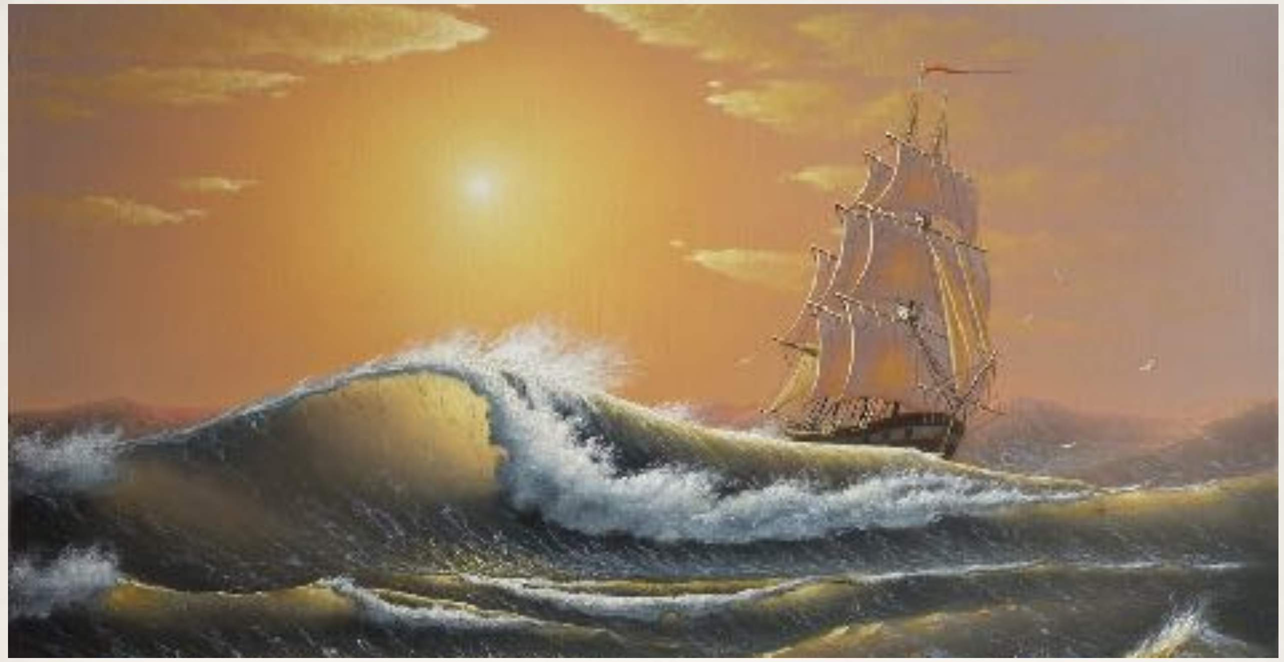


Act V: Waves Mechanics

What's a Wave?

- A wave is a wiggle in time and space
- The source of a wave is almost always a vibration
  - A vibration is a wiggle in time
- So a wave is basically a traveling vibration
  - BUT carries *energy* from the vibrating source to the receiver; it does NOT transfer matter

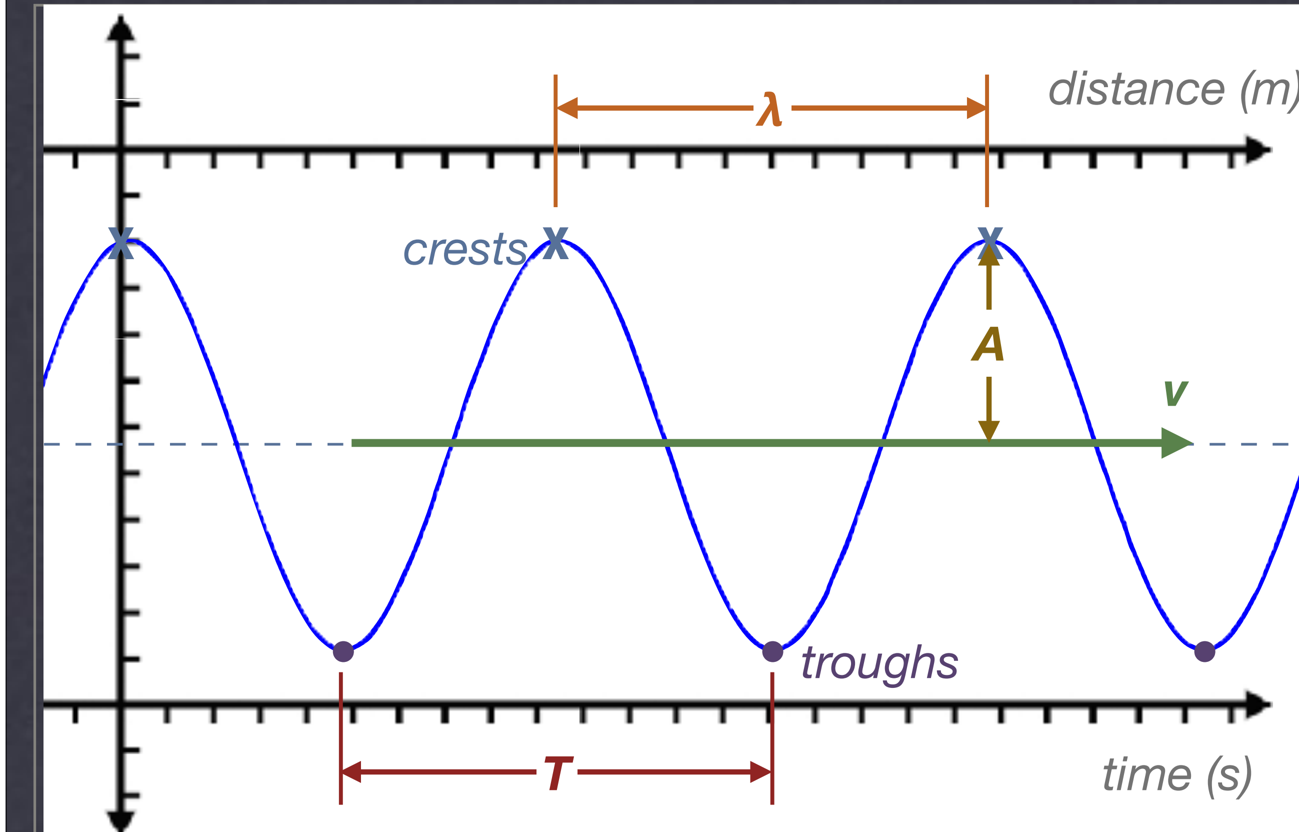
SF 14 12:07
JAX 0 2ND
2ND & GOAL
FOX
FANTASY
TE 4. S. McGrath 2.20 PTS (REC, 22 YDS)
RedZone

Qualities of a Wave

- Period (T)
  - Time it takes for one back-and-forth cycle
  - In seconds (s)
- Wavelength (λ)
  - Distance between successive identical parts of the wave
  - In meters (m)
- Frequency (f)
  - Number of vibrations in a given time
  - In Hertz (Hz)
  - $f = 1/T$

Qualities of a Wave

- Velocity
  - Speed and direction of the wave
  - In m/s
  - $v = \lambda f$
- Crests
  - Peaks or high point of the wave
- Troughs
  - Valleys or low points of the wave
- Amplitude (A)
  - Distance from midpoint to crest (or trough)
  - Maximum displacement from equilibrium



QUALITIES OF A WAVE

WAVE MOTION

Wave Speed

- In a freight train, each car is 10 m long. If two cars roll by you every second, how fast is the train moving?
  - v = d/t = 2x(10 m)/(1 s) = 20 m/s
- A wave has a wavelength of 10 m. If the frequency is 2 Hz, how fast is the wave traveling?
  - $v = \lambda f$ = (10 m)(2 Hz) = 20 m/s

Wave Speed

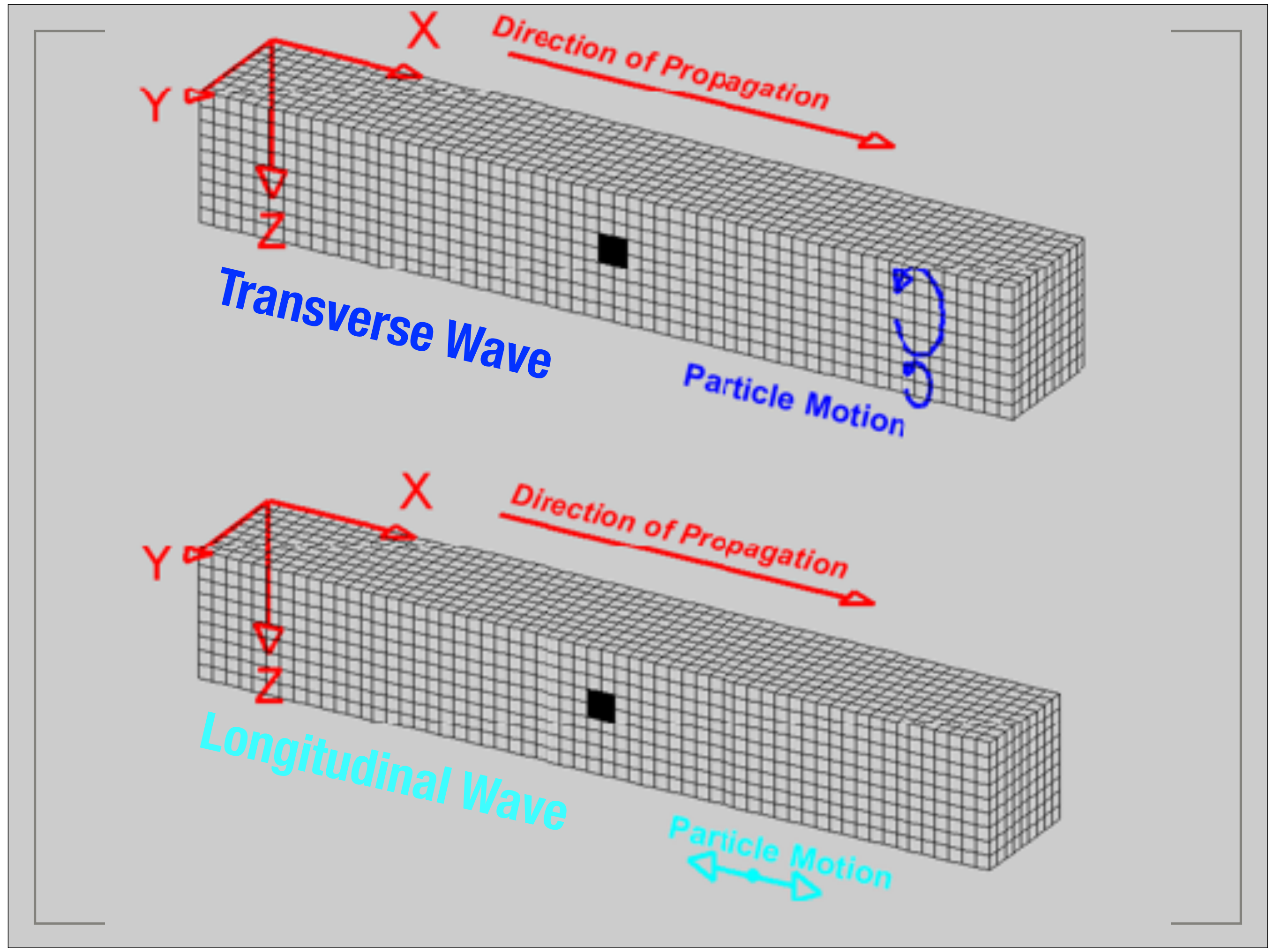
- **Speed of a light wave**
  - ***c* = 299,792 km/s (186,282 mi/s)**
- **Speed of sound (in dry air at 20º C)**
  - ***v* = 343.59 m/s (768.59 mph)**
  - **Speed of sound in a vacuum?**
    - ***v* = 0 m/s**

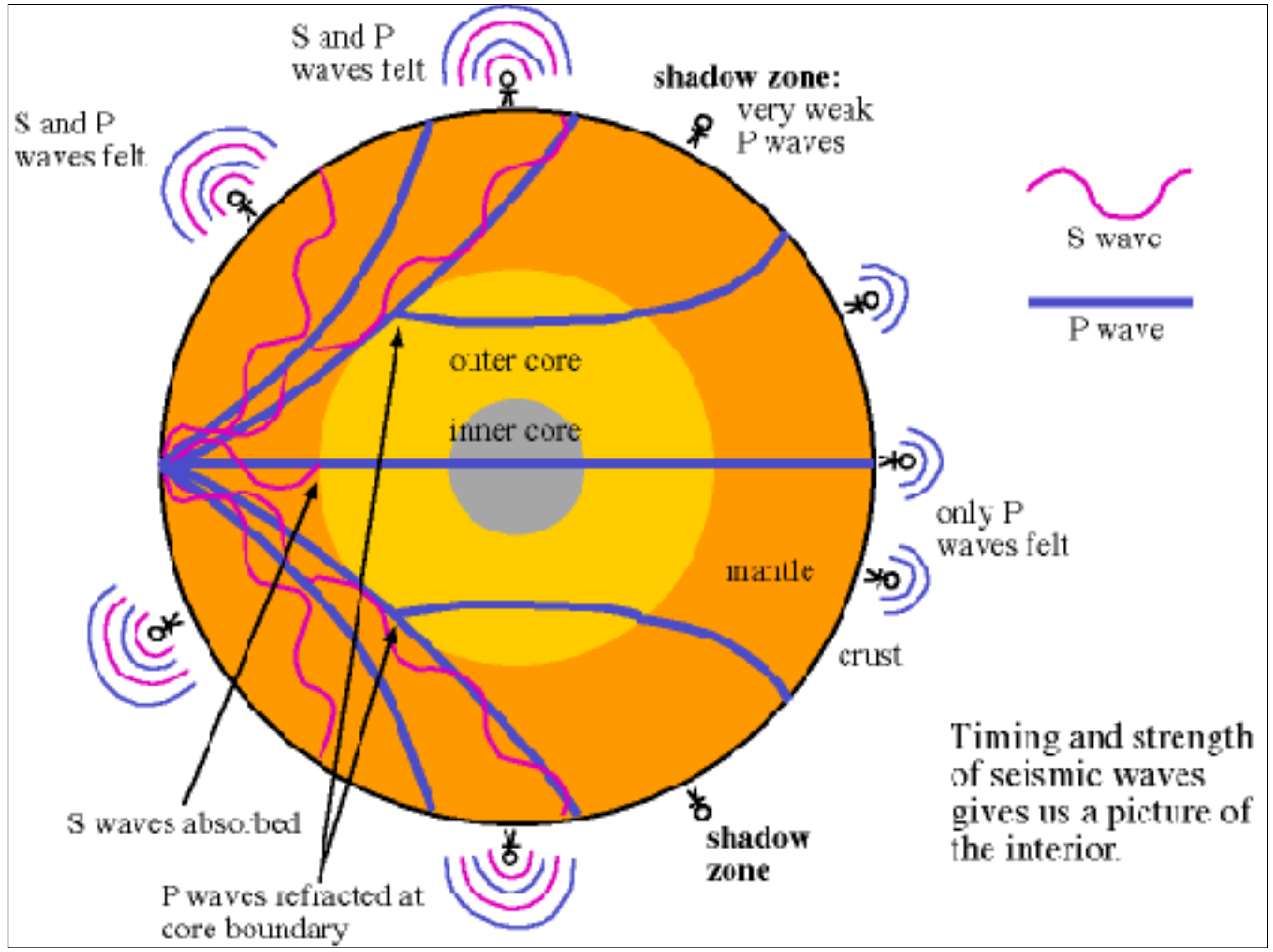
Types of Waves

- Transverse Waves
  - Motion of the medium is perpendicular to the direction in which the wave travels
  - Examples:
    - Ripples in the water
    - A whip
    - Light
    - Earthquake secondary waves

Types of Waves

- Longitudinal Waves
  - Motion of the medium is in the same direction as in which the wave travels
  - Also called *compression waves*
  - Examples:
    - Earthquake primary waves
    - Sound


X
Y
Z
Direction of Propagation
Transverse Wave
Particle Motion
X
Y
Z
Direction of Propagation
Longitudinal Wave
Particle Motion


S and P waves felt
S and P waves felt
shadow zone: very weak P waves
S wave
P wave
outer core
inner core
only P waves felt
mantle
crust
S waves absorbed
P waves refracted at core boundary
shadow zone
Timing and strength of seismic waves gives us a picture of the interior.

Practice I: Waves of Sound

- Sound travels at 343 m/s through dry air. What frequencies and wavelengths correspond to sound waves with the following periods?

a. 0.10 s

b. 5 s

c. 1/60 s

d. 24 hr

- Extra credit: Which of those sound waves could we hear?

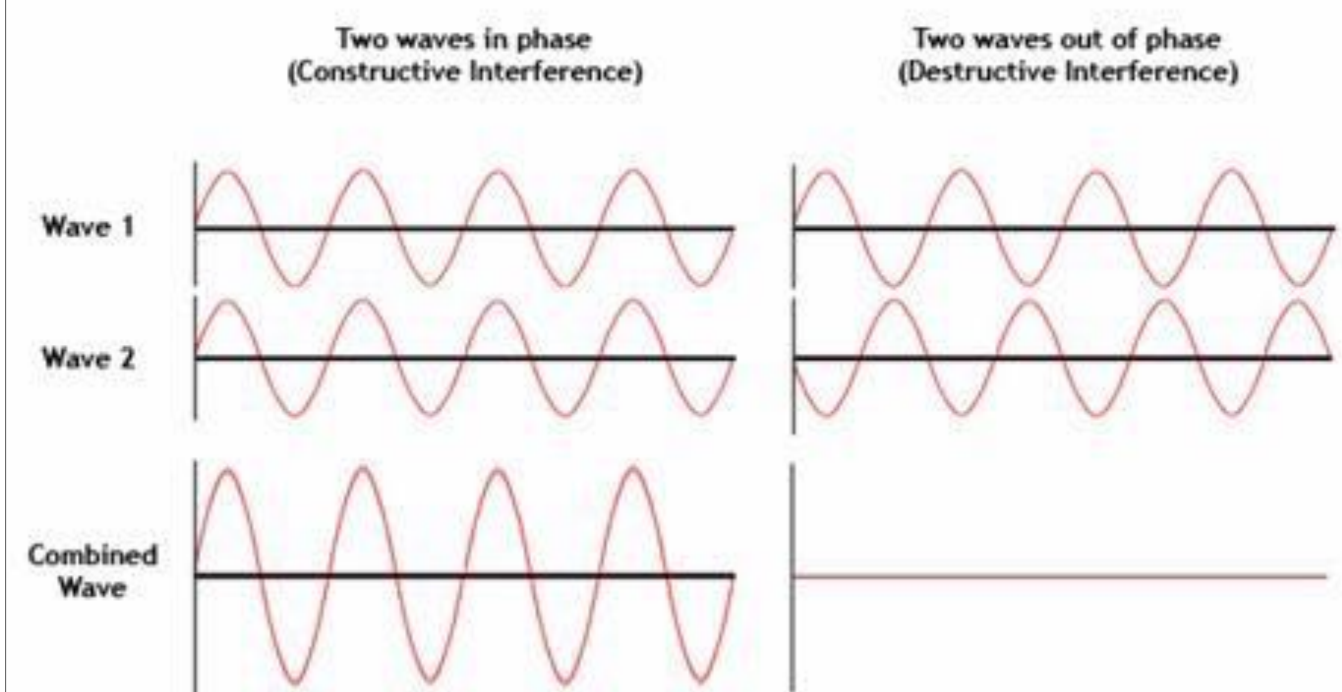
a. $f = 10$ Hz; $\lambda = 34.3$ m
b. $f = 0.2$ Hz; $\lambda = 1{,}715$ m
c. $f = 60$ Hz; $\lambda = 5.7$ m
d. $f = 1.16\times10^{-5}$ Hz; $\lambda = 30{,}000$ km

Interference

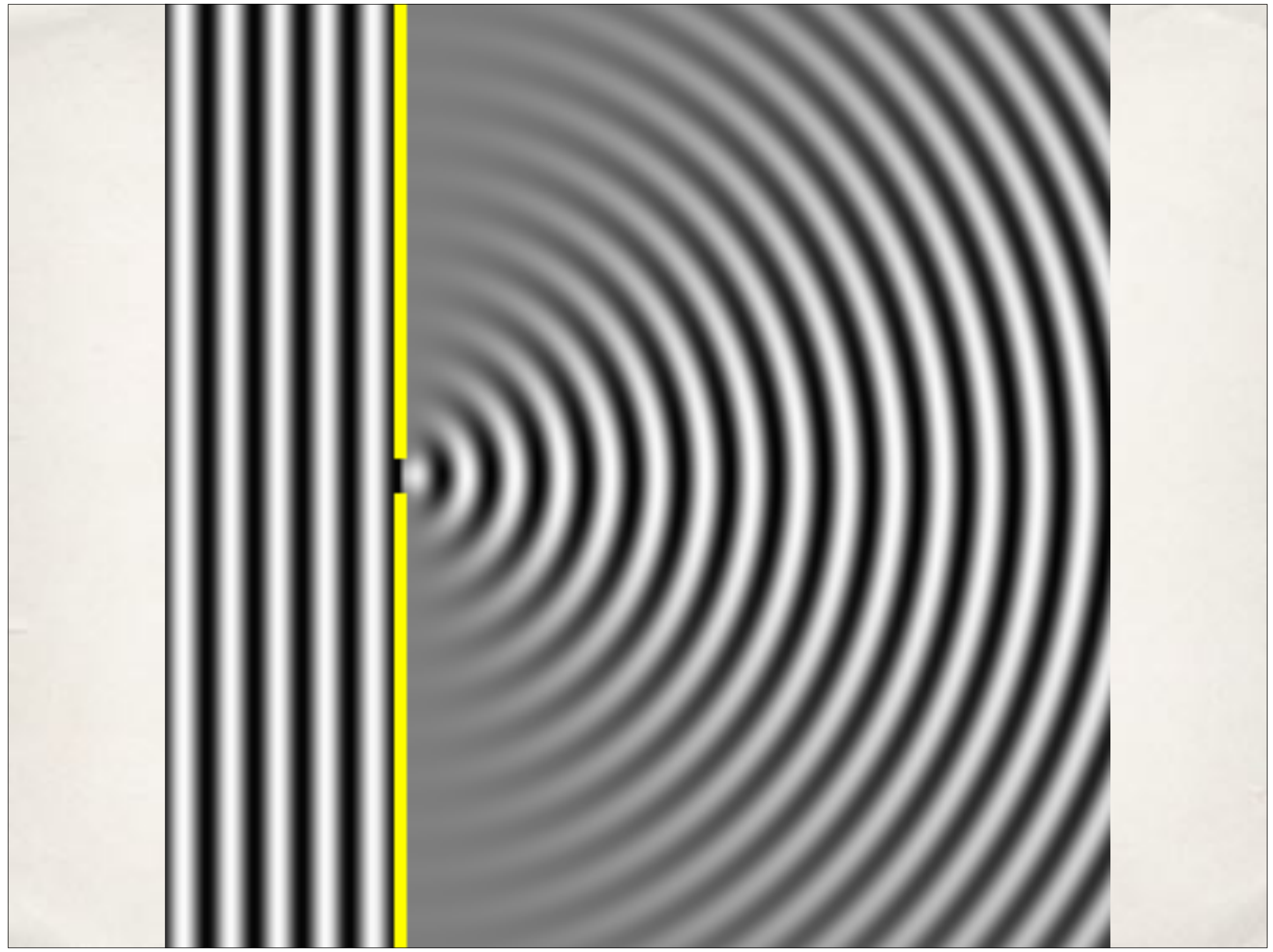
- Occurs when two of more waves meet
- Parts of the waves may overlap and form an *interference pattern*
    - Wave effects may be increased, decreased, or neutralized

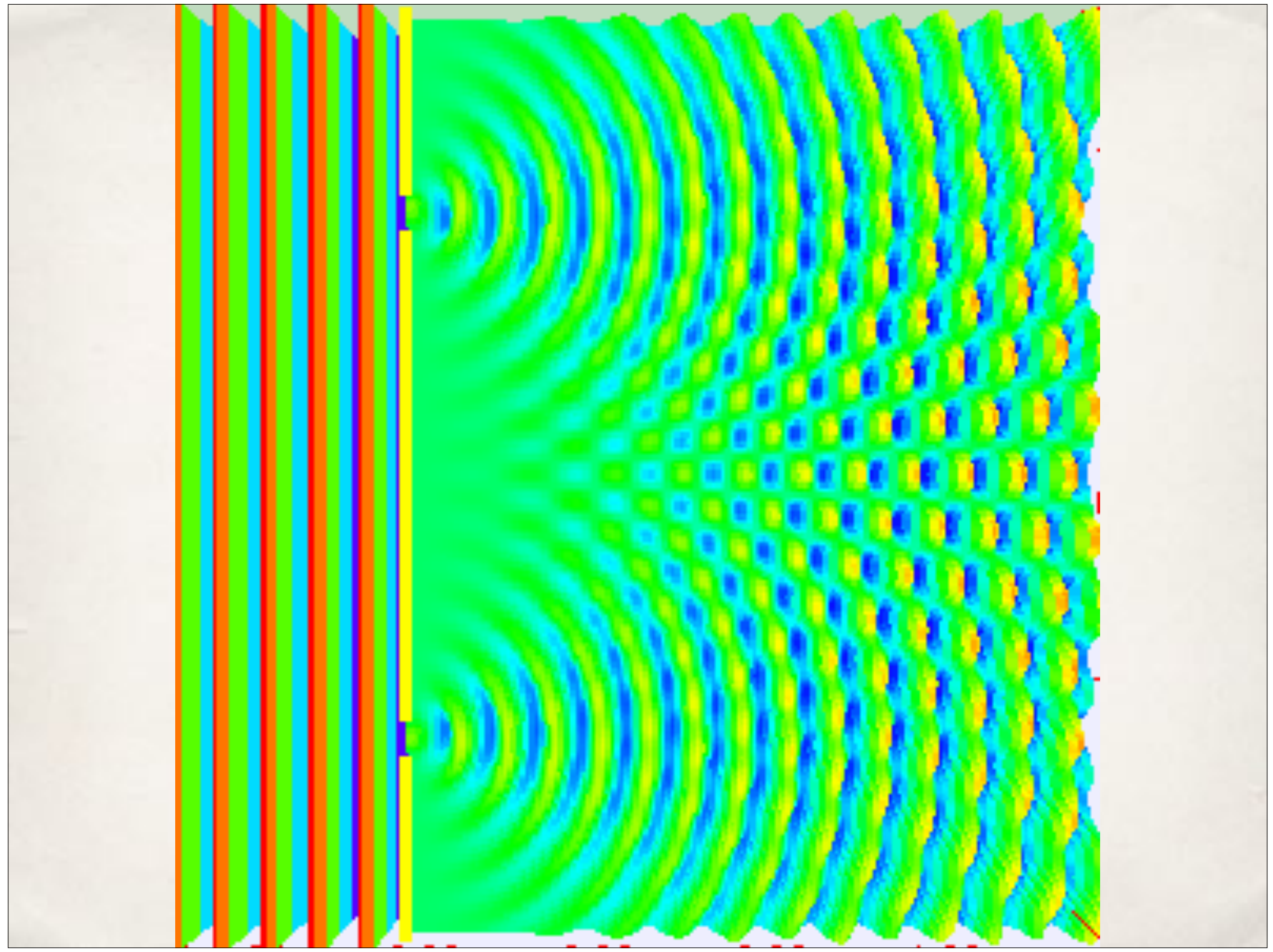
Interference

- When the crest of one wave overlaps with the crest of another, their individual effects add up
    - Called *constructive interference*
- When the crest of one wave meets the trough of another, their individual effects decrease
    - Called *destructive interference*
- Characteristic of *all* wave motion, whether water waves, sound waves, or light waves



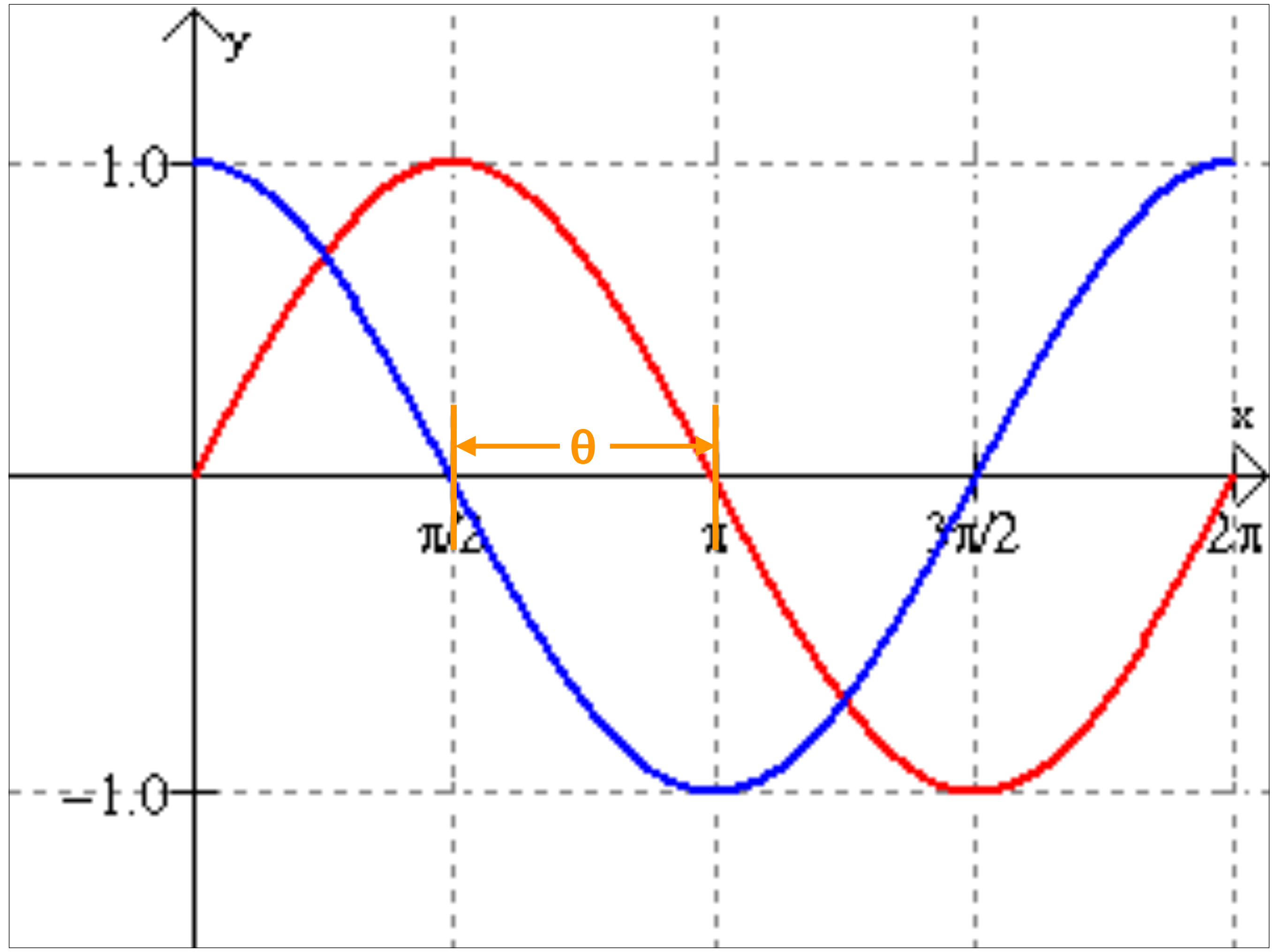
Two waves in phase
(Constructive Interference)
Two waves out of phase
(Destructive Interference)
Wave 1
Wave 2
Combined
Wave





Phase

- Phase is the relationship between the period of a wave and an external reference point
- Two waves which are *in phase* are in synch
- Two waves which are *out of phase* are out of synch

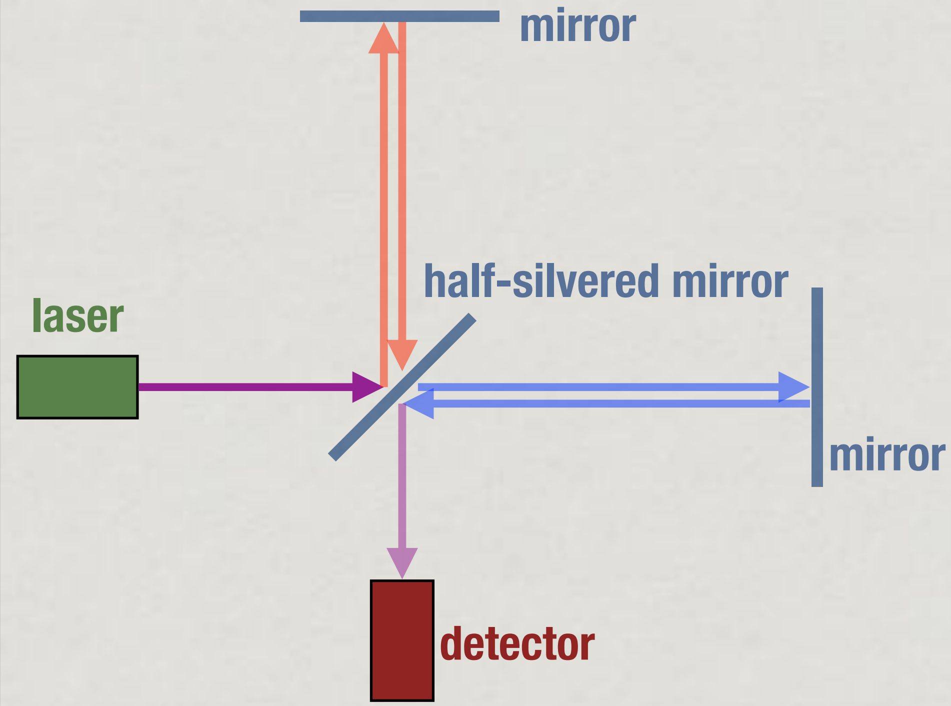


y
1.0
−1.0
θ
x
π/2
π
3π/2
2π

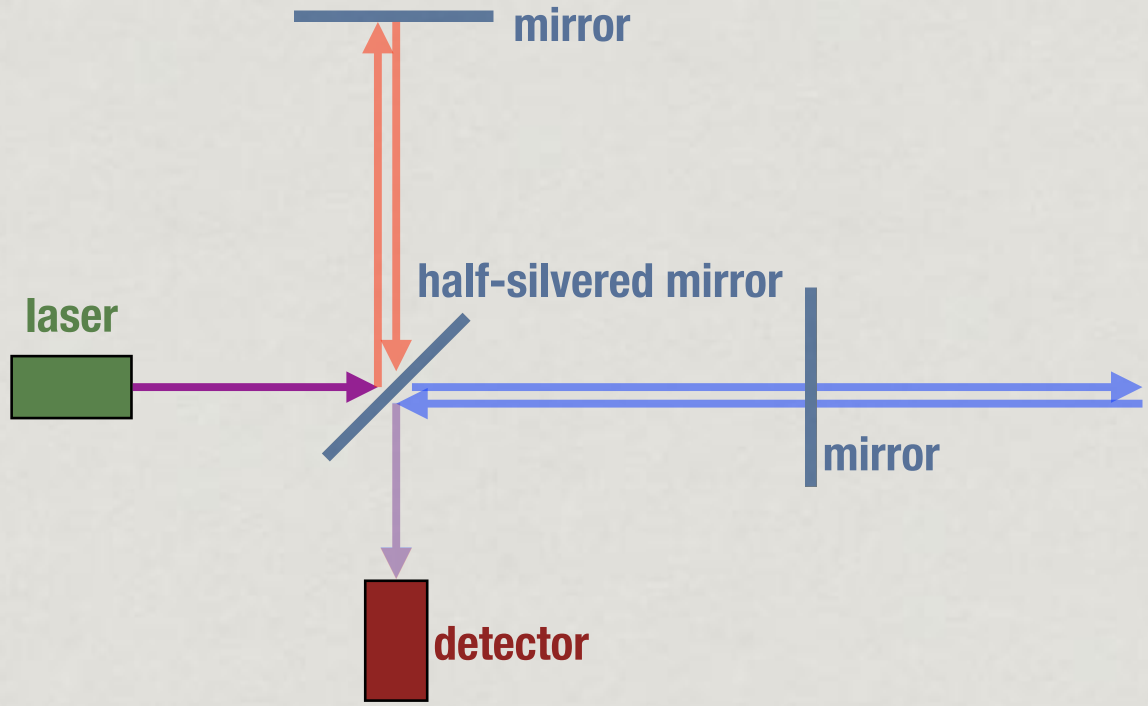
Interferometry

- A family of techniques in which you use wave interference patterns to extract information about the wave is called interferometry
    - Usually measures interference between light waves (especially from lasers)

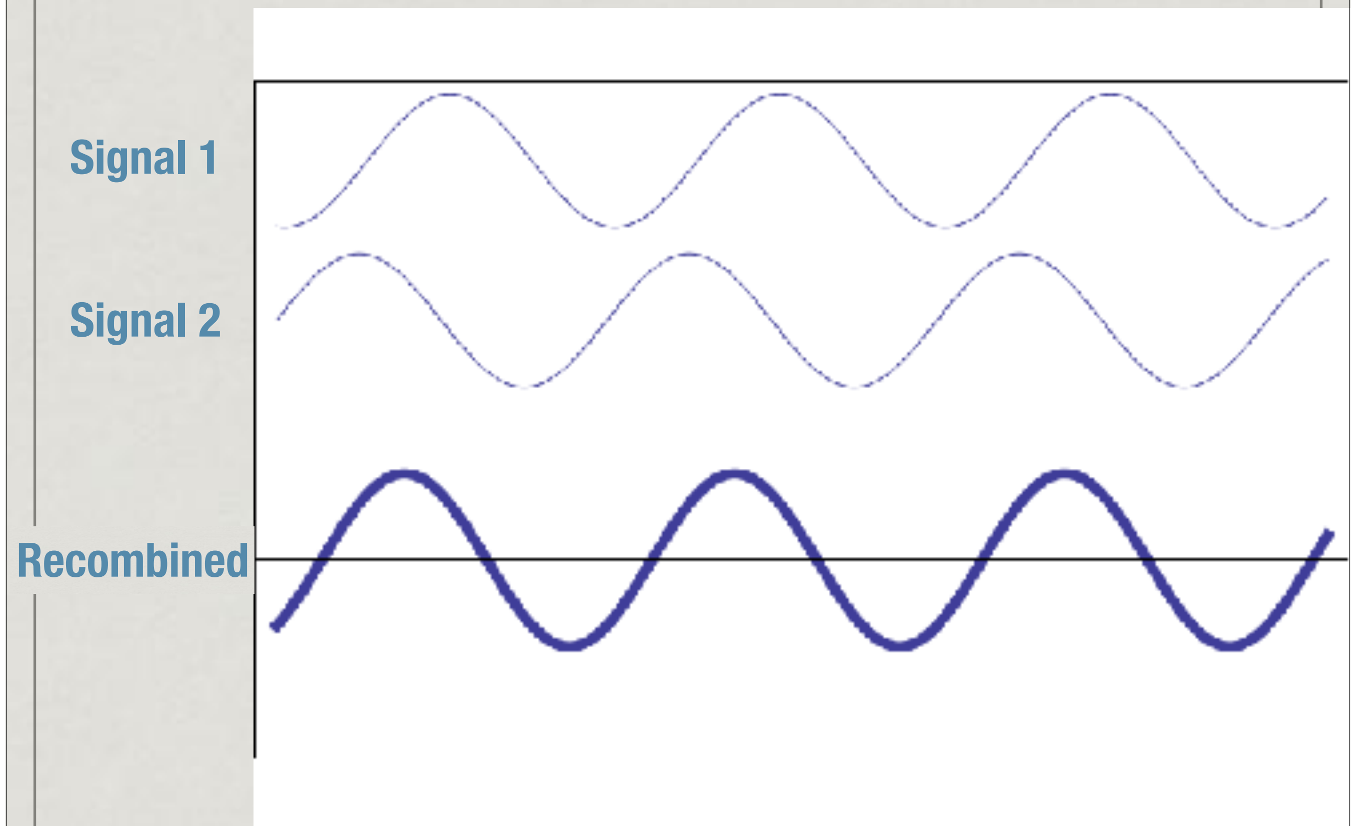
Interferometry

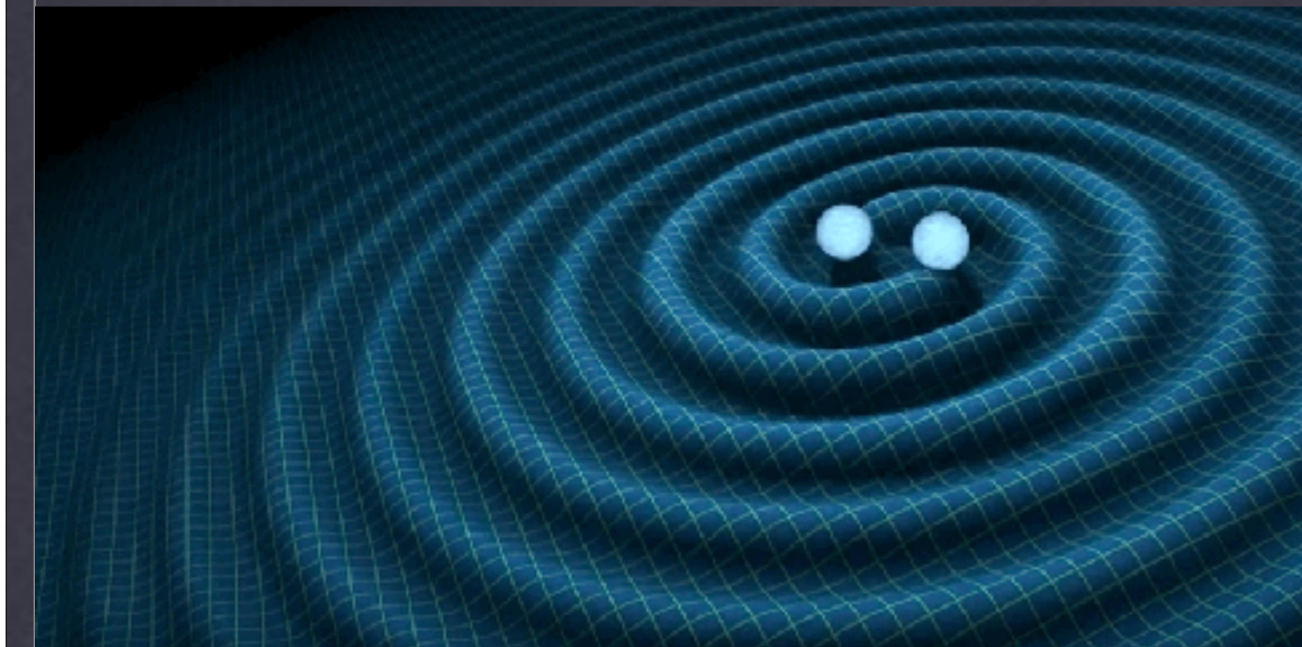


Interferometry



Interference





GRAVITATIONAL WAVES

FROM TWO ORBITING BLACK HOLES

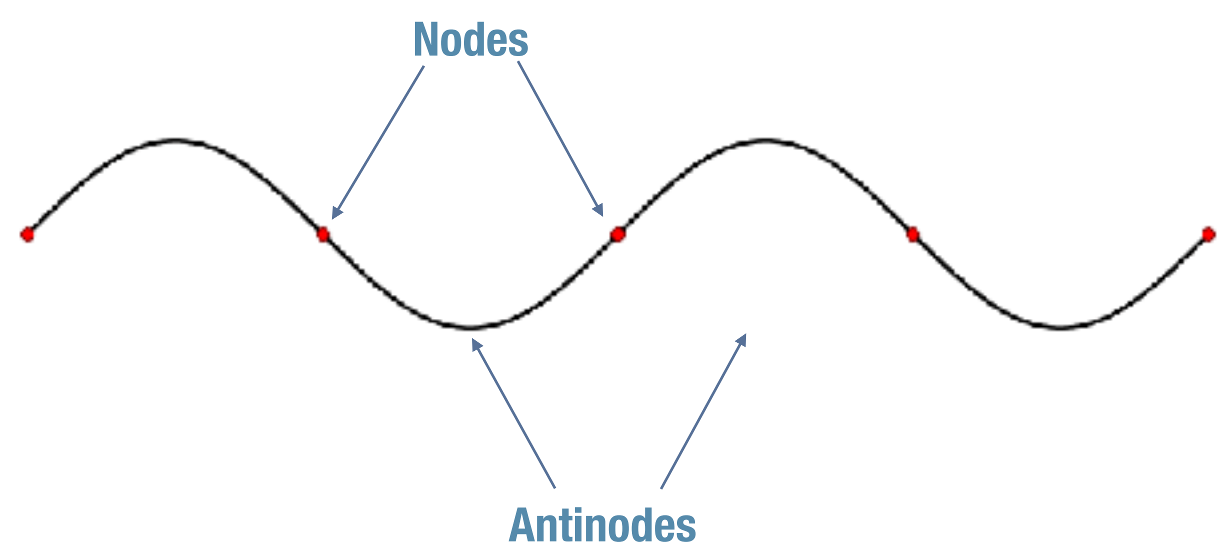
GRAVITATIONAL WAVES & INTERFEROMETRY

HTTPS://WWW.YOUTUBE.COM/WATCH?V=HRDUBZ319XI

Standing Waves

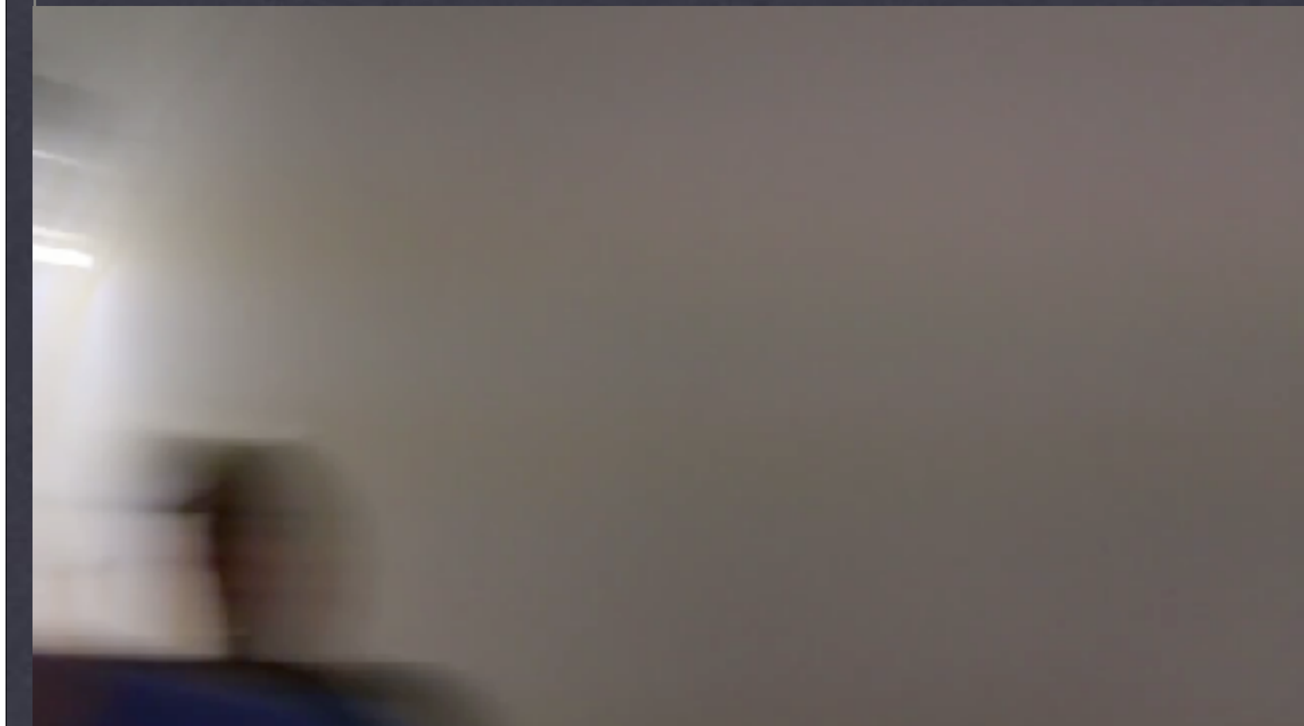
- Also known as a *stationary wave*
- A standing wave is one where particular points on the wave are "fixed," or stationary
  - Fixed points on a standing wave are called *nodes*
  - Positions on a standing wave with the largest amplitudes are called *antinodes*
    - Antinodes occur halfway between nodes

Standing Waves



Standing Waves

- Standing waves are the result of interference
  - Two waves of equal amplitude and wavelength pass through each other in opposite directions
  - Waves are always out of phase at the nodes
  - Nodes are are stable regions of destructive interference



ACOUSTIC LEVITATION

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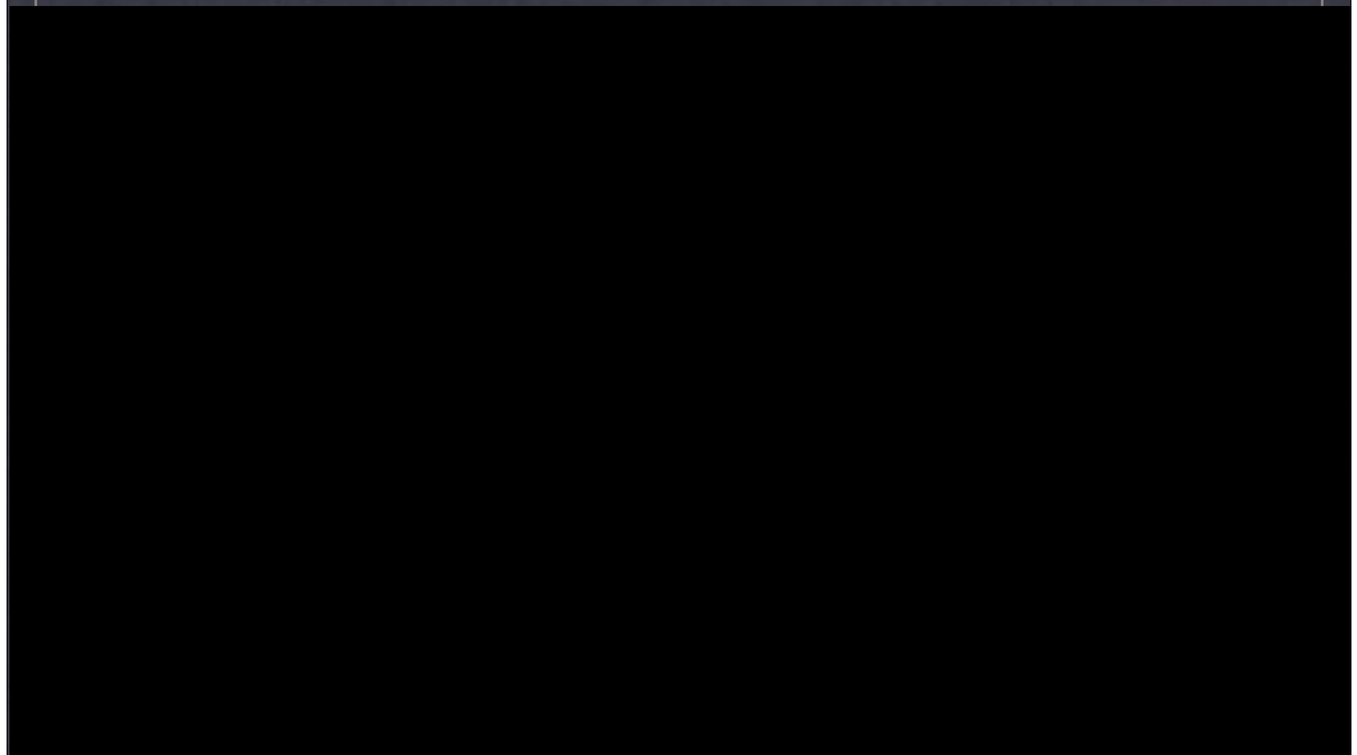


2D STANDING WAVES

HTTPS://WWW.YOUTUBE.COM/WATCH?V=WVJAGRUBF4W

Electron Orbitals

- Electrons move around the nucleus in orbital shells. But why do the shells have electron-holding capacities of 2, 8, 18, 32…. specifically?
- Electrons are both particles *and waves*
- Electrons bound to the nucleus are 3 dimensional standing waves!

Sound

"Each celestial body, in fact each and every atom, produces a particular sound on account of its movement, its rhythm or vibration. All these sounds and vibrations form a universal harmony in which each element, while having it's own function and character, contributes to the whole."

Pythagoras (569-475 BC)

Origin of Sound

- Produced by vibrations
  - Those vibrations compress and decompress the air (or other medium) around the vibrating object
  - The compressed areas are areas of higher pressure
    - *Compressions*
  - Decompressed areas have lower pressure
    - *Rarefactions*
- The frequency of the vibrating source almost always equals the frequency of the sound waves

Frequency of Sound

- *Pitch* is our brain's interpretation of frequency
  - High frequency → high pitch
  - Low frequency → low pitch
- Average young person can hear pitches from around 20 to 20,
  000 Hz
- Sound frequencies below 20 Hz are called *infrasonic*
- Sound frequencies above 20,000 Hz are called *ultrasonic*

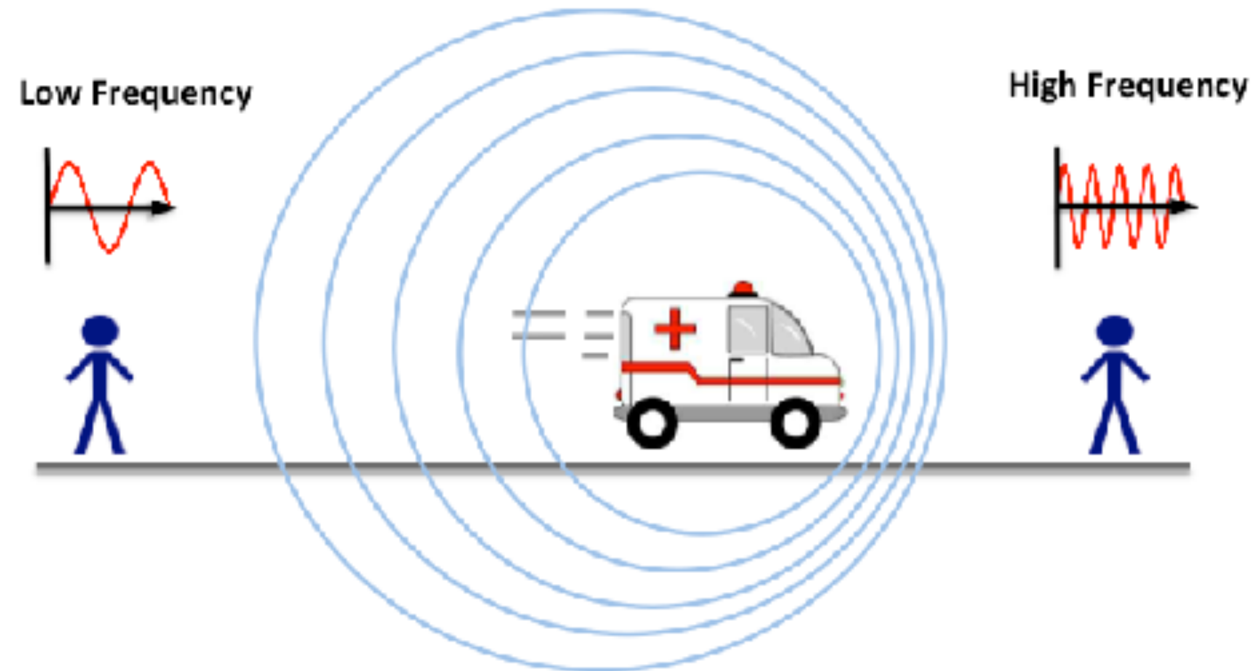
The Doppler Effect

https://www.youtube.com/watch?v=h4OnBYrbCjY

The Doppler Effect

- The Doppler Effect is the apparent change in *frequency* due to the motion of the source (or receiver)
  - The pitch sounds higher when the source is moving toward you
  - and lower when it's moving away

Doppler Effect



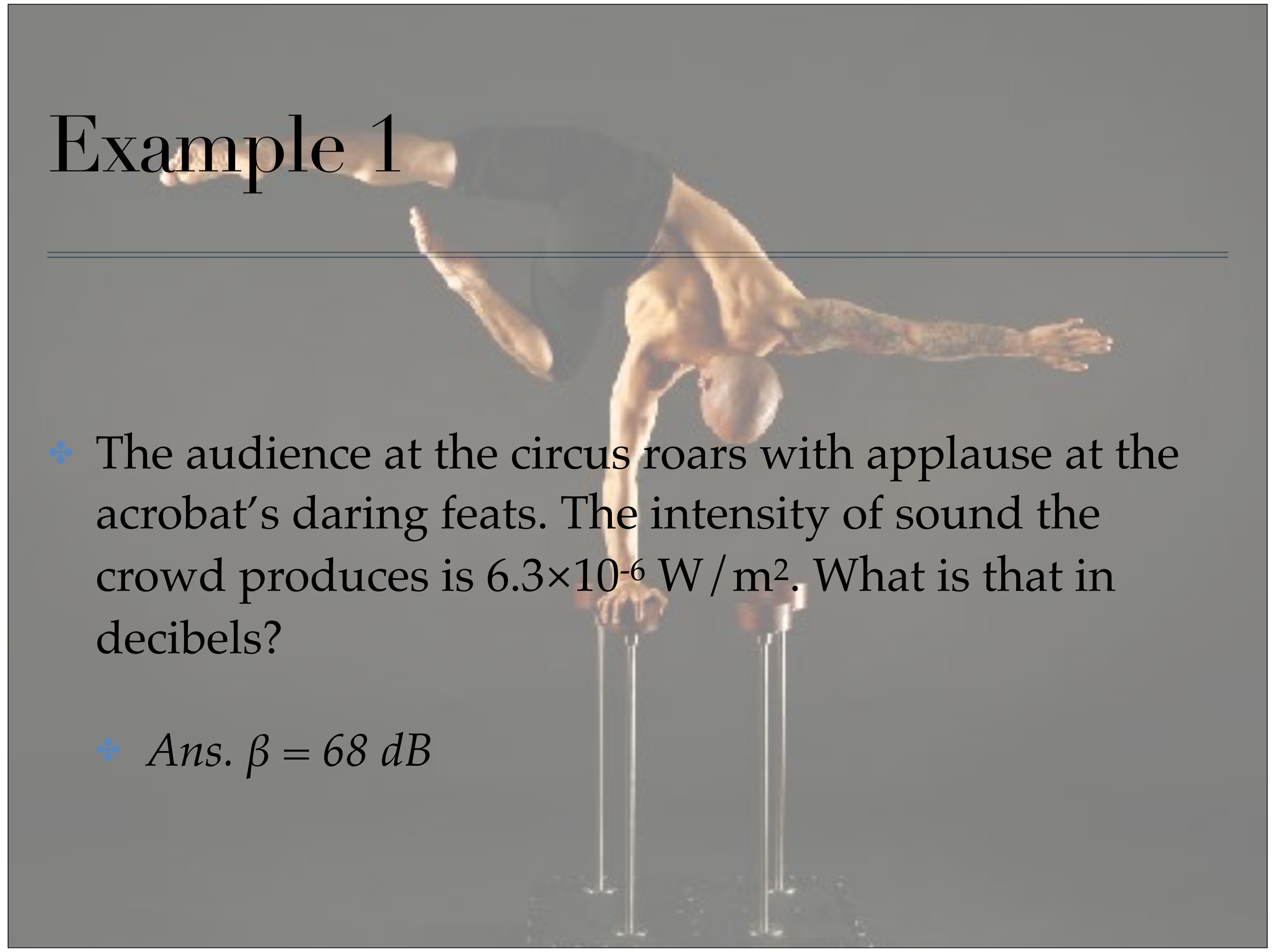
Sanity Check

- When a source moves toward you, do you measure an increase or decrease in wave speed?
- Neither! It is the *frequency* of a wave that undergoes a change where there is motion of the source, not the *wave speed*

Loudness

- Loudness is the brain's interpretation of sound *intensity*
  - Intensity = power / area
  - $I \propto A^2$
- $\beta = 10 \log(I_1 / I_0)$
  - $I_0 = 10^{-12}$ W / m^2
  - Threshold of hearing
- Measure loudness in decibels (dB)

Example 1



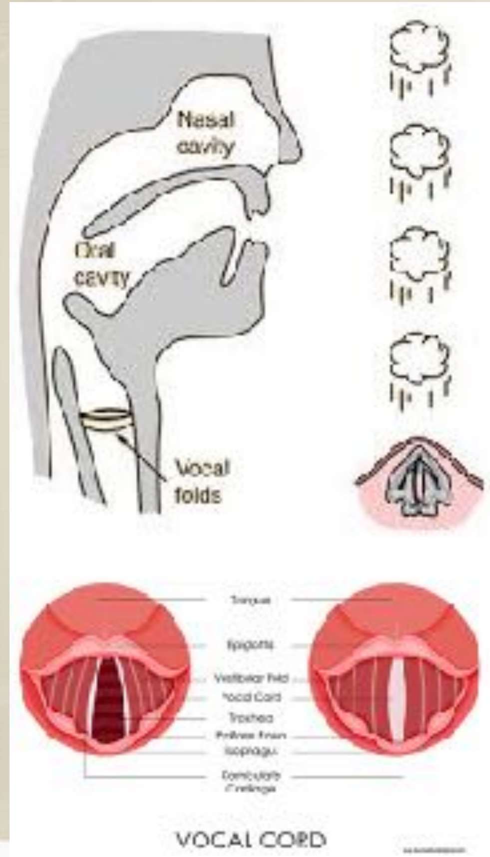
- The audience at the circus roars with applause at the acrobat's daring feats. The intensity of sound the crowd produces is 6.3×10^{-6} W/m^2. What is that in decibels?
    - *Ans.* $\beta = 68$ *dB*

Source of Sound	Decibel Level (dB)
Jet engine, at 30 m	140
Threshold of pain	120
Loud rock music	115
Old subway train	100
Average factory	90
Busy street traffic	70
Normal speech	60
Library	40
Close whisper	20
Normal Breathing	10
Hearing threshold	0

Loudness

- Loudness is logarithmic
  - For each increase in 10 dB, the intensity increases by a factor of 10
  - i.e. 10 dB is 10 times as intense as 0 dB and a tenth as intense as 20 dB
- Roughly speaking, the sensation of loudness follows the decibel scale
  - Thus, we say human hearing is approximately logarithmic

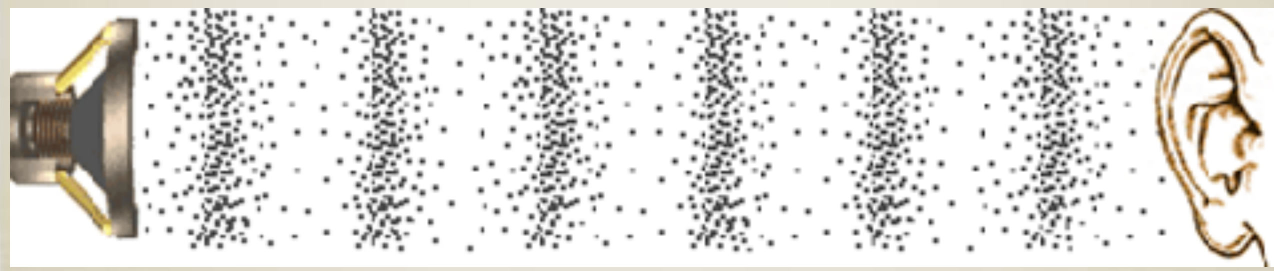
Transmission of Sound Waves



1. Vibration of the source

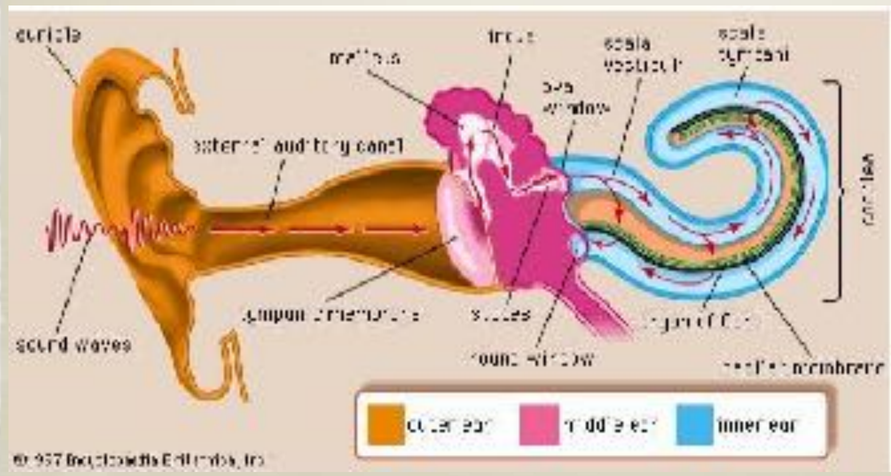
Transmission of Sound Waves

1. Vibration of the source
2. Compression waves thru the media



Transmission of Sound Waves

1. Vibration of the source
2. Compression waves thru the media
3. Vibration of our eardrums



Transmission of Sound Waves

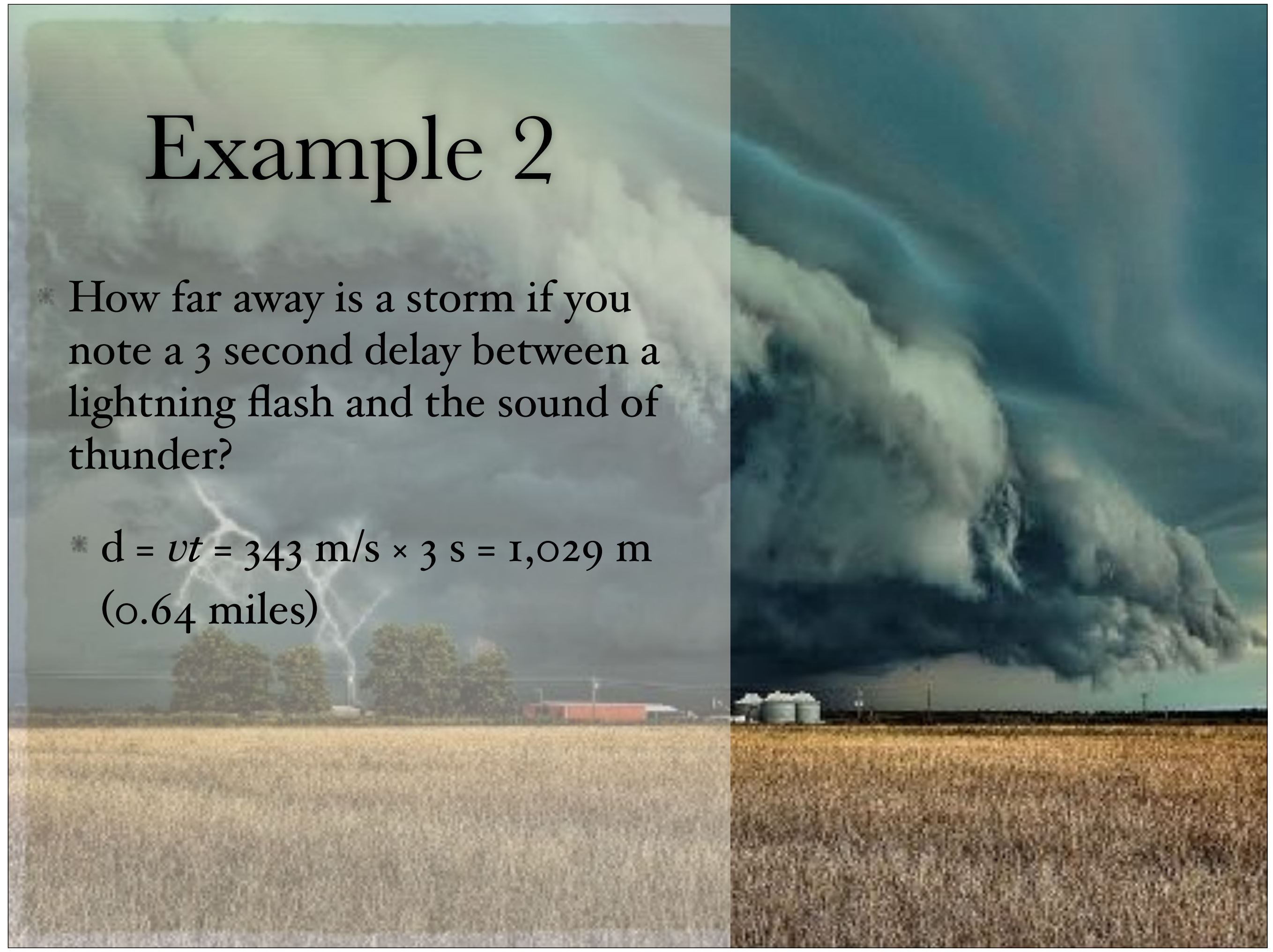
1. Vibration of the source
2. Compression waves thru the media
3. Vibration of our eardrums
4. Electrical pulses to the brain

Transmission of Sound Waves

- Sound needs a medium through which to travel
  - CANNOT travel through a vacuum
- The speed of sound is dependent on the *elasticity* of the medium
  - Elasticity is a measure of a material's propensity to retain its shape
  - Elasticity of: solids > liquids > gasses
  - Speed of sound: solids > liquids > gasses

Speed of Sound

- In air (dry; 20ºC):
  - $v \approx 343$ m/s (767 mph)
- In water (fresh; 20ºC):
  - $v \approx 1{,}482$ m/s (3,315 mph)
- In steel:
  - $v \approx 5{,}960$ m/s (13,330 mph)
- In addition to faster, also clearer and louder


Example 2
How far away is a storm if you note a 3 second delay between a lightning flash and the sound of thunder?
d = vt = 343 m/s × 3 s = 1,029 m (0.64 miles)

Speed of Sound

- Why does higher elasticity mean a faster sound wave?
- Answer: Energy!
  - Sound waves move through oscillations that push and pull the material
  - Materials with high elasticity have greater internal energy to retain their shape
  - When the wave pushes the material, the material pulls *itself* back
  - This leaves more energy for the wave to put towards its kinetic motion

The Science of Music

"Music is the movement of sound to reach the soul for the education of its virtue."

– Plato

Forced Vibrations

- When vibrations in one medium cause, or *force*, vibrations in another medium
- Virtually unavoidable, but much more interesting when used in clever ways
  - Such as by utilizing the *natural frequency* of the vibrating medium

Natural Frequency

- Frequency at which minimum energy is required to produce and sustain forced vibrations
- Depends on the elasticity and shape of the vibrating object

Resonance

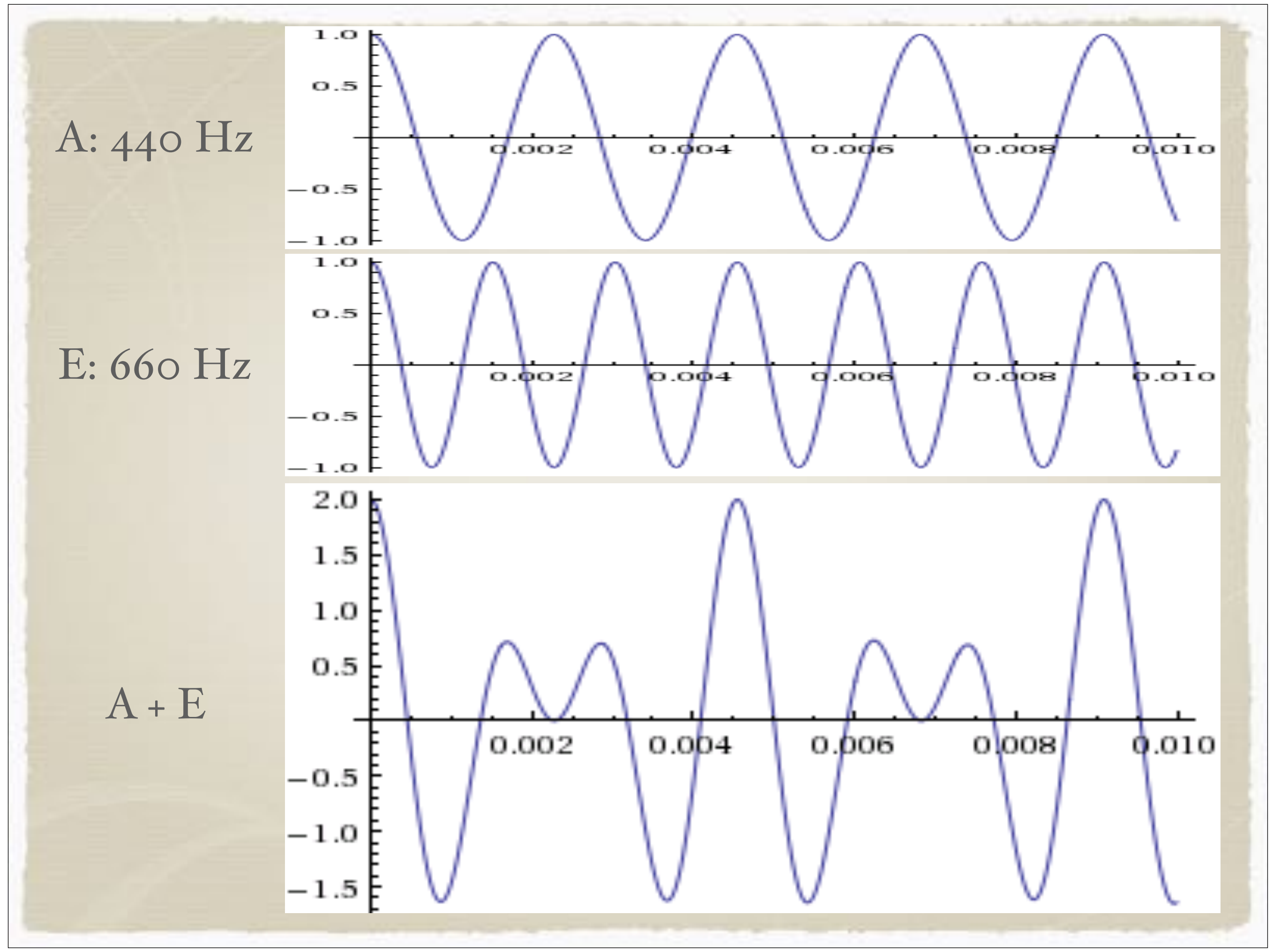
- When the frequency of a forced vibration on an object matches the object's natural frequency, a dramatic increase in amplitude occurs
  - This phenomenon is called *resonance*
- Only occurs in elastic materials
  - Need a strong enough restoring force to pull the material back to its starting position
  - And enough energy to keep the object vibrating
- Ex. Swing

Tacoma Narrows Bridge

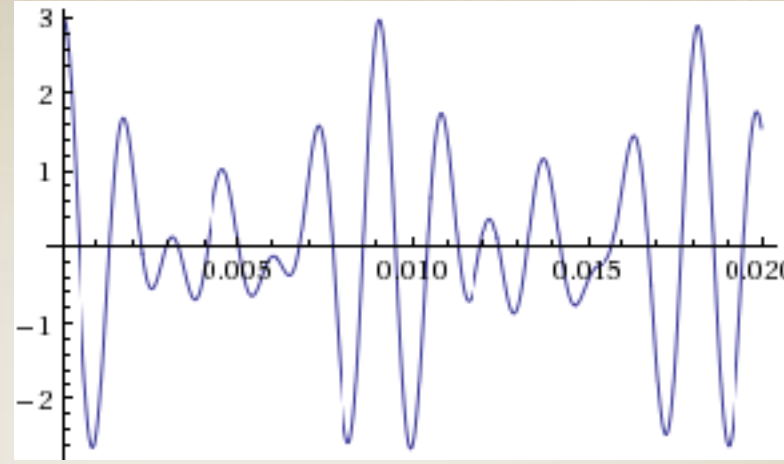
https://www.youtube.com/watch?v=j-zczJXSxnw

Interference

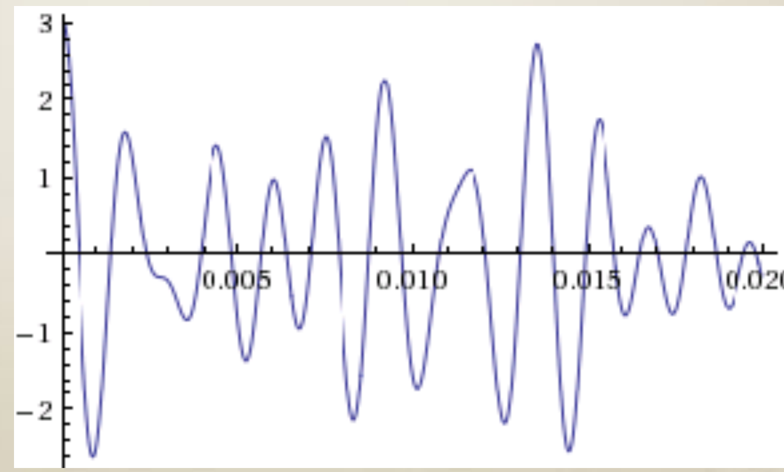
- Same rules for constructive and destructive interference apply
- What about interference between waves with different frequencies?


A: 440 Hz
E: 660 Hz
A + E
1.0
0.5
−0.5
−1.0
2.0
1.5
−1.5
0.002
0.004
0.006
0.008
0.010

A Major

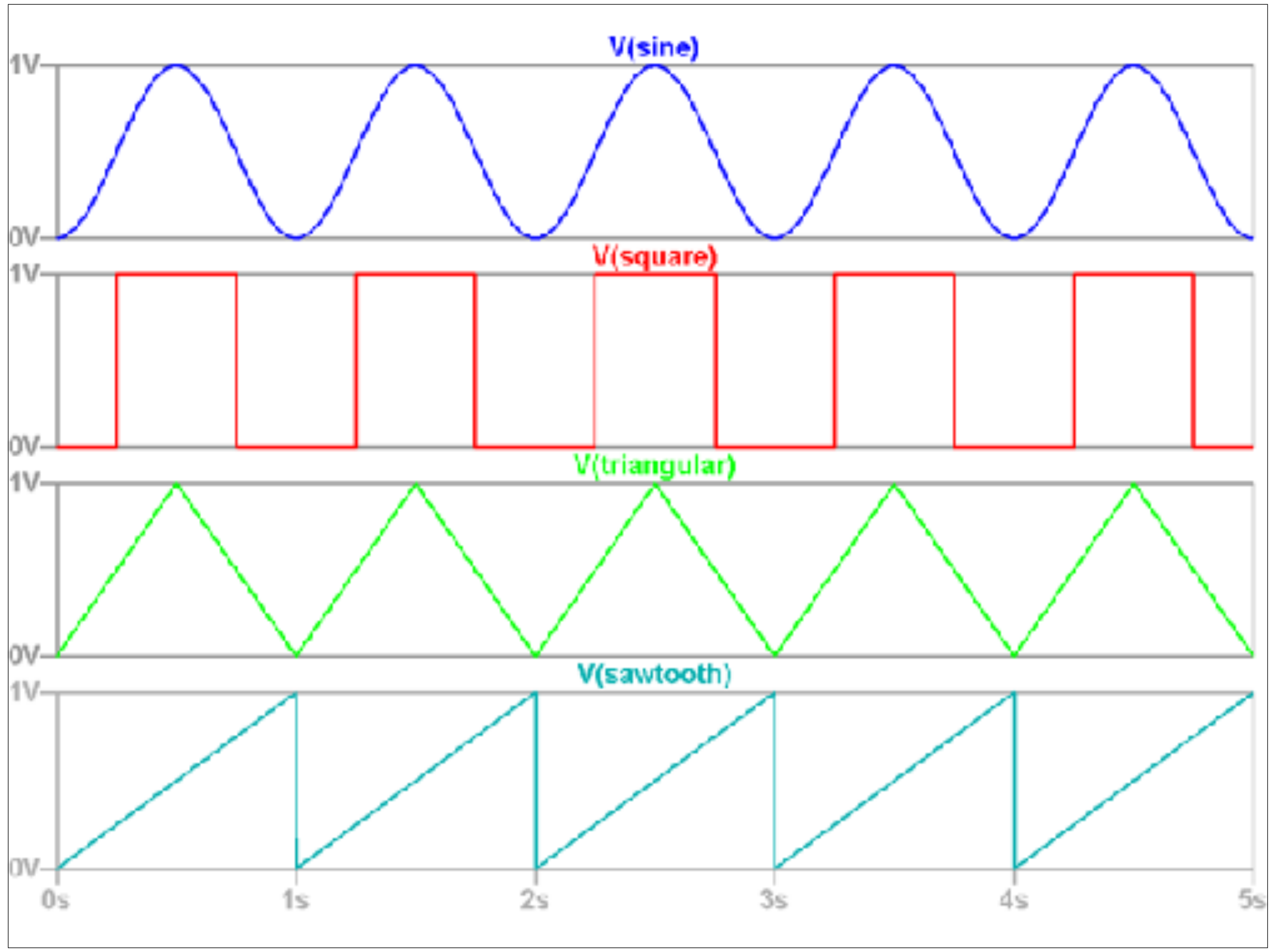


A Minor



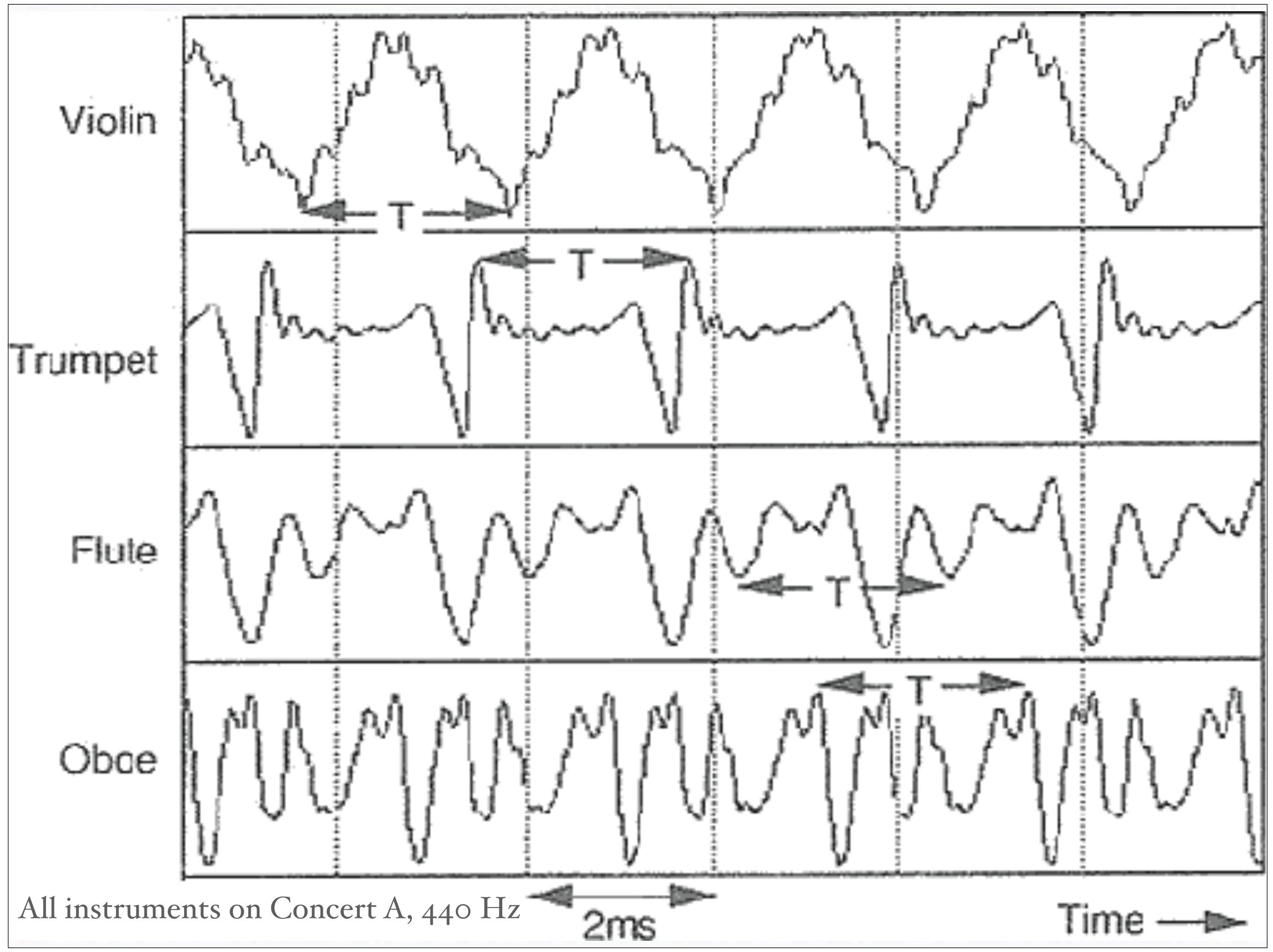
Timbre

- The character or quality of a musical sound or voice as distinct from its pitch and intensity
  - Also known as the tone quality or tone color
  - Bright vs Dark; Harsh vs Round
  - Biological interpretation of *wave form*



Online wave generator: http://onlinetonegenerator.com/

- Test different wave forms for the same pitch. Hear the difference?



All instruments on Concert A, 440 Hz

Harmonic Series

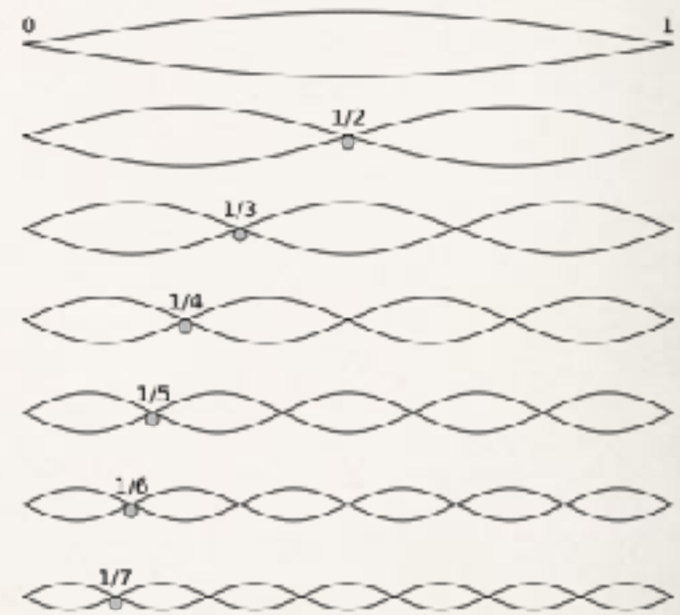
- The sequence off all multiples of a base frequency
  - E.g. base frequency, 1st harmonic: 110 Hz
  - 2nd harmonic: 220 Hz
  - 3rd harmonic: 330 Hz

Online wave generator: http://onlinetonegenerator.com/

- What’s the harmonic series sound like? Open up 8 tabs to play the first 8 harmonics simultaneously

Harmonic Series

- Pitched musical instruments are built to resonate at several frequencies simultaneously
- All you need are standing waves where the end points are nodes



iPhone inside acoustic guitar oscillations - rtists
https://www.youtube.com/watch?v=lNqfM1kdfUc

Question 1

- The highest key on a piano corresponds to a frequency about 150 times that of the lowest key. If the string for the highest note is 5.0 cm long, how long would the string for the lowest note have to be if it had the same mass per unit length and was under the same tension?

Answer 1

- The velocity would be the same on each string, so the frequency is inversely proportional to the length L of the string ($f = v/\lambda = v/2L$). Thus
- $L_L/L_H = f_H/f_L$
- $L_L = L_H(f_H/f_L) = (5.0 \text{ cm})(150) = 750 \text{ cm}$, or 7.5 m

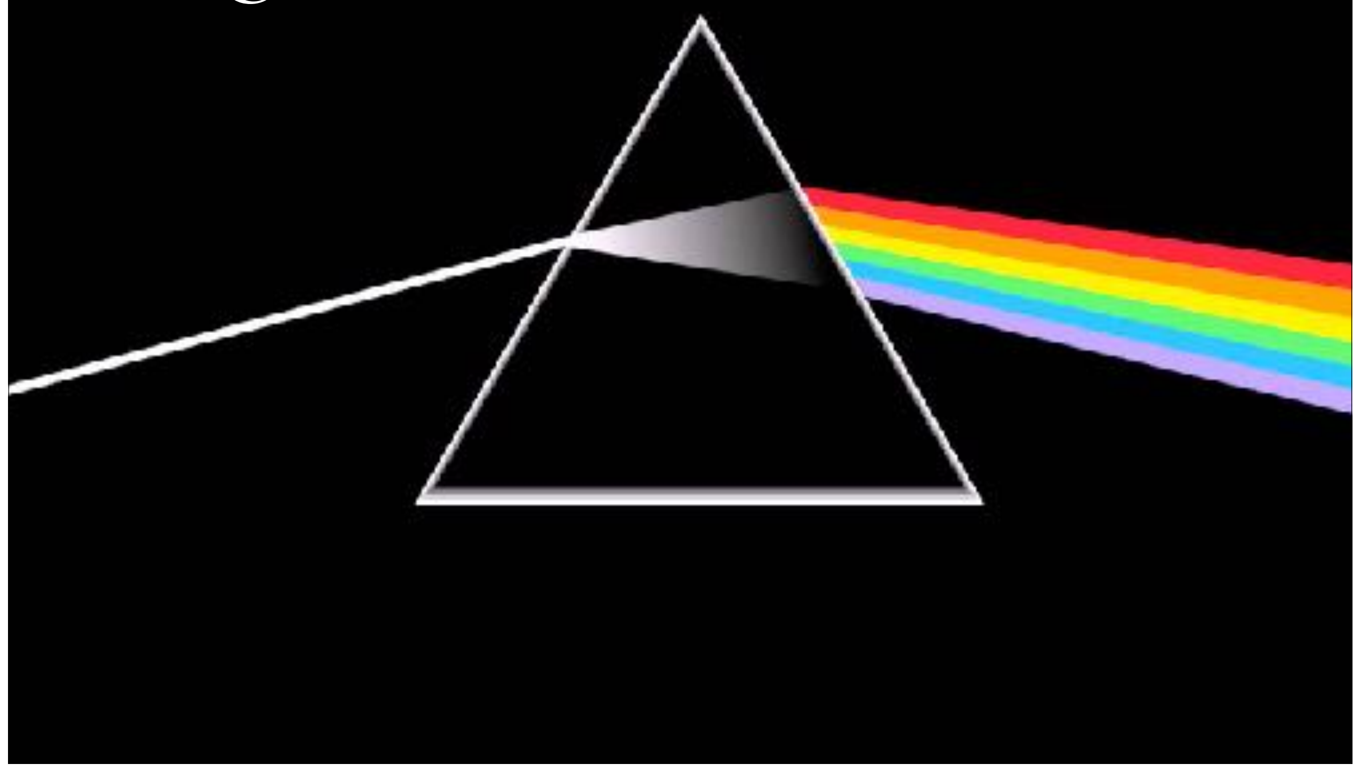
Question 2

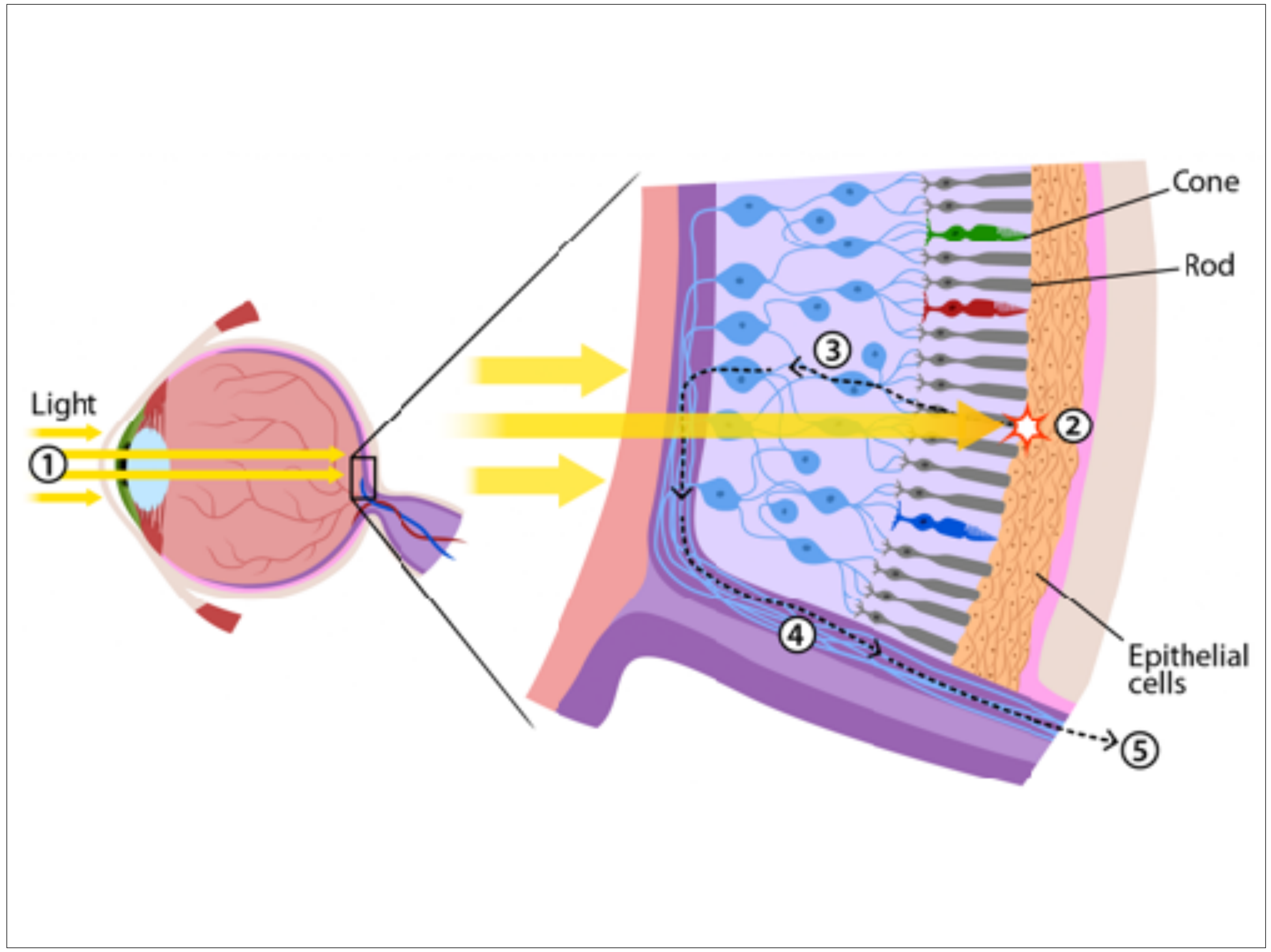
- A 0.32-m-long violin string is tuned to play A above middle C at 440 Hz.
- What is the wavelength of the fundamental string vibration?
- What is the frequency and wavelength of the sound wave produced?

Answer 2

- The wavelength of the fundamental is the wavelength of the standing wave on the string
  - $\lambda = 2L = 0.64$ m, or 64 cm
- The sound wave that travels outward in the air has the *same* frequency, 440 Hz. Its wavelength is
  - $\lambda = v/f = (343 \text{ m/s})/(440 \text{ Hz}) = 0.78$ m, or 78 cm
- Why is there a difference?

Light





1. Light moves through the lens of the eye to the back of the eye, which is the retina. Here, there are millions of rods and cones.
2. When light hits the discs in the outer segment of the rods and cones, the little bits of light (photons) activate the cells. Rods can be activated in low light, but cones require much brighter light (many more photons).
3. When the signal reaches the inner end (left side) of the rods and cones, the signal is passed to sets of neural cells.
4. The signal moves through neural cells in the optic nerve.
5. The optic nerve will send this information to the brain, where separate signals can be processed so you see them as a complete image.

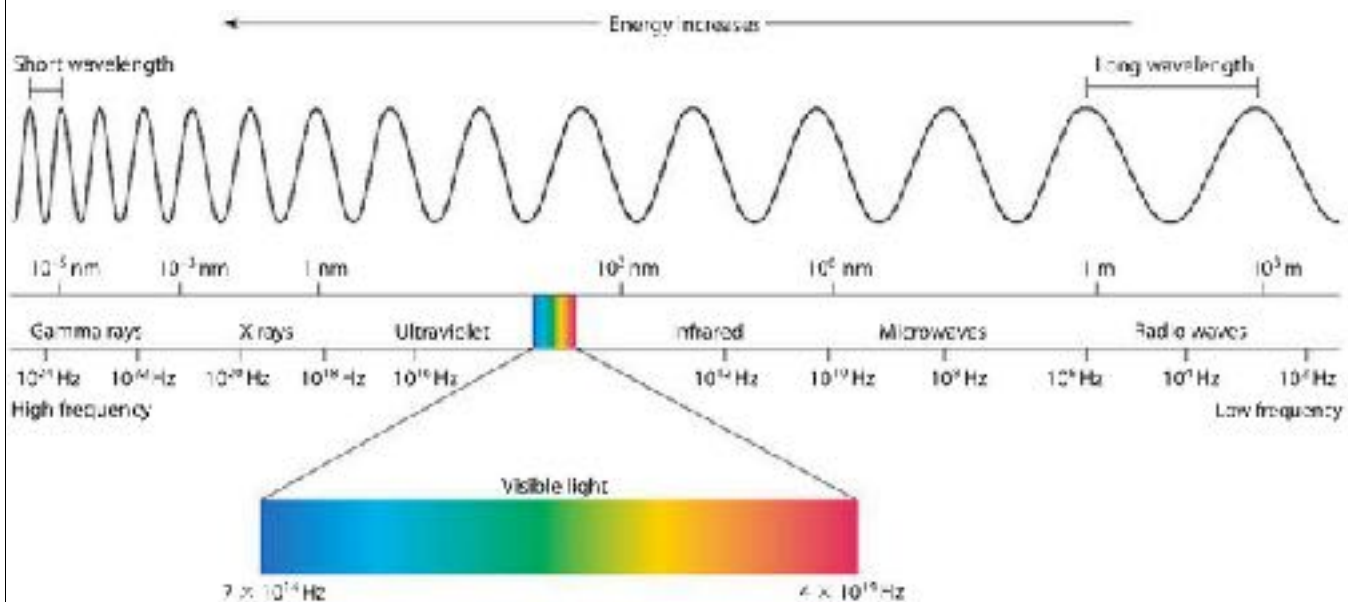
Origin of Light

- Light is energy emitted by vibrating electric charges
  - This energy travels as an electromagnetic wave
- Electromagnetic waves include radio waves, microwaves, X-rays, and others, in addition to the light we can see

Frequency of Light

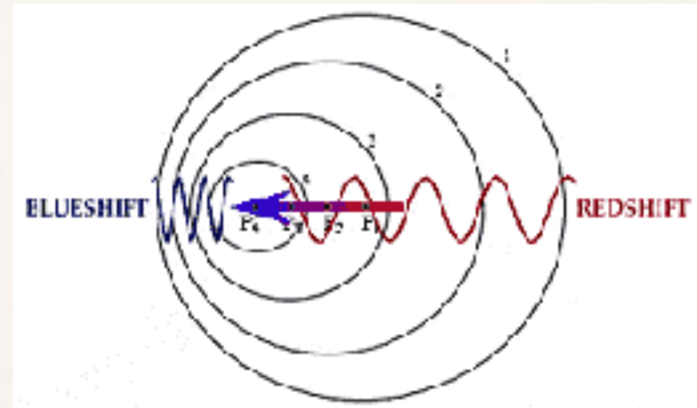
- ***Color*** is our brain's interpretation of the frequency of light
  - Low frequency → "redder" light
  - High frequency → "bluer" light
- The typical human eye will respond to frequencies ranging from 430 THz to 770 THz
- Light frequencies below 430 THz are called ***infrared***
- Light frequencies above 770 THz are called ***ultraviolet***

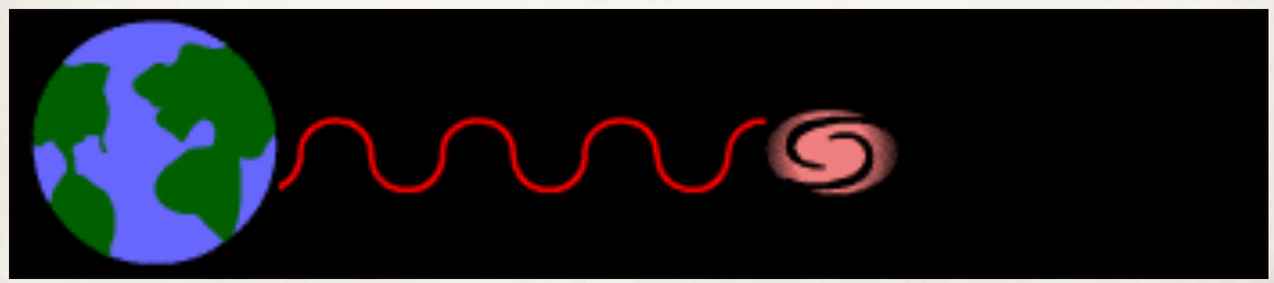
Electromagnetic Spectrum



- Heat lamps give off infrared waves, ultraviolet waves are responsible for sunburns
- That said, the descriptive names of different sections on the spectrum are merely for convenience — all the waves are the same in nature, differing principally in frequency and wavelength (all have the same speed)

Doppler Shift for Light





Same thing happens to light that happens to sound when the source moves

Sanity Check

Is it correct to say that a radio wave is a low-frequency light wave? Is a radio wave also a sound wave?

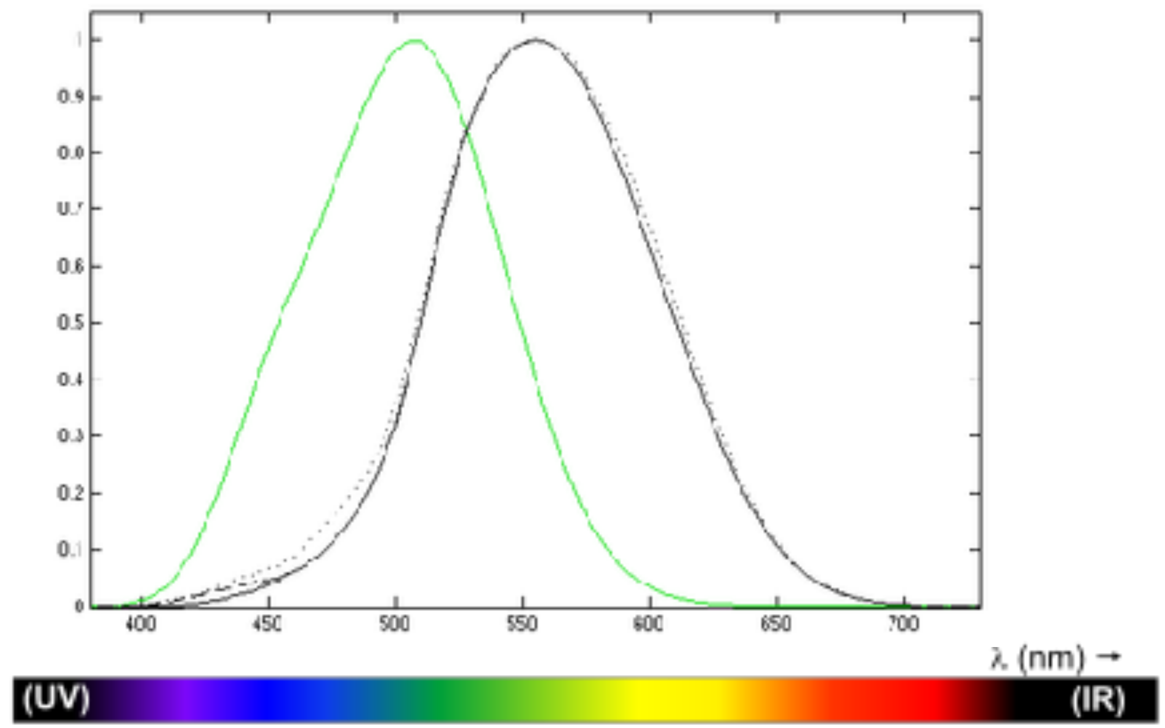
Both a radio wave and a light wave are electromagnetic waves originating from the vibrations of electrons. Radio waves have much lower frequencies than visible light waves, so a radio wave may be considered to be a low-frequency light wave. A sound wave, however, is a mechanical vibration of matter and is not electromagnetic. A sound wave is fundamentally different from an electromagnetic wave

Intensity of Light

- *Brightness* is the brain's interpretation of light *intensity*
  - Measured in Lux

Brightness (lux)	Surfaces illuminated by
0.0001	Moonless, overcast night
0.05 - 0.3	Full moon on a clear night
50	Family living room lights
100	Very dark overcast day
320 - 500	Office lighting
400	Sunrise or sunset on a clear day
1000	Normal overcast day
10,000 - 25,000	Full daylight (not direct sun)
32,000 - 100,000	Direct sunlight

Luminosity Function



- We don't see all colors equally well, though
- The graph shows the apparent brightness of different wavelengths of visible light
    - The curve in black shows the colors we see best under well-lit conditions (when cones in your eyes do most of the work in seeing)
    - The green curve shows the colors we see best under low-light conditions (when the rods take over)

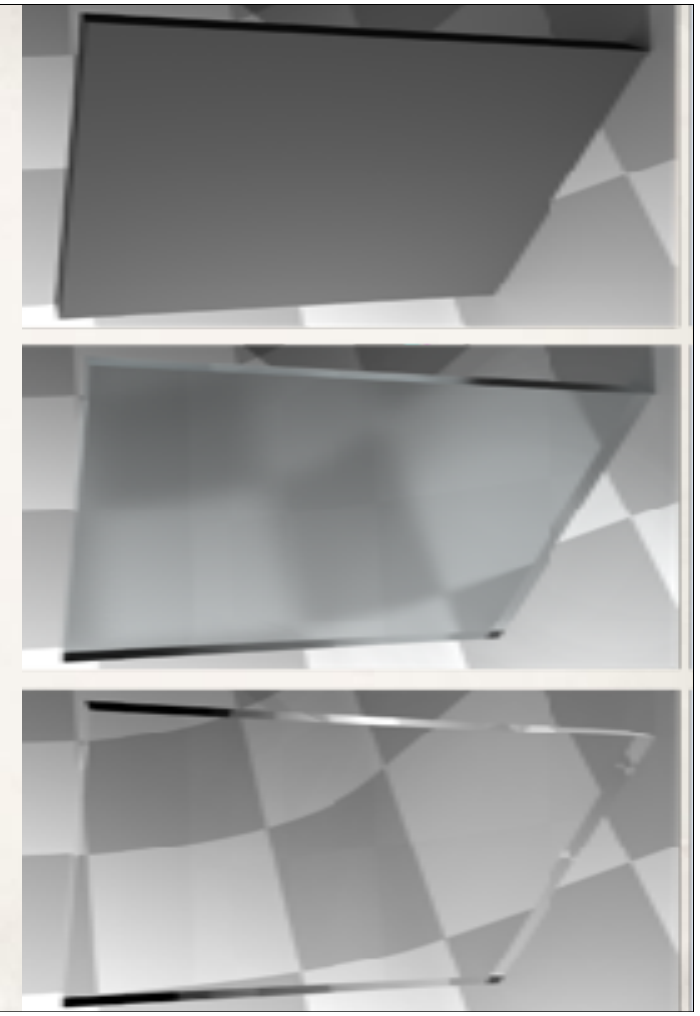
Light Thru Different Media

- When light hits matter, the electrons in that matter are forced into vibration
- How that material responds to the light depends on the frequency of the light and the natural frequency of the electrons in the material

- Imagine the electrons in an atom as connected to the nucleus by springs
    - A spring oscillates naturally at a specific frequency, which depends on the spring's stiffness
    - In this analogy, "stiffness of the spring" holding the electron to the nucleus is determined by the electric force that holds that electron in orbit

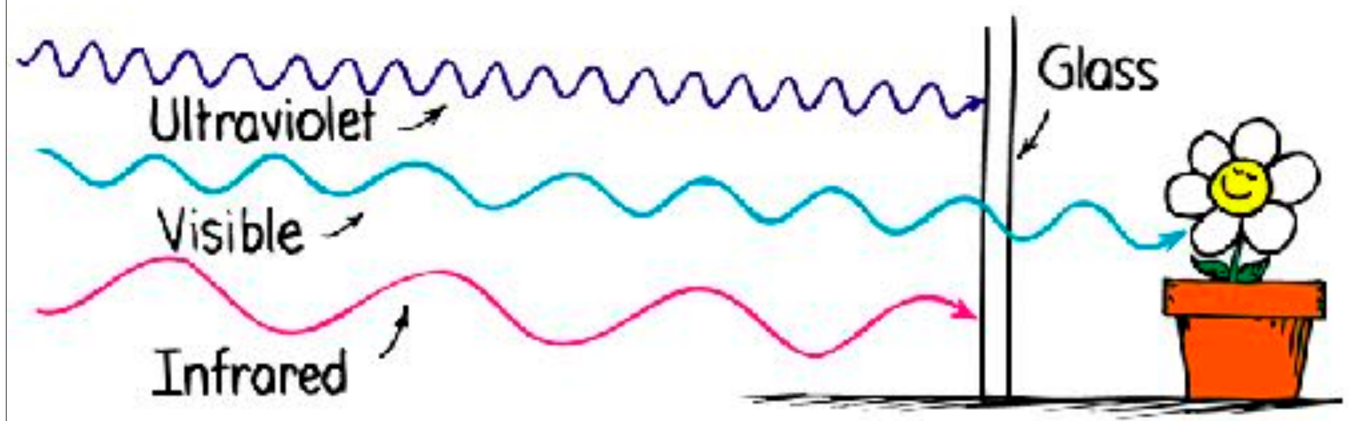
Opaque Materials

- If the frequency of the light matches the natural frequency of the electrons, the atom resonates & vibrates like crazy
- The material heats up instead of letting the light pass thru



Transparent Materials

- If the frequency of light does **not** match the natural frequency of the material, the electrons won’t be able to sustain the forced vibration
- In order to “settle down” into sustainable motion, the electron re-emits the light, passing it to the next atom
- This game of hot potato continues until the light has made its way to the other side of the material



Glass is transparent to visible light, but not to ultraviolet or infrared light. What does that tell us about glass?

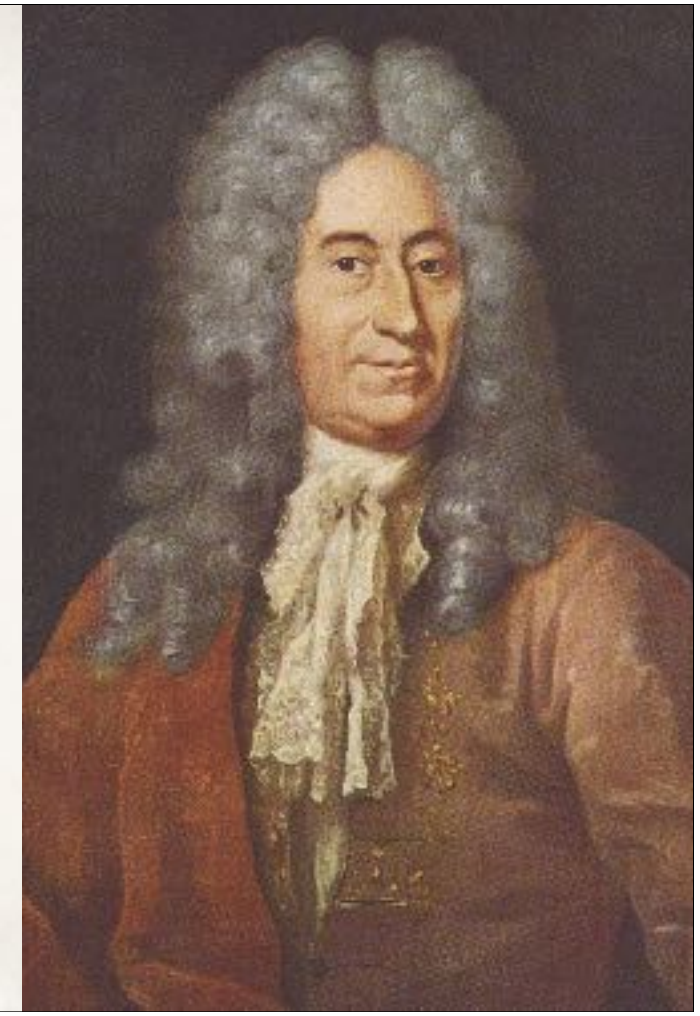
The Speed of Light

- Until the late 17th century, nobody was sure if light traveled instantaneously or had a finite speed
- Scientists, like Galileo, had tried to measure the speed of light by covering and uncovering lanterns on distant mountain tops, but failed to get anything meaningful

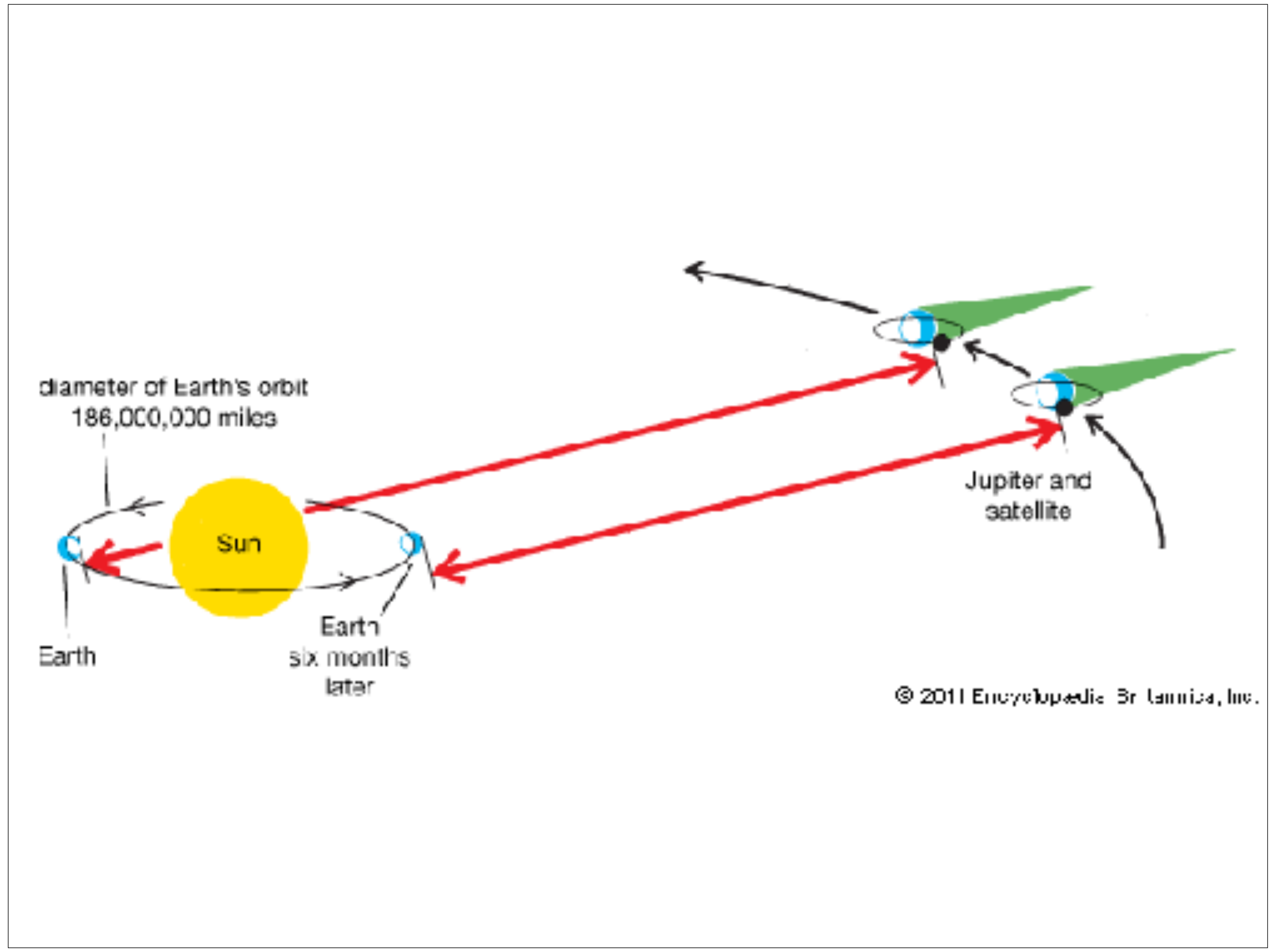
- The light actually did take longer to reach the distant mountains, but we’re talking lags of ~10 microseconds — way too quick to notice

Olaus Roemer

1644 — 1710



First to demonstrate the finite speed of light, ca. 1675

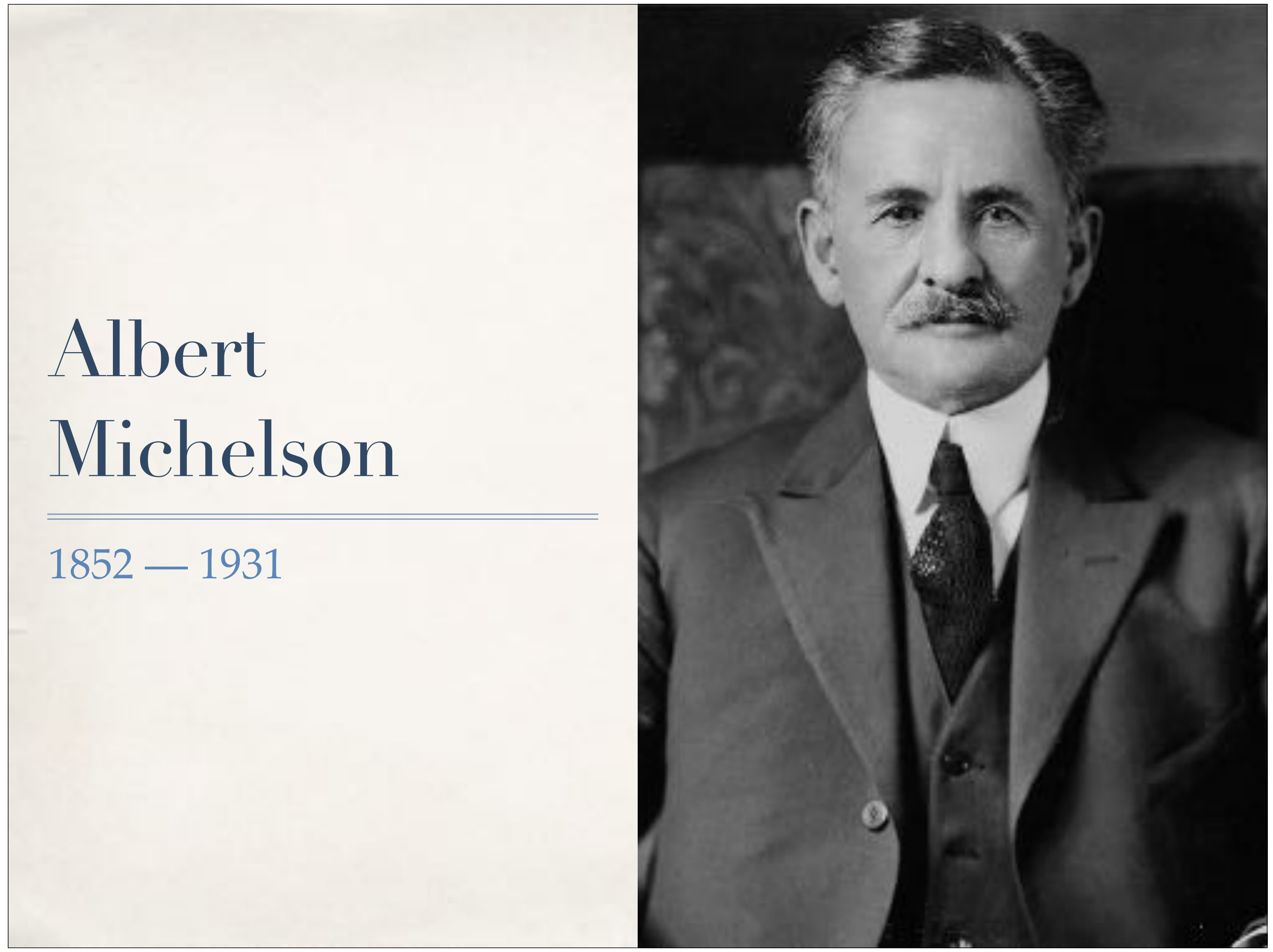


- Roemer knew what the orbital period of Jupiter's moon Io should be (thanks Kepler) but noticed it peeked out from behind Jupiter ahead of schedule when Earth and Jupiter were close and behind schedule when the two planets were further apart

Christian Huygens

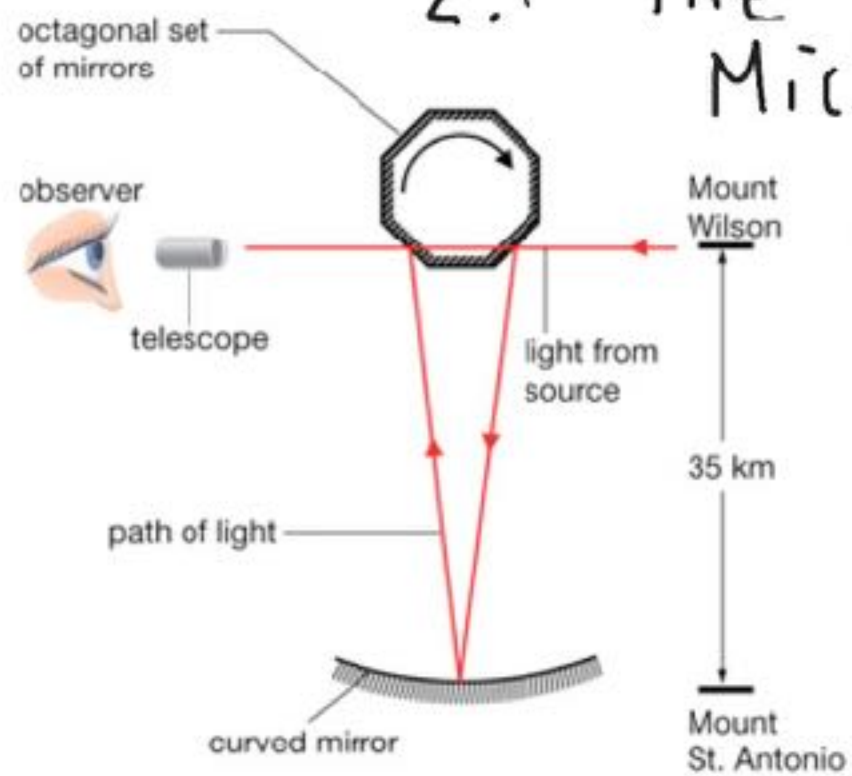
1629 — 1695

- Huygens realized the discrepancy arose, not because there was anything wrong with Io’s orbit, but because the light needed more time to reach Earth when it was further away
- Huygens used the time lag to make a pretty decent calculation for the speed of light



- 200 years later, American physicist Albert Michelson came up with an accurate, reliable method for measuring the speed of light

2.1 The Michelson Experiment



- Changing the speed the octagonal set of mirrors rotates changes where the light reflects to
- Michelson adjusted the rotational speed until the light reflected into his telescope
    - By knowing the rate of rotation and the distances between mirrors, Michelson could calculate the speed of light with unprecedented accuracy

299,792,458 m/s

= Speed of Light

Michelson became the first American to receive a Nobel Prize in physics for this experiment

Practice

- The circumference of the Earth is about 40 million meters
- How many times could light travel around the Earth in 1 second?

Answer: 7.5 times

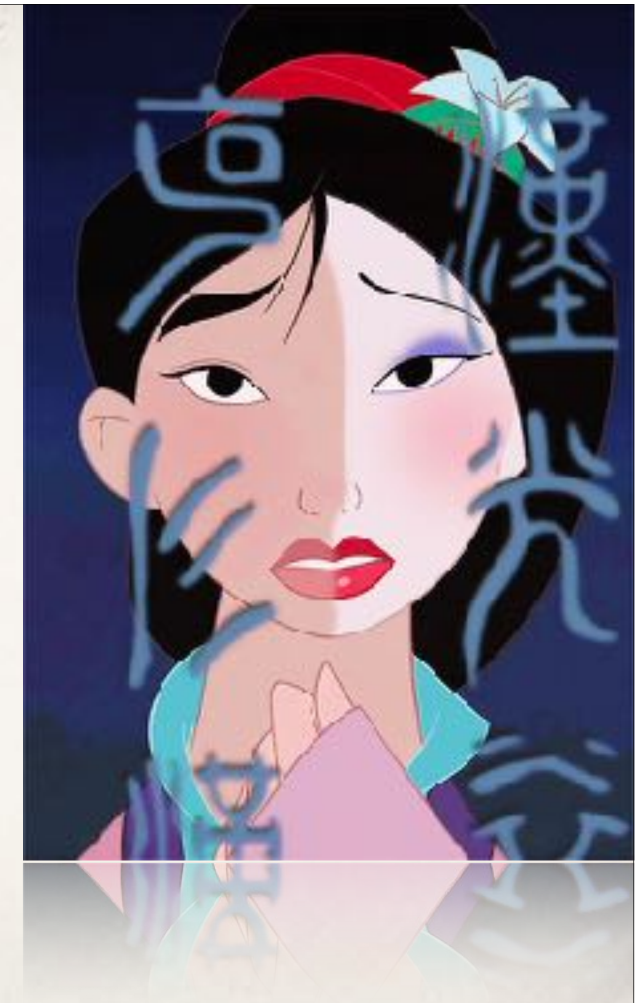
Practice

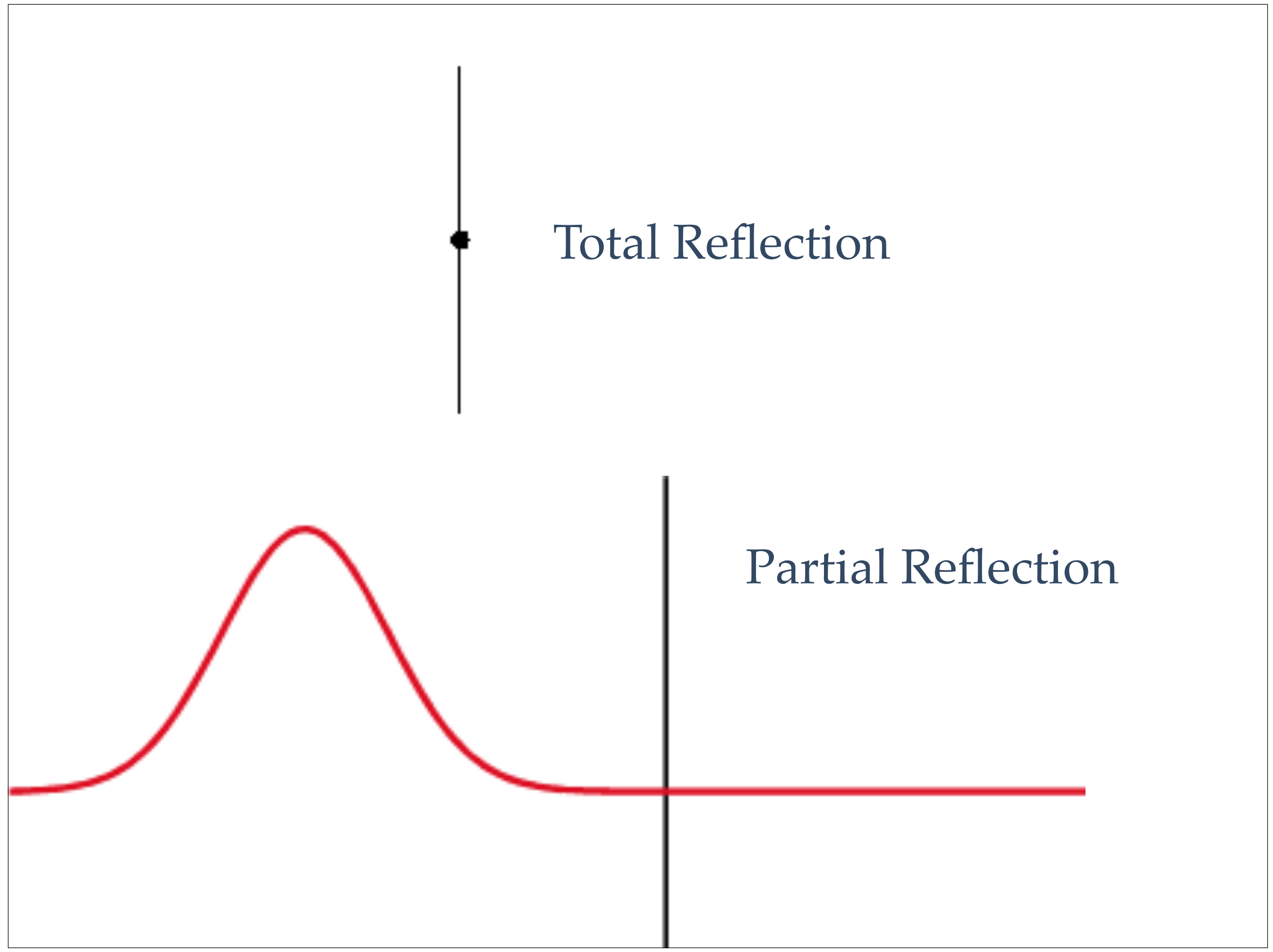
- The next closest star to Earth, Alpha Centauri, is 41.32 trillion km away
- How long would it take to get there traveling at the speed of light?

Answer: 4.4 years

Reflection

- ***Reflection*** — when a wave reaches a boundary between two media, some or all of the wave bounces back into the first medium

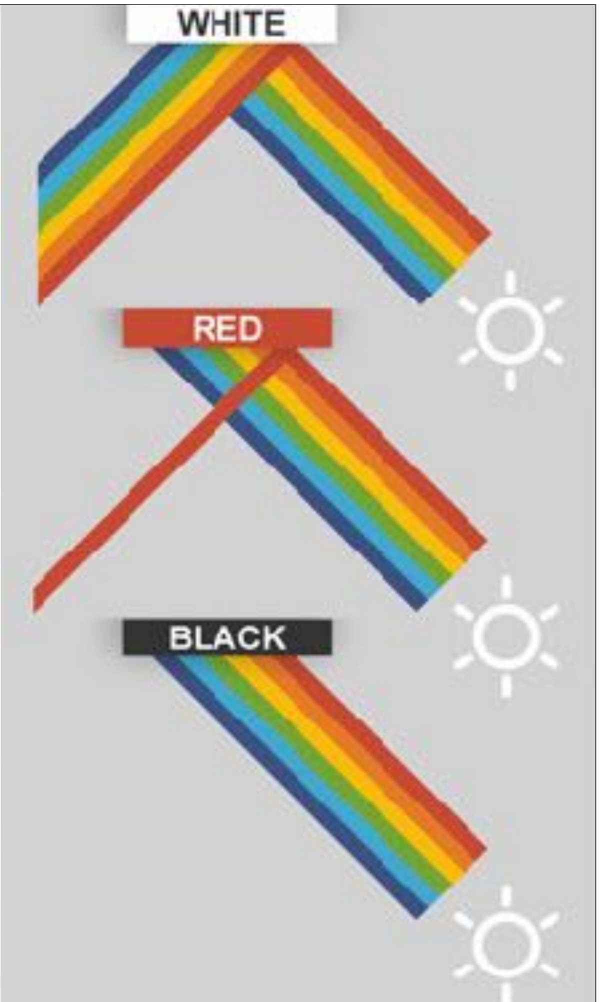




- Total reflection - all wave energy is reflected, none is transmitted
- Partial reflection - some wave energy is reflected, some is transmitted
- How much of the wave reflects depends on how rigid the medium is to the wave
    - Metal surfaces are very rigid to light waves, so light is totally reflected when it hits a metal surface (which is why they make good mirrors)
    - Other materials are less rigid to light. Still water reflects about 2% of light energy, while glass reflects 4%. Except for slight losses, the rest is trasmitted

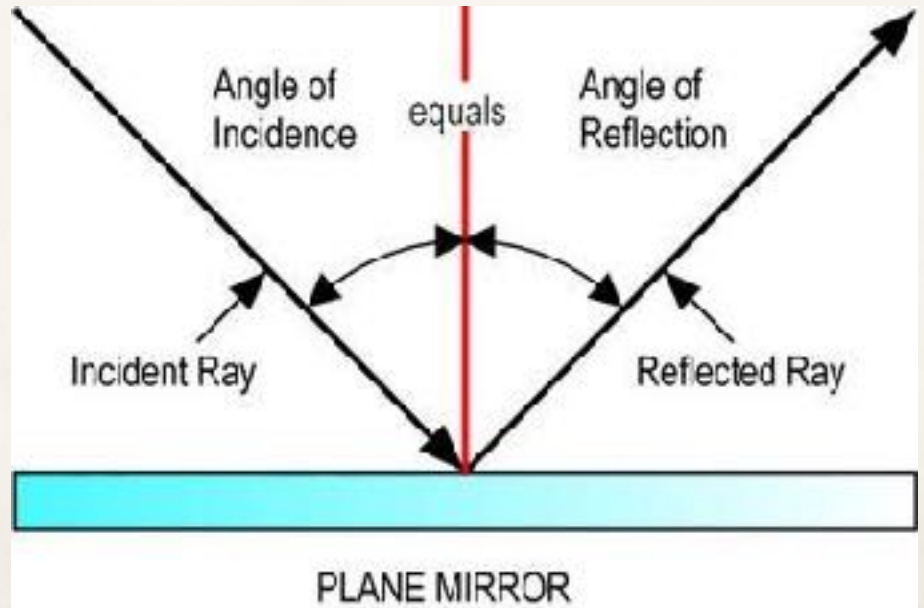
Color by Reflection

- Most materials absorb light of some frequencies and reflect the rest
  - If a material absorbs most visible frequencies and **reflects red**, for example, the material appears **red**
  - If it **reflects** light of **all** visible frequencies, it appears **white**
  - If it **absorbs** light of **all** visible frequencies, it appears **black**



The Law of Reflection

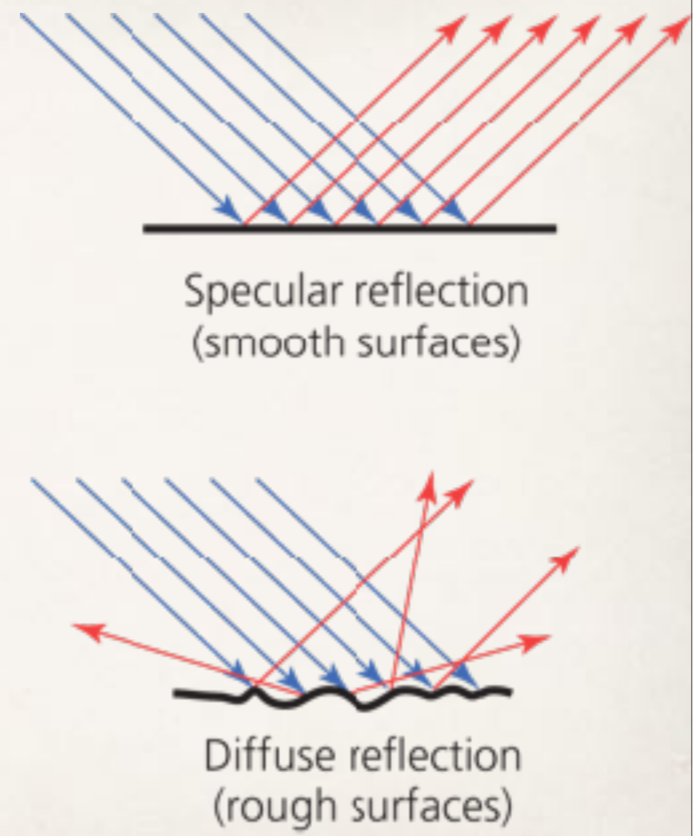
The angle of incidence equals the angle of reflection



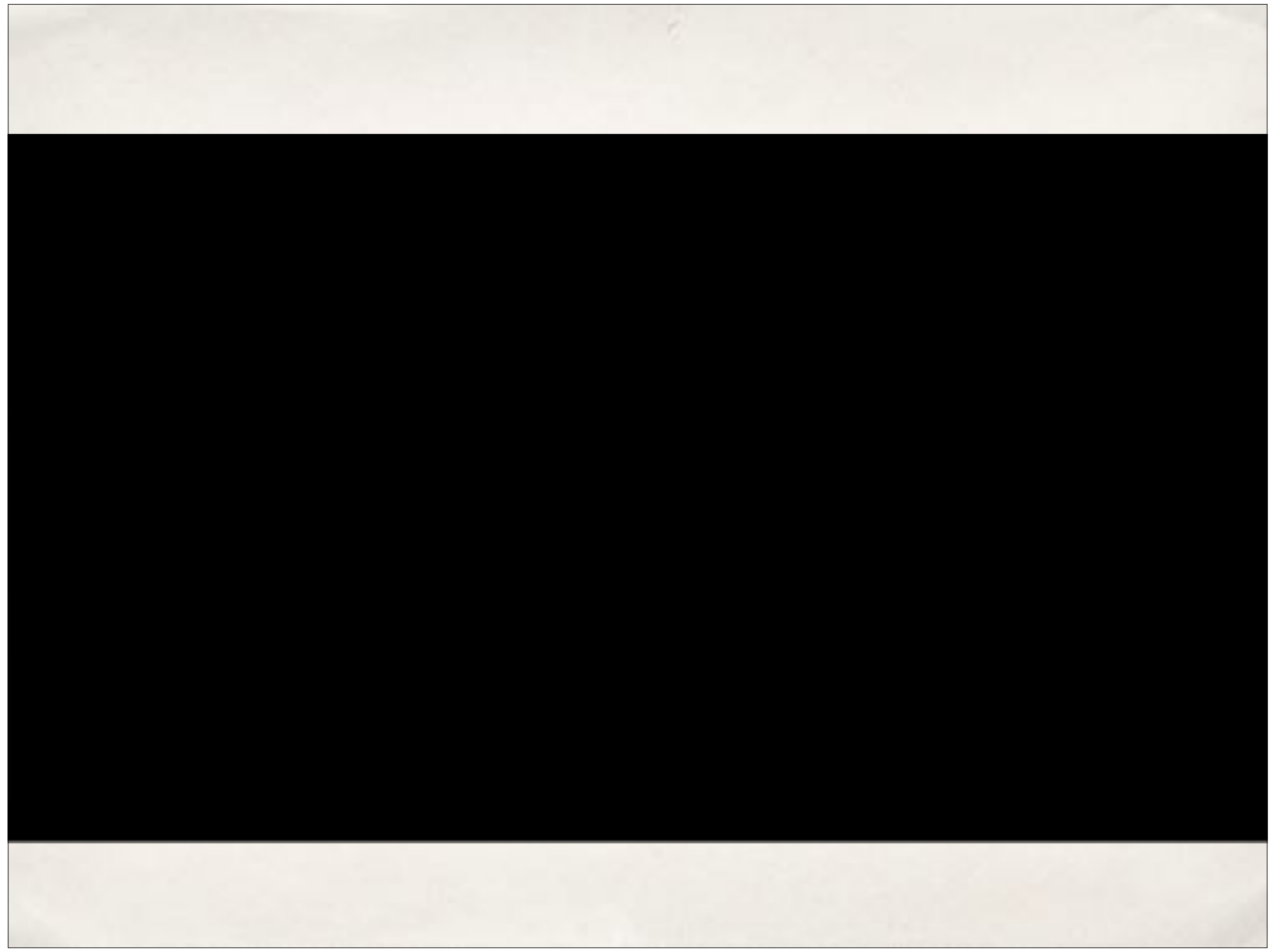
- The angle the incoming (incident) light ray makes with a line perpendicular to the surface, called *normal*, equals the angle the reflected light ray makes with that same line

Specular vs. Diffuse Reflection

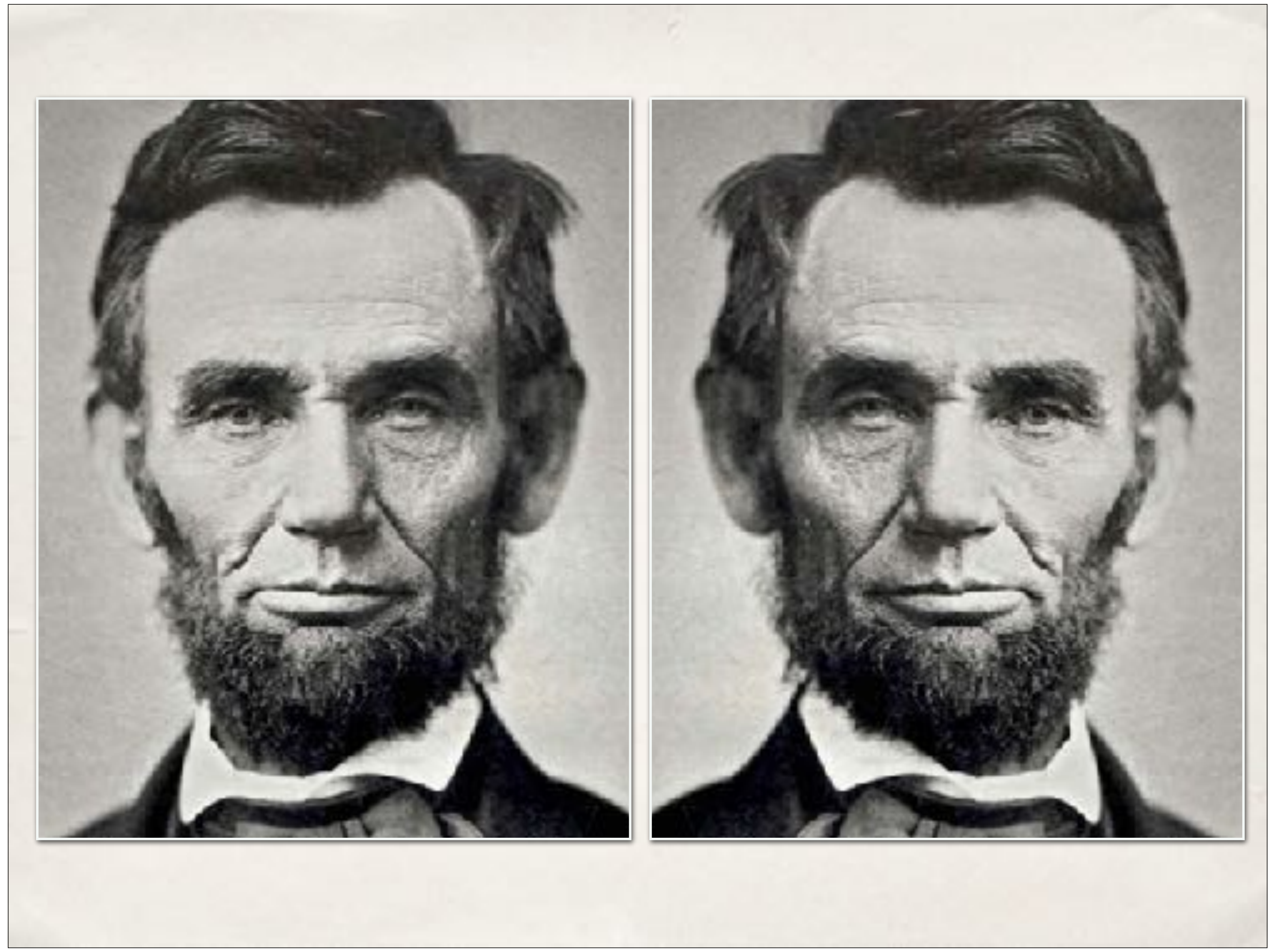
- When light is incident on a **smooth surface**, all the light is reflected in the **same direction**
- When light is incident on a **rough surface**, it is reflected in **many directions**



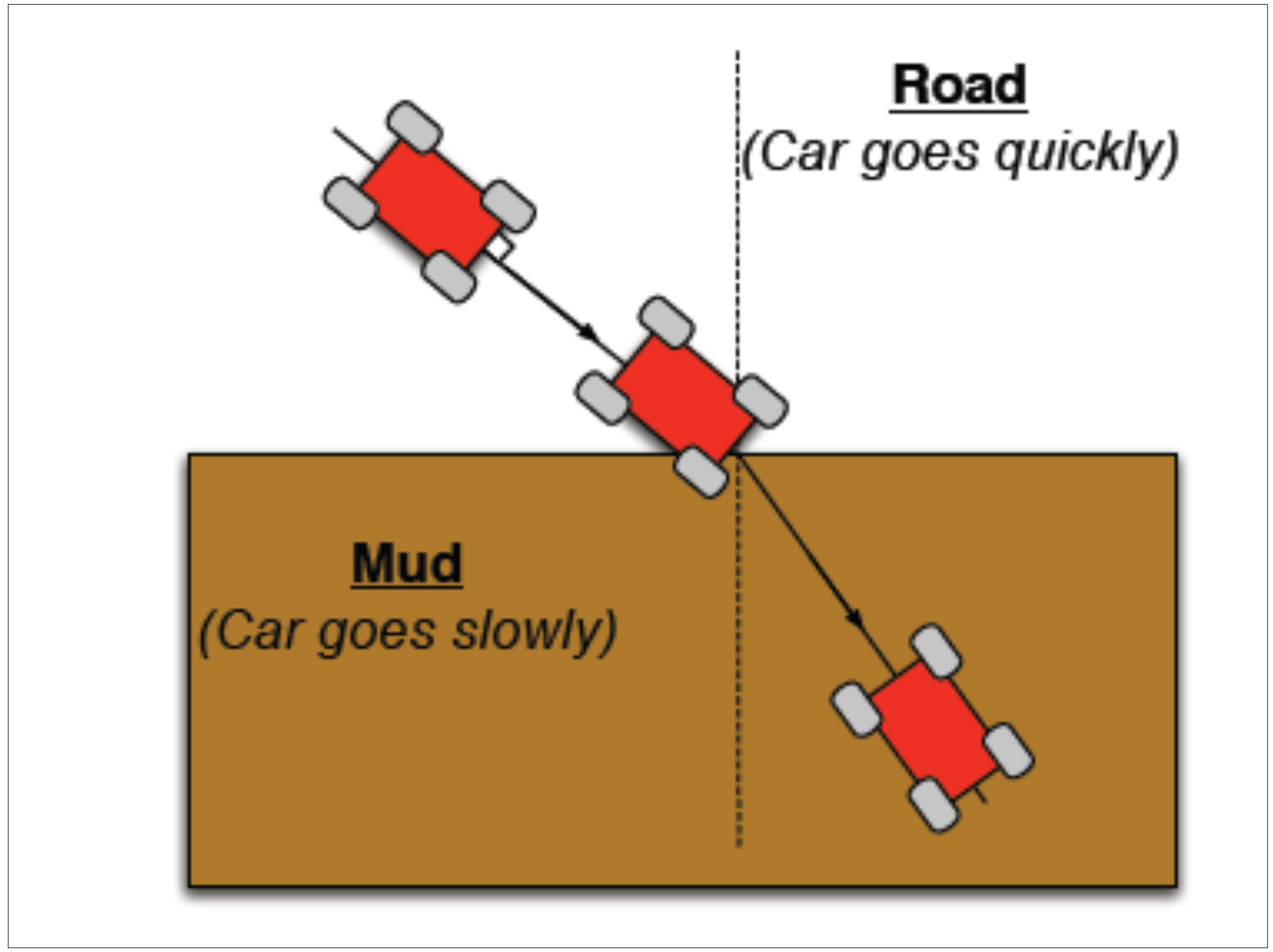
- This is why we polish metal to make good mirrors
- Light can also diffuse as it transmits through a medium, which is the difference between transparency and translucence



- Why do mirrors flip horizontally (but not vertically)? - Physics Girl
    - https://www.youtube.com/watch?v=vBpxhfBlVLU



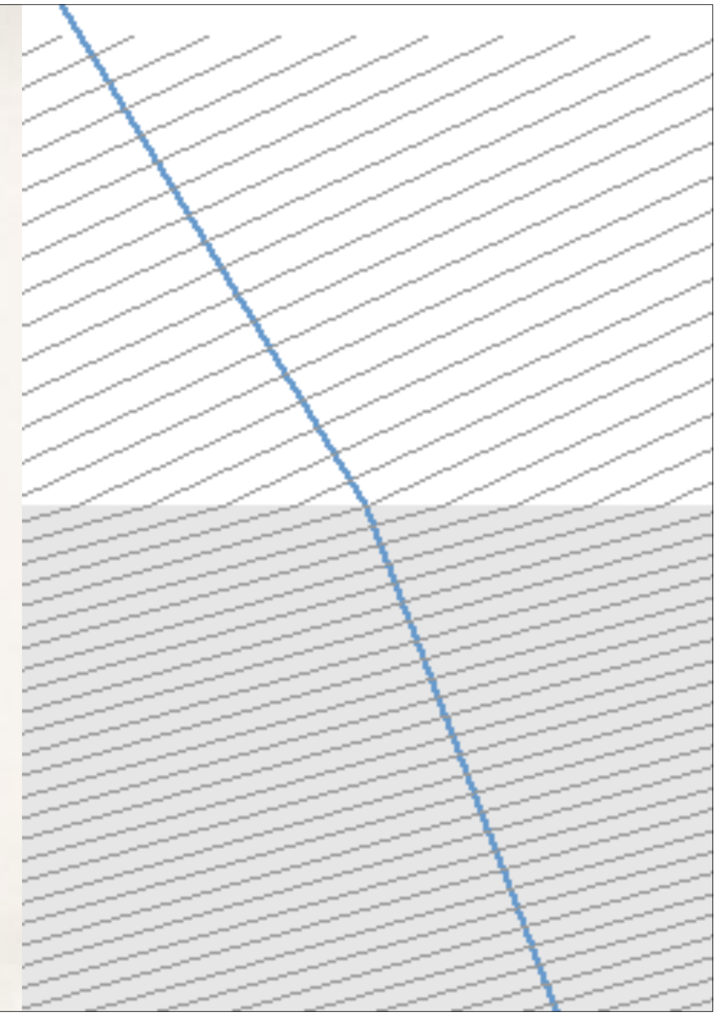
- Left: How we see Lincoln (in pictures, or how people saw him in real life)
- Right: How Lincoln saw himself (in mirrors)



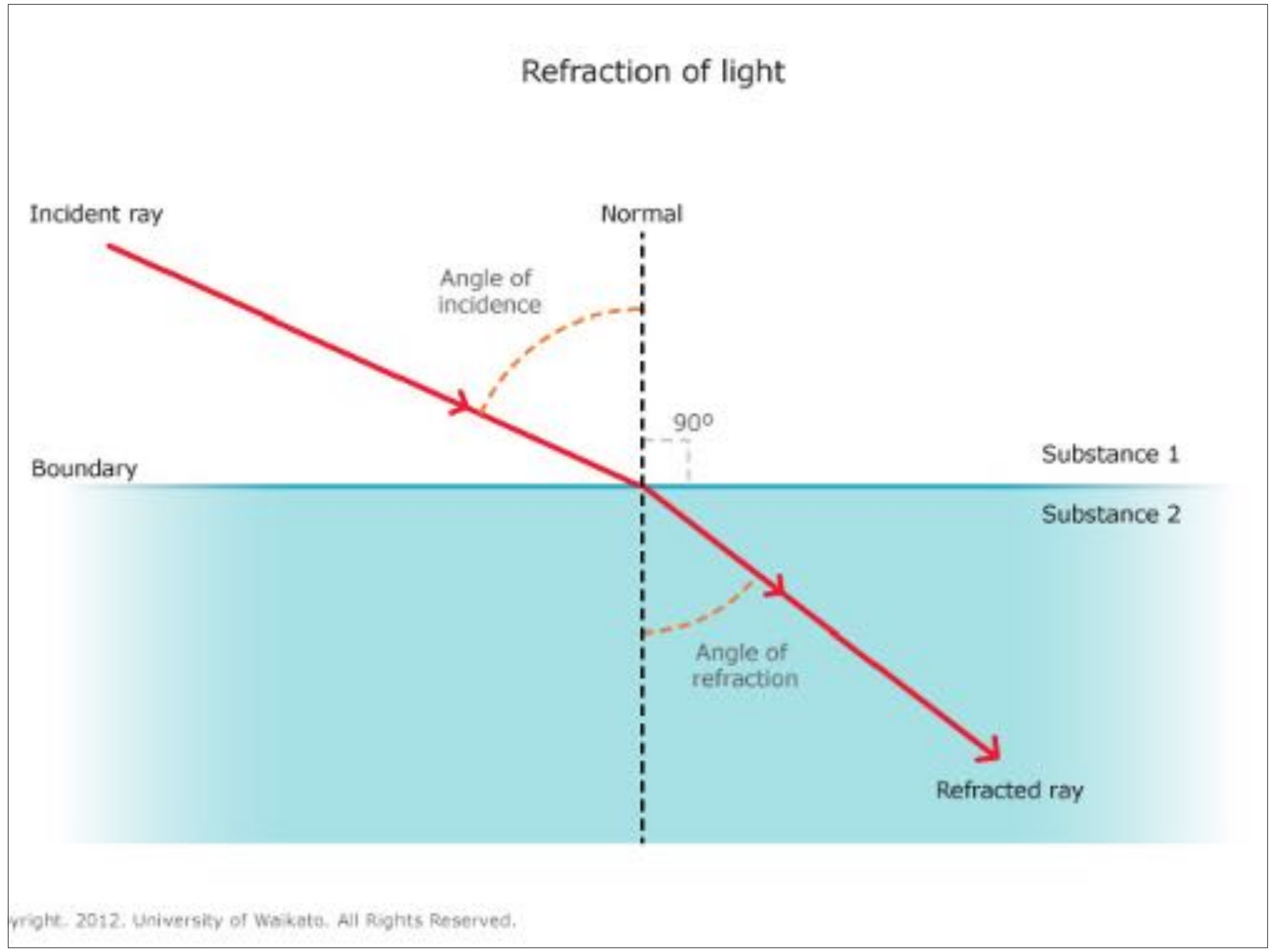
- When the first wheel hits the mud, it moves slower than the wheel that hasn't met the mud yet, and so the car turns as it enters the mud

Refraction

- Waves similarly deflect when they pass from one medium to another. This is called ***refraction***

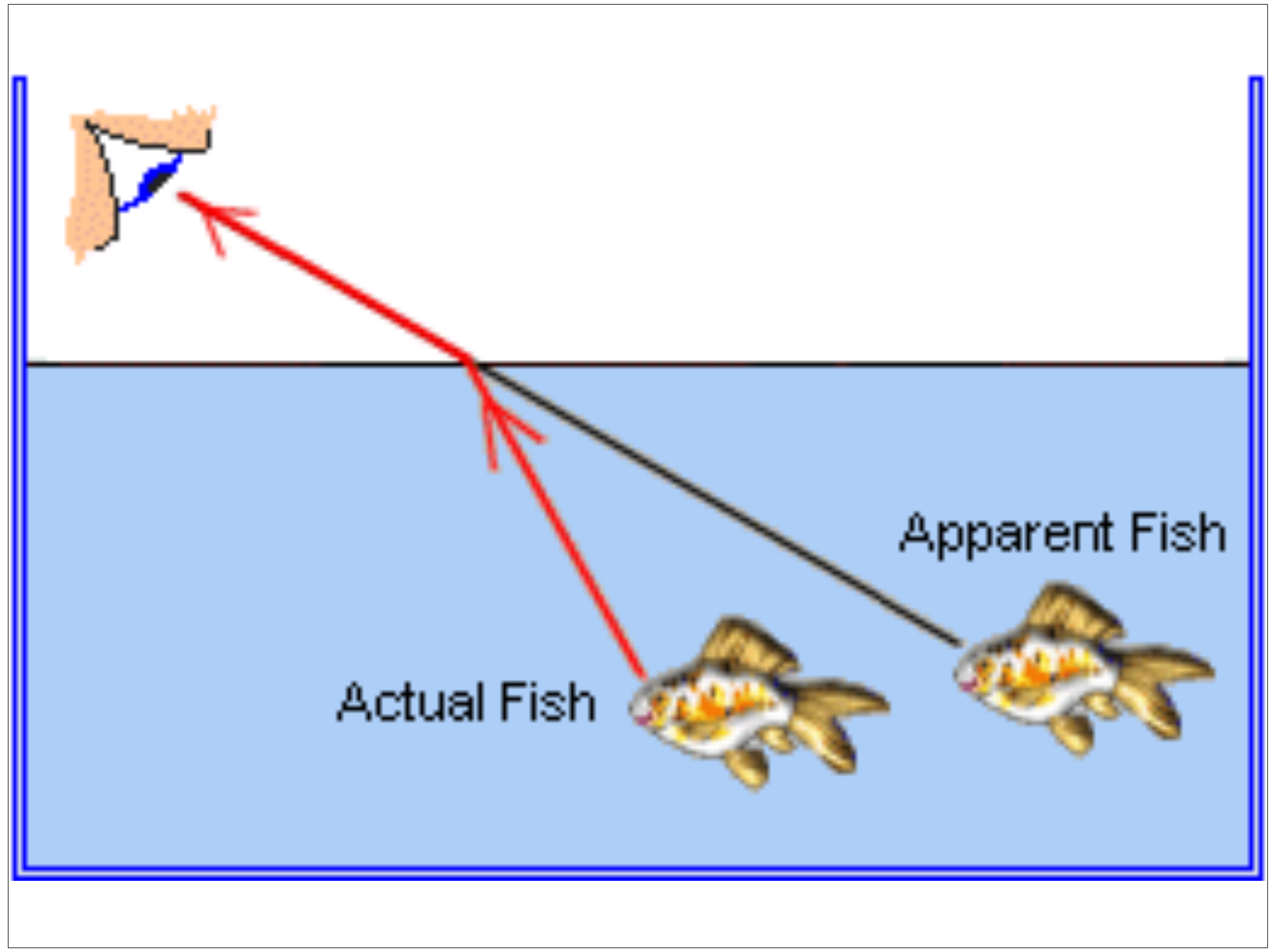


- For example, this happens when water waves move from deep water (where they move quickly) to shallow water (where they move slower)



- Same thing happens to light when it moves from one medium to another

- Refraction is the reason straws look broken in a glass of water



- The fish isn’t where it appears to be because the image is refracted
- To know how much the image is deflected, we need to know how well light moves through both media

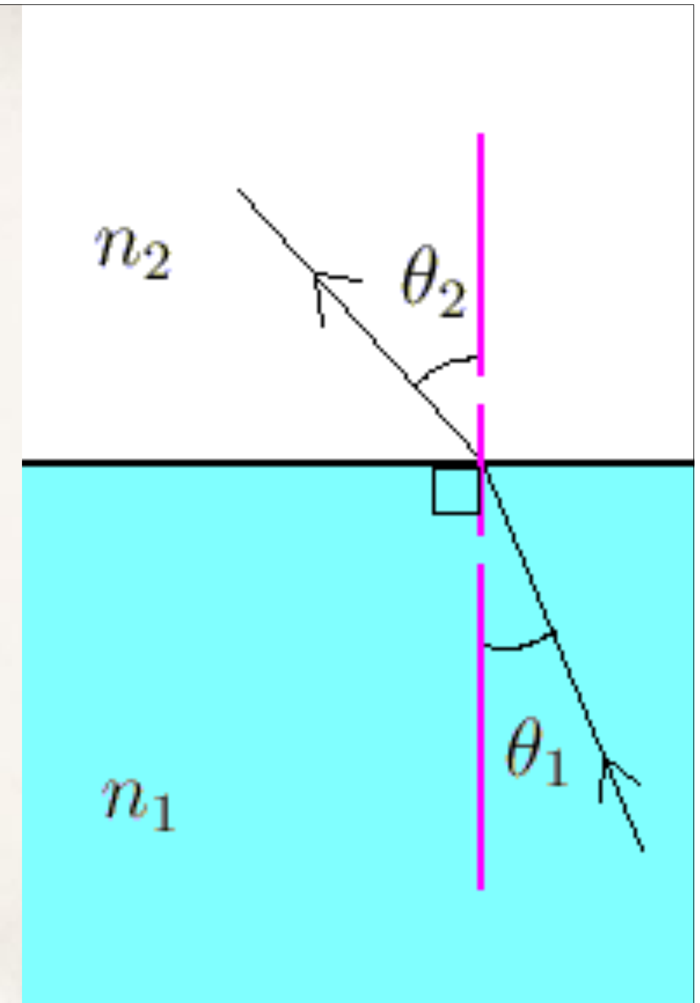
Index of Refraction

$$n = \frac{\text{speed of light in vacuum}}{\text{speed of light in material}}$$

- Light moves fastest in a vacuum, so the index of refraction will always be ≥1

Snell's Law

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



- So if light moves faster in the first medium than the second, then the light will defect inward ($\theta_1 > \theta_2$)

Practice

a. On average, how fast does light travel through water?

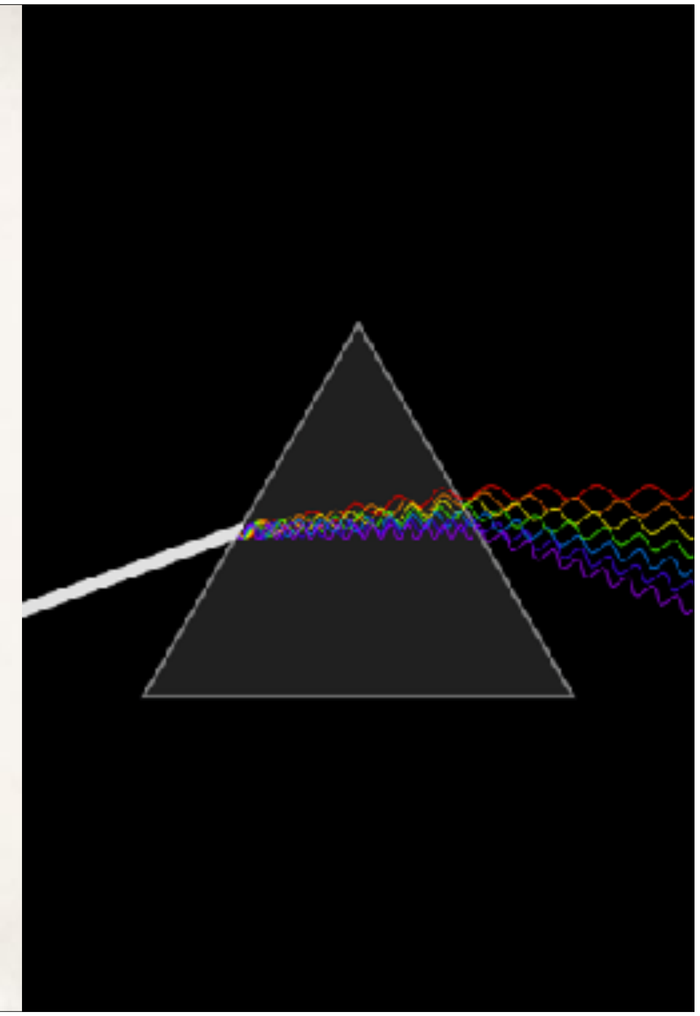
b. If light travels through air and hits water at a 45° angle, at what angle will it deflect through the water (i.e. what's the angle of refraction)?

Media	Index of Refraction
Vacuum	1.00
Air	1.0003
Carbon dioxide gas	1.0005
Ice	1.31
Pure water	1.33
Ethyl alcohol	1.36
Quartz	1.46
Vegetable oil	1.47
Olive oil	1.48
Acrylic	1.49
Table salt	1.51
Glass	1.52
Sapphire	1.77
Zircon	1.92
Cubic zirconia	2.16
Diamond	2.42
Gallium phosphide	3.50

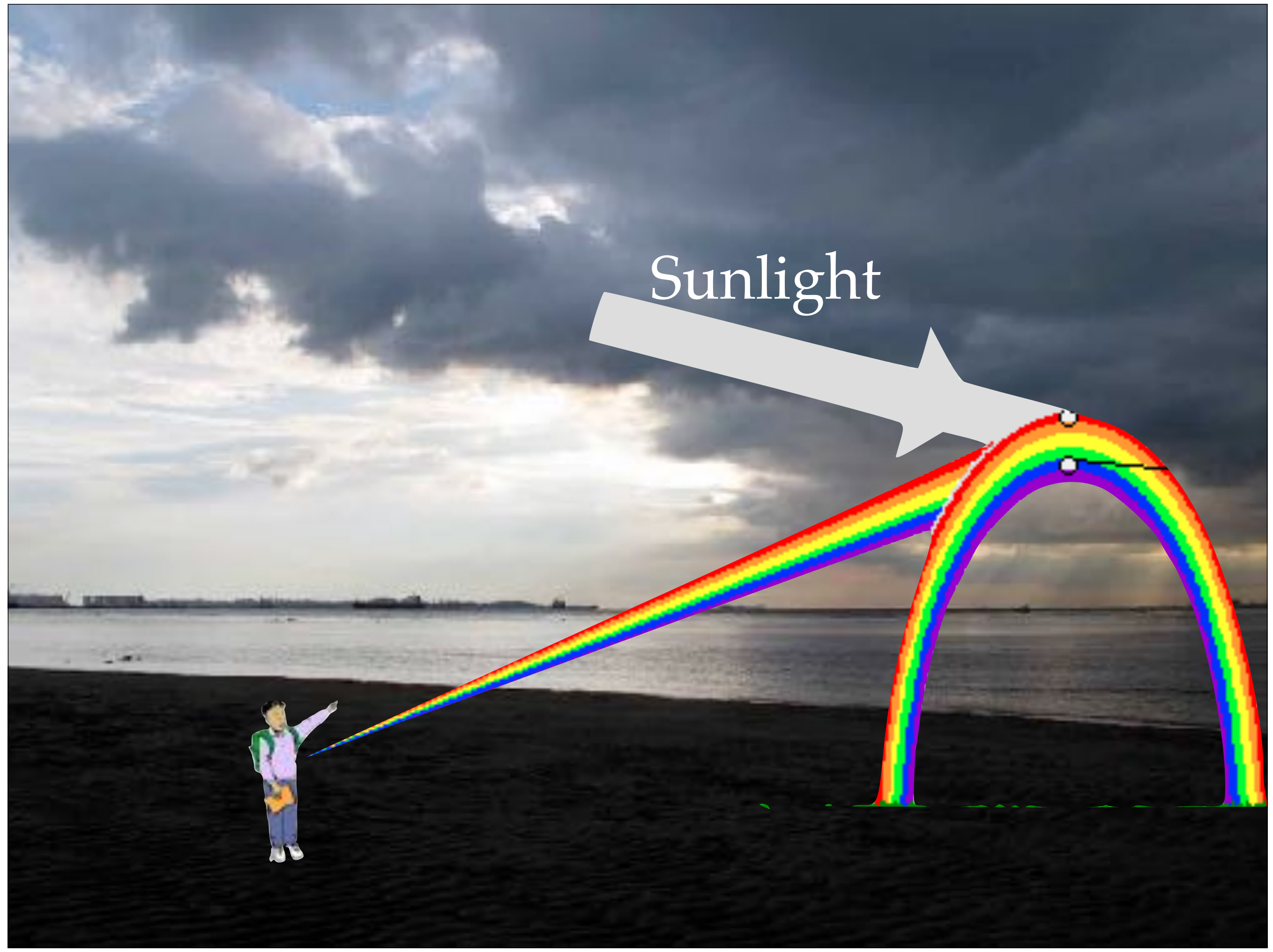
a. ~226,000,000 m/s (~75% its speed through a vacuum)
b. 32° with normal

Dispersion

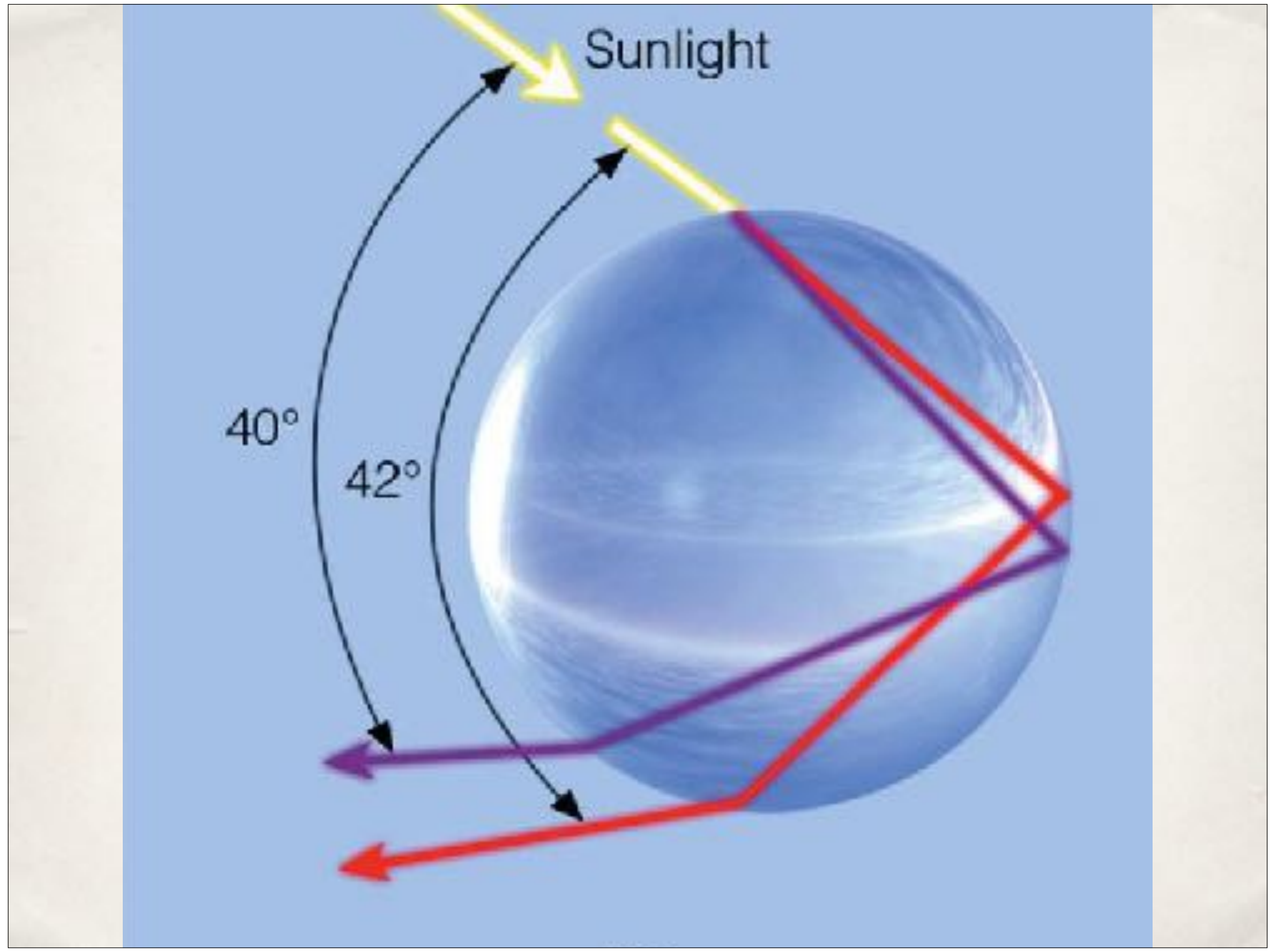
- How much light is refracted inside a medium depends on frequency
  - Light of frequencies closer to to the natural frequency of the material refract more



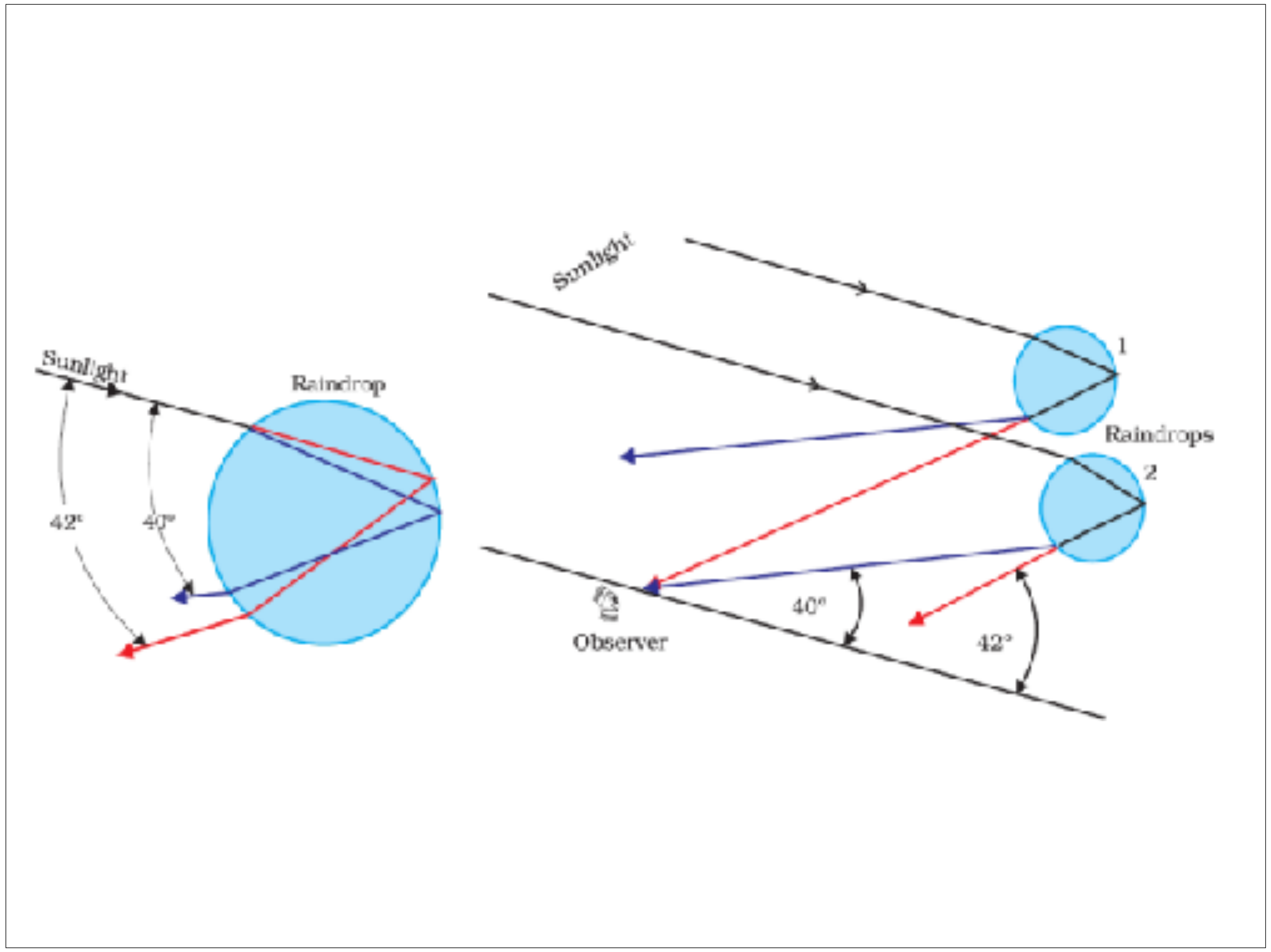
- The closer the light frequency is to the material’s natural frequency, the more interactions that light has with the medium in the process of absorption and transmission, slowing its progress
  - Glass resonates in the ultraviolet range, so violet light, whose frequency is closer to resonance, travels about 1% slower through glass than red light and thus refracts more
  - When light is refracted twice at nonparallel boundaries, as in a prism, the separation of colors is even more exaggerated



- Rainbows are also the result of refraction
- In order to see a rainbow, you need the sun shining in one part of the sky and rain in another. You might see a rainbow if you put yourself between the sun and rain with the sun behind you



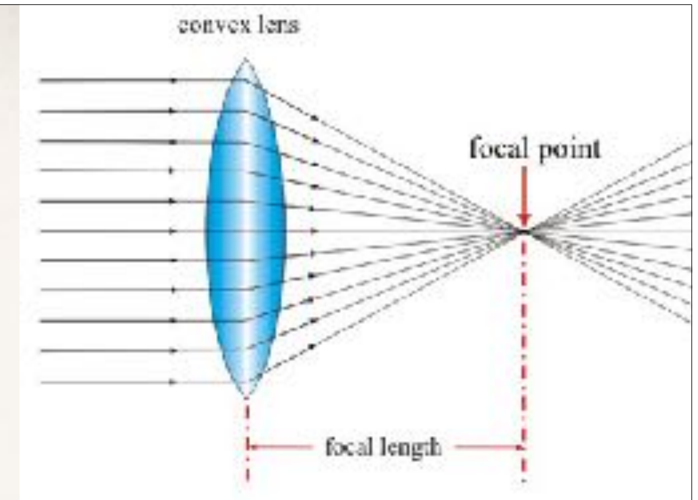
- When light from the air hits a water droplet, the light both refracts and reflects at the interface between the media
- The light that you see in the rainbow first refracts when it passes into the water, then reflects off the back of the droplet, and finally refracts again when it refracts back into the air, now in your direction



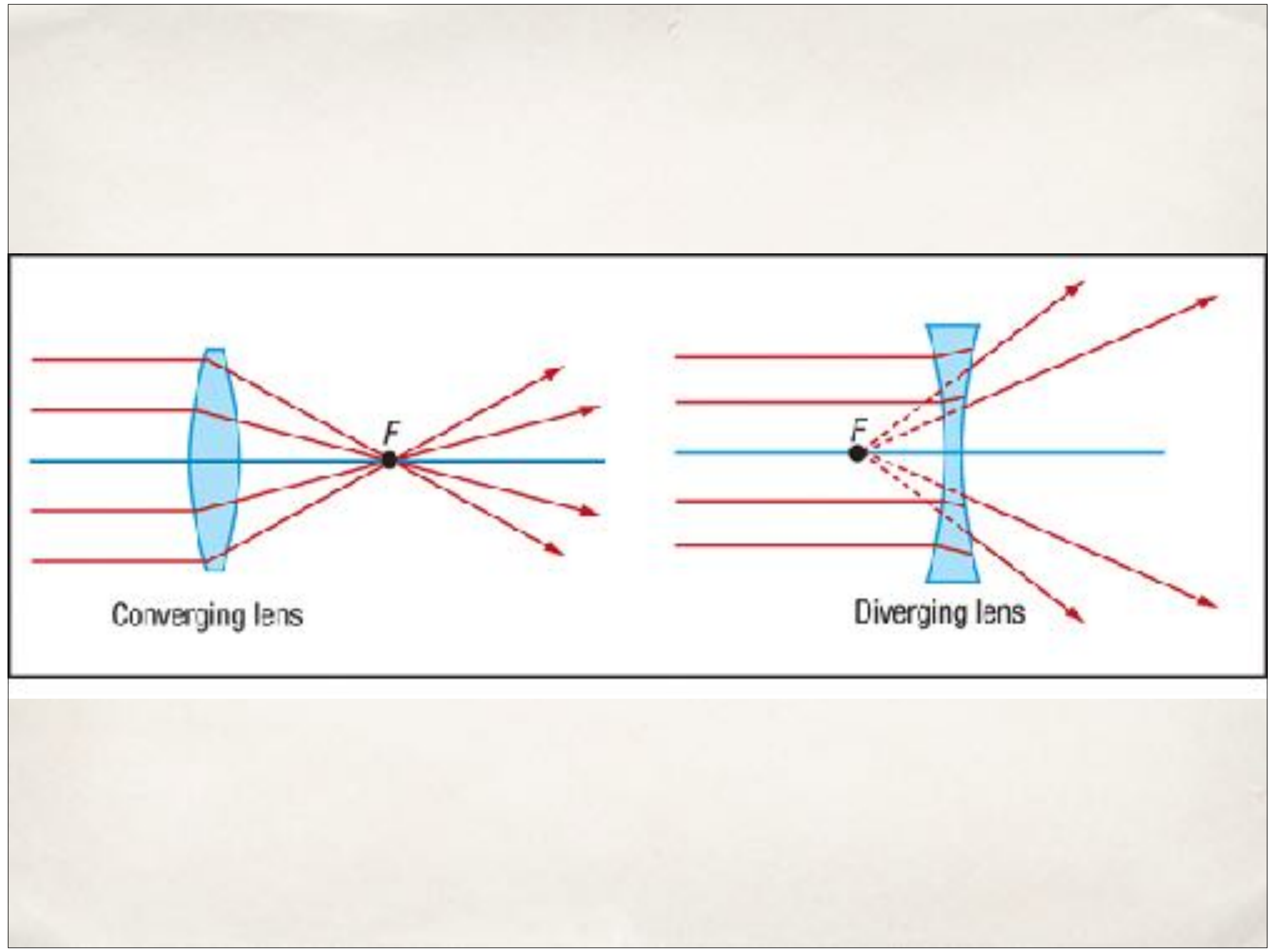
- The rainbow you see is formed from light reflected and refracted from many raindrops. You only see the light that is angled to your eyes, and the angle of refraction is always the same for a given color. So no matter how you move, as long as you can still see the rainbow, it'll always look like the rainbow is centered dead ahead with the violet band 40° away from center and the red band 42° away

- Those are the angle away from center where the colors show up is the same in every direction, but we can’t usually see the bottom half because the ground gets in the way. But not in an airplane :)

Lenses



- Light refracts when it enters and leaves glass
- Changing the shape of the glass changes the angle the light exits out with
- When a piece of glass has just the right shape, it bends parallel rays of light so that they cross and form an image. Such a piece of glass is a **lens**



- The lens on the left is built to converge light to a point. This is a **converging lens**
- The lens on the right is built to diverge light away from a point. This is a **diverging lens**

Lenses

- When light passes through a lens from straight on, it converges to (or appears to diverge from) a point. That point is called the **focal point**
- The distance from the center of the lens to the focal point is called the **focal length**

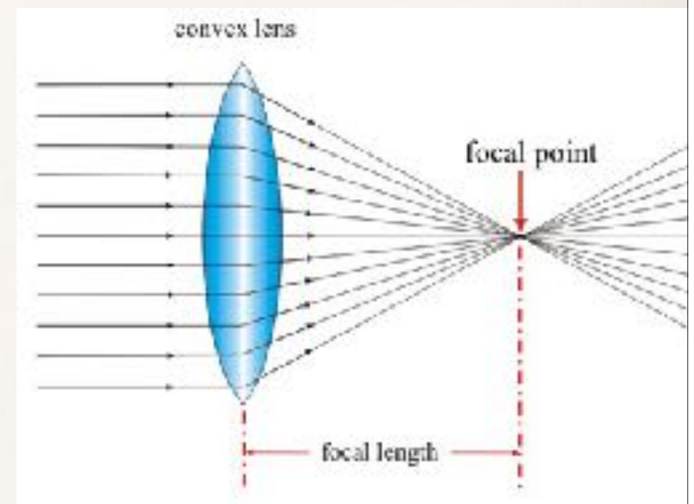
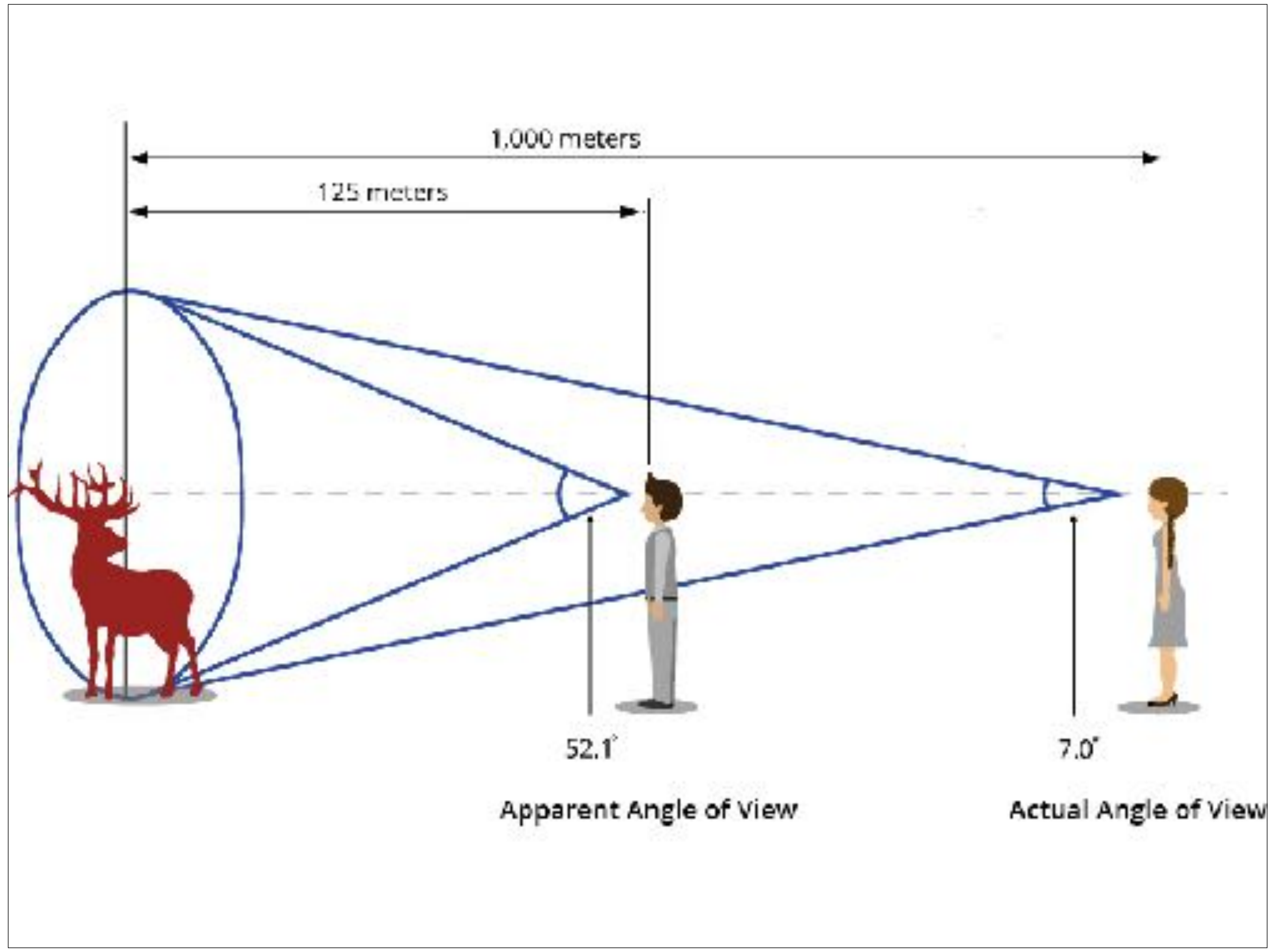


Image Formation by a Lens

- An object seen from far away is seen through a smaller angle than it is when it's close
- Magnification occurs when an image is viewed through wider angle with the lens than it is without one


1,000 meters
125 meters
52.1˚
7.0˚
Apparent Angle of View
Actual Angle of View

Light —

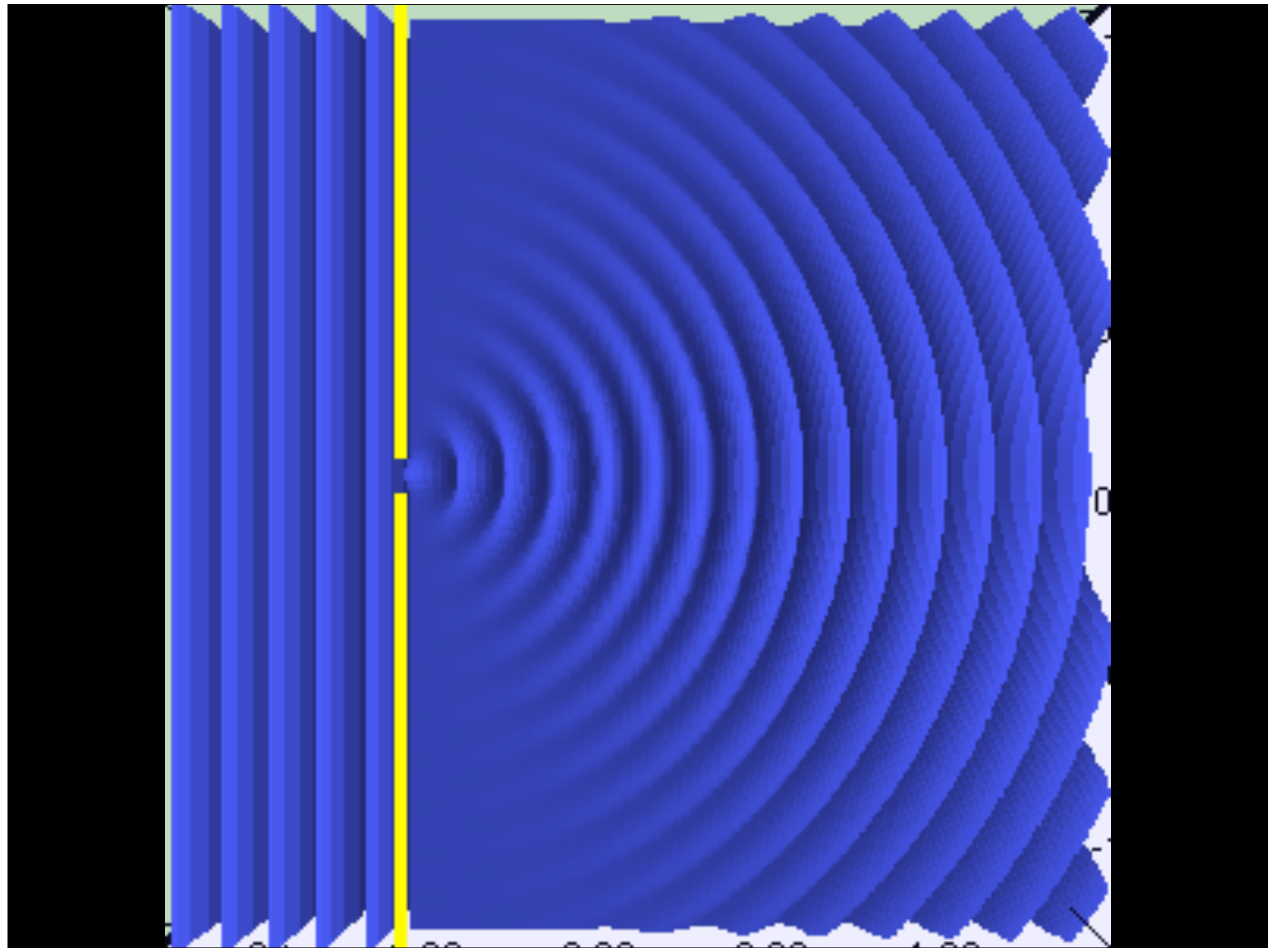
Wave or Particle?

Newton said light was a particle, Huygens said light was a wave. The debate raged on

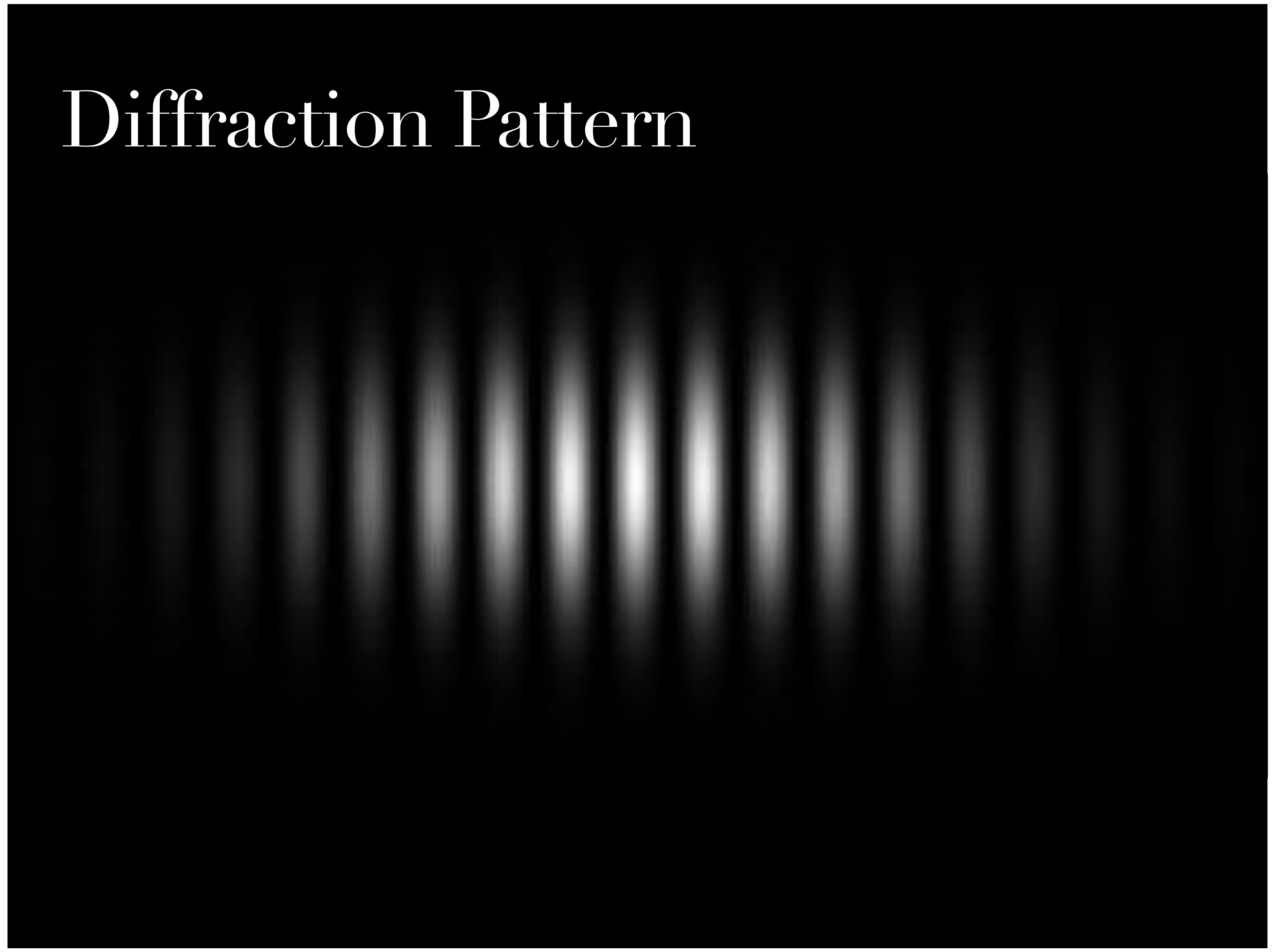
Thomas Young

1773 — 1829

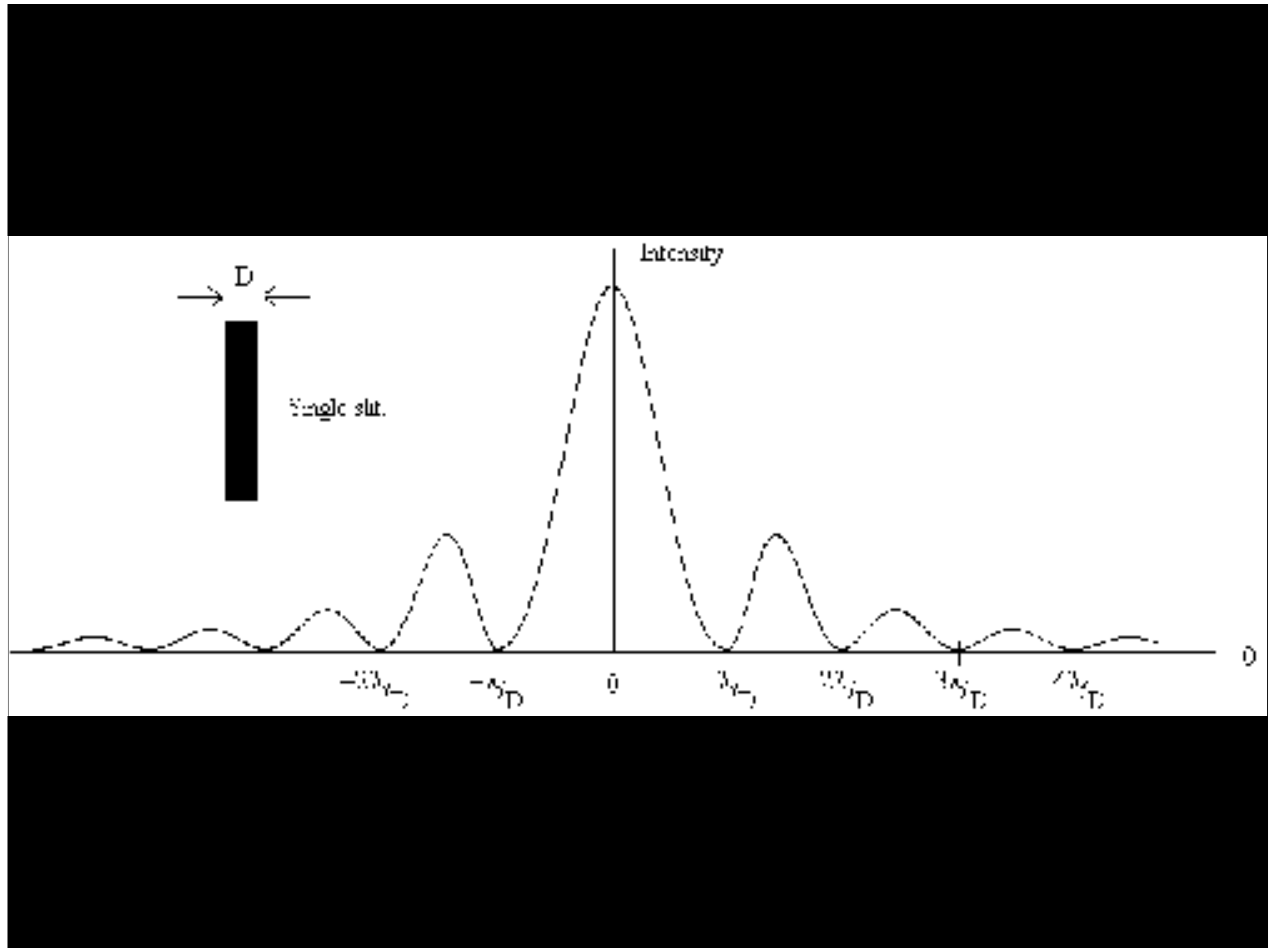
- In 1803, English scientist Thomas Young seemed to settle the matter through his famous double-slit experiment



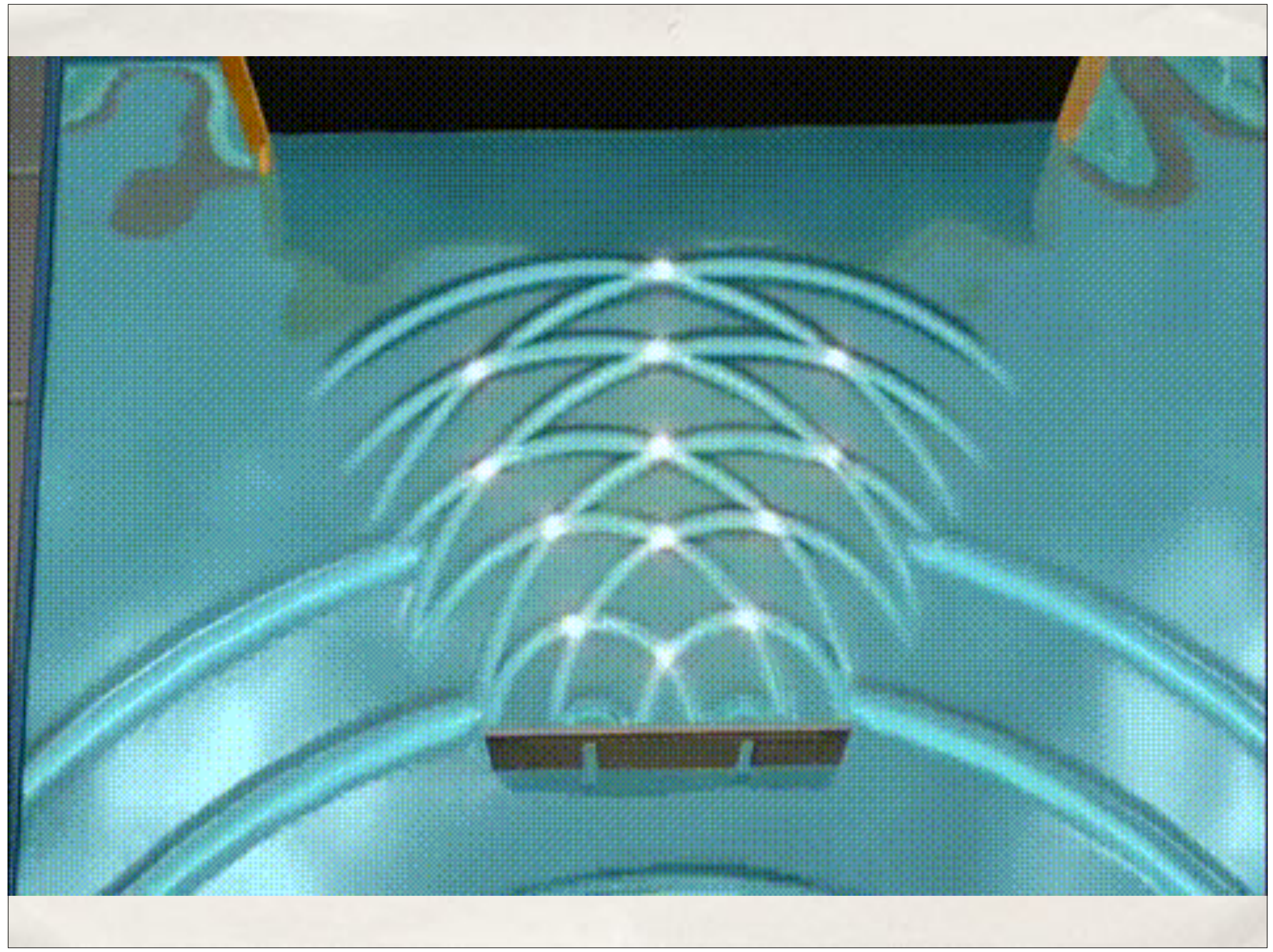
- Single-slit experiment, water wave diffraction
    - Diffraction refers to how a wave spreads out when it meets a small opening or the edge of a barrier



By sending light through a single slit, you can see the diffraction pattern very clearly



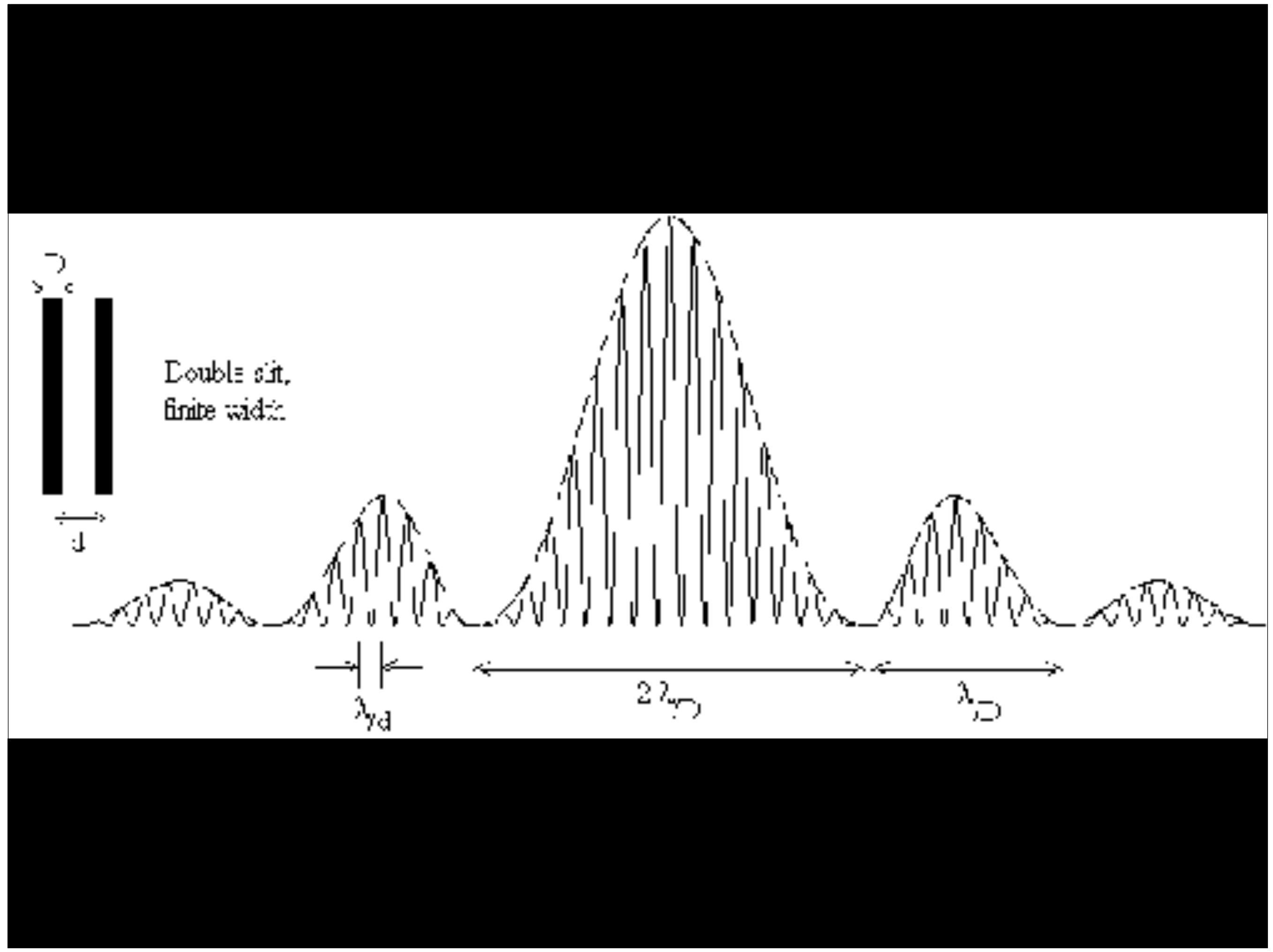
- Graph of the wave's intensity as it meets the wall behind the slit. 0 is centered directly behind the slit



Double-slit experiment, water wave interference

Single-Slit Diffraction Pattern (Top)

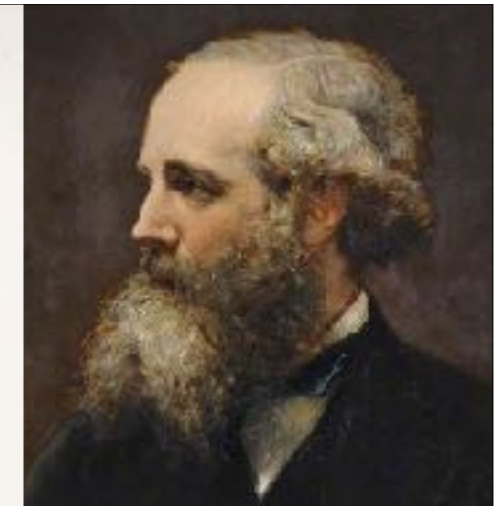
Double-Slit Interference Pattern (Bottom)



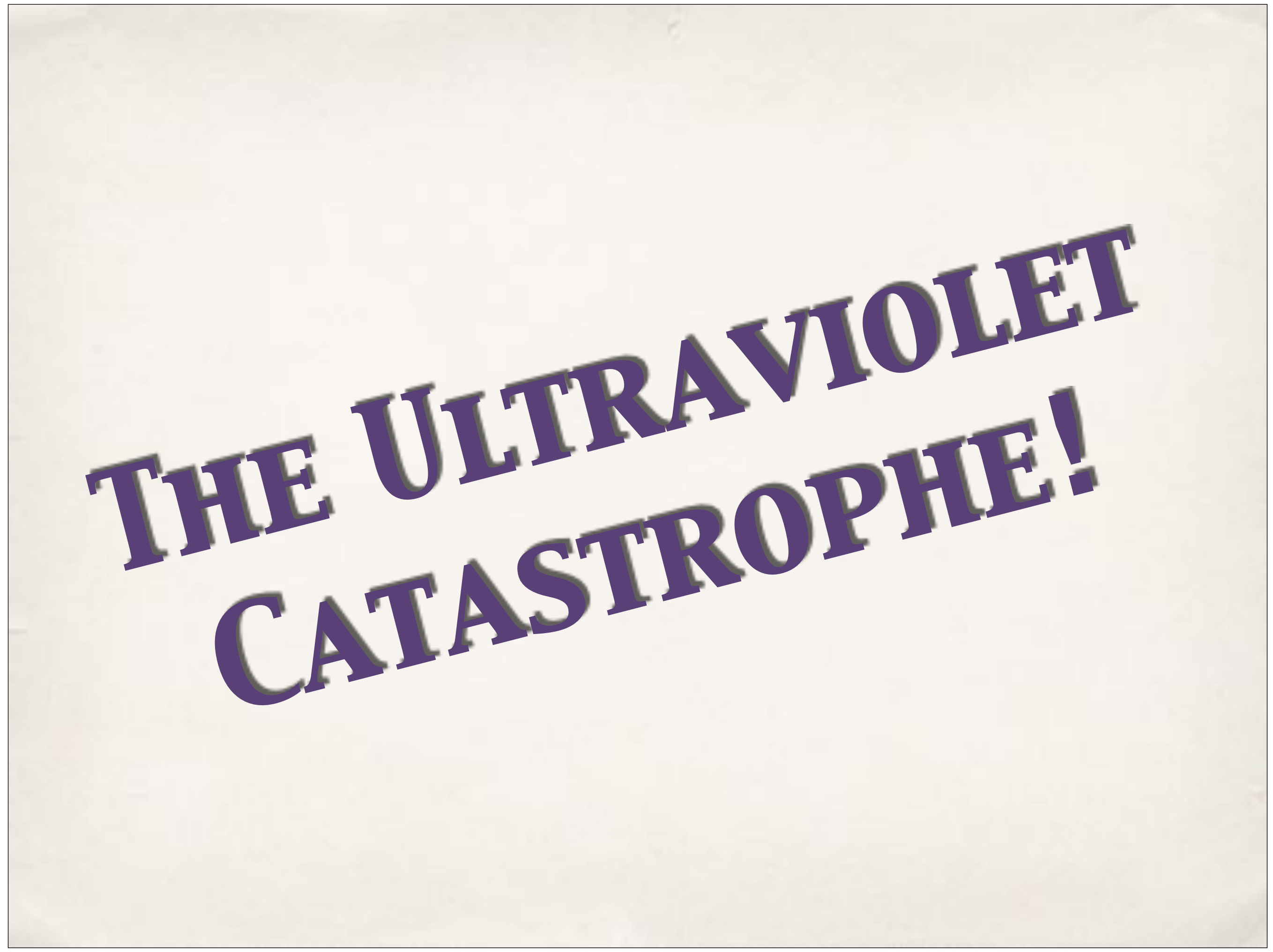
- Graph of the wave's intensity as it meets the wall behind the double-slit
- Notice the similarities and differences when compared to the intensity measured behind the single slit

Fact: *Light produces a diffraction pattern when passed through a single-slit as well as an interference pattern when passed through a double-slit, exactly like a wave. Therefore,* light is a wave

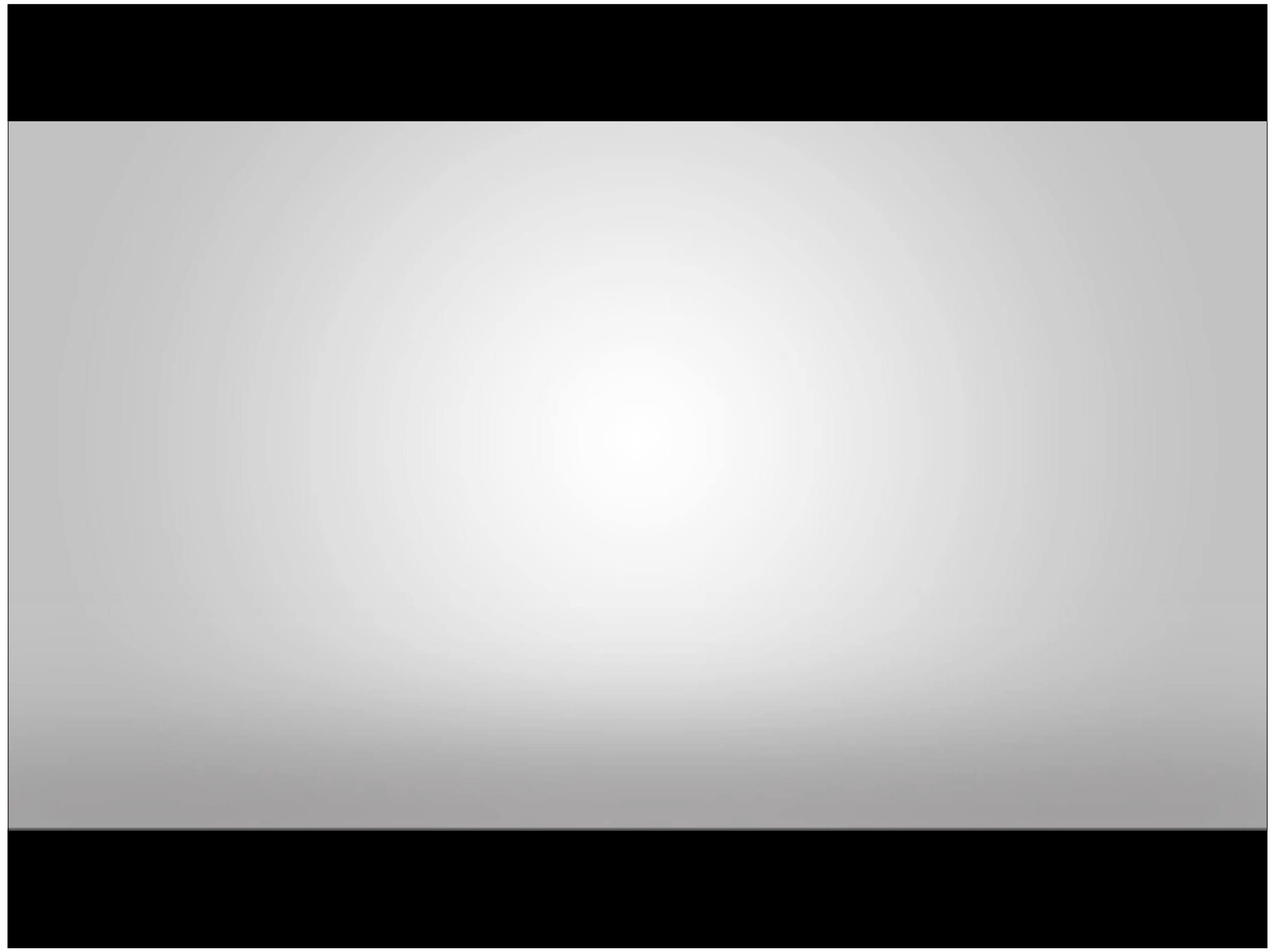
Allies of the Wave Model



- Later, **James Clerk Maxwell** proposed that light is a wave of electricity and magnetism
- The wave model gained support when **Heinrich Hertz** produced radio waves that matched Maxwell's predictions



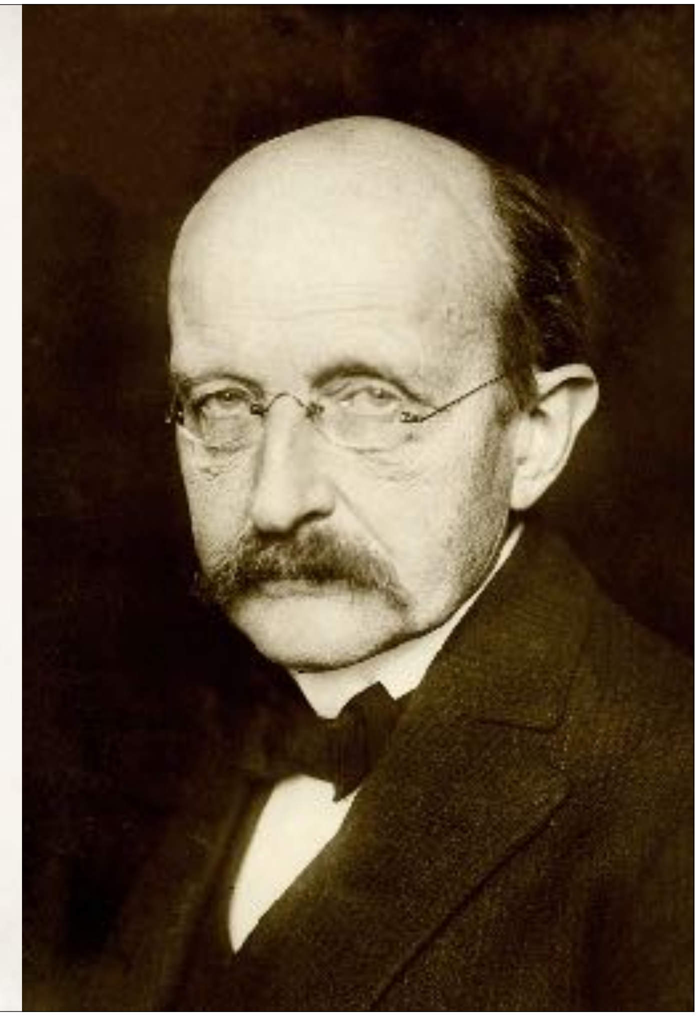
The matter seemed to be settled, until the turn of the 20th Century when physicist discovered a gaping problem with the theory, later dubbed the “ultraviolet catastrophe”

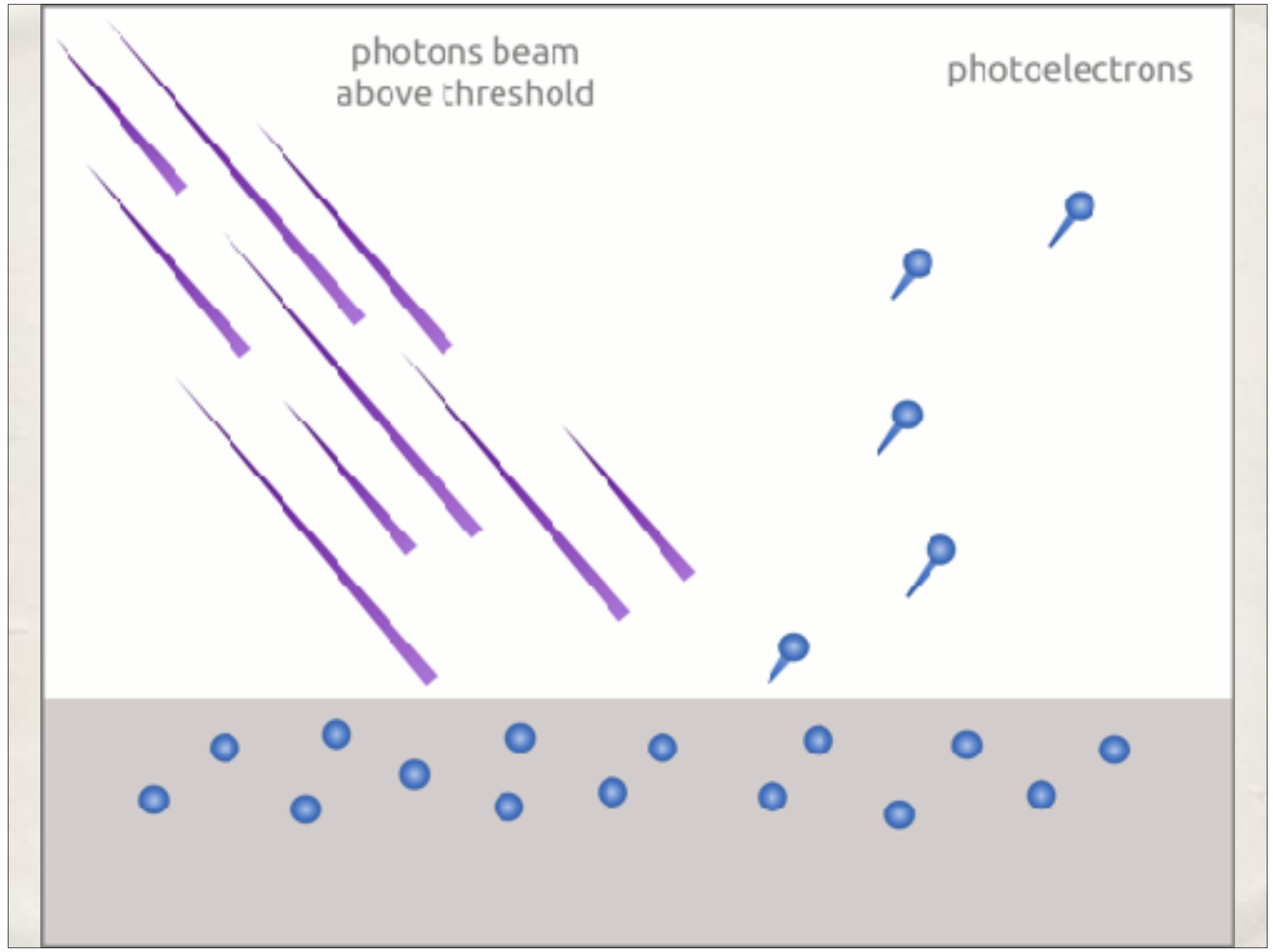


- The Ultraviolet Catastrophe - Physics Girl
  - https://www.youtube.com/watch?v=FXfrncRey-4

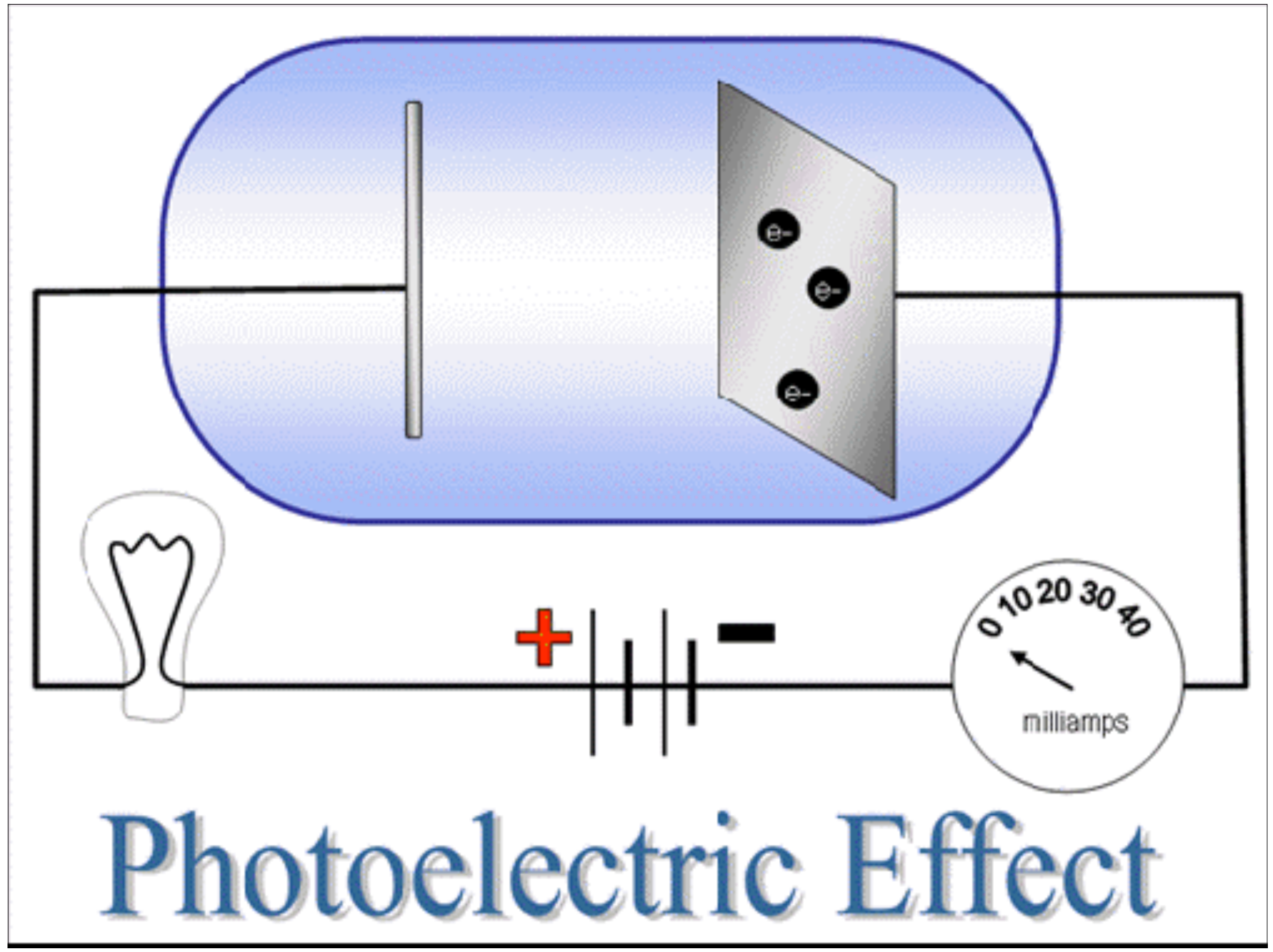
Photons of Light

- **Max Planck** proposed that light comes in little chunks, eventually called ***photons***
  - Treating light in this way allow scientists to fix the theory to match observations
  - This revelation kickstarted the field of quantum mechanics





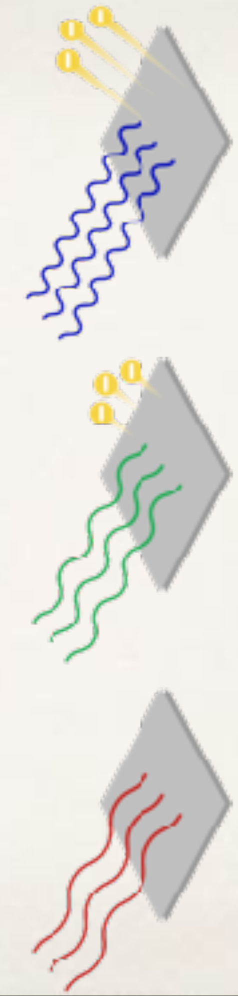
- Thinking of light in term of particles, in terms of photons, helped physicists explain the photoelectric effect — the effect when light hits certain metals and the metal ejects electrons



- You can measure how many electrons are ejected and how fast they are ejected by attaching two metal plates to a battery and ammeter. Separate those plates some distance and hit one of them with light. Electrons will be ejected by the plate hit with the light and caught by the second plate. When the plate catches the electrons, it'll show up as a reading on the ammeter

Here's the problem:

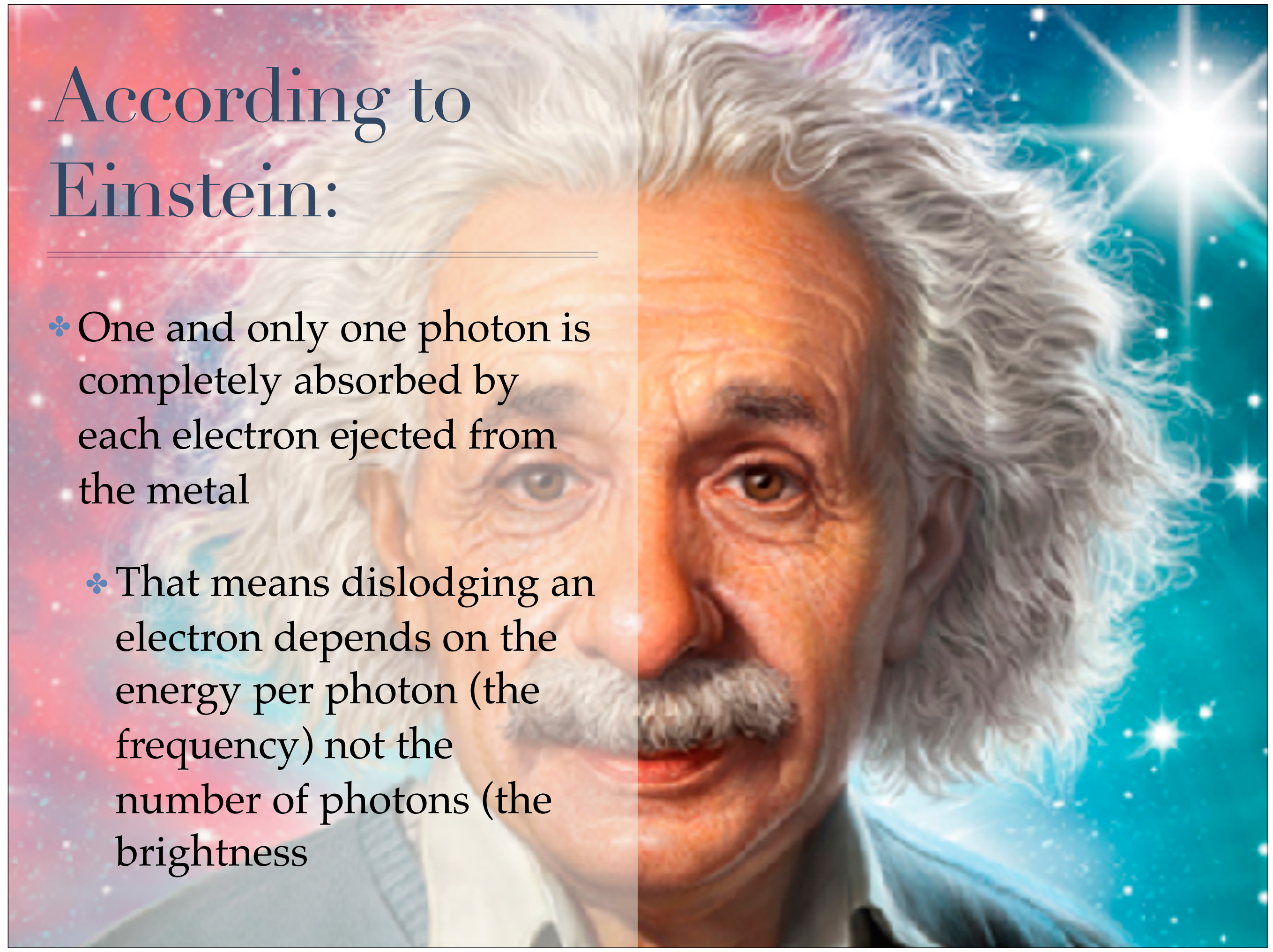
- High-frequency light, even if from a dim source, is capable of ejecting electrons
- Low-frequency light, even if from a very bright source, cannot dislodge electrons



- Since bright light carries more energy than dim light, it was puzzling that dim blue or violet light could dislodge electrons from certain metals when bright red light could not

Light as a Particle

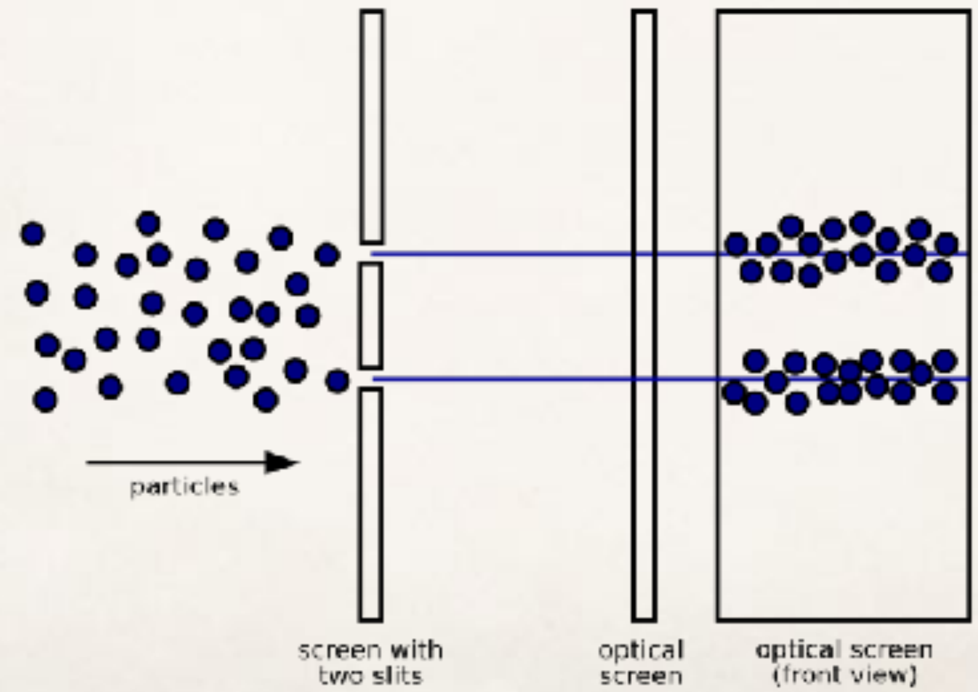
- Photons have **energy** proportional to their **frequency**
- **Brightness** is proportional to the **number of photons**



- The absorption of a photon by an atom is an all-or-nothing process
- A few blue or violet photons have enough energy to dislodge a few electrons, but hordes of red or orange photons cannot eject a single photon
- It was for this (and not for his theory of relativity) that Einstein won the Nobel Prize

Fact: *In its interaction with matter, light can be observed and measured in discreet, localized quantities, exactly like a particle. Therefore,* light is a particle

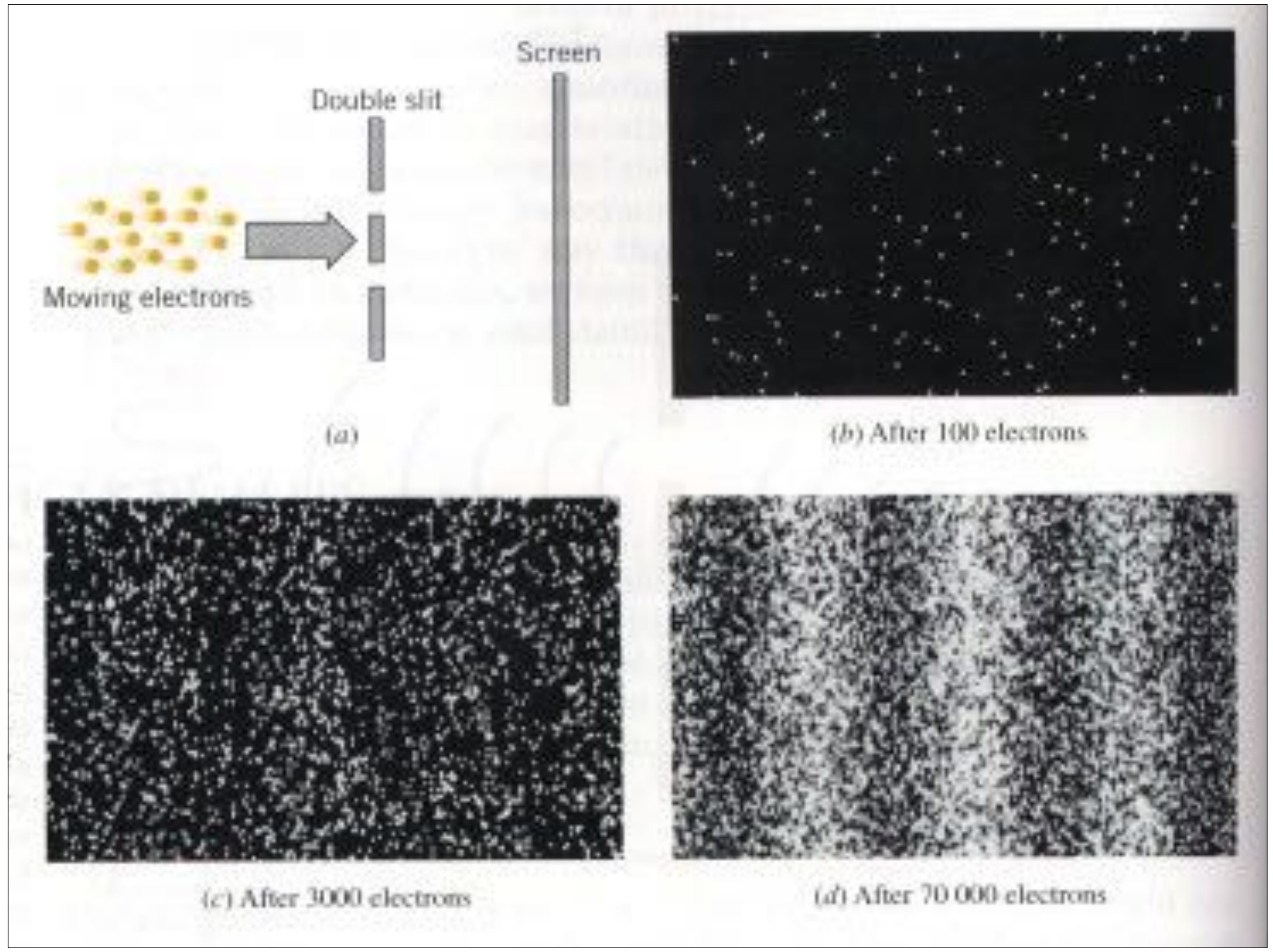
Expectation:



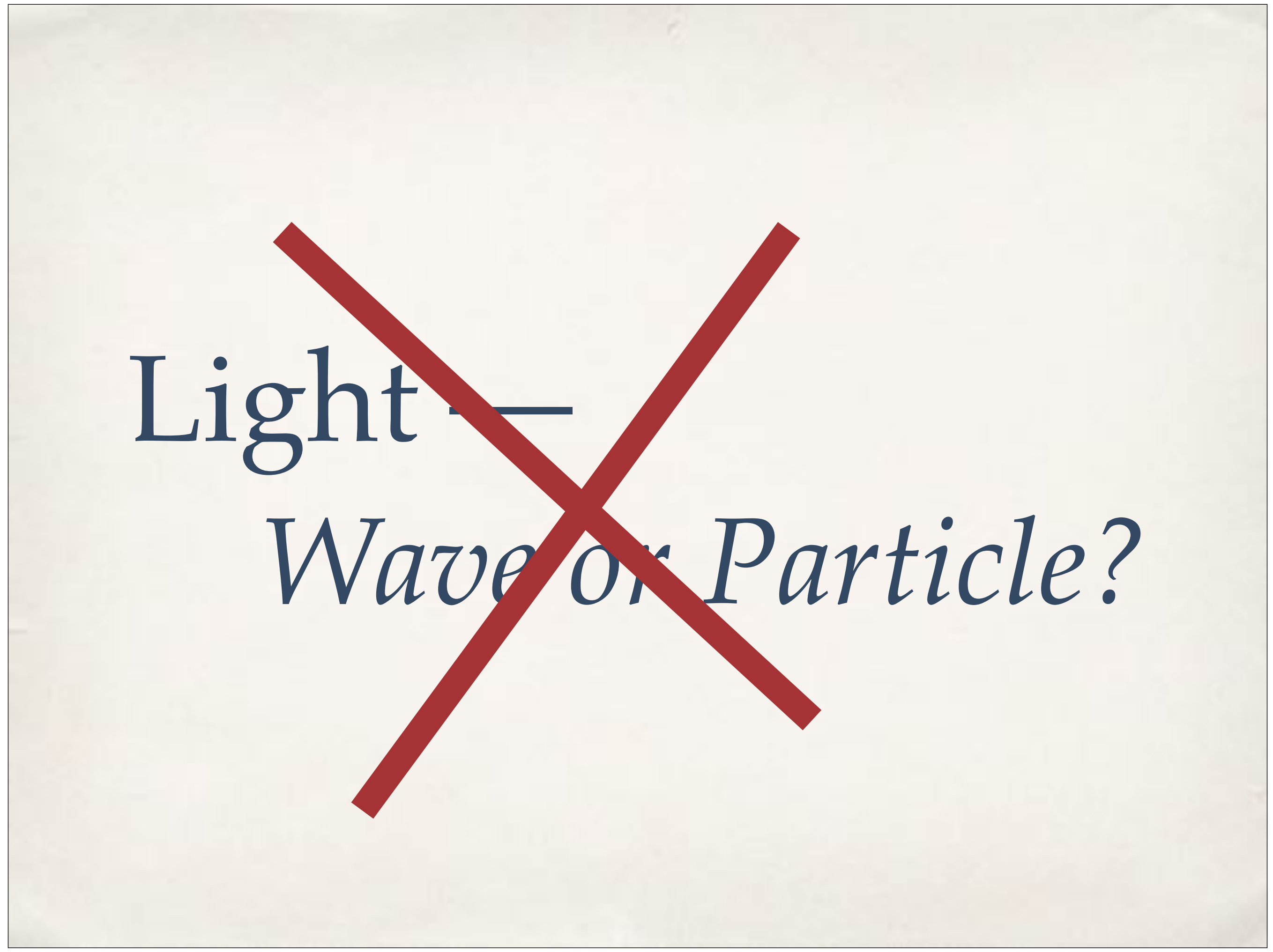
- Go back to the single- and double-slit experiments. If light was a particle, we'd expect all the photons to lump up directly behind either slit, but we know that's not actually what happens

Photon-by-Photon Interference Pattern

- Even when you send in light one photon at a time, you still get the *exact same* diffraction and interference patterns as before



- Send in a stream of electrons (or even one electron at a time), and you get the *exact same* interference pattern as light! Same thing happens to protons or atoms. It's even been done with whole molecules!



- Light (or electrons or any of the other building blocks of the Universe) are fundamentally different than waves or particles. They can behave *like* waves or particles, but that description is more useful than it is accurate