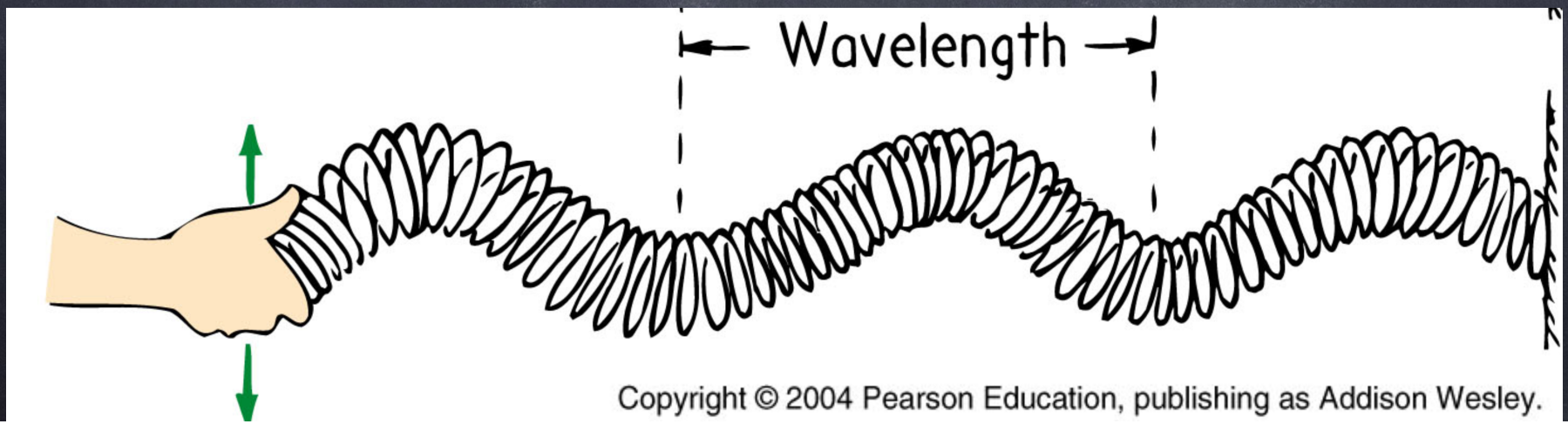
Optics Refresher

"We are tiny compared with the Galaxy, but have the power to comprehend its greatness. It is easy—but misleading—to confuse size with significance."

--James B. Kaler

Waves

- Waves need a medium to travel through (waves are a disturbance in a medium).
- A medium can be a solid, liquid, or gas.
- When creating a wave, how often a vibration occurs is known as the frequency.
- Transverse:
- Displacement is perpendicular to the direction of wave travel.

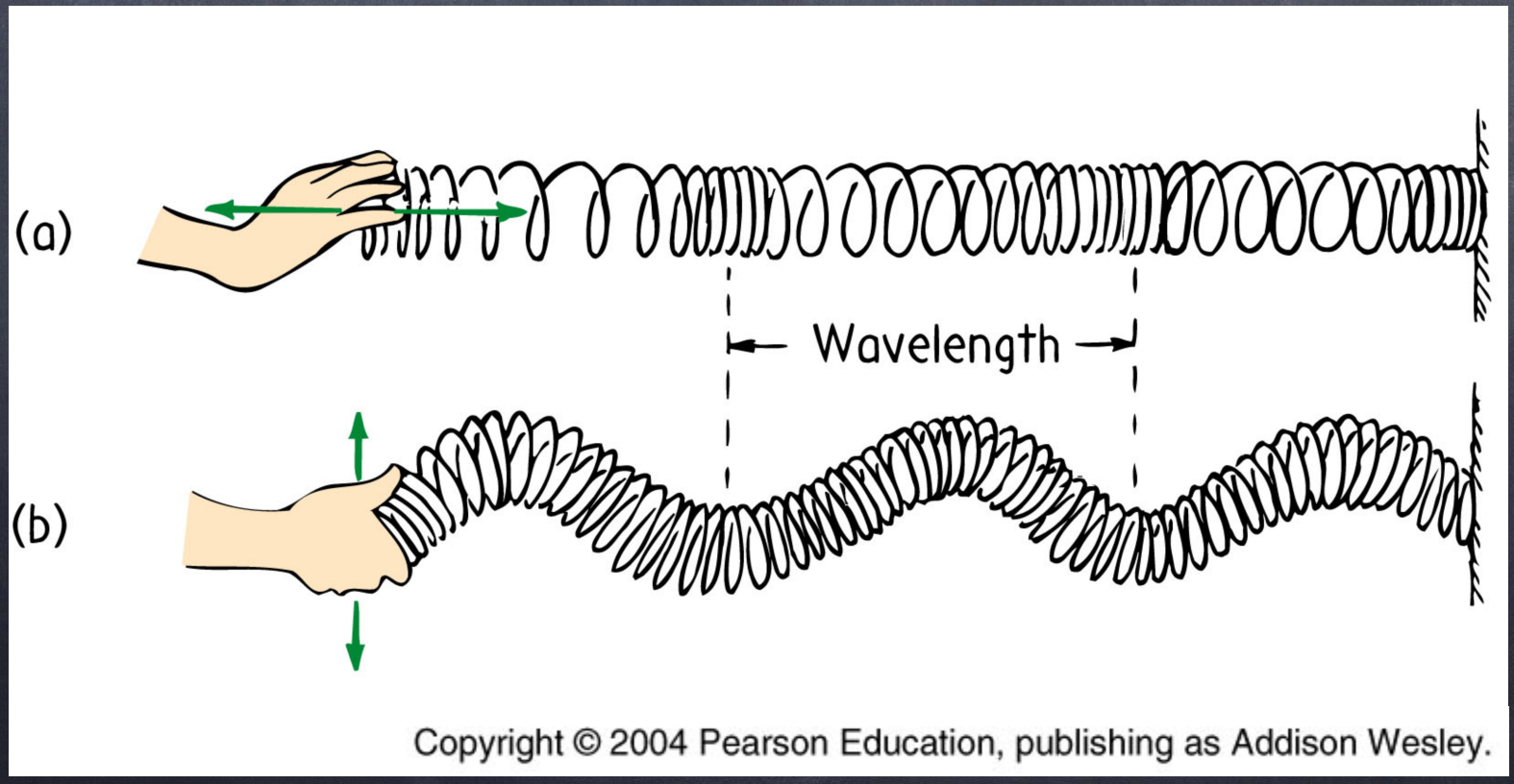


Transverse wave

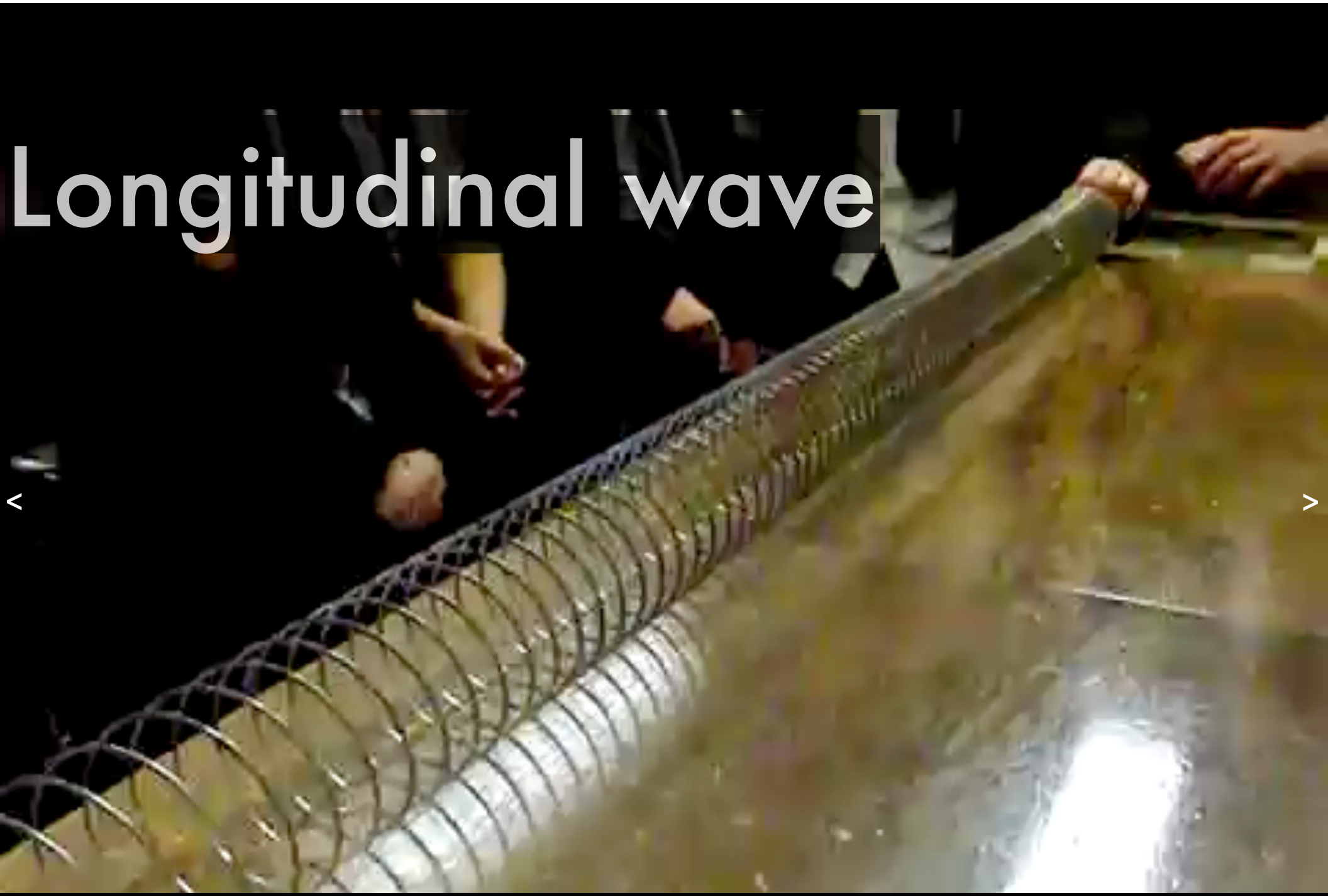
"Transverse wave travel along a bungee cord"
(Source: ©The Orchard - 果樹園)
http://www.youtube.com/watch?v=g49mahYeNgc

Types of Waves

- Longitudinal:
- Displacement is in the direction of wave travel.



Longitudinal wave



"Longitudinal waves in a spring in slow motion"
(Source: ©scienceinslowmotion)
http://www.youtube.com/watch?v=ubRlaCCQfDk

Speed of a Wave

- Very often you will be asked how fast the wave is traveling.
- From the variables that we have described earlier, the speed of a wave is given by:

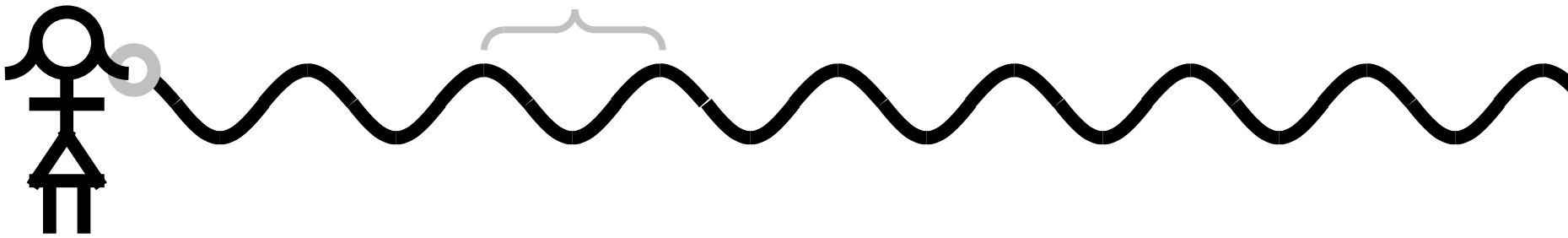
$$v_{wave} = \frac{\lambda}{T} = \lambda f$$

- It comes from the fact that speed equals distance over time.
- It is a very useful equation that we will use quite often.

Wave Properties

speed v [m/s]

wavelength λ [m]



source frequency f

[Hz], [1/s]

Activity 1

A wave created by a certain source travels from medium 1 to another medium 2. It is noticed that its velocity is slower in medium 2 than in medium 1. Three students are discussing what happens to the properties of the wave as it moves into medium 2.

Student 1: The frequency of this wave decreases as this wave moves into medium 2 in order to keep the equation of velocity of a wave valid.

Student 2: No, the frequency of the wave will remain the same as it is only dependent on the source, it will be the wavelength that will decrease in order to keep the equation of the velocity of a wave valid.

Student 3: No, you are both wrong. Both parameters will adjust in order to keep the equation of the velocity of a wave valid.

Which of these students, if any, do you agree with? Justify your response with words and/or equations.

Clicker Question 1

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Student 3: No, you are both wrong. Both parameters will adjust in order to keep the equation of the velocity of a wave valid.

- A) I agree with student 1.
- B) I agree with student 2.
- C) I agree with student 3
- D) I disagree with all three students.

Independent Parameters

$$\lambda = \frac{v}{f}$$

speed (string)

frequency (source)

Dependent Parameter

wavelength (set by *v*, *f*)

String Wave Speed

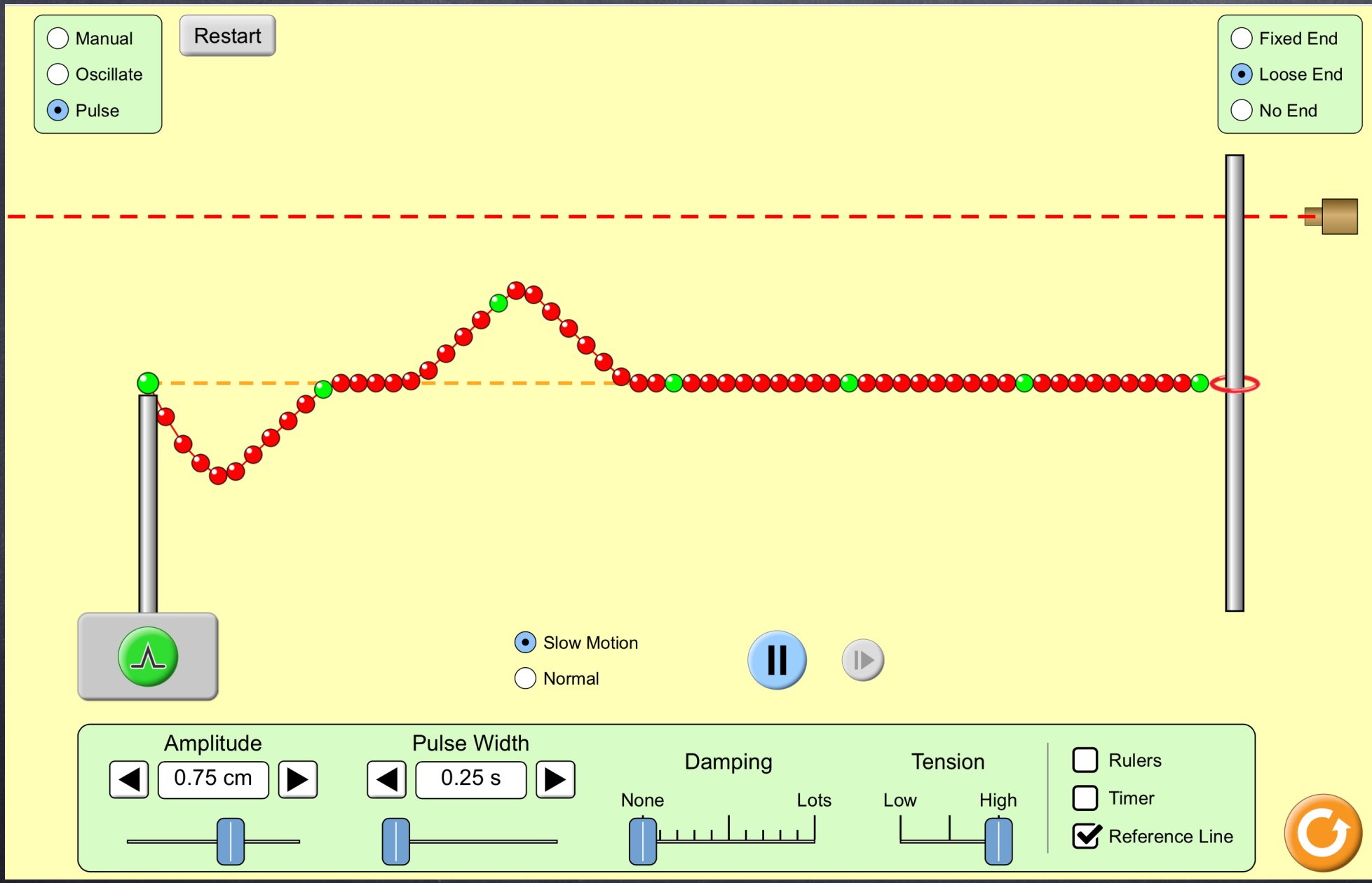
$$v = \sqrt{\frac{T}{\mu}}$$

T ← tension

μ ← "thickness" $\left(\frac{\text{mass}}{\text{length}}\right)$

Set by properties of string (T, μ)

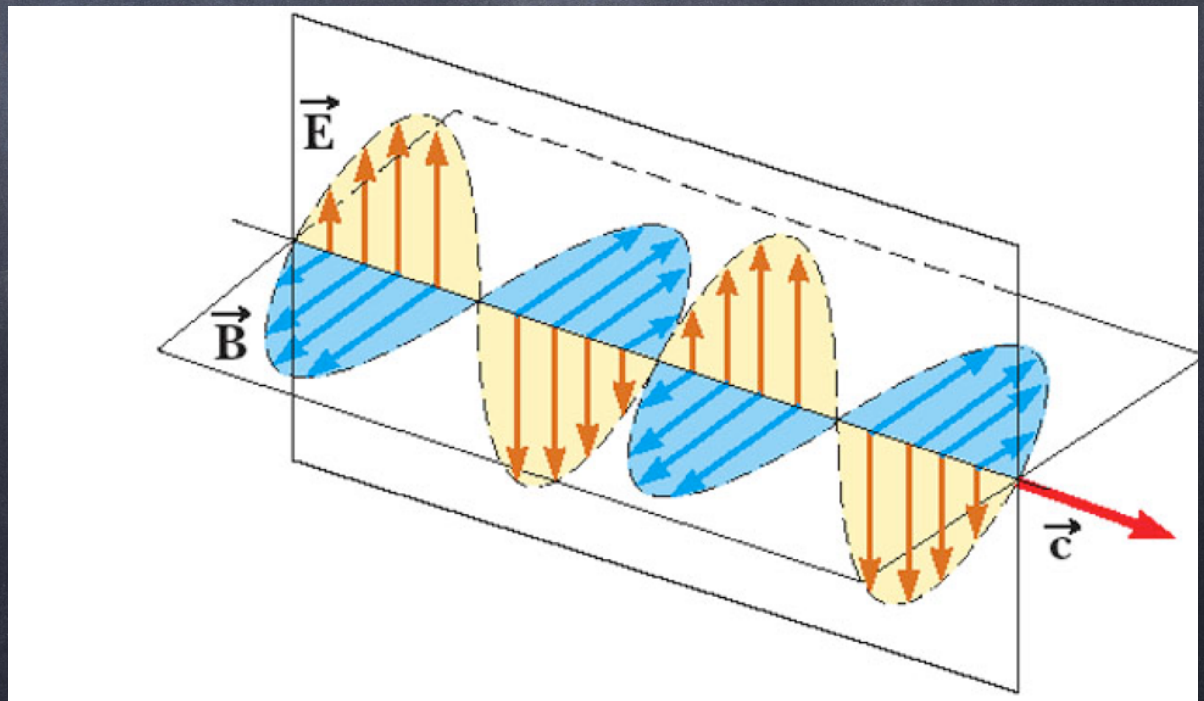
Superposition



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

EM Waves

- A "special" type of wave is the electromagnetic wave.
- Accelerated charges produce electromagnetic waves.
- In EM waves, the electric and magnetic fields are perpendicular to each other.
- Both fields are also perpendicular to the direction of motion.
- This makes EM waves to be transverse waves.



EM Waves

- Electromagnetic waves travel at the speed of light.

$$c = \frac{1}{\sqrt{\mu_o \varepsilon_o}} = 3.0 \times 10^8 \, \mathrm{m/s}$$

- where ε_o = $8.85 \times 10^{-12} C^2/(Nm^2)$ and μ_o = $1.26 \times 10^{-6} (Tm/A)$.
- The average power per unit area of the EM wave is known as intensity, I.
- There are distinct forms of EM waves at different frequencies (and wavelengths).
- Recall that the wave speed will be given by:

$$v_{wave} = c = \lambda f$$

Activity 2

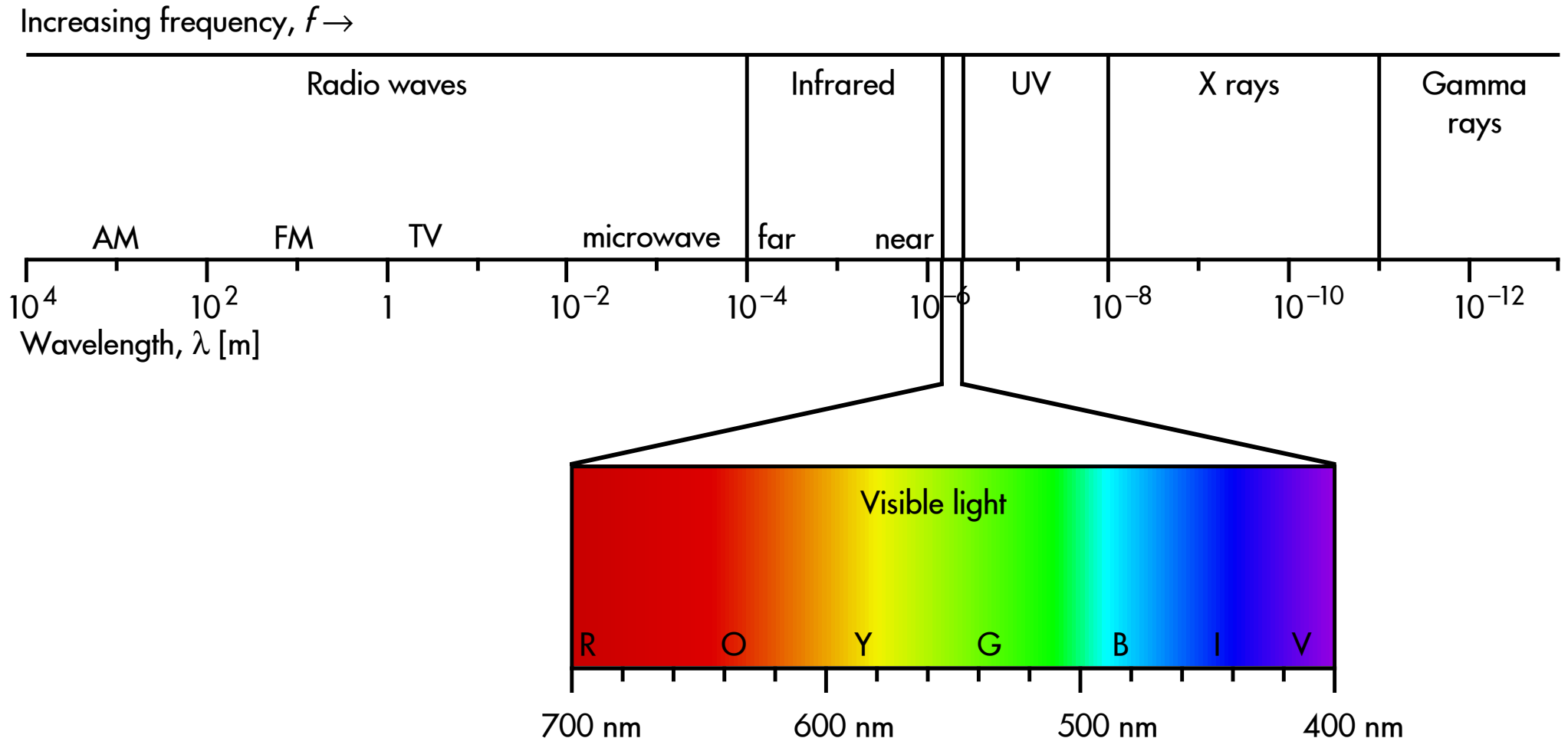
a) Calculate the wavelength of a microwave with frequency 3.0×10^{10} Hz. Using this, explain why the front window on your microwave oven has small grates on it.

b) Calculate the wavelength of radio waves with frequency 3.0×10^{6} Hz. Using this, explain why you don't lose radio reception when a person stands in between your antenna and the broadcast tower.

c) Calculate the wavelength of gamma rays with frequency 3.0×10^{22} Hz. Using this, explain why gamma rays can deeply penetrate through most objects (and thus are dangerous to humans).

d) Estimate an order-of-magnitude frequency for an electromagnetic wave with wavelength equal to your height. What is the classification of this wave on the electromagnetic spectrum?

E/M Spectrum



(Source: Adapted from Fig. 4-2, Seeds & Backman, *Perspectives in Astronomy, 1/e*, 2008)

Gamma rays

"Vehicle and Cargo Inspection System"
(Source: Solid Waste Operations)
http://www.lanl.gov/orgs/pa/News/072899.html

X rays

"Cyborg Girl: Cephalometric Radiograph (side)"
(Source: Emily Beighley)
http://www.flickr.com/photos/nullalux/2614819558/

Ultraviolet (UV)

"090529-1090772"
(Source: Waifer X)
http://www.flickr.com/photos/waiferx/3577276128/

Visible light

"lost in your eyes"
(Source: vebeeldingskr8)
http://www.flickr.com/photos/verbeeldingskr8/3284650304/

Infrared (IR)

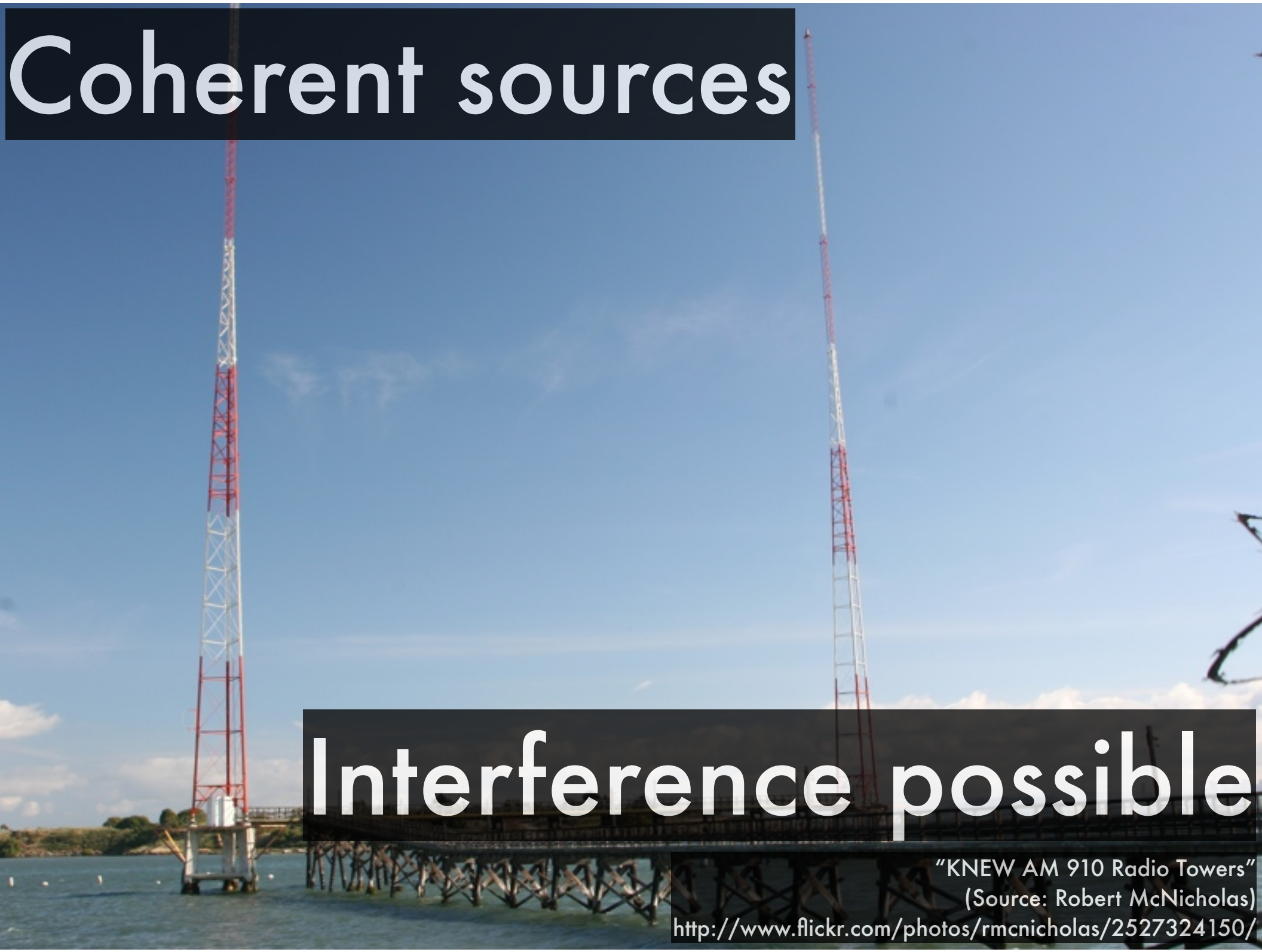
"infrared heat cam"
(Source: Exploratorium)
http://www.youtube.com/watch?v=6fASzACILH4

Radio waves

Microwaves/TV/FM/AM

"CONELRAD 640 kHz & 1240 kHz"
(Source: Radio Rover)
http://www.flickr.com/photos/radiorover/323527185/

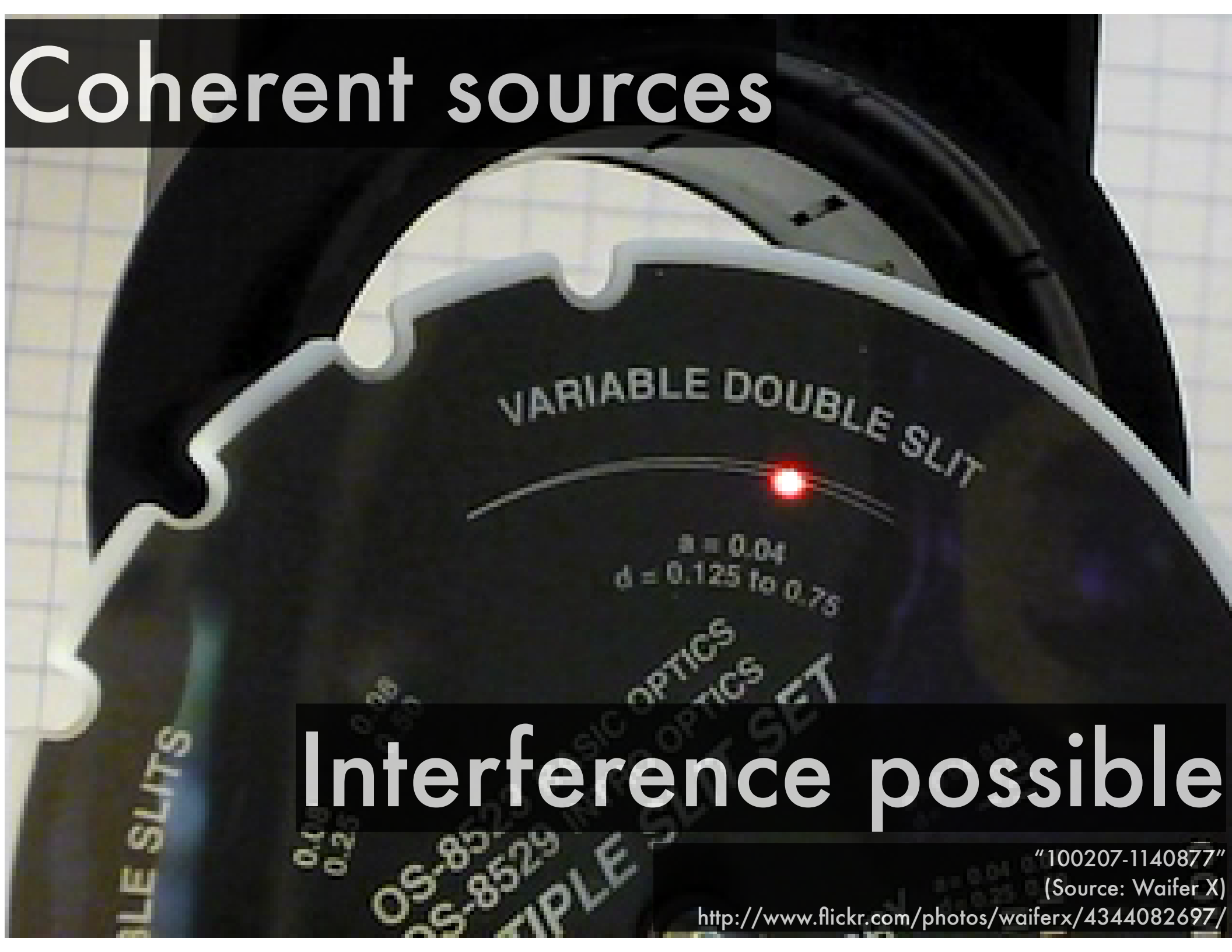
Coherent sources



Interference possible

"KNEW AM 910 Radio Towers"
(Source: Robert McNicholas)
http://www.flickr.com/photos/rmcnicholas/2527324150/

Coherent sources

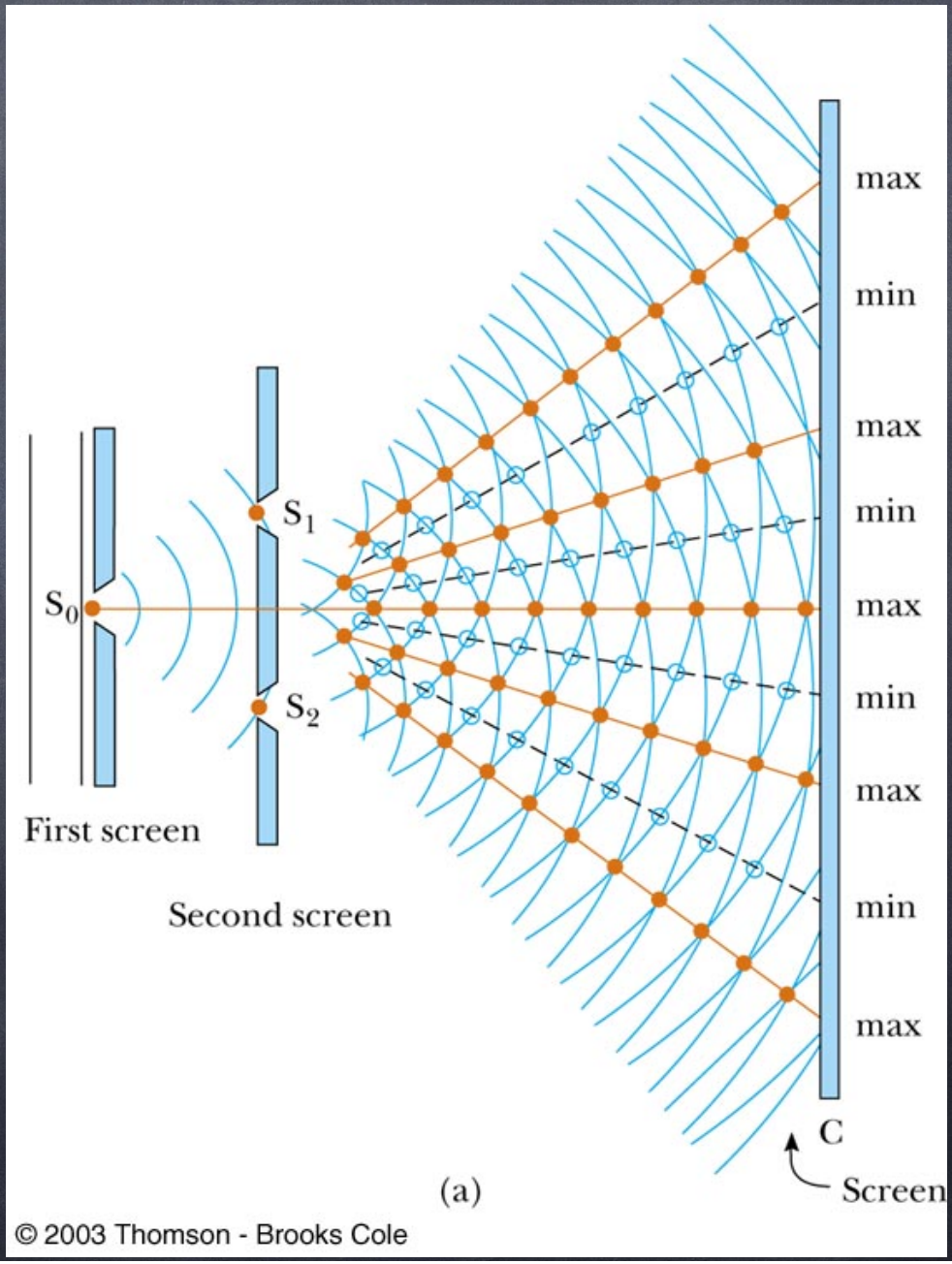


Interference possible

"100207-1140877"
(Source: Waifer X)
http://www.flickr.com/photos/waiferx/4344082697/

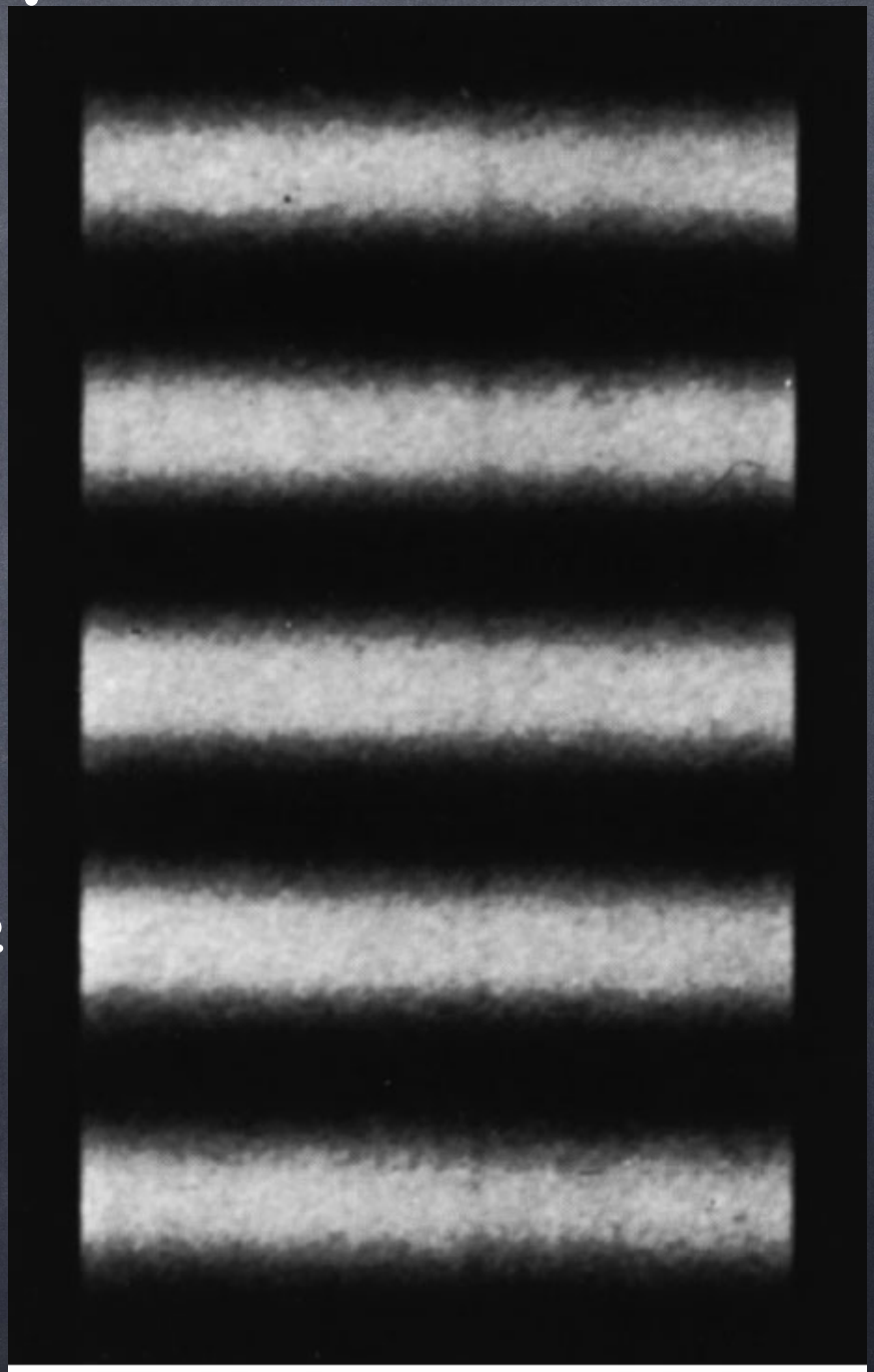
Double Slit Experiment

- Two narrow slits, S_1 and S_2, can act as sources of waves.
- The waves emerging from the slits originate from the same wavefront and therefore are always in phase (coherence).
- The light from the two slits form a visible pattern on a screen.
- The pattern consists of a series of bright and dark parallel bands called fringes.

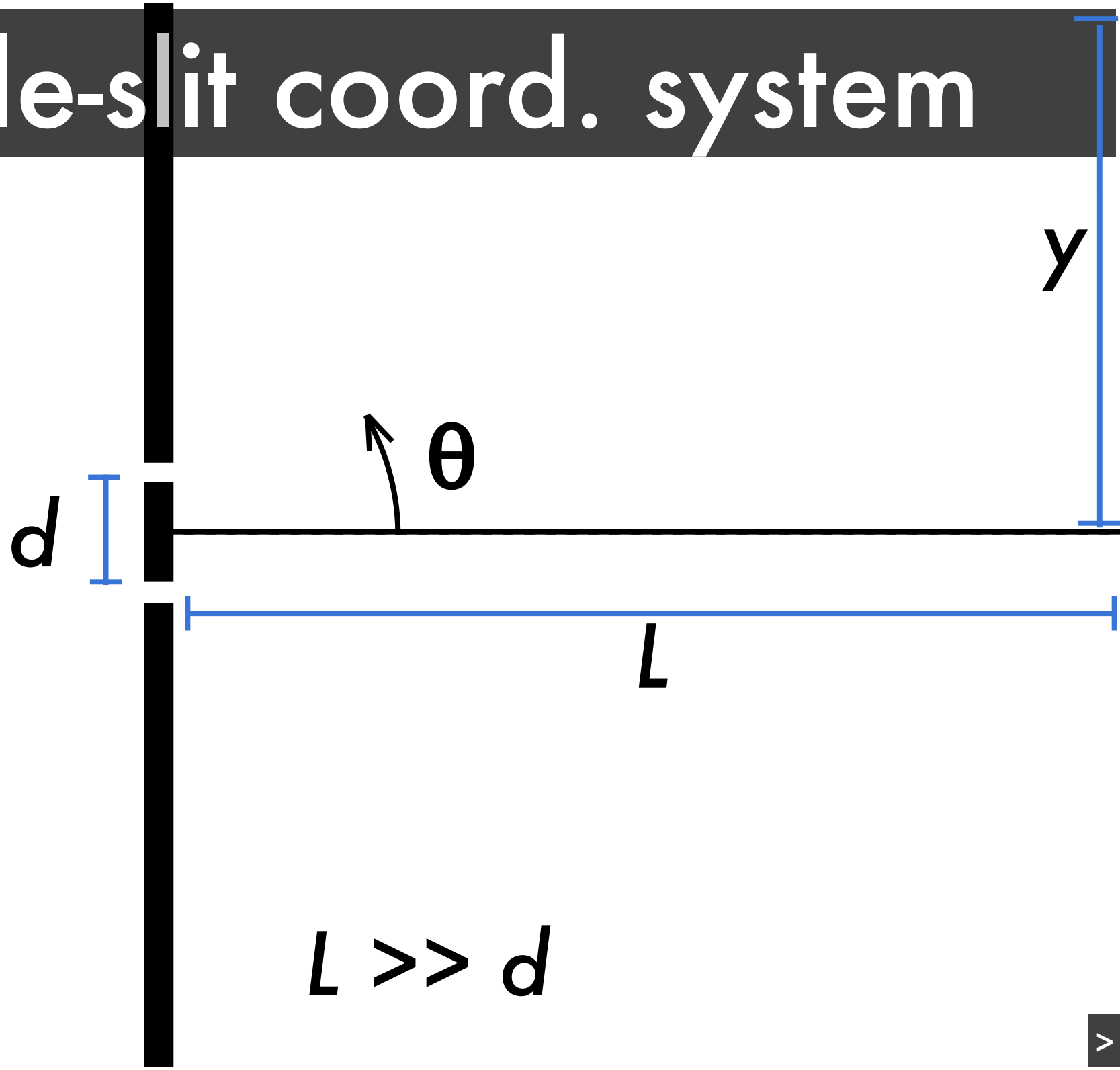


Double Slit Experiment

- The fringe pattern formed by a Young's Double Slit Experiment would look like the picture to the right.
- Alternating bright and dark fringes are created.
- Constructive interference occurs where a bright fringe appears.
- Destructive interference results in a dark fringe.



Double-slit coord. system



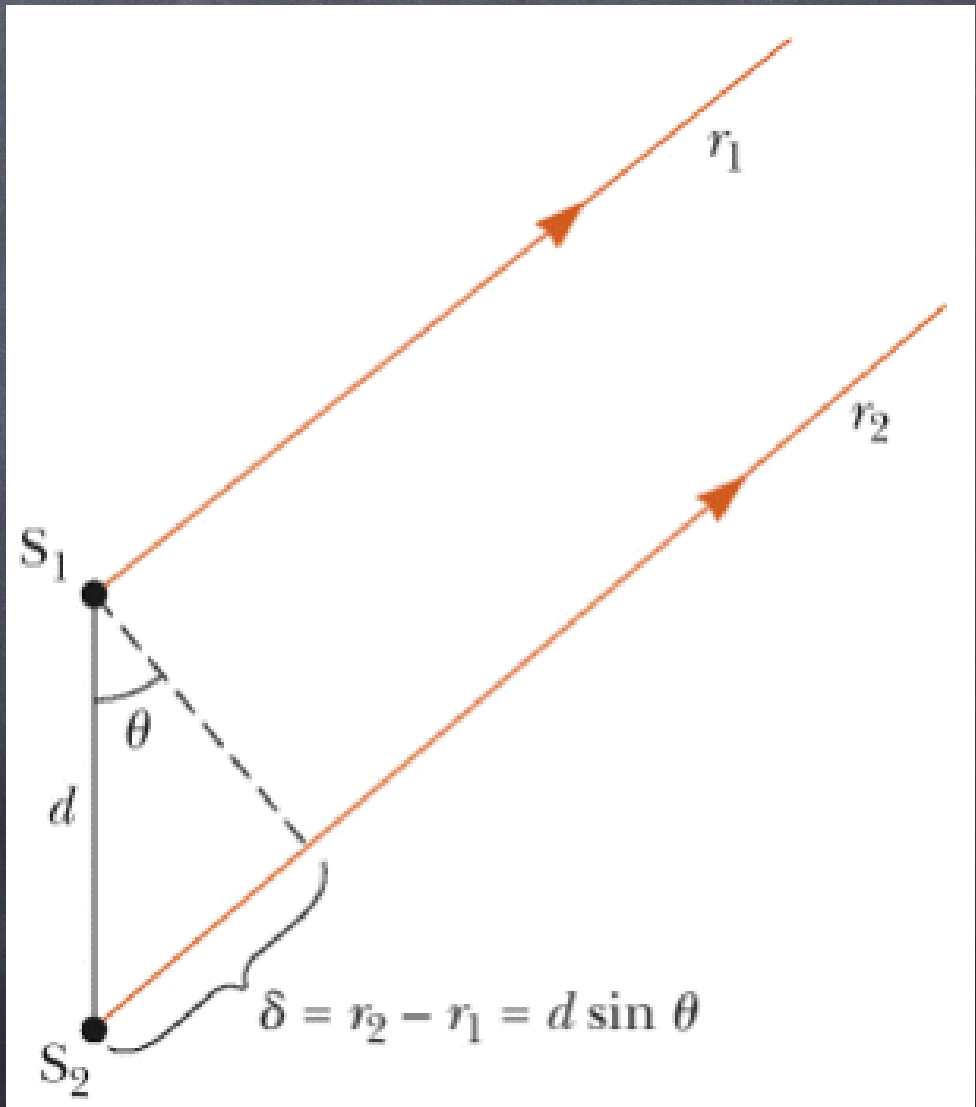
$L >> d$

Double Slit Experiment

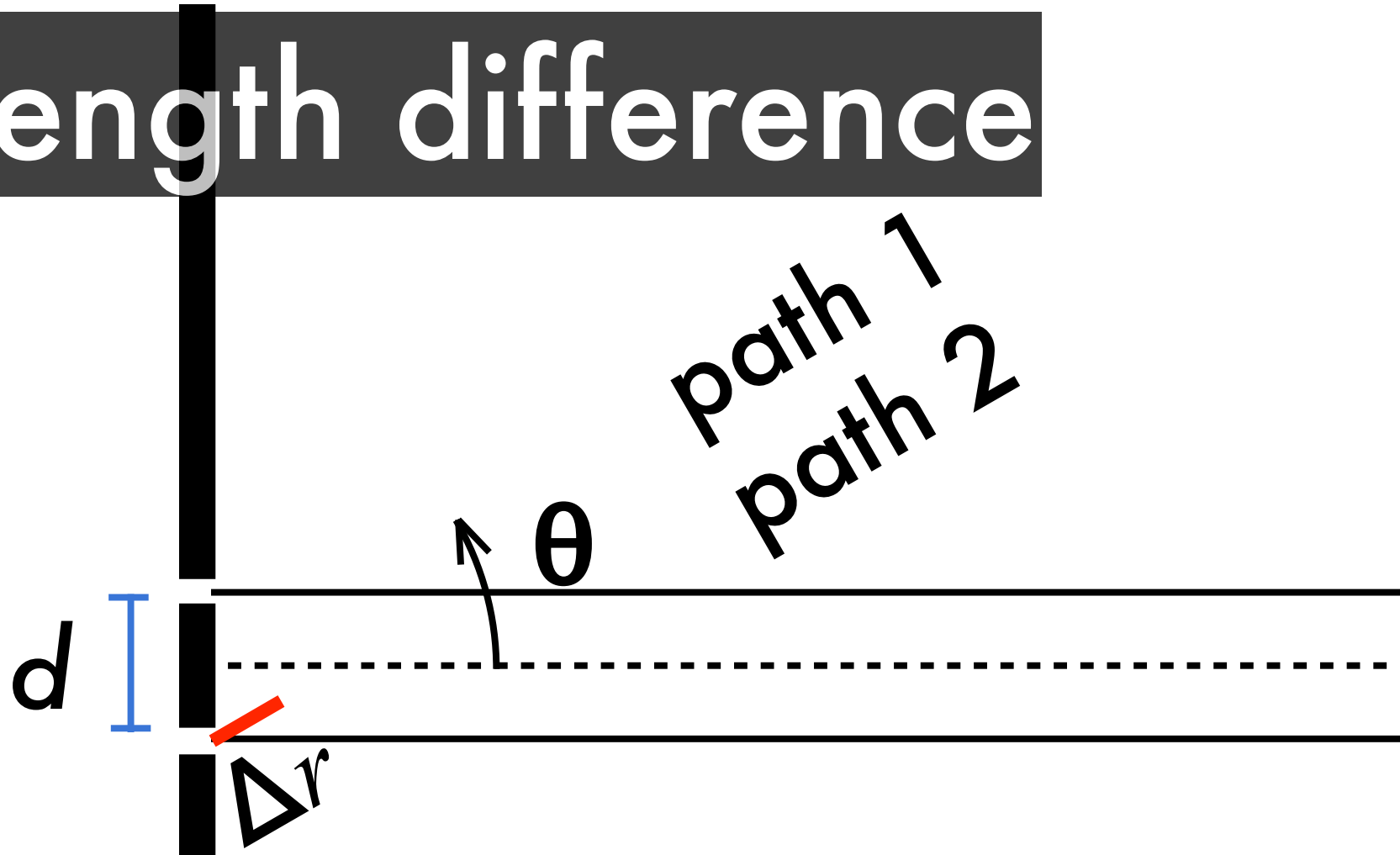
- Via trigonometry we find that the path length difference, δ, is related to the slit distance, d, and the angle θ by:

$$\delta = d \sin\theta$$

- This will be just the path length difference part of the total phase difference (you may or may not also have a phase constant difference).



Path length difference



$$\Delta r = d\sin\theta$$

Index of Refraction

- When light passes from one medium to another, it is the wavelength will change because the speed of light is different in the two media.
- The index of refraction, n, of a medium can be defined:

$$n = \frac{\text{speed of light in a vacuum}}{\text{speed of light in a medium}} = \frac{c}{v}$$

  - n is a unitless ratio.
  - For a vacuum, n = 1 (exactly).
  - For all other media, n > 1.

Indices of Refraction

TABLE 22.1

Indices of Refraction for Various Substances, Measured with Light of Vacuum Wavelength $\lambda_0 = 589$ mn

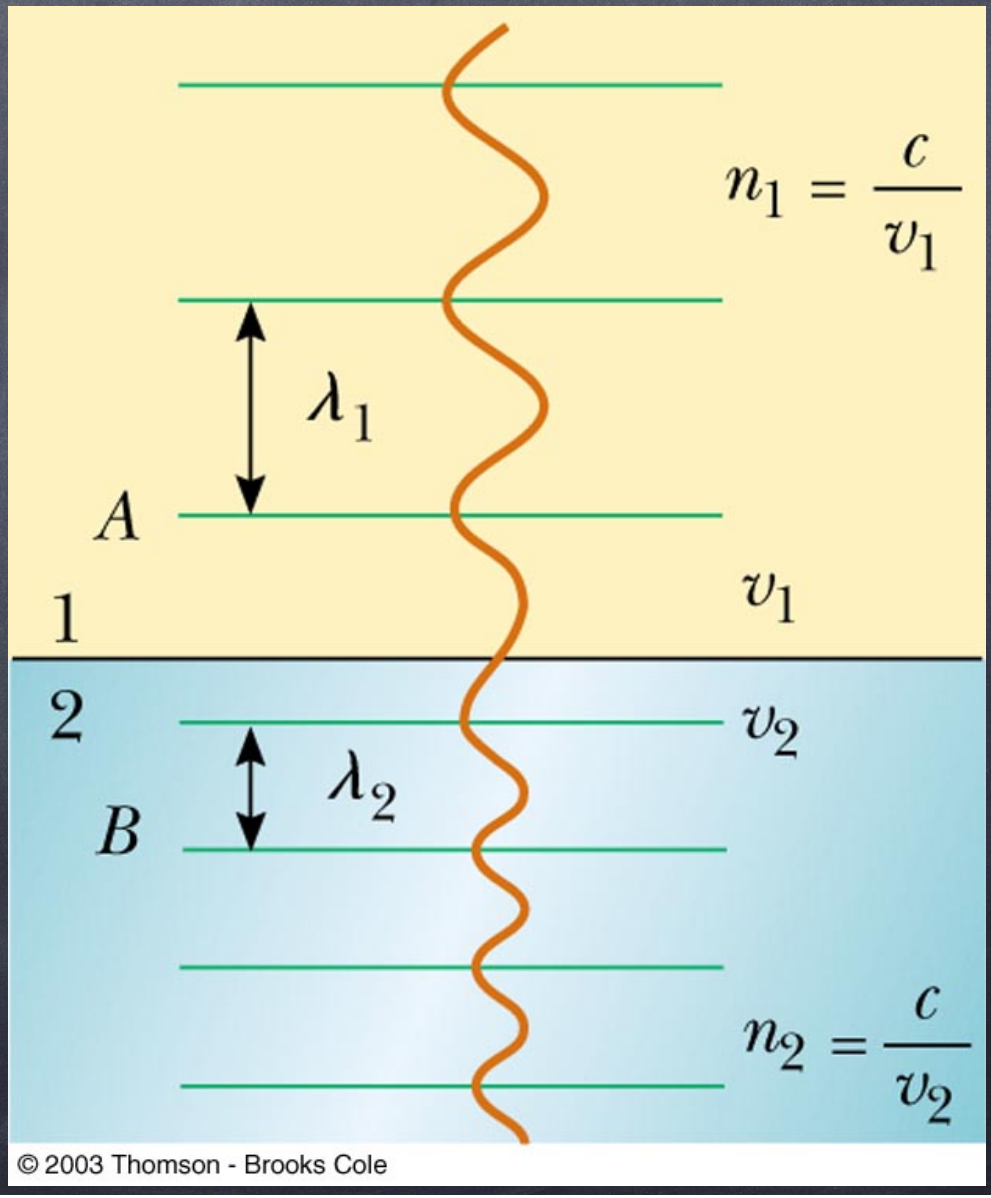
Substance	Index of Refraction	Substance	Index of Refraction
Solids at 20°C		**Liquids at 20°C**	
Diamond (C)	2.419	Benzene	1.501
Fluorite (CaF_2)	1.434	Carbon disulfide	1.628
Fused quartz (SiO_2)	1.458	Carbon tetrachloride	1.461
Glass, crown	1.52	Ethyl alcohol	1.361
Glass, flint	1.66	Glycerine	1.473
Ice (H_2O) (at 0°C)	1.309	Water	1.333
Polystyrene	1.49		
Sodium chloride (NaCl)	1.544	**Gases at 0°C, 1 atm**	
Zircon	1.923	Air	1.000 293
		Carbon dioxide	1.000 45

[1]The speed of light varies between media because the time lags caused by the absorption and reemission of light as it travels from atom to atom depend on the particular electronic structure of the atoms constituting each material.

Frequency Between Media

- As light travels from one medium to another, its frequency does not change.
- Both the wave speed and the wavelength do change.
- The wavefronts do not pile up, nor are created nor destroyed at the boundary, so the frequency must stay the same.

$$\frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$$



Changing Media

$$\lambda = \frac{v}{f}$$

fast $\uparrow v_1$ | $v_2 \downarrow$ slow

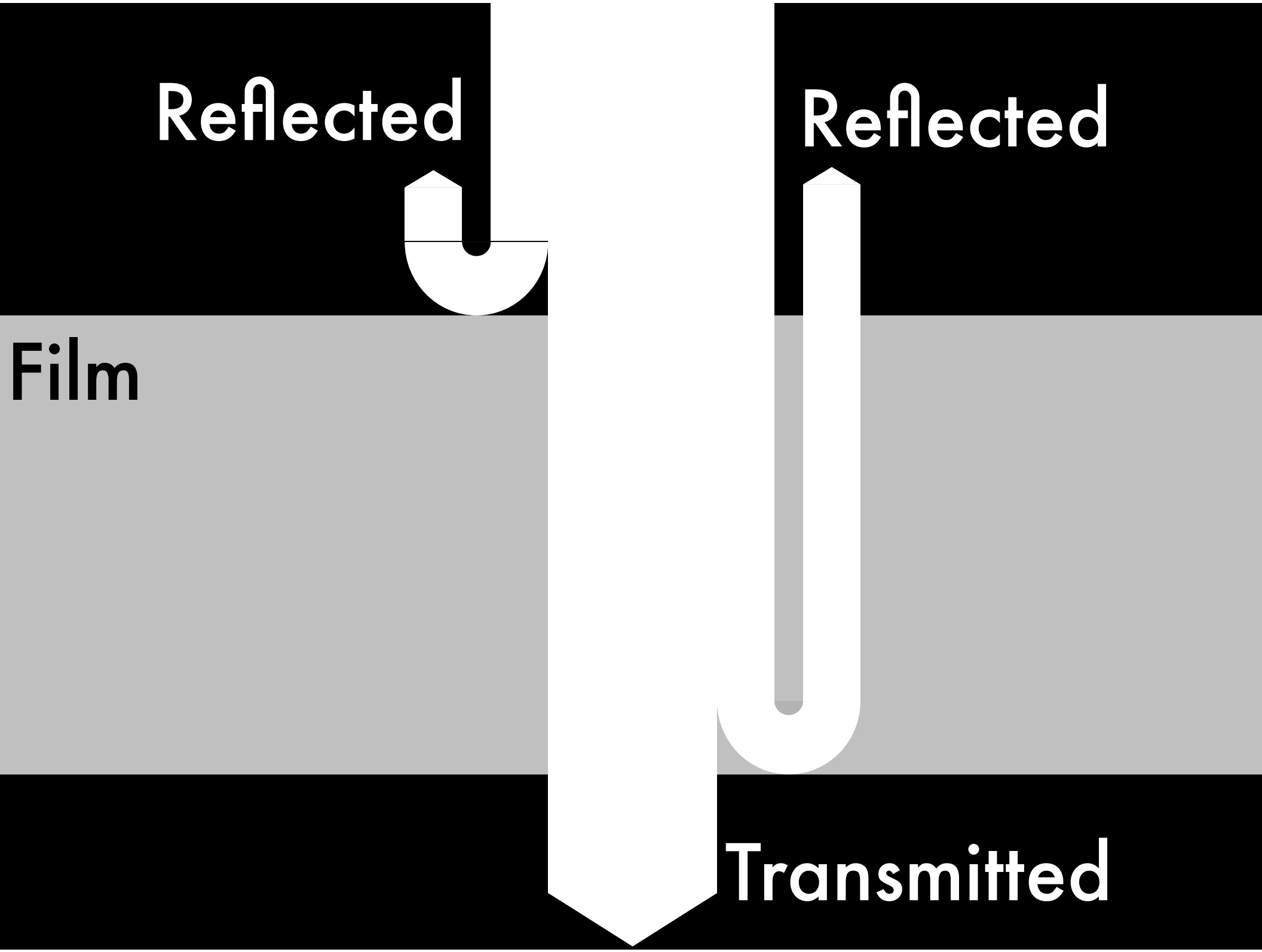
$f_1 = f_2$

$\uparrow \lambda_1$ | $\lambda_2 \downarrow$

Interference in Thin Films

- Have you ever looked a soap bubble and observed patterns of different colors?

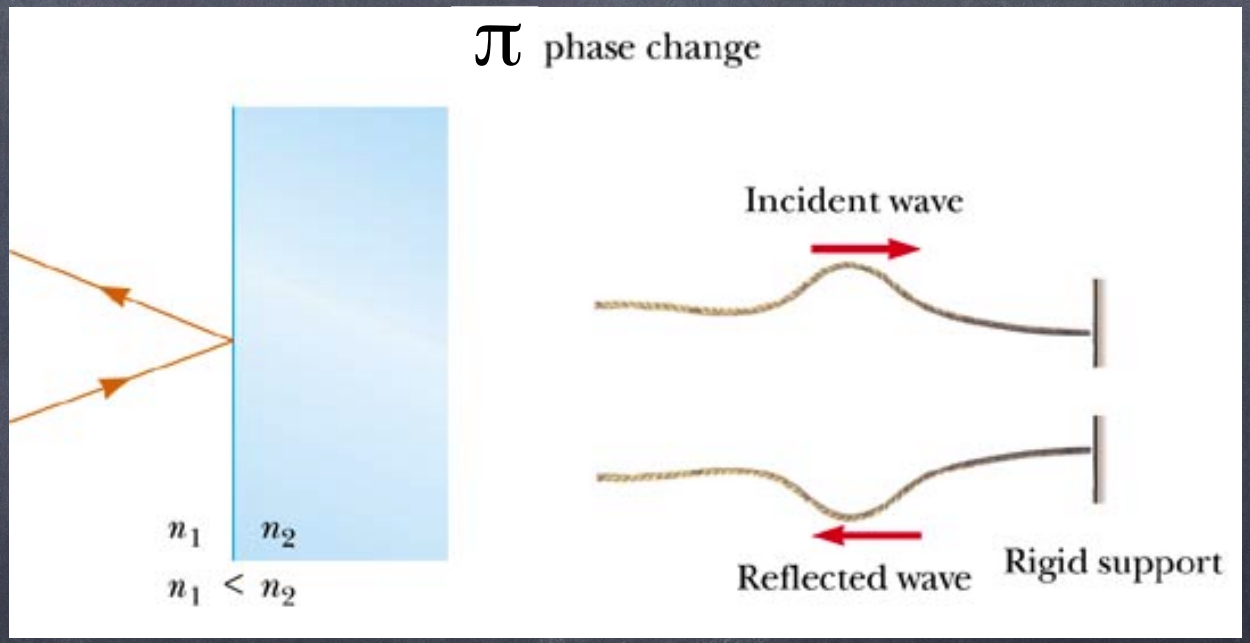
- Light wave interference can be observed in thin films (such as an oil film on water or soap bubbles).
- The interference in thin films is caused by not only a path length difference but also by a phase shift as the light ray reflects off of a different medium.


Reflected
Reflected
Film
Transmitted

Interference in Thin Films

- A light wave will undergo a phase change of π upon reflection from a medium of higher index of refraction than the one in which it was traveling.

- So, a light wave traveling in air will undergo a π phase shift if it reflects off an oil surface.

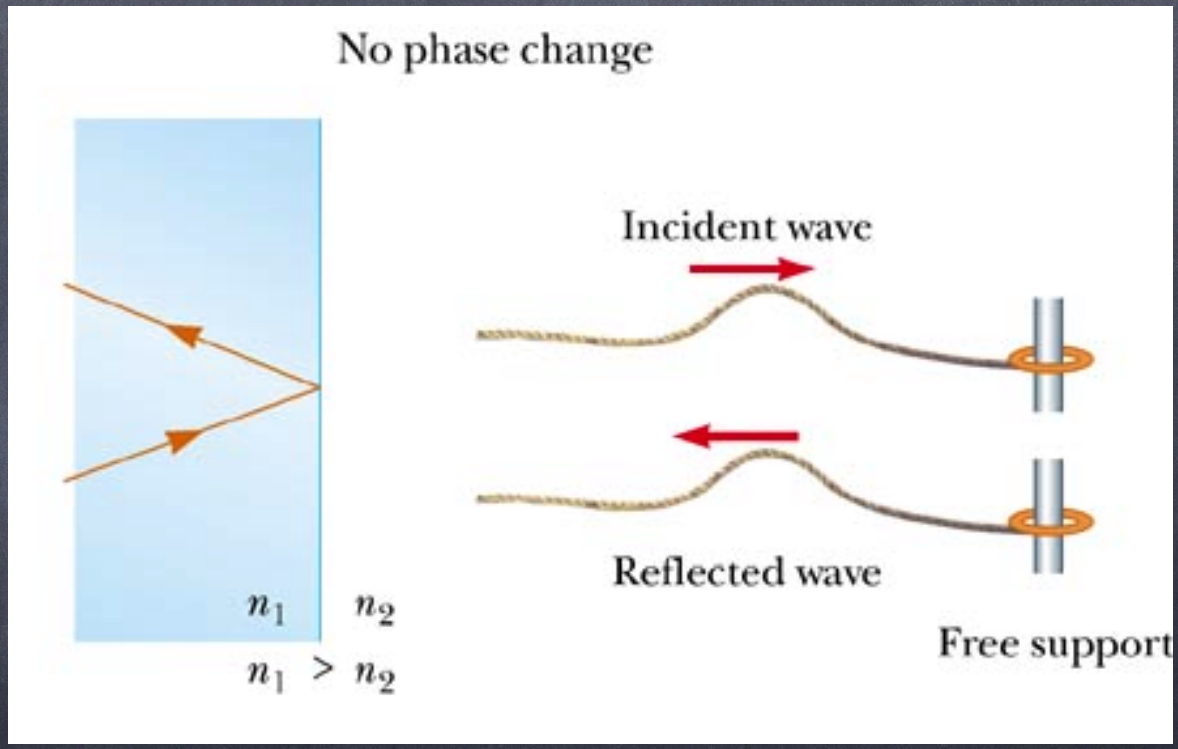


- This is similar to the reflection of a transverse wave that we observed earlier off of a rigid surface.

Interference in Thin Films

- A light wave will not undergo a phase change upon reflection from a medium of lower index of refraction than the one in which it was traveling.

- So, a light wave traveling in oil will not undergo a phase shift if it reflects off an air boundary.



- This is similar to the reflection of a transverse wave that we observed earlier off of a free surface.

"Slow off of fast"

no reflection phase shift

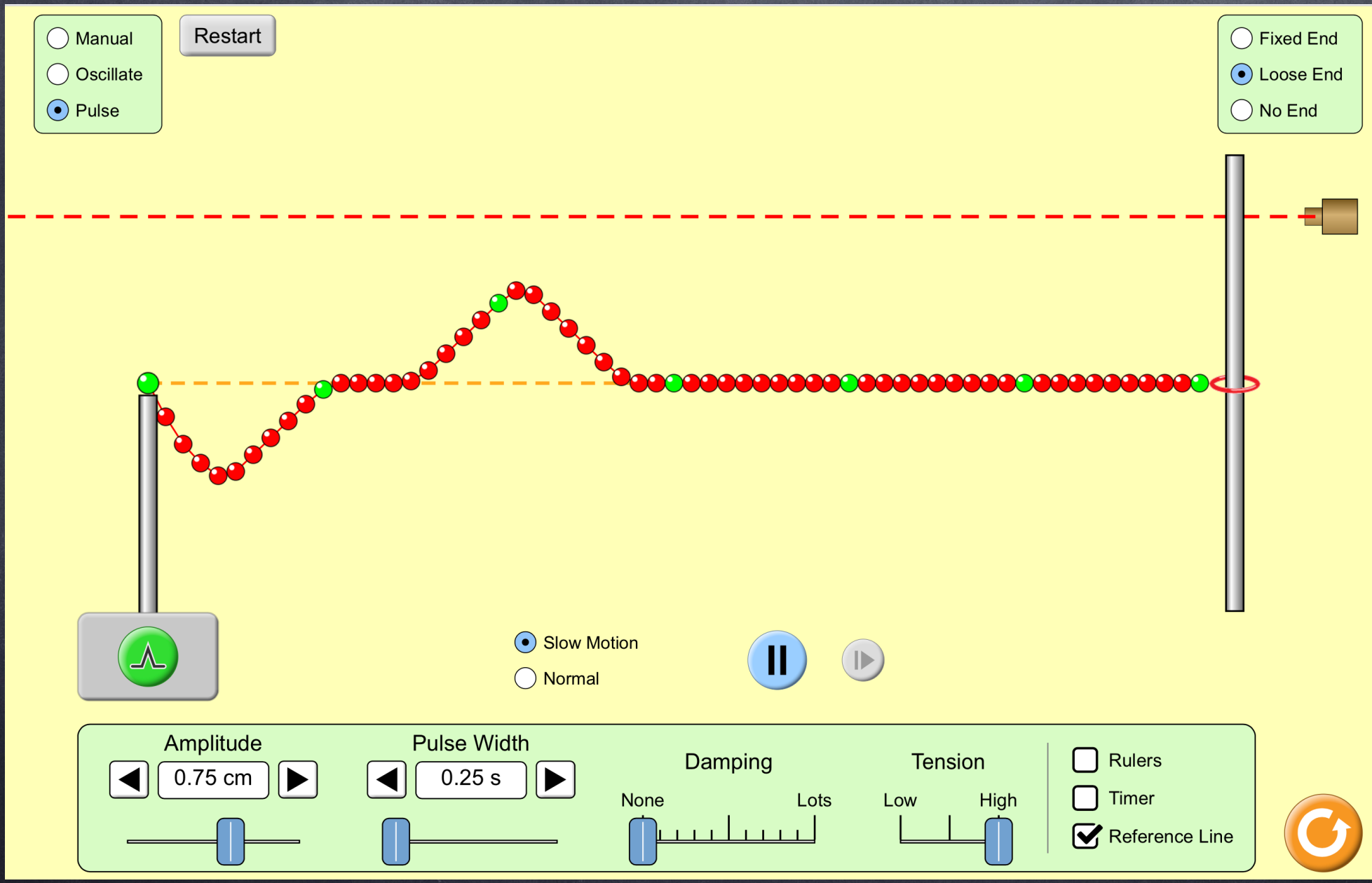
(Source: Haber-Schaim/Dodge/Gardner/Shore/Walter, *PSSC Physics*, Kendall Hunt Publishing, Dubuque, IA 1991)

"Fast off of slow"

π reflection phase shift

(Source: Haber-Schaim/Dodge/Gardner/Shore/Walter, *PSSC Physics*, Kendall Hunt Publishing, Dubuque, IA 1991)

Superposition



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

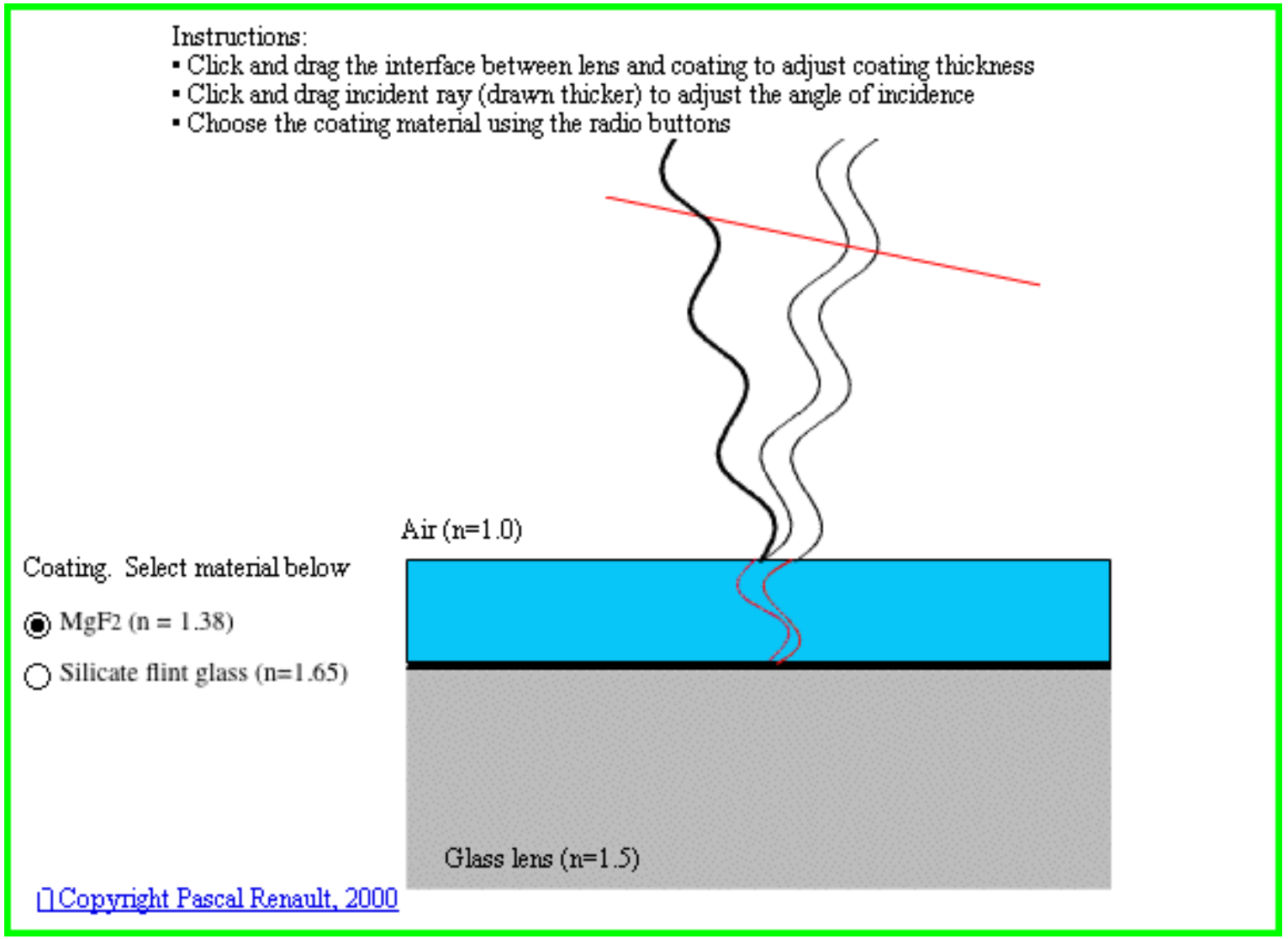
"Newton's Rings"
(Source: Harvard University Lecture Demonstration Services)
http://www.fas.harvard.edu/~scdiroff/lds/LightOptics/NewtonsRings/NewtonsRings.html

Air-soap-air

Fast-slow-fast

"DSC_0145"
(Source: tkkn2)
http://www.flickr.com/photos/tk_kn/543875981/

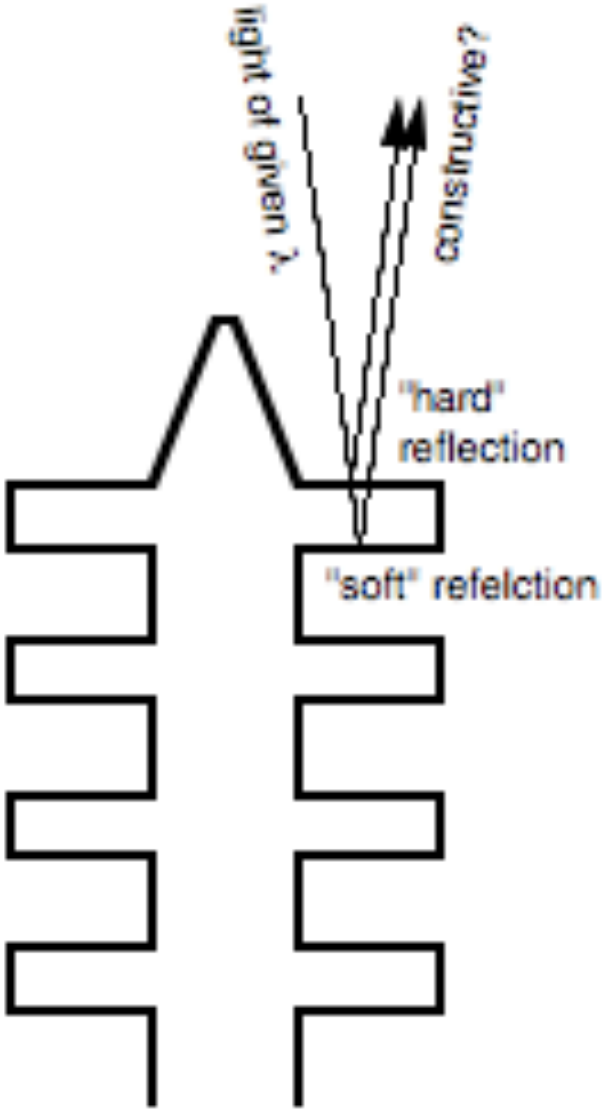
Path difference



"Thin Films"
(Source: Pascal Renault)
http://mysite.verizon.net/vzeoacw1/thinfilm.html

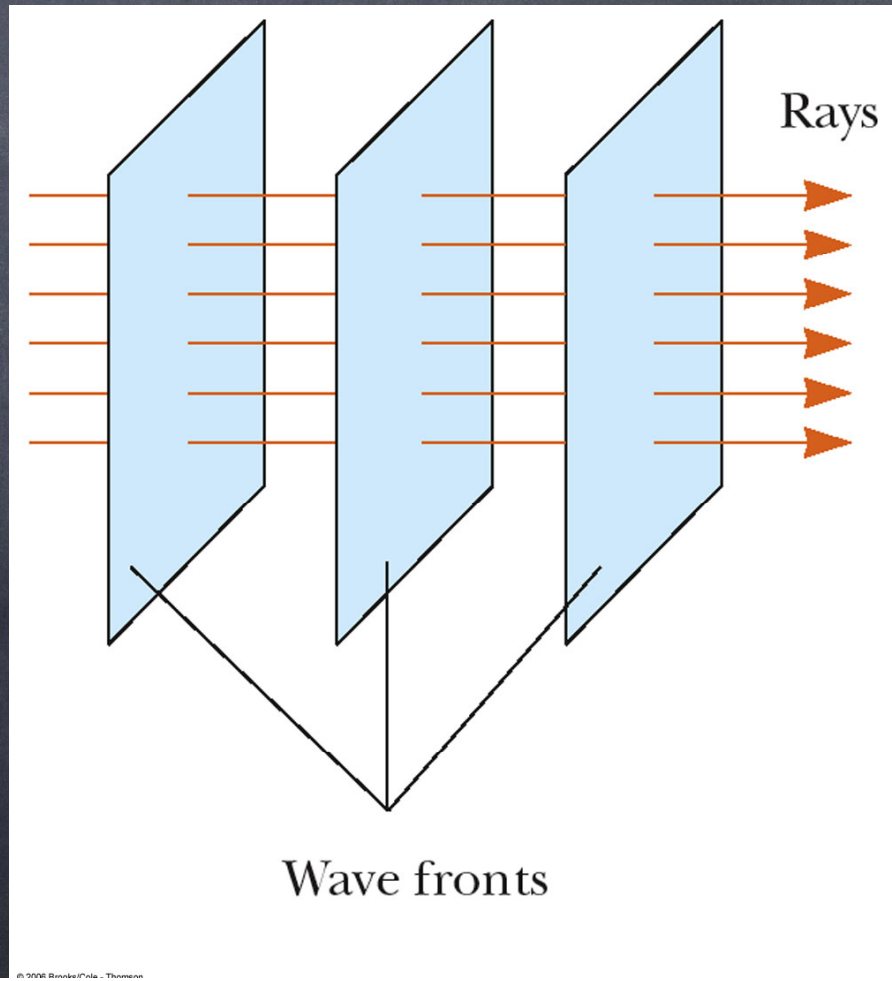
Thin Film Interference

- Thin film interference is used by Morpho butterflies to intensify the colors reflected.



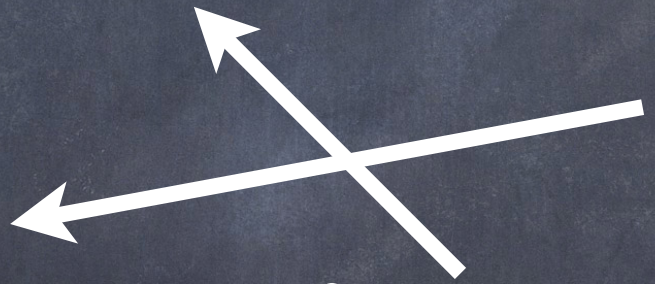
The Nature of Light

- From now on we will have to treat light as having both properties (wave and particle).
- As light moves through a medium (such as air) it will move in a straight line path.
- We draw imaginary lines (known as light rays) to represent this path.
- We can also represent this motion with wave fronts.
- A wave front is a surface where the wave has the same phase and amplitude.



Ray Model of Light

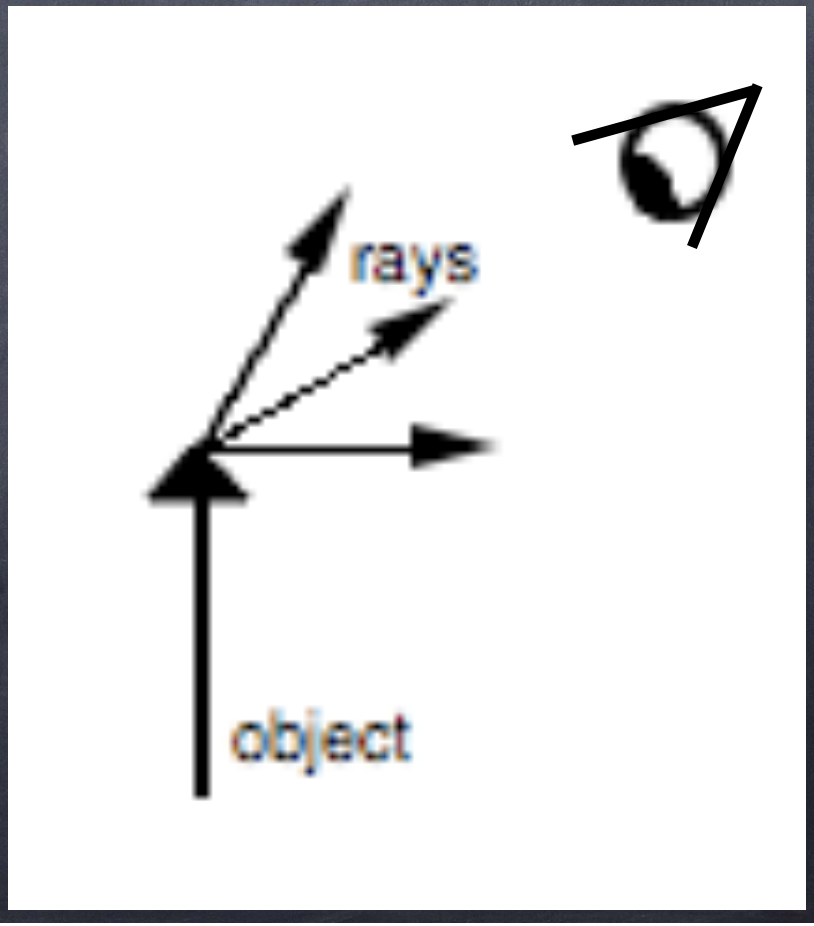
- 1) Light rays travel in straight lines in a given medium.
- 2) Light rays can cross. They do not interact with each other. Two rays can cross without either being affected in any way.



- 3) A light ray travels forever unless it interacts with matter.
- It can interact with matter by either: reflection, refraction, scattering or absorption.

Ray Model of Light

- An object is a source of light rays.
- Rays originate from every point on the object, and each point sends rays in all directions.
- If the object is far away, the rays will appear parallel to the observer.
- We make no distinction between self-luminous objects and reflective objects.
- The eyes sees by focusing a diverging bundle of rays.

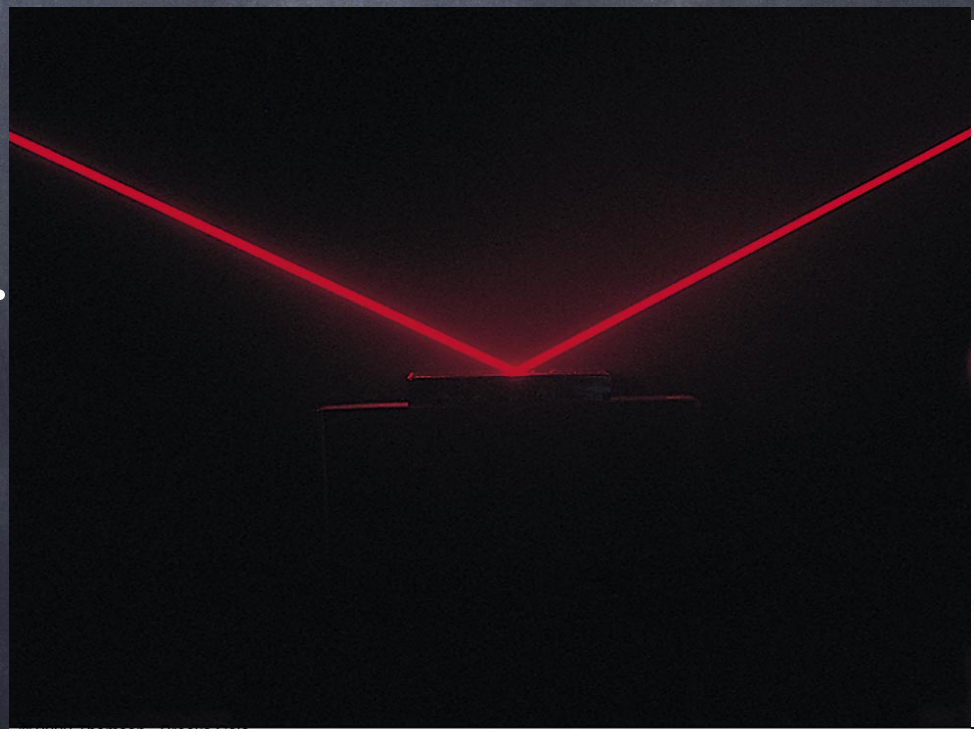


The Nature of Light

- The incident light ray will move in a straight line path as long as the medium does not change.
- But, when it encounters a boundary with a second medium, (at least) part of this incident ray is reflected back into the first medium.

If the boundary is a smooth surface, the reflection is known as specular reflection.

This means all the reflected rays will be parallel to one another.

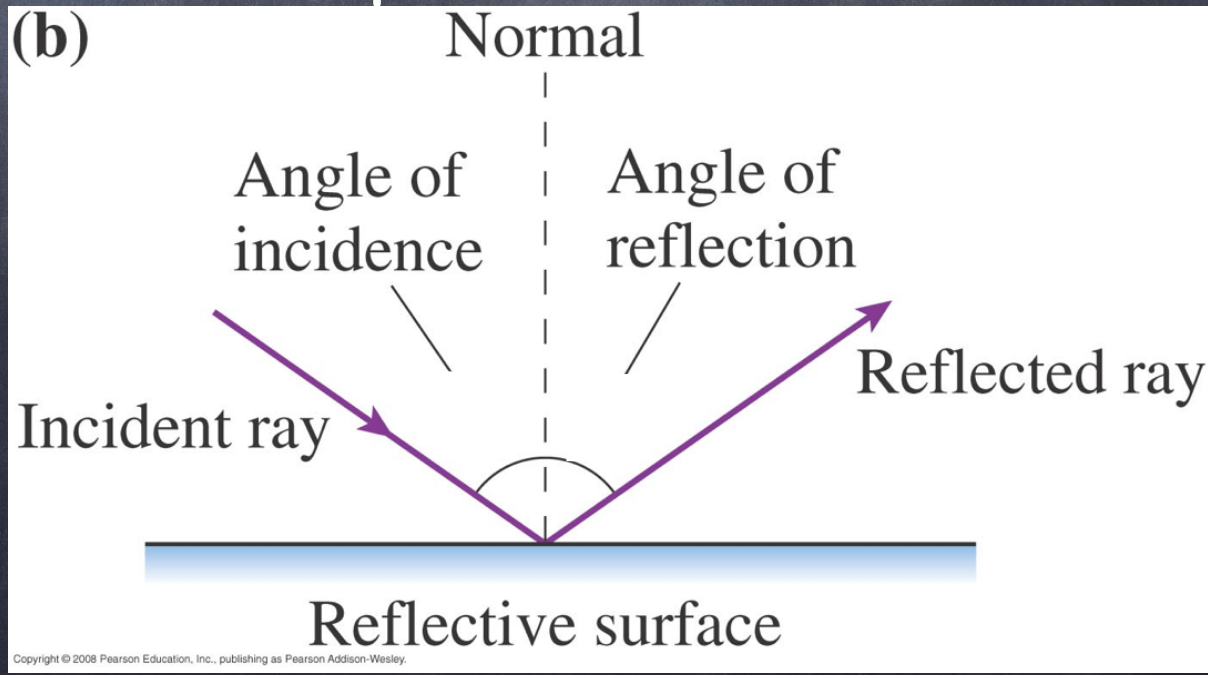


Law of Reflection

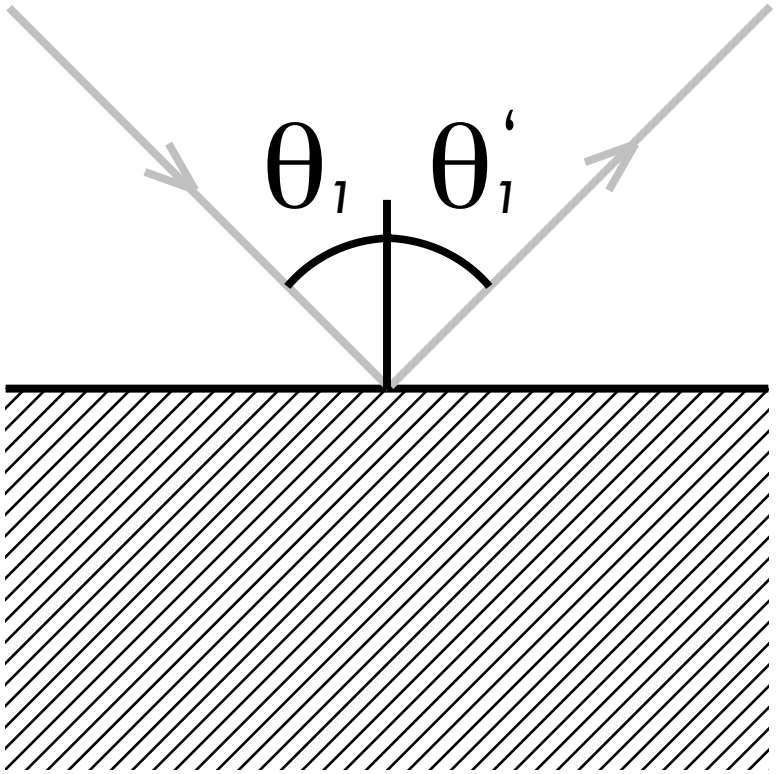
- We define a normal (perpendicular line to the surface) at the point where the incident ray hits strikes the surface.

- The incident angle, θ_1, is the angle that the incident ray makes with respect to the normal.
- The reflected angle, θ'_1, is the angle that the reflected ray makes with respect to the normal.
- The angle of incidence is equal to the angle of reflection.

$$\theta_1 = \theta'_1$$



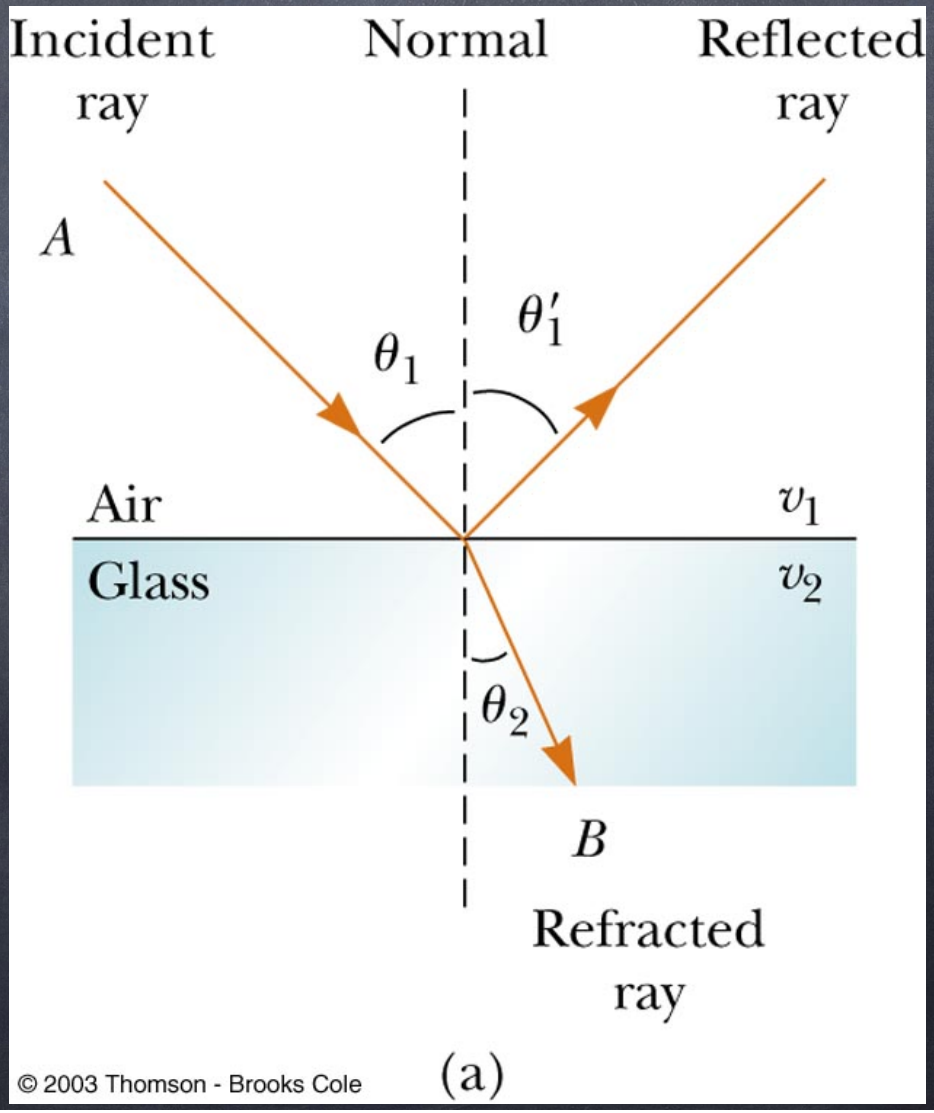
Law of Reflection



$$\theta_1 = \theta'_1$$

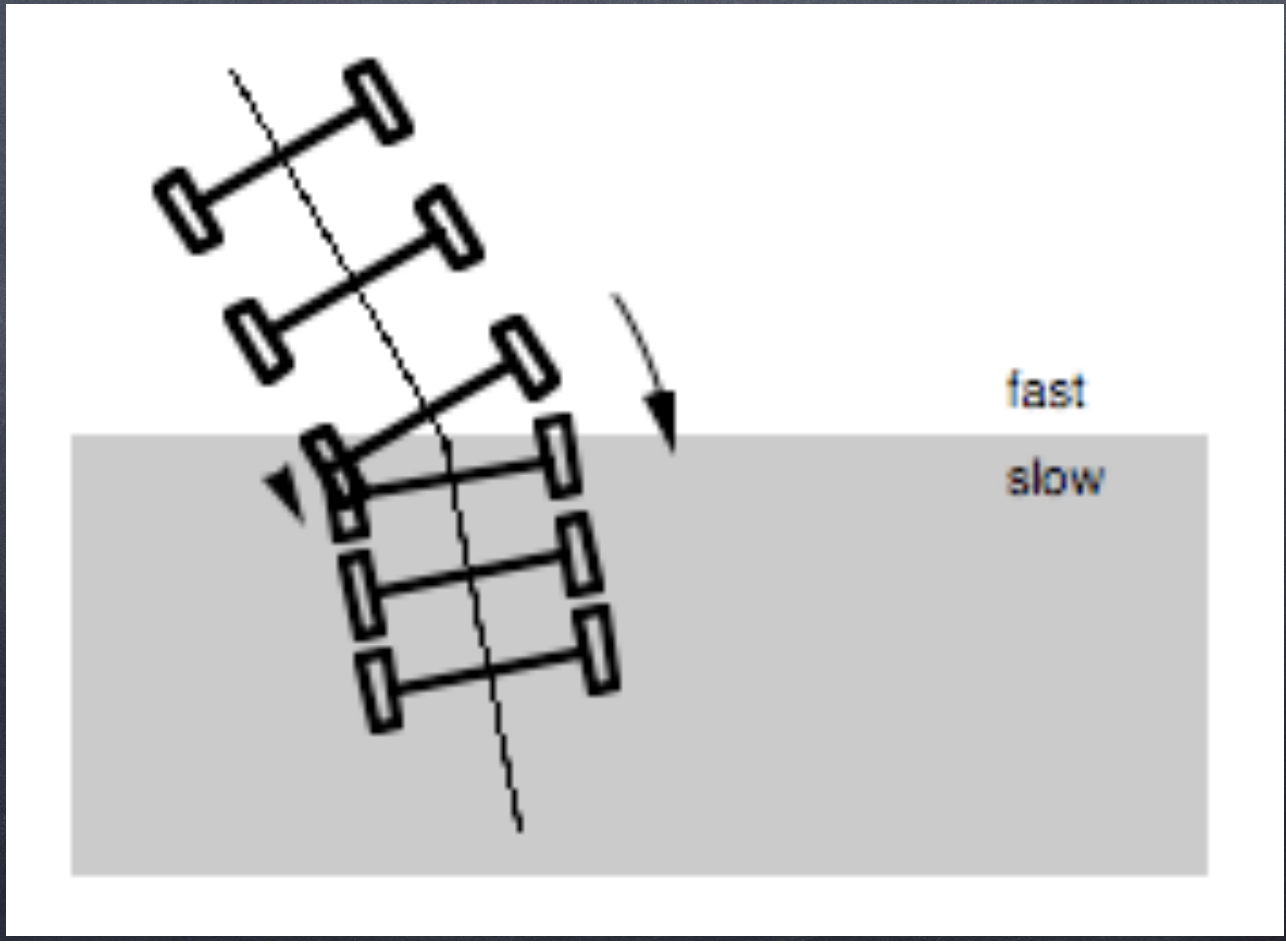
Refraction of Light

- Also, when an incident ray of light in a medium encounters a boundary with a second medium, part of this incident ray may enter the second medium.
- The ray that enters the second medium is bent at the boundary.
- This bending of the ray is called refraction.
- The incident ray, the reflected ray, the refracted ray, and the normal all lie in the same plane.

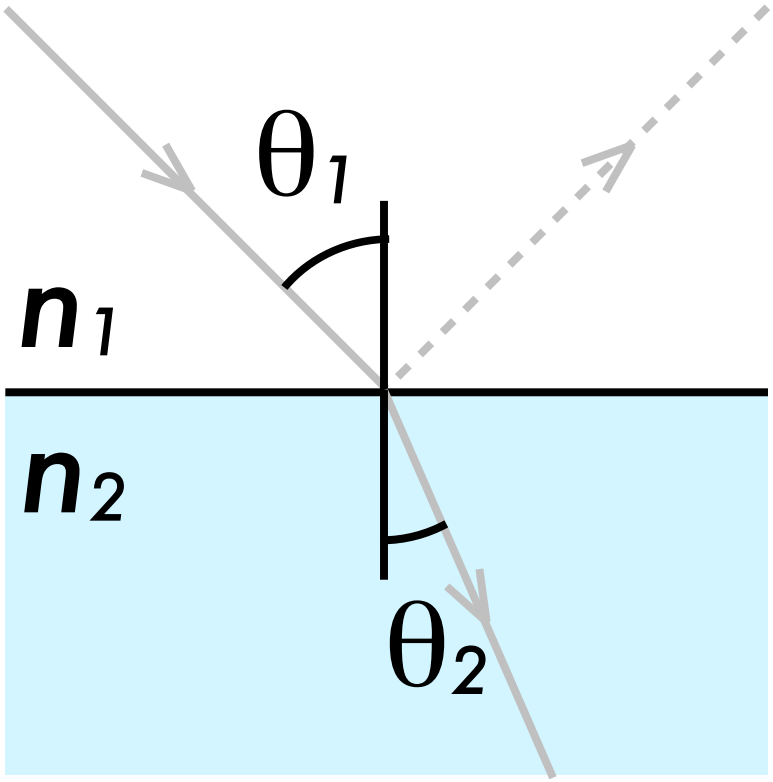


Snell's Law

- "Fast to slow, light bends towards the normal."
- Or think of a car axle: one wheel stuck in mud (slow), other wheel on pavement (fast) pivots around.
- "Slow to fast, light bends away from the normal."
- This is the basis for Snell's Law.



"Snell's" Law (1)



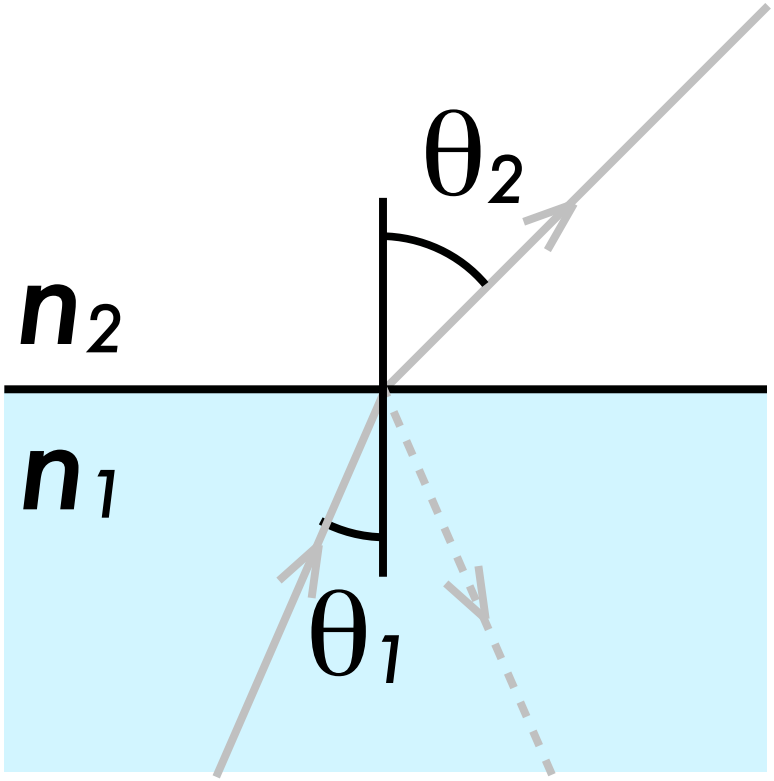
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$n_1\downarrow\ \theta_1\uparrow = n_2\uparrow\ \theta_2\downarrow$$

"Fast-to-slow"

"Fénytörés.jpg"
(Source: Zántonyi Sándor)
http://en.wikipedia.org/wiki/File:Fénytörés.jpg

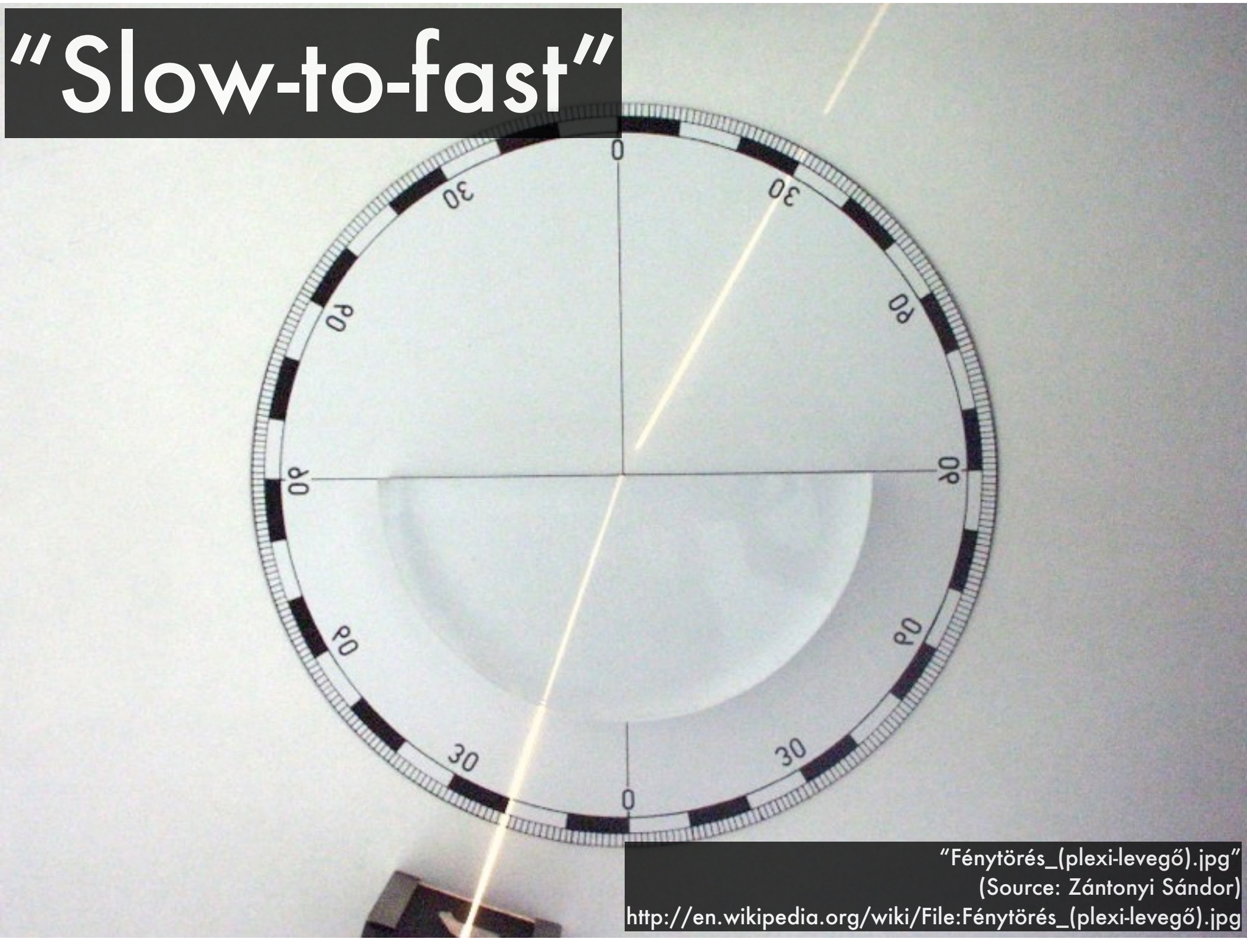
"Snell's" Law (2)



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

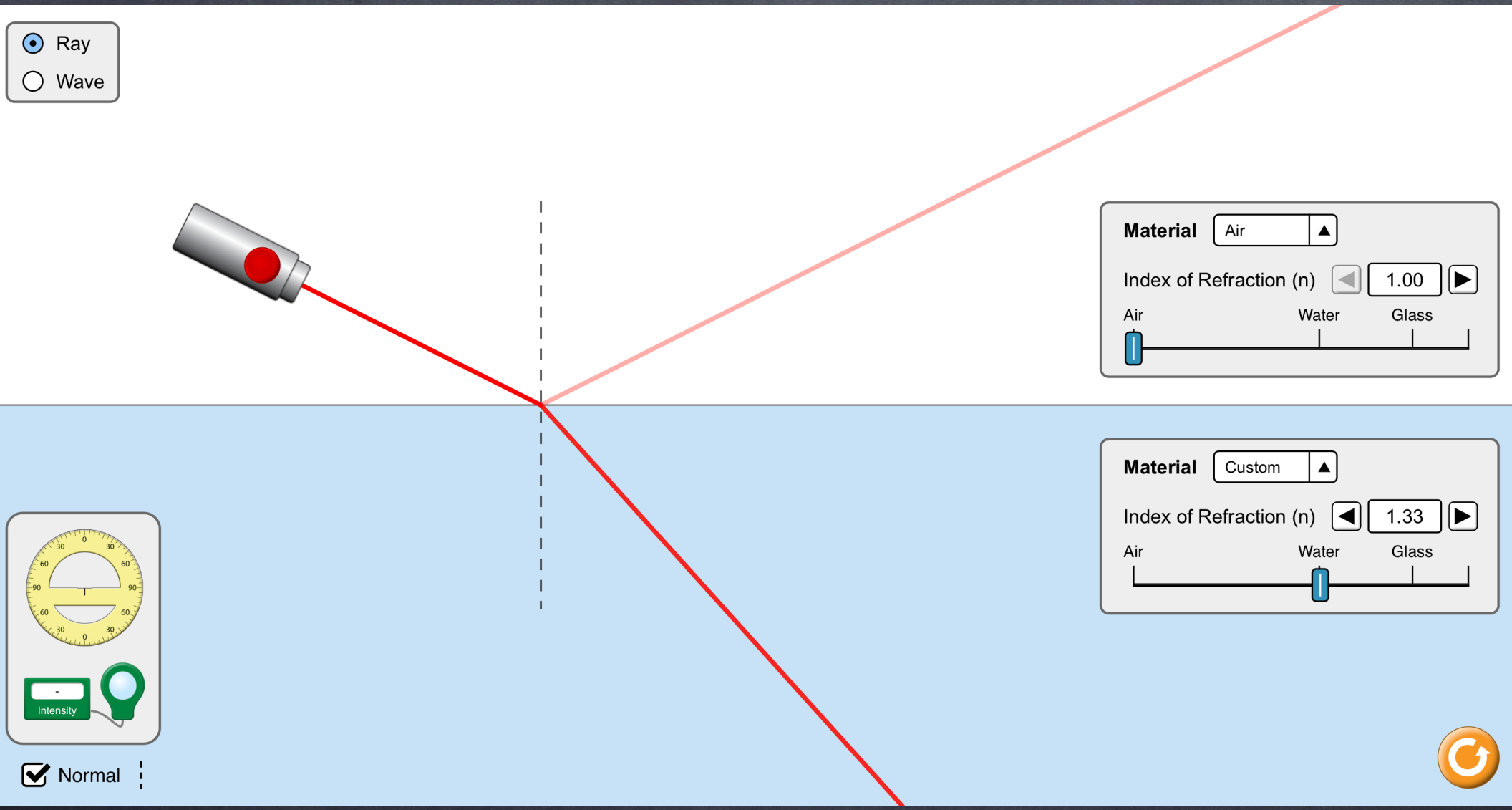
$$n_1\uparrow\ \theta_1\downarrow = n_2\downarrow\ \theta_2\uparrow$$

“Slow-to-fast”



“Fénytörés_(plexi-levegő).jpg”
(Source: Zántonyi Sándor)
http://en.wikipedia.org/wiki/File:Fénytörés_(plexi-levegő).jpg

Ray Model of Light

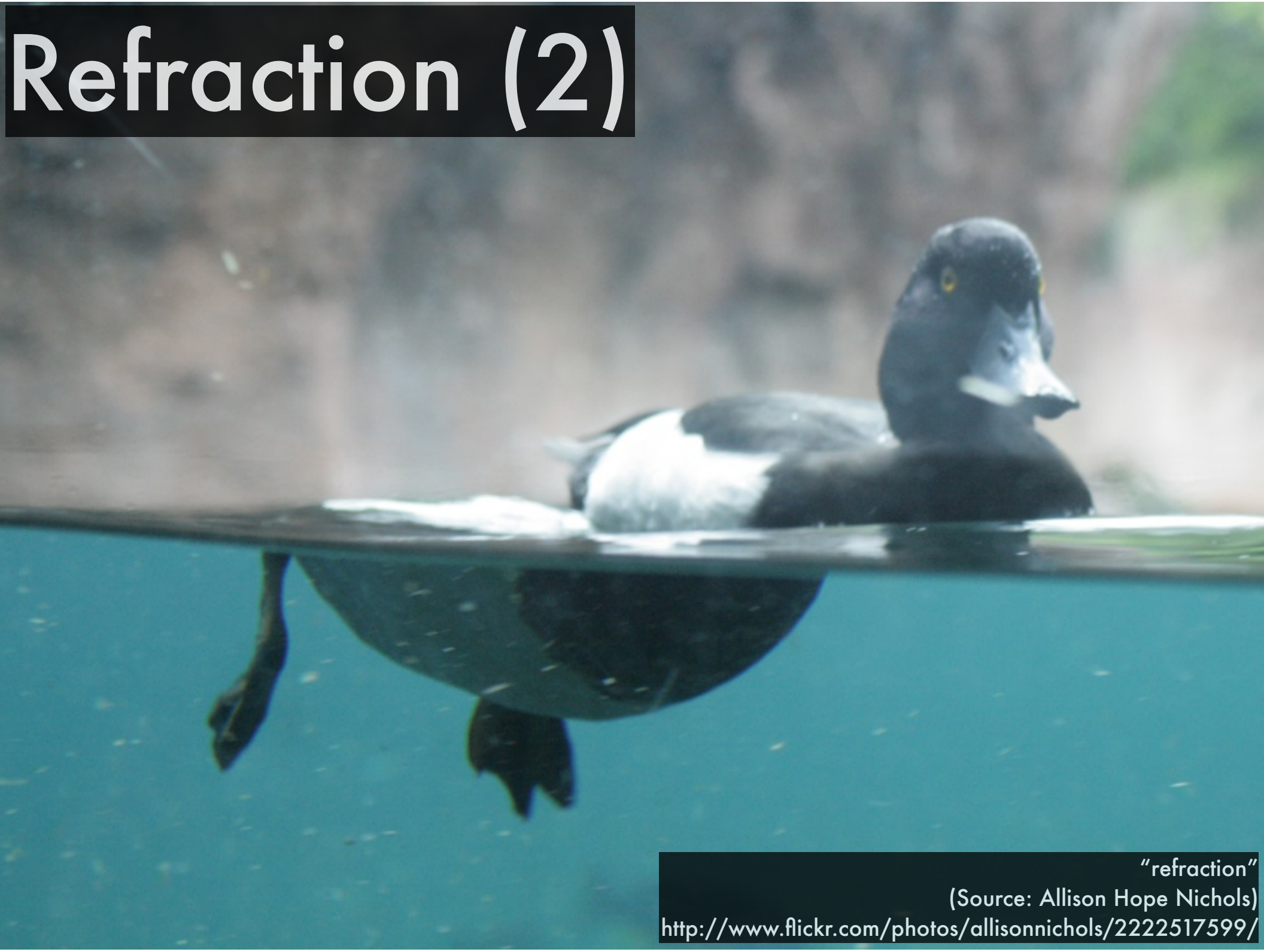


https://phet.colorado.edu/sims/html/bending-light/latest/bending-light_en.html

Refraction (1)

"DSC_7901a_crop.jpg"
(Source: AzCyco)
http://i172.photobucket.com/albums/w35/AzCyco/2007%20air%20show/DSC_7901a_crop.jpg

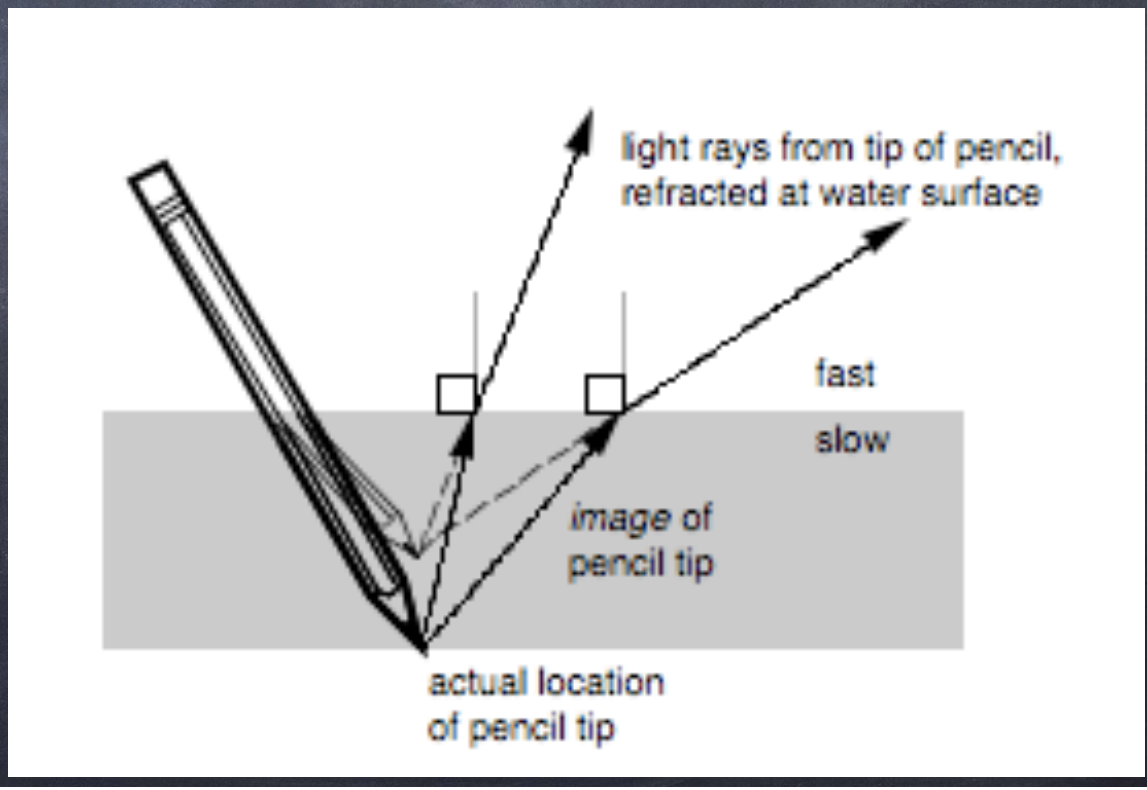
Refraction (2)



"refraction"
(Source: Allison Hope Nichols)
http://www.flickr.com/photos/allisonnichols/2222517599/

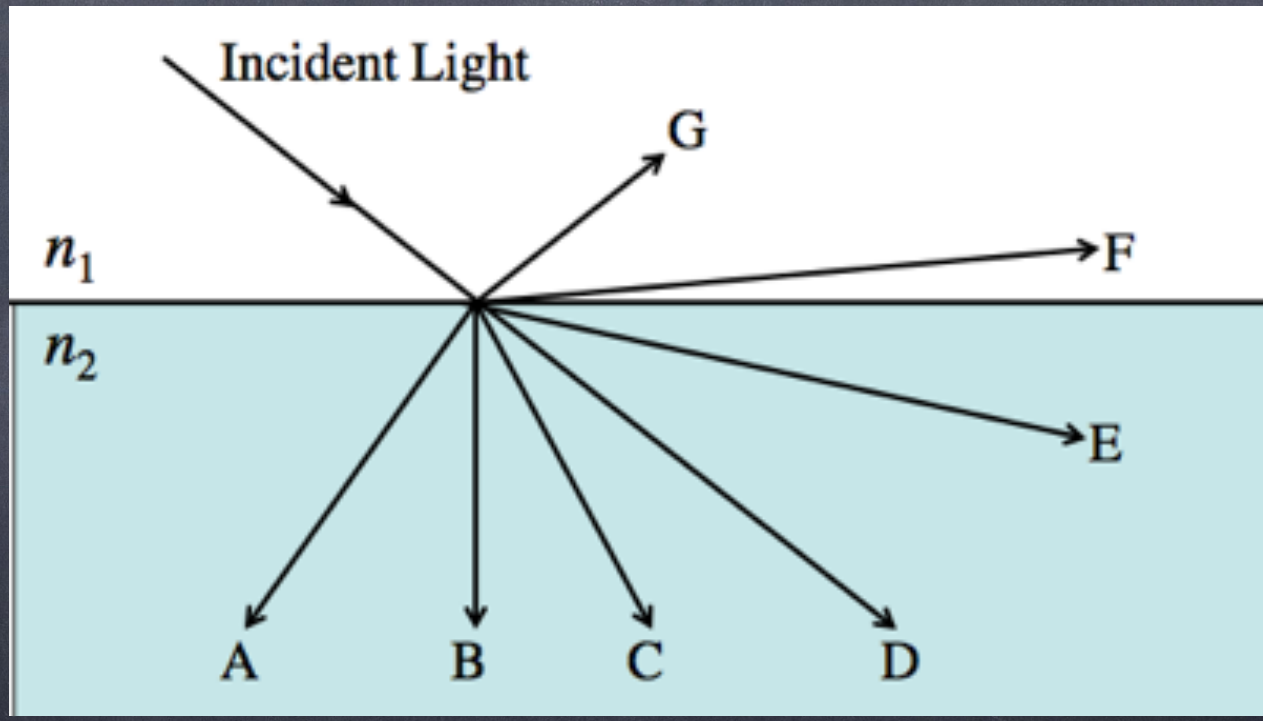
Snell's Law

- Why do things look bent when placed in water?
- Take a pencil for instance.
- The pencil is the object that light diverges from.
- The water surface refracts the light as it hits the boundary.
- The pencil rays now appear to diverge from a new shallower location.



Activity 3

b) The figure to the right shows seven conceivable trajectories of light rays leaving an object. The incident light from this object is indicated on the diagram. Which, if any, or these trajectories are impossible? For each that is possible, what are the requirements of the index of refraction, n_2?



i. Impossible?

_____

ii. Requires $n_2 > n_1$?

_____

iii. Requires $n_2 = n_1$?

_____

iv. Requires $n_2 < n_1$?

_____

v. Possible for any n?

_____

Clicker Question 5

The figure below shows seven conceivable trajectories of light rays leaving an object. The incident light from this object is indicated on the diagram. You may assume D is a straight line continuation of the incident light. Assume n_1 is air and n_2 is water, which of the trajectories are possible?

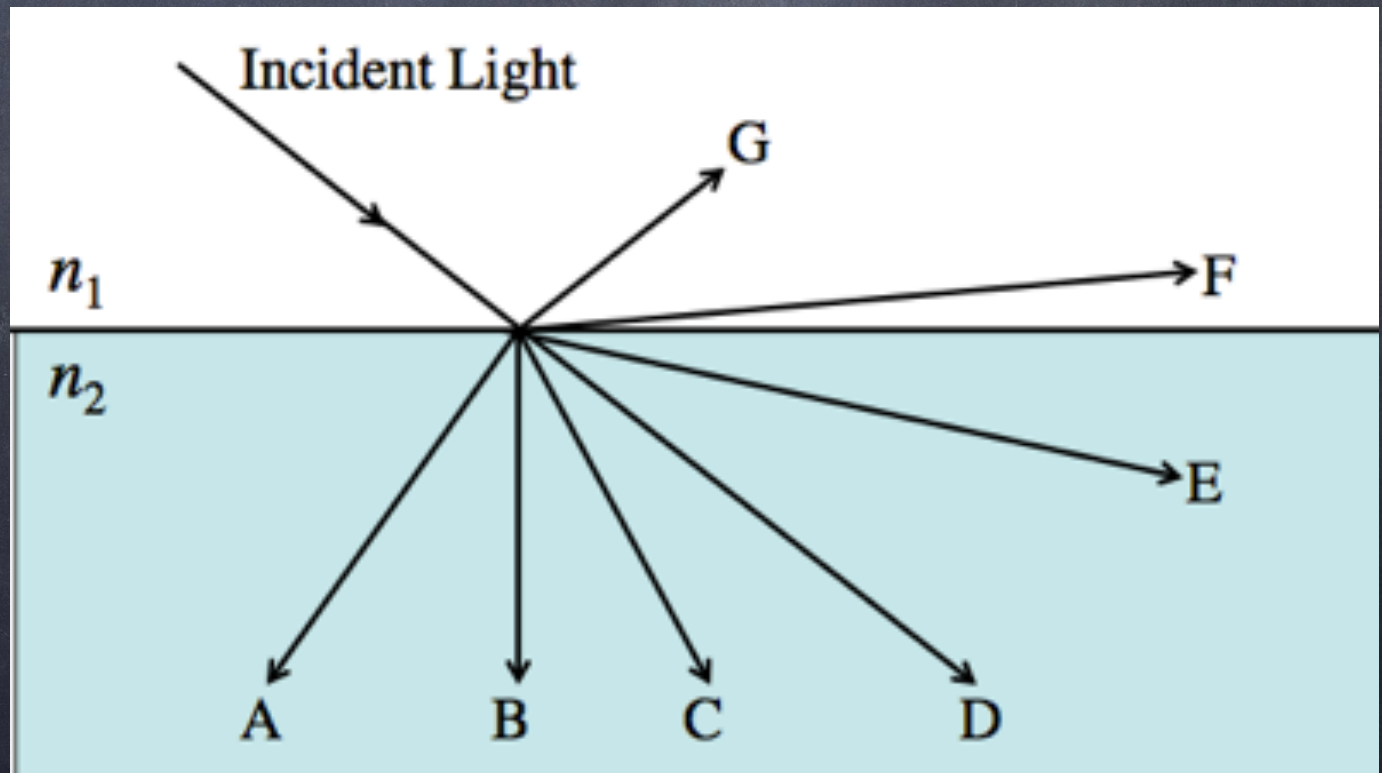
A) Only C is possible.

B) Only C and G are possible.

C) Only E and G are possible.

D) Only A, B, C, D, and G are possible.

E) Only E and F are possible.



Clicker Question 6

The figure below shows seven conceivable trajectories of light rays leaving an object. The incident light from this object is indicated on the diagram. You may assume D is a straight line continuation of the incident light. Assume n_1 is water and n_2 is air, which of the trajectories are possible?

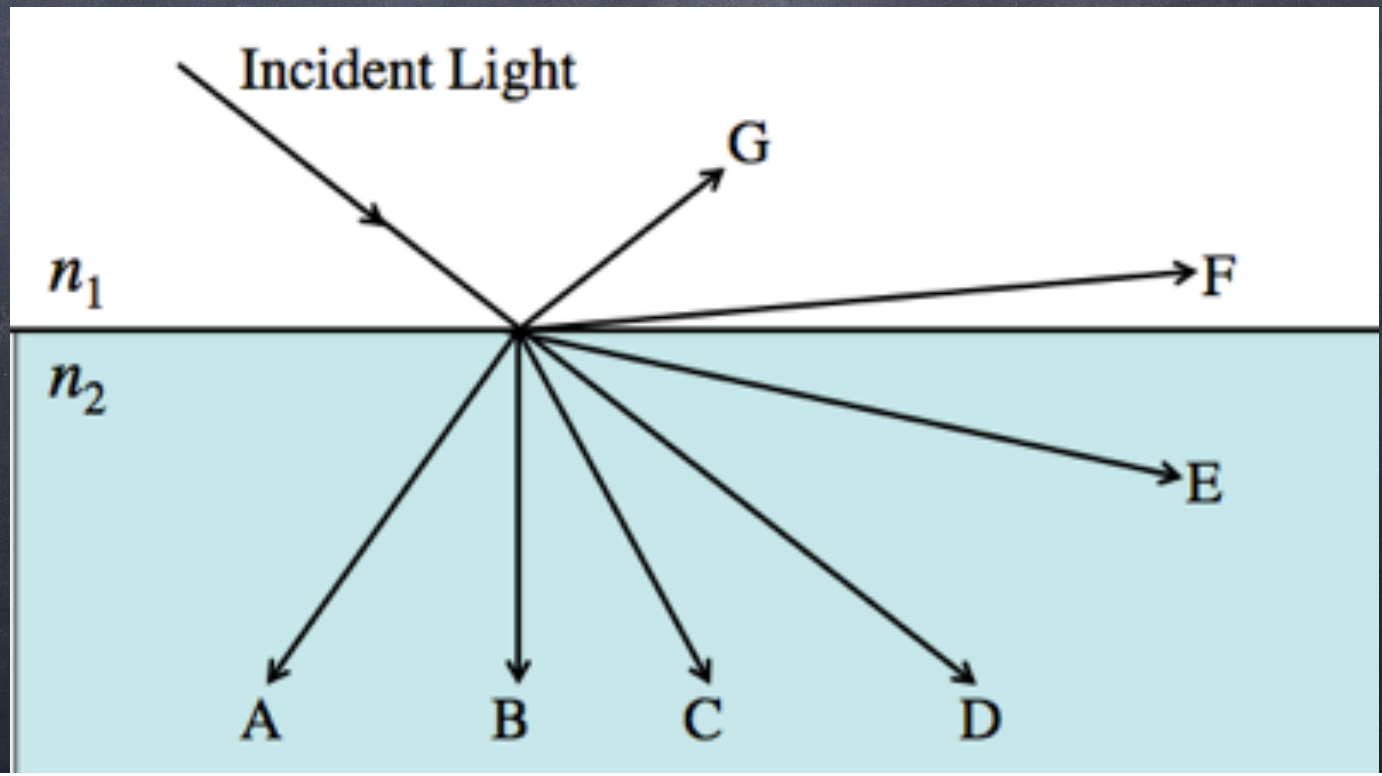
A) Only C is possible.

B) Only C and G are possible.

C) Only E and G are possible.

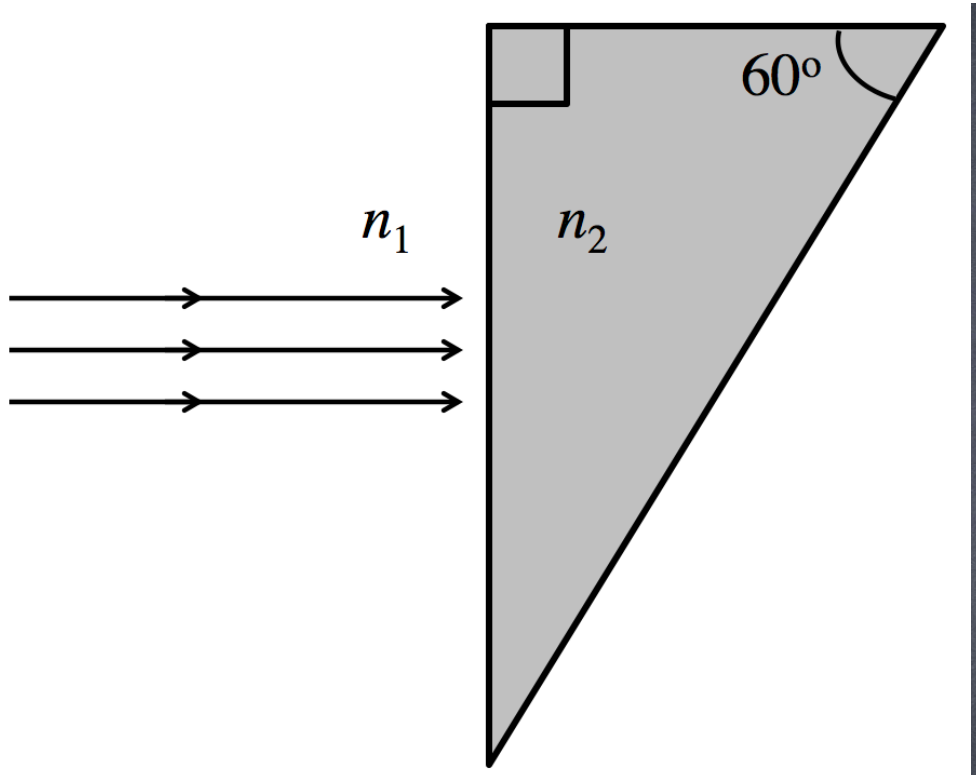
D) Only A, B, C, D, and G are possible.

E) Only E and F are possible.



Activity 4

A horizontal light ray initially in air (n_1=1) approaches a prism as shown in the diagram to the right. The prism is in the shape of a right triangle and has an index of refraction of 1.5 (i.e. n_2=1.5)



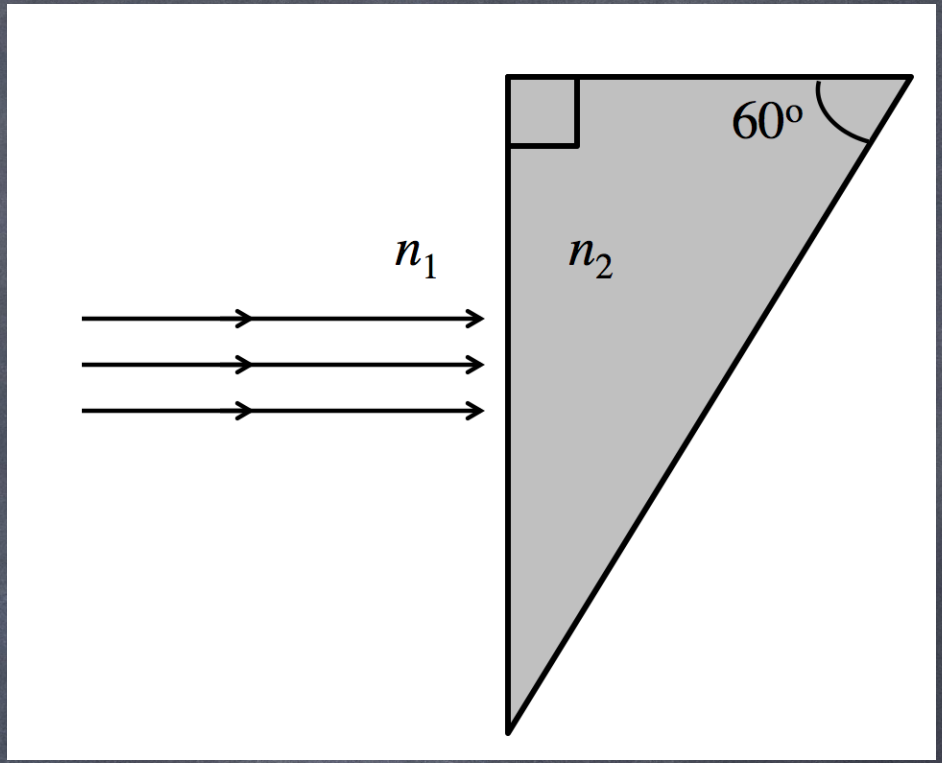
a) Calculate the angle at which it both enters and exits the prism (draw the trajectory for this light ray).

b) If the prism were to have a lower index of refraction, say 1.25, but the same shape, would the exiting angle of the light ray be smaller, greater, or equal to what you calculated in part a)?

c) The index of refraction for red light in the glass is slightly smaller than the index of refraction for violet light in glass, if white horizontal light were to hit the prism would you see a rainbow? If so, which color light (violet/red) would be at the top it?

Clicker Question 7

Horizontal light rays initially in air approach a glass prism (n=1.5) as shown in the diagram to the right. The light rays exit the prism on the right. Which way will the light rays be deflected?



A) The light rays will be deflected upward.

B) The light rays will be deflected downward.

C) The light rays will not be deflected in this situation.

Refraction of Light

- What happens with a light ray with an incident angle of 60.0° starting in glass heading out to air:

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

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

$$\theta_2 = \sin^{-1}\left(\frac{n_1}{n_2}\sin\theta_1\right)$$

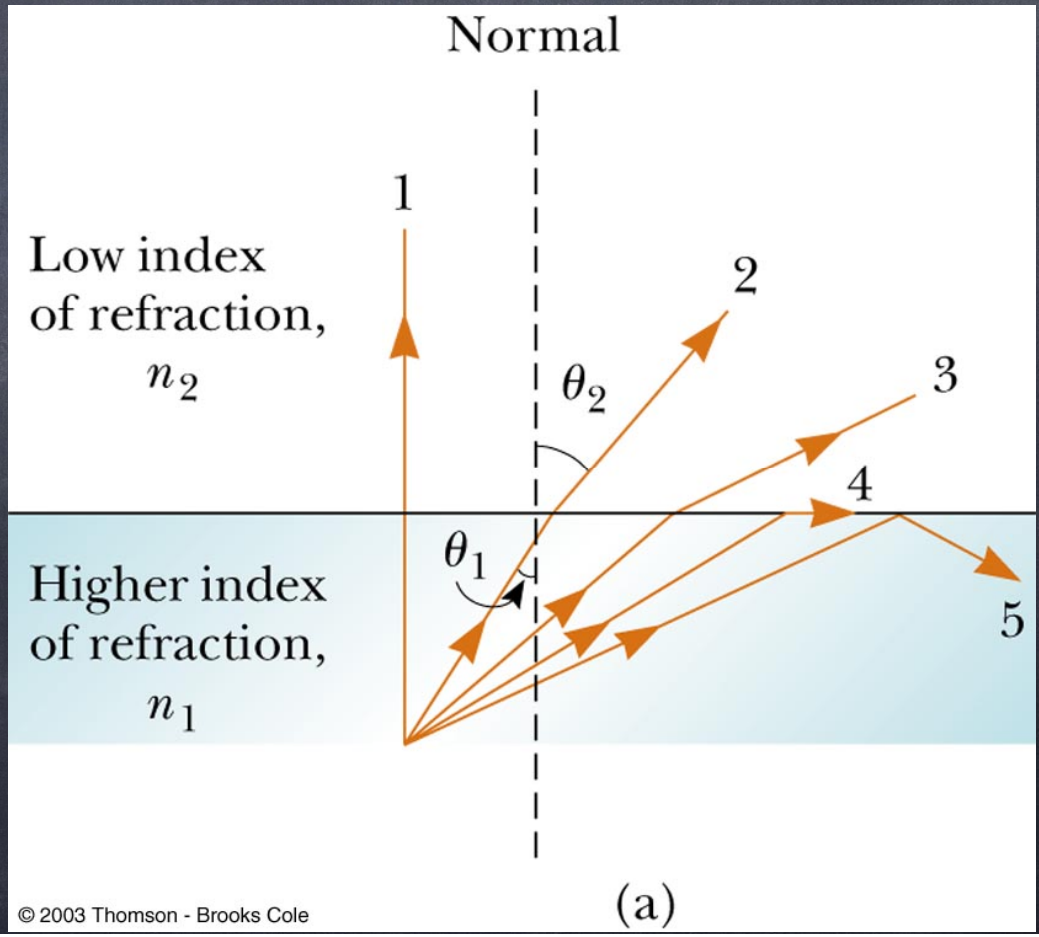
$$\theta_2 = \sin^{-1}\left(\frac{1.52}{1.0003}\sin 60°\right)$$

$$\theta_2 = \sin^{-1}(1.32) = \text{?????}$$

- Here the angle doesn't exist. The angle was so great that it refracted the incident ray back to the first medium (reflected?).

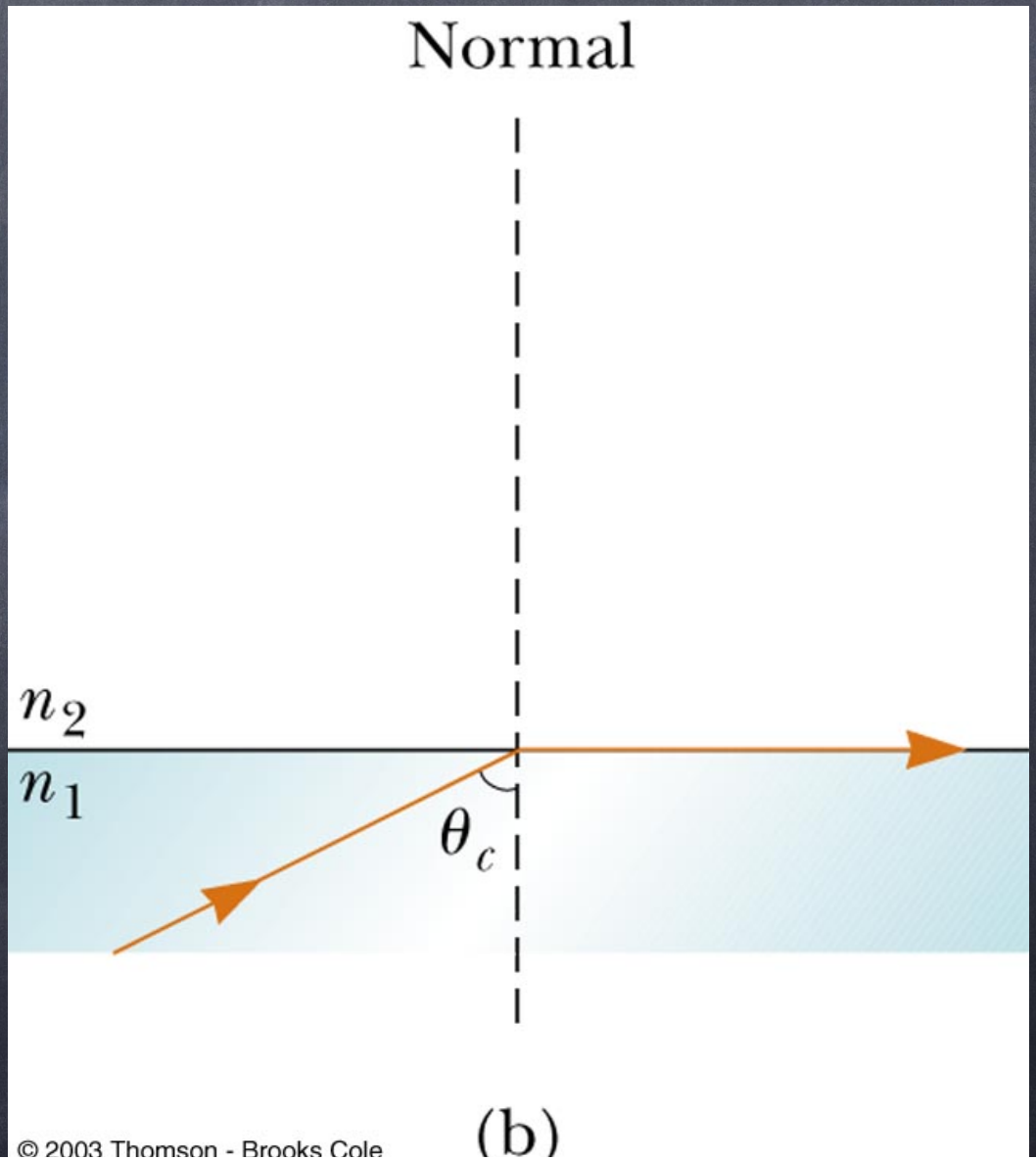
Total Internal Reflection

- This is known as Total Internal Reflection (TIR).
- It can only occur if you move from a slow medium to a fast medium such that the refracted ray is bent away from the normal compared to the incident ray.
- Here you can see light ray 5 undergoing total internal reflection.
- This means that at the angle that light ray 5 hits at, no light enters the second medium.



Total Internal Reflection

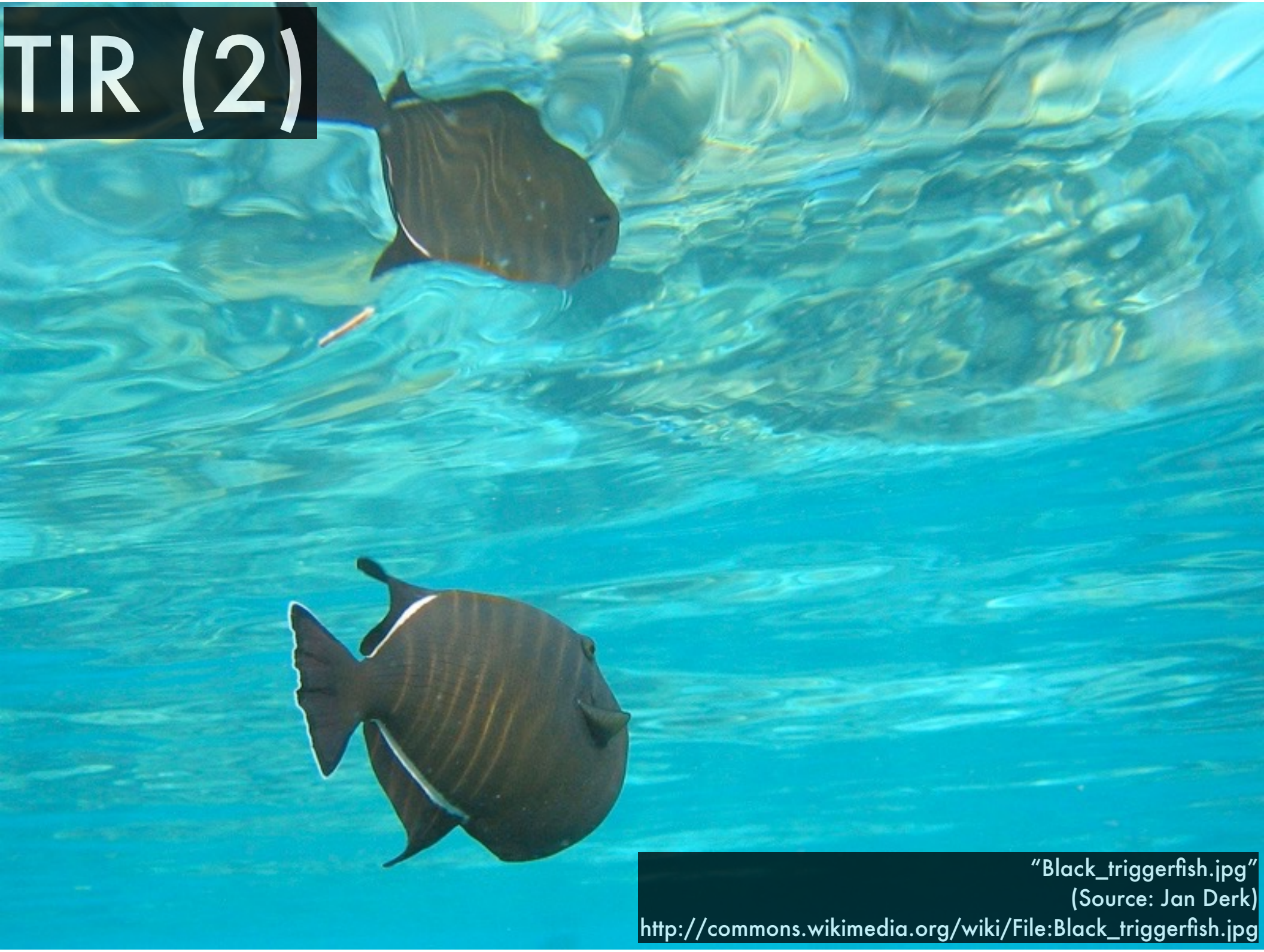
- We define the critical angle as a particular angle of incidence that will result in an angle of refraction of 90°.
- For angles of incidence greater than the critical angle, the beam is entirely reflected at the boundary (TIR).
- This ray will obey the Law of Reflection at the surface boundary.



TIR (1)

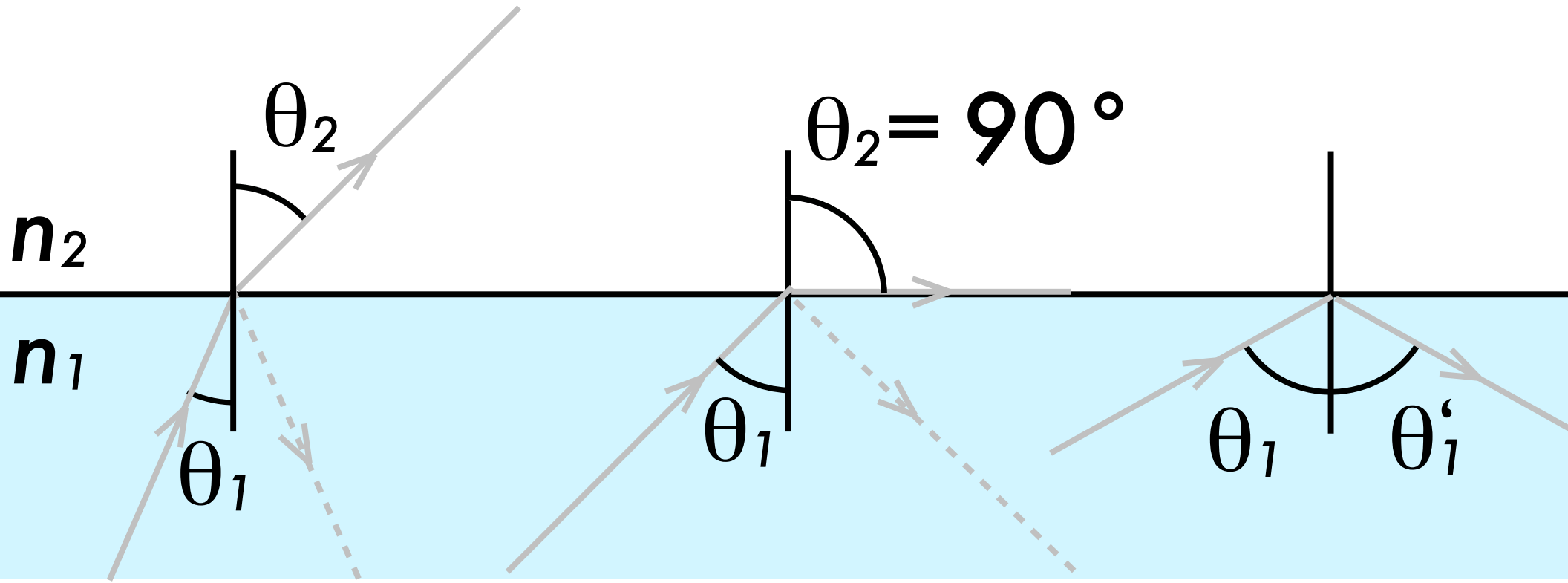
"Underwater Pure Pleasure"
(Source: Elena Kalis)
http://elenakalis.carbonmade.com/projects/2155061

TIR (2)



"Black_triggerfish.jpg"
(Source: Jan Derk)
http://commons.wikimedia.org/wiki/File:Black_triggerfish.jpg

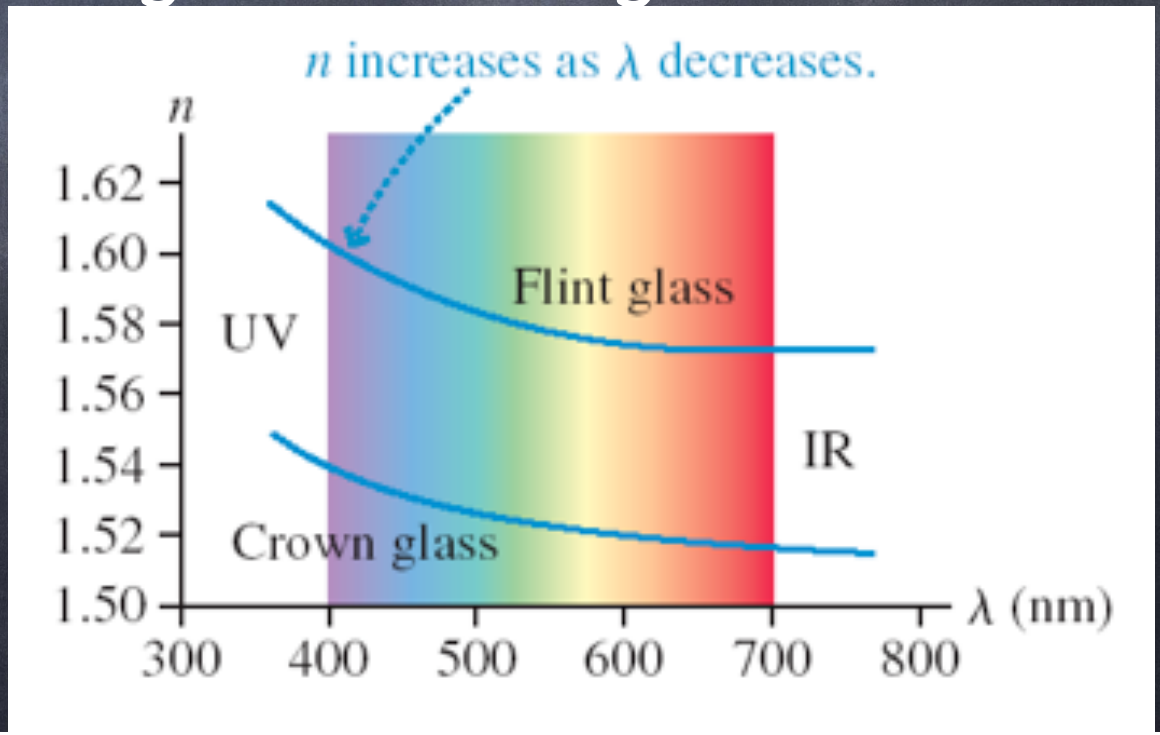
Summary: Three Cases



$\theta_1 < \theta_c$ $\theta_1 = \theta_c$ $\theta_1 > \theta_c$

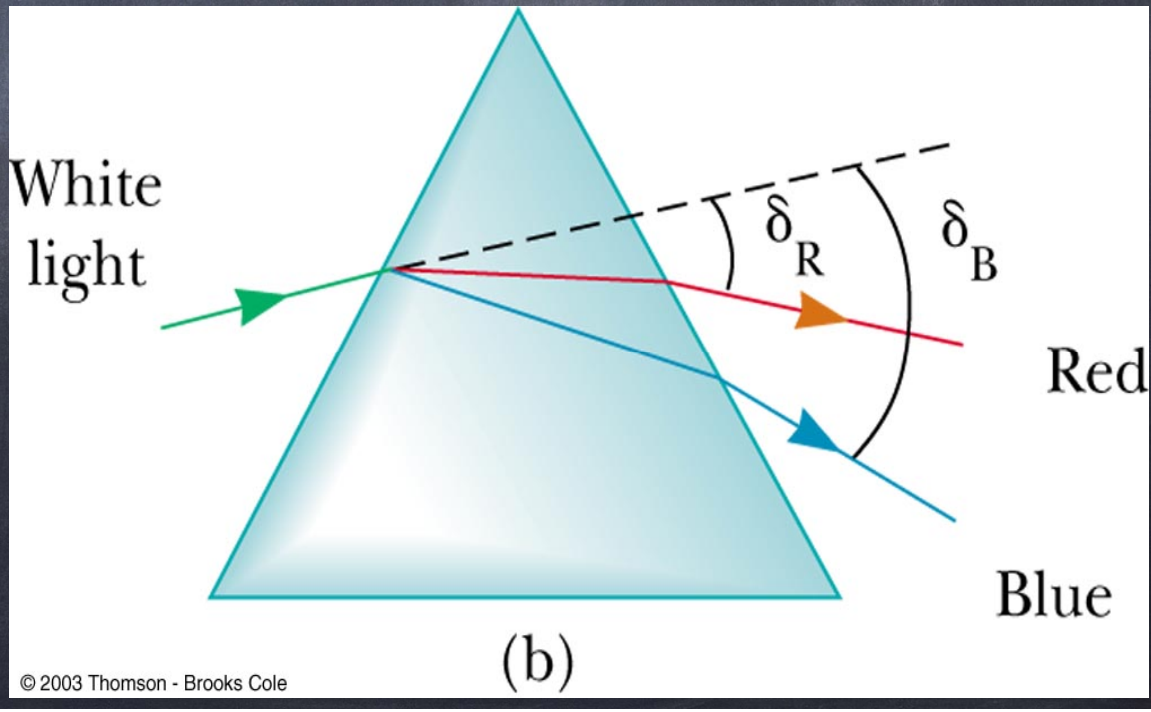
Dispersion

- The index of refraction in anything except a vacuum depends on the wavelength of the light.
- The dependence of n on λ is called dispersion.
- Snell's Law indicates that the angle of refraction made when light enters a material depends on the wavelength of the light.
- The index of refraction for a material usually decreases with increasing wavelength.



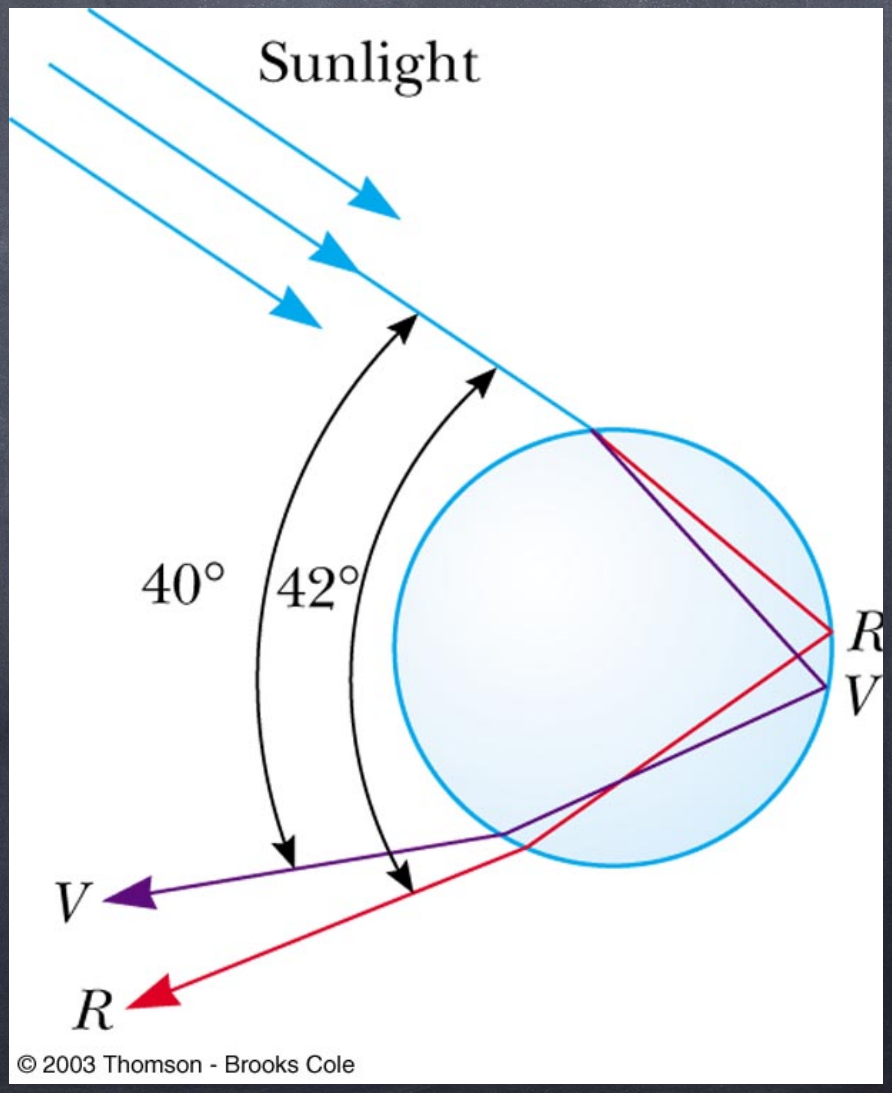
Dispersion

- This means that violet light refracts more than red light when passing from air into a material.
- The amount the ray is bent away from its original direction is called the angle of deviation, δ.
- Since all the colors have different angles of deviation, they will spread out into a spectrum.
- Violet deviates the most.
- Red deviates the least.



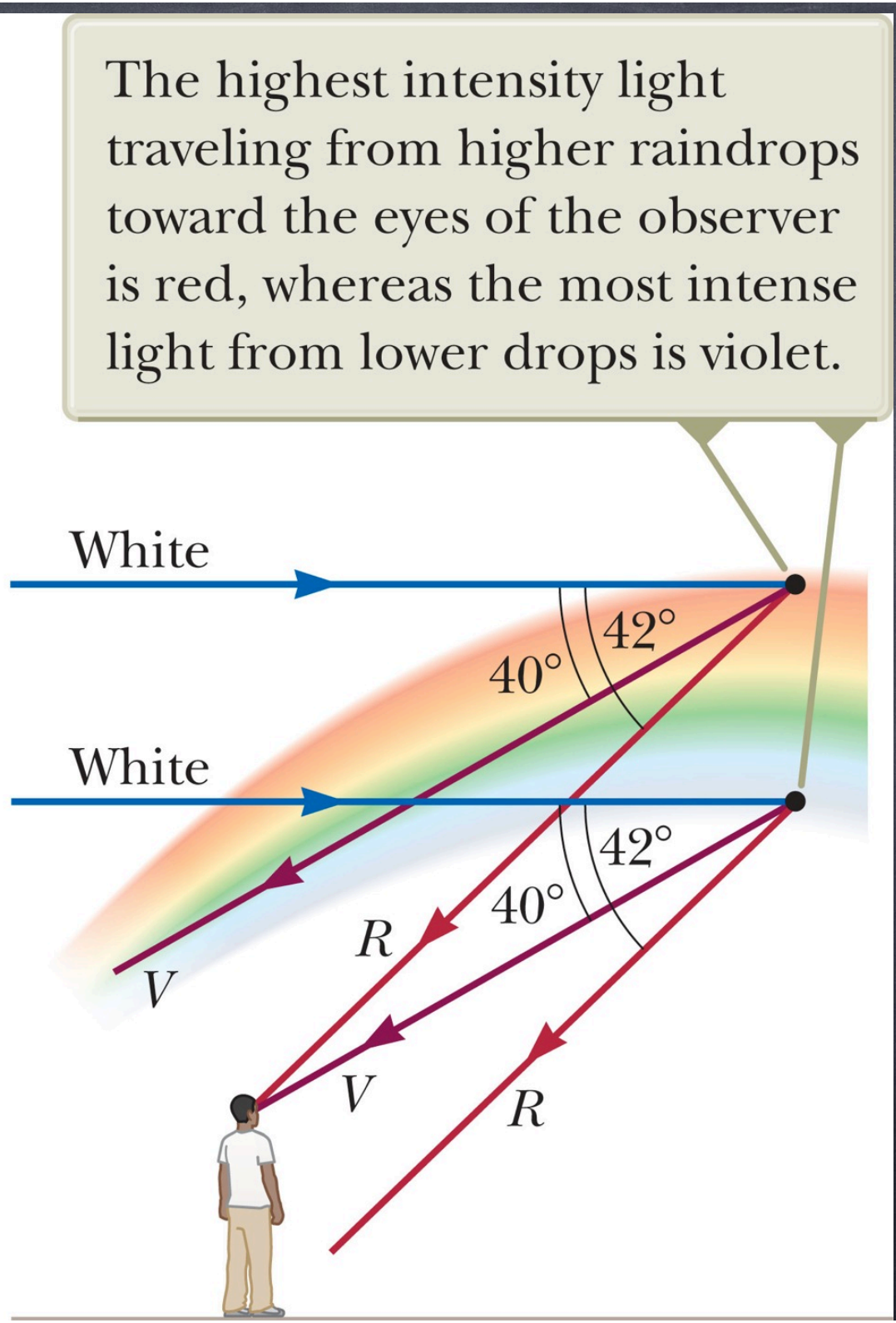
Rainbows

- Rainbows appear when a ray of light strikes a drop of water in the atmosphere.
- The incident white light ray will undergo both reflection and refraction.
- At the first boundary (air-water), refraction will occur (with red deviating the least).
- At the second boundary (water-air), reflection will occur.
- It refracts again as it hits a third boundary (water-air).



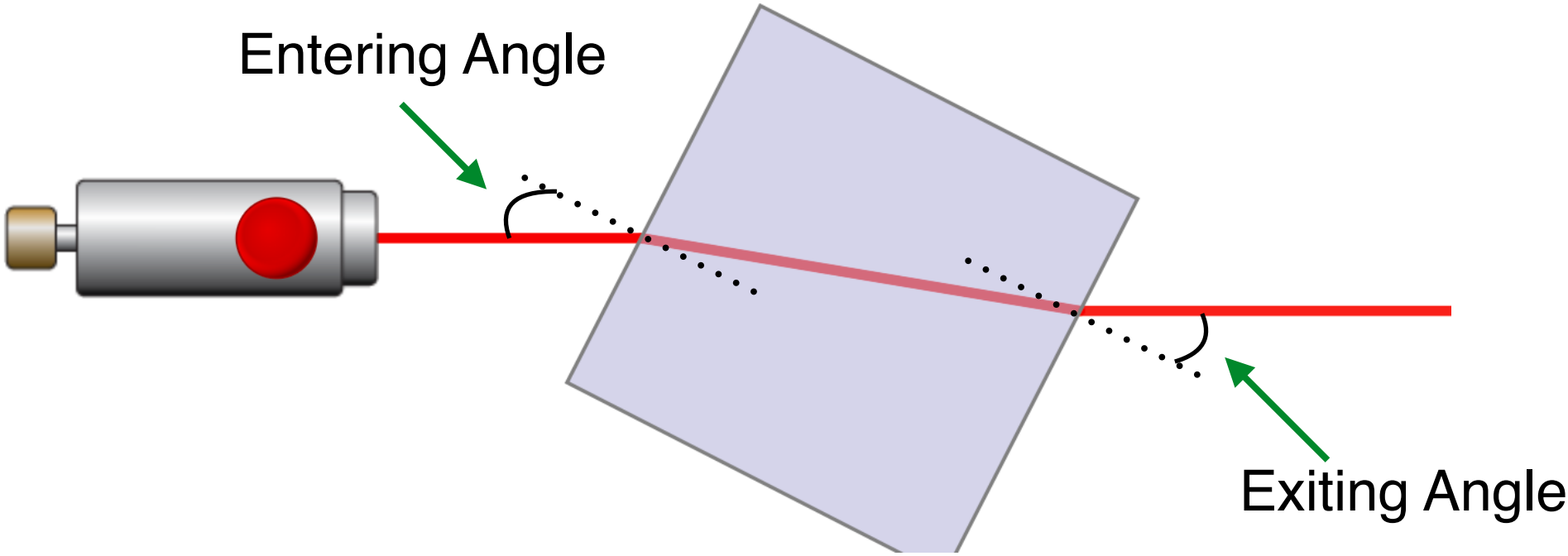
Rainbows

- For a raindrop very high in the sky, red will be bent more and will be directed toward the observer.
- A raindrop lower in the sky would direct violet toward the observer.



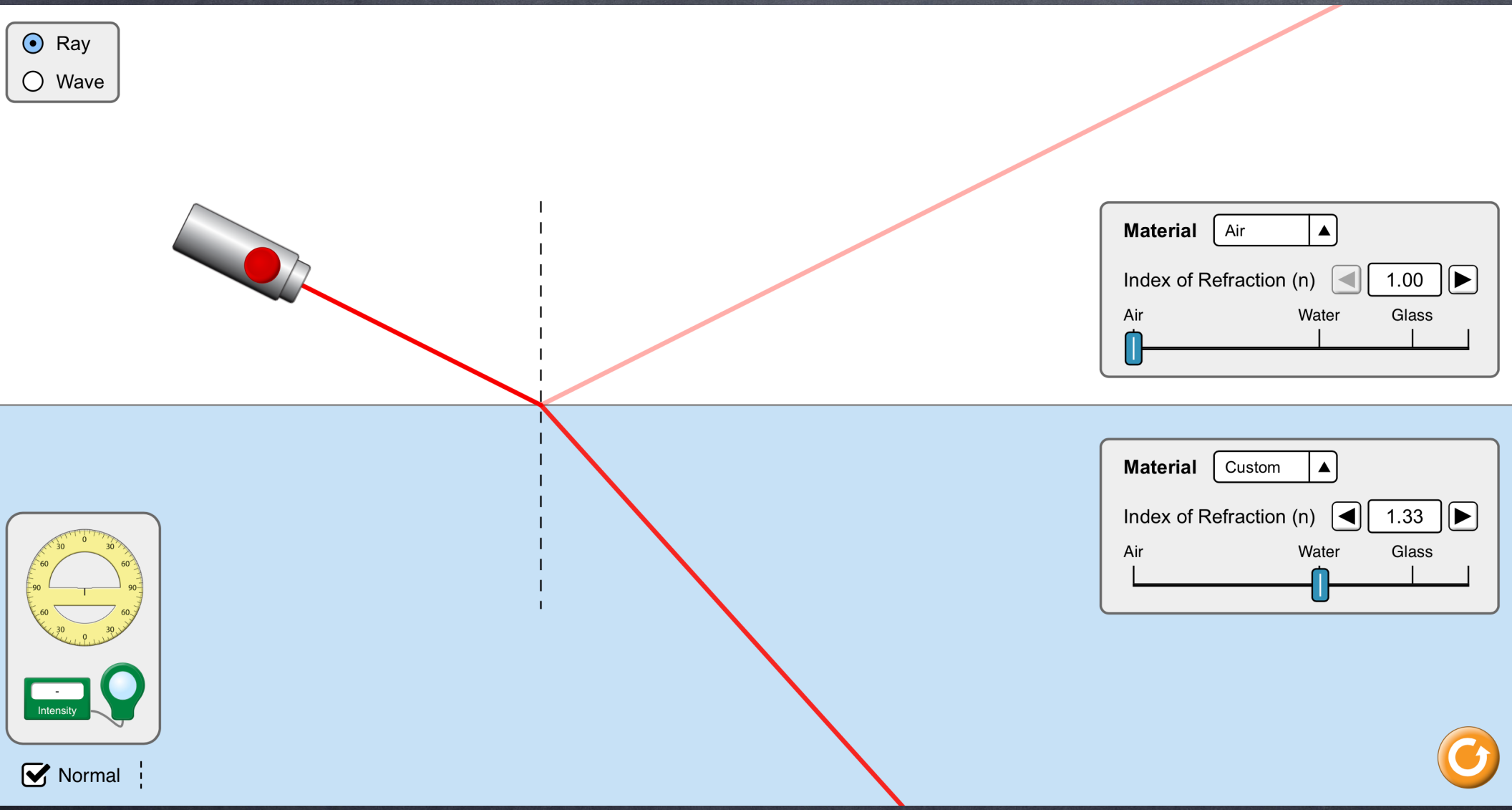
"Sunlight through a glass door"
(Source: "wonderferret" (Mark))
http://www.flickr.com/photos/wonderferret/290014648/

Prisms



Recall that all angles are measured with respect to the surface normal.

Ray Model of Light



https://phet.colorado.edu/sims/html/bending-light/latest/bending-light_en.html

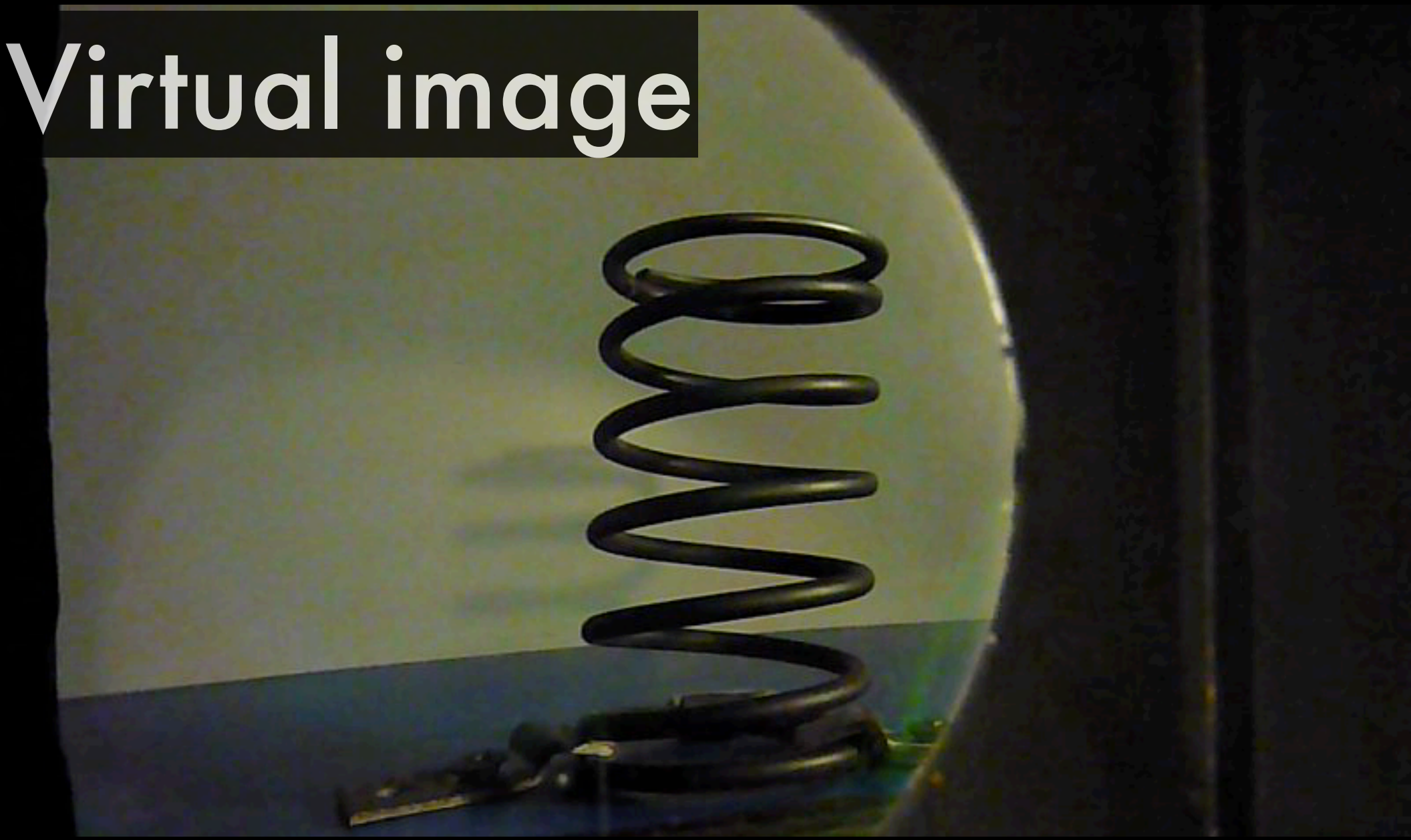
Mirrors and Lenses

- Mirrors and lenses will divert light rays from an object source and create an image.
- Images are formed at the point where rays actually intersect or appear to originate.
- A real image is one in which light actually passes through the image point.
- Real images can be displayed on a screen.
- A virtual image is one in which the light does not pass through the image point.
- The light appears to diverge from that point. Virtual images cannot be displayed on screens.

Real image

"080916-1050623"
(Source: Waifer X)
http://www.flickr.com/photos/waiferx/2873313059/

Virtual image



"080724-1040074"
(Source: Waifer X)
http://www.flickr.com/photos/waiferx/2766109677/

(Lateral) Magnification

$$m \equiv \frac{h'}{h} = -\frac{s'}{s}$$

s' ← image distance

s ← object distance

ratio of image vs. object heights

h, h' { +: upright
−: inverted

Upright image

m positive

"I'm shrinking..."
(Source: Eric Heupel)
http://www.flickr.com/photos/eclectic-echoes/4213784501/

"Camera Obscura Test 2"
(Source: Jon Lewis)
http://www.flickr.com/photos/jonlewisphotography/258711295/

Enlarged image

$|m| > 1$

"slide projectors are hip"
(Source: Nadya Peek)
http://www.flickr.com/photos/nadya/172147013/

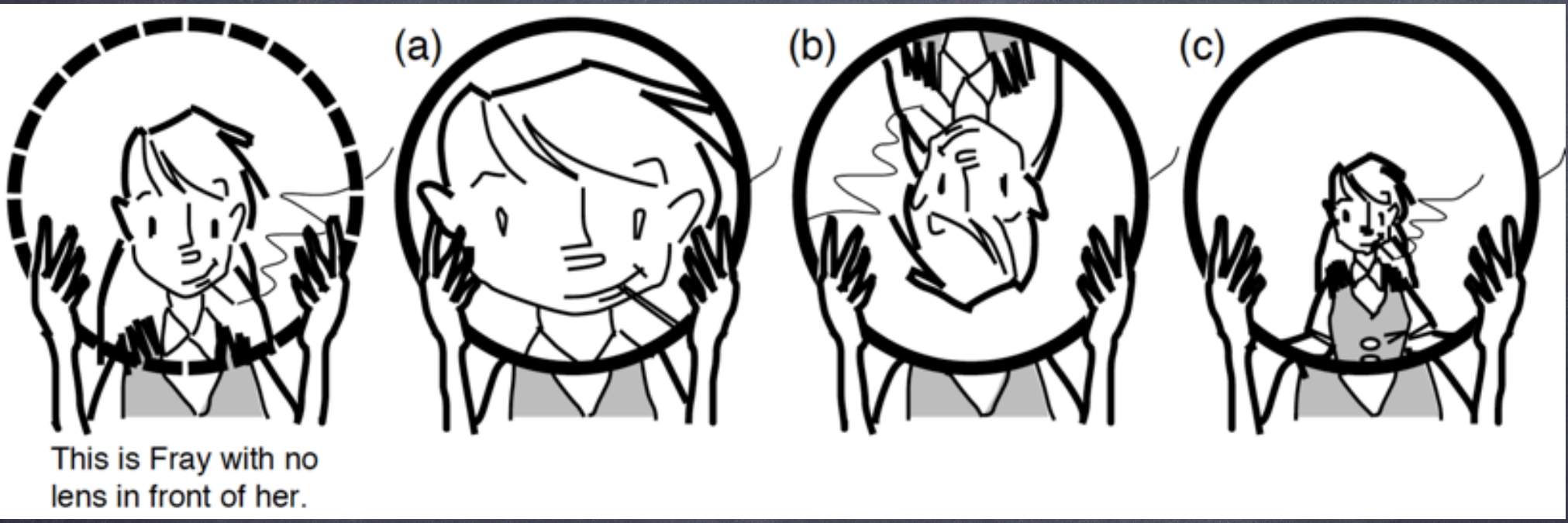
Diminished image

$|m| < 1$

"smiley face"
(Source: Steve Wall)
http://www.flickr.com/photos/stevewall/1361325457/

Activity 5

Fray is holding up several large pieces of curved glass in front of her.



Determine in each case (a through c) whether Fray's magnification is either:

- I) $m > +1$.
- II) $+1 > m > 0$.
- III) $0 > m > -1$.
- IV) $m = -1$

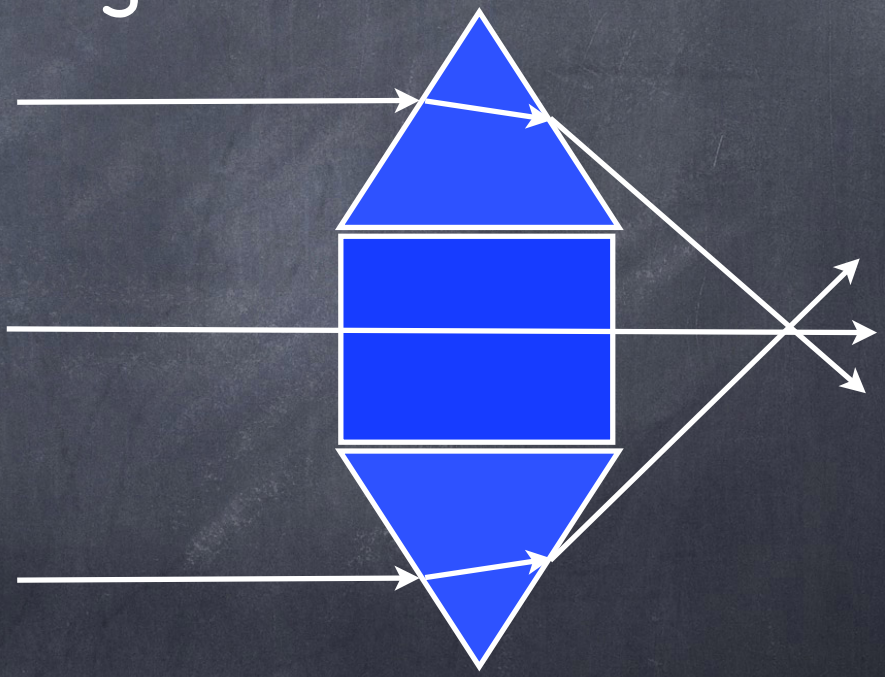
Clicker Question 8

- For the image below, is the magnification:

- A) $m > +1$.
- B) $+1 > m > 0$.
- C) $0 > m > -1$.
- D) $m < -1$

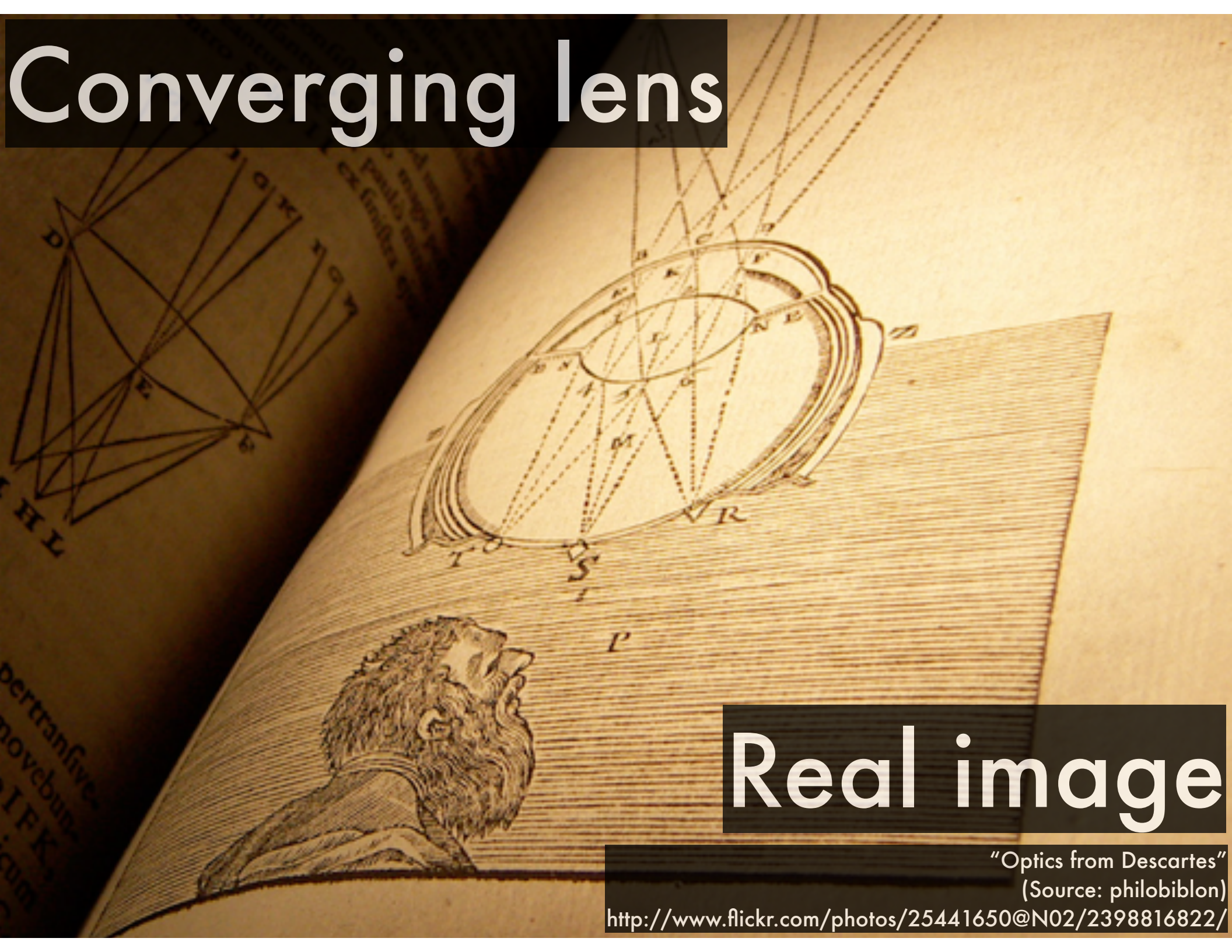
Converging Lens

- What if we wanted to use refraction to converge parallel light rays to a single focal point? What type of shape should we use?
- We can construct the following lens:
- This is known as a converging lens.
- It is a lens consisting of plastic or glass that refracts light.
- It focuses parallel light rays at a single point known as the focal point.



"Richoflex focus adjustment for dummies (1)"
(Source: Gueorgui Tcherednitchenko)
http://www.flickr.com/photos/spacelion/2585176584/

Converging lens

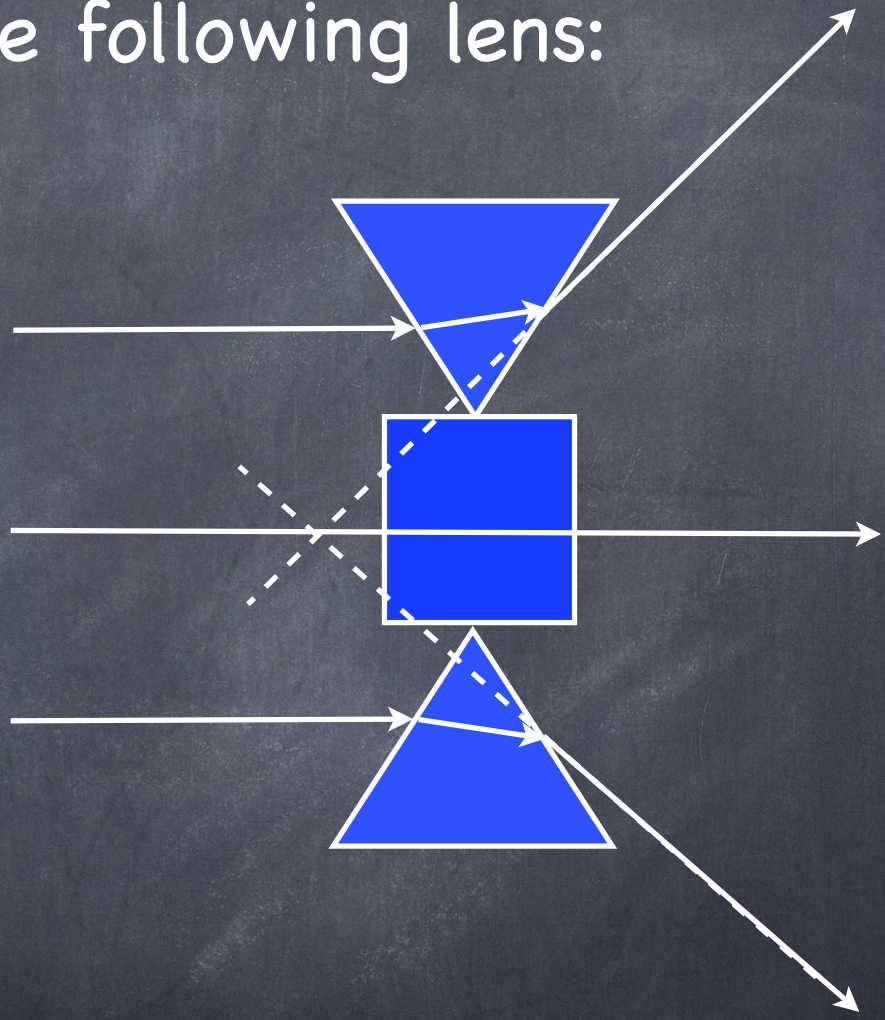


Real image

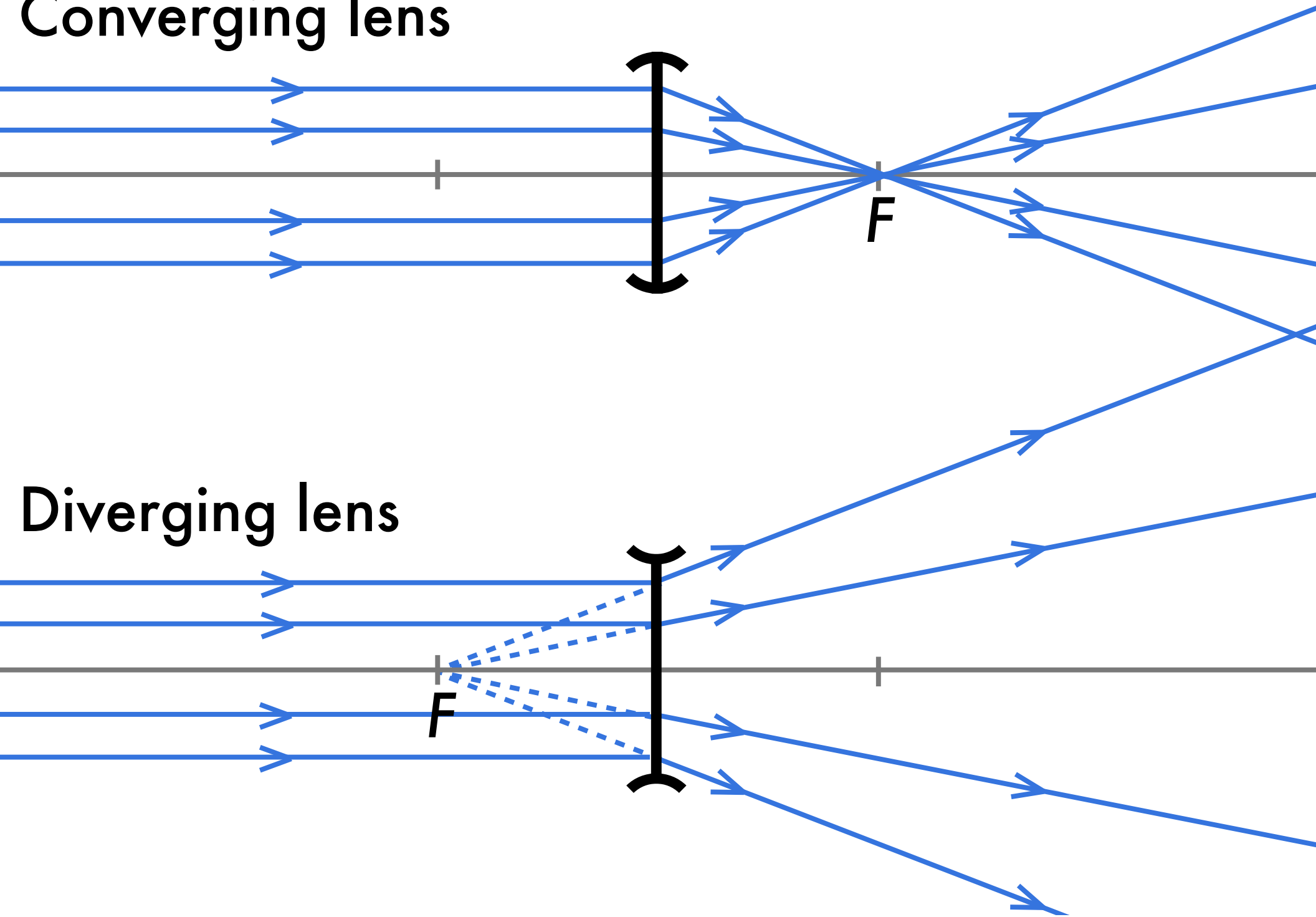
"Optics from Descartes"
(Source: philobiblon)
http://www.flickr.com/photos/25441650@N02/2398816822/

Diverging Lens

- We can also construct the following lens:
- This is known as a diverging lens.
- It is also a lens consisting of plastic or glass that refracts light.
- It defocuses parallel light rays to make it appear that it came from a single point known as the focal point.



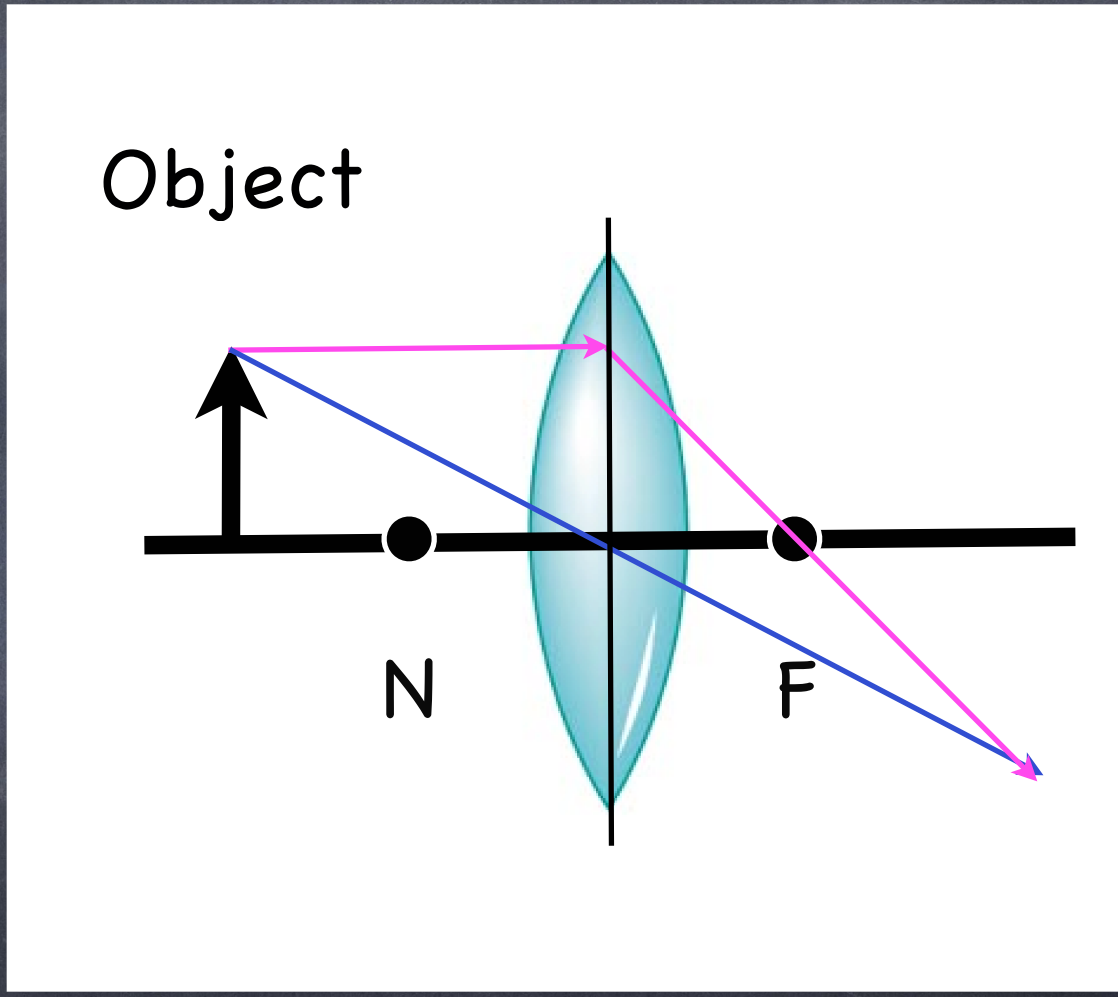
Converging lens



Diverging lens

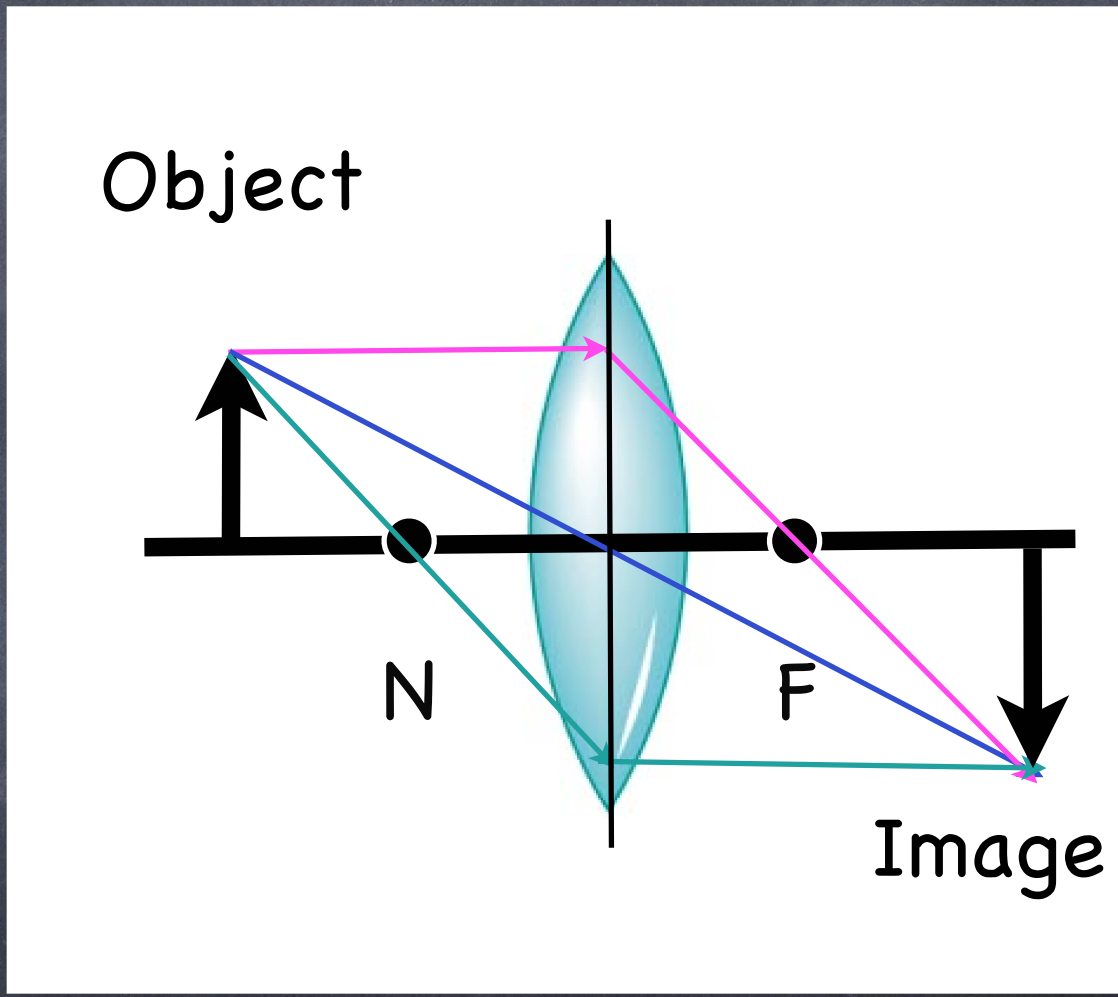
Ray Diagrams

- Ray 1 is drawn parallel to the principal axis and is refracted through the far focal point, F.
- Ray 2 is drawn through the center of the lens and continues in a straight line.



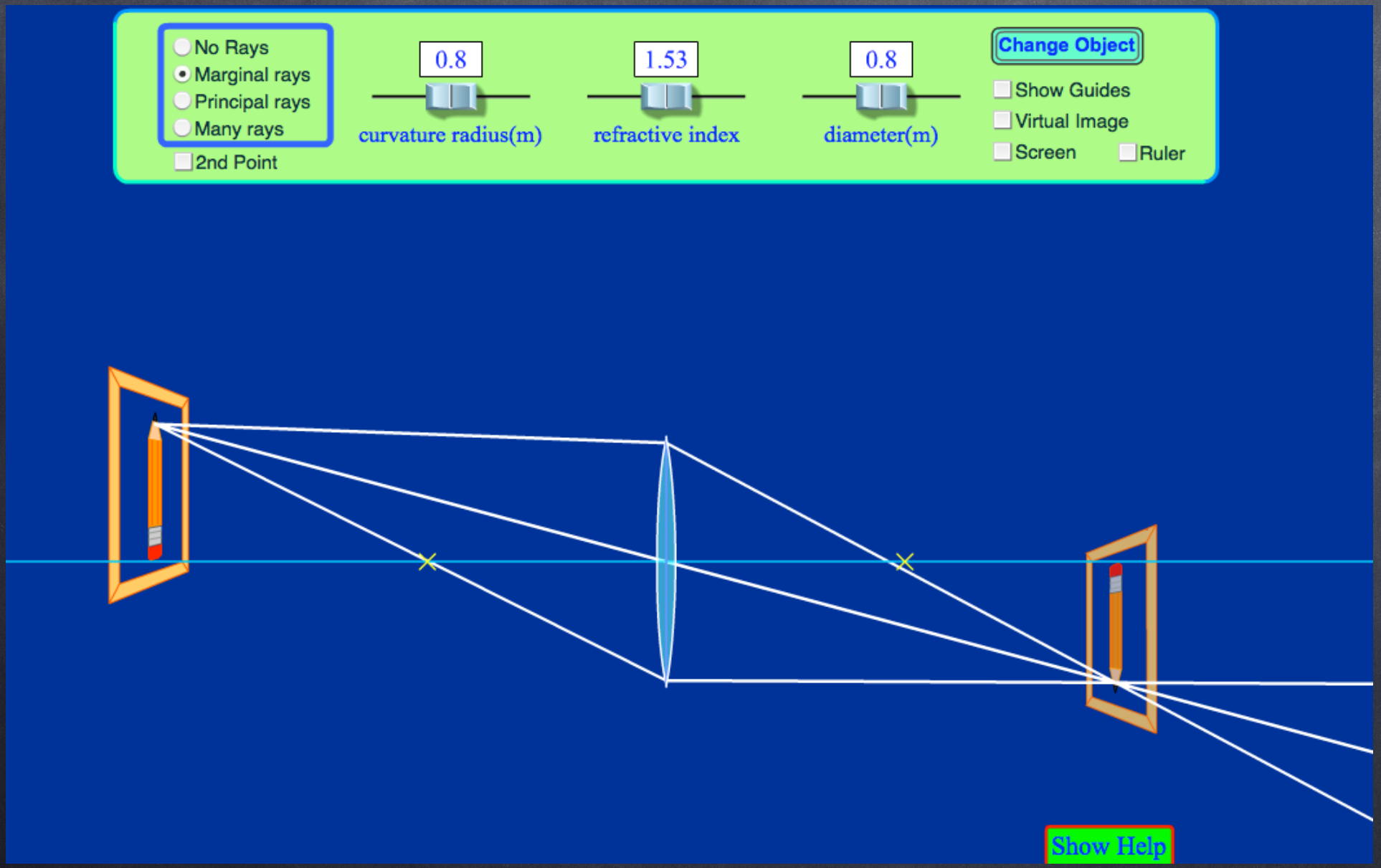
Ray Diagrams

- Ray 3 is drawn through the near focal point, N, and is refracted parallel to the principal axis.
- Where the three rays converge is where the image will be formed.



- For this exact situation (object outside the near focal point) the image is:
  - real and inverted.

Ray Diagrams



https://phet.colorado.edu/sims/geometric-optics/geometric-optics_en.html