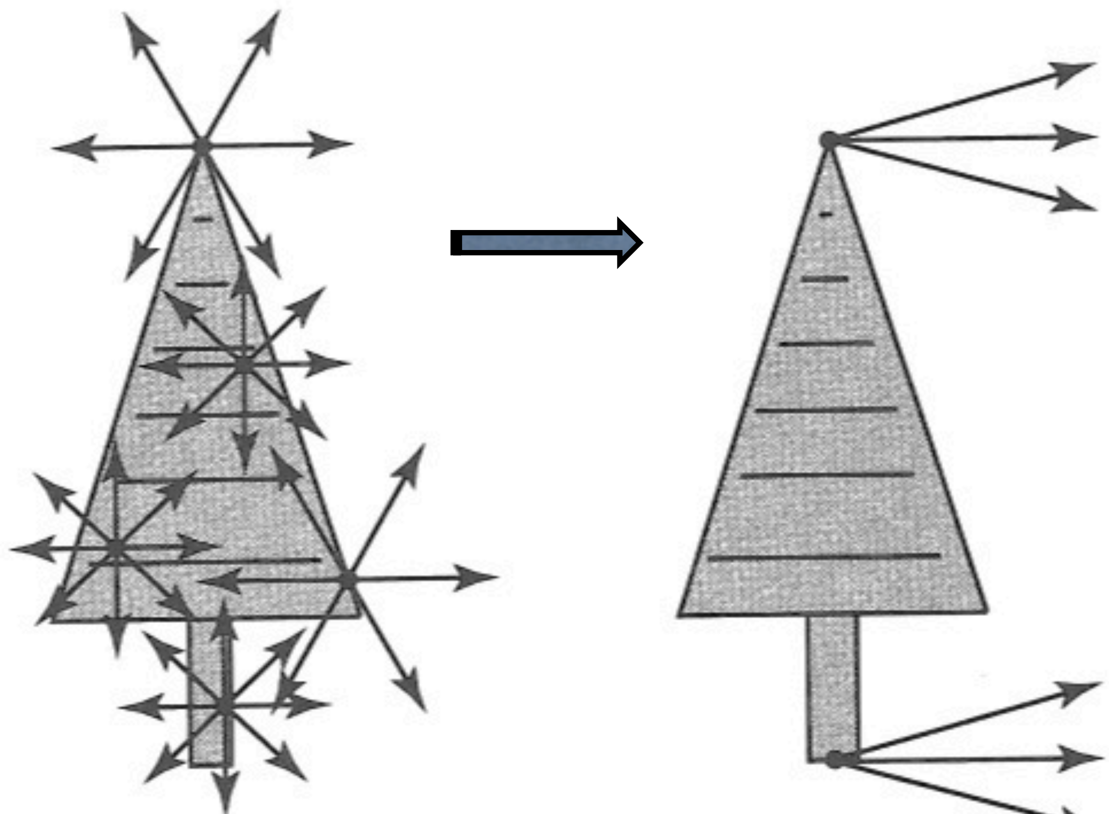
Light rays are invisible unless they enter directly into our eye or are scattered by smoke, fog or some object into your eye! *That's how we see non-luminous objects*



Bob sees Alex's nose because a reflected light ray enters Bob's eye!

Non-luminous sources of light

seeing non-luminous objects:



a) Reality　　　　　　b) Ray diagram

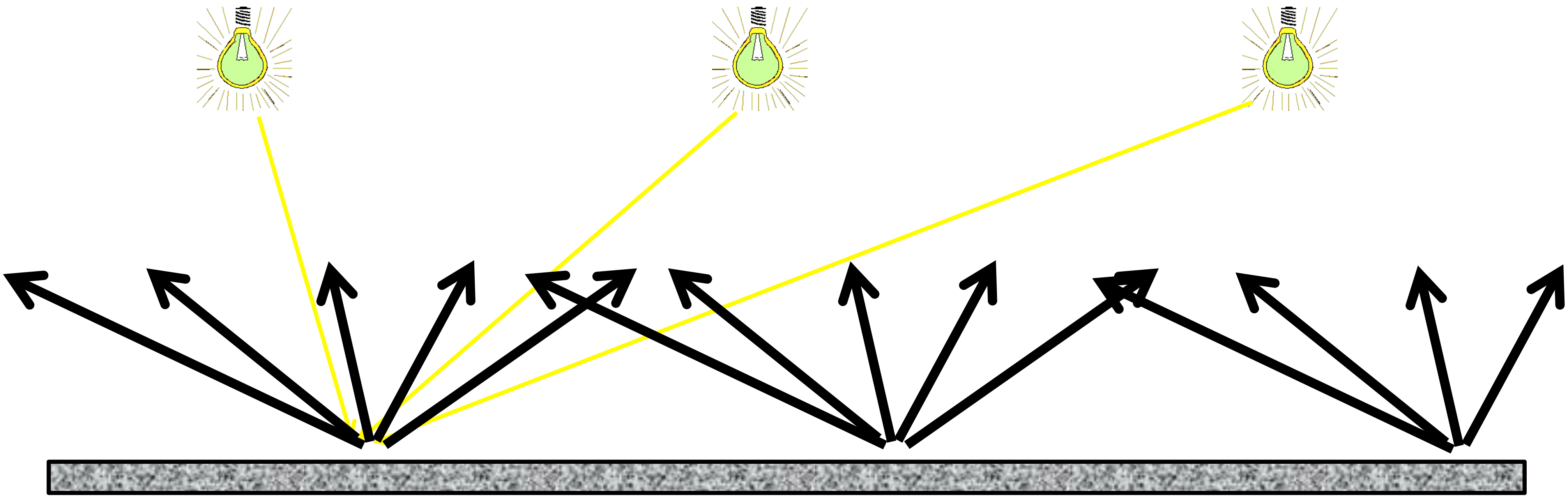
a) An object emits light rays in all directions from all points.
b) A ray digram is a simplified view.

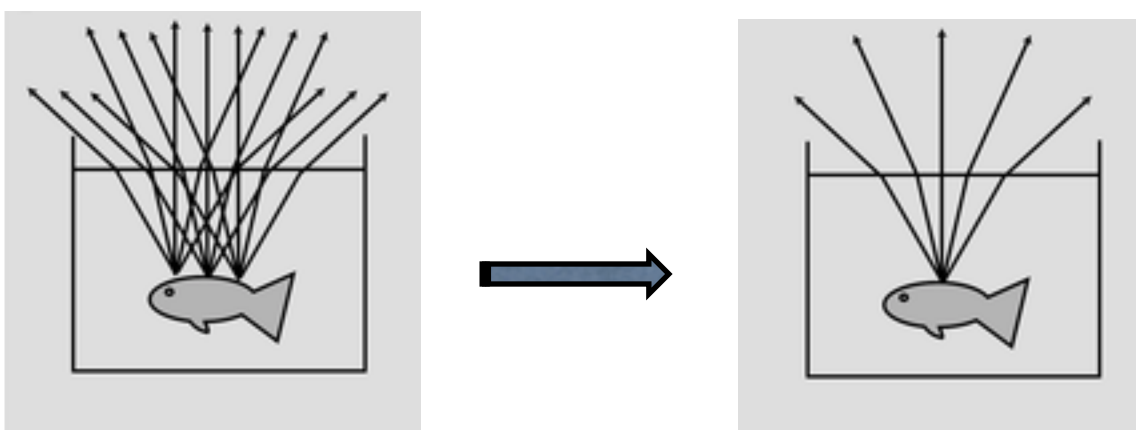
"real"　　　　　　simplified

Each point "emits" a diverging bundle of rays

Non-luminous sources of light

seeing non-luminous objects:



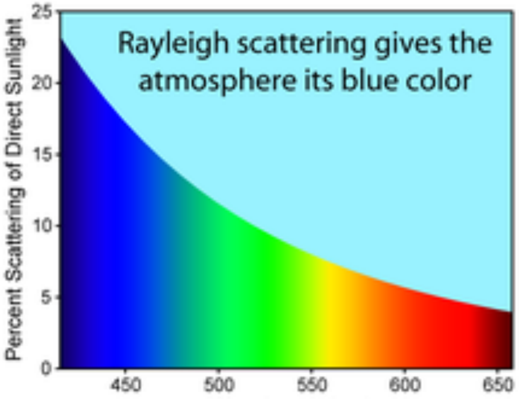


"real" simplified

Each point "emits" a diverging bundle of rays

Why sky is blue, sunset red?

$S \approx 1/\lambda^4$

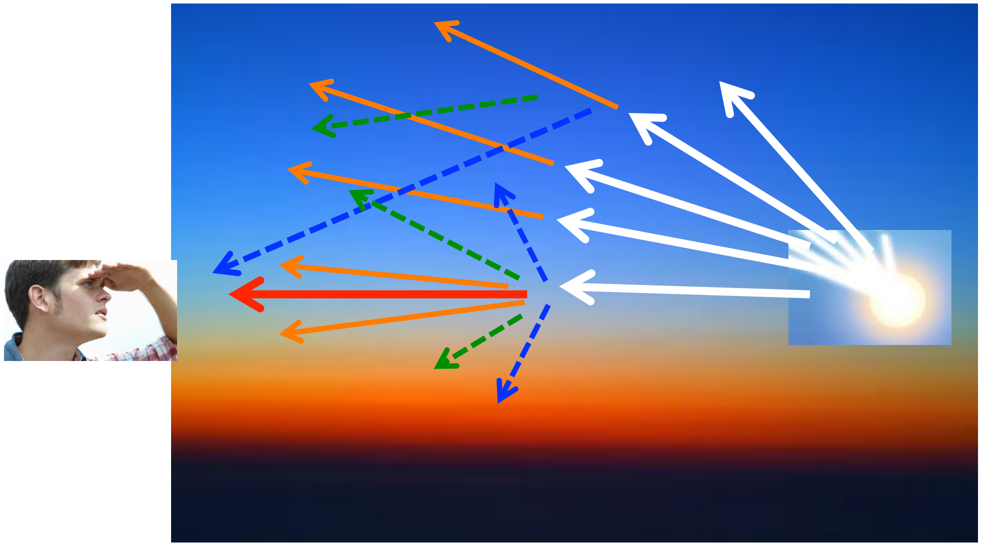


wavelength

Blue scatters most strongly
Red scatters least strongly

- blue sky:

Light from the sky is strongest scattered -> blue

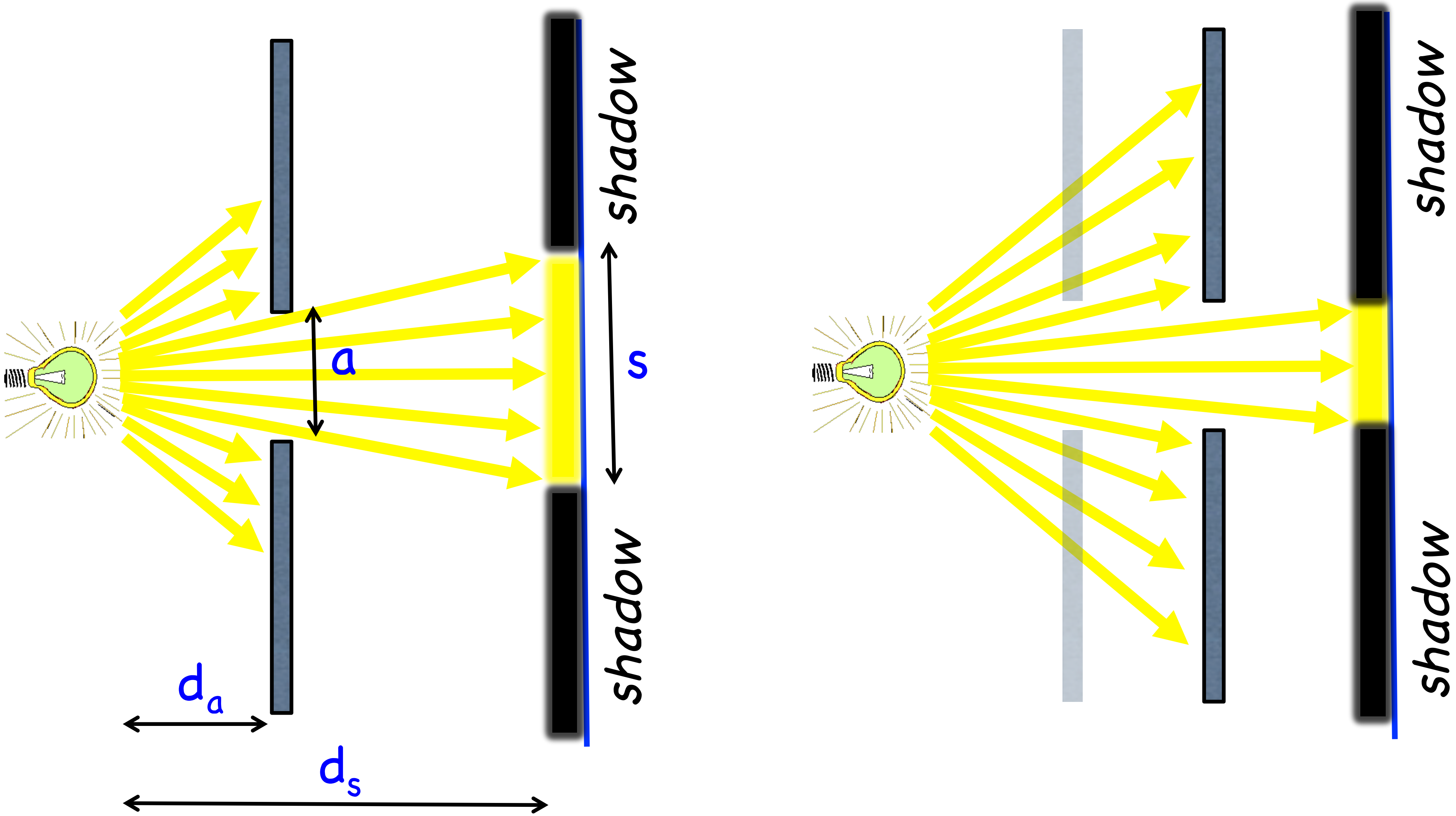


- red sunset:

At sunset (sun on horizon) direct light is non-scattered -> red

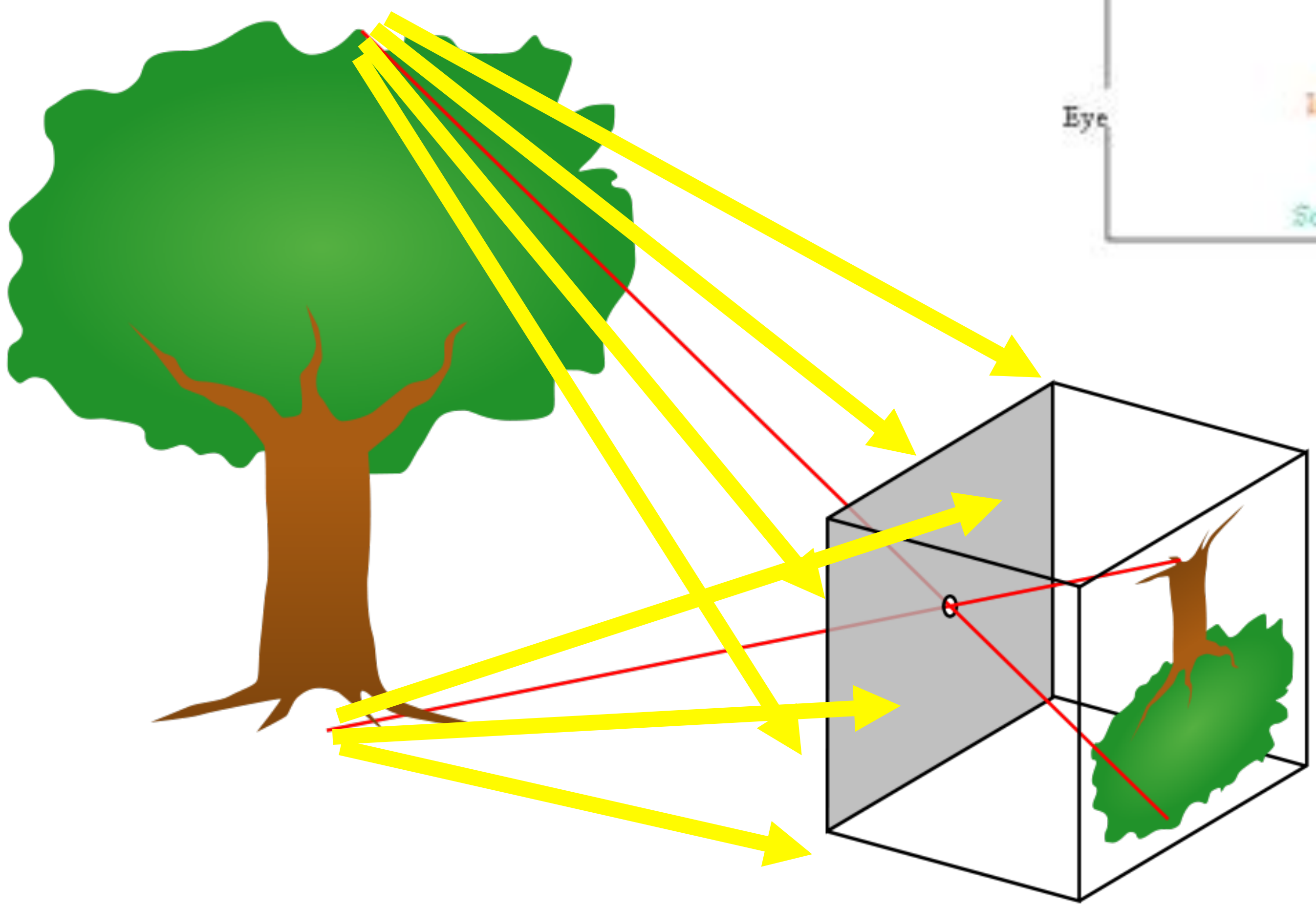
Luminous source through aperture

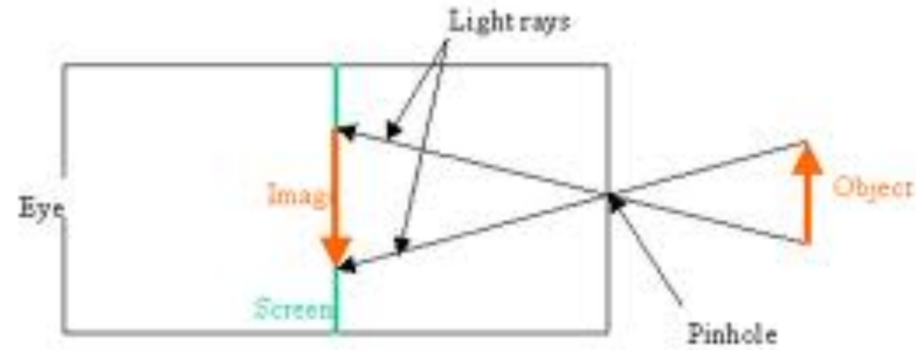
Image of aperture



similar triangles: $a/d_a = s/d_s \rightarrow s = d_s(a/d_a)$

Non-luminous source through pinhole: camera



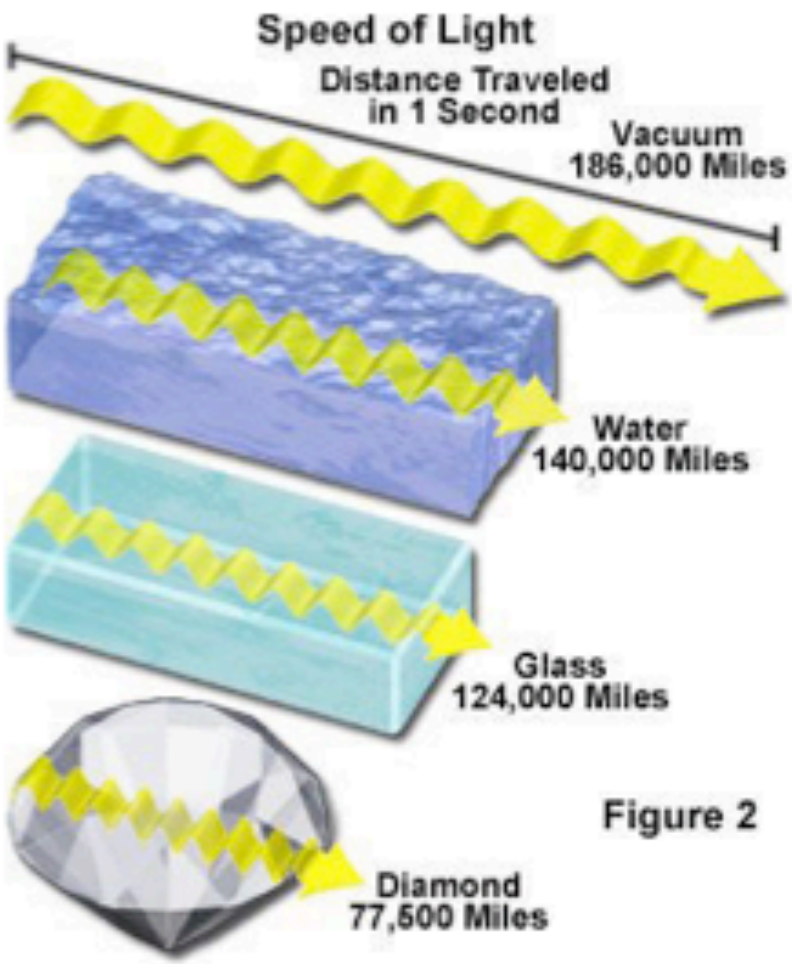


only "one" ray from each point makes it through pinhole -> *image of the object*

... but much dimmer

Refraction

Speed of light in different materials



Medium	Index n
Vacuum	1 (exactly)
Air	1.0003
Water	1.33
Glass	1.5
Diamond	2.4

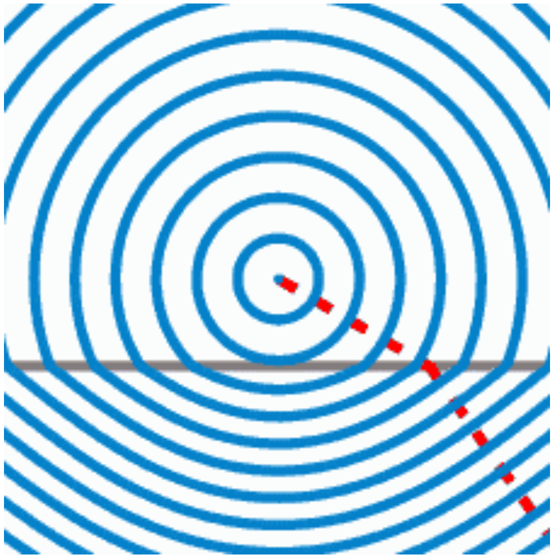
speed of light in medium

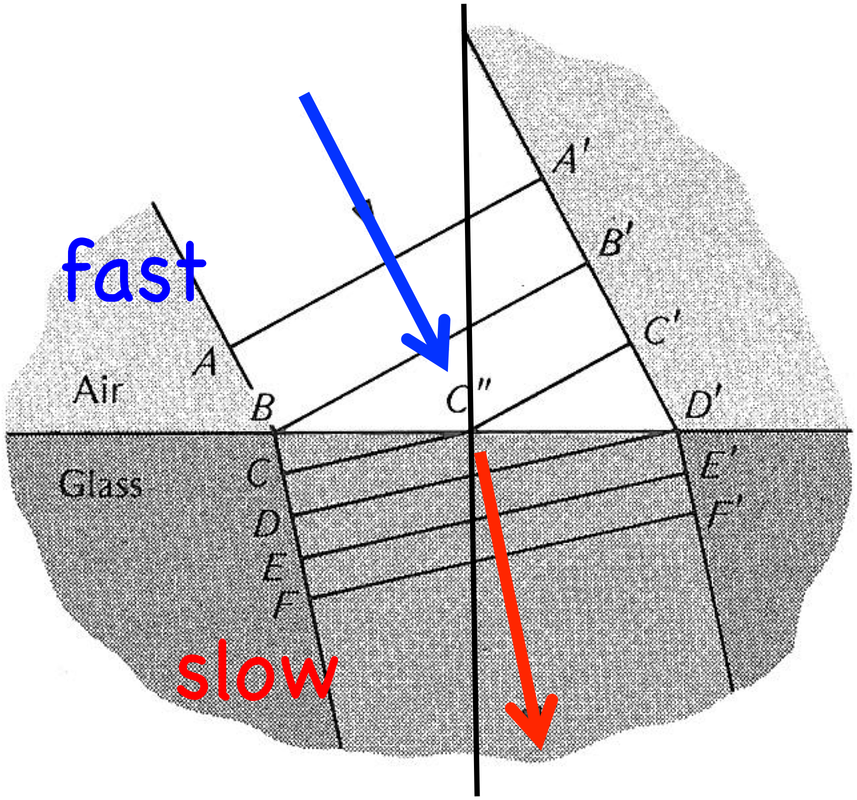
$$v = c/n$$

index of refraction

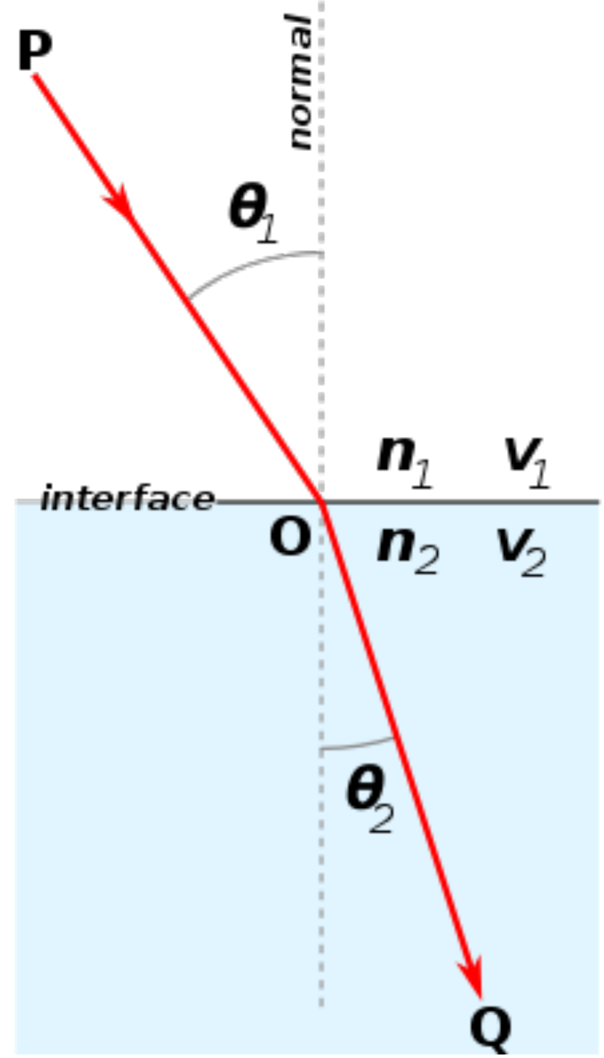
APPLET
http://micro.magnet.fsu.edu/primer/java/speedoflight/index.html

Refraction





Reveals wave nature of light



Snell's law:

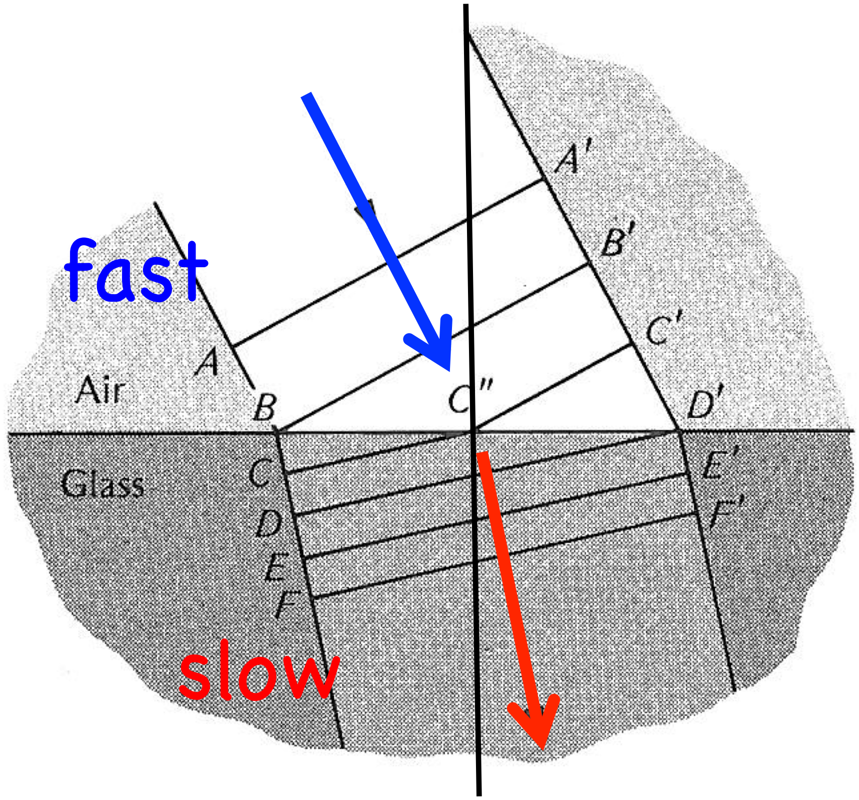
for $n_1 < n_2$ slow down from 1 to 2

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

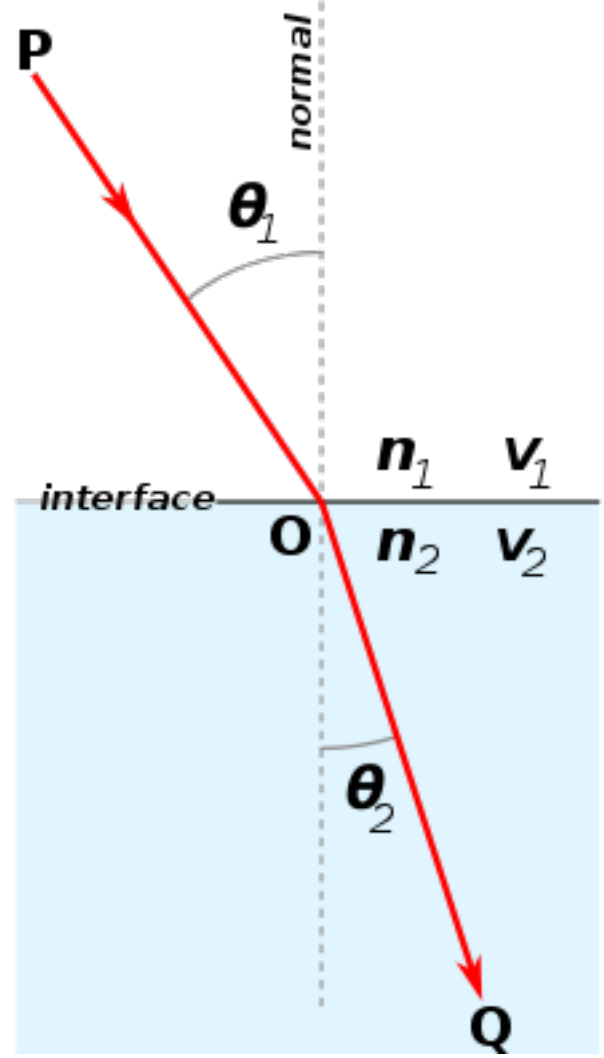
$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$$

Refraction

Medium	Index n
Vacuum	1 (exactly)
Air	1.0003
Water	1.33
Glass	1.5
Diamond	2.4



Reveals wave nature of light



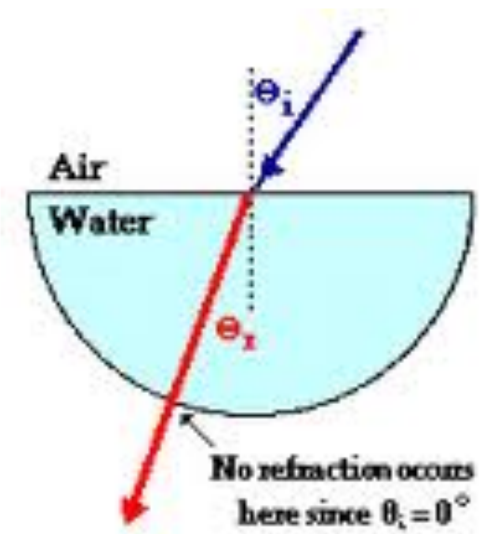
for $n_1 < n_2$ slow down from 1 to 2

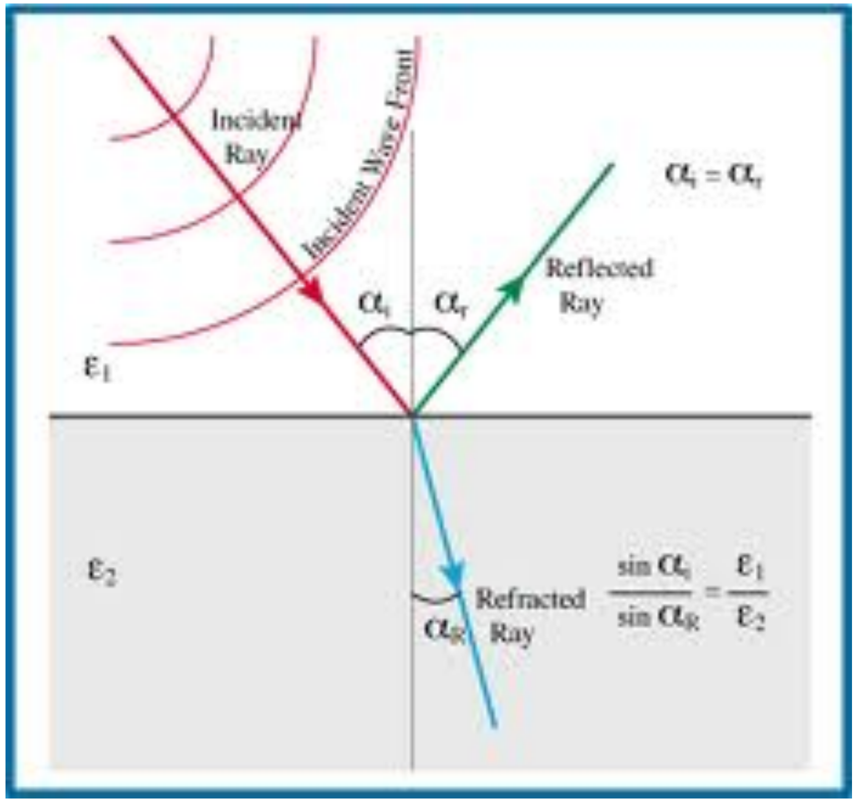
Snell's law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$$

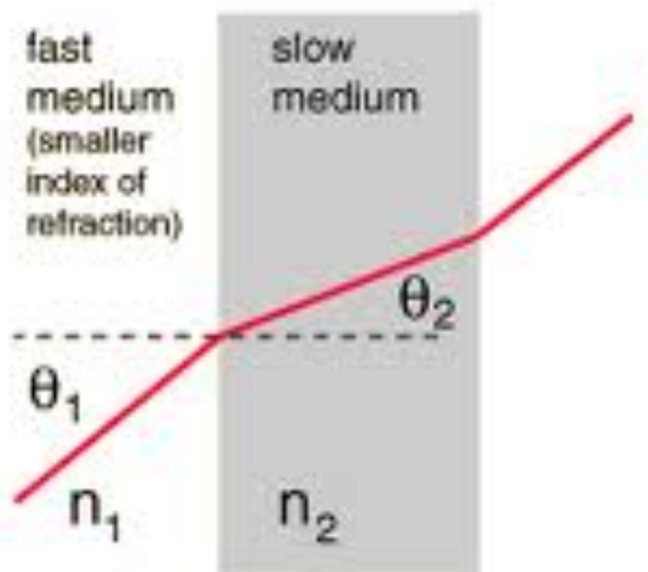
Refraction and reflection



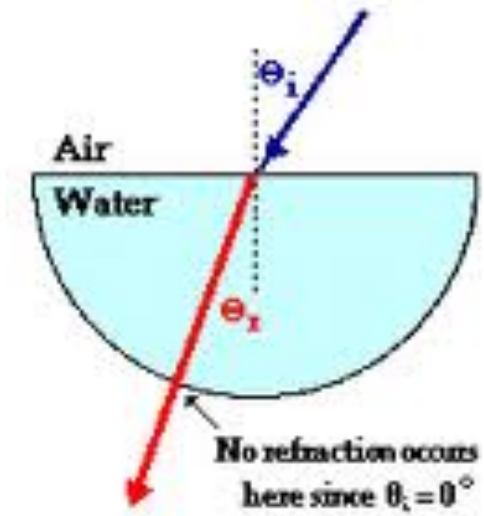


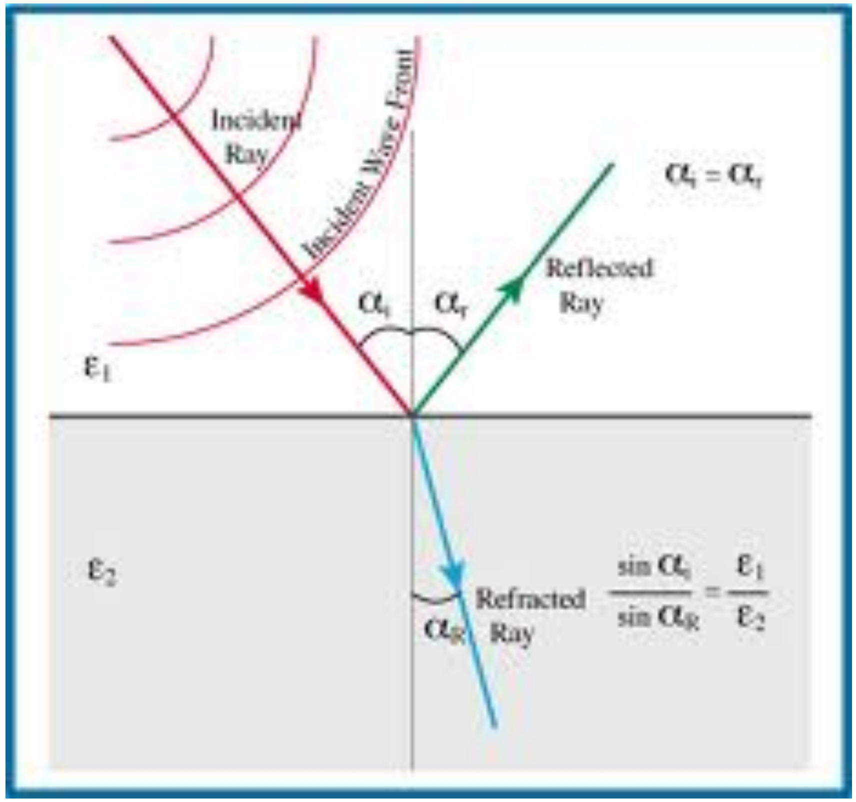
Snell's Law

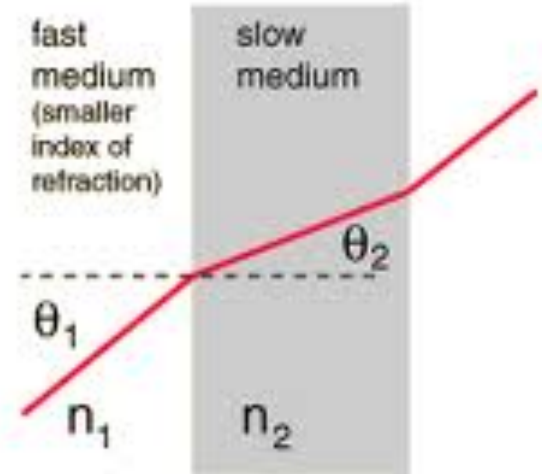
$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}$$

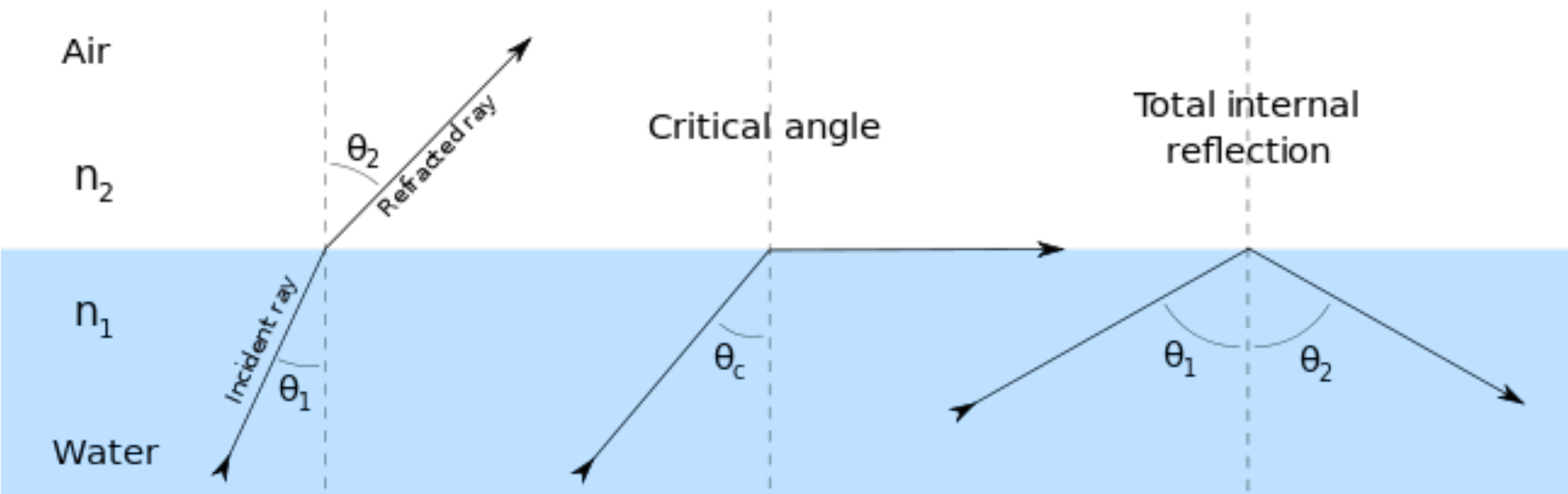


Refraction and reflection

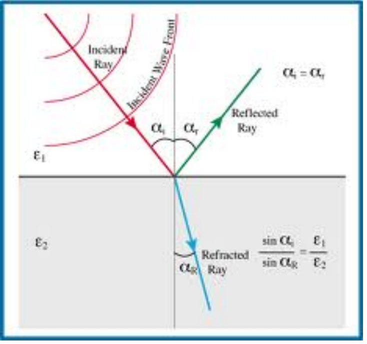


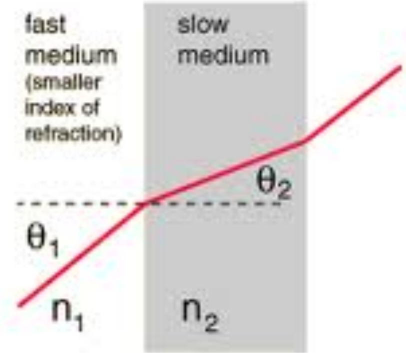


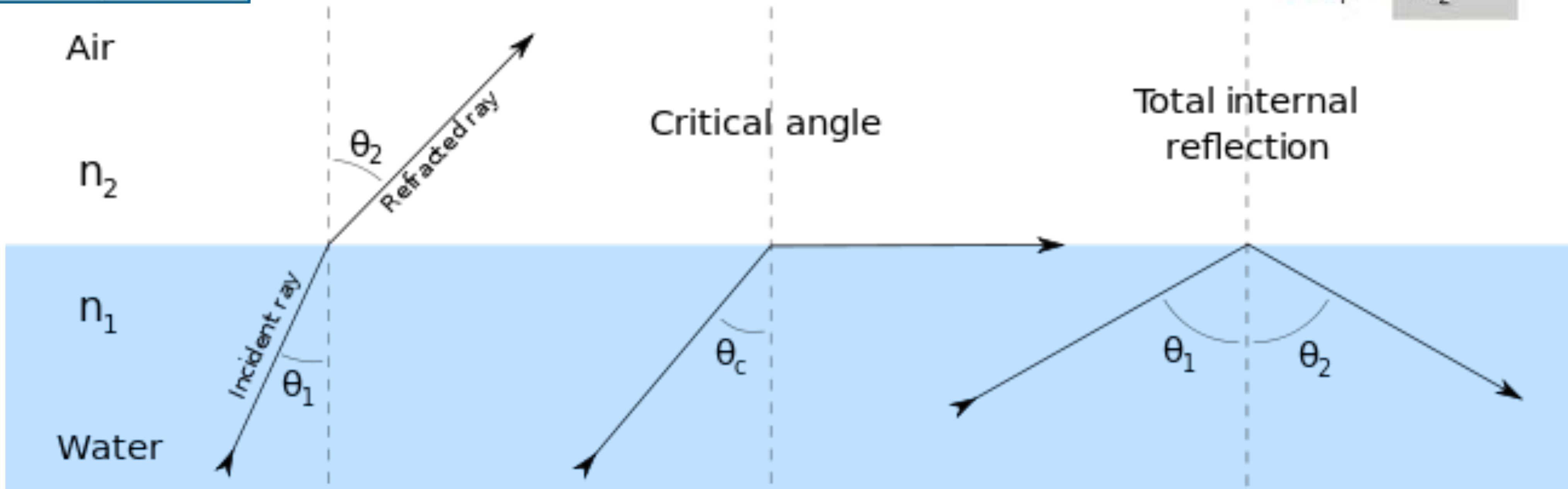




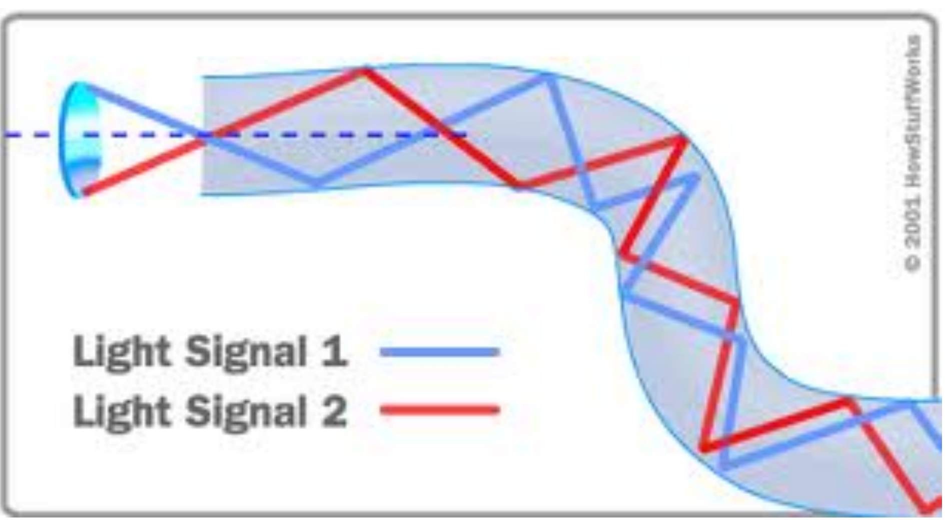
Total internal reflection



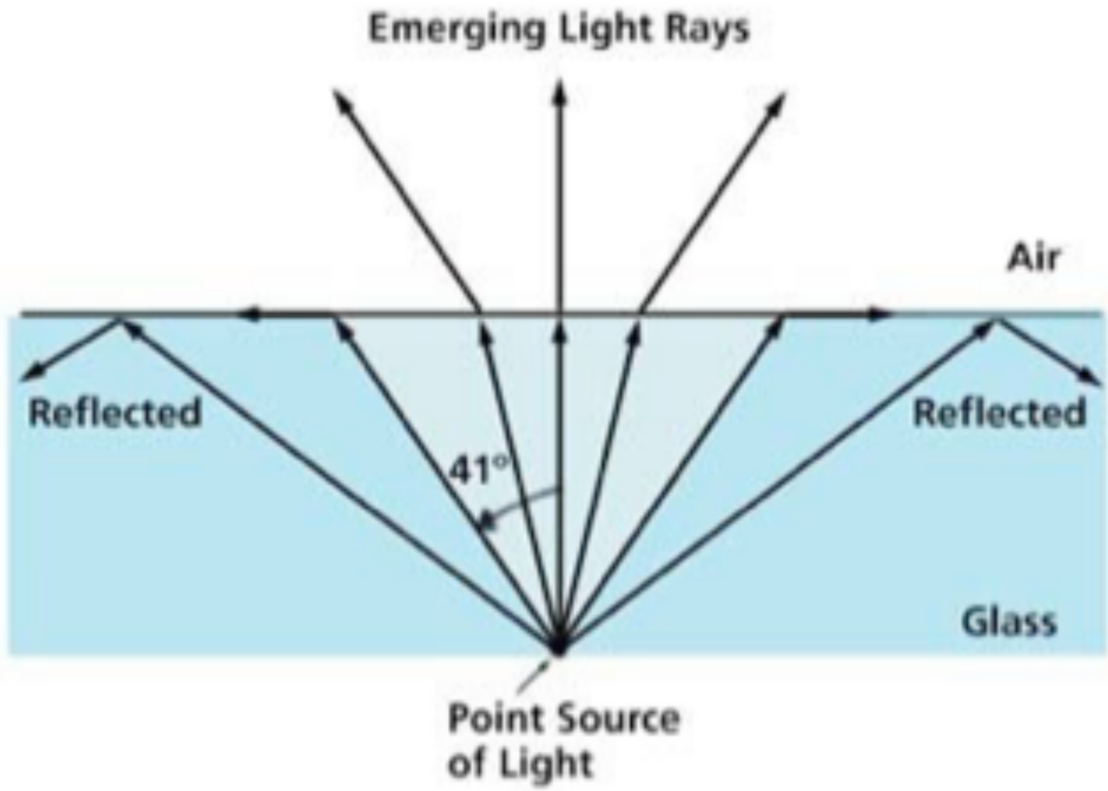




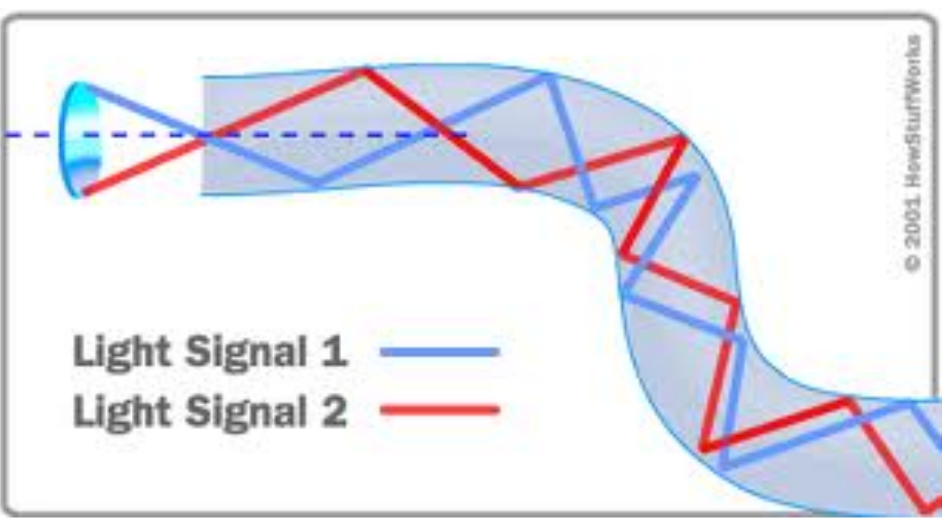
optical fiber – a "wire" for lights



Total internal reflection

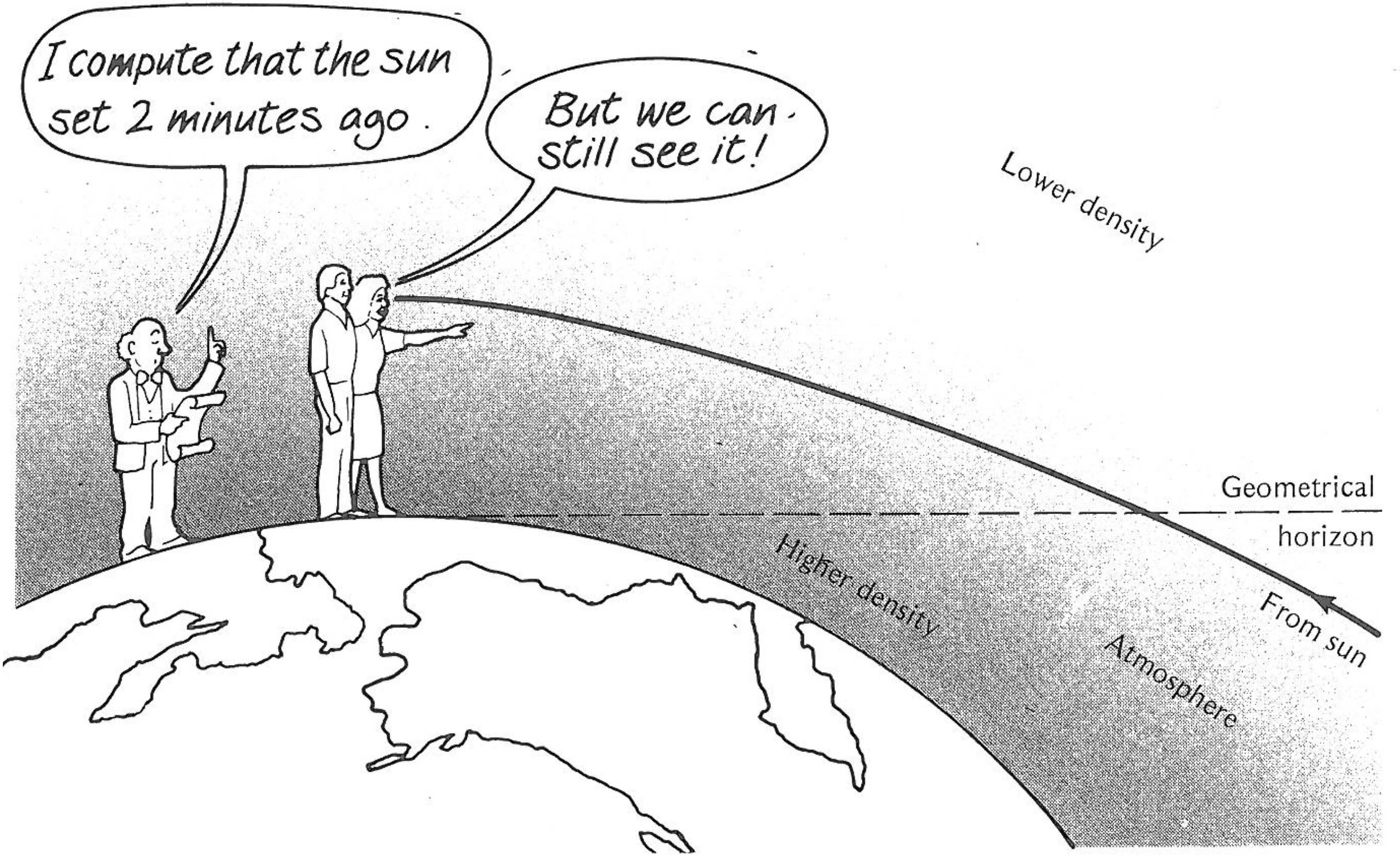


optical fiber – a "wire" for lights



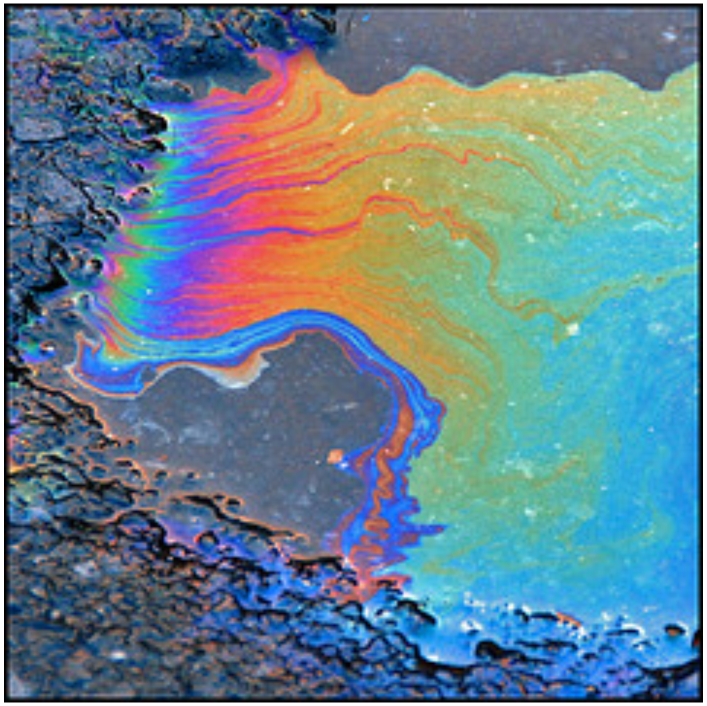
Refraction through atmosphere

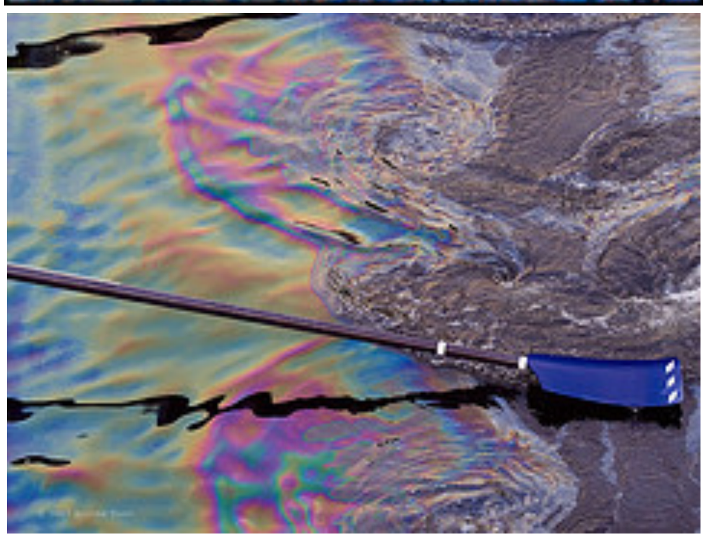
optical illusion

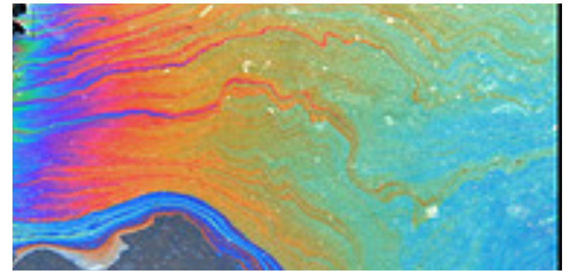


Thin film refraction & interference

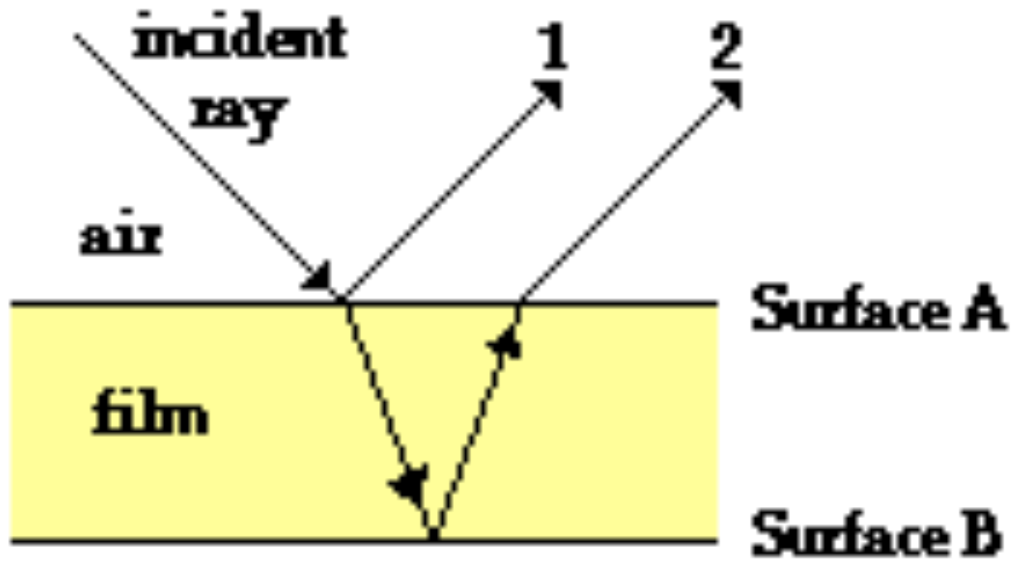
oil film on water:







interference

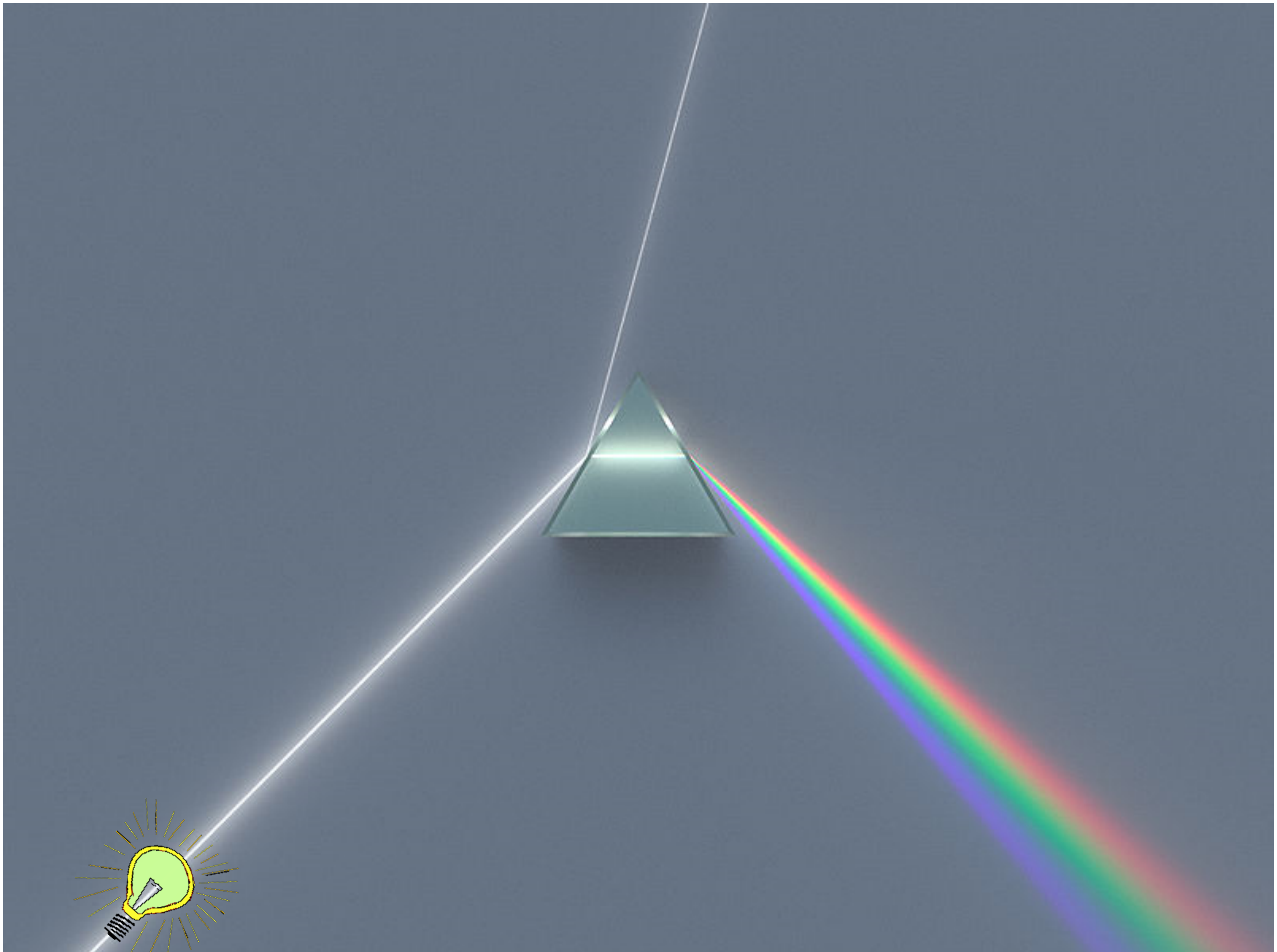


Prism: refraction and dispersion

Dispersion: different wavelenths (colors) refract at different angles:

$1 < n_{red} < n_{blue} < n_{UV}$ (for glass)

A prism spreads out the overlapping wavelengths of white light into different spatial locations where they can be seen as colors



Prism and rainbow

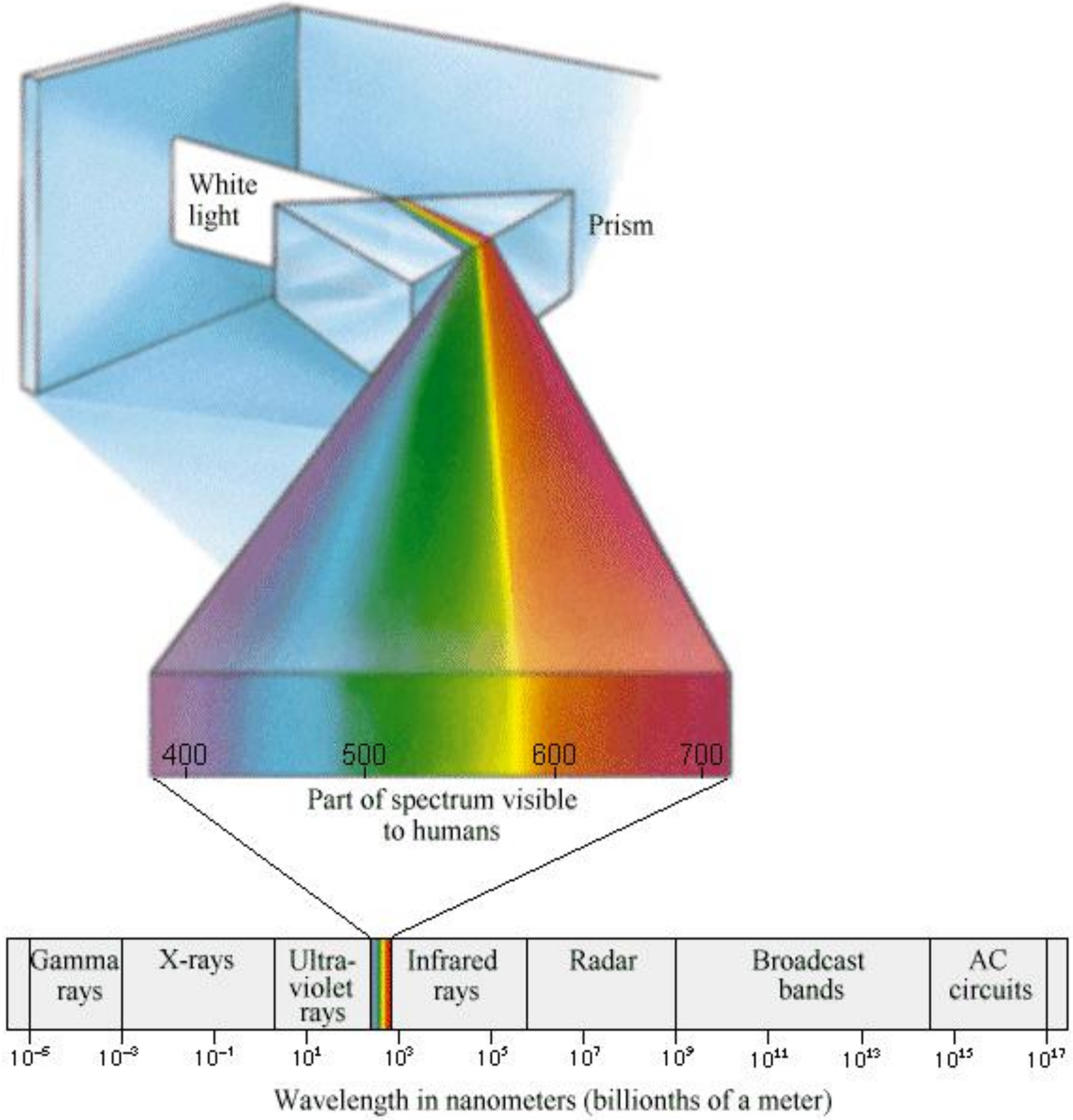
Dispersion: different wavelenths (colors) refract at different angles:

$1 < n_{red} < n_{blue} < n_{UV}$ (for glass)

A prism spreads out the overlapping wavelengths of white light into different spatial locations where they can be seen as colors

quartz glass

wavelength	n (index of refraction)
300 nm (UV)	1.486 (bent more)
500 nm	1.462
700 nm (deep red)	1.455 (bent less)



Prism and rainbow

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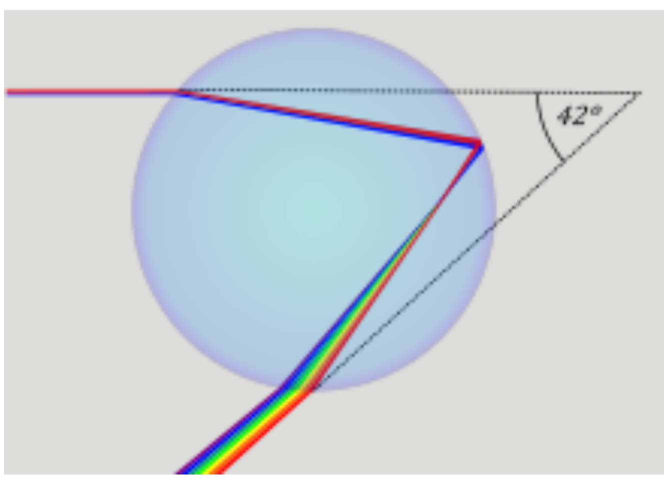
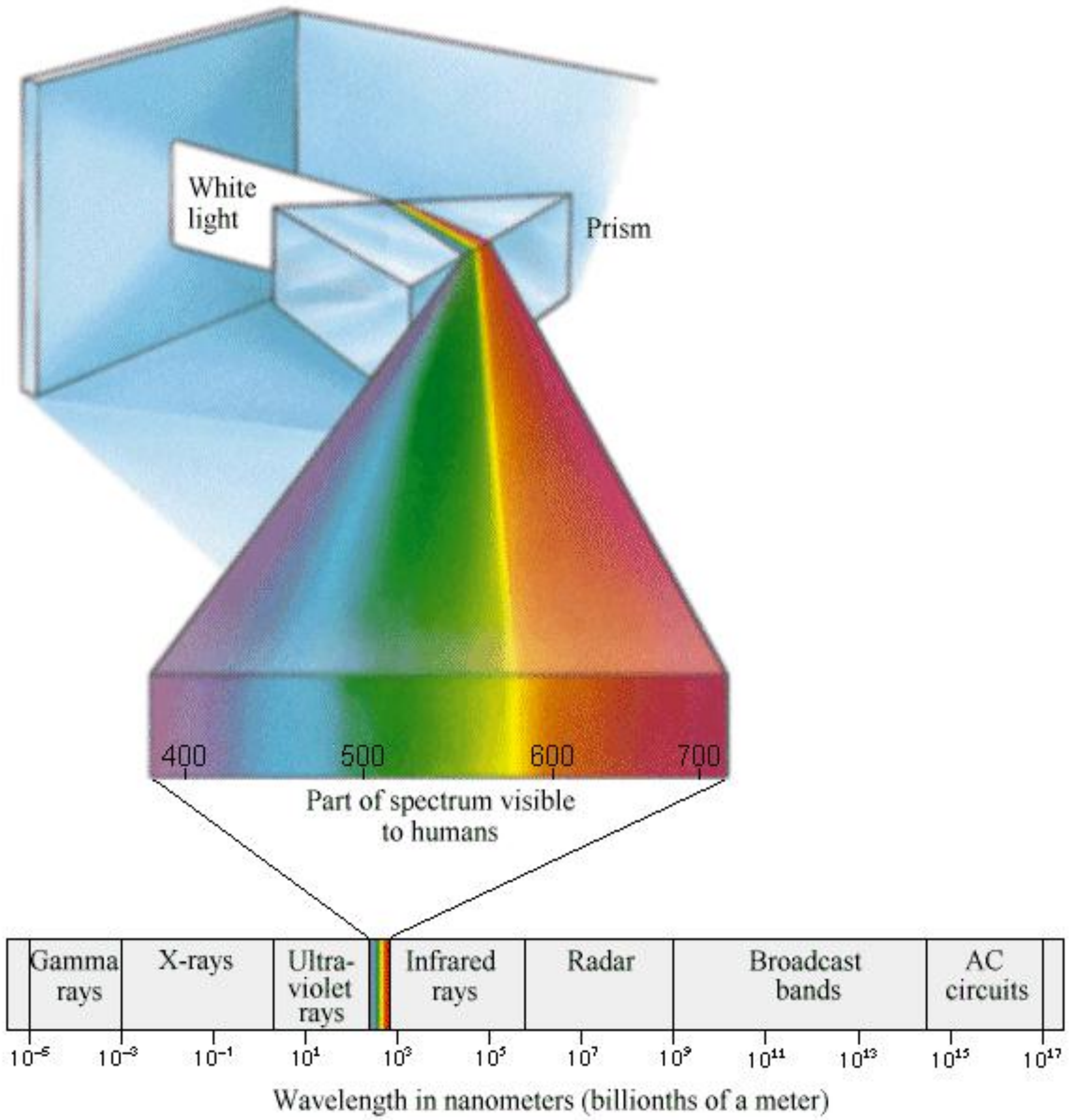
rainbow



water drop



clicker question

Interference

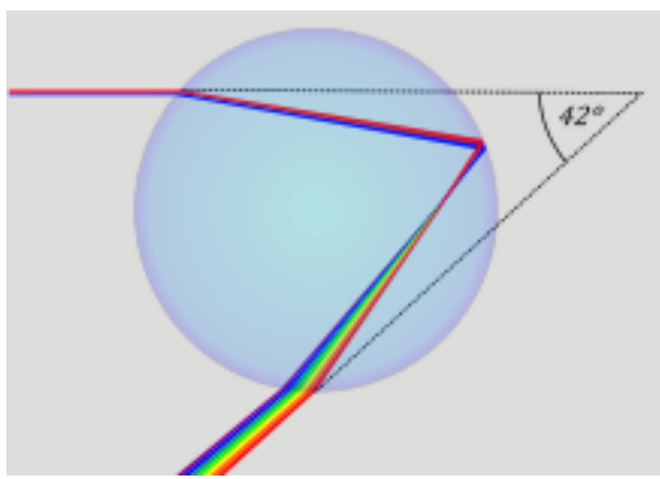
Q: *In vacuum, how does the speed of light depend on frequency and wavelength?*

a) Faster for higher frequencies and shorter wavelengths

b) Independent of the frequency and wavelength

c) Slower for higher frequencies and shorter wavelengths

A: *In vacuum speed of light is independent of color (frequency/wavelength).*
In a medium $v = c/n$ depends on color rainbow, prism



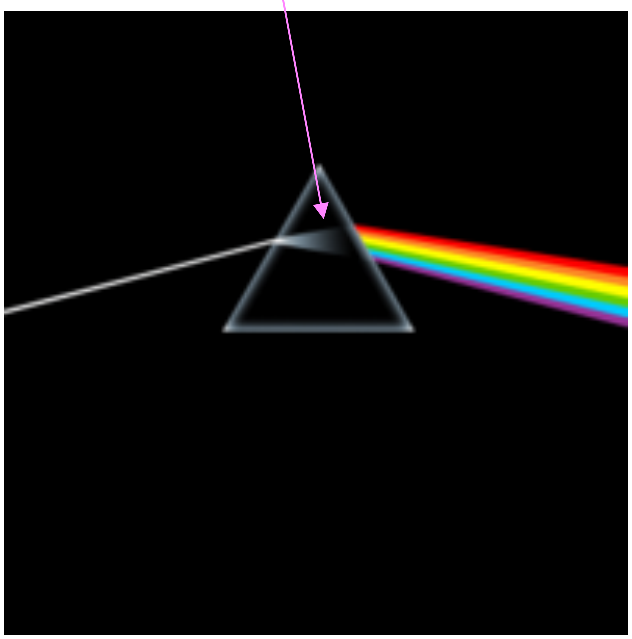
water drop

Rainbow

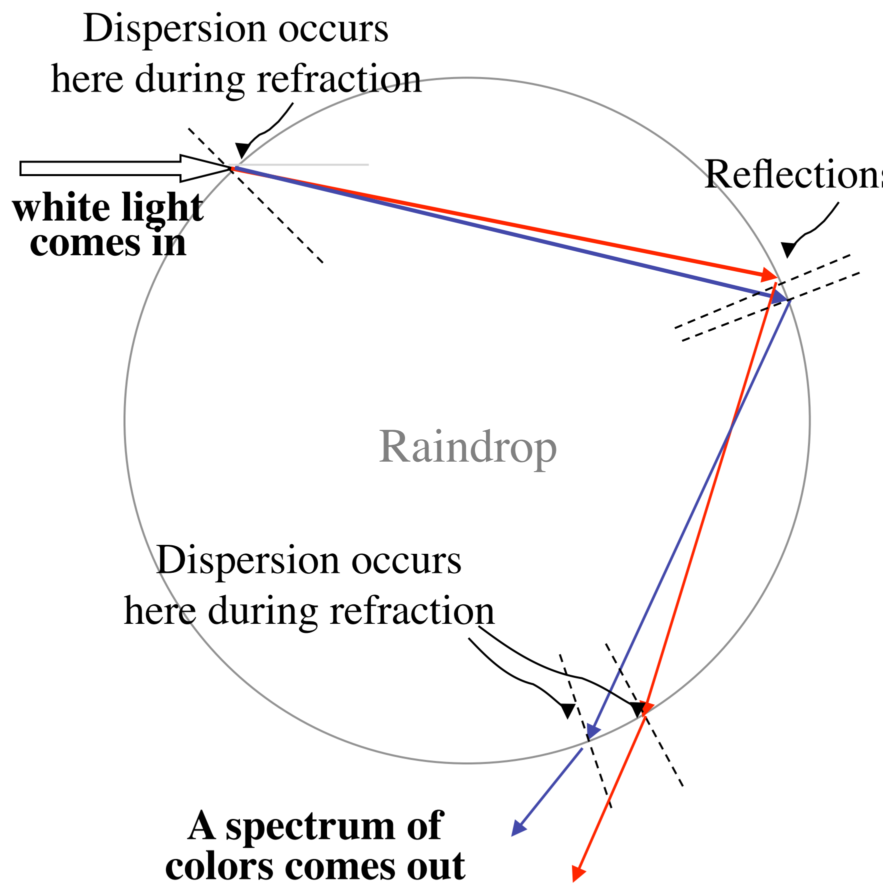
Q: *How do we see a rainbow?*

Pink Floyd is slightly wrong.

The colors are spread inside the prism as well as outside.



The colors start to spread inside the raindrop.

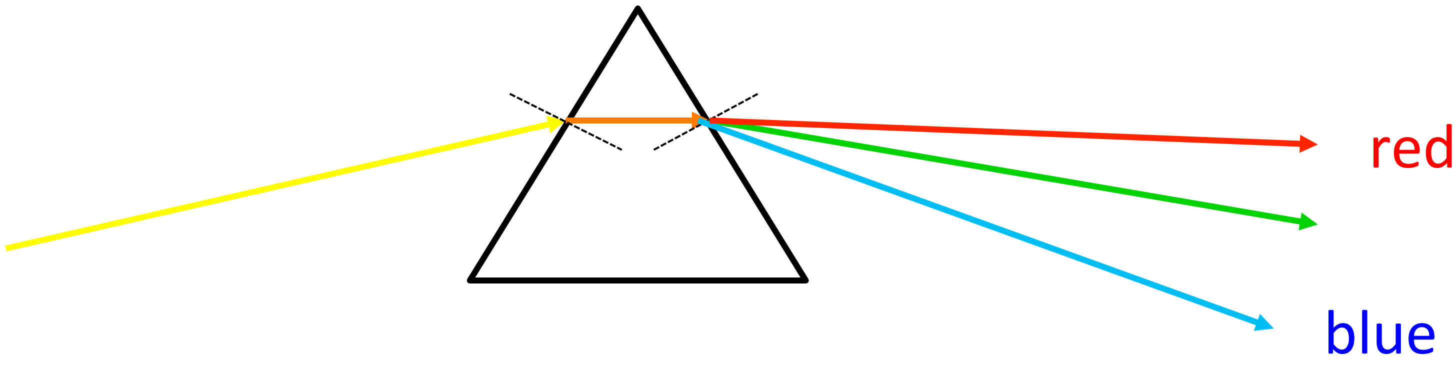


clicker question

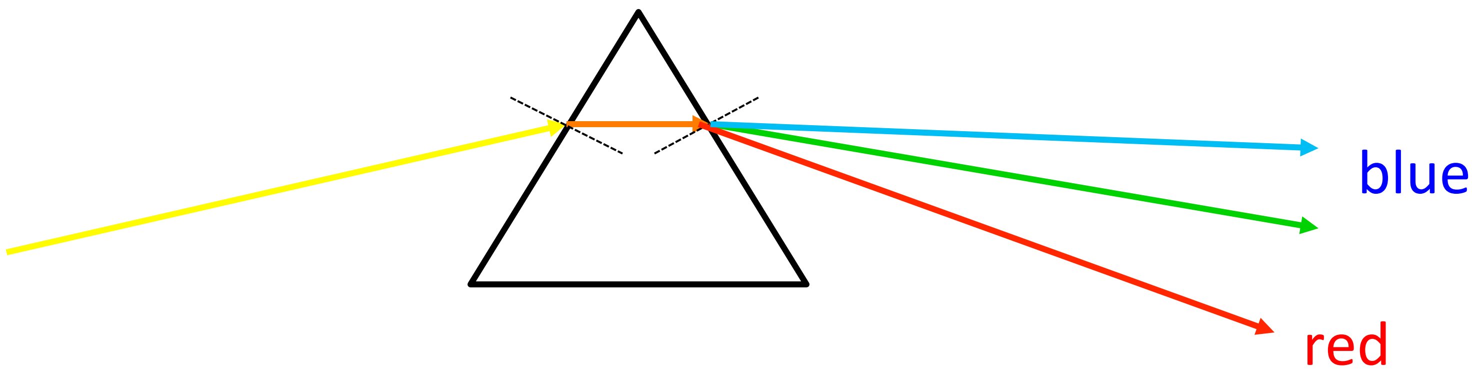
Dispersion: prism and rainbow

Q: *Where does blue come out of prism, compared to red?*

$\boxed{\text{a)}}$



b)

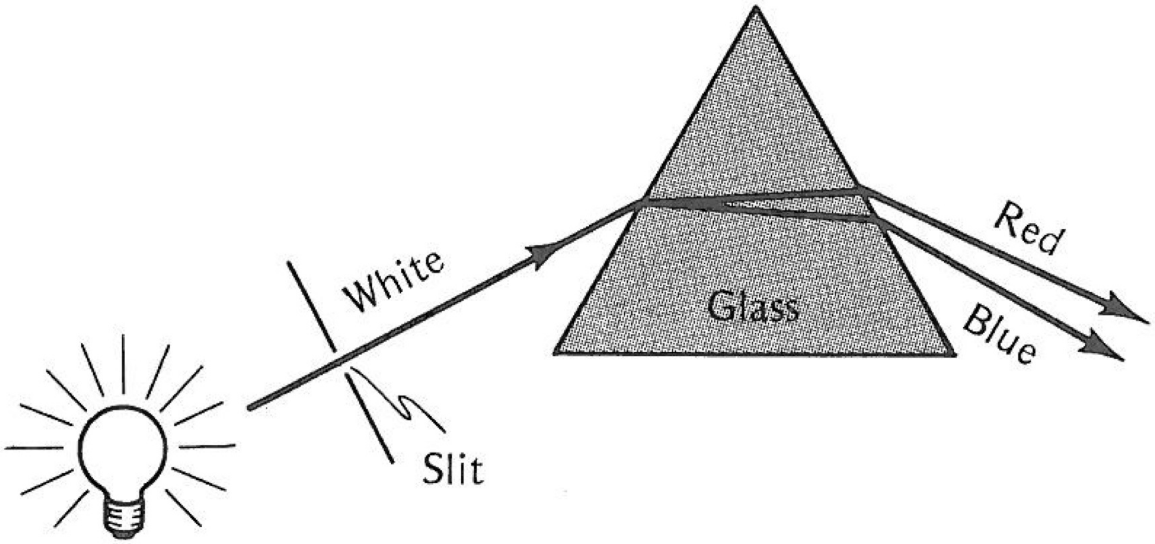


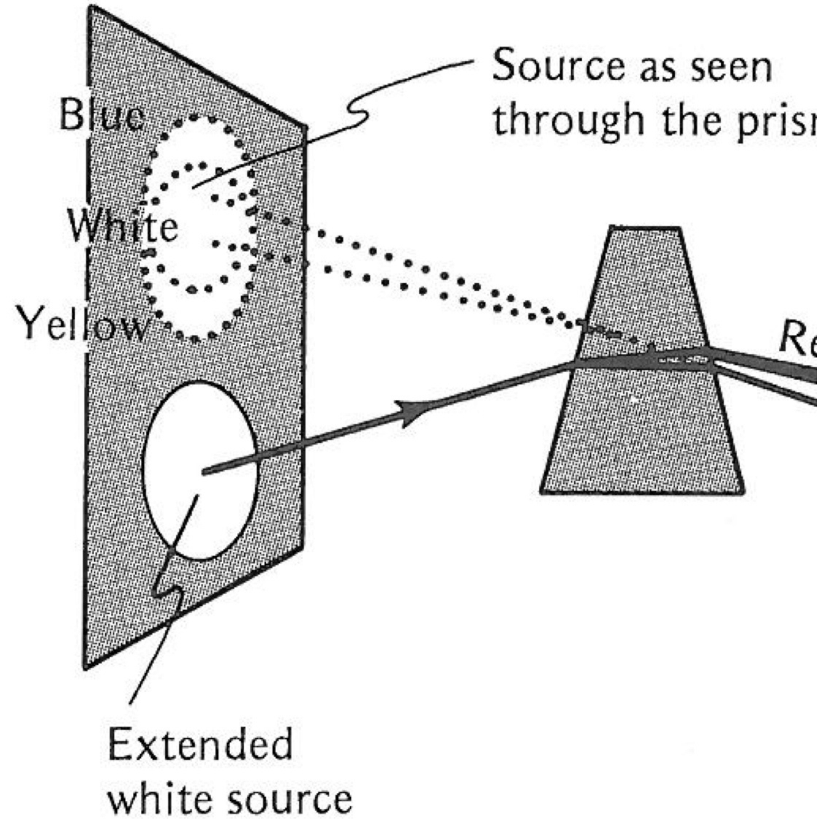
c) somewhere in the middle

A: *In glass blue slows down more than red*

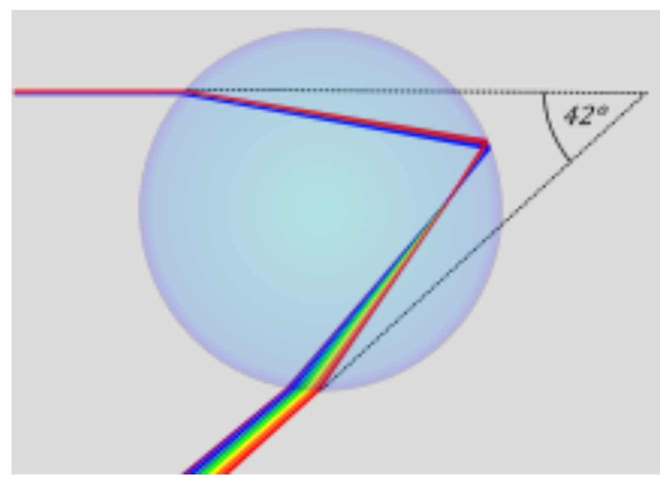
$1 < n_{red} < n_{blue} < n_{UV}$ (for glass)

Refracted dispersive images



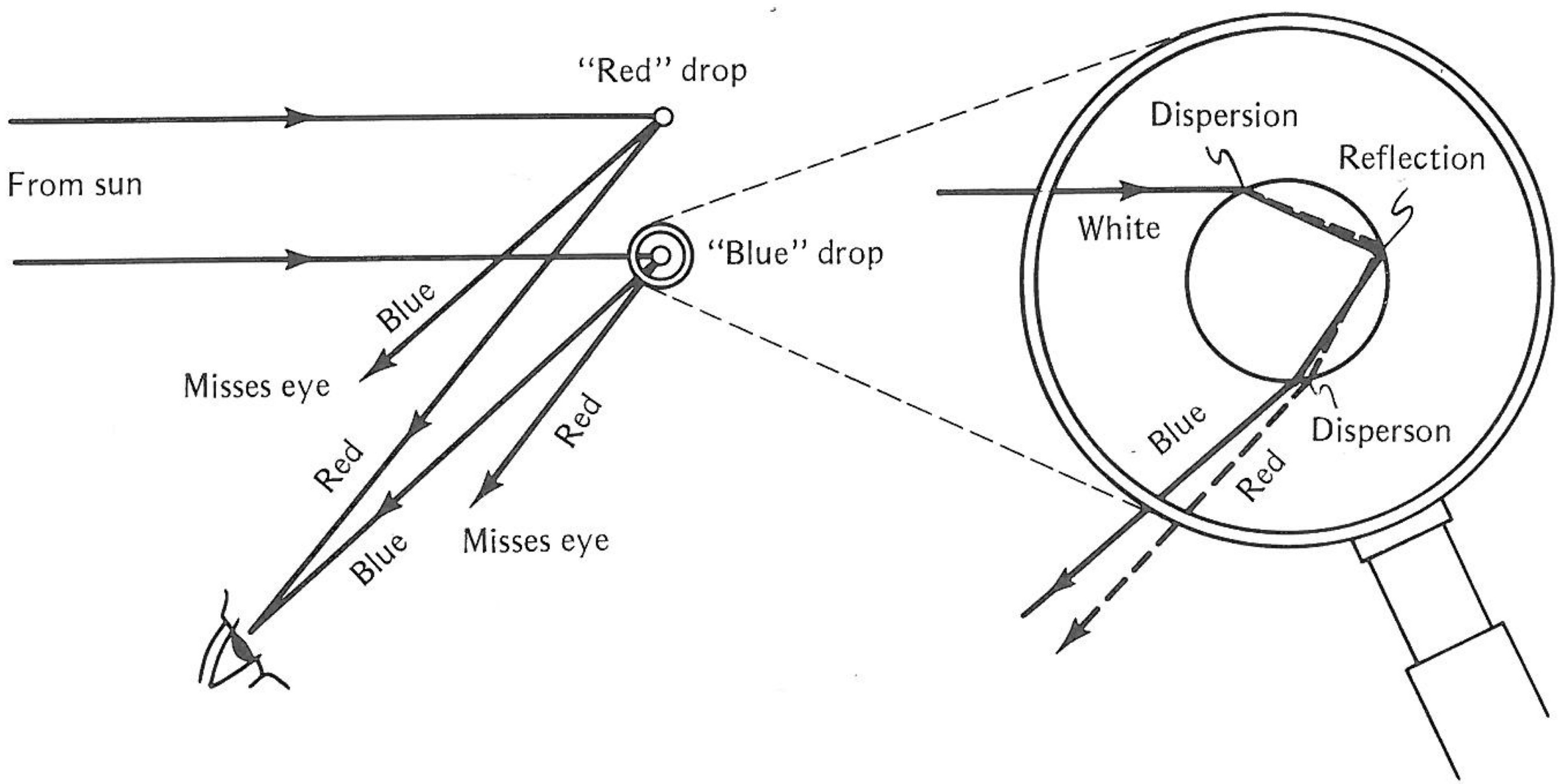


rainbow

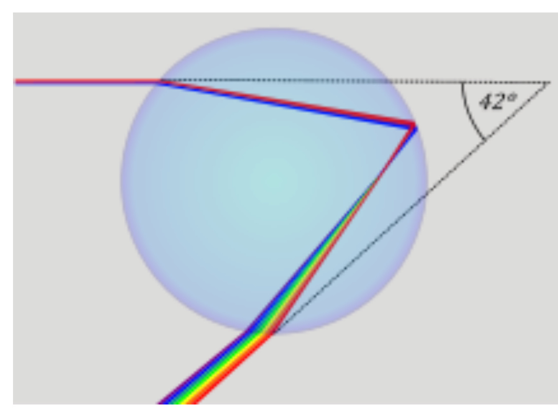


water drop

Refracted dispersive images

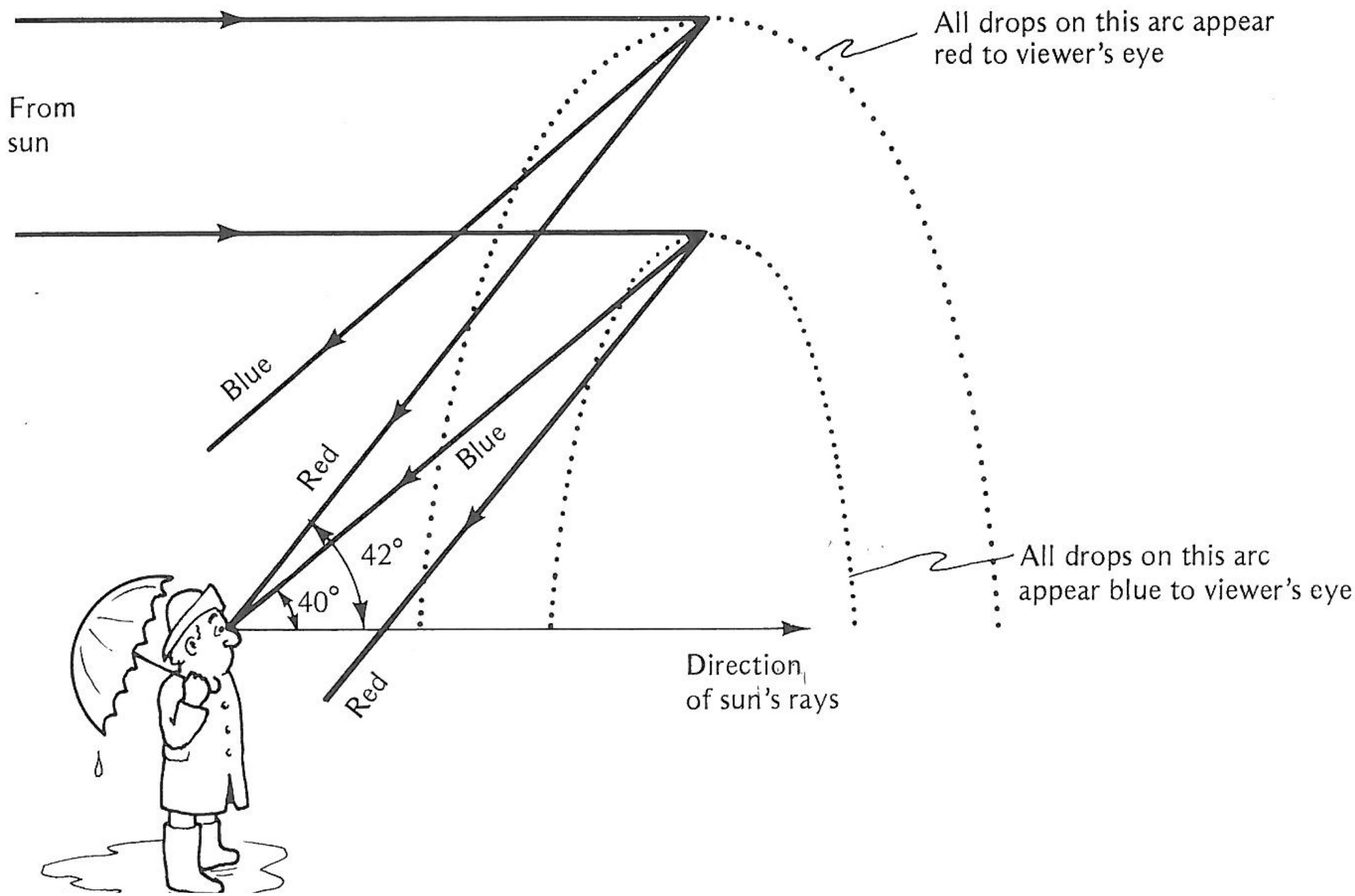


rainbow

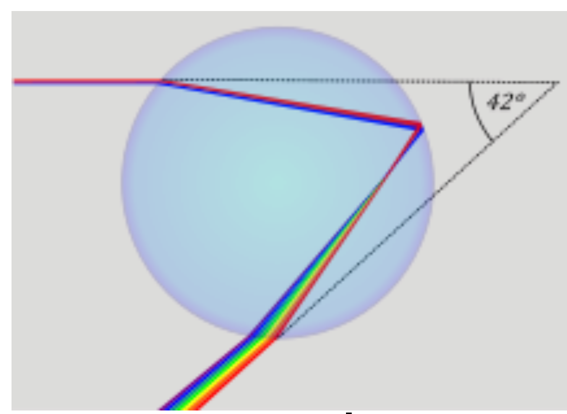


water drop

Refracted dispersive images



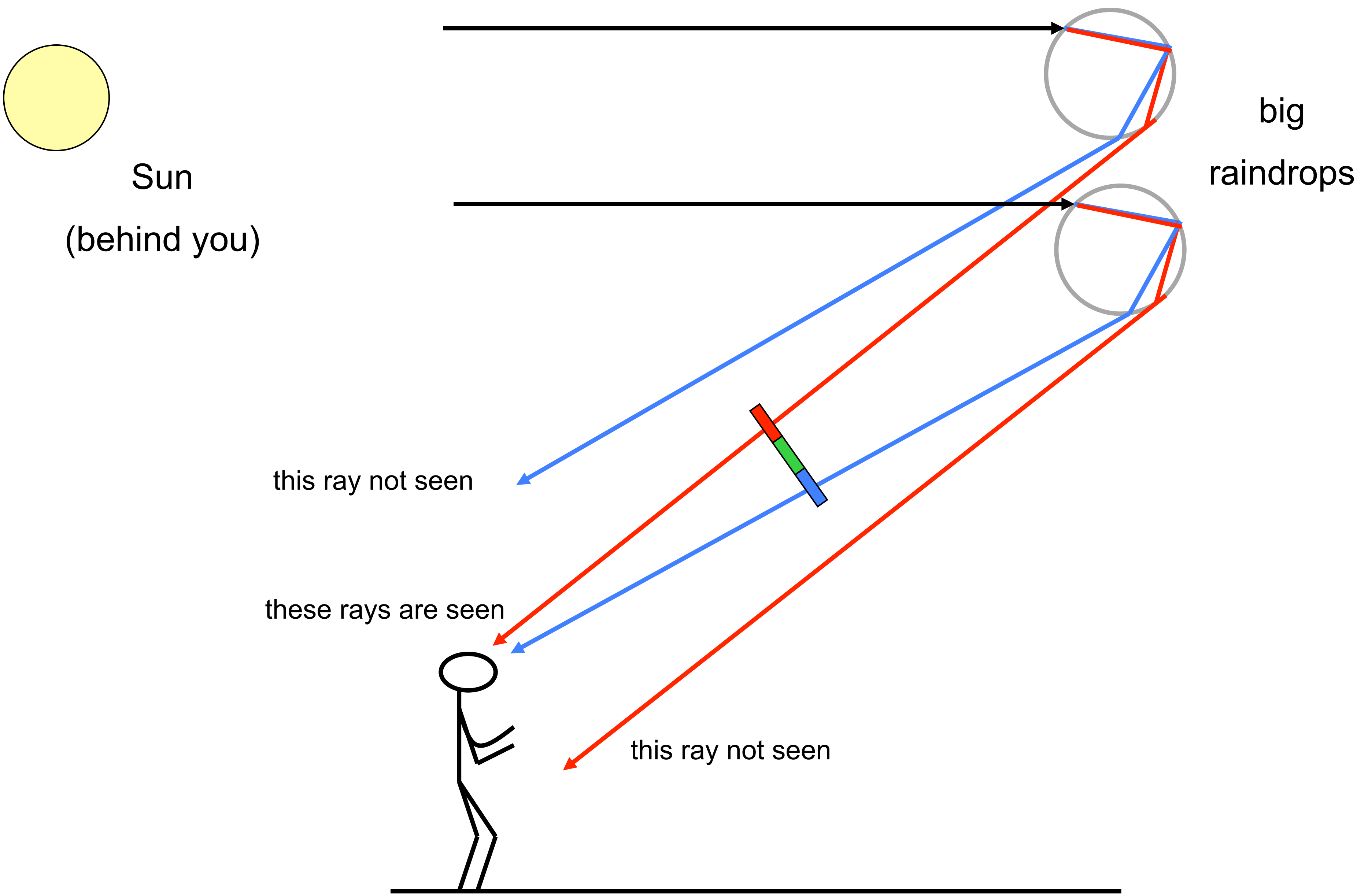
rainbow



water drop

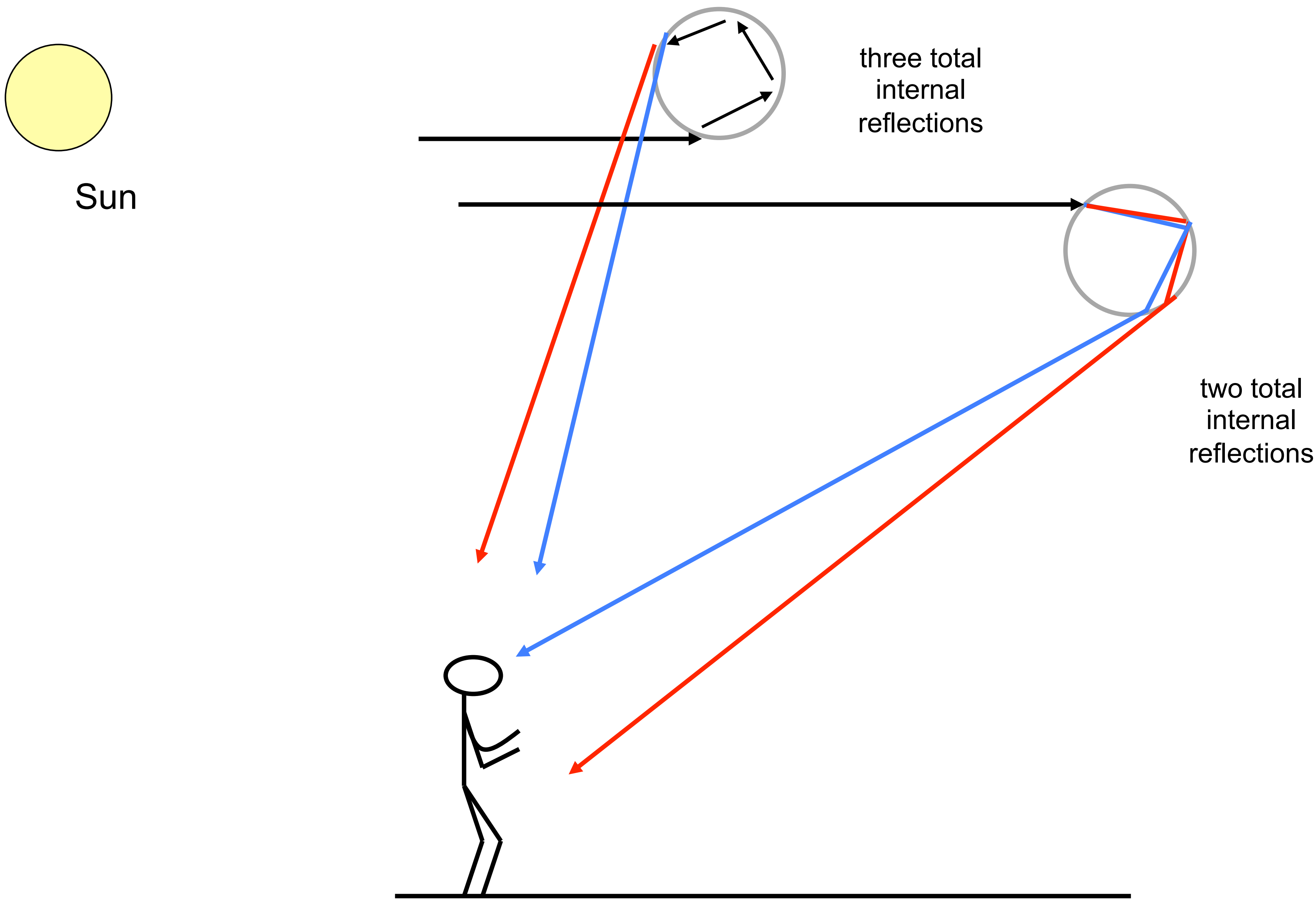
Rainbow

Q: *How do we see a rainbow?*



Double-rainbow

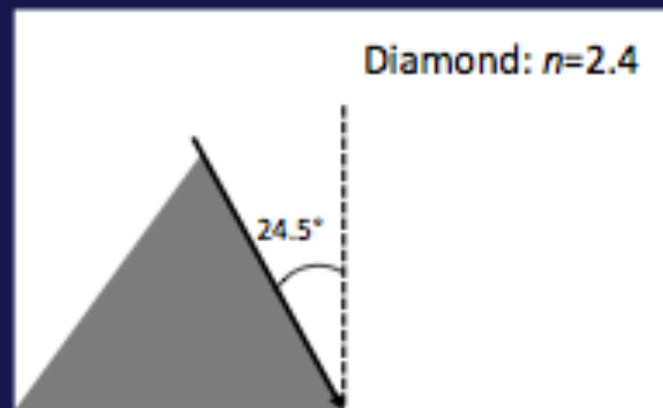
Q: *How do we see two rainbows?*



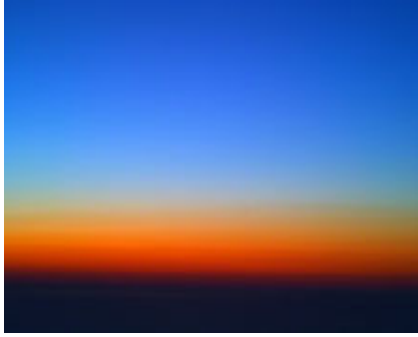
Diamond's brilliance

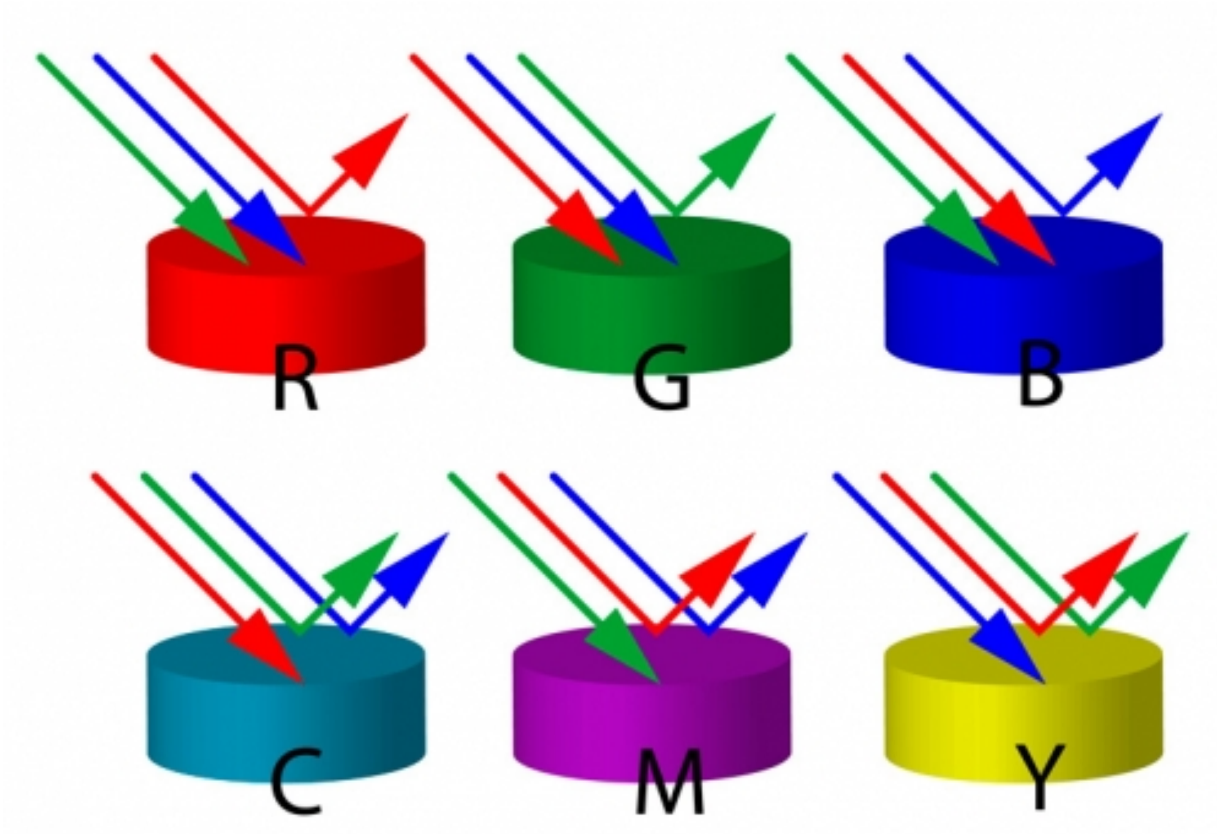
Diamonds

- Diamond has a very high index of refraction leading to a small critical angle for total internal reflection
- Diamonds are cut such that most light entering will hit a back facet at more than the critical angle, reflecting many times before returning out the front
- This long path through the diamond leads to a lot of dispersion, spreading the colors out



Colors by absorption and reflection





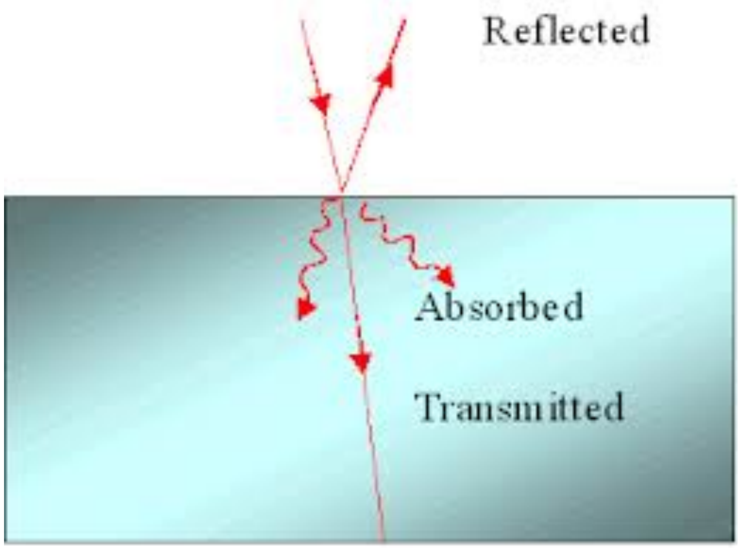
Object's color is determined by the frequencies of illuminating light that it reflects back into your eyes. Colors that its molecules absorb are the colors you do not see.

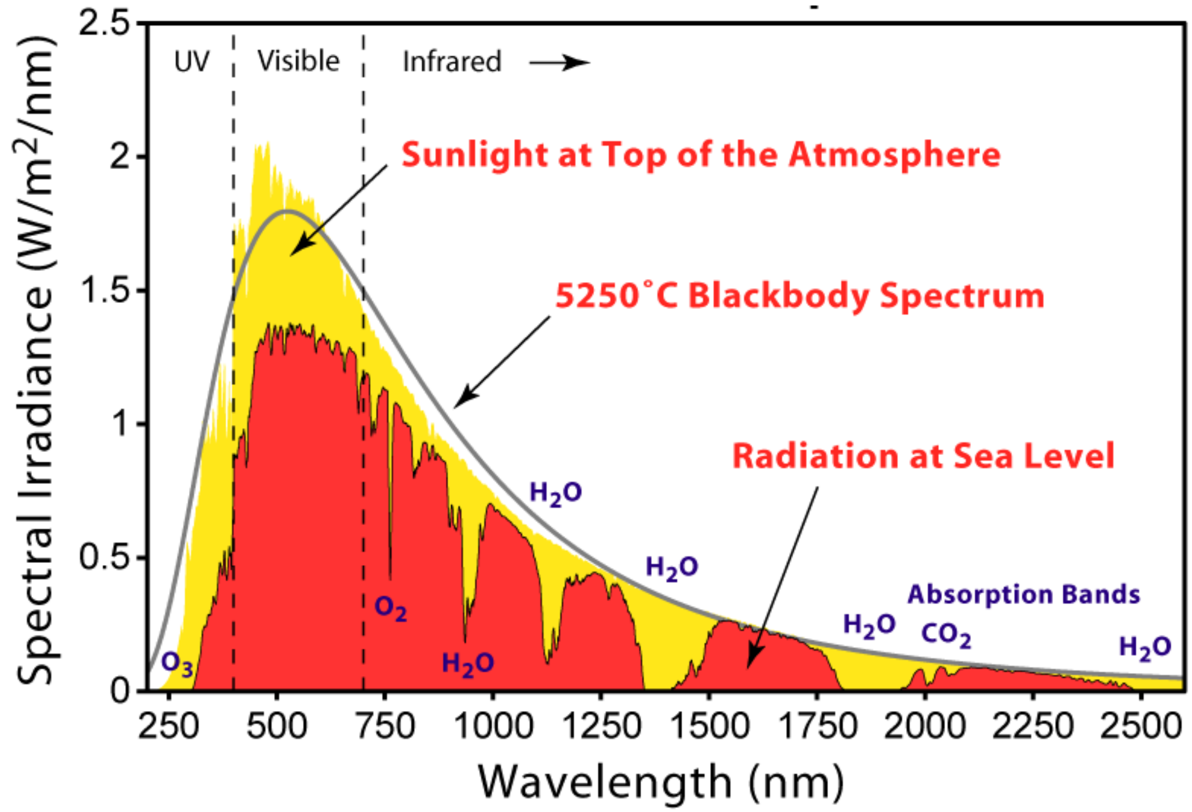
Black = all frequencies are absorbed, none reflected

White = none of the frequencies are absorbed, all reflected

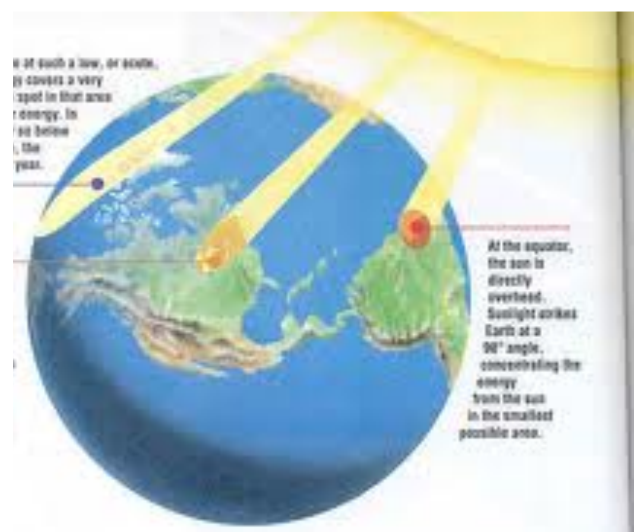
Absorption of light

- sun light absorption by atmosphere:





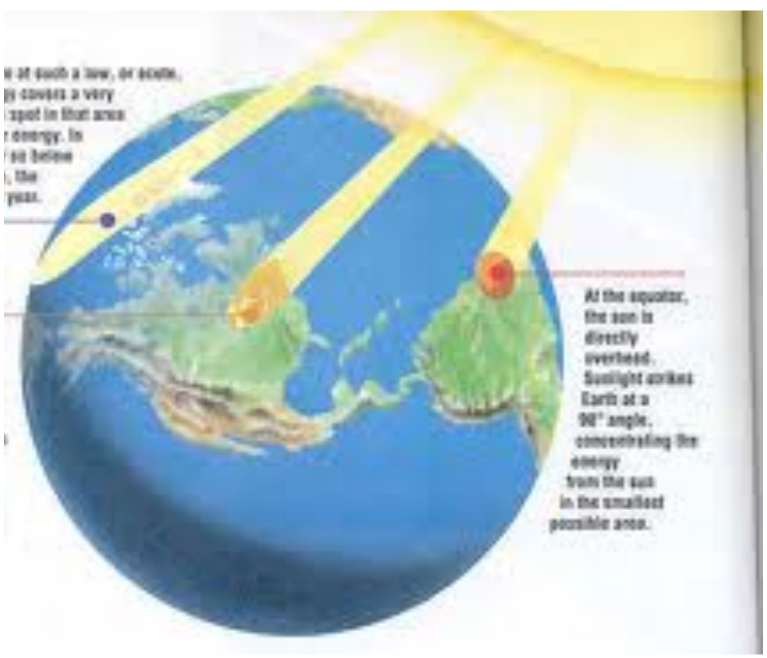
- absorption by medium -> heat

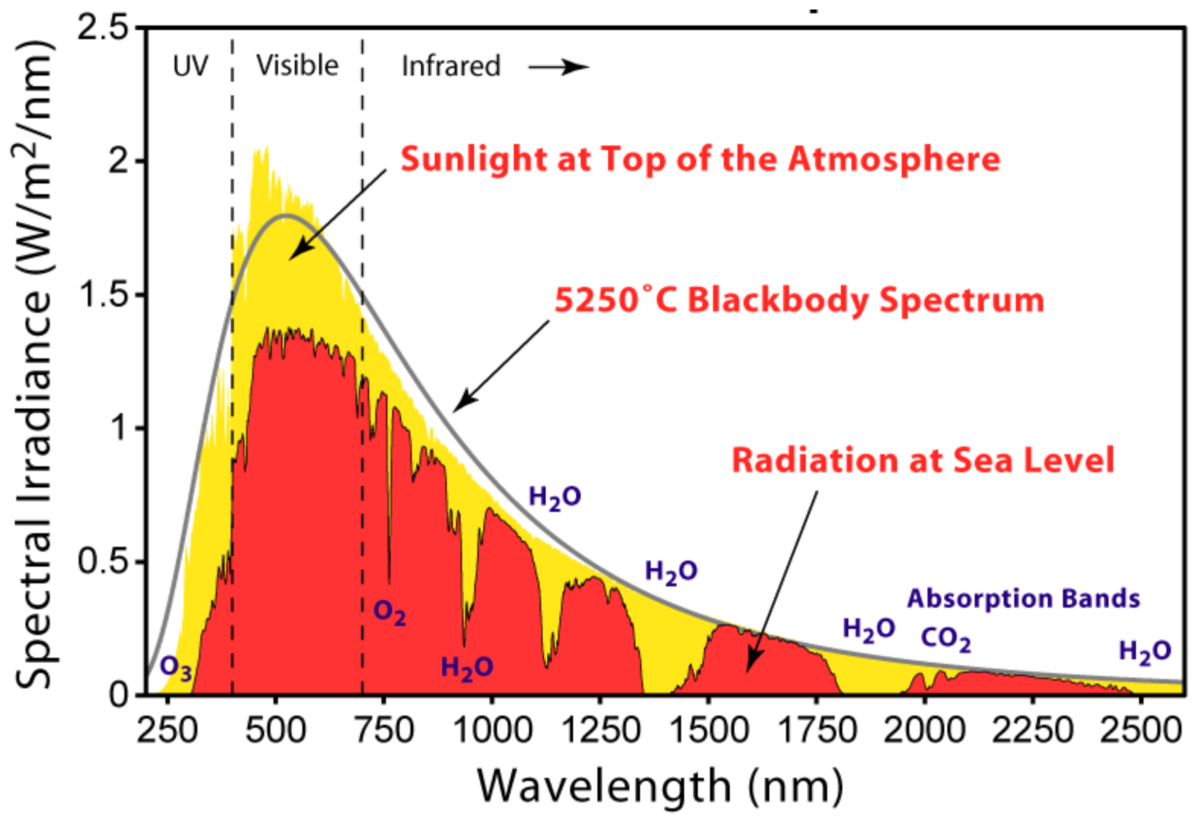


Absorption of light

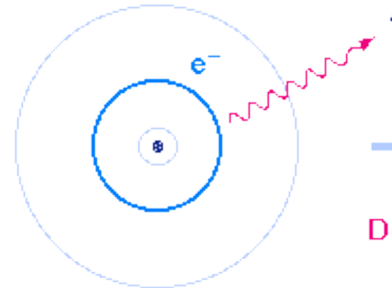
sun light absorption and earth emission

- Sunlight power is constant at 1000 W/m^2 (UV and x-ray output varies)
- Earth's temperature is a balance between sunlight in and infrared radiation out
- Carbon dioxide blocks infrared going out and has a warming effect

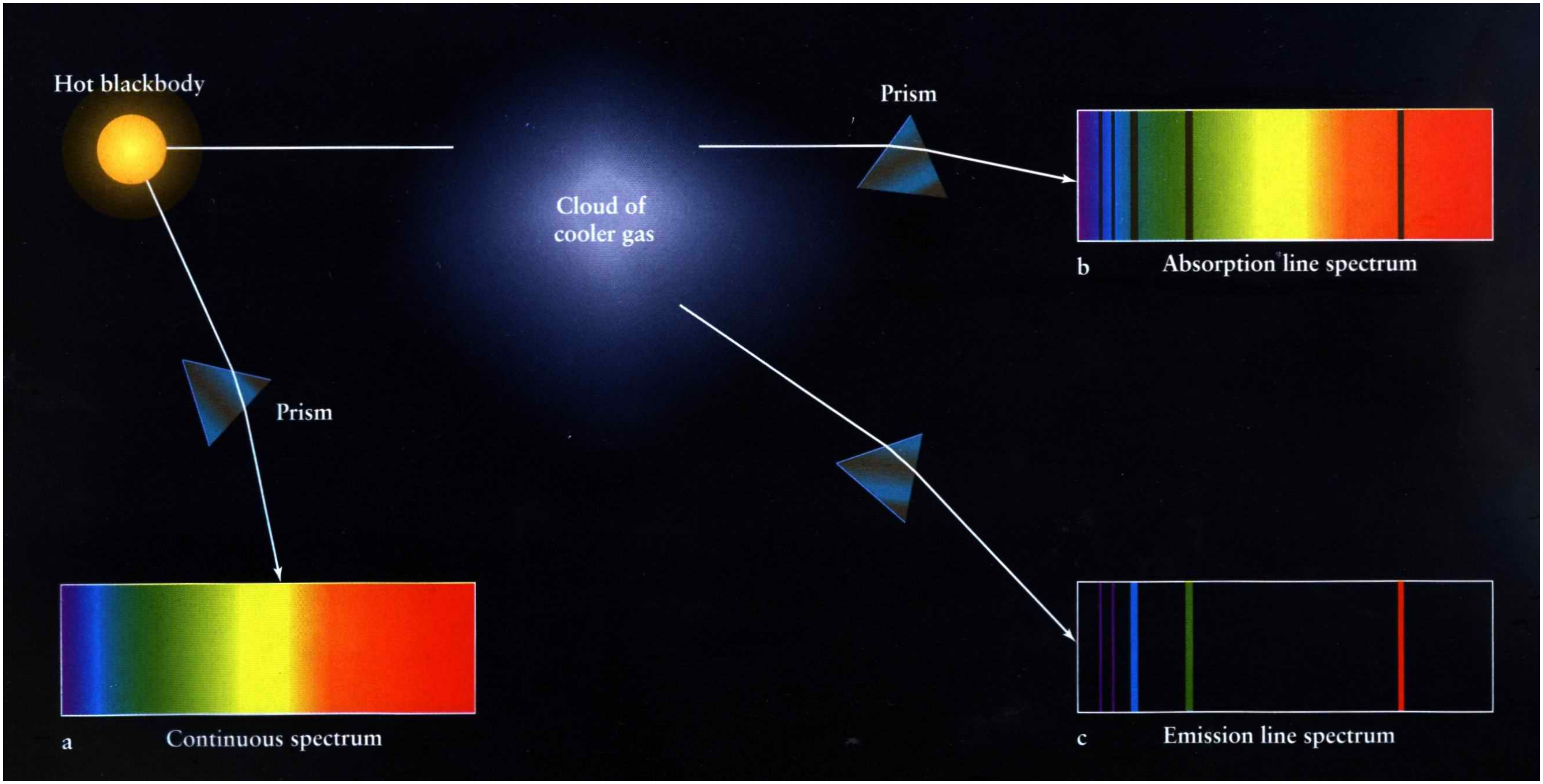




Absorption of light



- Absorption and Fraunhofer lines:



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

clicker question

Double-rainbow

Q: *How do you get double-rainbow?*

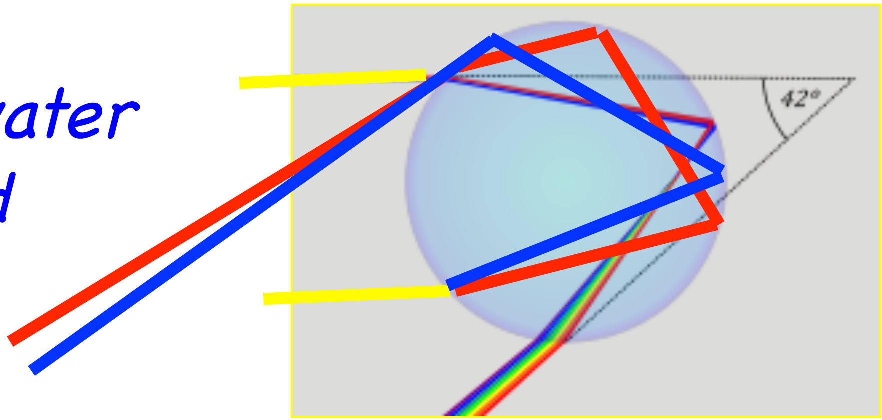
a) Magic

b) Double-reflection within droplets, before light comes out toward you

c) Inteference from multiple droplets

d) No idea

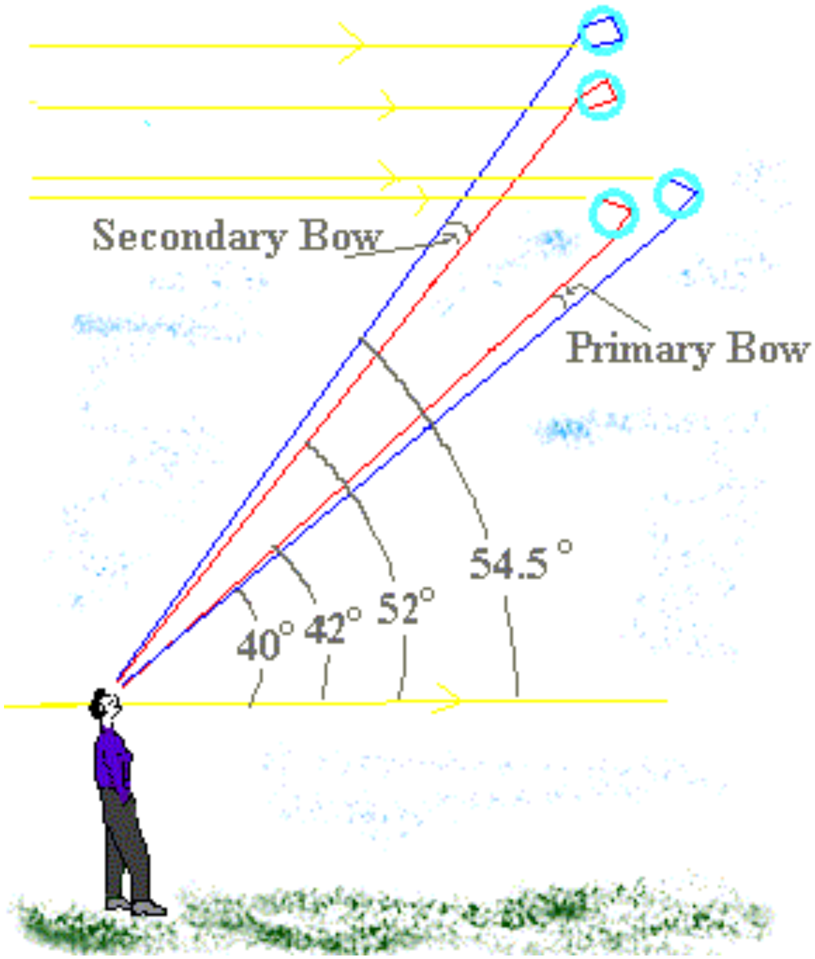
A: *Light reflects twice inside the water droplet before coming out toward your eyes*



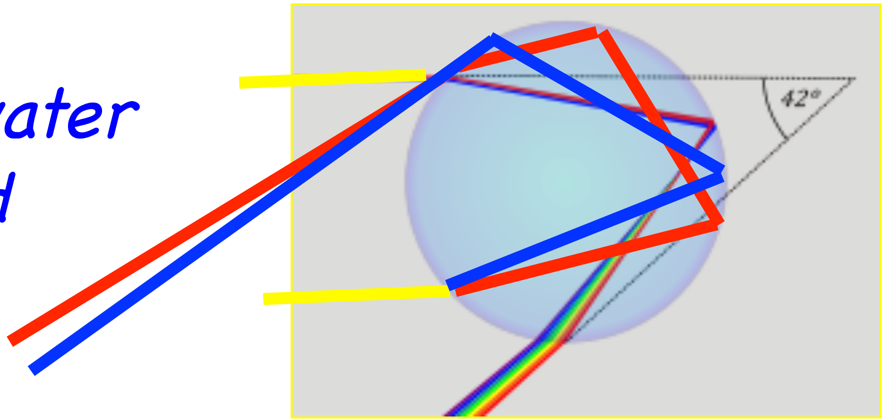
clicker question

Double-rainbow

Q: *How do you get double-rainbow?*



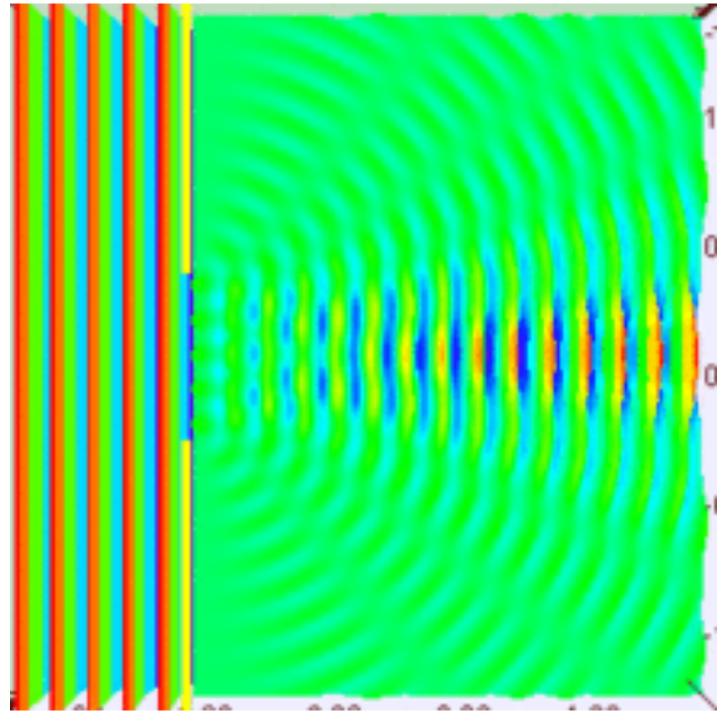
A: *Light reflects twice inside the water droplet before coming out toward your eyes*



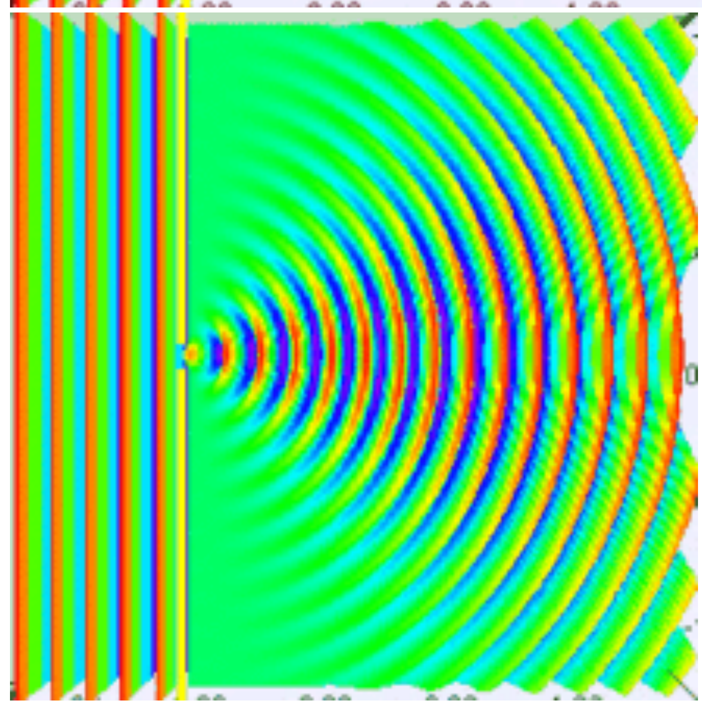
Diffraction

Breakdown of ray optics:

- $d = 5\lambda$



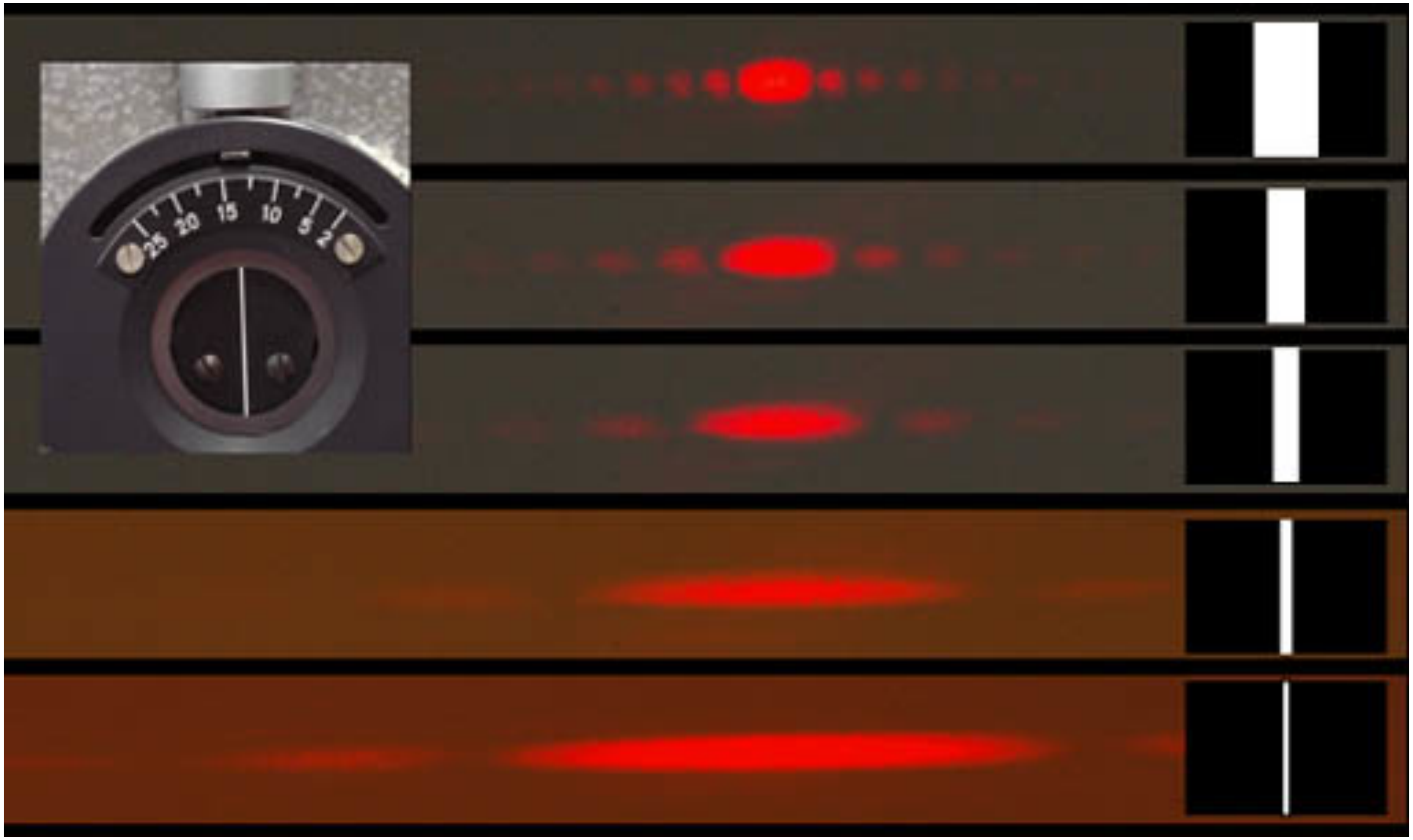
- $d = \lambda$



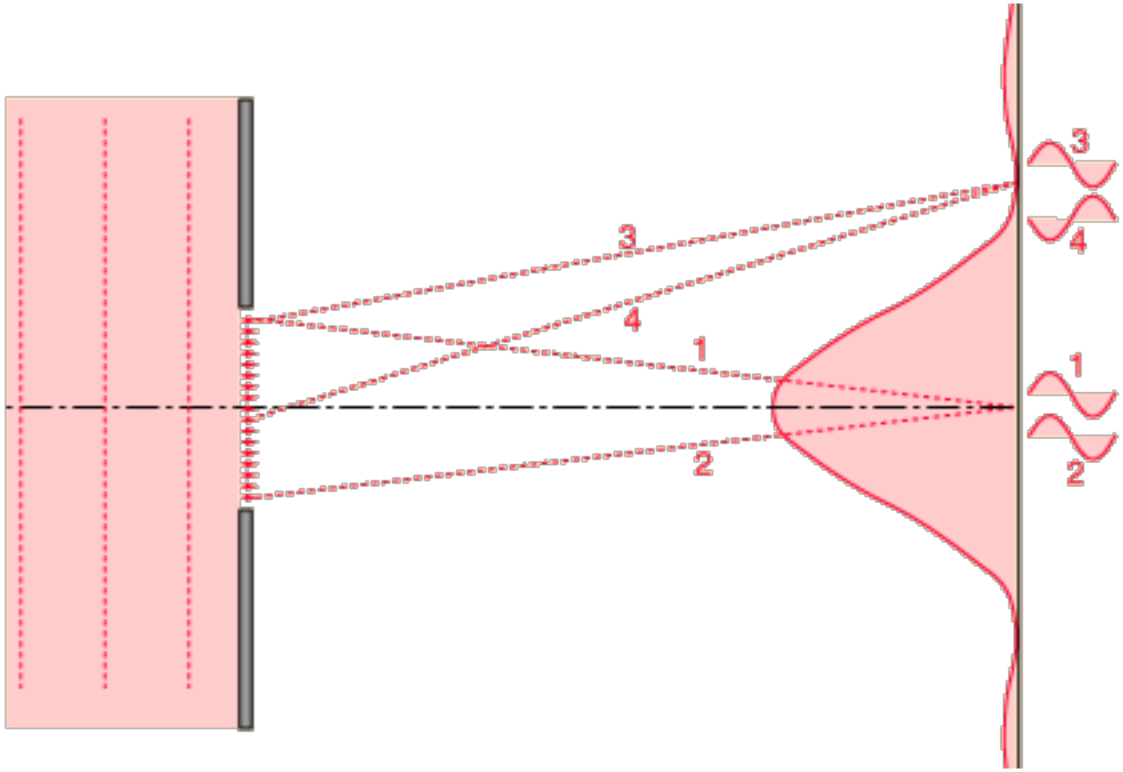
Diffraction

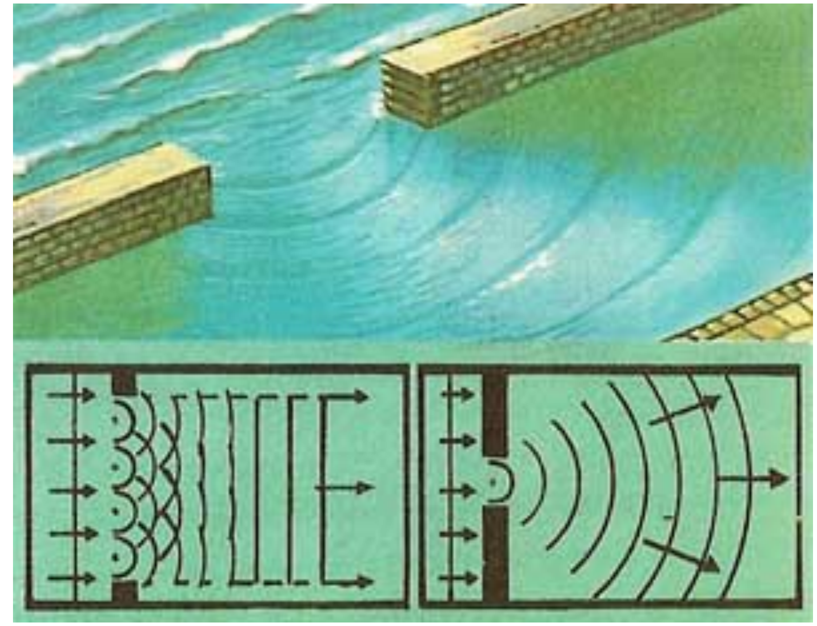
Breakdown of ray optics: *single slit, with $d \approx \lambda$*

slits

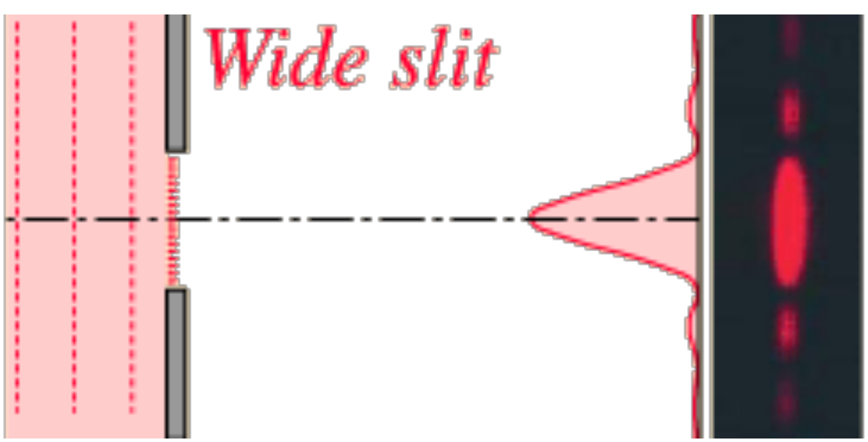


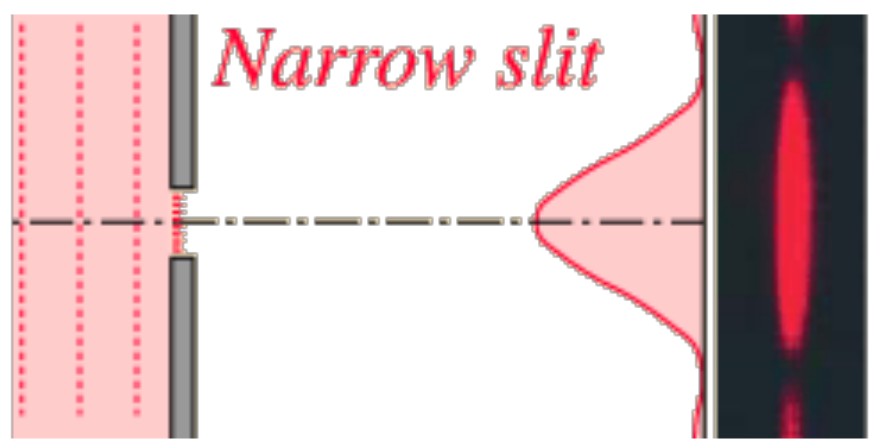
Diffraction



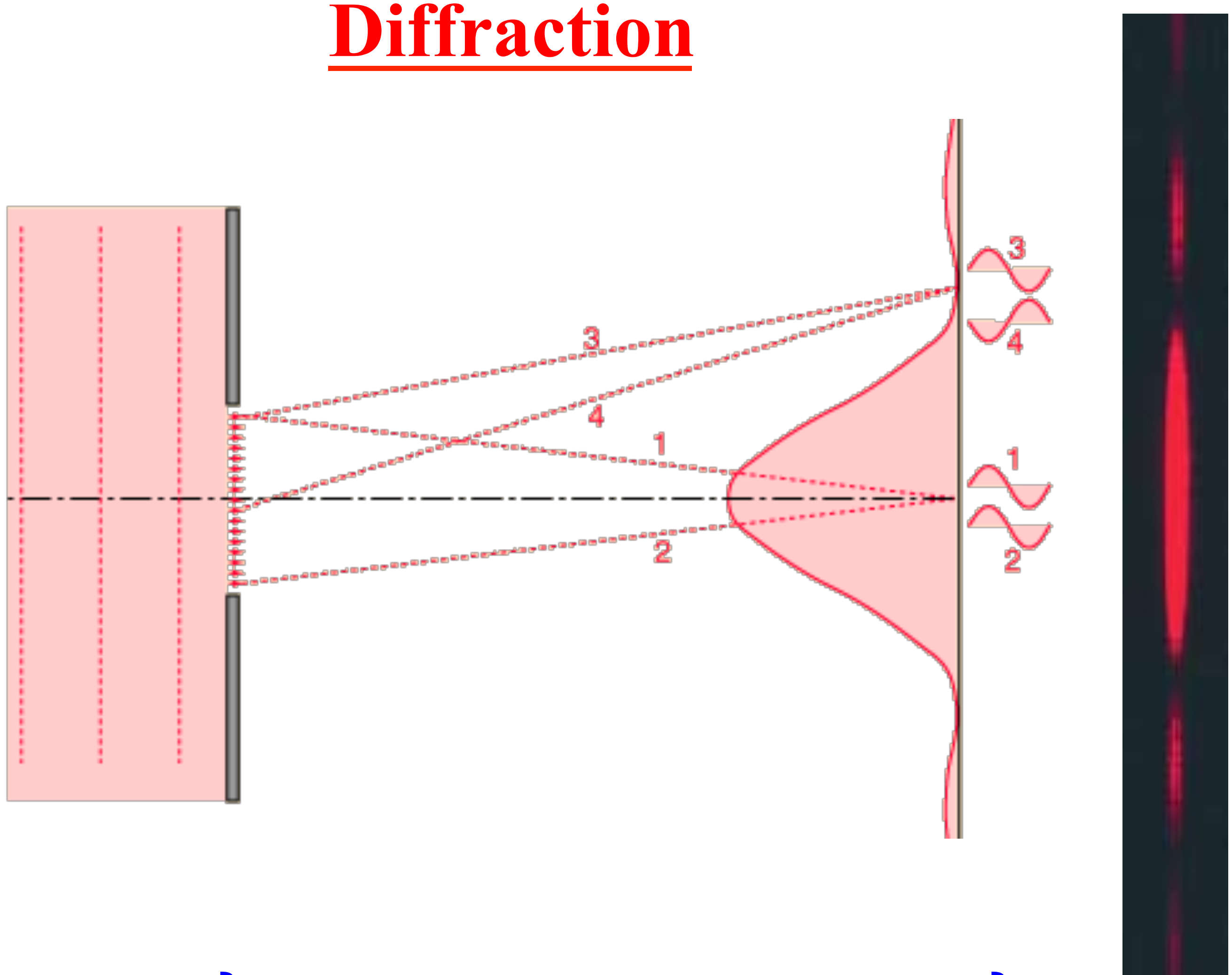


$d >> \lambda$ $d \approx \lambda$



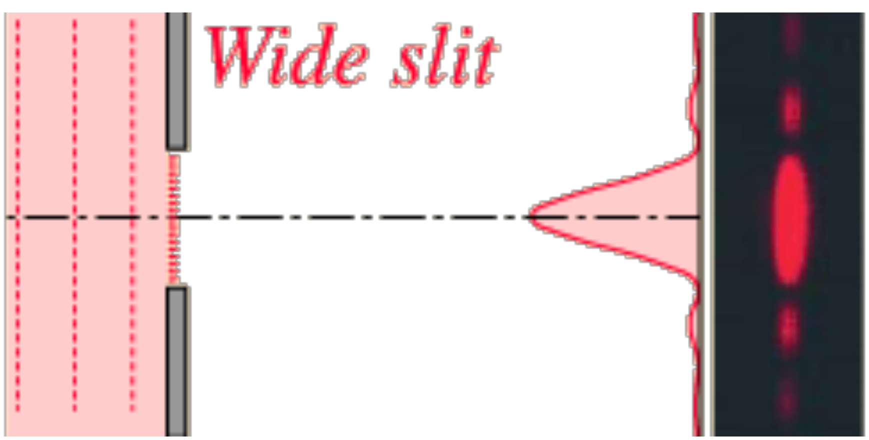


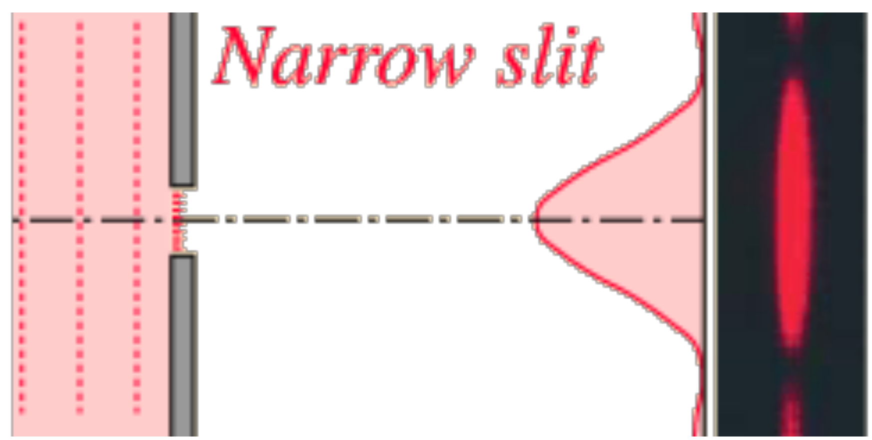
Diffraction



$d \gg \lambda$

$d \approx \lambda$





Reflection in more detail

- light travels in straight line in a homogeneous medium
- reflection takes place when medium changes abruptly to one with different speed
- large change in speed -> strong reflection
  no speed change -> no reflection

. string analogy: tied to a wall vs tied to a heavy rope

. full reflection from vanity mirror

. partial reflection from a glass or half-silvered mirror

. colored reflection from gold, aluminum, silver mirrors

Reflection: RADAR

- RADAR = RAdio Detection And Ranging: *(microwaves 1cm – 1m 300MHz – 30GHz)*

  measures time to reflect EM waves

  . infers distance (to object) = speed x time

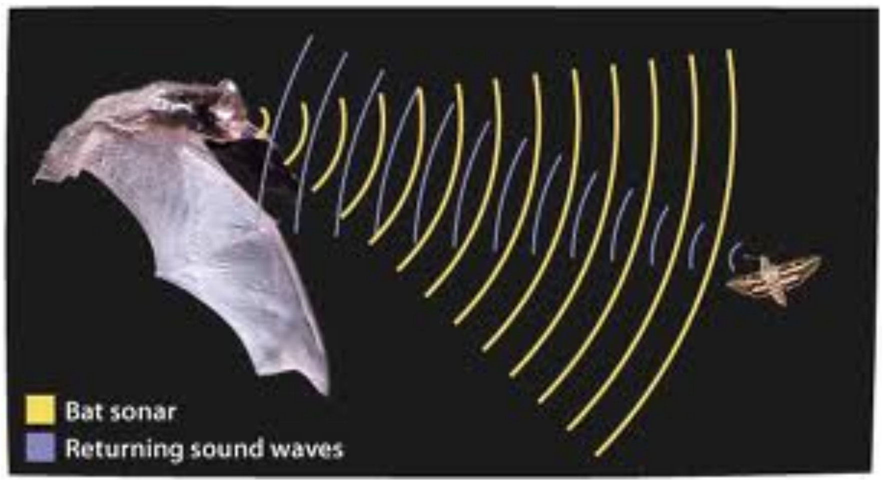
  . infers speed of moving object from change in wavelength of reflected light

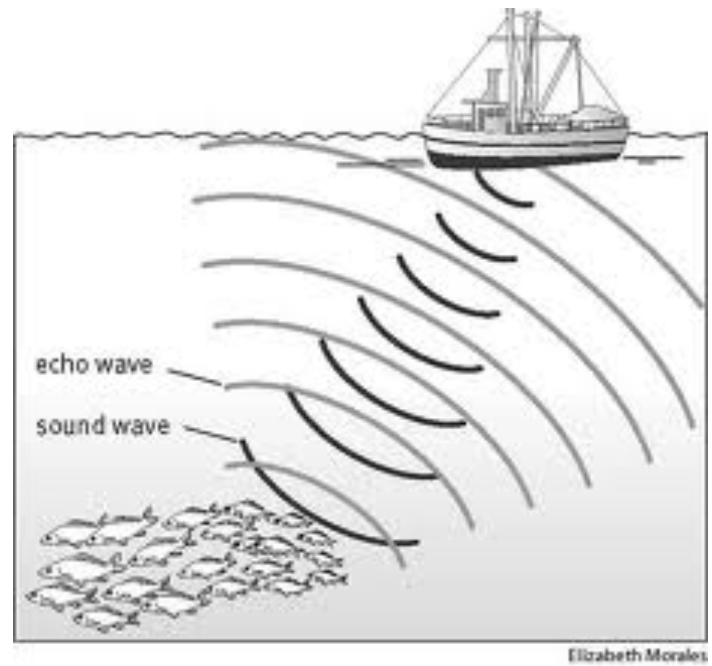
Reflection: SONAR

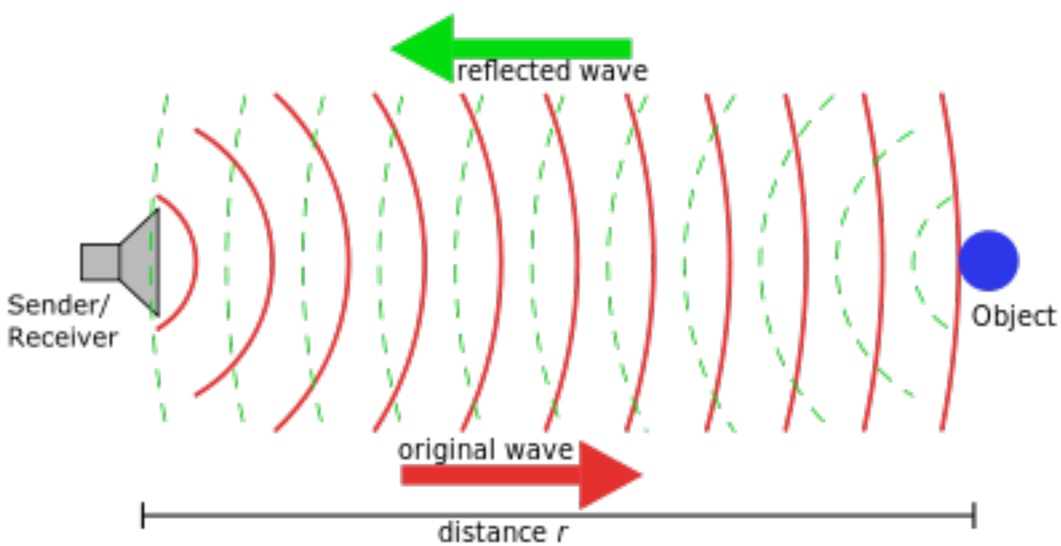
- SONAR *measures time to reflect* *__sound__* *waves*

  . infers distance (to object) = speed x time

  . infers speed of moving object from change in wavelength of reflected light







clicker question

Reflection from metals

Q: *Metals reflect all light colors with frequency*

a) Smaller than plasma frequency

b) Larger than plasma frequency

c) All frequencies

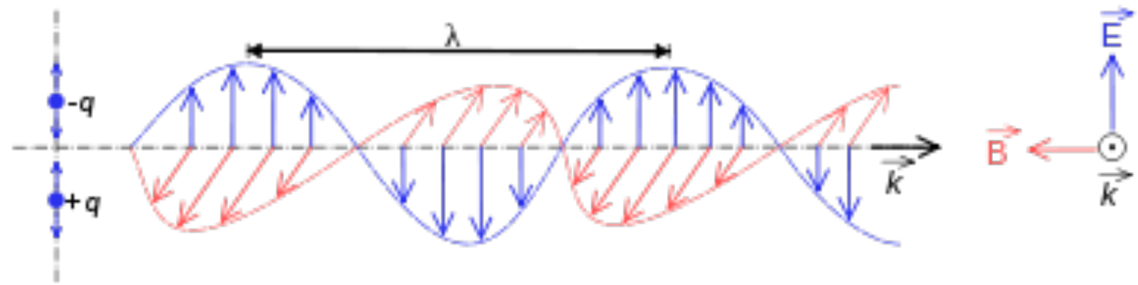
d) At the plasma frequency

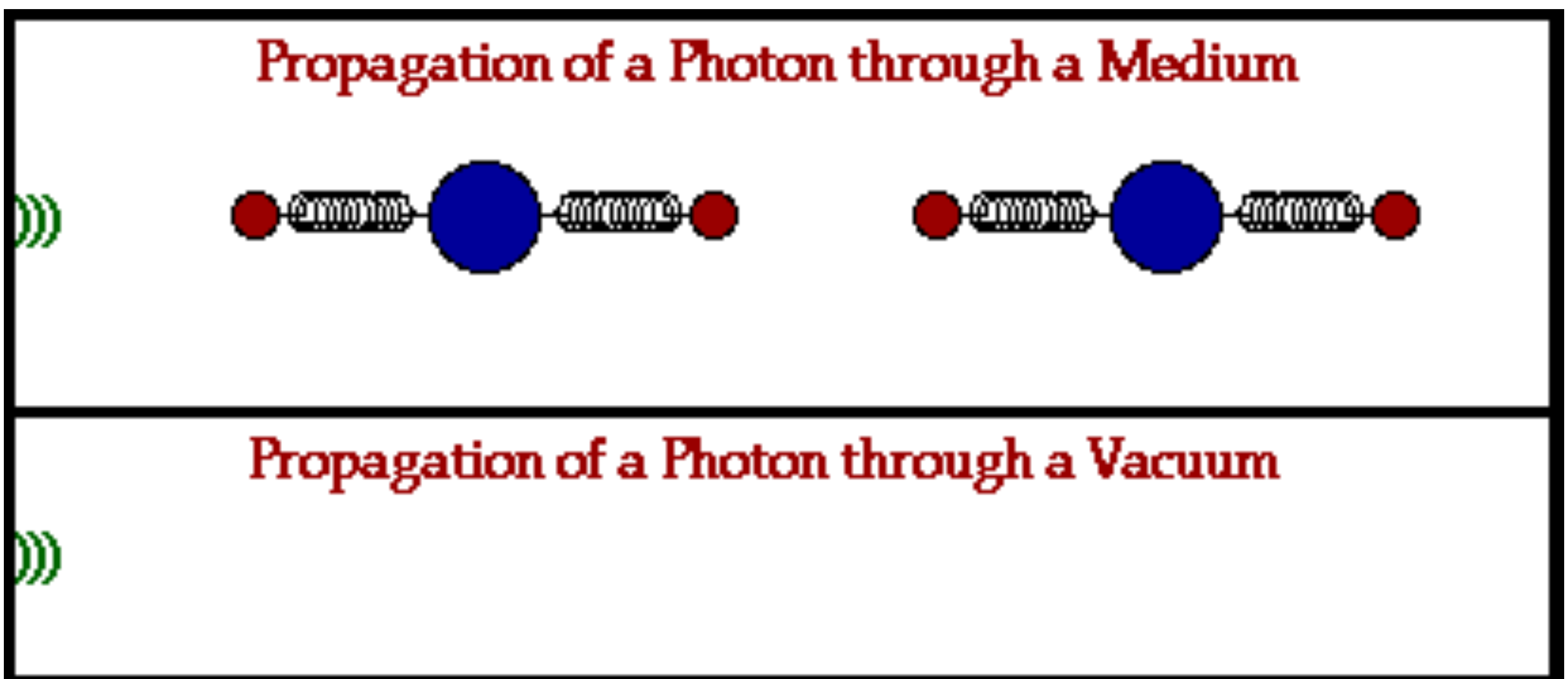
A: *Smaller than the plasma frequency, because at these smaller frequencies electrons can keep up with oscillating electric field of EM and cancel it out, thereby not letting it transmit, thereby "forcing" it to fully reflect*

Light in a transparent medium

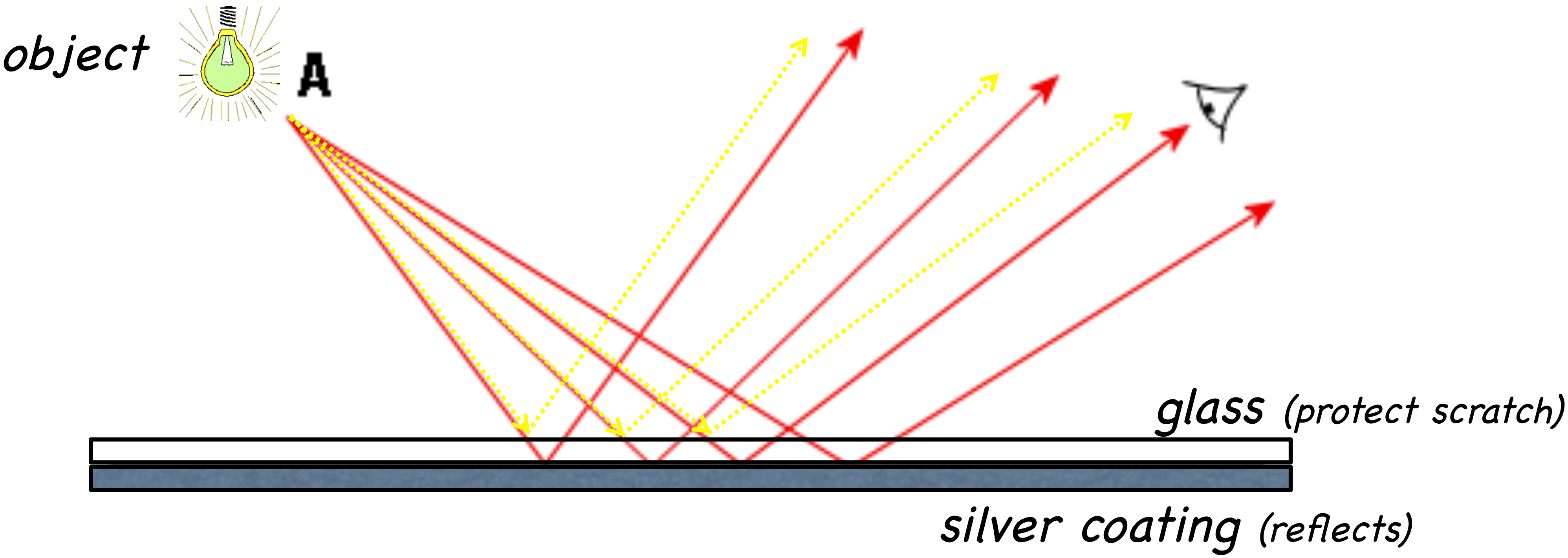
Why light slows down in a medium (glass, water, air, ...)

- EM wave makes electrons bound in atoms oscillate like in an antenna
- Oscillating atoms reemitted light, causing slower partial transmission





Reflection: mirror



- silver – 99% reflection
- glass – protects silver from scratching (only 4% reflection)

Multiple reflections

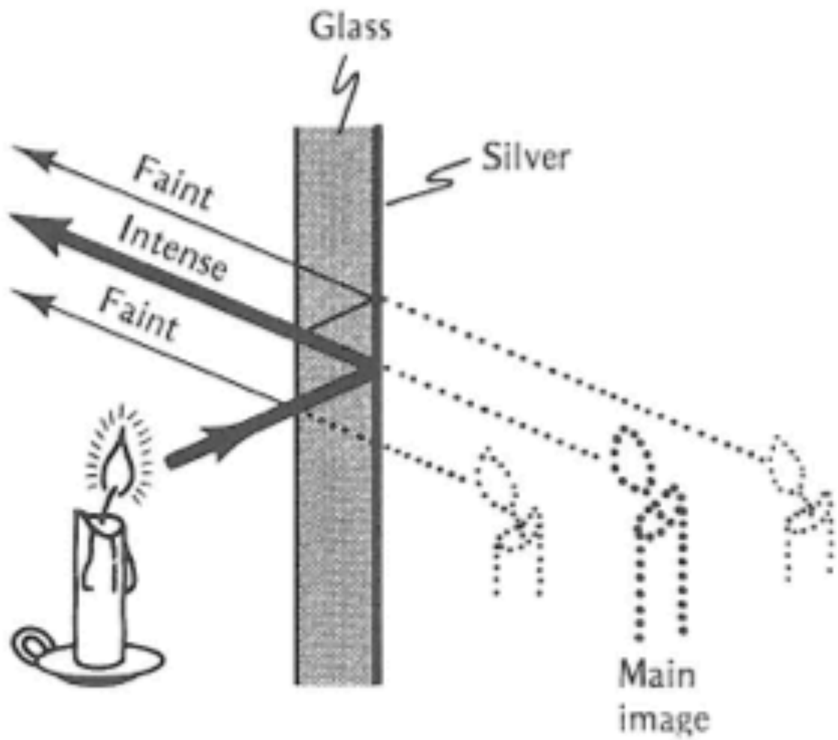
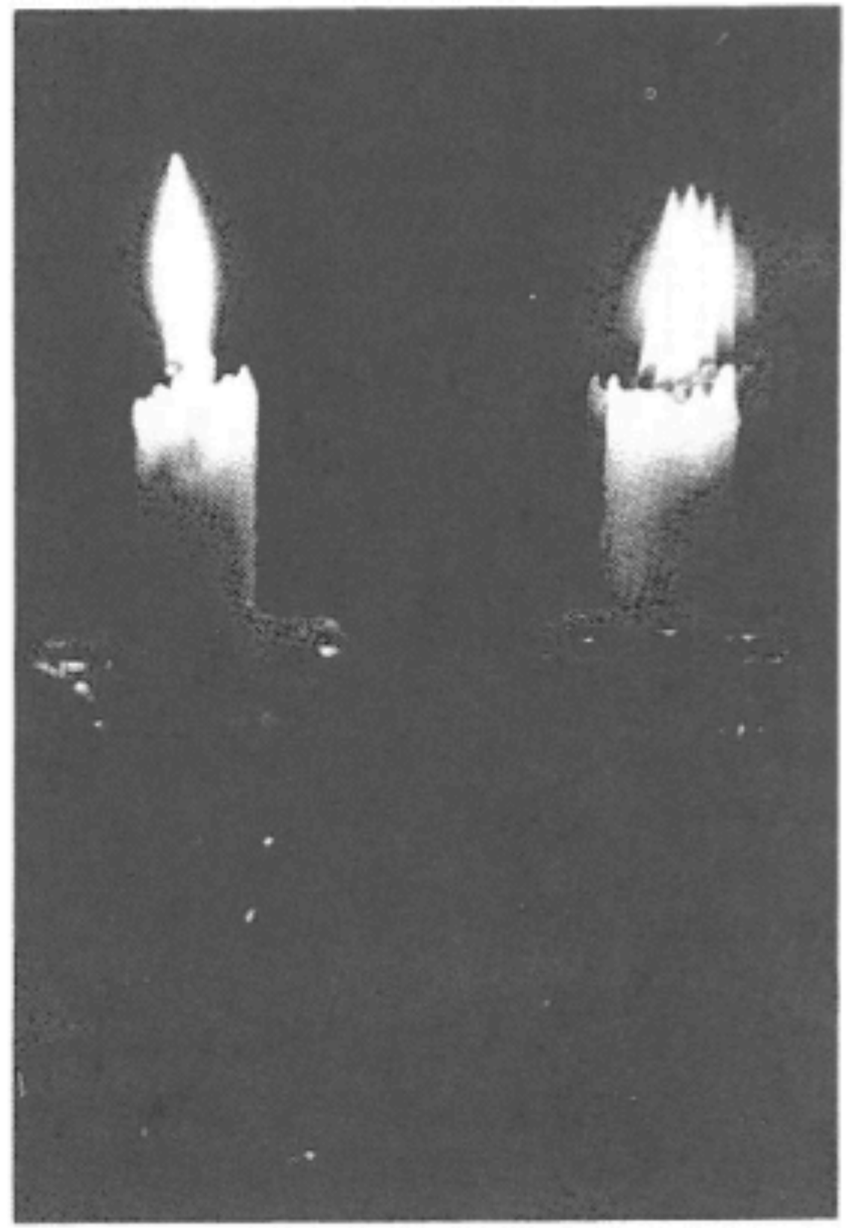


FIGURE 2.42

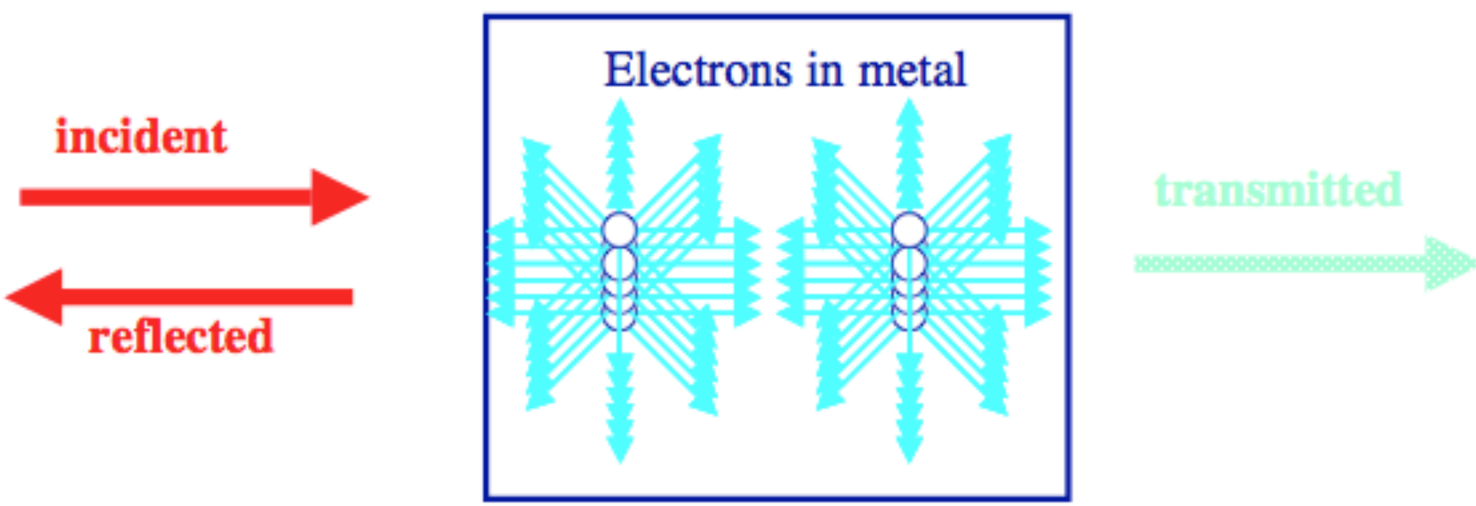
A single mirror can form several images of a candle. If both the candle and the viewer's eye are held close to the glass surface, the better glass reflectivity at grazing incidence makes the extra images brighter.



Reflection from metals

Why are metals (e.g. silver) good reflectors of light?

- in a metal electrons are free to move, not attached to to individual atoms -> good conductor of electricity
- in response to EM wave, electrons move to screen, cancel out EM electric field -> no transmission of light
- oscillating free electrons generate strong reflection, > 99%
- works for $\omega < \omega_{plasma}$, otherwise too fast to follow EM

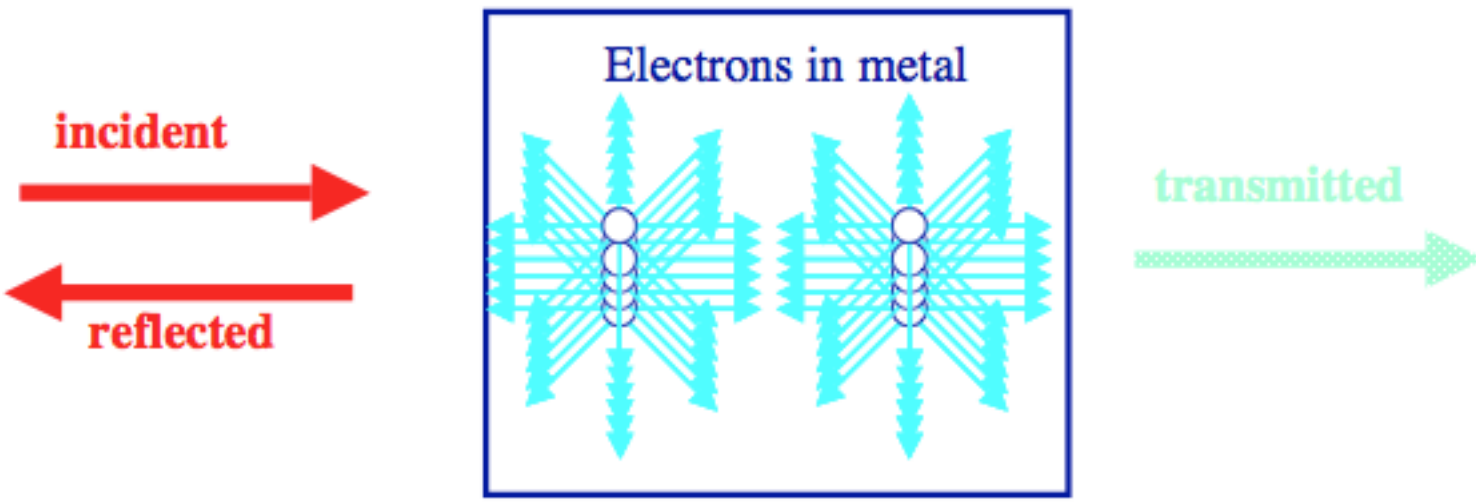


Reflection from metals

Why are metals (e.g. silver) good reflectors of light?

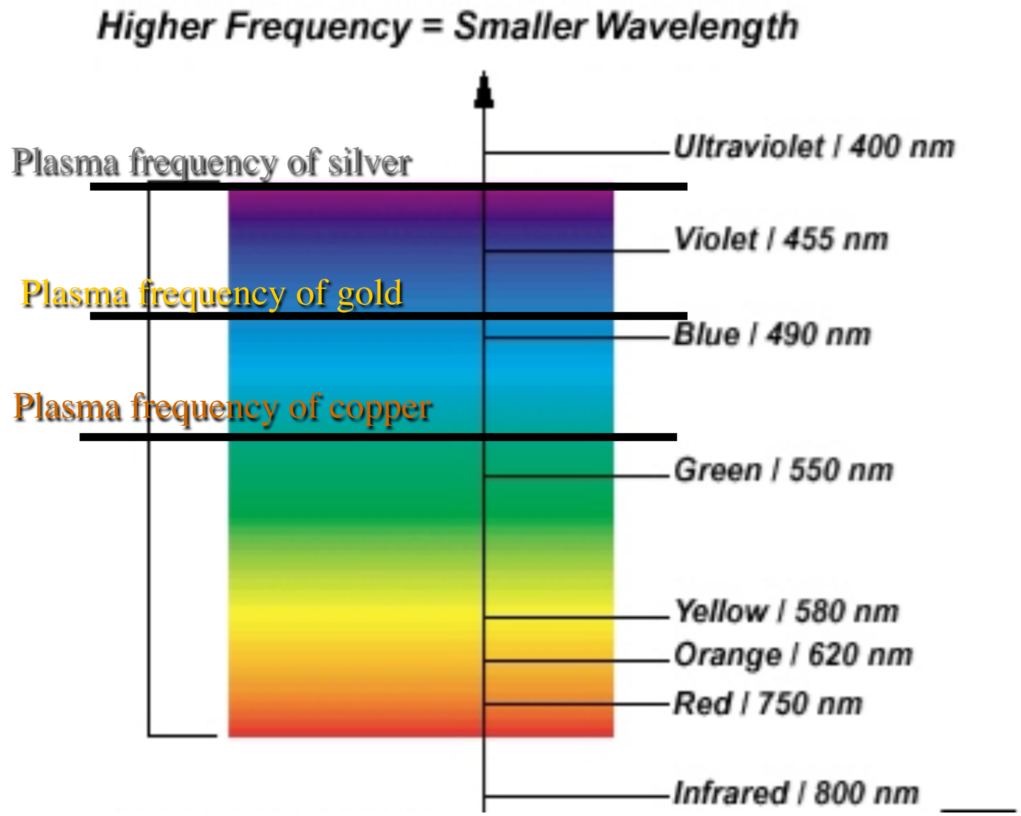
- **Visible light frequency** — **10^{14} Hz**
- **Ionosphere plasma frequency** — **10^{8} Hz**
- **TV, FM** — **10^{8} Hz or 100MHz**
- **AM radio** — **10^{6} Hz or 1000kHz**

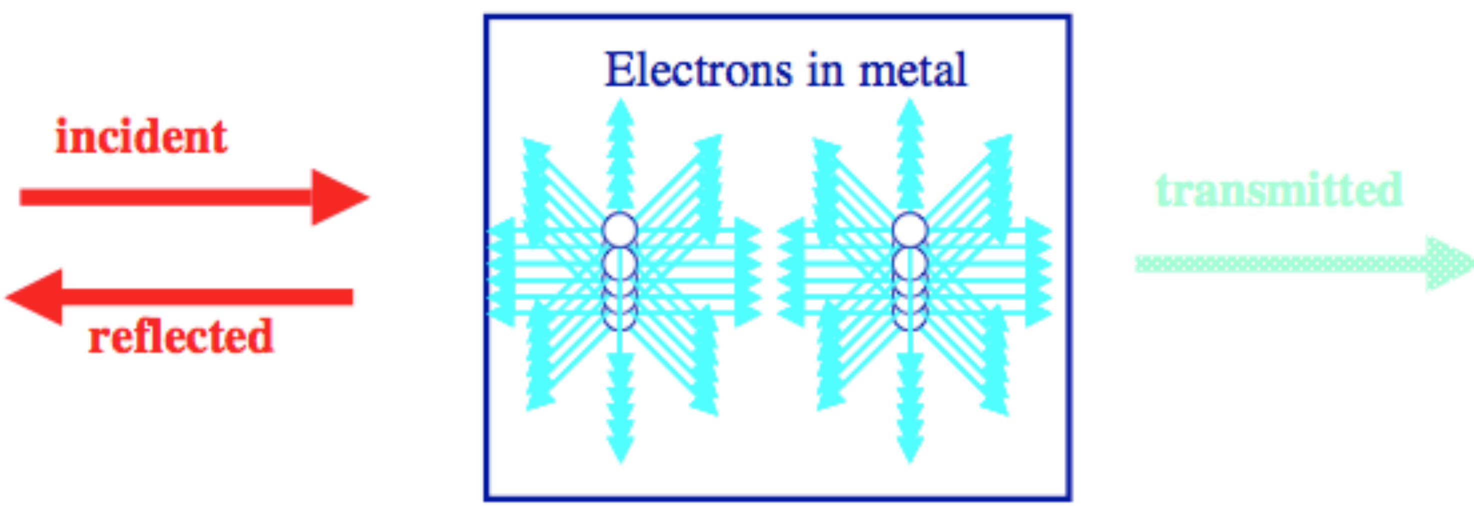
Waves reflect from mirrors or the ionosphere if their frequency is **less** than the plasma frequency.



Reflection from metals

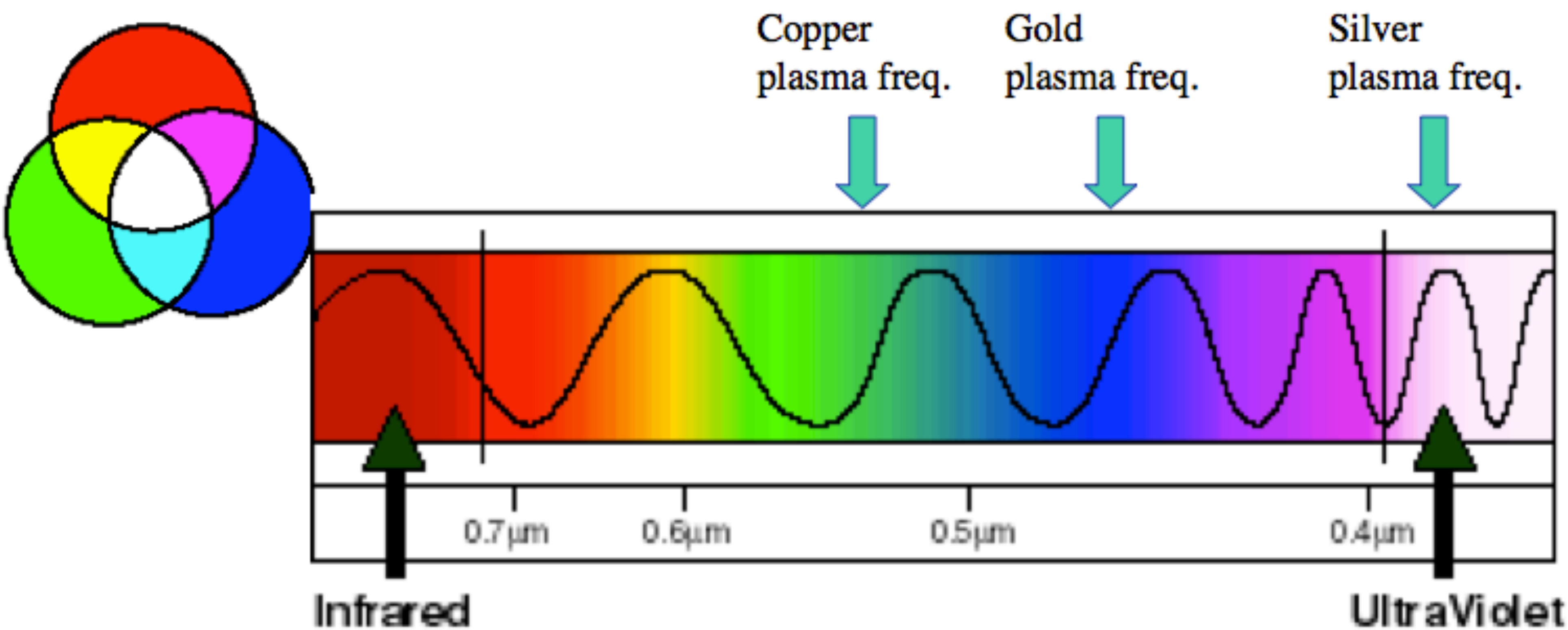
Why are metals (e.g. silver) good reflectors of light?





Reflection from metals

Metal	Plasma frequency	Color of metal
Silver	above visible	white - since reflects all colors
Gold	in the blue	yellow - since reflects red and green
Copper	in the blue-green	reddish - since transmits blue & green



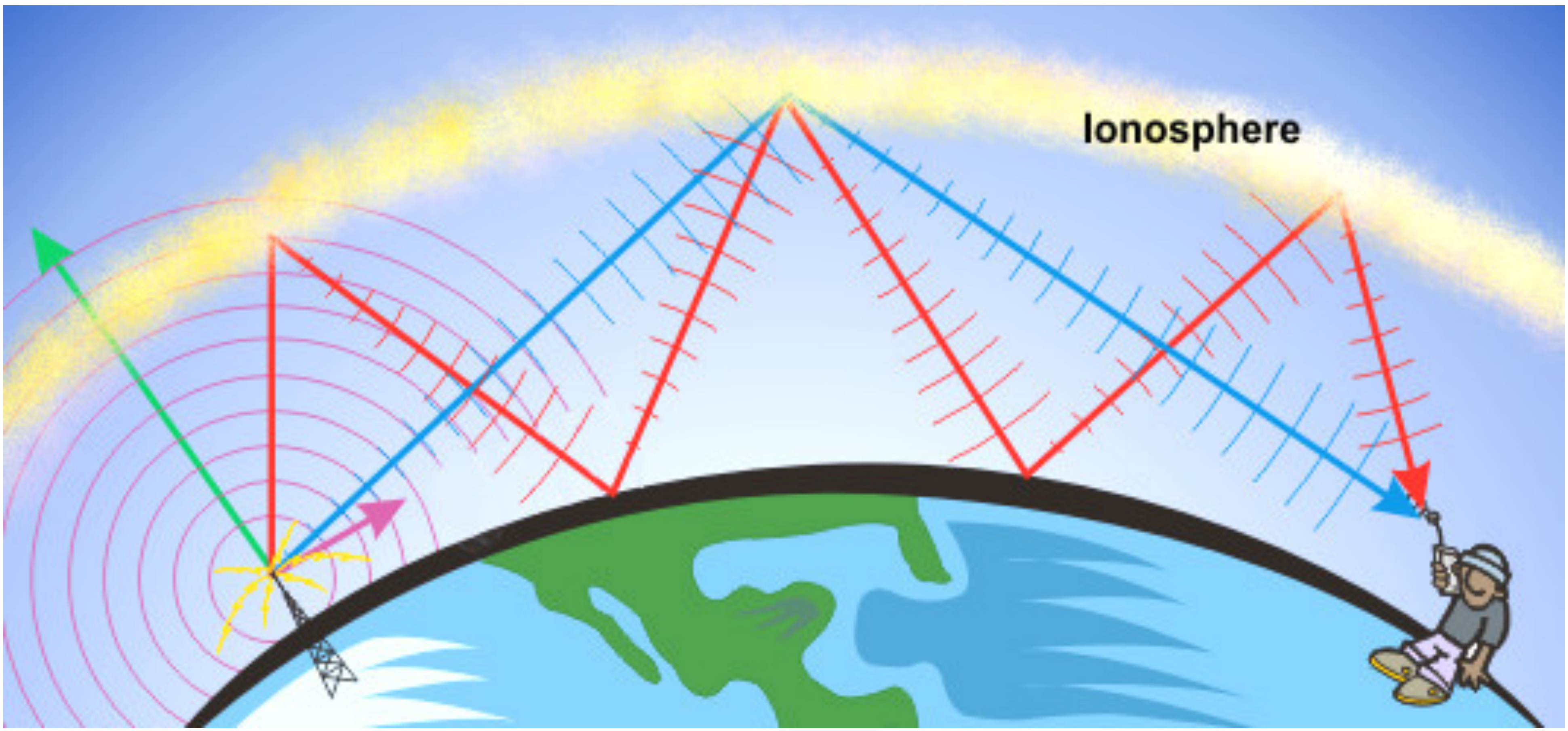
Reflection from ionosphere

Extends 40-200 miles above the earth's surface

Composed of electrically charged gas particles

Plasma frequency: 10^8 Hz

AM radio frequencies: 10^6 Hz



Reflection from metals