WAVES - LIGHT

IB PHYSICS | COMPLETED NOTES

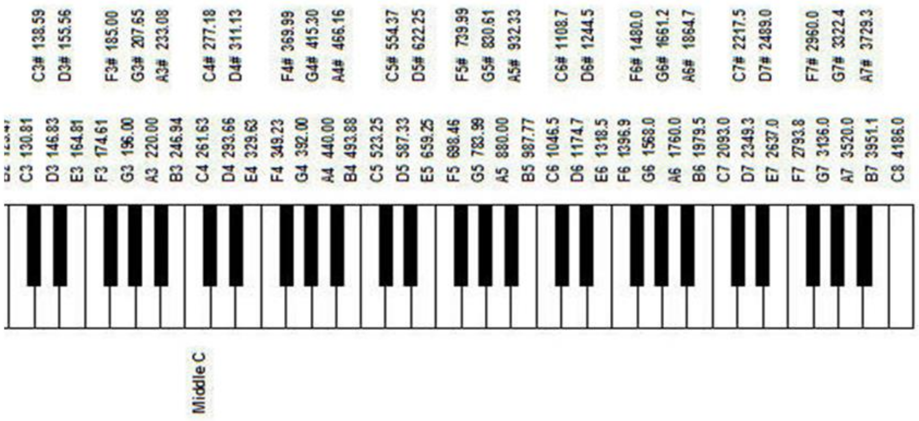
Light and the EM Spectrum

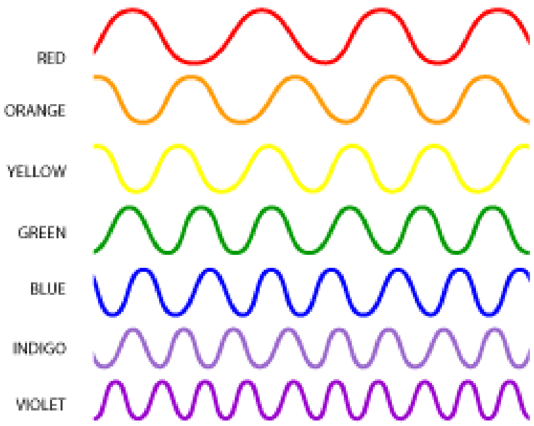
IB PHYSICS | WAVES - LIGHT

Frequency and Light

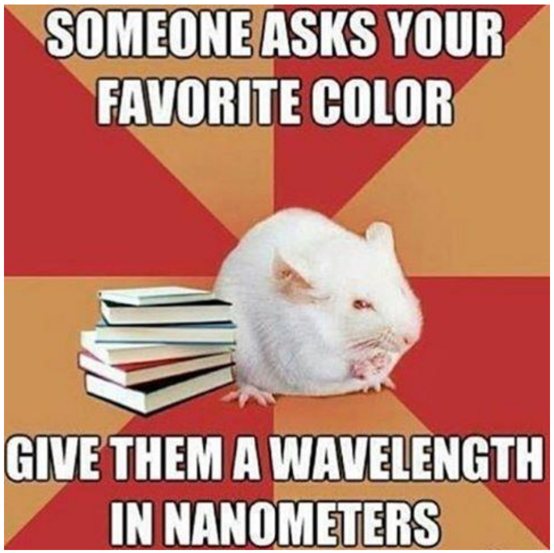
Sound —Change in Frequency→ **Pitch**

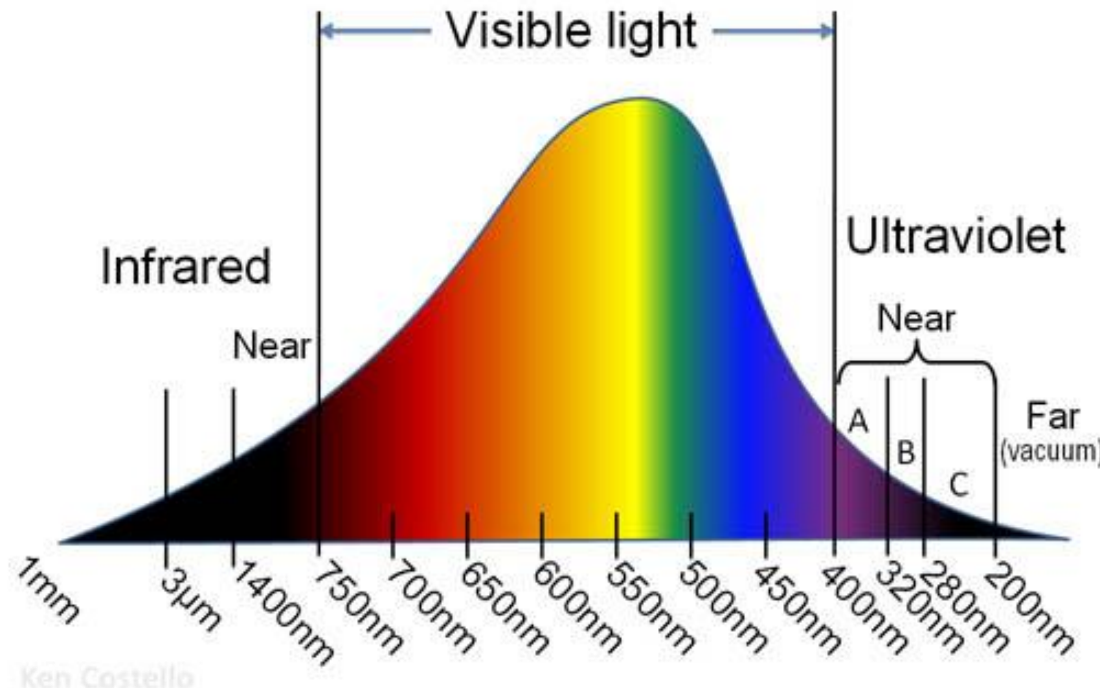
Light —Change in Frequency→ **Color**





Frequency and Light





Speed of Electromagnetic Waves

In a vacuum All electromagnetic waves travel at:

$$c = 299{,}792{,}458 \text{ m s}^{-1}$$

$$c = 3.00 \times 10^{8} \text{ m s}^{-1}$$

Speed of Electromagnetic Waves

Fundamental constants

Quantity	Symbol	Approximate value
Acceleration of free fall (Earth's surface)	g	$9.81\ \mathrm{m\ s^{-2}}$
Gravitational constant	G	$6.67 \times 10^{-11}\ \mathrm{N\ m^2\ kg^{-2}}$
Avogadro's constant	N_A	$6.02 \times 10^{23}\ \mathrm{mol^{-1}}$
Gas constant	R	$8.31\ \mathrm{J\ K^{-1}\ mol^{-1}}$
Boltzmann's constant	k_B	$1.38 \times 10^{-23}\ \mathrm{J\ K^{-1}}$
Stefan–Boltzmann constant	σ	$5.67 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$
Coulomb constant	k	$8.99 \times 10^{9}\ \mathrm{N\ m^2\ C^{-2}}$
Permittivity of free space	ε_0	$8.85 \times 10^{-12}\ \mathrm{C^2\ N^{-1}\ m^{-2}}$
Permeability of free space	μ_0	$4\pi \times 10^{-7}\ \mathrm{T\ m\ A^{-1}}$
Speed of light in vacuum	c	$3.00 \times 10^{8}\ \mathrm{m\ s^{-1}}$
Planck's constant	h	$6.63 \times 10^{-34}\ \mathrm{J\ s}$

Try this...

The sun is roughly 149,600,000 km from Earth, how long has the light from the sun been traveling before it gets here?

$$v = \frac{d}{t} \rightarrow t = \frac{d}{v} = \frac{149{,}600{,}000{,}000 \text{ m}}{3.00 \times 10^{8} \text{ m s}^{-1}}$$

$$t = 499 \text{ s} = \mathbf{8.31\ min}$$

Light Equation

You already know the wave speed equation

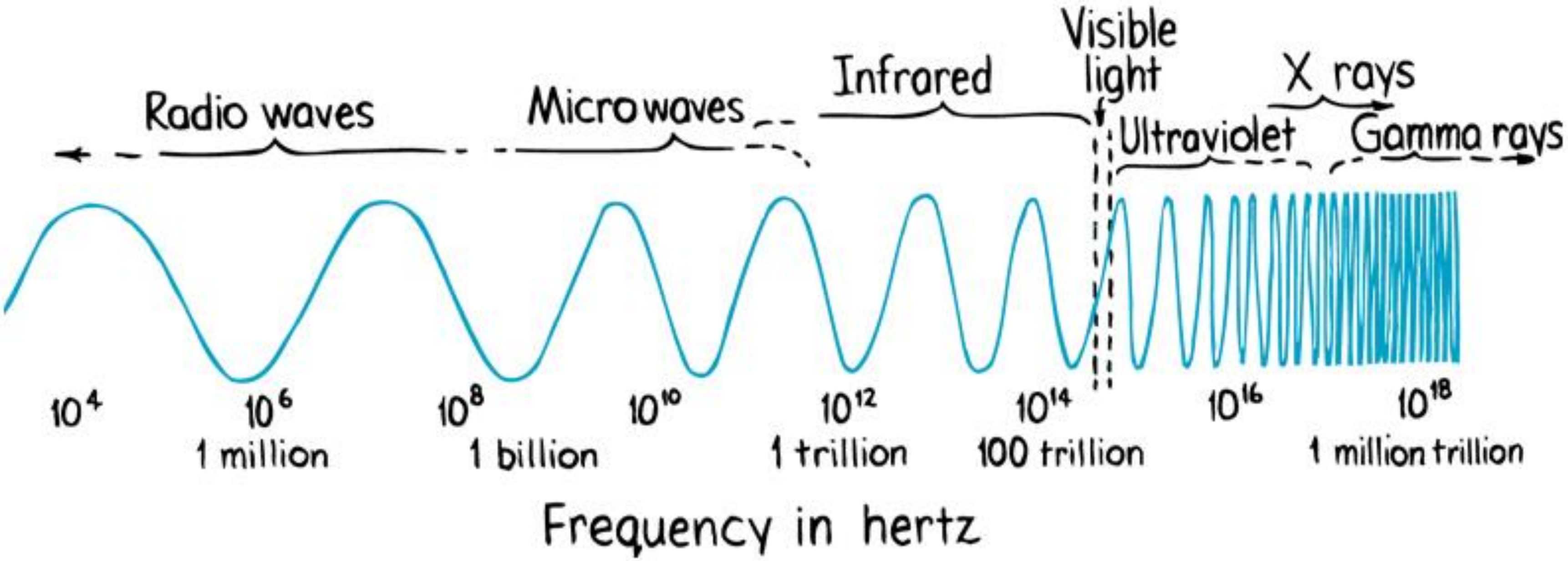
$$v = f\lambda$$

Works the same for electromagnetic waves

$$c = f\lambda$$

Electromagnetic Spectrum

Visible light is just part of the picture…

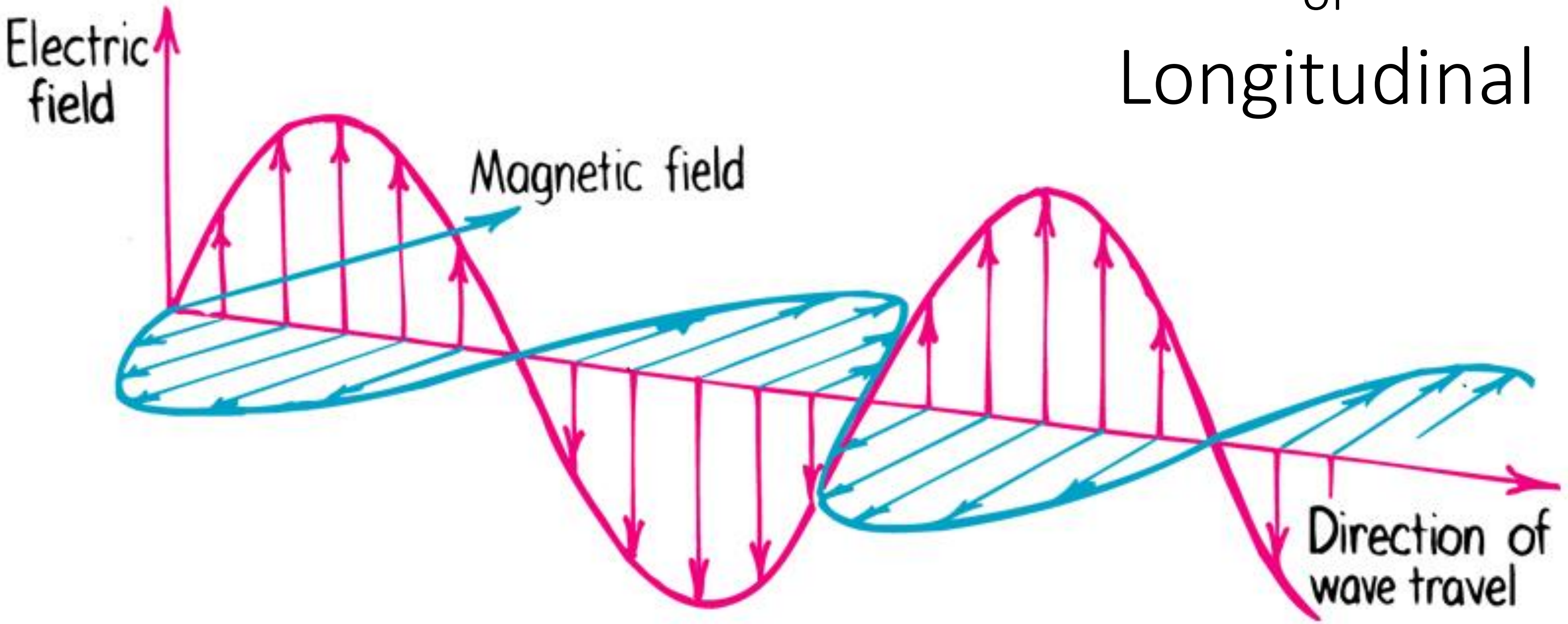


Electromagnetic Waves

? Transverse ?

or

Longitudinal

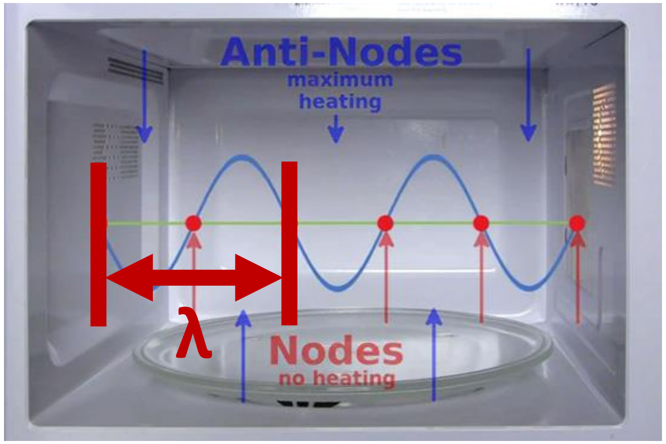


Standing Waves in a Microwave

How far between antinodes of a 2450 MHz standing wave in a microwave?

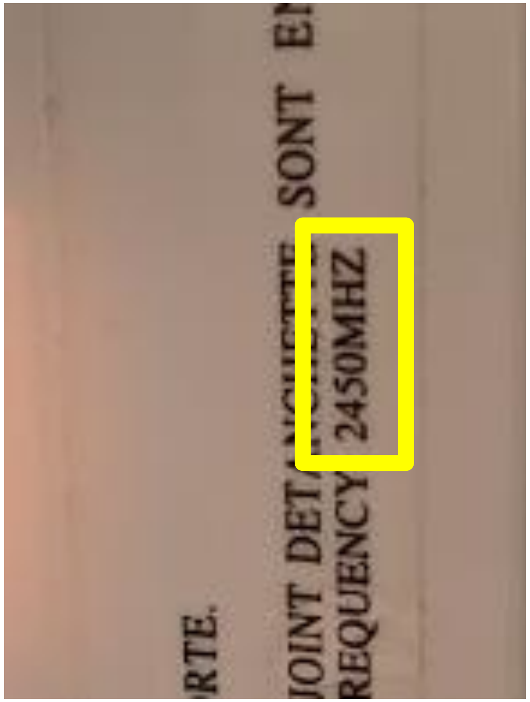
$$v = f\lambda$$

$$\lambda = \frac{v}{f} = \frac{3.00 \times 10^8}{2450 \times 10^6} = 0.12 \text{ m}$$



$$\frac{0.12 \text{ m}}{2} = 0.06 \text{ m}$$

$$= \mathbf{6\ cm}$$



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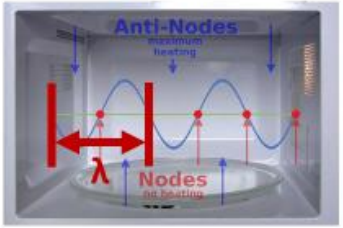

$$\frac{0.12 \text{ m}}{2} = 0.06 \text{ m}$$

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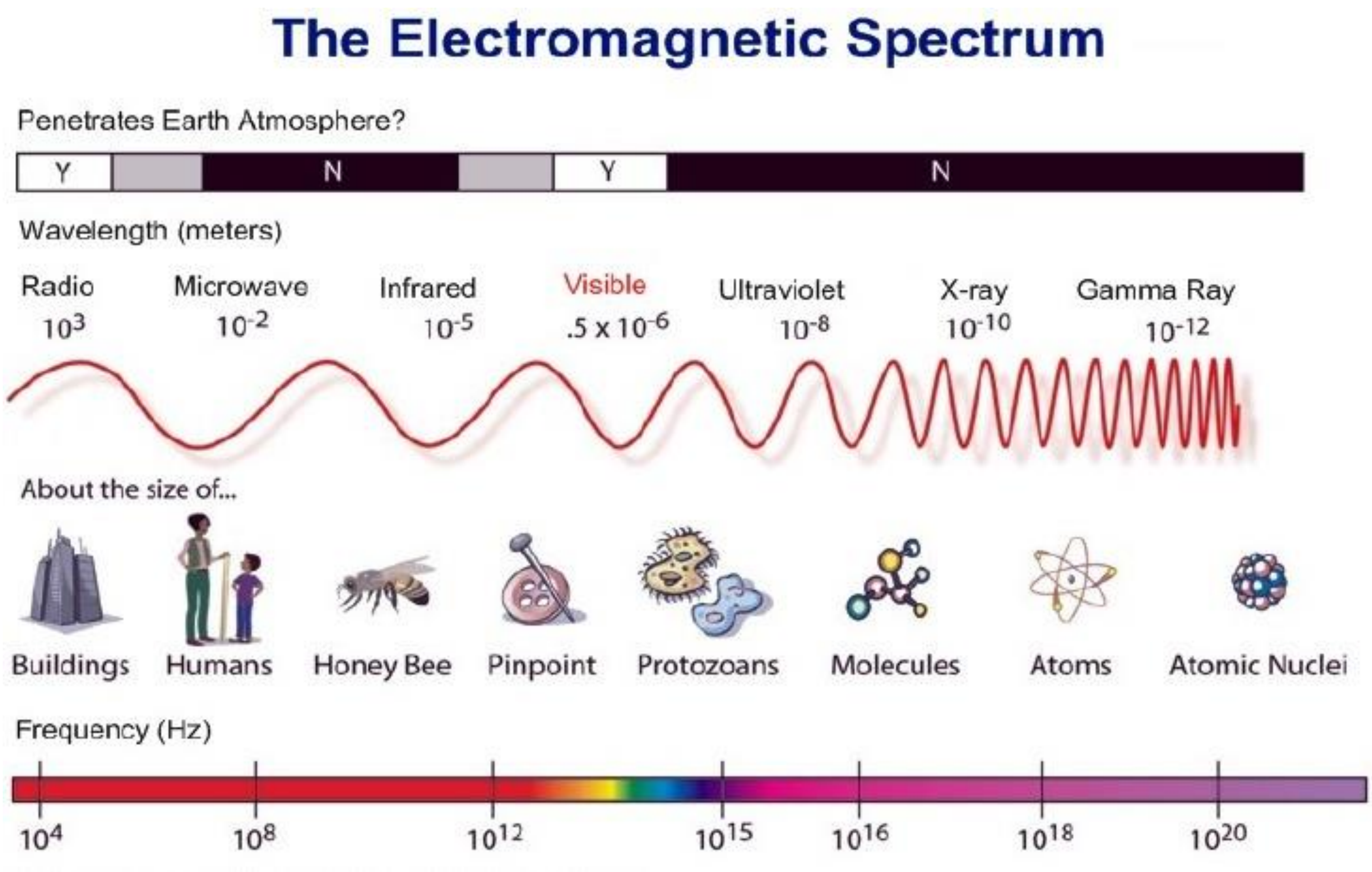
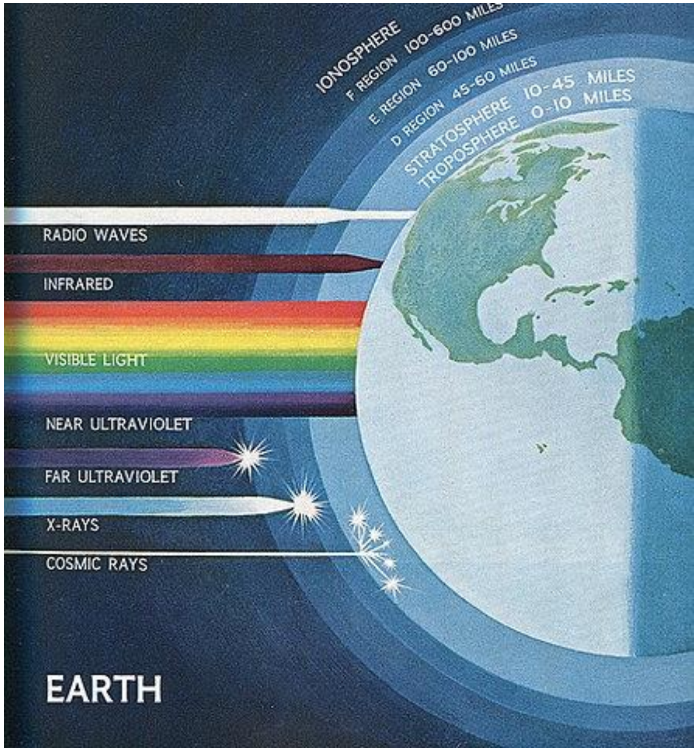
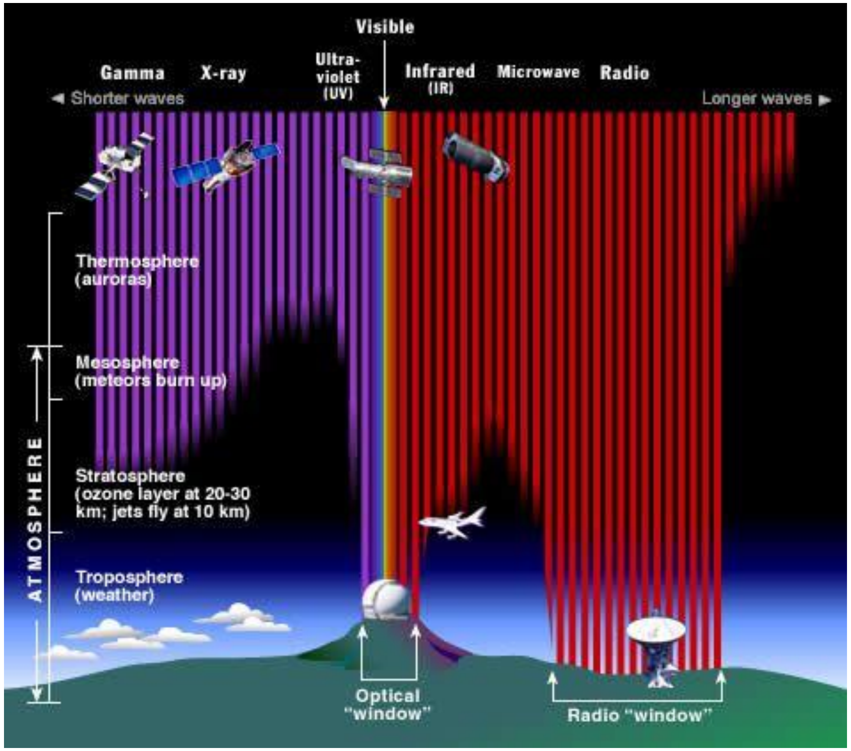
Electromagnetic Spectrum

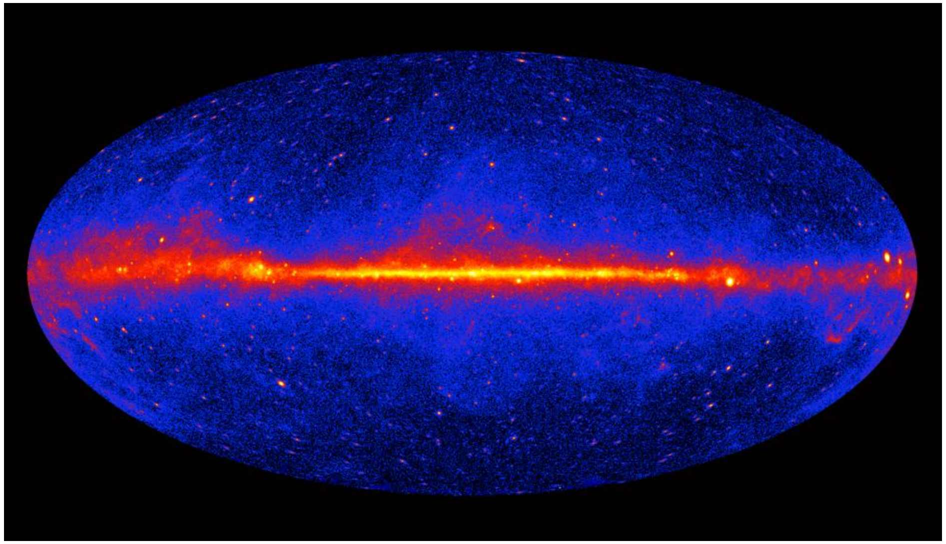


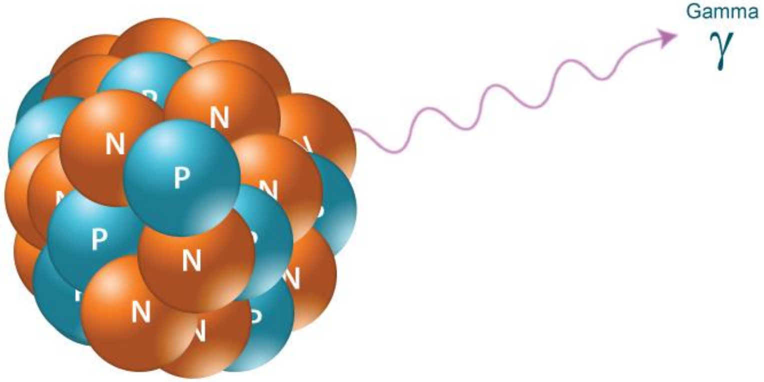
Not everything makes it to Earth





Gamma Ray



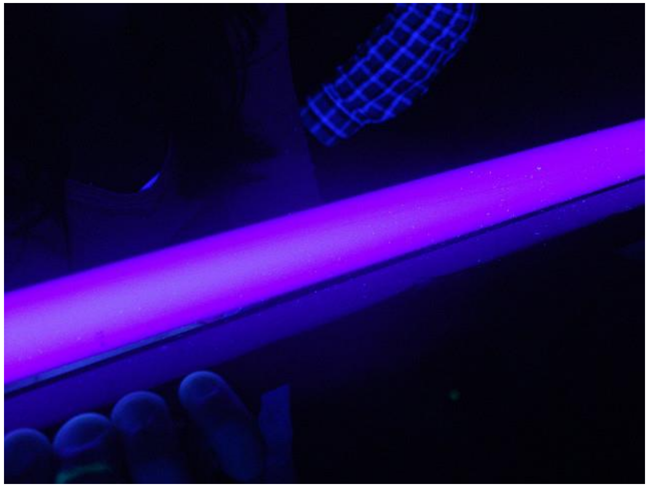


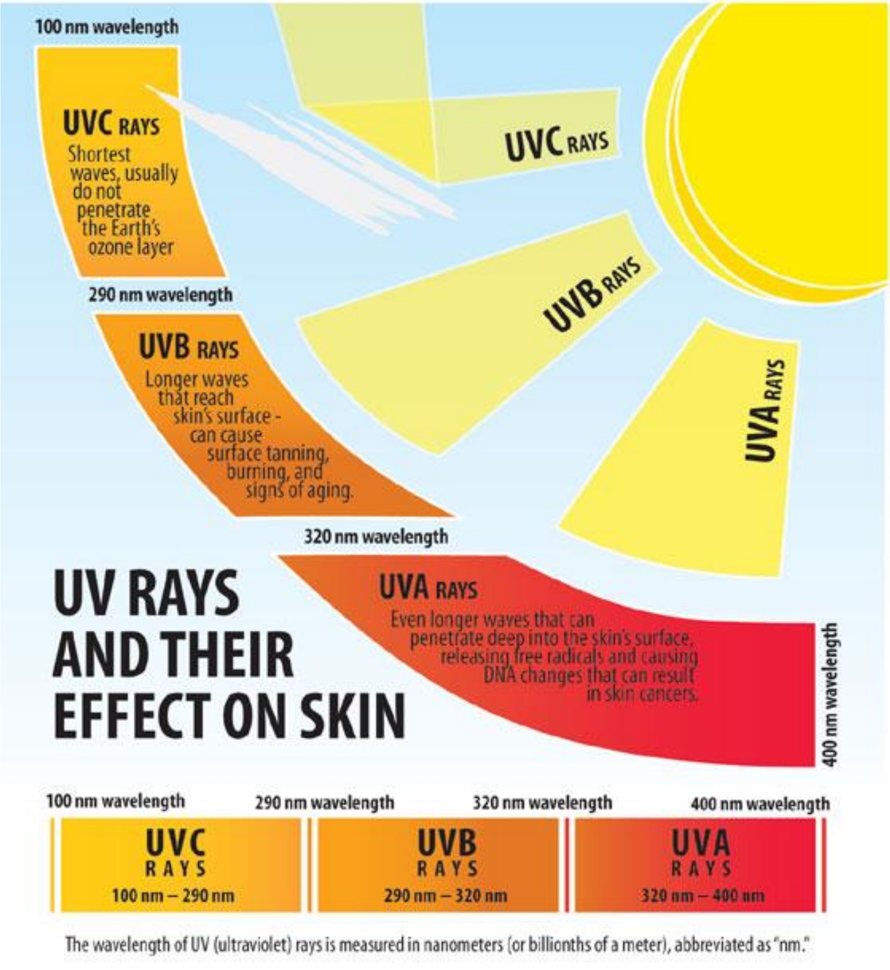
Wavelength: 10^{-12} m | 1 pm

X-Rays

Wavelength: 10^{-10} m | 10 nm

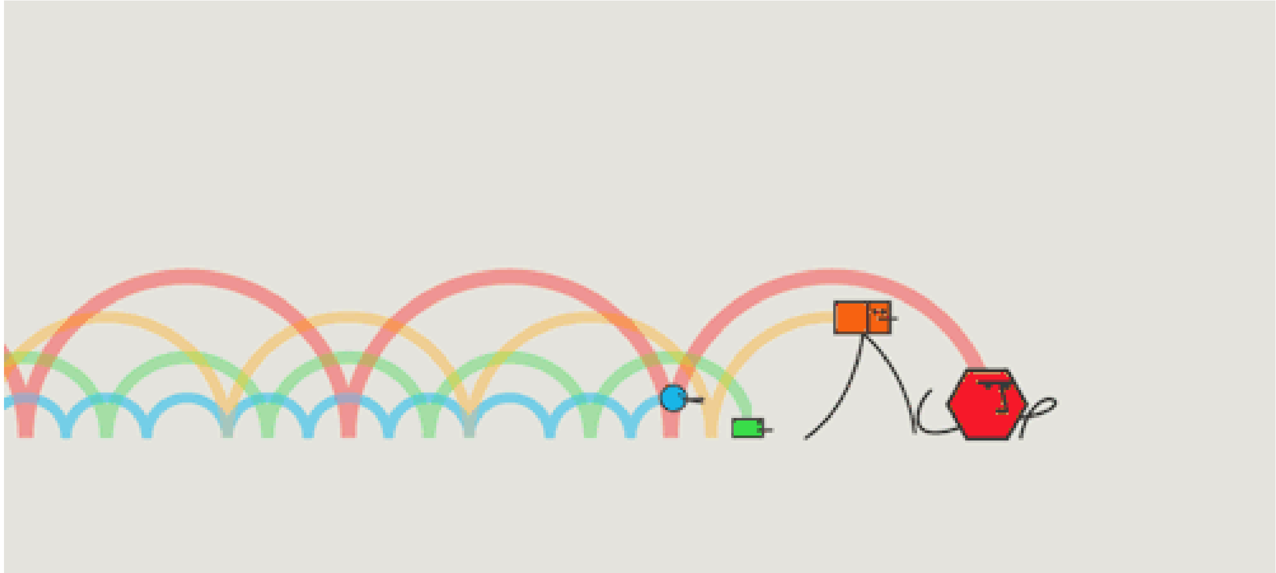
Ultraviolet

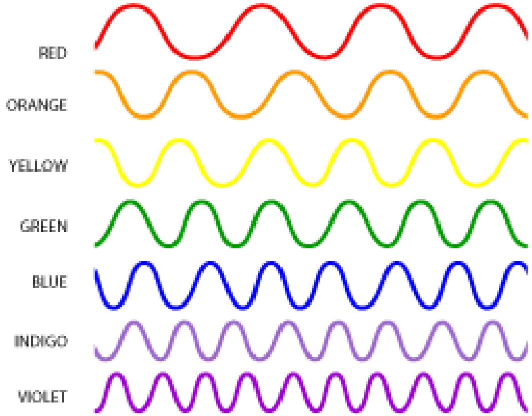




Wavelength: 10^{-8} m | 10 nm

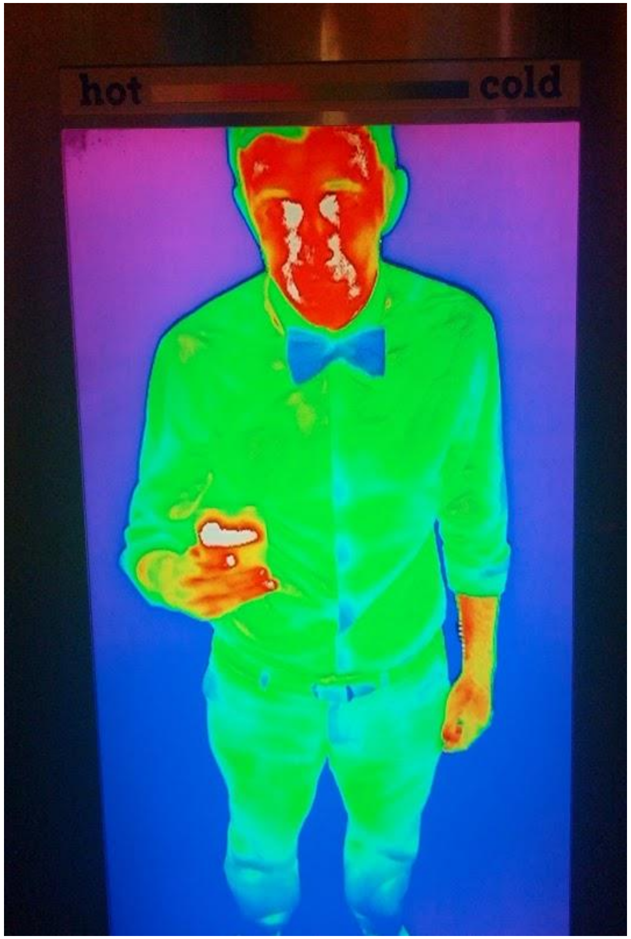
Visible Light





Wavelength: 0.5×10^{-12} m | 500 nm

Infrared



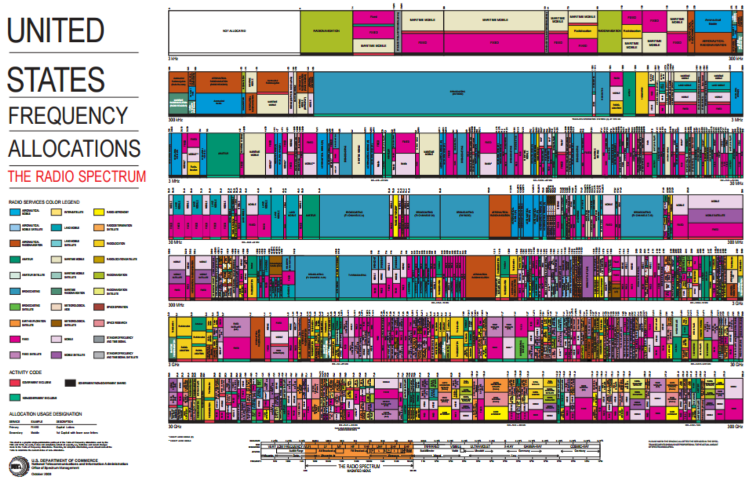
Wavelength: 10^{-5} m | 0.01 mm

Microwaves

Wi-Fi

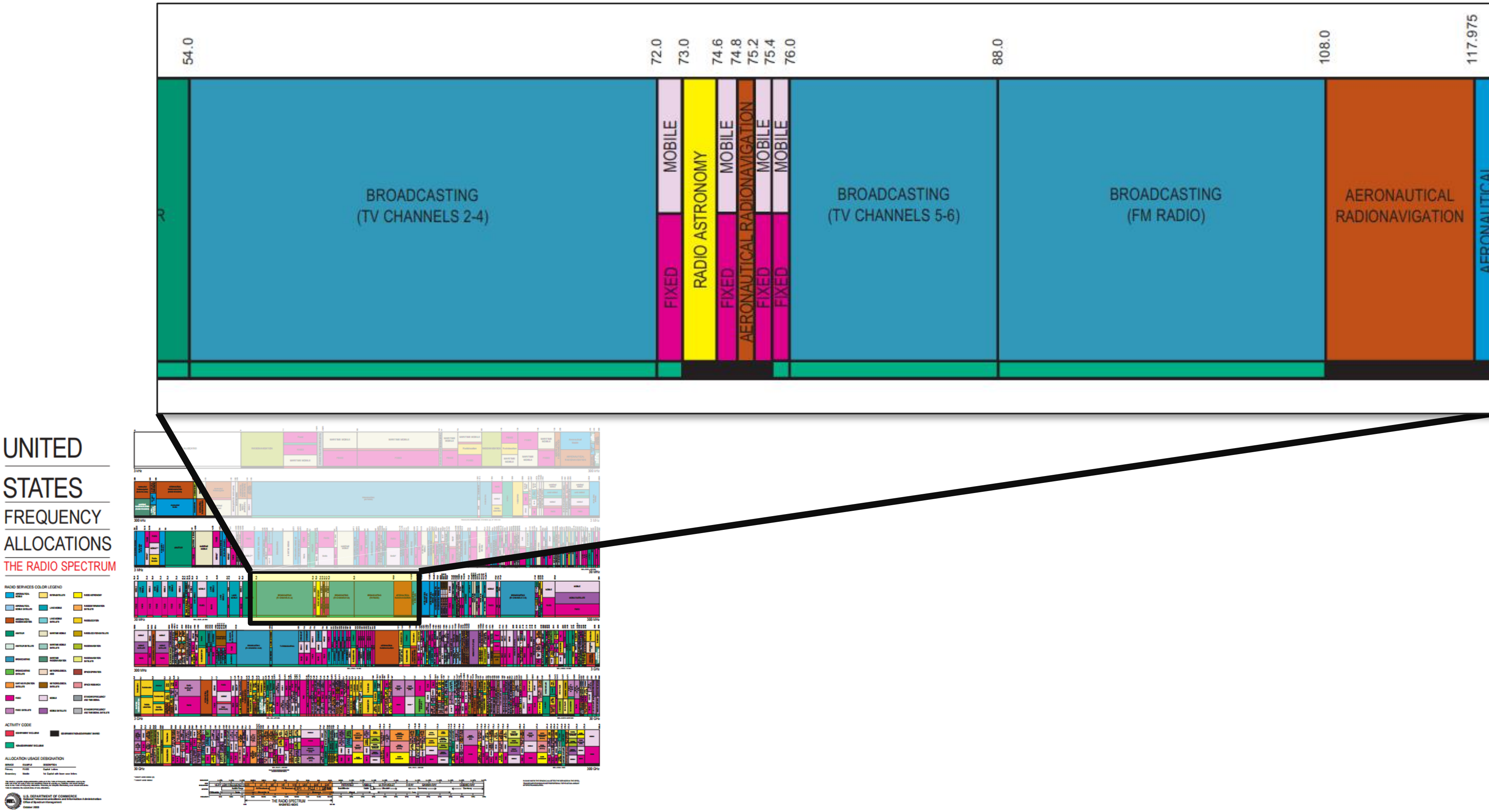
Wavelength: 10^{-2} m | 1 cm

Radiowaves



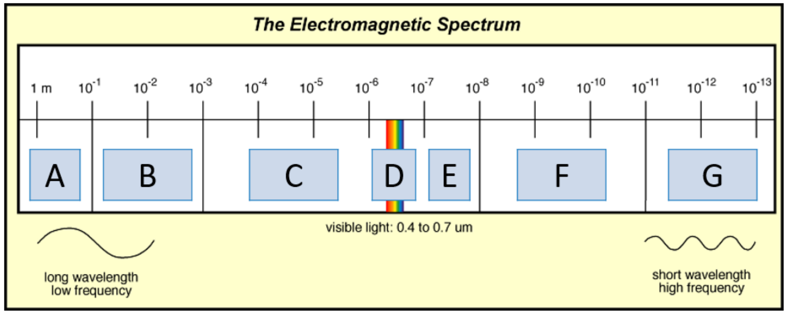
Wavelength: 10^3 m | 1 km

Wireless Data Transfer



Can you name them? You should.

A	Radio
B	Microwaves
C	Infrared
D	Visible
E	Ultraviolet
F	X-Rays
G	Gamma



Higher Frequency

More Energy

Lesson Takeaways

- ❑ I can identify and use the speed of light to solve wave problems with the wave equations
- ❑ I can estimate the wavelength magnitude for the different EM waves
- ❑ I can provide real world examples for each of the electromagnetic waves

Reflection & Refraction

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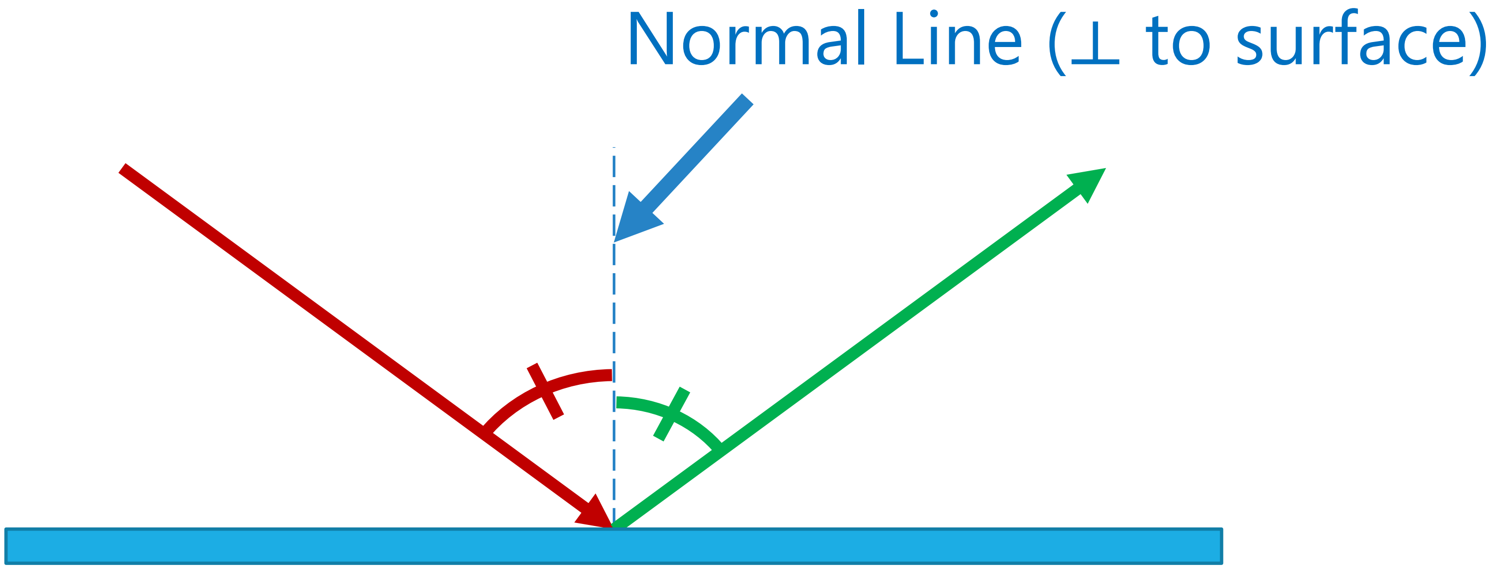
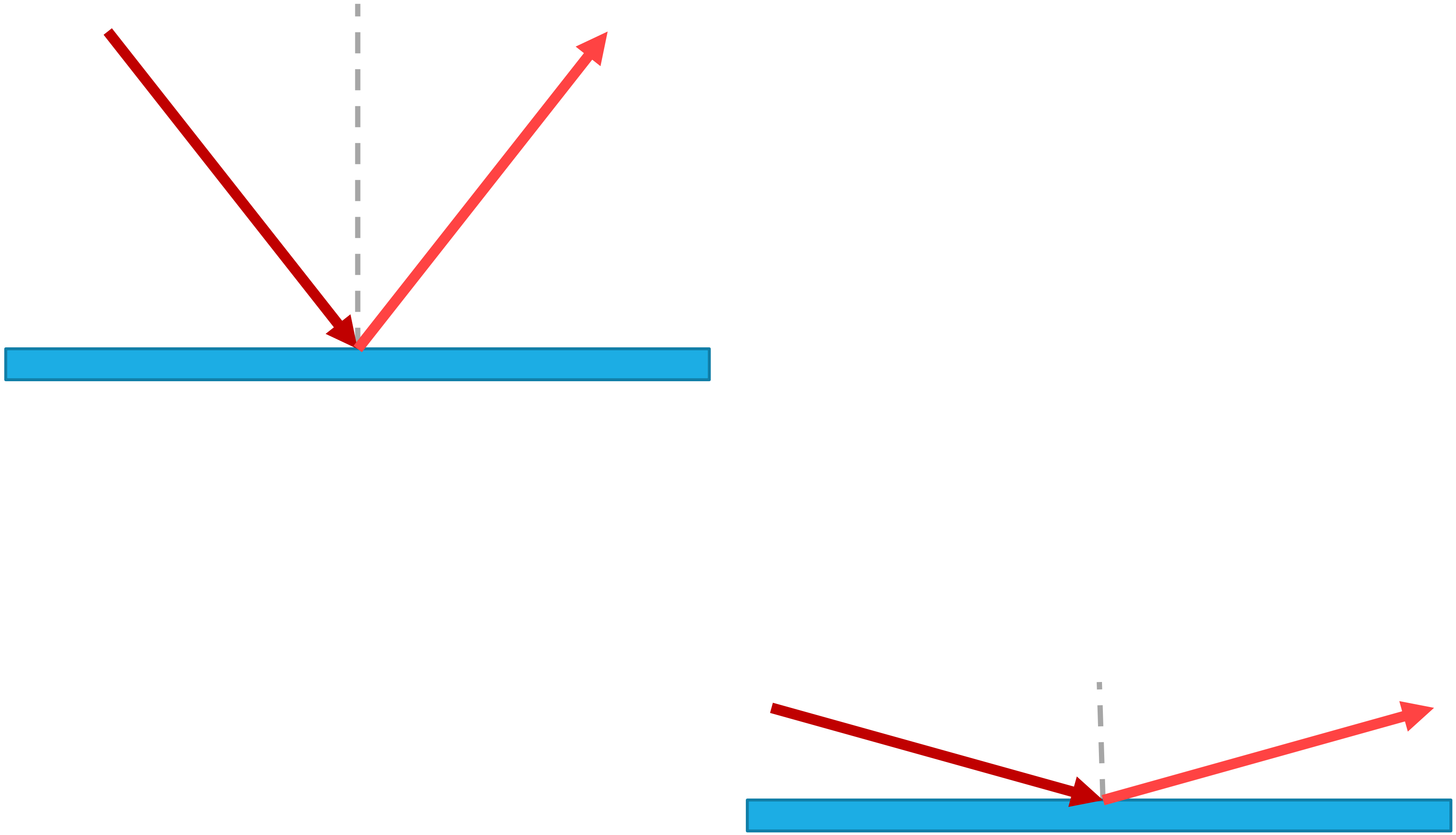
Reflection

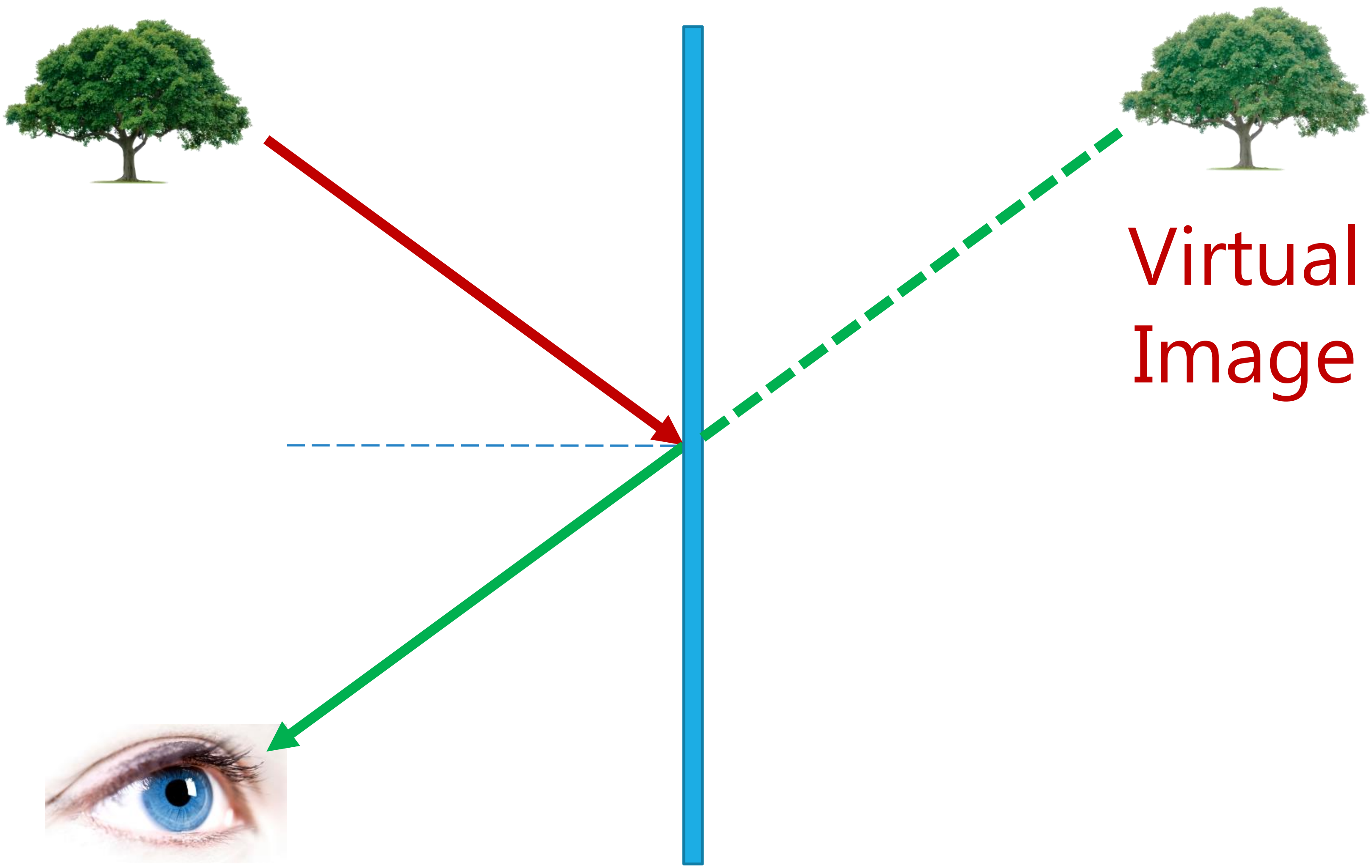
Angle of ___Incidence___ = Angle of ___Reflection___



Reflection

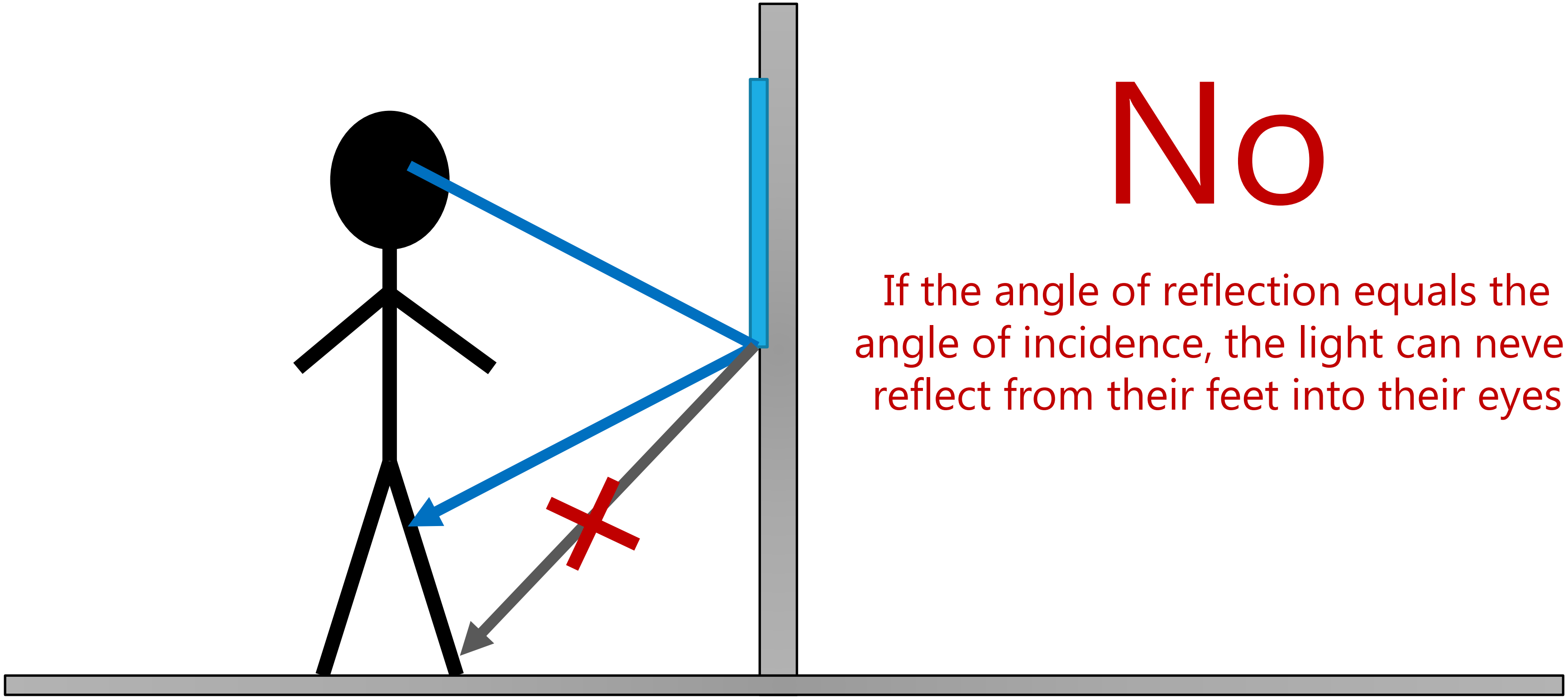


Reflection



Predict

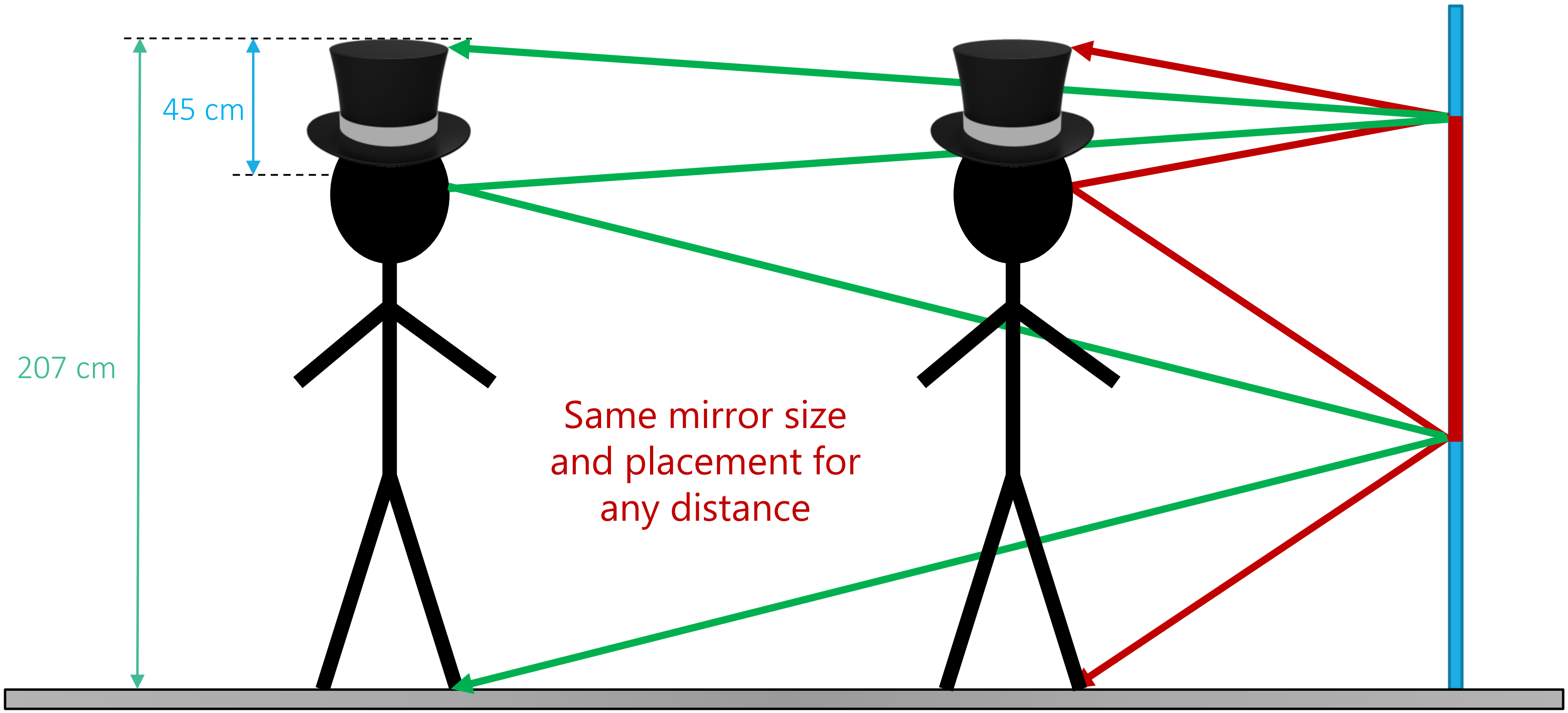
Can this person see their feet in the mirror?



No

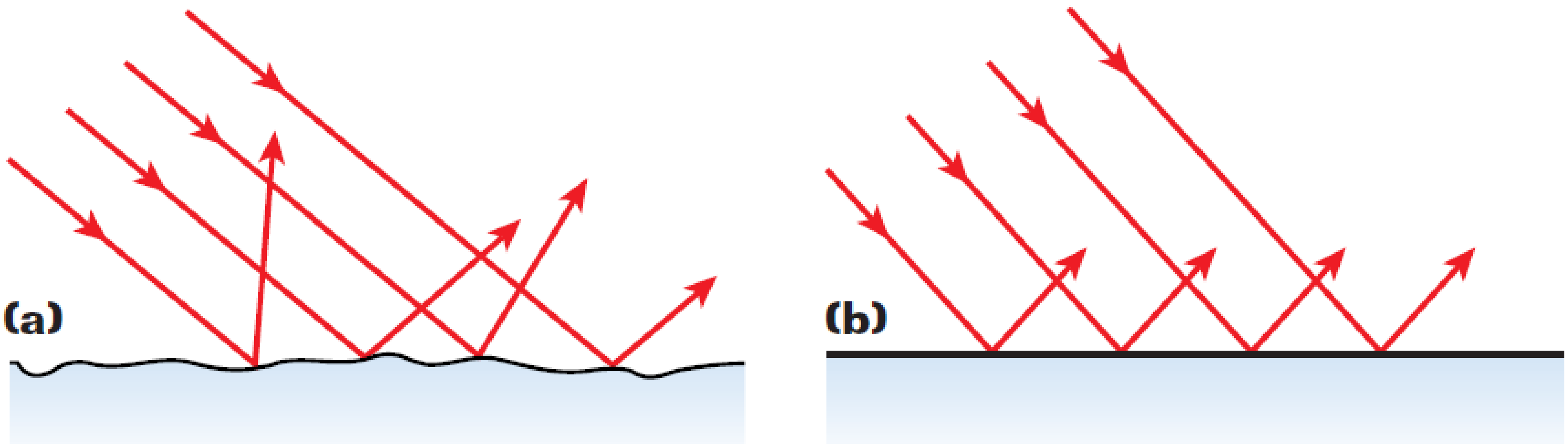
If the angle of reflection equals the angle of incidence, the light can never reflect from their feet into their eyes

“Full Length” Mirrors



Not every surface is a flat mirror

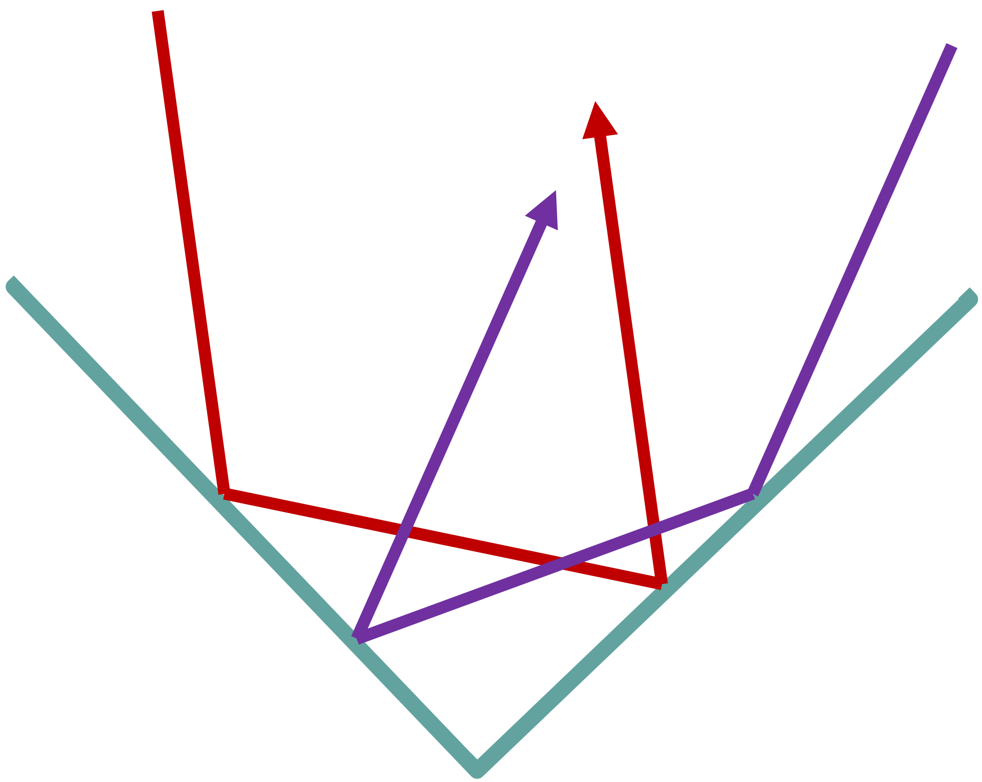
Even surfaces that seem nice and flat are often textured



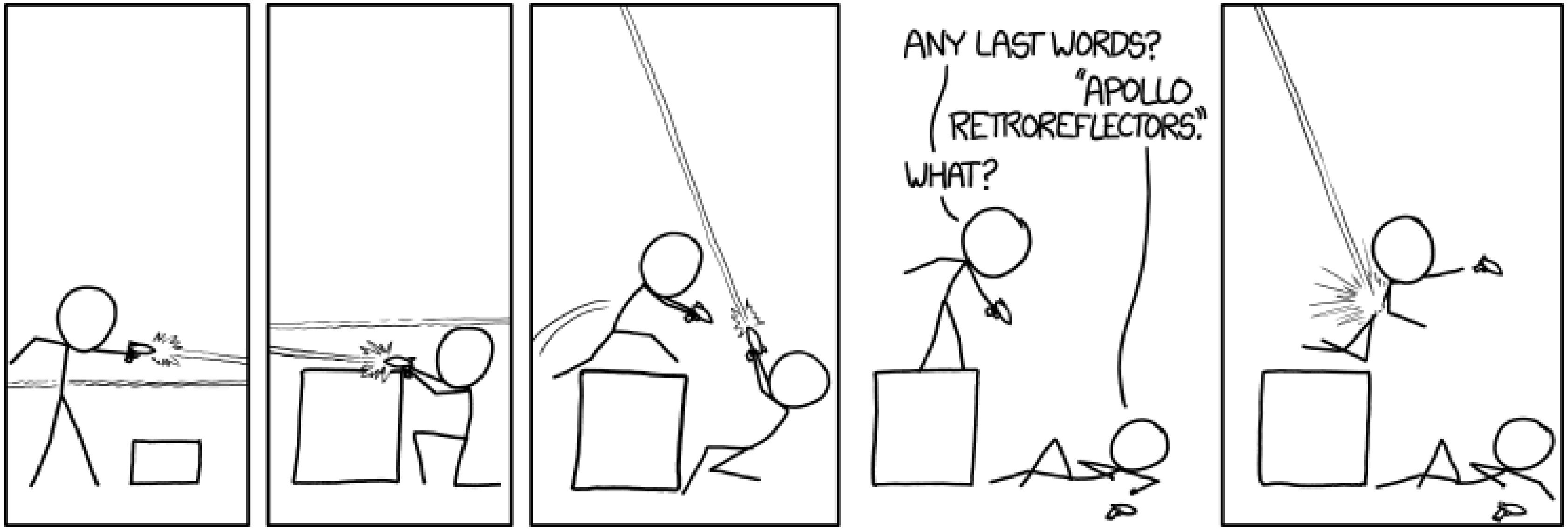
Diffuse Reflection

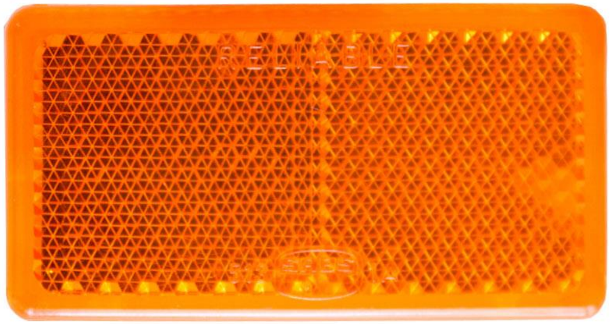
Retro-reflective Mirrors

Light always reflects directly back to the source



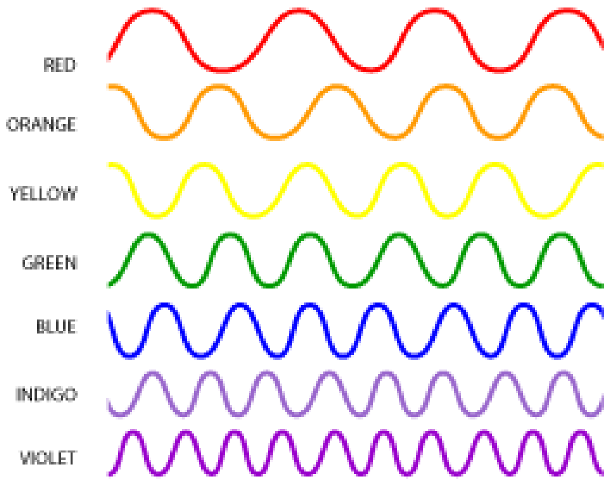
Retro-reflective Mirrors

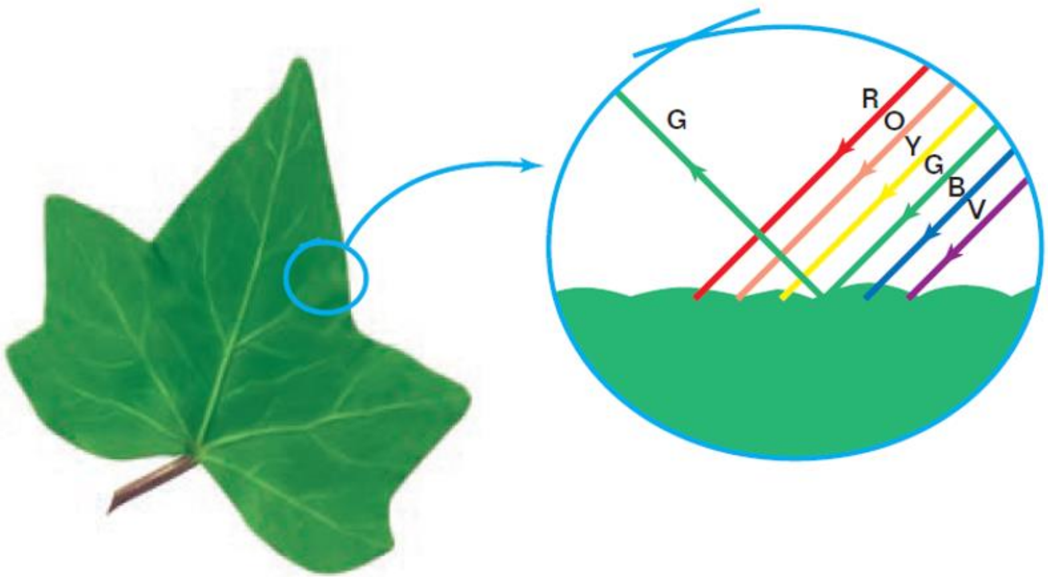




Colors

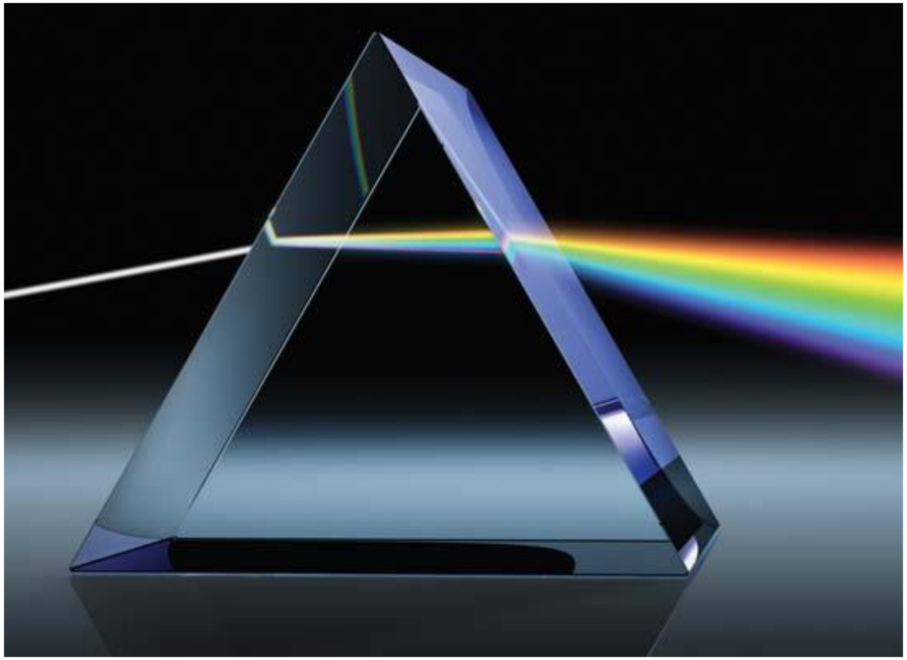
We perceive colors in objects depending on how different wavelengths are reflected





Refraction

Bends because of a change in medium



Speed of Light

In a vacuum all electromagnetic waves travel at:

$$c = 299{,}792{,}458 \text{ m/s} = 3.00 \times 10^8 \text{ m/s}$$

Light slows down when it travels through different mediums

Air	2.999×10^8 m s^{-1}
Water	2.256×10^8 m s^{-1}
Glass	1.974×10^8 m s^{-1}

Index of Refraction → **n**

$$\frac{n_1}{n_2} = \frac{v_2}{v_1}$$

$$\frac{n_1}{n_2} = \frac{v_2}{v_1}$$

1	Vacuum	3.00×10^8 m s^{-1}	1
	Air	2.999×10^8 m s^{-1}	1.0003 ~ 1
	Water	2.256×10^8 m s^{-1}	1.33
2	Glass	1.974×10^8 m s^{-1}	1.52

Try This

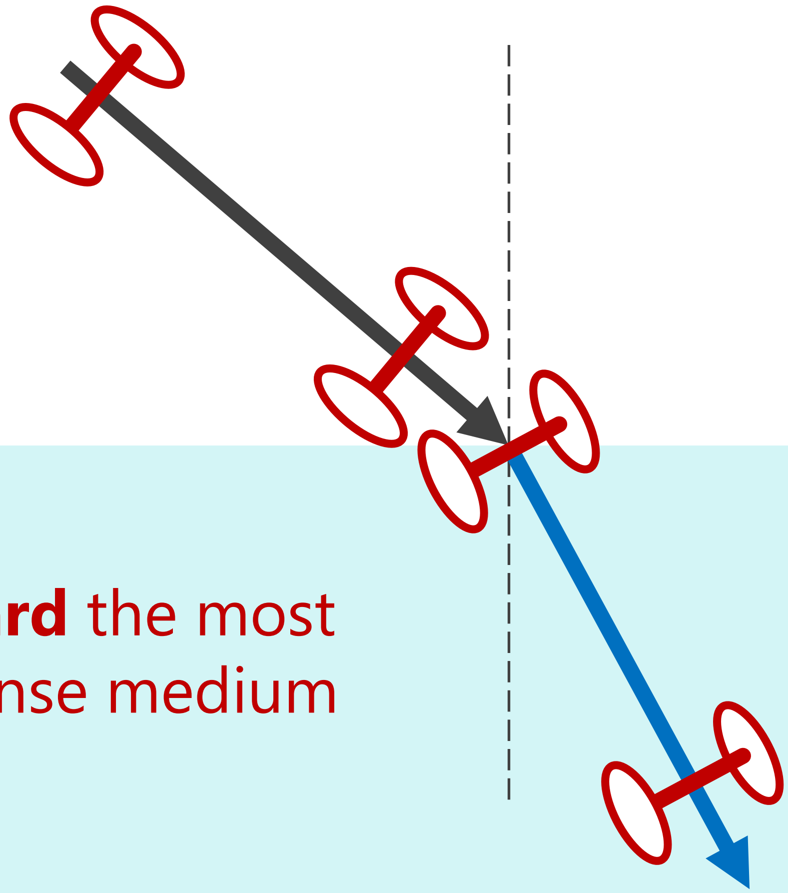
How fast does light travel through cubic zirconia (n = 2.15)?

$$\frac{n_1}{n_2} = \frac{v_2}{v_1}$$

$$\frac{1}{2.15} = \frac{v_2}{3.00 \times 10^8}$$

$$v_2 = 1.40 \times 10^8\ \mathrm{m\ s^{-1}}$$

Refraction Boundary



faster

n = 1

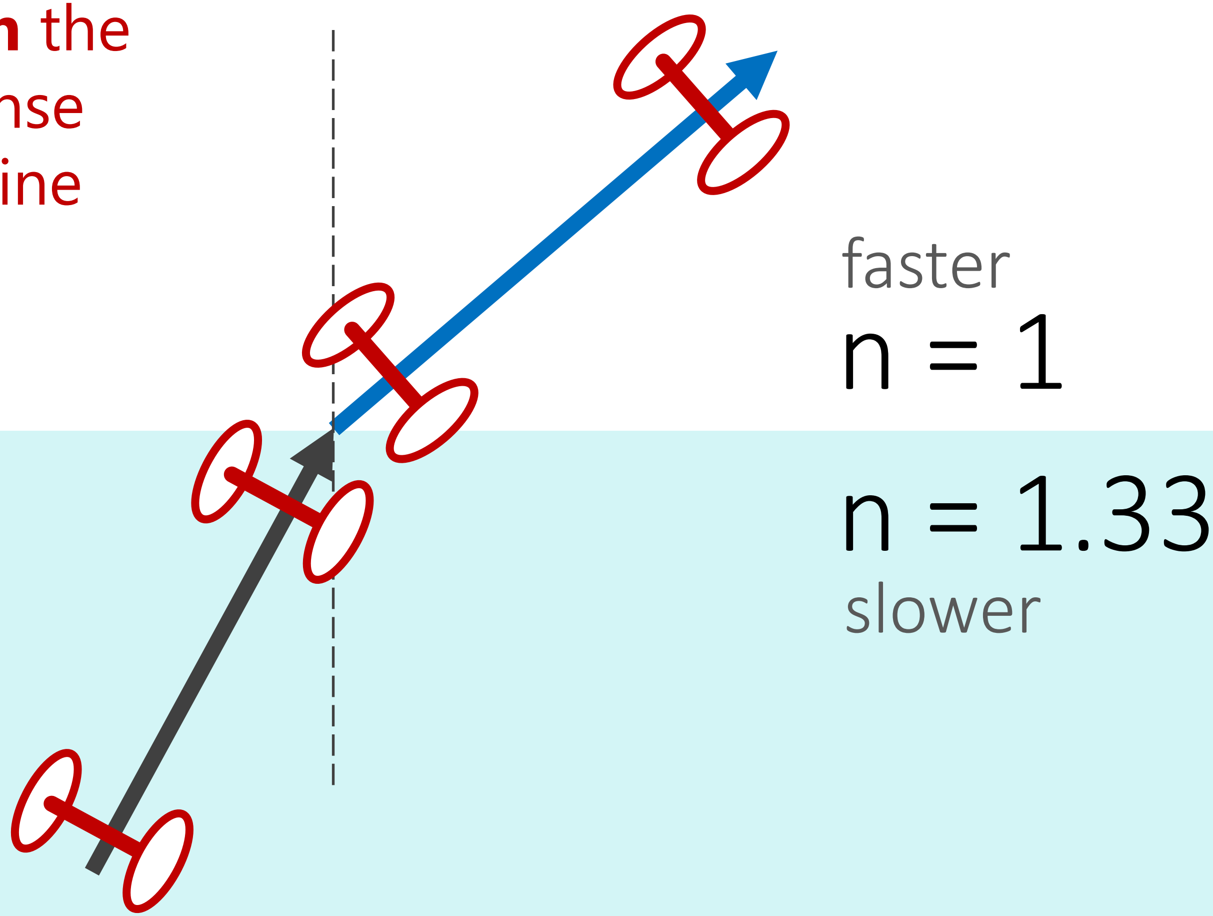
n = 1.33

slower

Bends **toward** the most optically dense medium normal line

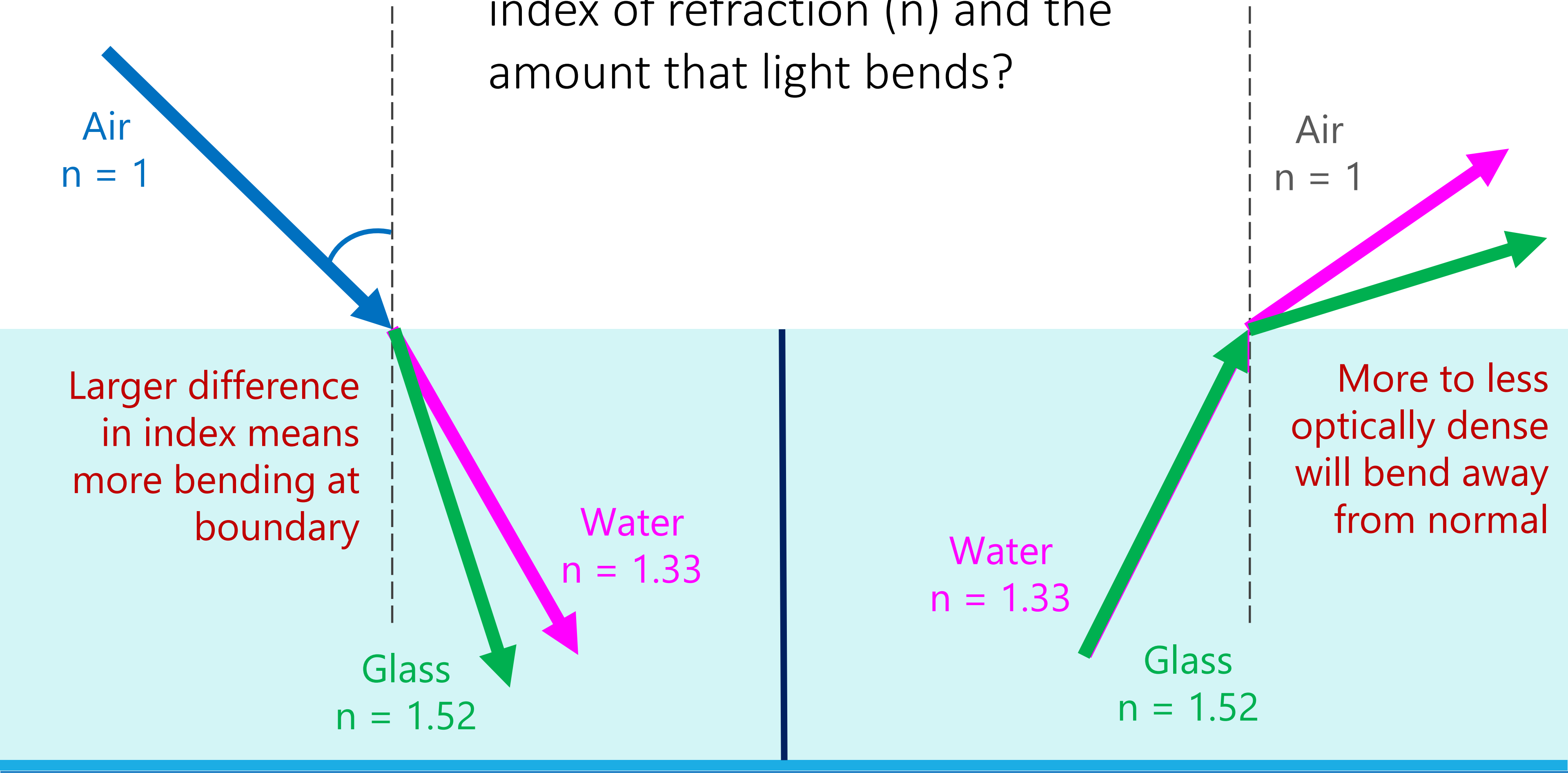
Refraction Boundary

Bends **away from** the least optically dense medium normal line



How Much Bend?

What's the relationship between index of refraction (n) and the amount that light bends?



Lesson Takeaways

- ❑ I can identify the angle of incidence and angle of reflection for a reflected wave ray
- ❑ I can use the law of reflection to predict the way light bounces off of a plane mirror
- ❑ I can relate the index of refraction of a material to the speed of light as it travels through
- ❑ I can qualitatively predict how light bends when transitioning between boundaries

Snell's Law & Critical Angle

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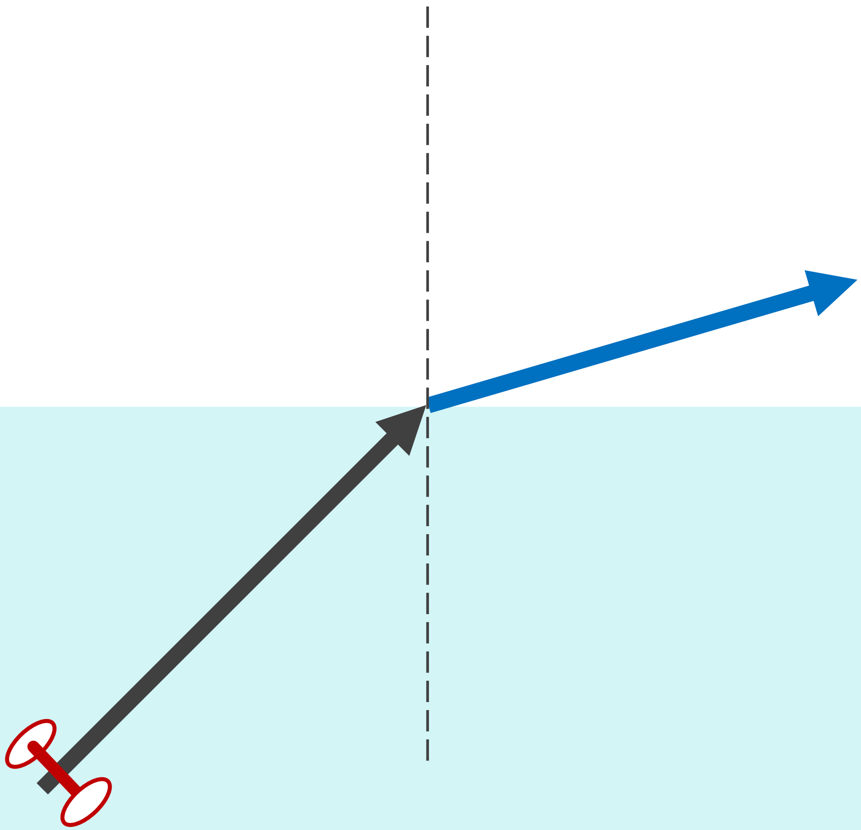
Remember the Bend



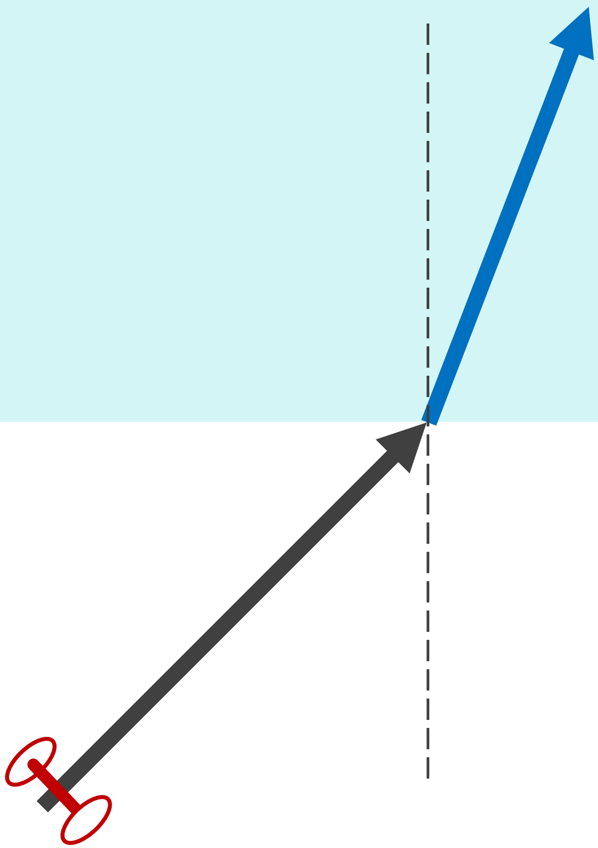
faster

n = 1

n = 1.33

slower

Remember the Bend



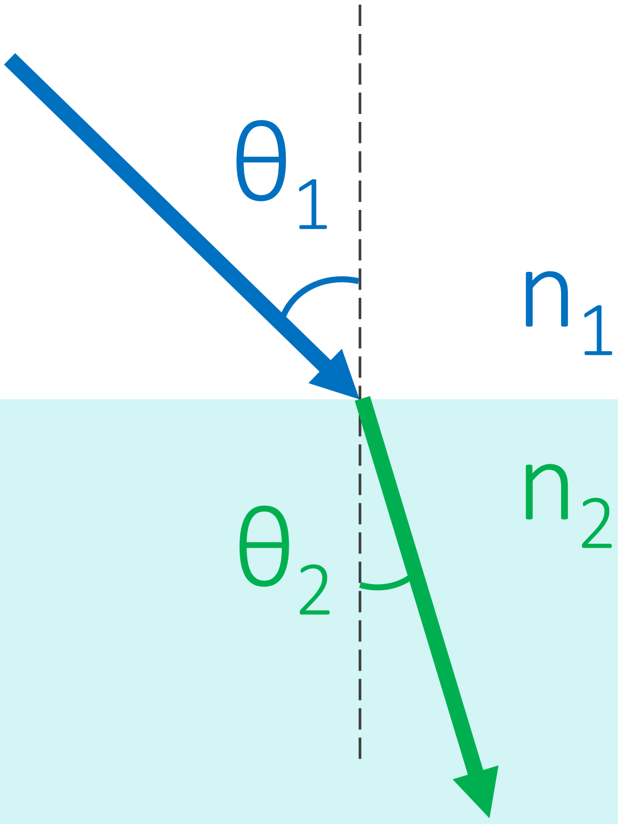
slower

n = 1.33

n = 1

faster

Snell's Law



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

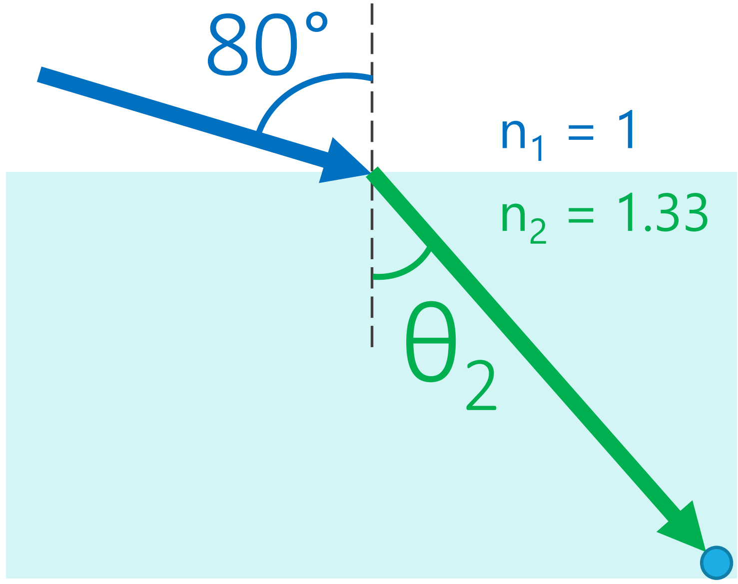
IB Physics Data Booklet

Sub-topic 4.1 – Oscillations	Sub-topic 4.4 – Wave behaviour
$T = \frac{1}{f}$	$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$ $s = \frac{\lambda D}{d}$ Constructive interference: path difference $= n\lambda$ Destructive interference: path difference $= (n + \frac{1}{2})\lambda$
Sub-topic 4.2 – Travelling waves	
$c = f\lambda$	
Sub-topic 4.3 – Wave characteristics	
$I \propto A^2$ $I \propto x^{-2}$ $I = I_0 cos^2\,\theta$	

$$\frac{n_1}{n_2} = \frac{v_2}{v_1} \qquad \frac{n_1}{n_2} = \frac{sin\theta_2}{sin\theta_1} = \frac{v_2}{v_1} \qquad \frac{n_1}{n_2} = \frac{sin\theta_2}{sin\theta_1}$$

Using Snell's Law

While aiming at a marble at the bottom of a fish tank filled with water (n_2 = 1.33), you point so that you can measure the angle of your incident rays. What is the angle of refraction?



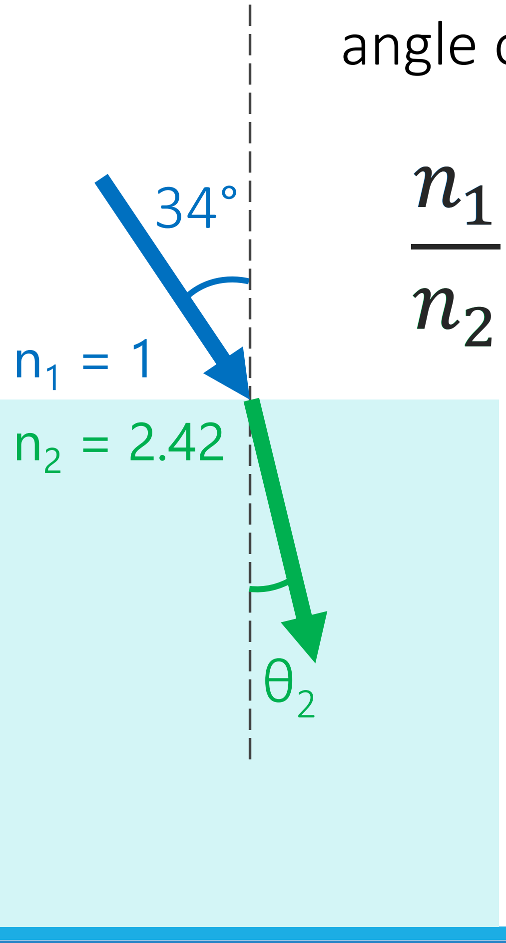
Where does it "appear" the marble is?

$$\frac{n_1}{n_2} = \frac{sin\theta_2}{sin\theta_1} = \frac{v_2}{v_1}$$

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

$$\theta_2 = sin^{-1}\left(\frac{1\sin(80°)}{1.33}\right) = \mathbf{47.8°}$$

Try this...

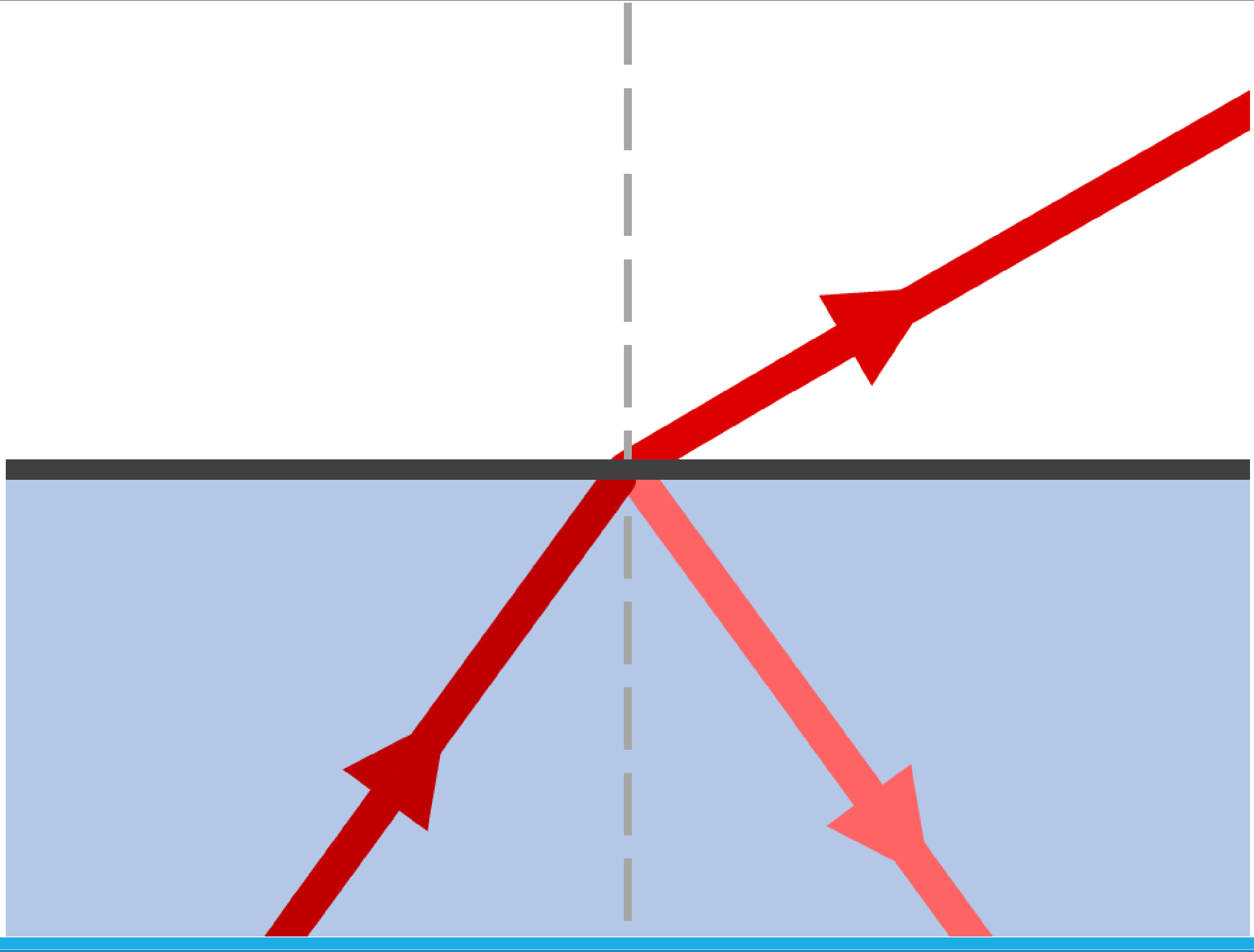


If the light travels from air to diamond (n = 2.42) at an angle of incidence of 34°, find the angle of refraction.

$$\frac{n_1}{n_2} = \frac{sin\theta_2}{sin\theta_1} = \frac{v_2}{v_1} \qquad \theta_2 = sin^{-1}\left(\frac{n_1 sin\theta_1}{n_2}\right)$$

$$\theta_2 = sin^{-1}\left(\frac{1\sin(34°)}{1.33}\right) = \mathbf{13.4°}$$

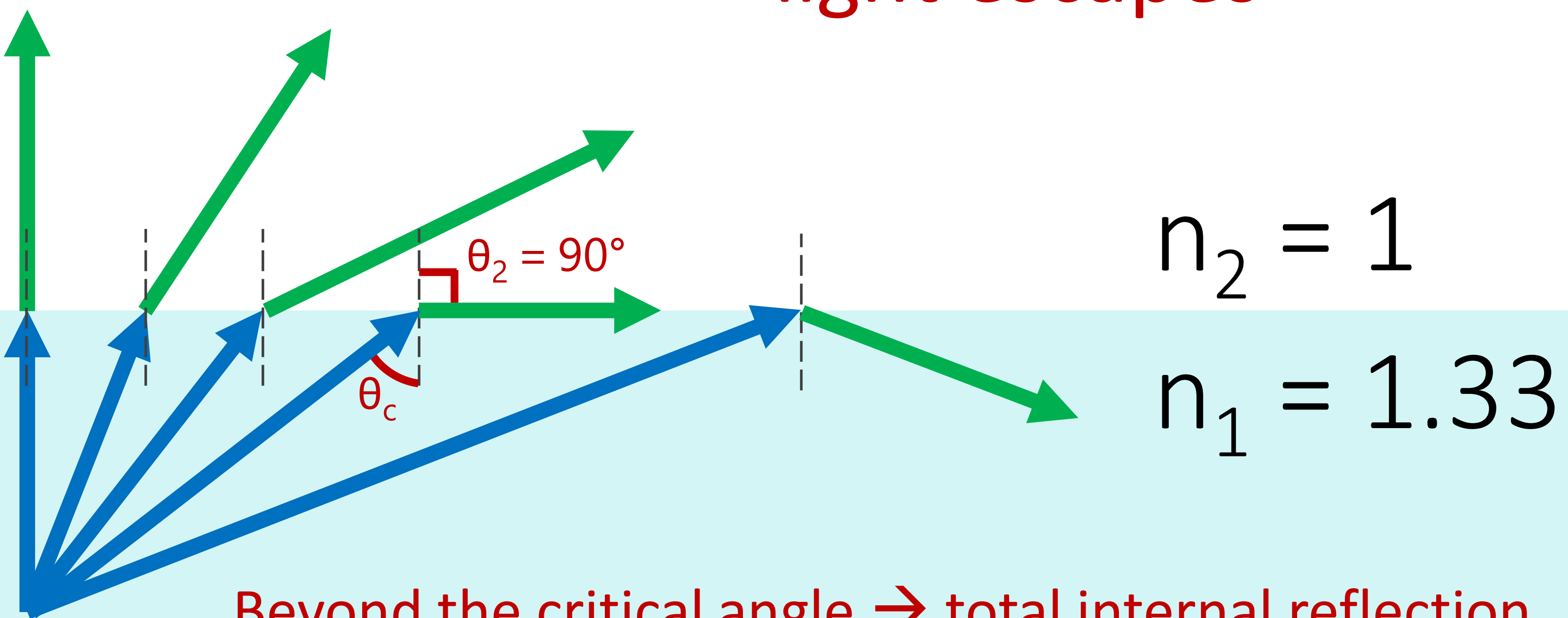
Refraction AND Reflection



Critical Angle

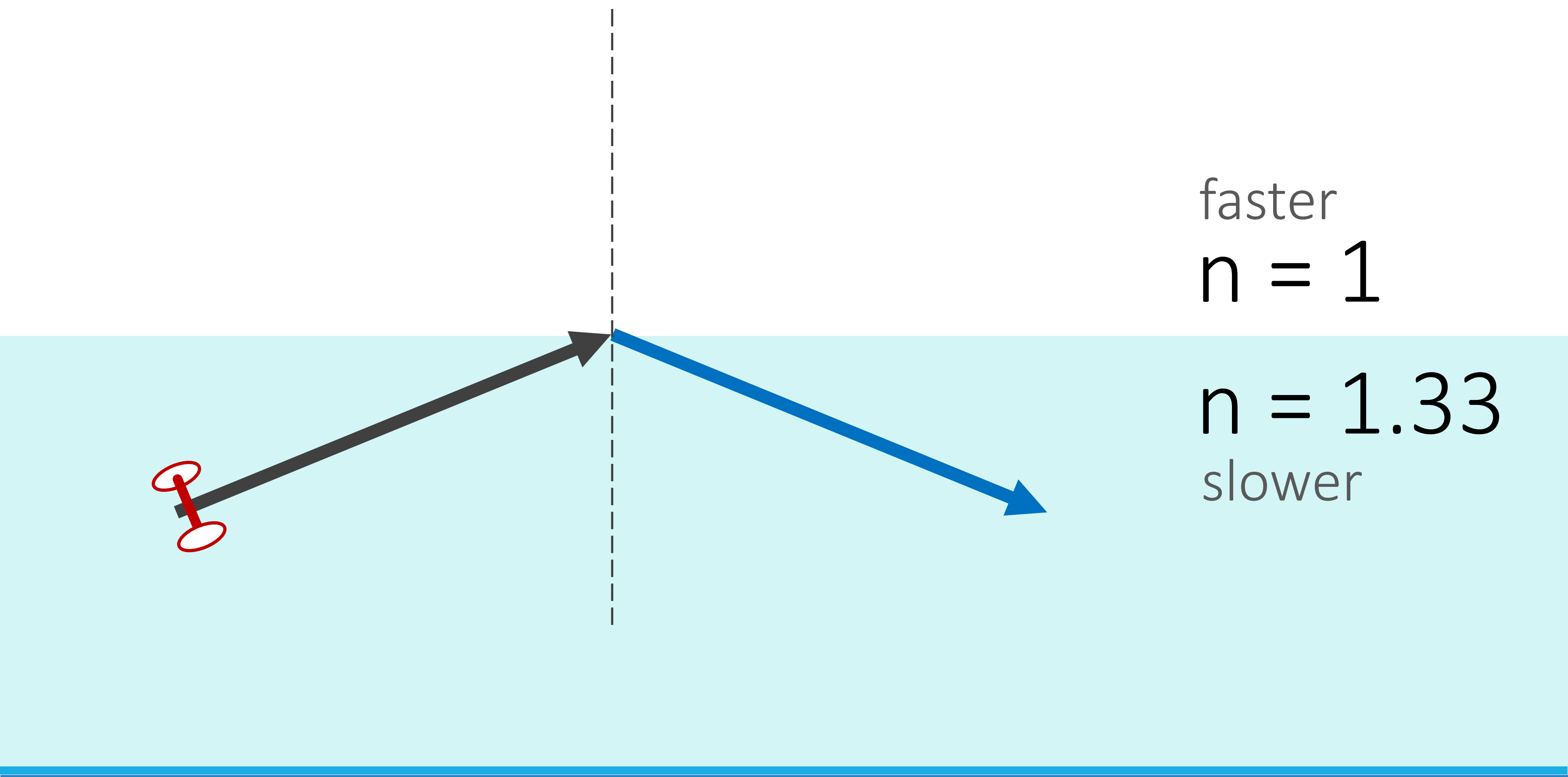
Critical Angle: θ_c

Angle at which $\theta_2 = 90°$ so no light escapes



Beyond the critical angle → total internal reflection

Remember the Bend

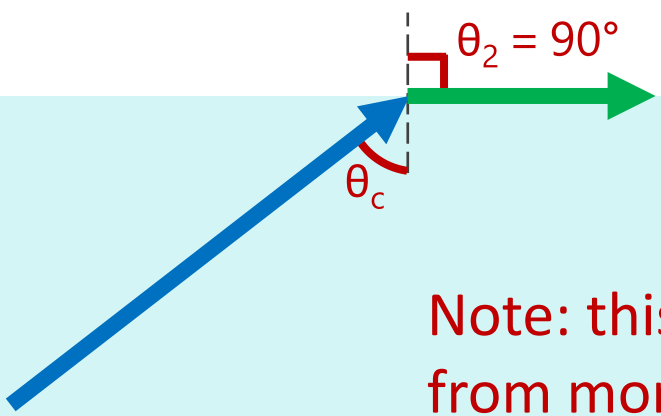


Critical Angle

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

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

$$\theta_c = sin^{-1}\left(\frac{n_2\mathbf{sin(90°)}}{n_1}\right) = sin^{-1}\left(\frac{n_2}{n_1}\right)$$



$n_2 = 1$

$n_1 = 1.33$

Note: this only happens when transitioning from more dense to less dense

Try This

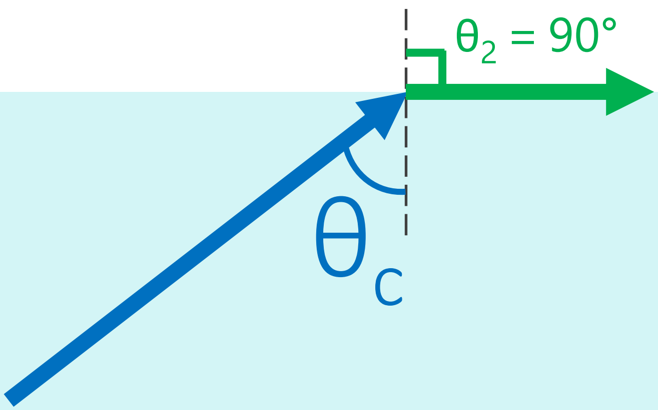
What's the critical angle between glass and air?

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

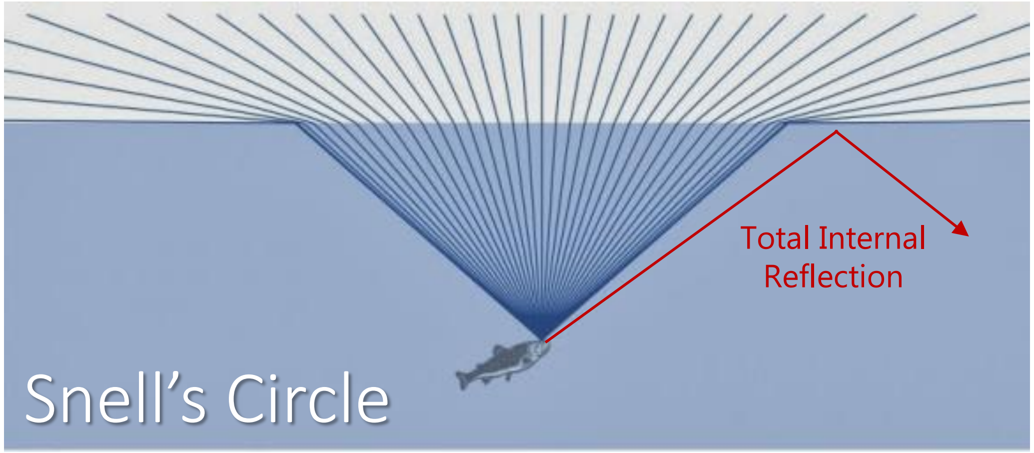
$$\theta_c = \sin^{-1}\left(\frac{1}{1.52}\right) = \mathbf{41.1^\circ}$$

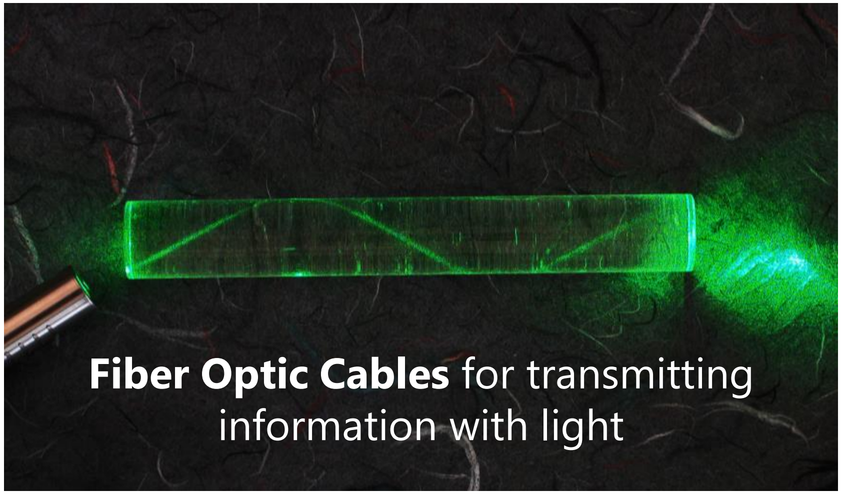
$n_2 = 1$

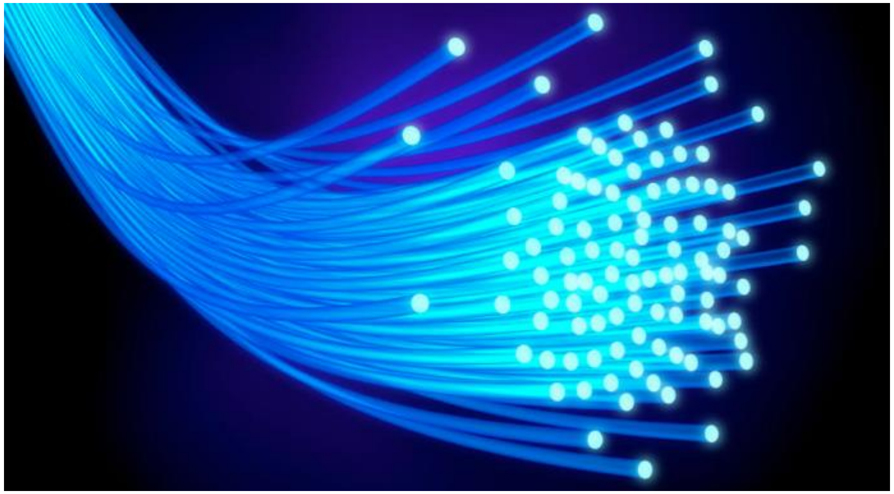
$n_1 = 1.52$



Why does it matter?

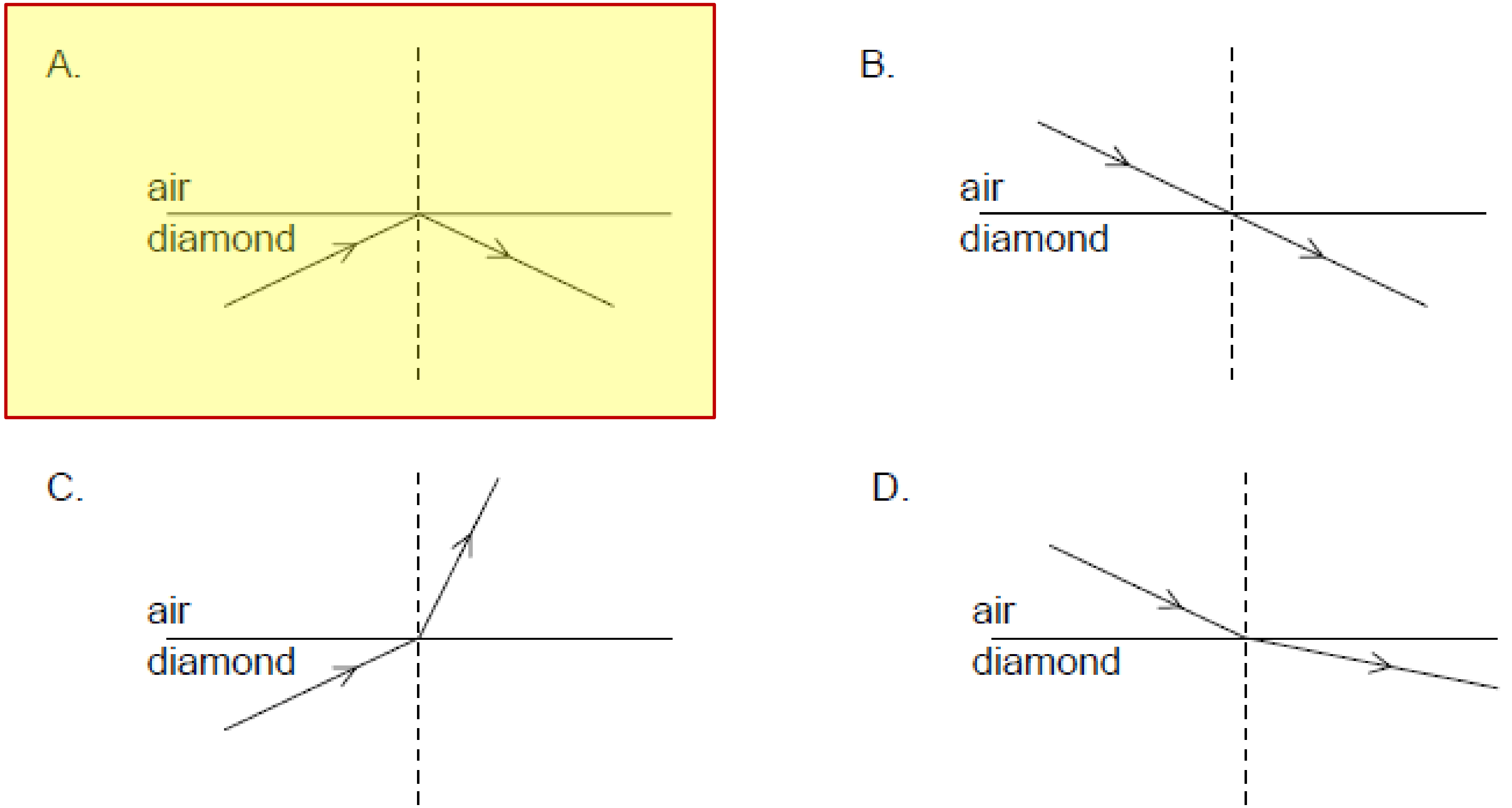






Sample IB Question

A light ray is incident on an air–diamond boundary. The refractive index of diamond is greater than 1. Which diagram shows the correct path of the light ray?



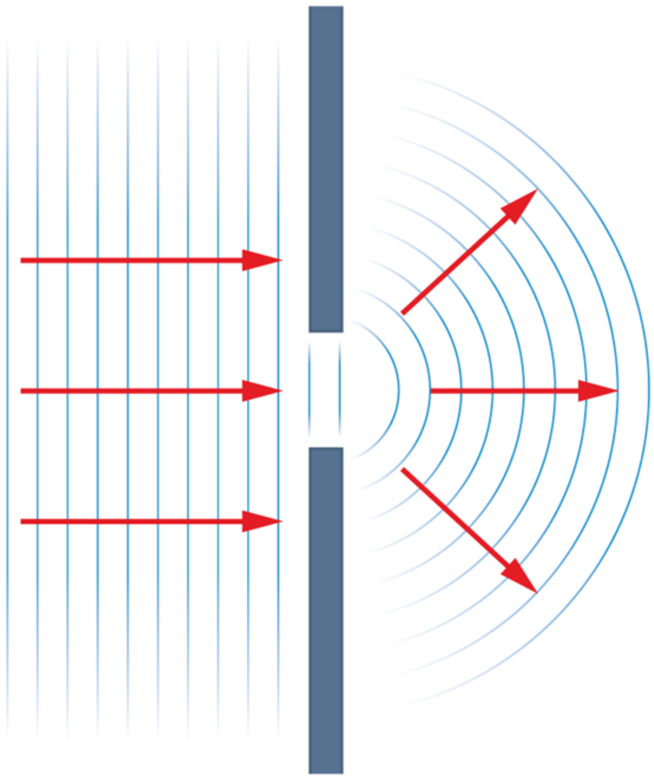
Lesson Takeaways

- ❑ I can mathematically relate the angles of refraction to the indices of refraction for the materials
- ❑ I can describe the phenomenon of total internal reflection
- ❑ I can calculate the critical angle of incidence so that the light cannot escape the medium

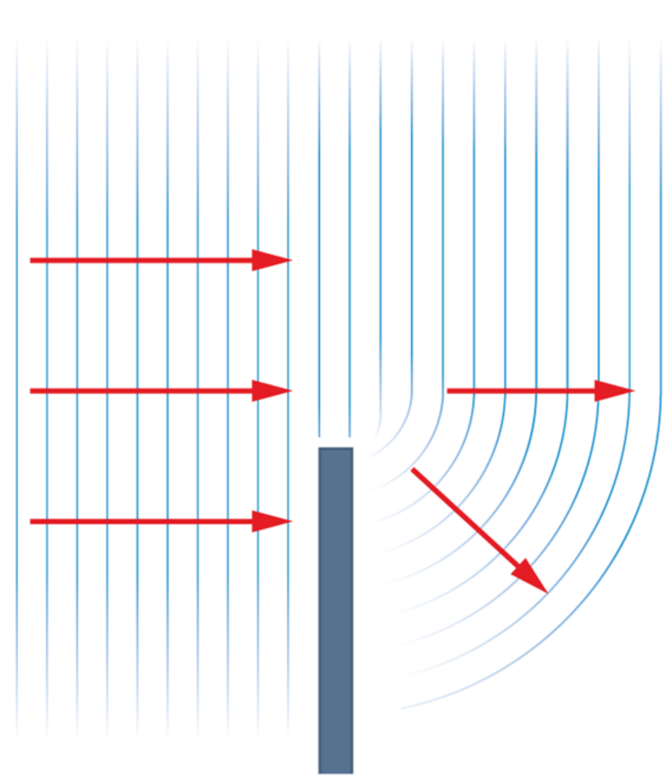
Diffraction

IB PHYSICS | WAVES - LIGHT

Diffraction



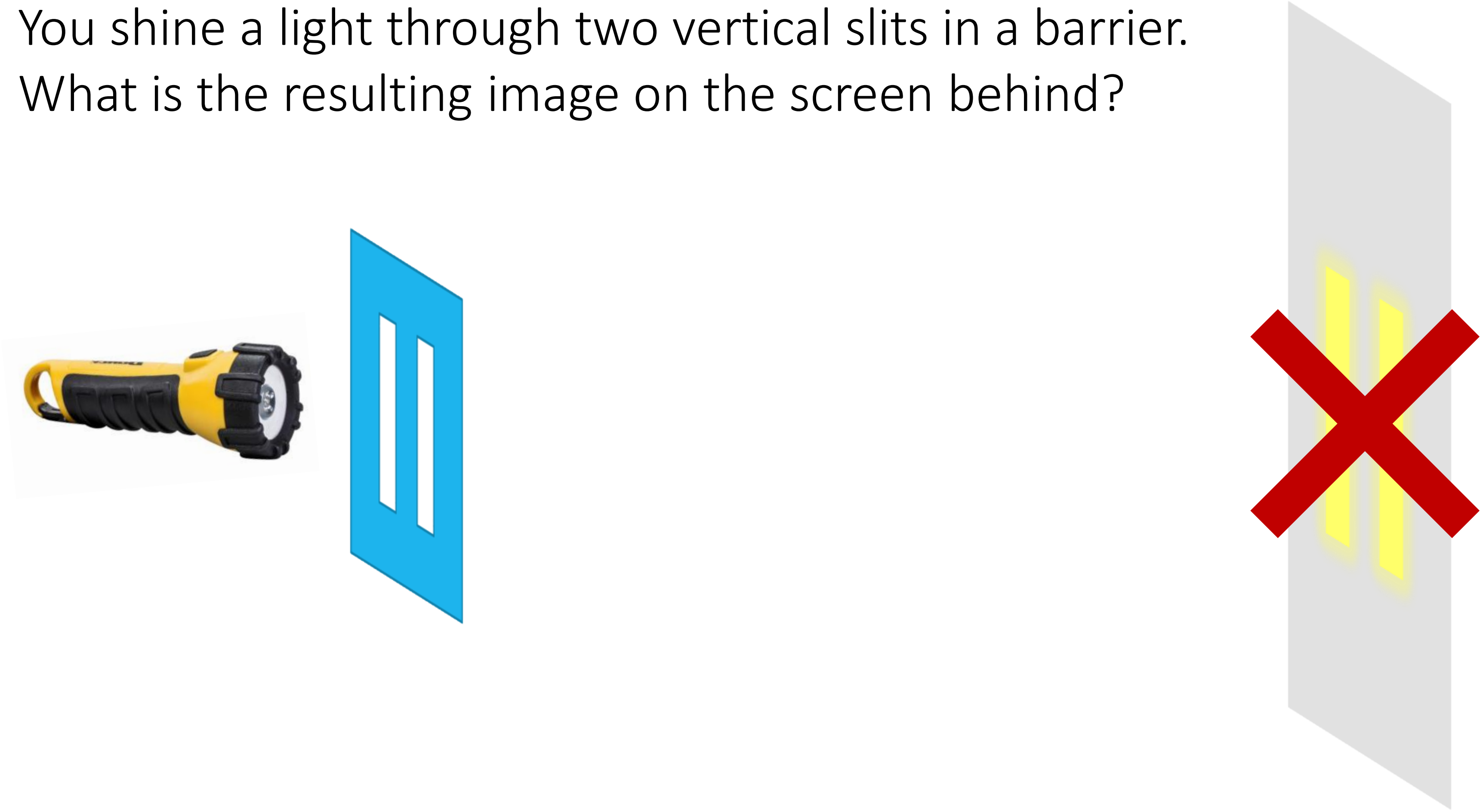
as the wave goes through
the gap it spreads out



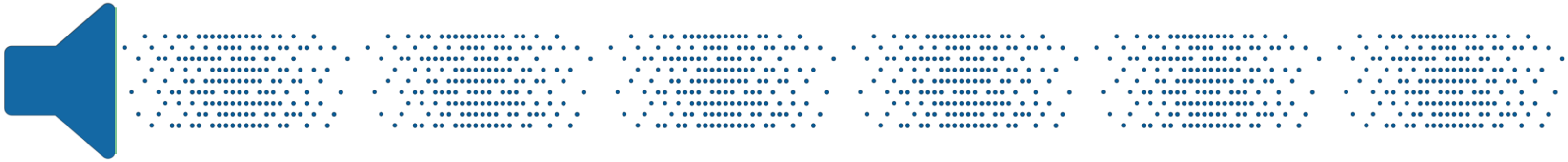
the same thing happens if
it goes around an obstacle

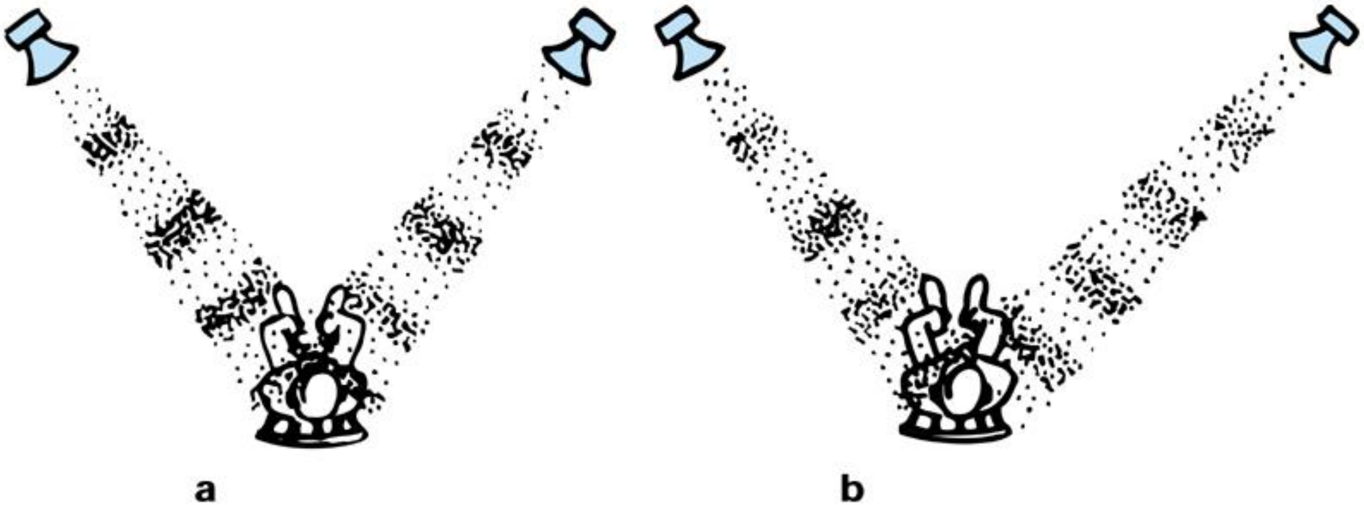
What would you expect?

You shine a light through two vertical slits in a barrier. What is the resulting image on the screen behind?



Remember Interference?

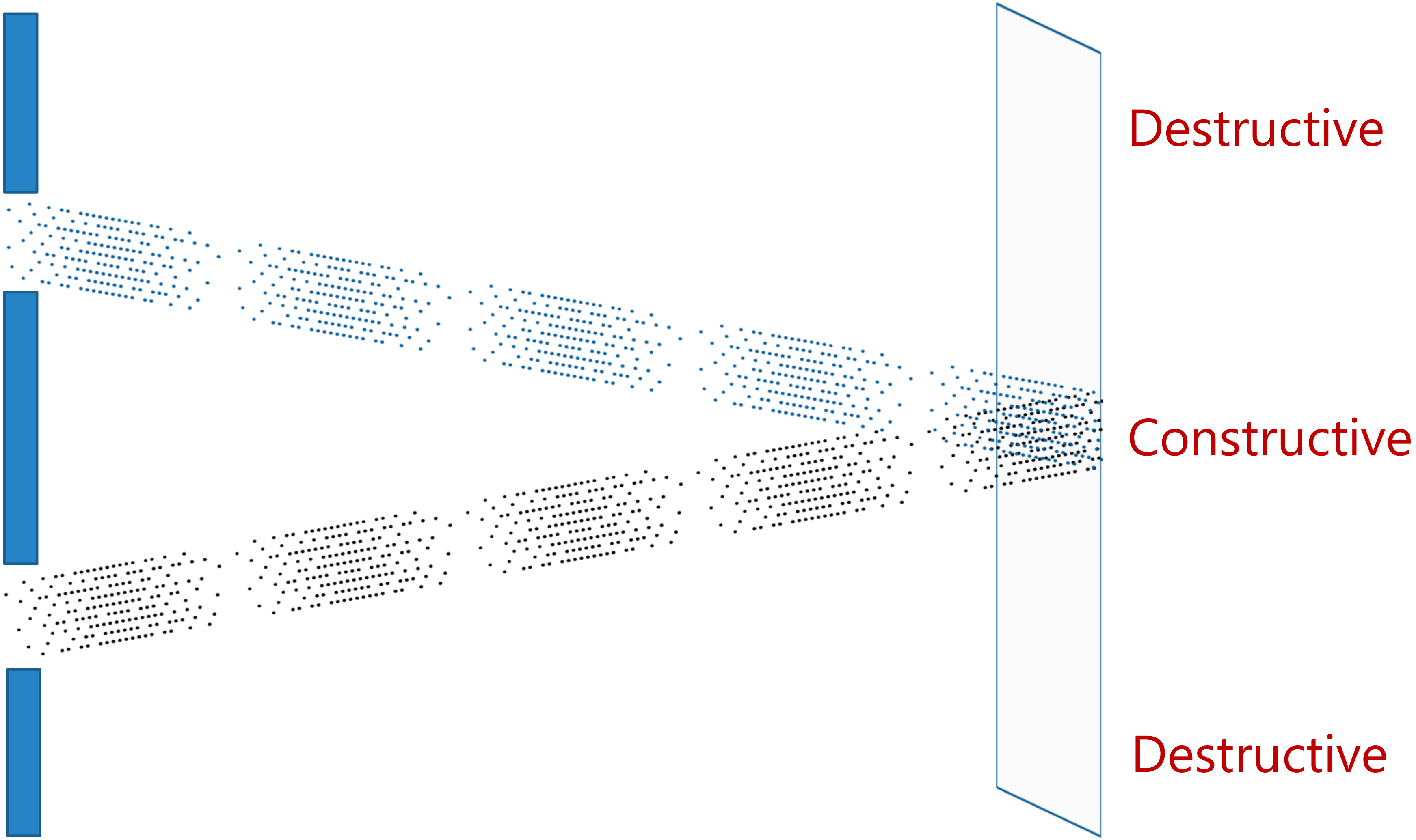




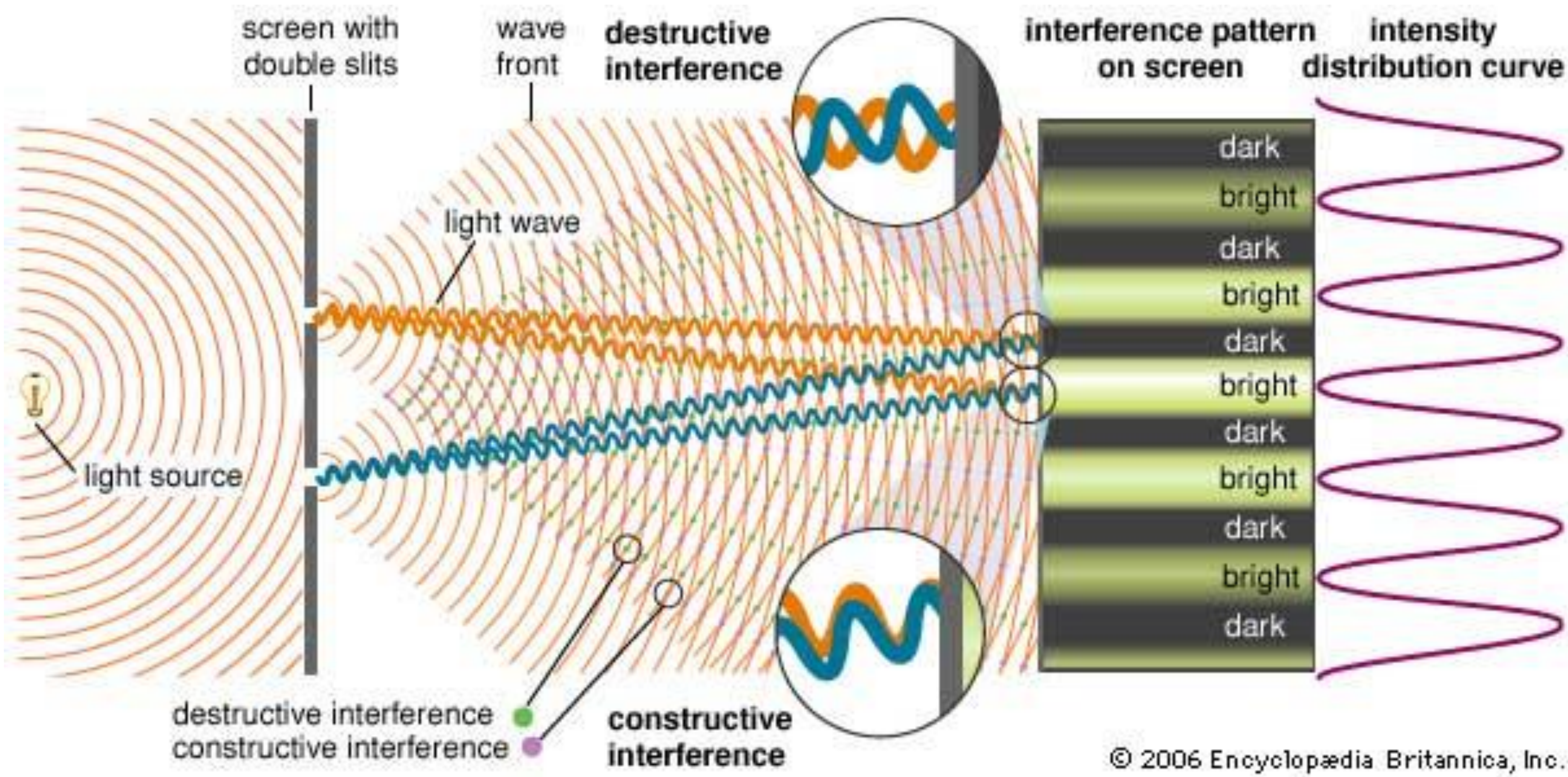
Constructive

Destructive

Diffraction

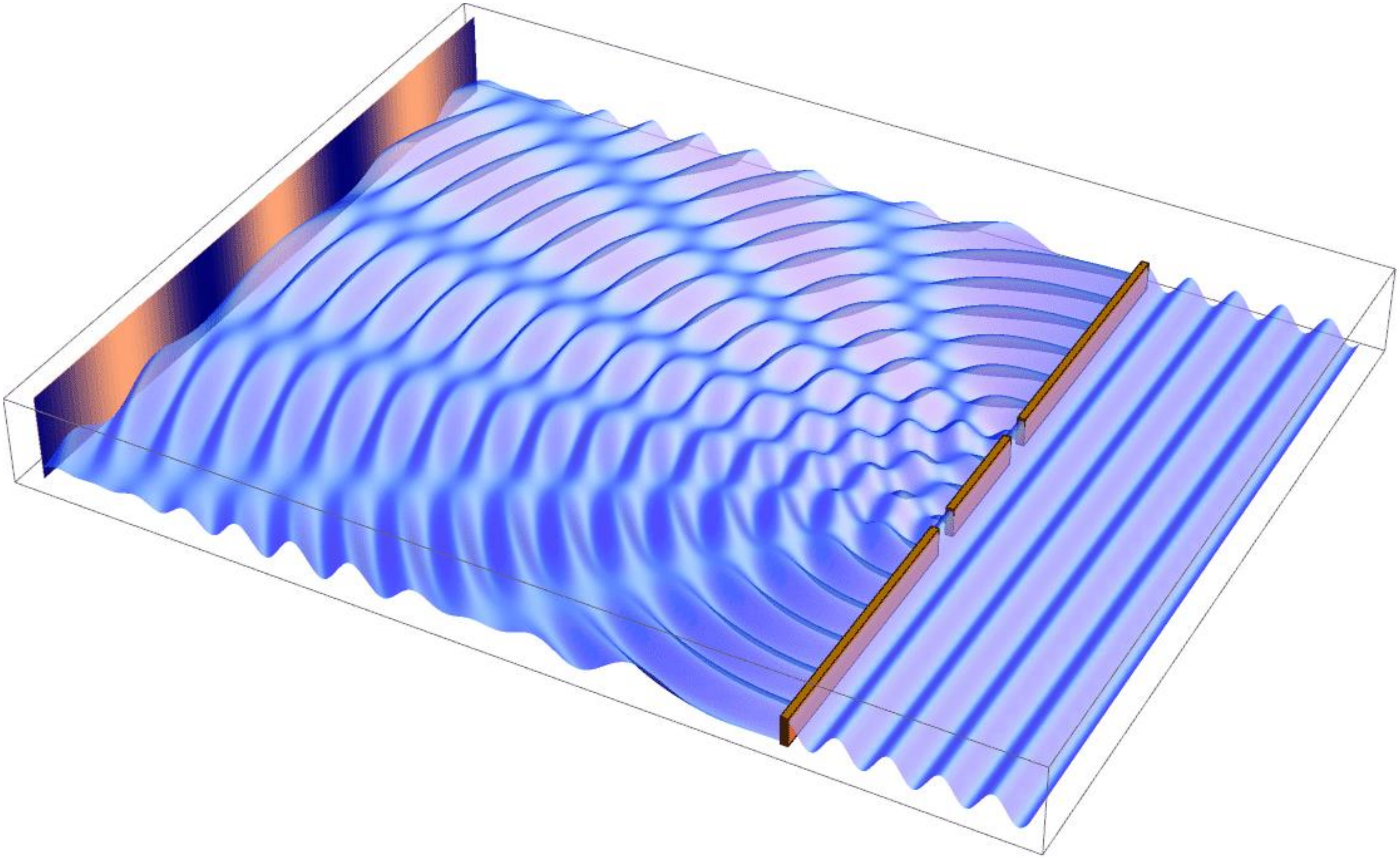


Double Slit Experiment

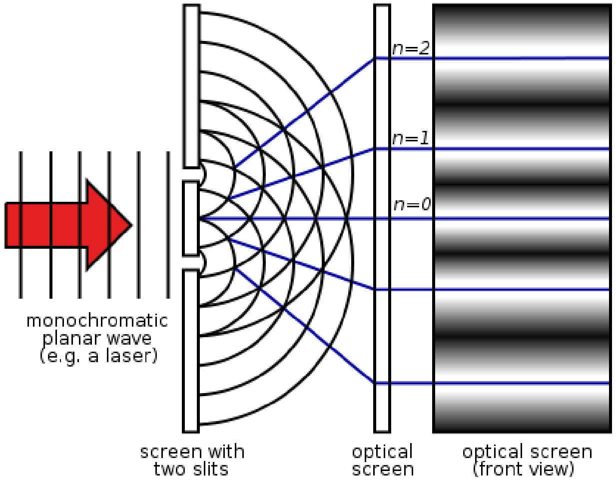


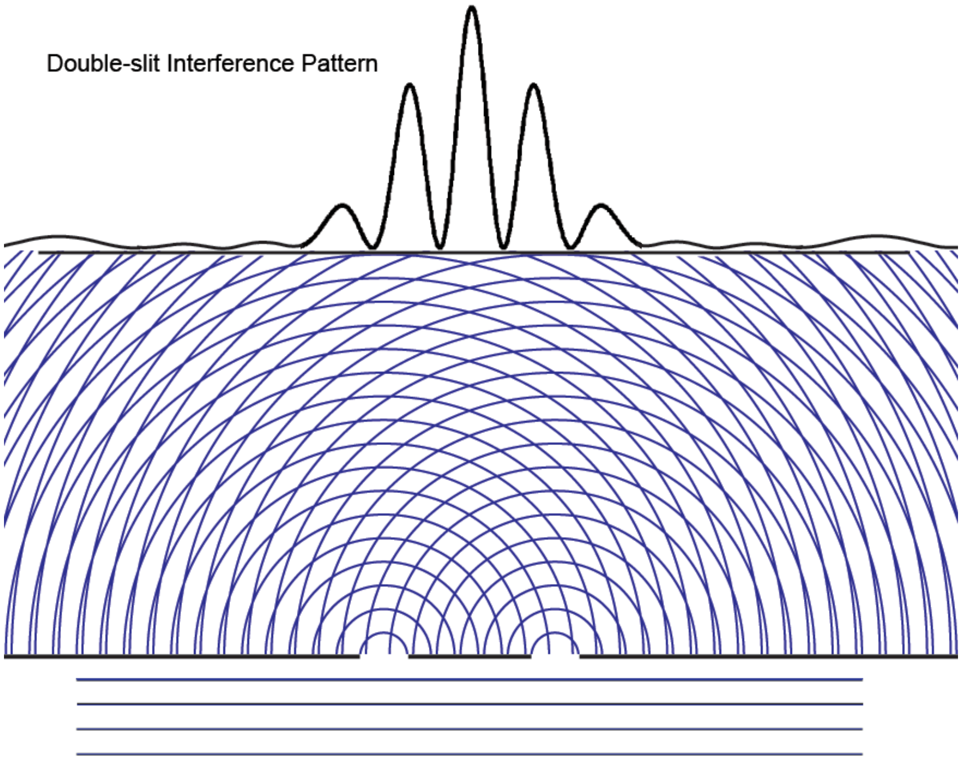
Double Slit Experiment

Double Slit Experiment



Double Slit Experiment

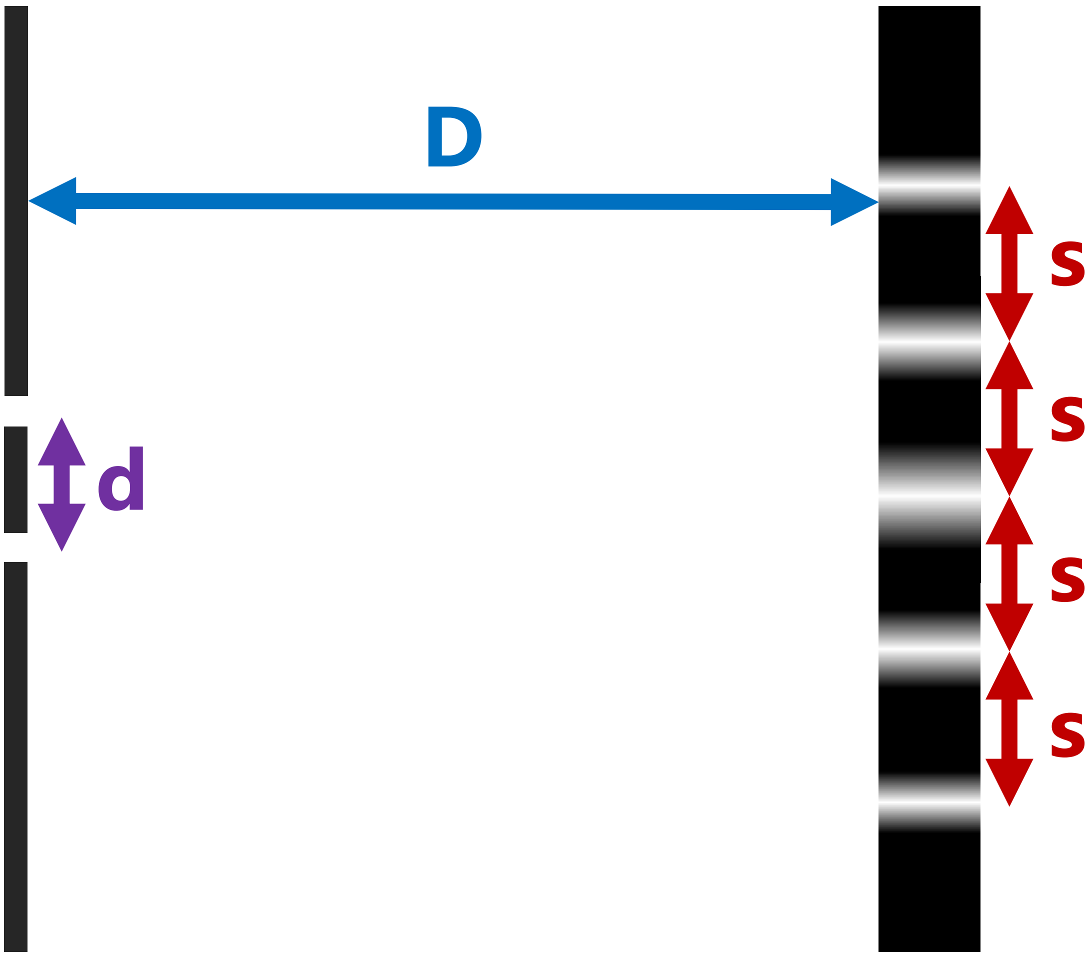




Double Slit Experiment

$$s = \frac{\lambda D}{d}$$

λ → wavelength



IB Physics Data Booklet

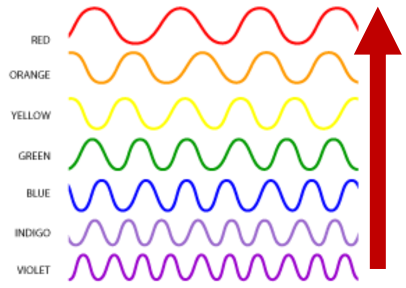
Sub-topic 4.1 – Oscillations	Sub-topic 4.4 – Wave behaviour
$T = \frac{1}{f}$	$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$ $s = \frac{\lambda D}{d}$ Constructive interference: path difference $= n\lambda$ Destructive interference: path difference $= (n + \frac{1}{2})\lambda$
Sub-topic 4.2 – Travelling waves	
$c = f\lambda$	
Sub-topic 4.3 – Wave characteristics	
$I \propto A^2$ $I \propto x^{-2}$ $I = I_0 cos^2\,\theta$	

milli	m	10^{-3}
micro	µ	10^{-6}
nano	n	10^{-9}

Double Slit Experiment

$$s = \frac{\lambda D}{d}$$

As wavelength (λ) increases,



s increases

As gap (d) increases,

s decreases

Try This

$$s = \frac{\lambda D}{d}$$

Blue laser light of wavelength 450 nm is shone on two slits that are 0.1 mm apart. How far apart are the fringes on a screen placed 5.0 m away?

λ = 450 nm = 450 × 10^{-9} m

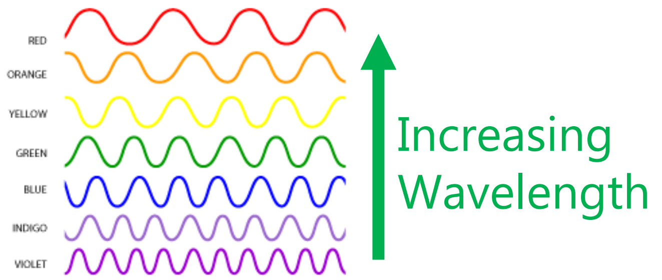
d = 0.1 mm = 0.1 × 10^{-3} m

D = 5 m

$$s = \frac{(450 \times 10^{-9})(5)}{(0.1 \times 10^{-3})}$$

$$s = \mathbf{0.02\ m}$$

Would red laser light have fringes closer together or farther apart?



As wavelength increases, fringes get farther apart

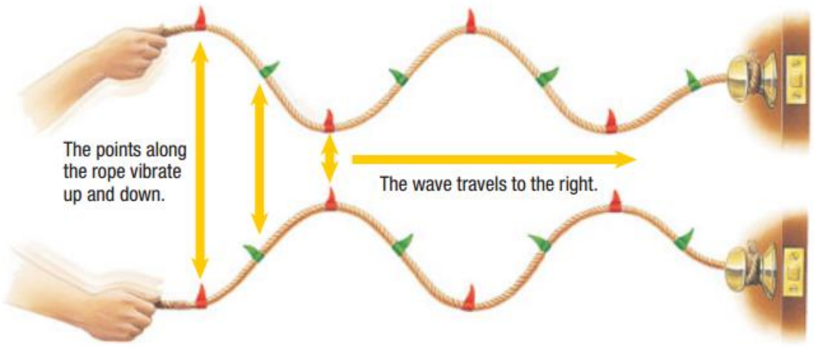
Lesson Takeaways

- ❑ I can describe how light bends around a boundary
- ❑ I can predict the resulting image from a double slit experiment
- ❑ I can calculate the spacing between bright spots for the double slit experiment
- ❑ I can conceptually relate band spacing with wavelength and gap distance

Polarization

IB PHYSICS | WAVES - LIGHT

Light is a Transverse Wave



This isn't the whole story though…

When unpolarized, light can be thought of as oscillating at every perpendicular to the wave's motion

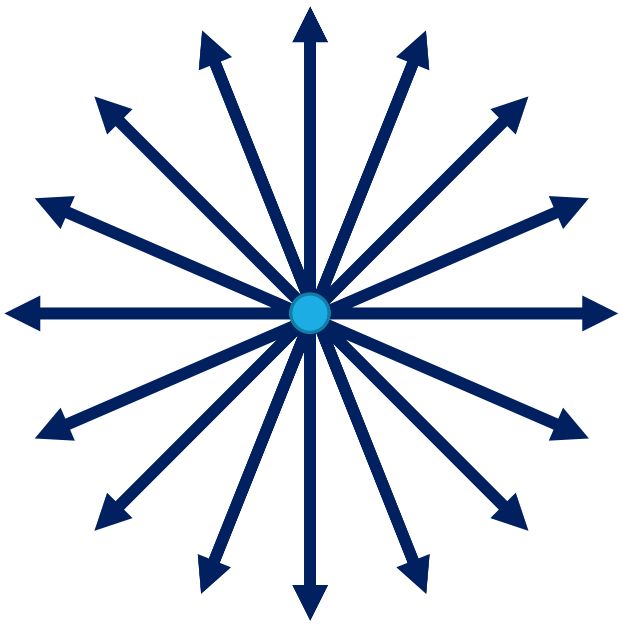
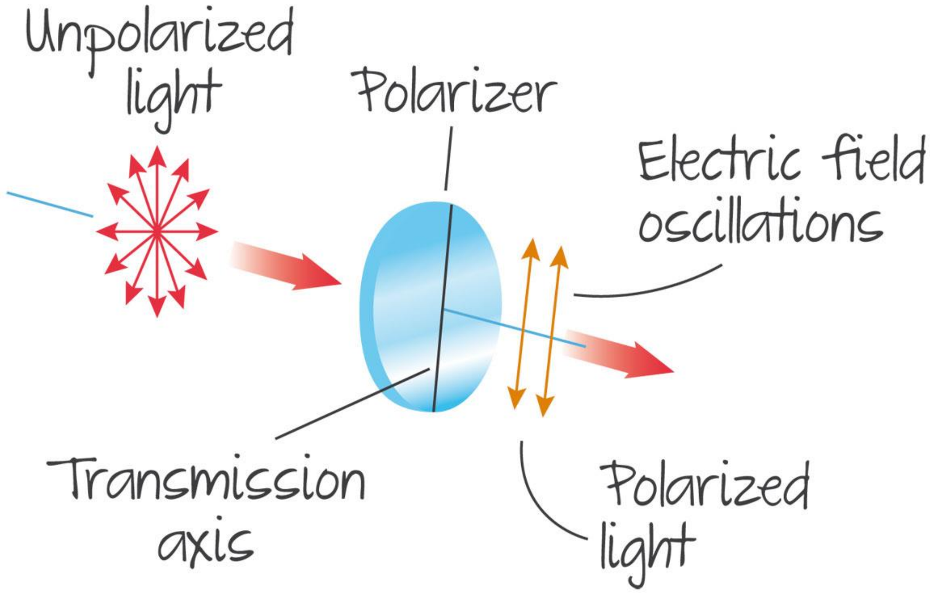


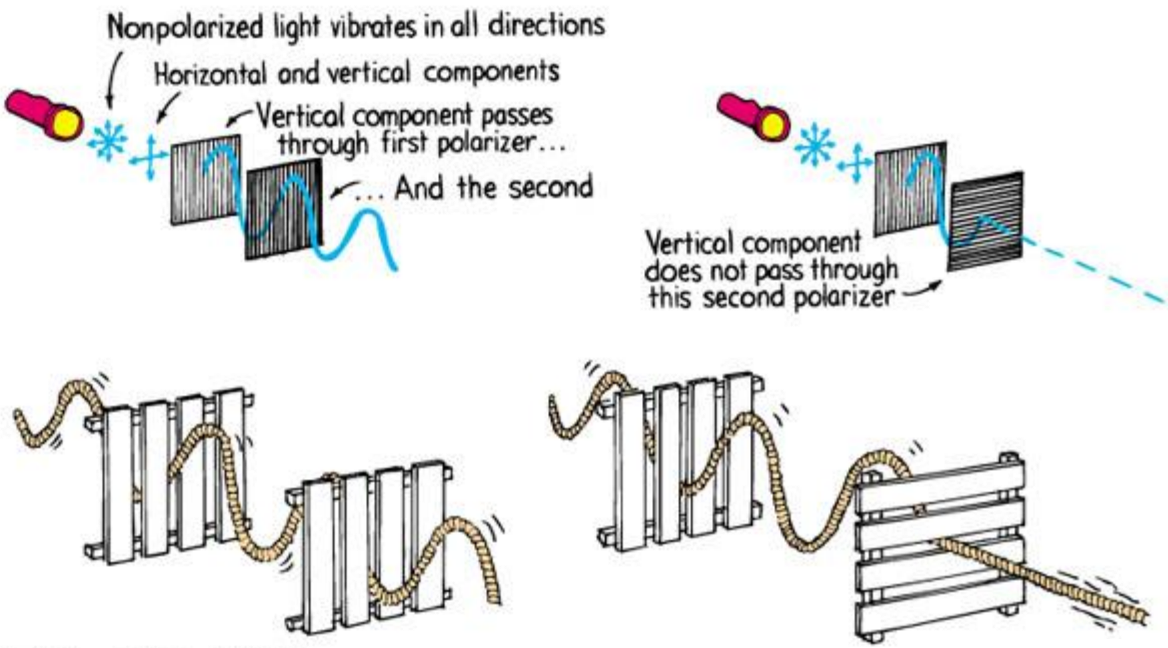
Diagram of a light ray coming out of the page

Polarizers

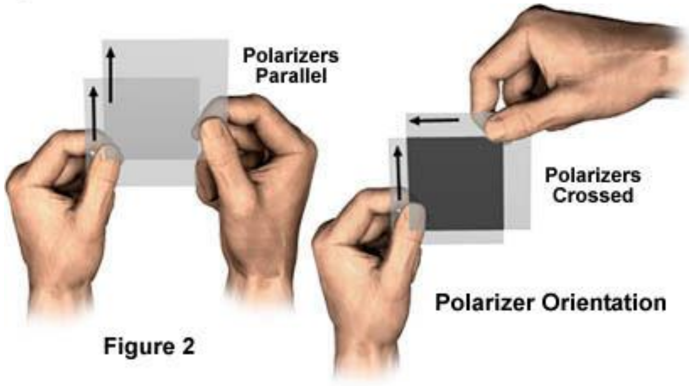


Unpolarized light loses 50% intensity when passing through a polarizer

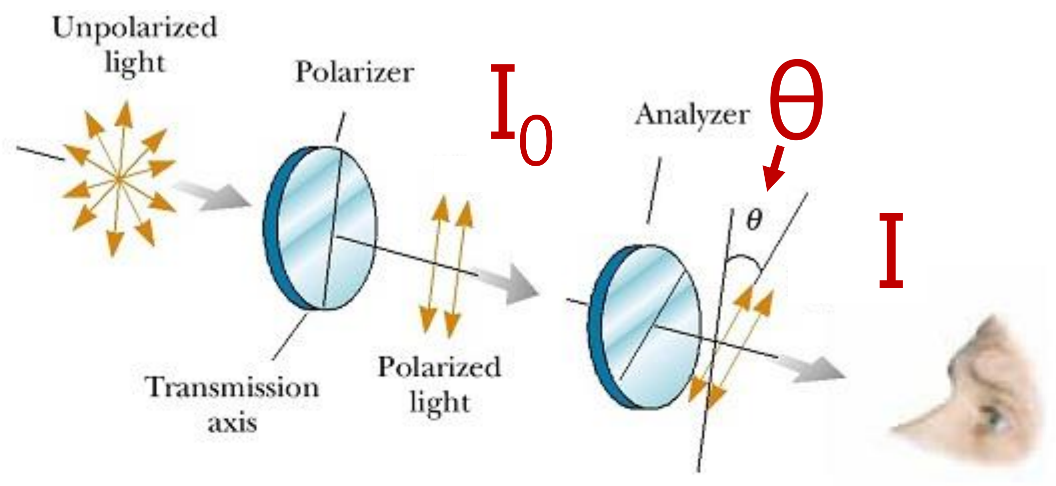
Polarized Light



Hewitt, *Conceptual Physics*, Ninth Edition.



Malus' Law



$$I = I_0 \cos^2\theta$$

θ = angle between filters

Same thing as

$$I = I_0 (\cos\theta)^2$$

IB Physics Data Booklet

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Sub-topic 4.2 – Travelling waves	
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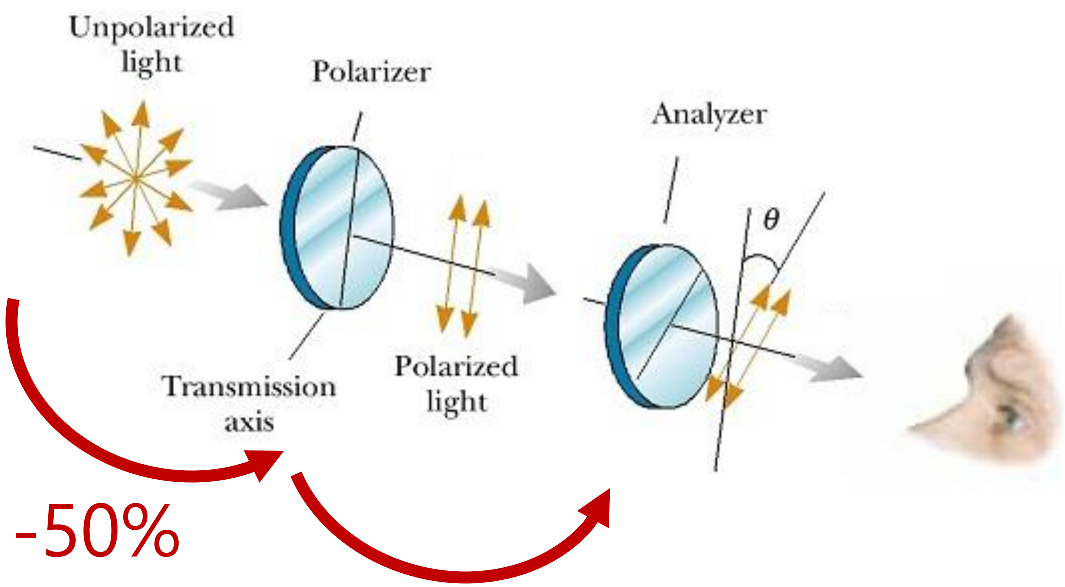
Sub-topic 4.3 – Wave characteristics	
$I \propto A^2$ $I \propto x^{-2}$ $I = I_0 cos^2\, \theta$	

Loses Intensity Twice



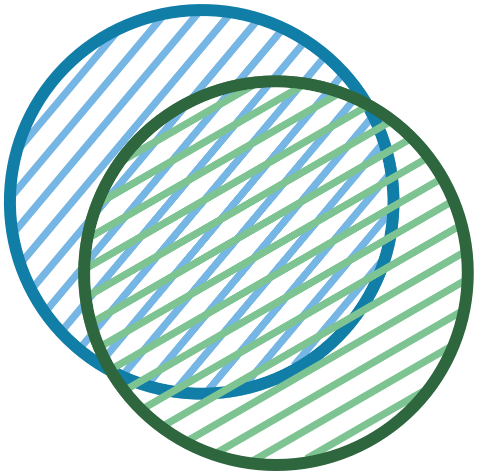
$$I = I_0 \cos^2\theta$$

50% loss when unpolarized light is polarized

Equation calculates loss through subsequent filters

Angle Difference

The intensity of plane polarized light, at 40° to the vertical is I_0. After passing through an analyzer at 60° to the vertical, what is the intensity measured?



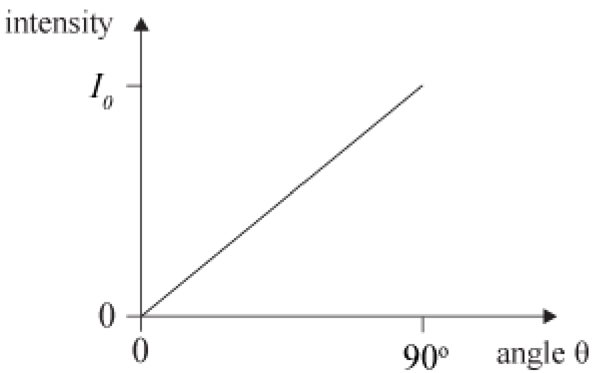
$$\theta = 60° - 40° = 20°$$

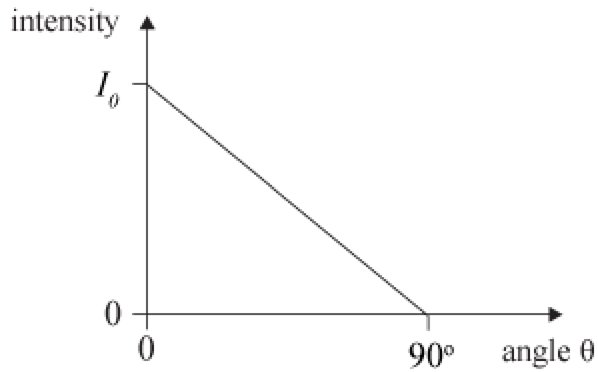
$$I = I_0 \cos^2(20°) = 0.883\, \boldsymbol{I_0}$$

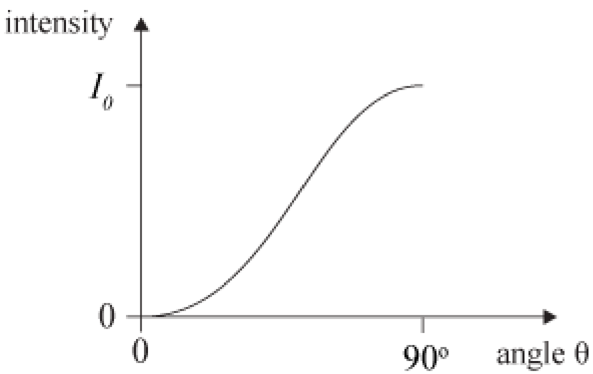
88.3% of the original intensity

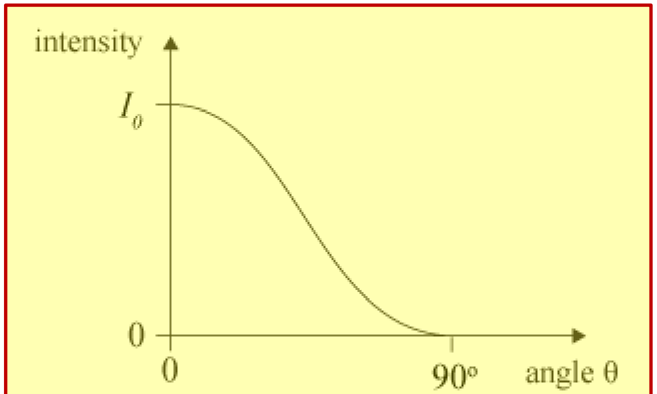
Sample IB Question

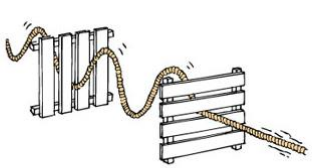
Polarized light of intensity I_0 is incident on a polarizing filter. The angle between the plane of polarization of the incident light and the transmission plane of the polarizer is θ. Which graph shows how the intensity I of the light transmitted through the polarizer varies with θ?











90° → Intensity = 0

$\cos^2$ shape

Try this Calculation

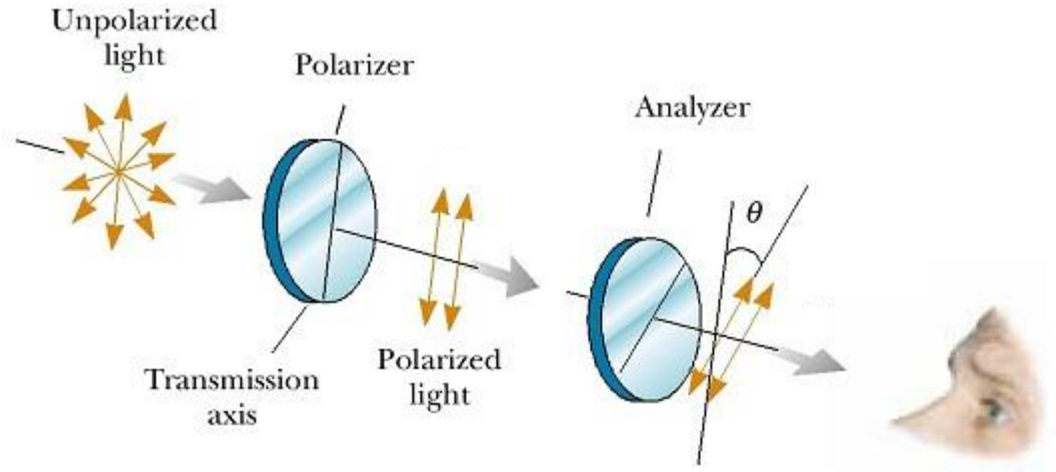
After passing through one polarized filter, the intensity of vertically polarized light is 60 W m^{-2}. What is the angle of the analyzer relative to the vertical if the intensity observed is 20 W m^{-2}?

$$I = I_0\, cos^2\theta$$

$$I = I_0\,(\cos\theta)^2$$

$$20 = 60\,(\cos\theta)^2$$

$$\theta = \cos^{-1}\left(\sqrt{\frac{20}{60}}\right) = \mathbf{54.7^\circ}$$

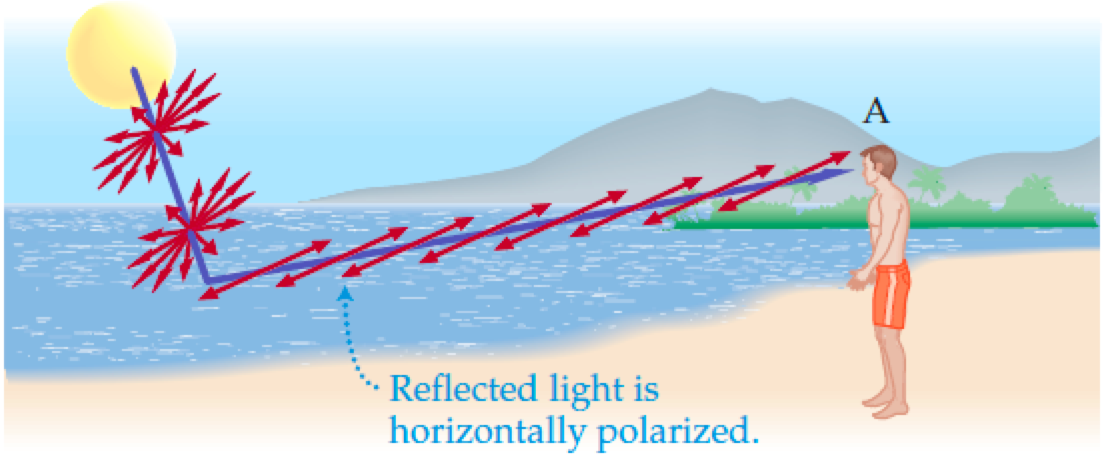


What was the intensity of the unpolarized light?

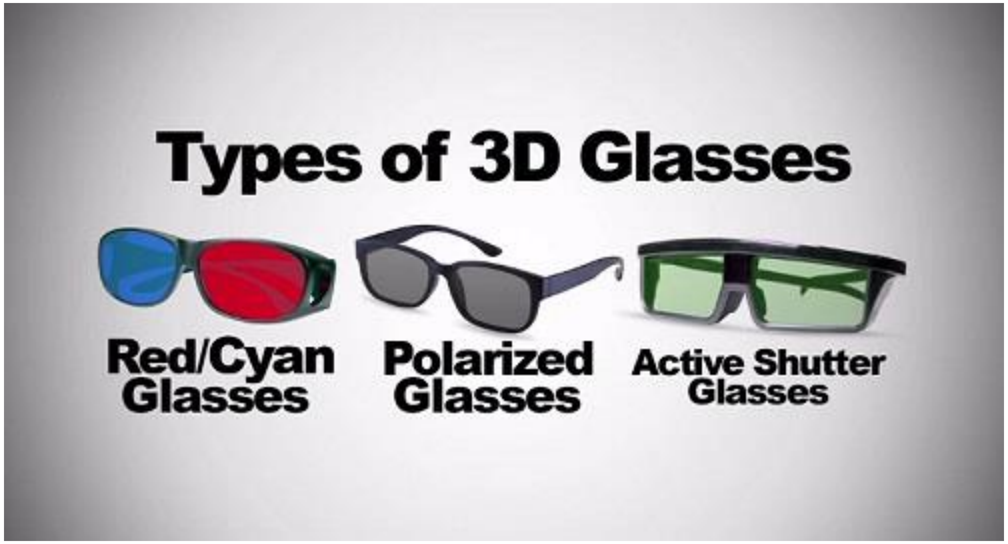
120 W m^{-2}

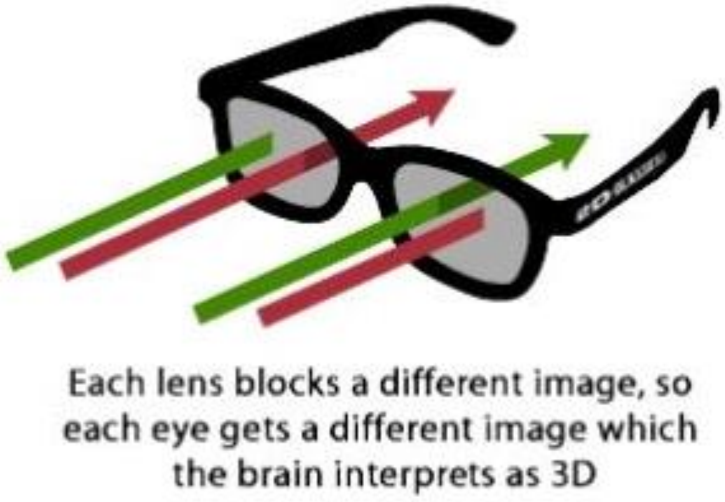
Loses 50% from first filter

This isn't the only way



What about 3D Movies?





Lesson Takeaways

- ❑ I can describe the transformation that takes place when unpolarized light is polarized
- ❑ I can describe the interaction between two polarized filters at different orientations
- ❑ I can use Malus's Law to calculate the change in intensity when passing through polarized filters