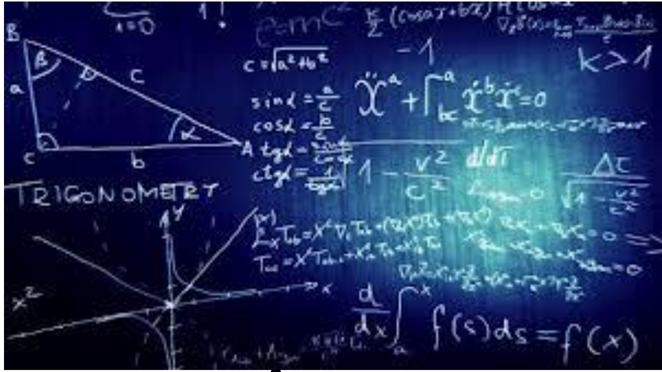


Physics Laboratory – I

Light and Optics - II

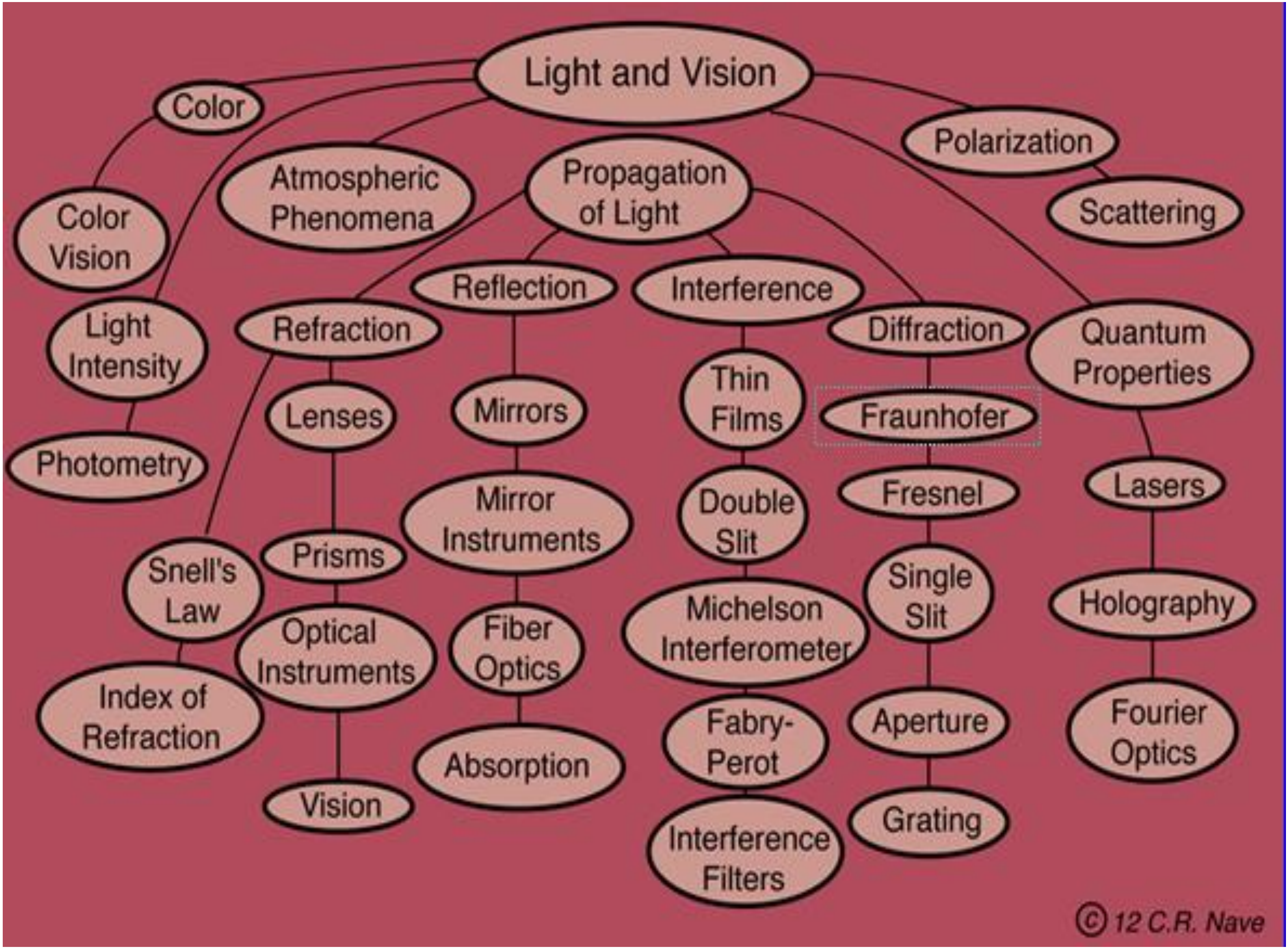
Experiment:

DIFFRACTION of LIGHT

a) Single Slit / b) Double Slit /

Ins. Fatma Nur AKI

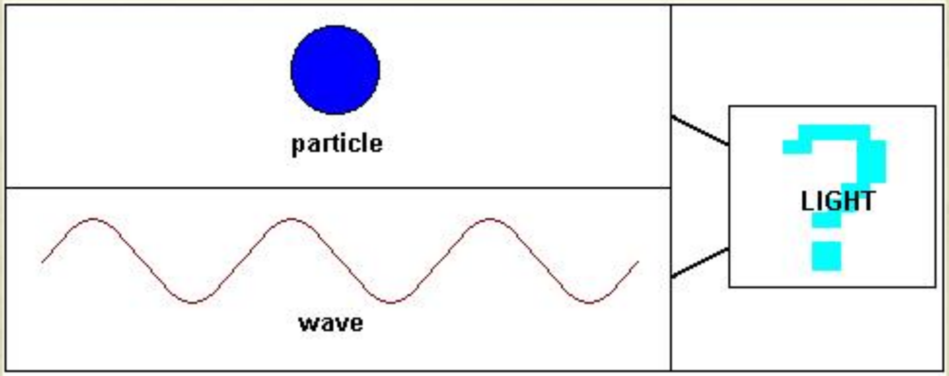
fnaki@ticaret.edu.tr


Light and Vision
Color
Color Vision
Light Intensity
Photometry
Atmospheric Phenomena
Propagation of Light
Polarization
Scattering
Reflection
Interference
Refraction
Diffraction
Quantum Properties
Lenses
Mirrors
Thin Films
Fraunhofer
Fresnel
Lasers
Snell's Law
Prisms
Mirror Instruments
Double Slit
Single Slit
Holography
Index of Refraction
Optical Instruments
Fiber Optics
Michelson Interferometer
Fabry-Perot
Aperture
Fourier Optics
Vision
Absorption
Grating
Interference Filters
© 12 C.R. Nave

History of Optics

last but not least…

Nowadays, we know that:
The light is neither wave nor particle.
It behaves like both.



How to imagine the wave-particle duality.

A strange dualism inherent to all matter, especially on the sub-atomic scale called the wave-particle duality.

https://actu.epfl.ch/news/the-first-ever-photograph-of-light-as-both-a-parti/

Objectives

1. Calculate the frequency or wavelength of light when given one of the two.
2. Describe the relationship between frequency, energy, color, and wavelength.
3. Interpret the interference pattern from a diffraction grating.

What is Light??

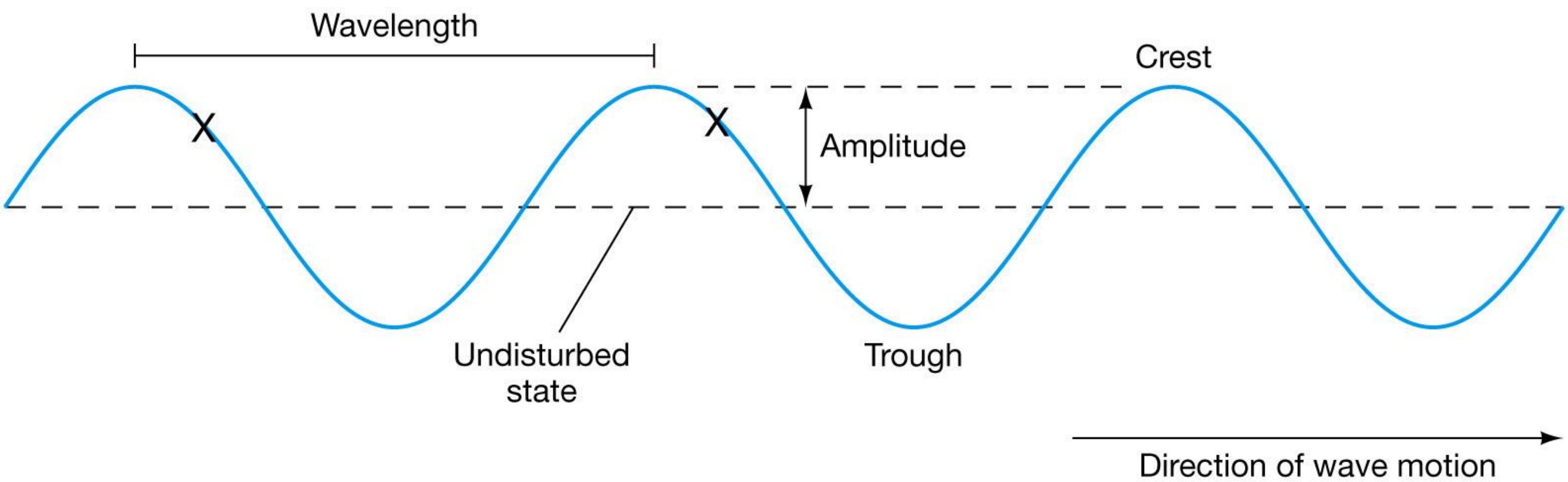
- The terms *light, radiation,* and *electromagnetic wave* can all be used to explain the same concept.
- Light comes in many forms and it took physicists some time to realize that X-rays, visible light, radio waves, etc. are all the same phenomena.

Light as a Wave

- **One way to think about light is as a traveling wave**
- A wave is just a disturbance in some medium (water, air, space)
- A wave travels through a medium but does not transport material
- **A wave can carry both energy and information**

Wave Terminology

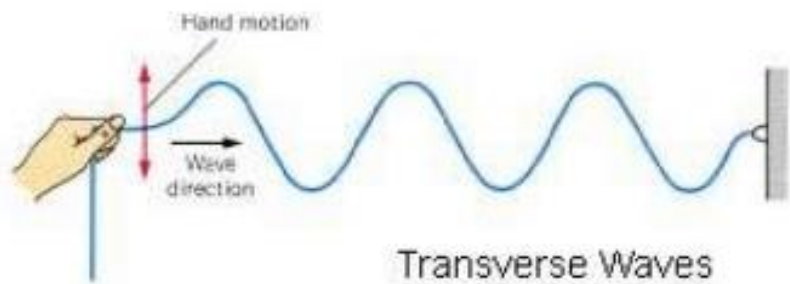
- ***Wavelength*** - distance between two like points on the wave
- ***Amplitude*** - the height of the wave compared to undisturbed state/ The amplitude of a periodic variable is a measure of its change over a single period.
- ***Period*** - the amount of time required for one wavelength to pass
- ***Frequency*** - the number of waves passing in a given amount of time



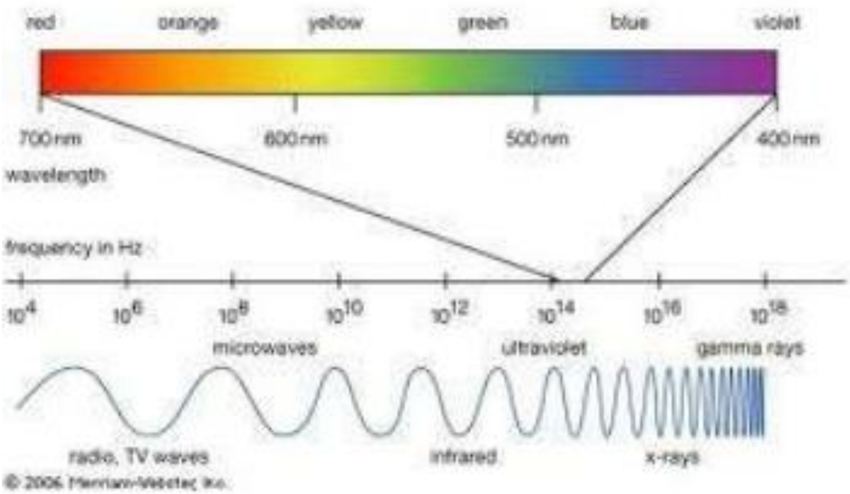
Main Types of Waves

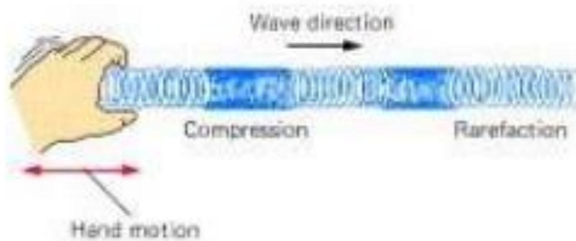
- Mechanical
- Electromagnetic
- Transverse
- Compressional

Ocean Waves are Mechanical Waves



Transverse Waves





Compressional Waves

Wave Relationships

- Notice from the definitions we can relate the properties of a wave to one another

$$frequency = {}^{1}\!/_{period}$$

$$velocity = \frac{wavelength}{period} = wavelength.frequency$$

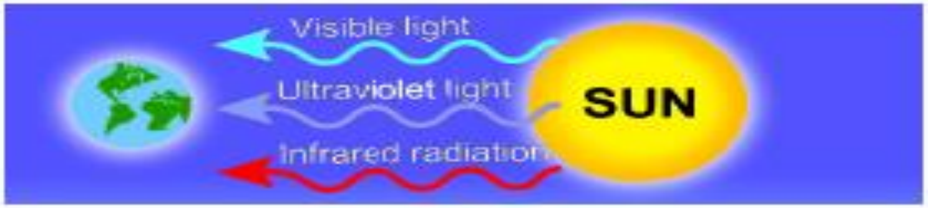
Speed of Light

Speed of light
3×10^8 m/sec

$$c = f\,\lambda$$

Wavelength (m)

Frequency (Hz)



Wave Relationships

- Frequency is usually expressed in the unit of ***Hertz***
  - This unit is named after a German scientist who studied radio waves

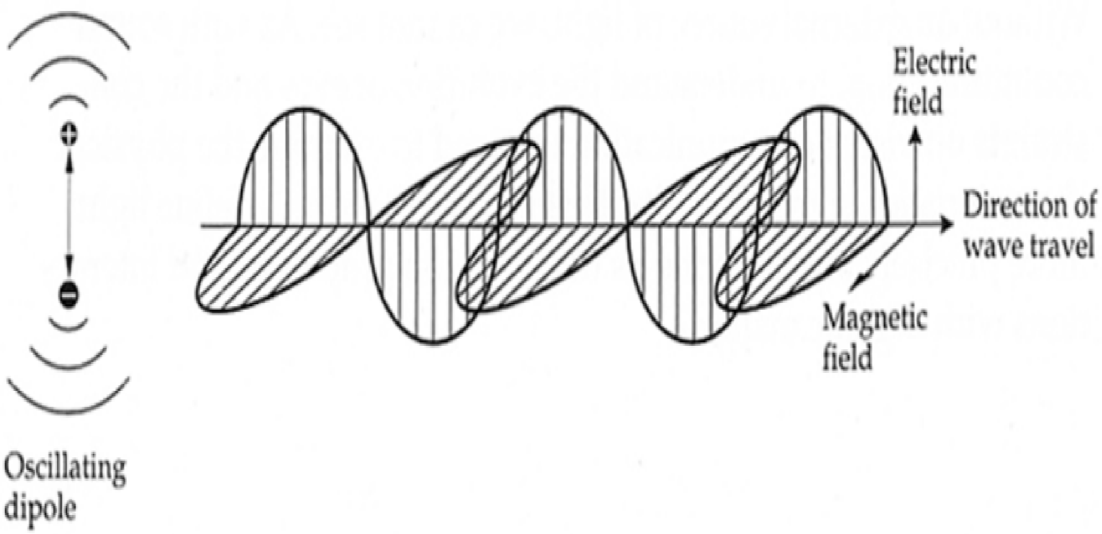
$$1Hz = \frac{1}{s}$$

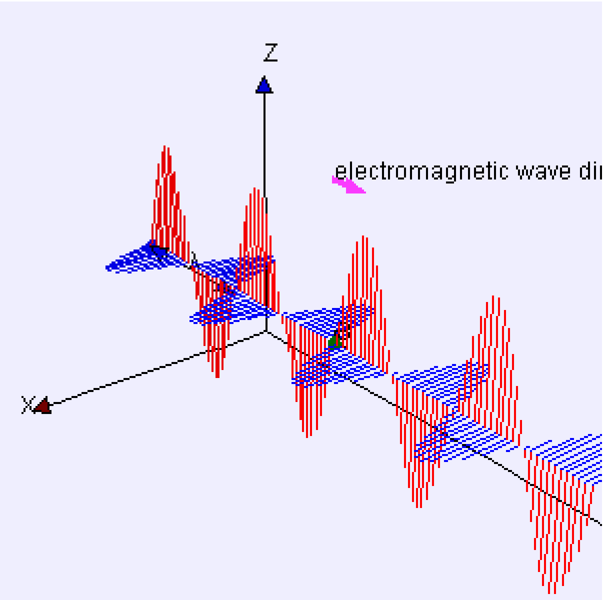
  - For example, if a wave has a period of 10 seconds, the frequency of the wave would be 1/10 Hz, or 0.1 Hz

- Note that light is always traveling at the same speed ($c \sim 3 \times 10^8$ m/s)

  - Remember: *velocity* = *wavelength* x *frequency*
    - If frequency increases, wavelength decreases
    - If frequency decreases, wavelength increases

EM Wave

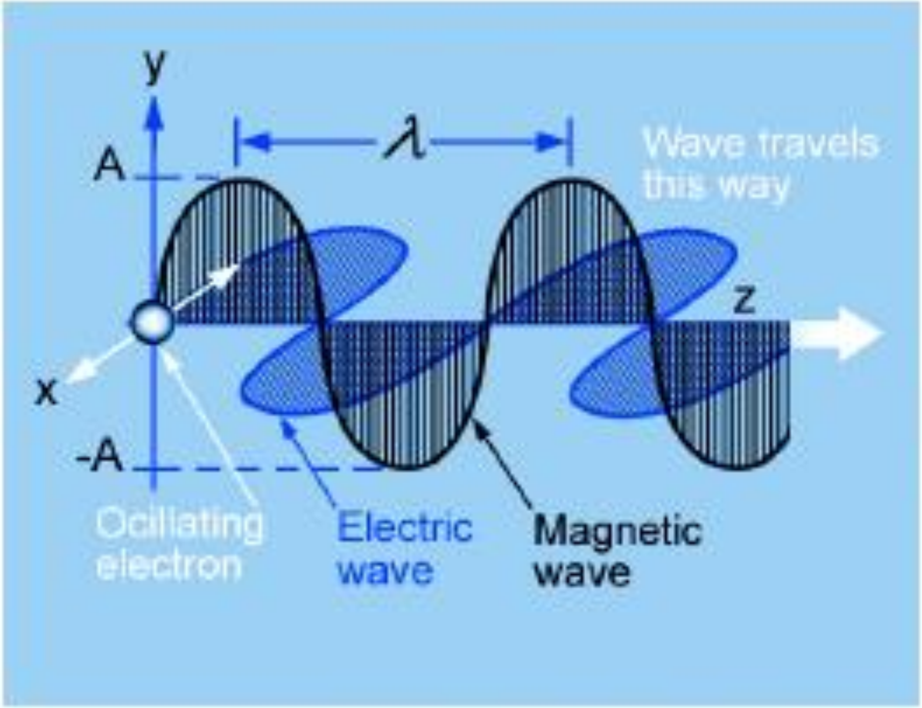




- EM waves are generated by vibrating electrons
- Composed of two perpendicular oscillating fields
- Can be characterized by its frequency, which is inversely related to wavelength ($f = c / \lambda$)
- Shares with sound the properties of spreading loss, attenuation, reflection, refraction, and diffraction, but can travel in vacuum

The Electromagnetic Spectrum

- Electromagnetic waves have both an electric part and a magnetic part and the two parts exchange energy back and forth.
- A 3-D view of an electromagnetic wave shows the electric and magnetic portions.



- **The wavelength and amplitude of the waves are labeled λ and A, respectively.**
- http://www.youtube.com/watch?v=nt-A1Cr6Aao

The Electromagnetic Spectrum

- The higher the frequency of the light, the higher the energy of the wave.
- Since color is related to energy, there is also a direct relation between color, frequency, and wavelength.

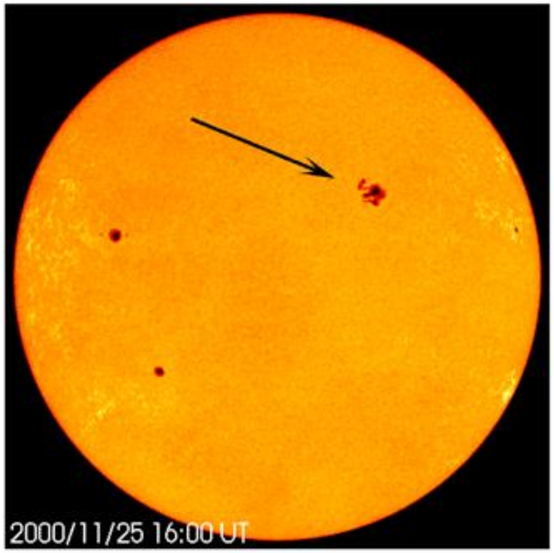
Color		Wavelength (nanometers)	Frequency (THz)
Red		650	462
Orange		600	500
Yellow		580	517
Green		530	566
Blue		470	638
Violet		400	750

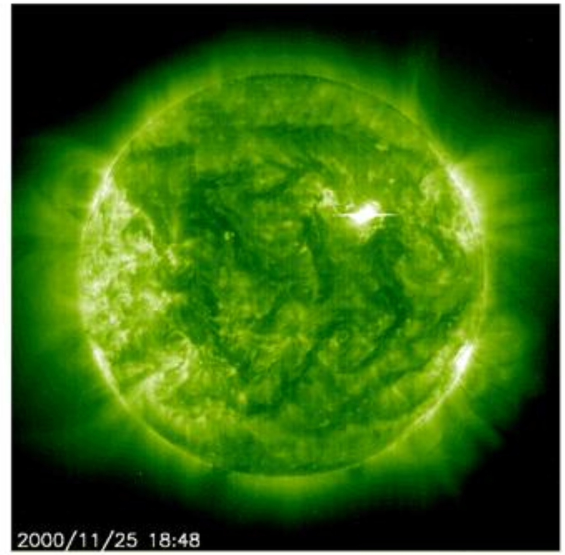
EM Spectrum in Astronomy

- If we could only observe in visible light, our knowledge of the universe would be greatly limited
- By looking at objects at different wavelengths, we get a different view and lots more information
- Some objects are only visible at certain wavelengths

The Sun at Different Wavelengths

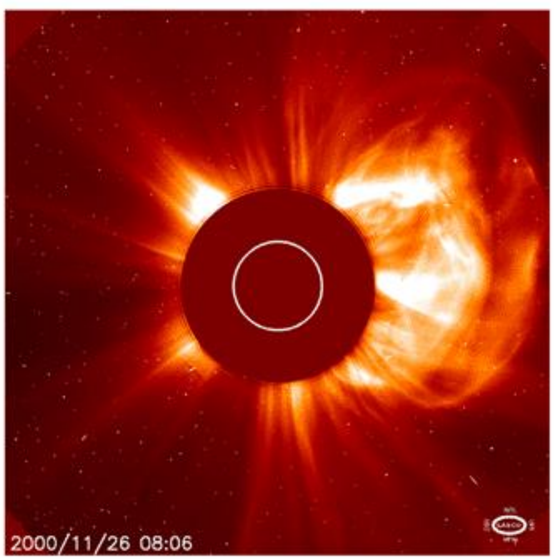
Visible

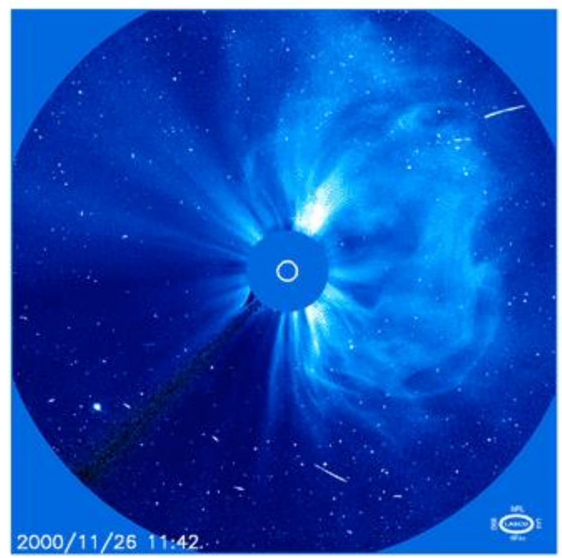




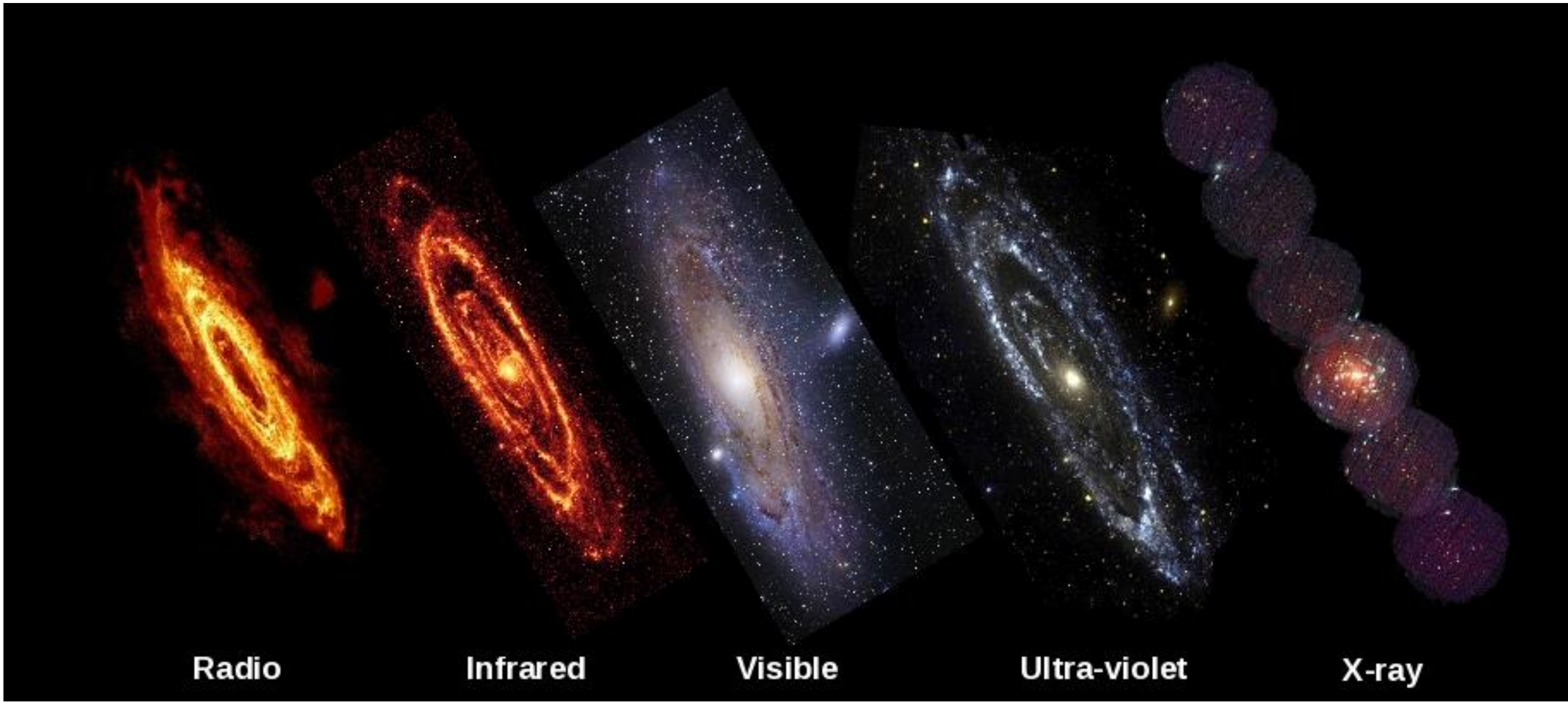
Ultraviolet

X-ray





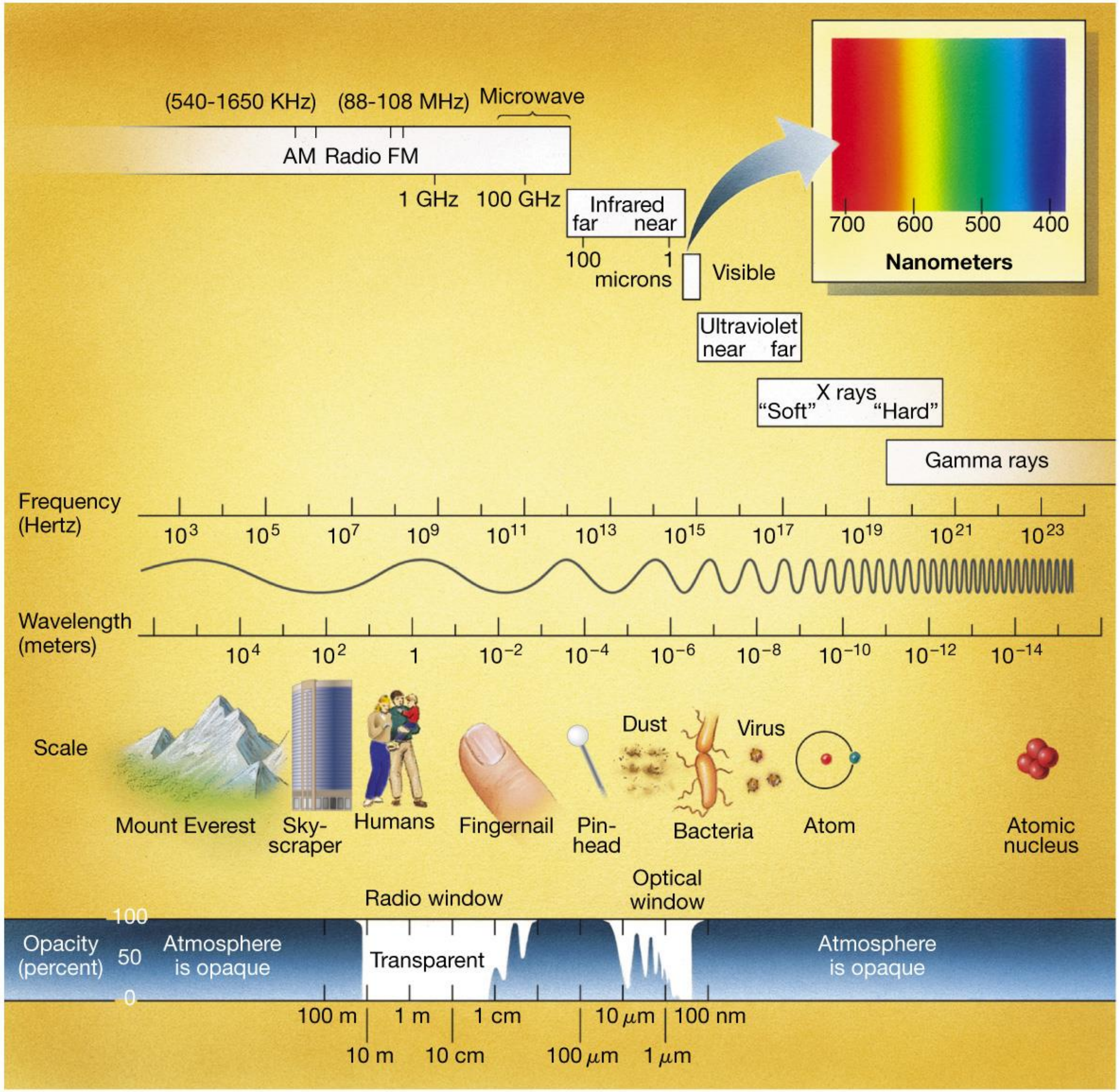
X-ray

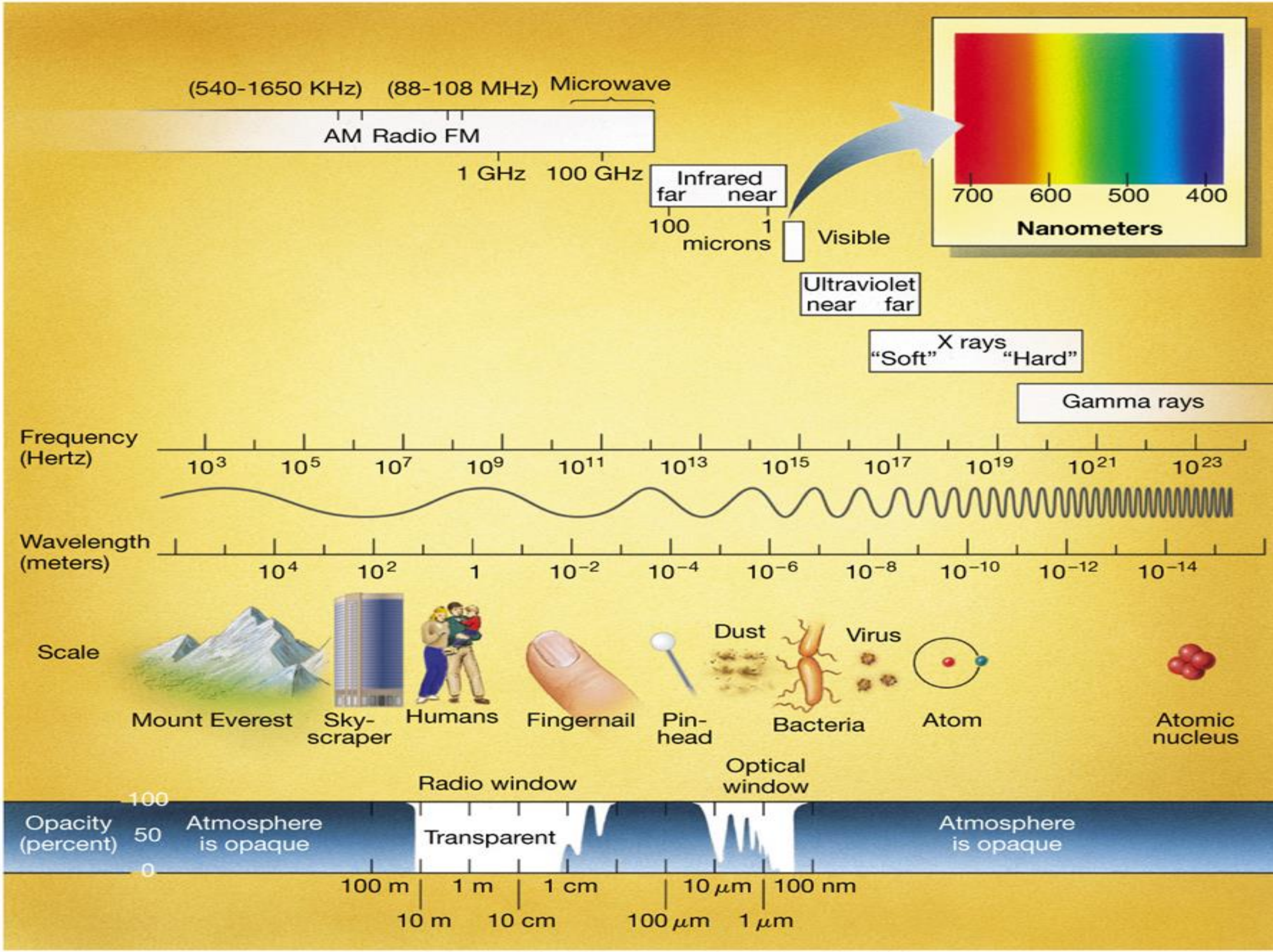

Radio
Infrared
Visible
Ultra-violet
X-ray

Radio
Microwave
Infrared
UV
X-Ray
Gamma Ray
Radio
60,000 nm
600 K
Infrared
1200-800 nm (10-3.6 um)
4,500 K
Optical
450-750 nm
6,000 K
Ultraviolet
400-200 nm
10,000 K
X-ray
100-10 nm
10,000,000 K
Multiwavelength Whirlpool Galaxy
COLD GAS: Radio waves reveal regions of gas cool enough for CO_2 molecules to exist.
COOL STARS: Infrared shows smaller cool red stars that make up most of the galaxy.
SOLAR STARS: Optical light comes from stars around the size of the Sun.
HOT STARS: Ultraviolet shows the larger hot blue stars that are less frequent in galaxies.
HOT GAS: X-rays are emitted from the hottest regions of gas where atoms are ionized.
COOL LOW ENERGY RADIATION
VISIBLE LIGHT
HOT HIGH ENERGY RADIATION

The Electromagnetic Spectrum

- Human eyes are only able to process information from the visible part of the spectrum
- Toward longer wavelengths, the spectrum includes infrared light, microwaves, and radio
- Toward shorter wavelengths, the spectrum includes ultraviolet light, X-rays, and gamma rays
- All of these are forms of electromagnetic radiation





(540-1650 KHz)
(88-108 MHz)
Microwave
AM Radio FM
1 GHz
100 GHz
Infrared
far near
100
1
microns
Visible
700
600
500
400
Nanometers
Ultraviolet
near far
X rays
"Soft"
"Hard"
Gamma rays
Frequency (Hertz)
10^3
10^5
10^7
10^9
10^11
10^13
10^15
10^17
10^19
10^21
10^23
Wavelength (meters)
10^4
10^2
1
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
Scale
Dust
Virus
Mount Everest
Sky-scraper
Humans
Fingernail
Pin-head
Bacteria
Atom
Atomic nucleus
Radio window
Optical window
100
Opacity (percent)
50
0
Atmosphere is opaque
Transparent
Atmosphere is opaque
100 m
1 m
1 cm
10 μm
100 nm
10 m
10 cm
100 μm
1 μm

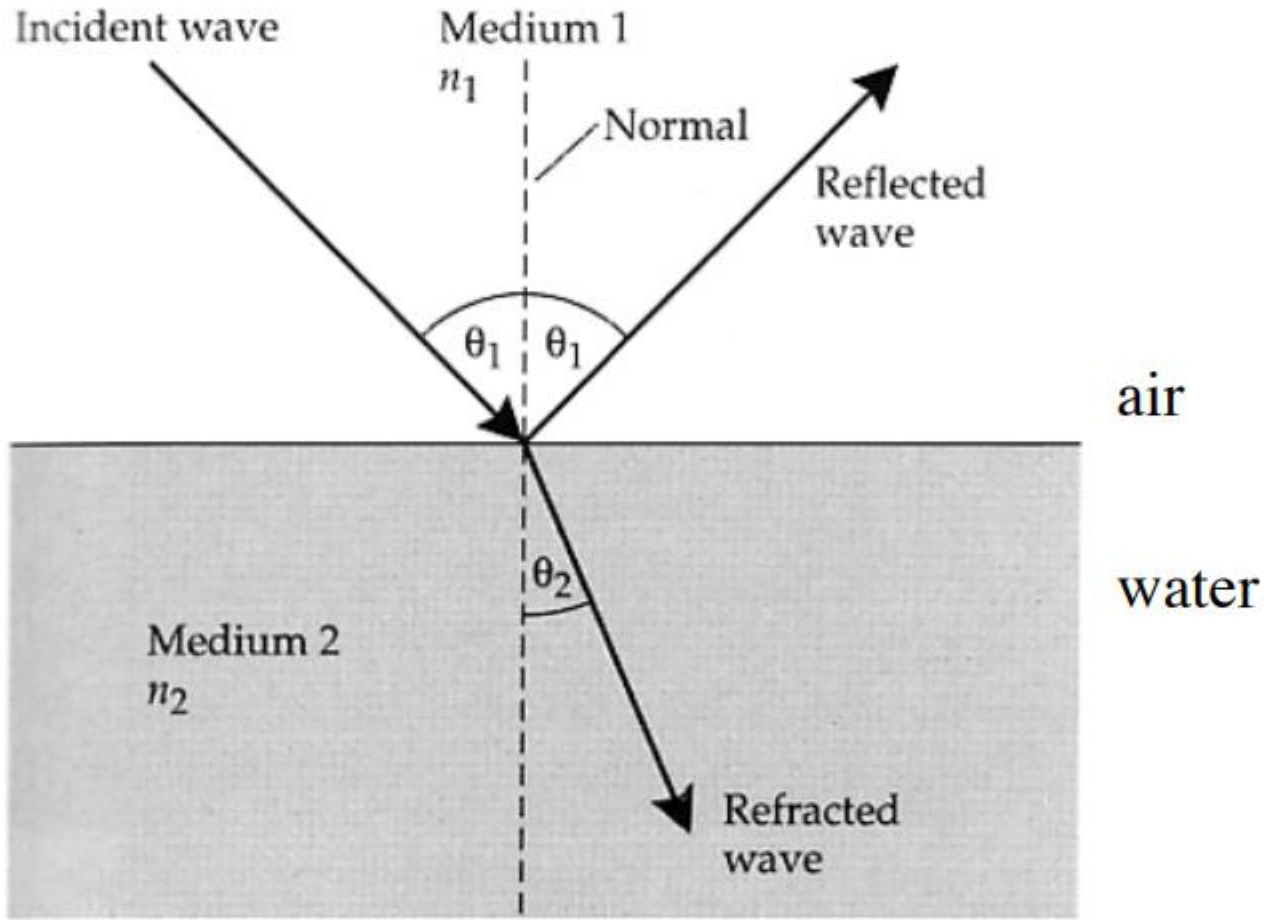
The Wave Nature of Light

Speed of light depends on media

Medium	Speed (m/s)	Refractive index
Vacuum	3×10^8	
Air	2.99×10^8	1.00028
Water	2.25×10^8	1.33
Glass	1.99×10^8	1.5
Diamond	1.25×10^8	2.4

Speed of light is slower in water than in air (opposite to sound)

Light reflects and refracts



When 2nd medium has slower speed, light refracts towards normal

Refraction

Figure 3

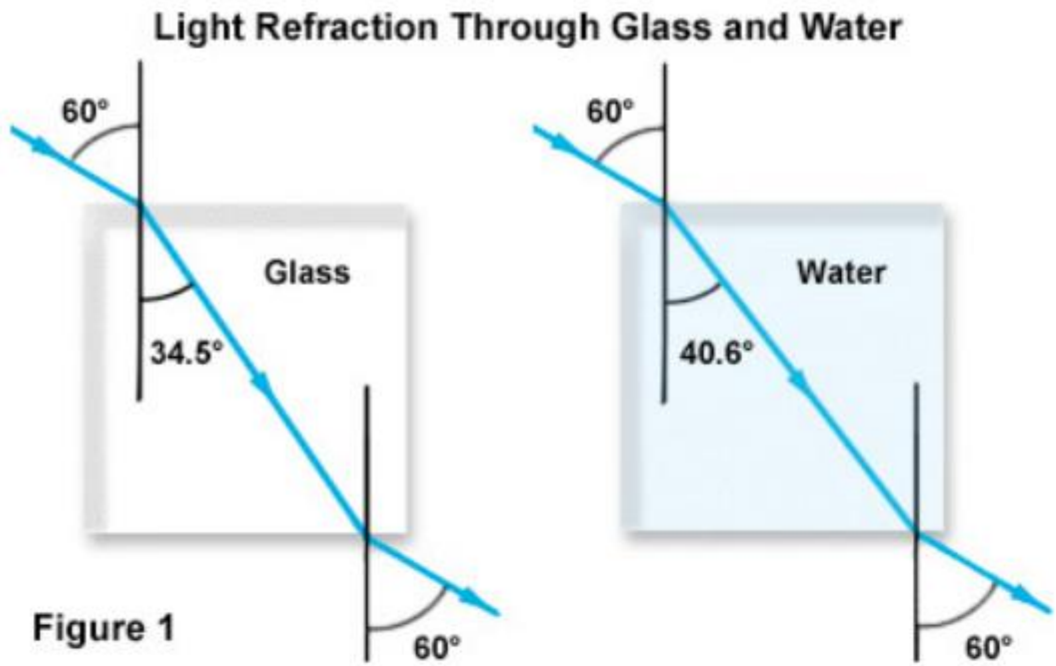
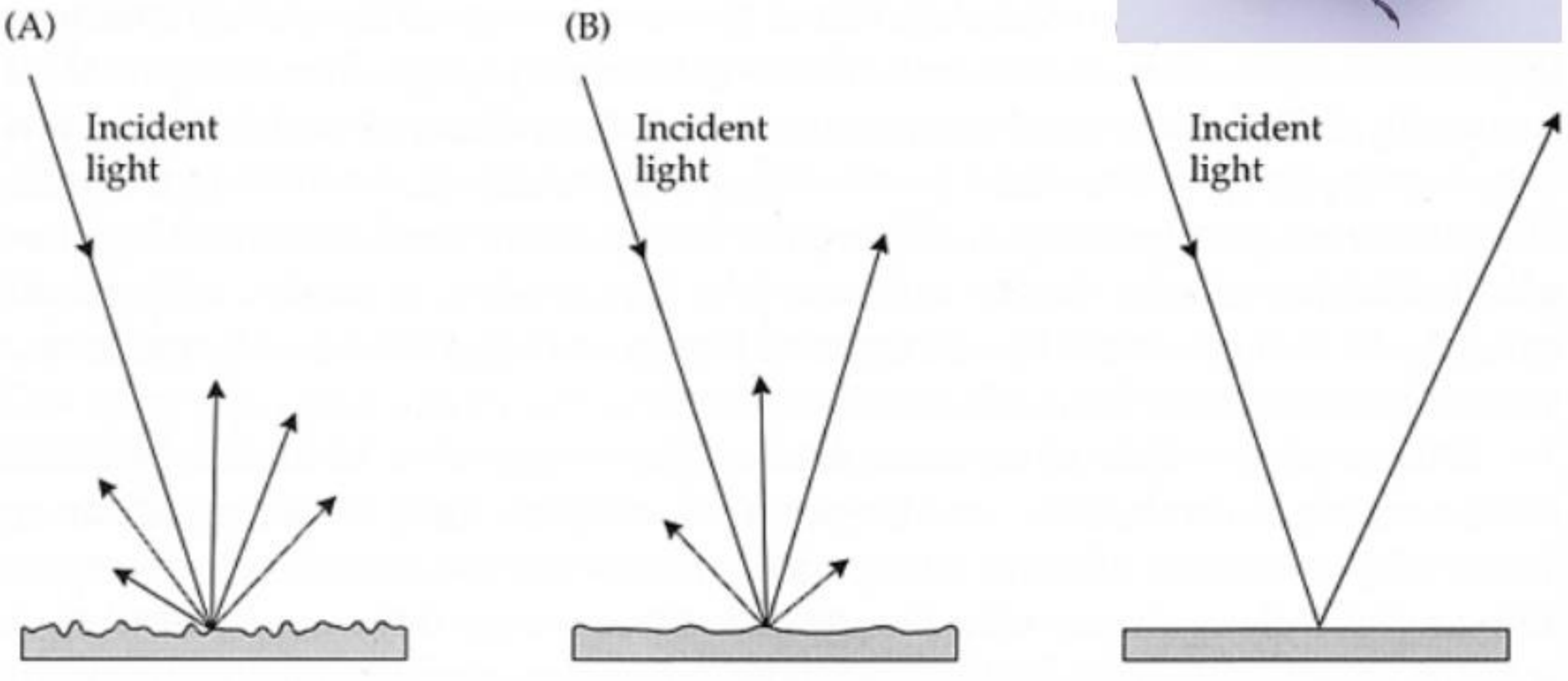


Figure 1

http://micro.magnet.fsu.edu/optics/lightandcolor/refraction.html

Reflectance



Diffuse (dull, matte)

Specular (shiny)

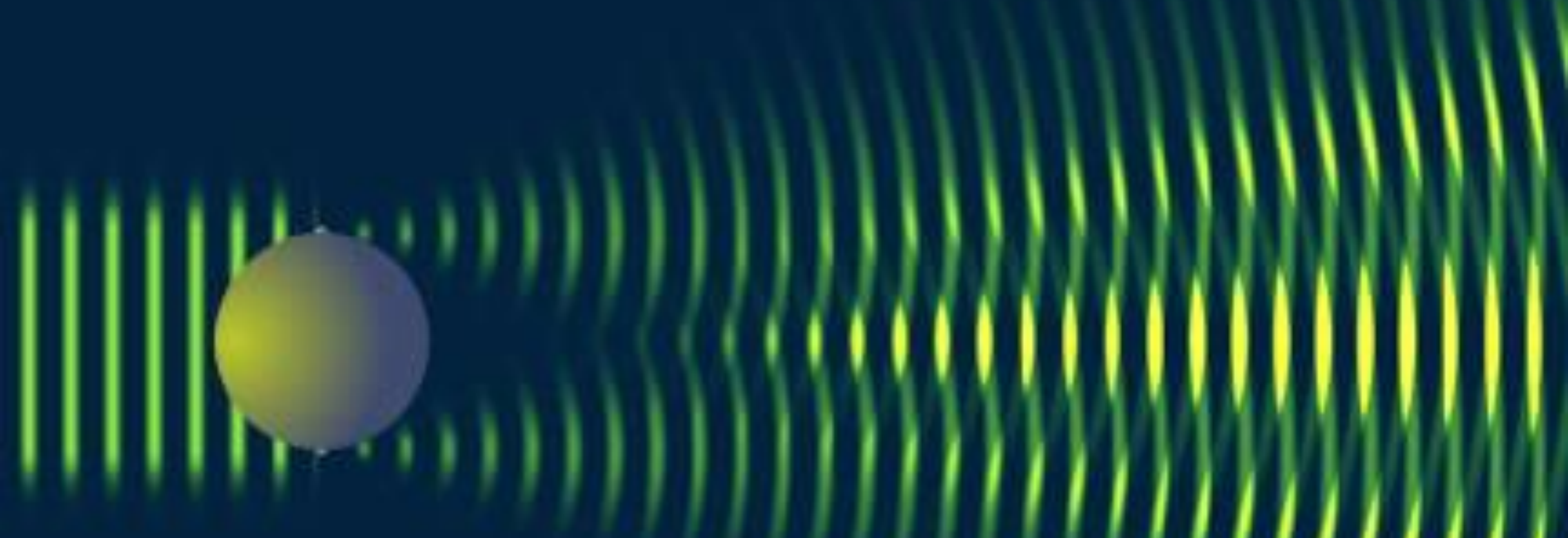
Water absorbs red faster than blue

Refraction depends on frequency

http://www.allfloyd.com/images/covers/darkside.jpg

Refraction causes rainbows

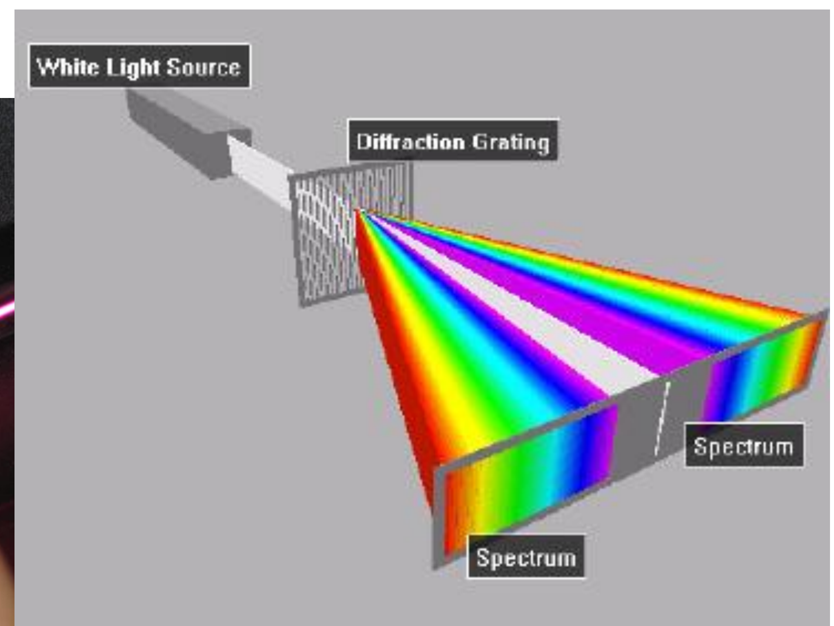
Diffraction



Any bending of a wave around an obstacle or edges of an opening by means other than reflection or refraction.

Diffraction Grating

- A series of closely spaced parallel slits or grooves that are used to separate colors of light by interference.
- Different colors have different wavelengths and diffract at different rates.
- So they constructively interfere at different places.



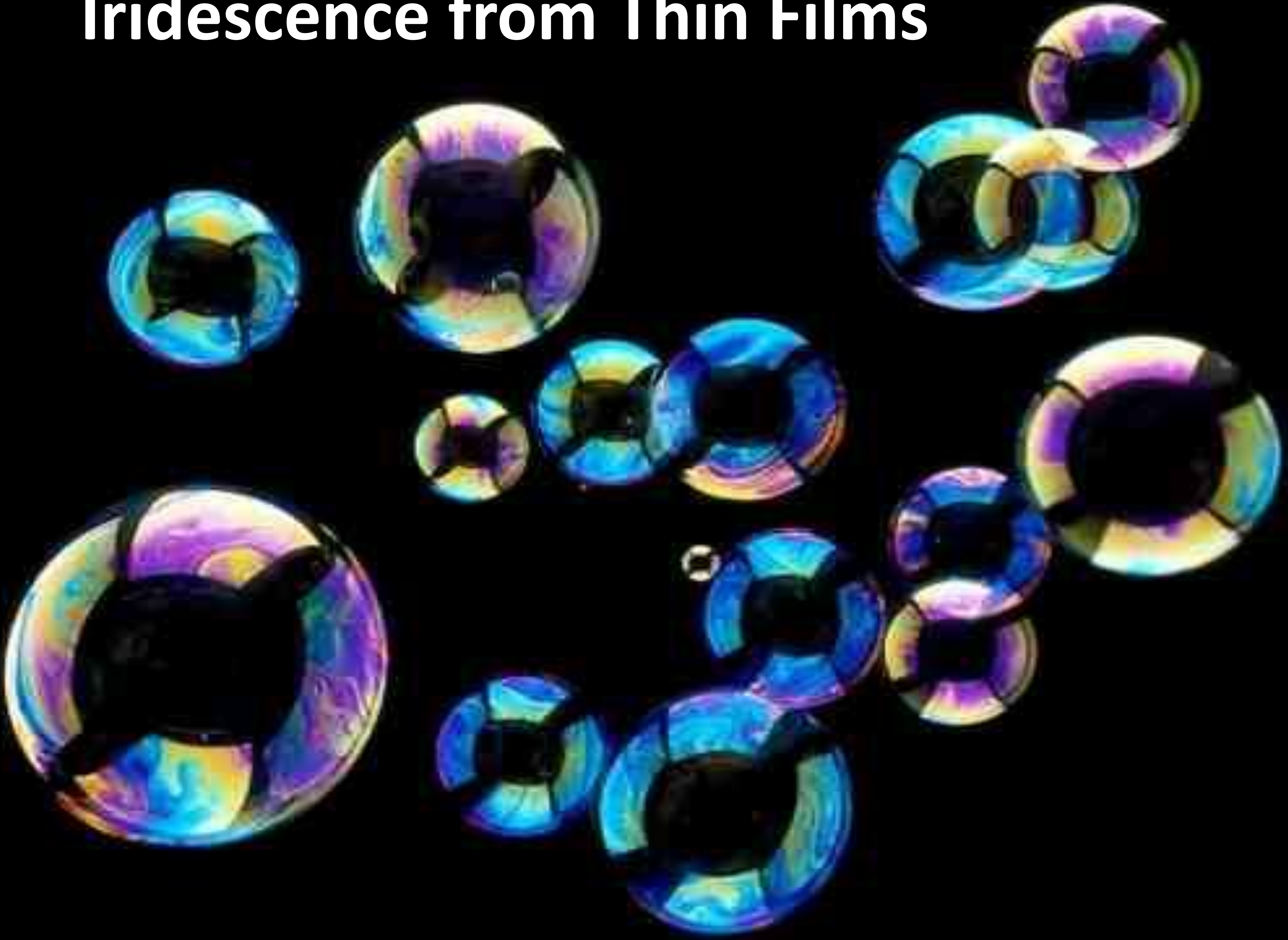
Natural Diffraction Gratings

Structural color: color arising from the diffraction of light by the surfaces and interference in an object, rather than from any absorption of light by pigments.

Image by Shyamal
http://commons.wikimedia.org/wiki/File:LabradoriteOslo.jpg on Wikimedia commons

Image by Geoff Gallice
http://www.flickr.com/photos/11014423@N07/5596526523 on flickr

Iridescence from Thin Films

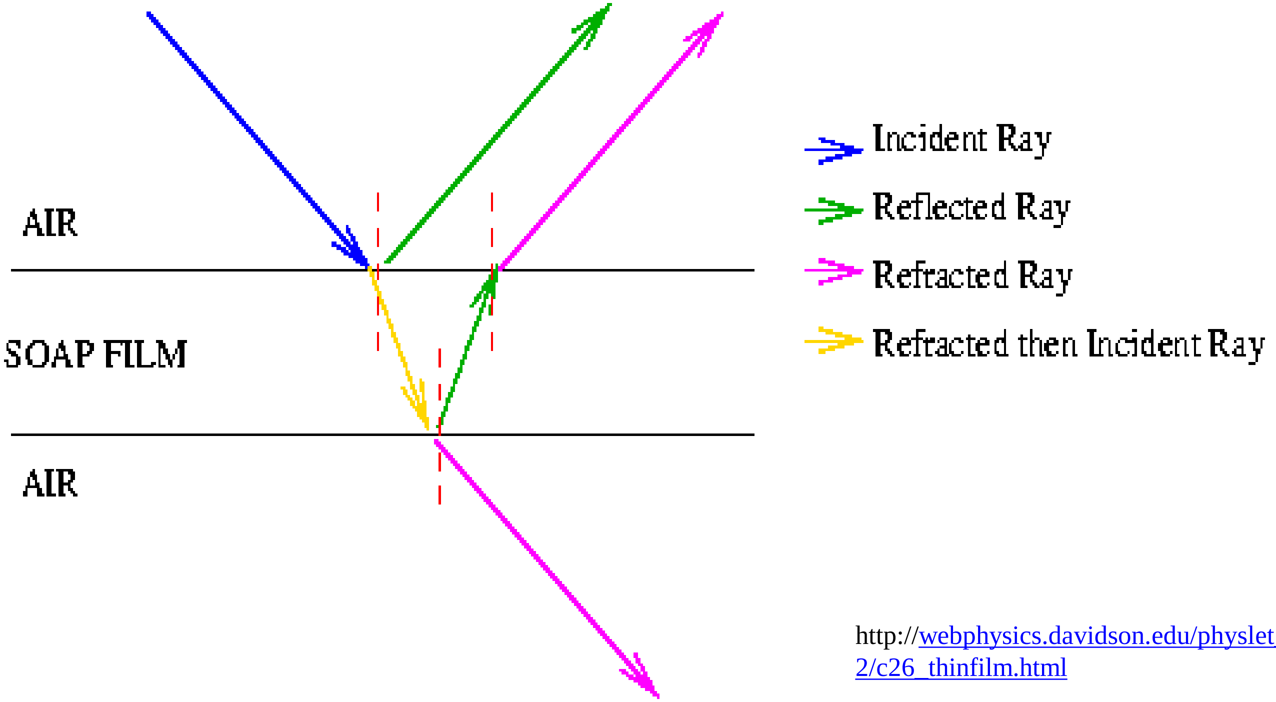


Iridescence from Thin Films

<u>**Iridescence:**</u> ***The phenomenon whereby interference of light waves of mixed frequencies reflected from the top and bottom of thin films produces a spectrum of colors.***

Iridescence From Thin Films

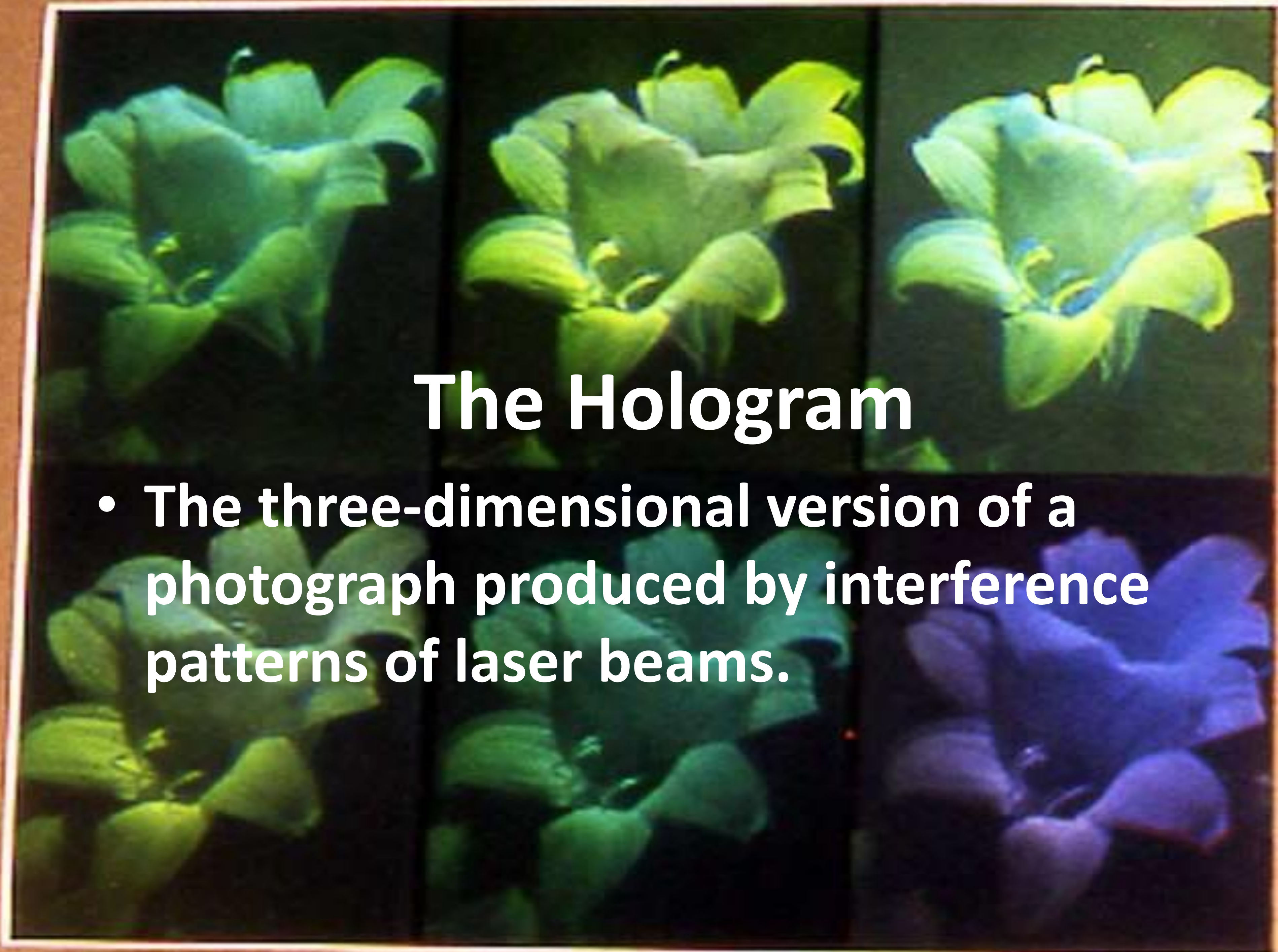
- A thin film, such as a soap bubble or oil on water, has two closely spaced surfaces.
- Light that reflects from one surface may cancel light of a certain frequency that reflects from the other surface.



http://webphysics.davidson.edu/physlet_resources/bu_semester2/c26_thinfilm.html

Laser Light

- Laser light is coherent.
- “LASER” = Light Amplification by Stimulated Emission of Radiation

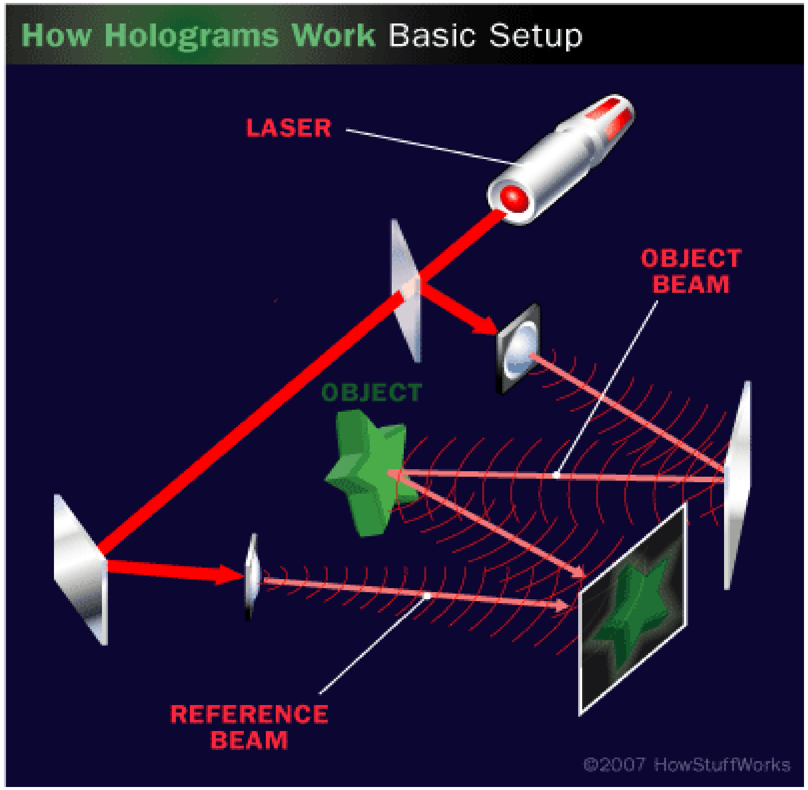


The Hologram

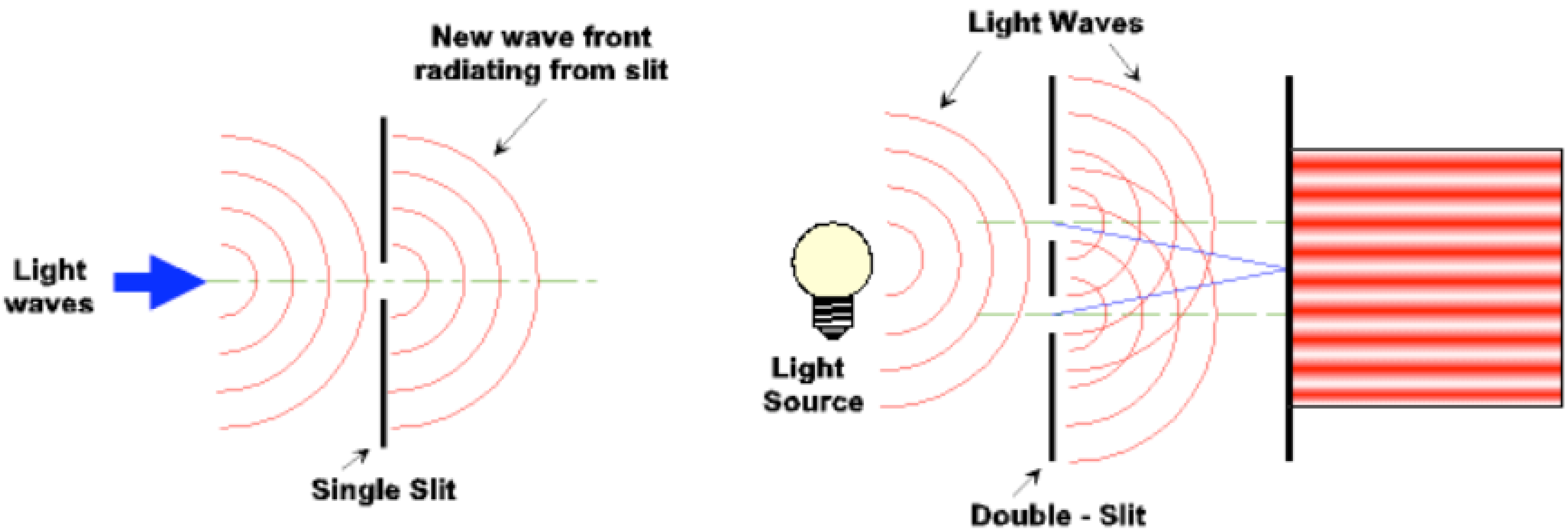
- The three-dimensional version of a photograph produced by interference patterns of laser beams.

The Hologram

- The interference of the laser beams produces fringe patterns on the photographic plate that record the depth of the surface of an object.



Light Diffraction



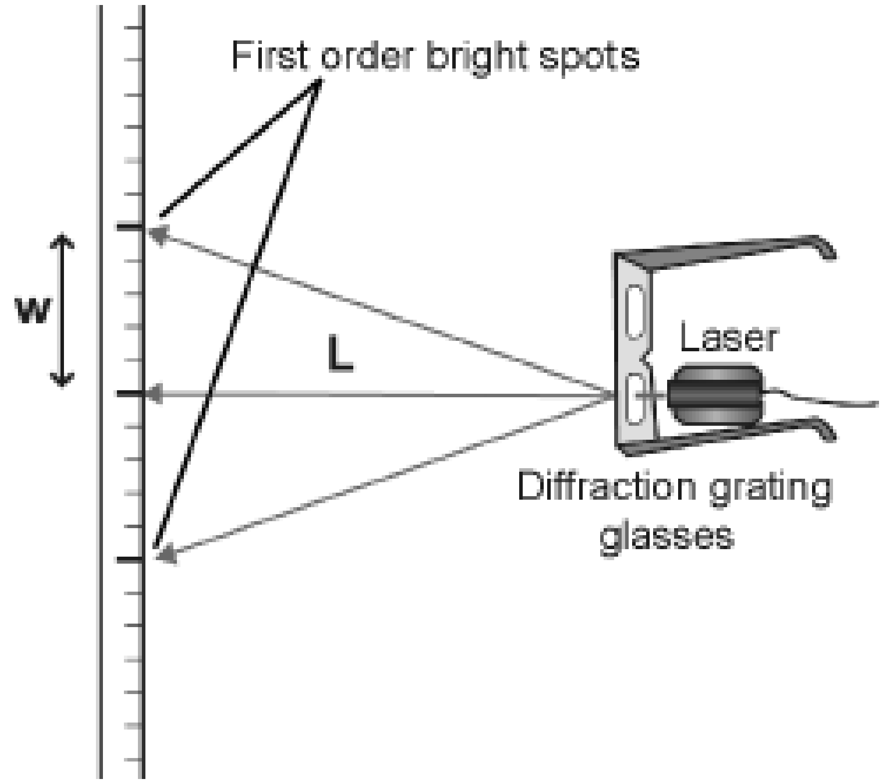
Propagation of light through a slit demonstrates wave properties. Cancellation and addition of diffracted waves results in striped pattern in contrast to what would be expected by particles.

http://www.physics.uoguelph.ca/applets/Intro_physics/kisalev/java/slitdiffr/index.html

Interference, Diffraction, and Polarization

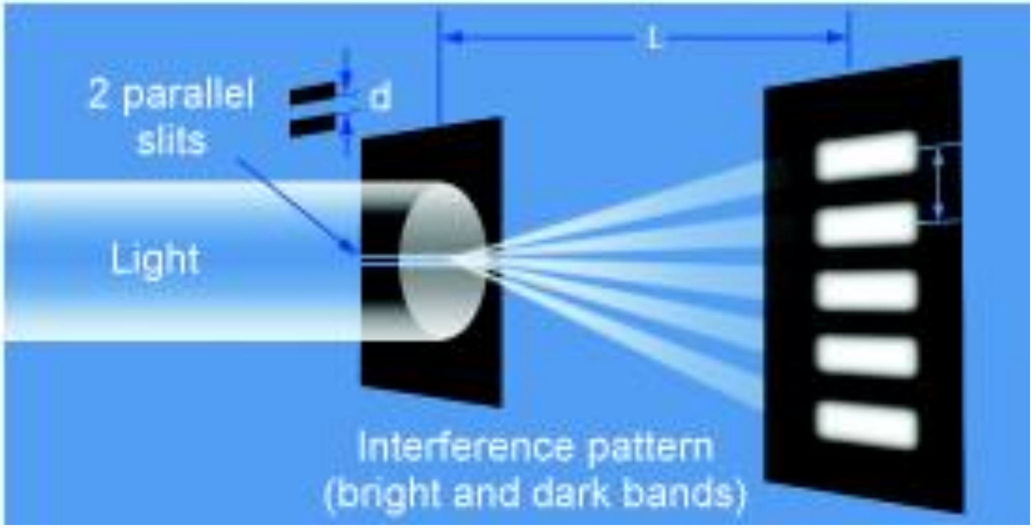
Key Question:

What are some ways light behaves like a wave?



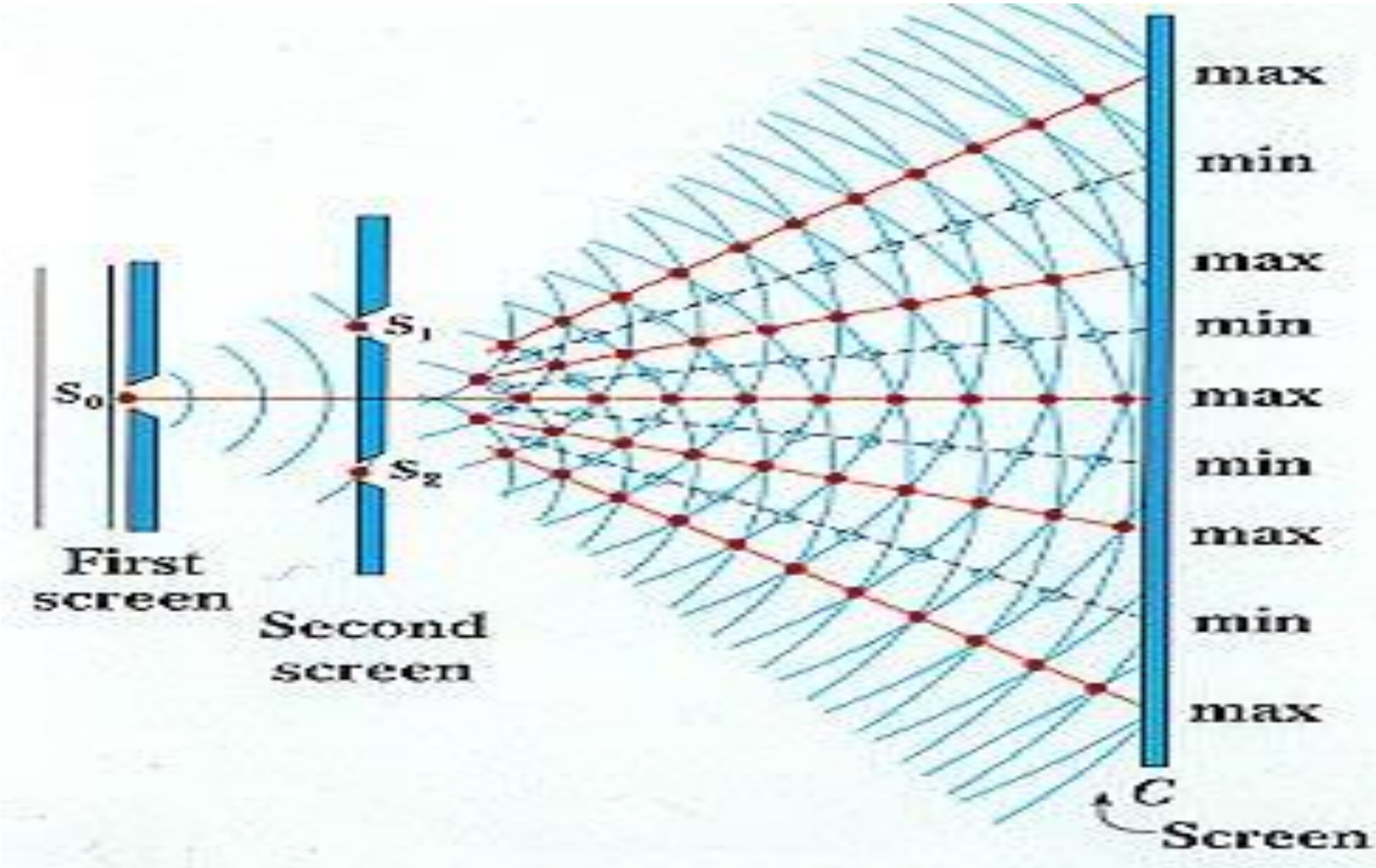
Interference, Diffraction, and Polarization

- In 1807, Thomas Young (1773-1829) did the most convincing experiment demonstrating that light is a wave.
- A beam of light fell on a pair of parallel, very thin slits in a piece of metal.
- After passing through the slits, the light fell on a screen.

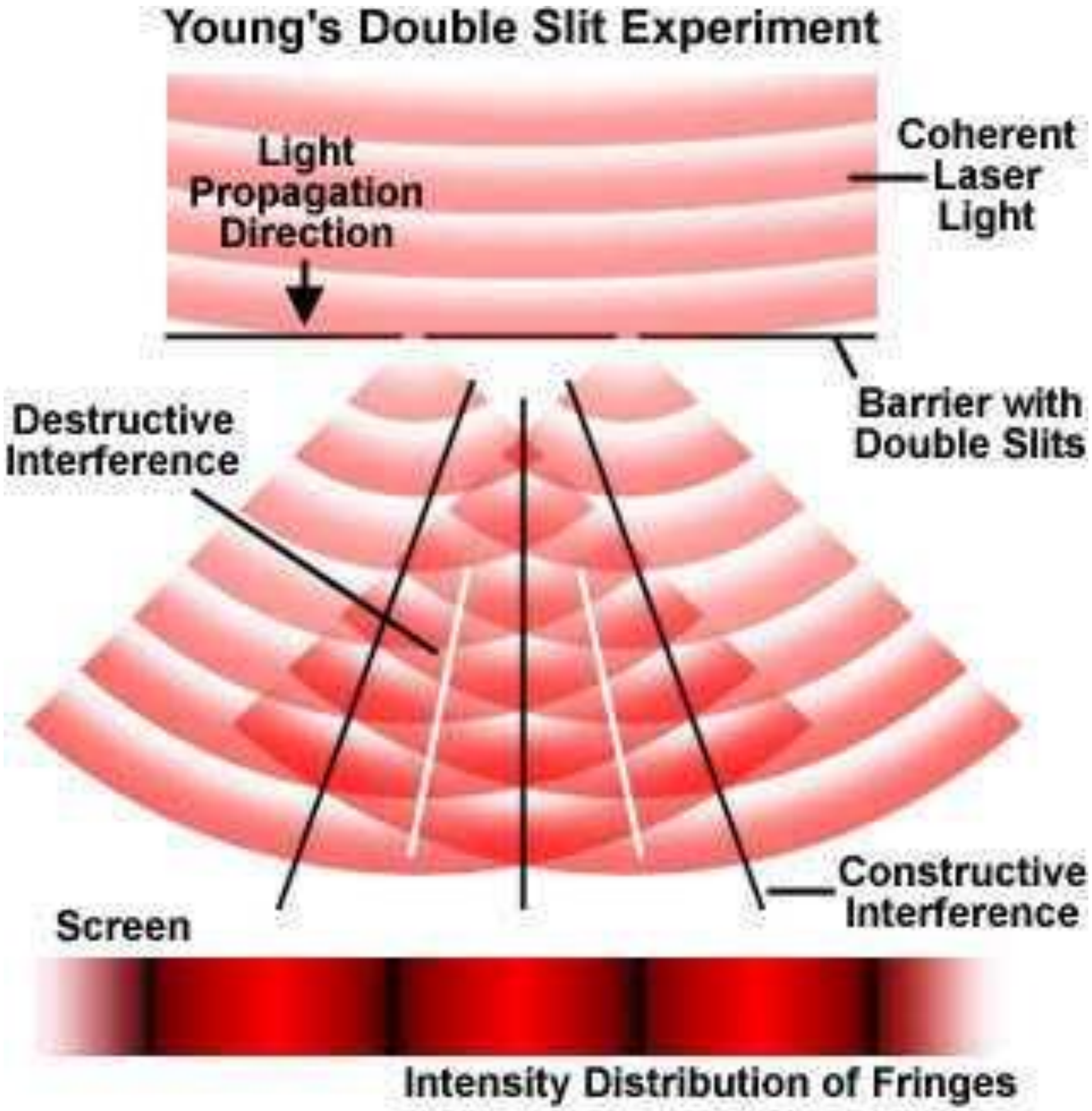


- A pattern of alternating bright and dark bands formed is called an interference pattern.

Young's experiment

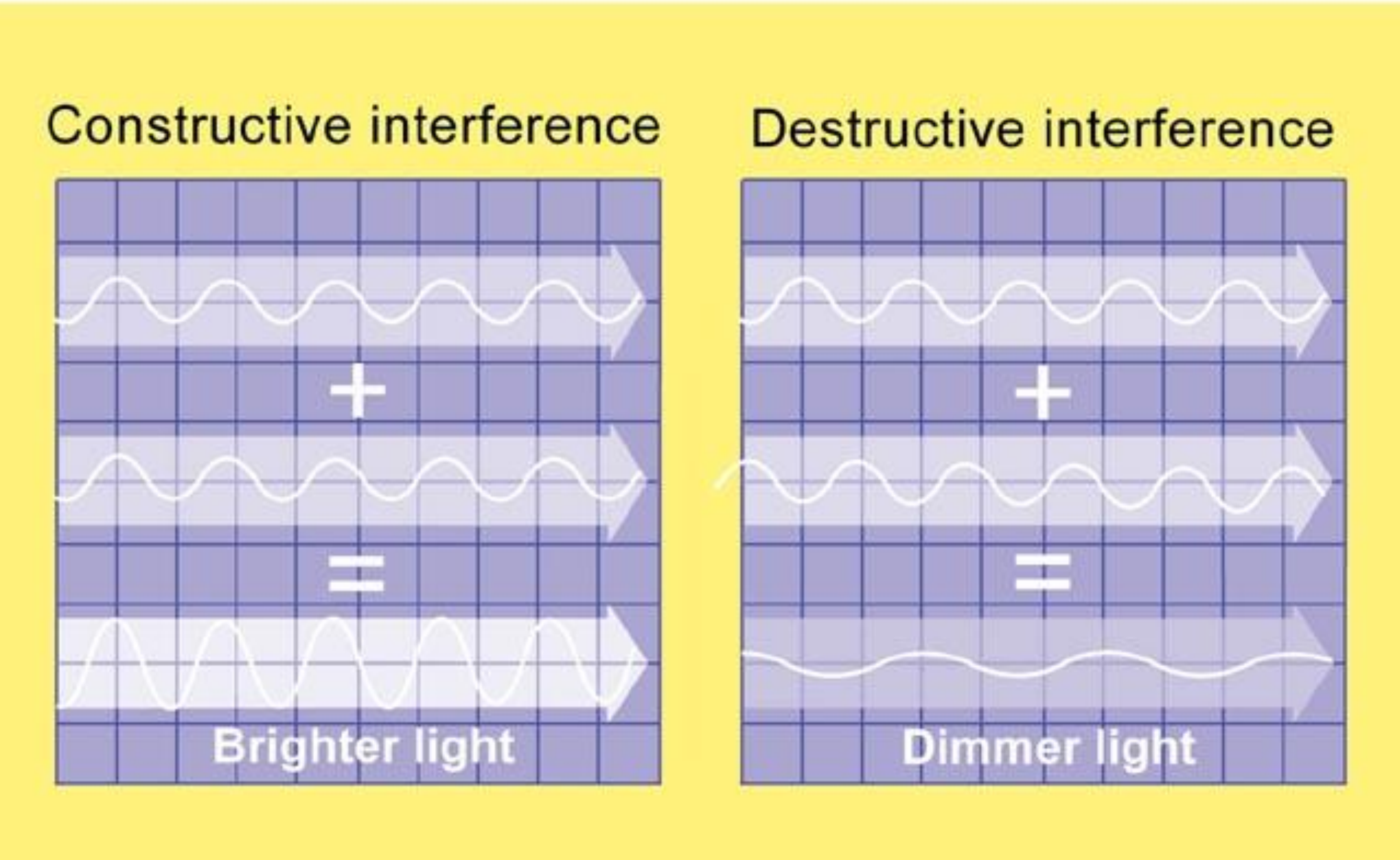


http://www.matter.org.uk/schools/Content/Interference/doubleslits_1.html

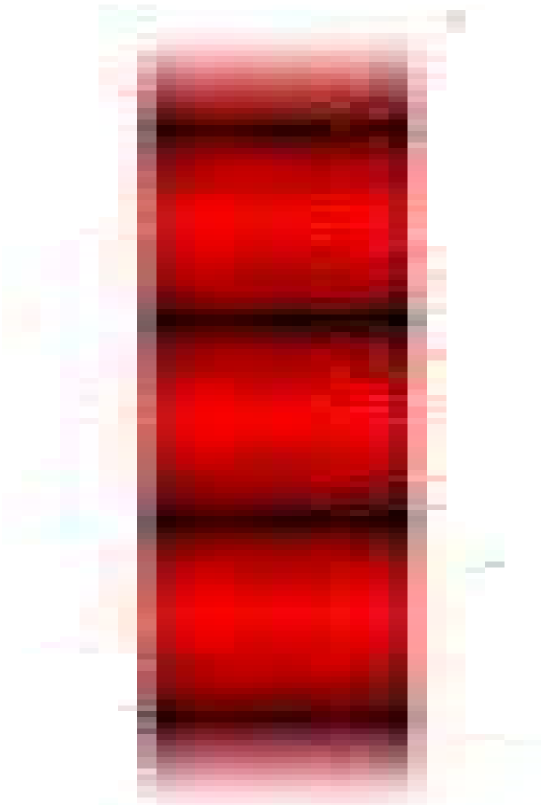


http://galileo.phys.virginia.edu/classes/USEM/SciImg/home_files/introduction_files/doubleslit.jpg

The Interference of Light Waves



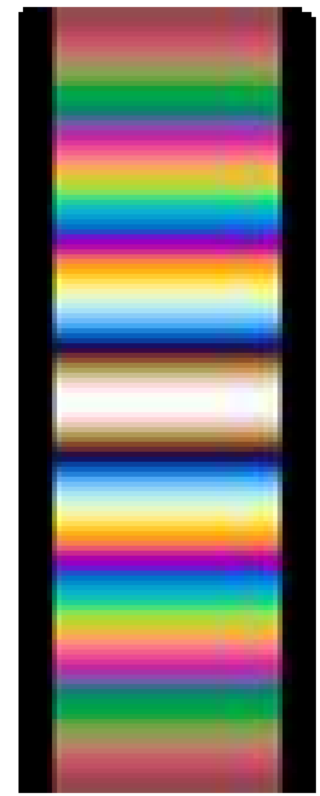
Red Light



Blue Light

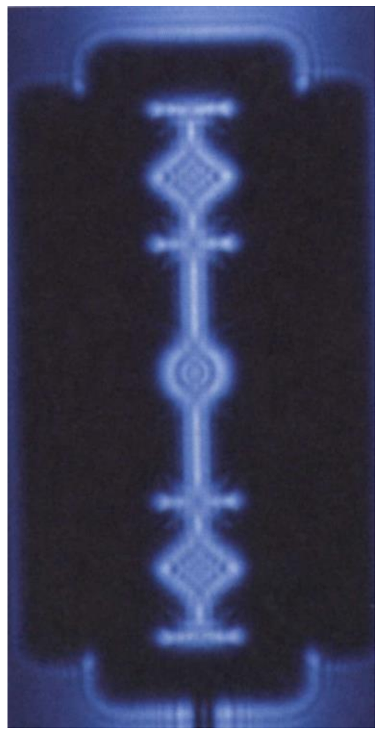
Karen Cooper

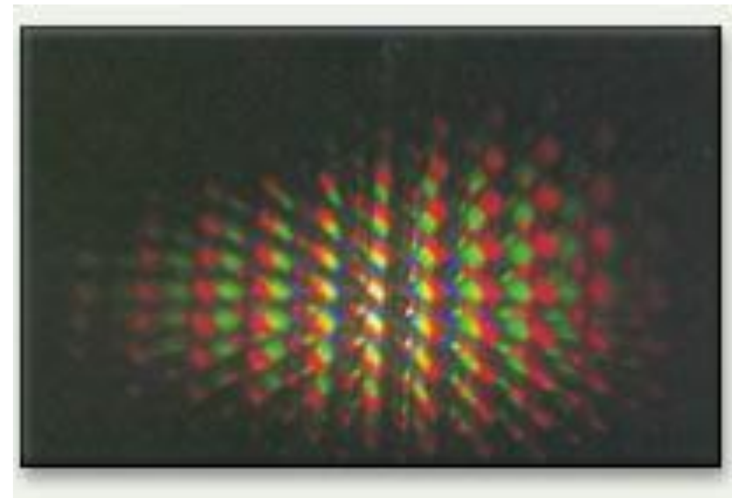
White Light

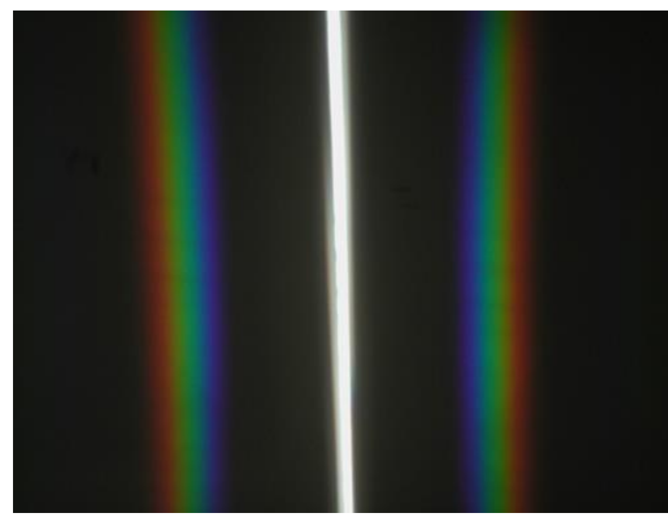


White Light. N.d. *Multiple-beam interference*. N.p., 2009. Web. 7 Feb.2011. <http://www.itp.uniannover.de/~zawischa/ITP/multibeam.html>.
Red Light. N.d. *Multiple-beam interference*. N.p., 2009. Web. 7 Feb.2011. <http://www.itp.uniannover.de/~zawischa/ITP/multibeam.html>.

Diffraction Patterns



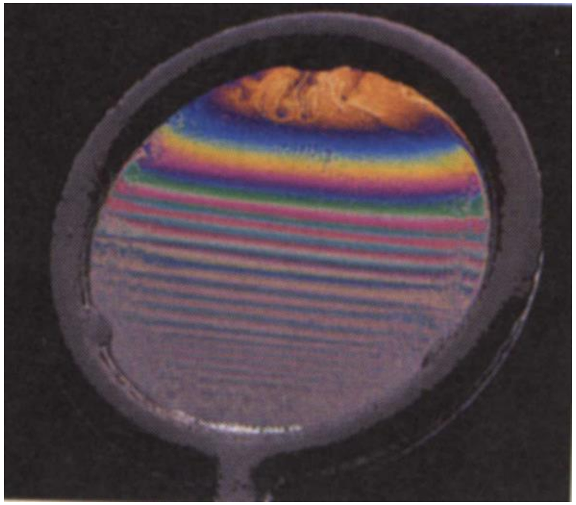


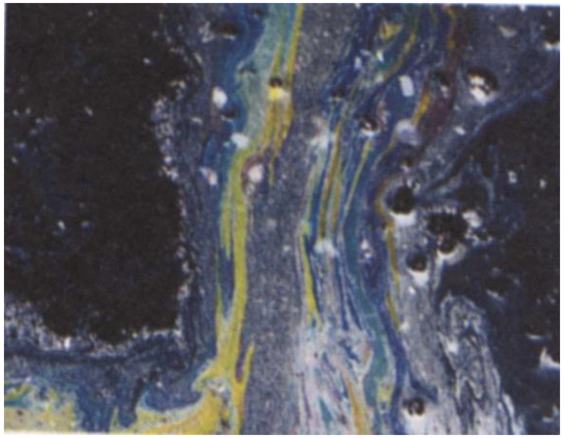


Interference by Thin Films

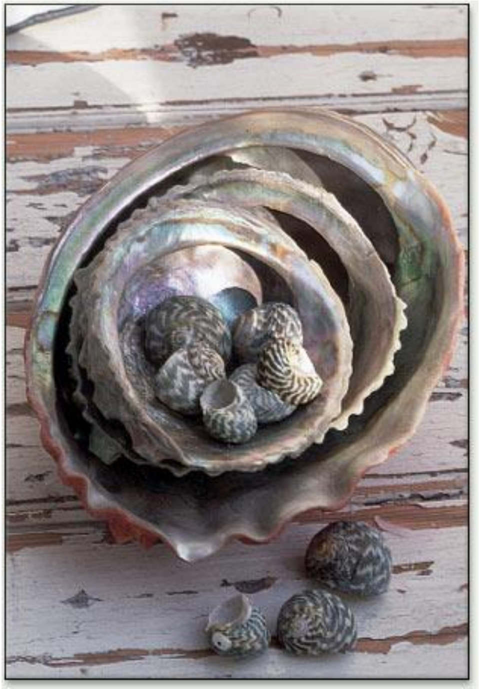
- Thin film interference patterns seen in

Thin film of soapy water





Seashell



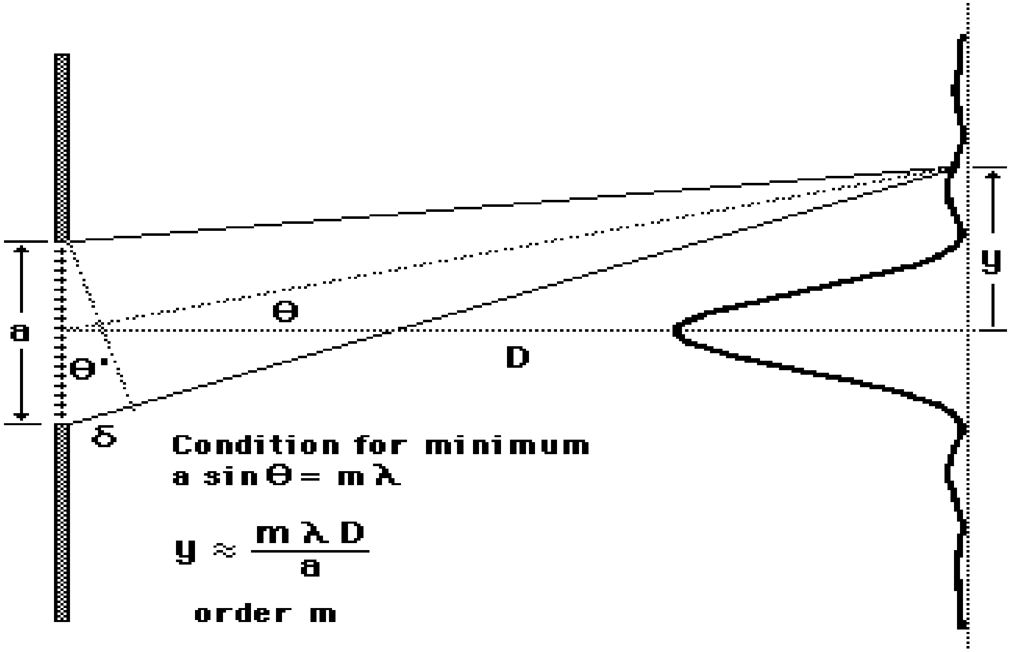
A thin layer of oil on the
Water of a street puddle

A compact disk acts as a diffraction grating. The colors and intensity of the reflected light depend on the orientation of the disc relative to the eye.

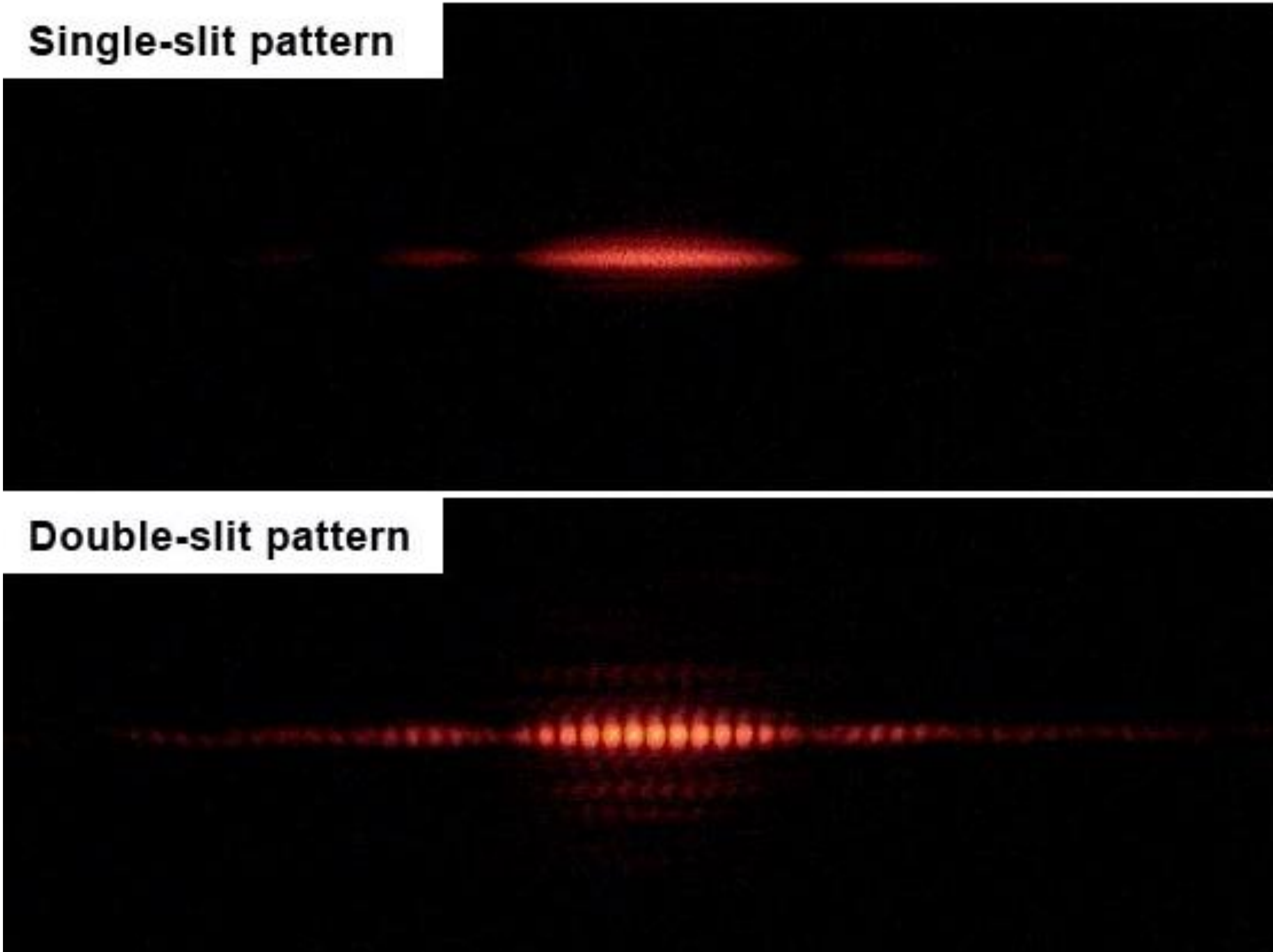
Diffraction through a single slit

http://physicsstudio.indstate.edu/java/physlets/java/slitdiffr/index.html

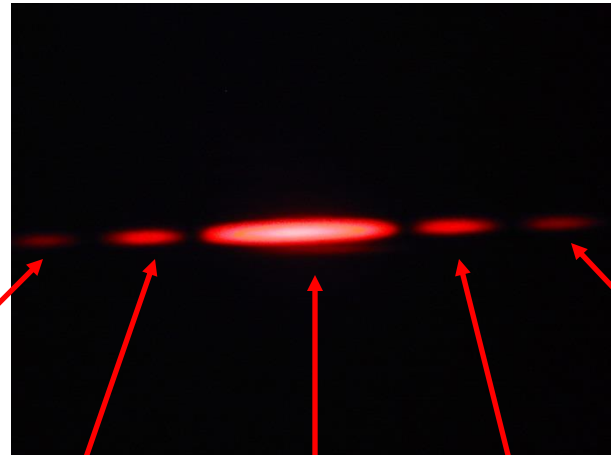
- Diffraction refers to the spreading or bending of waves around edges.



The fringe pattern formed by a single slit consists of Alternate bright and dark fringes and the fringes fade away from the centre.


Single-slit pattern
Double-slit pattern

Diffraction – Orders, m



We use the letter, **m**, to represent the ORDER of the fringe from the bright central.

Second Order
Bright Fringe
$m = 2$

First Order
Bright Fringe
$m = 1$

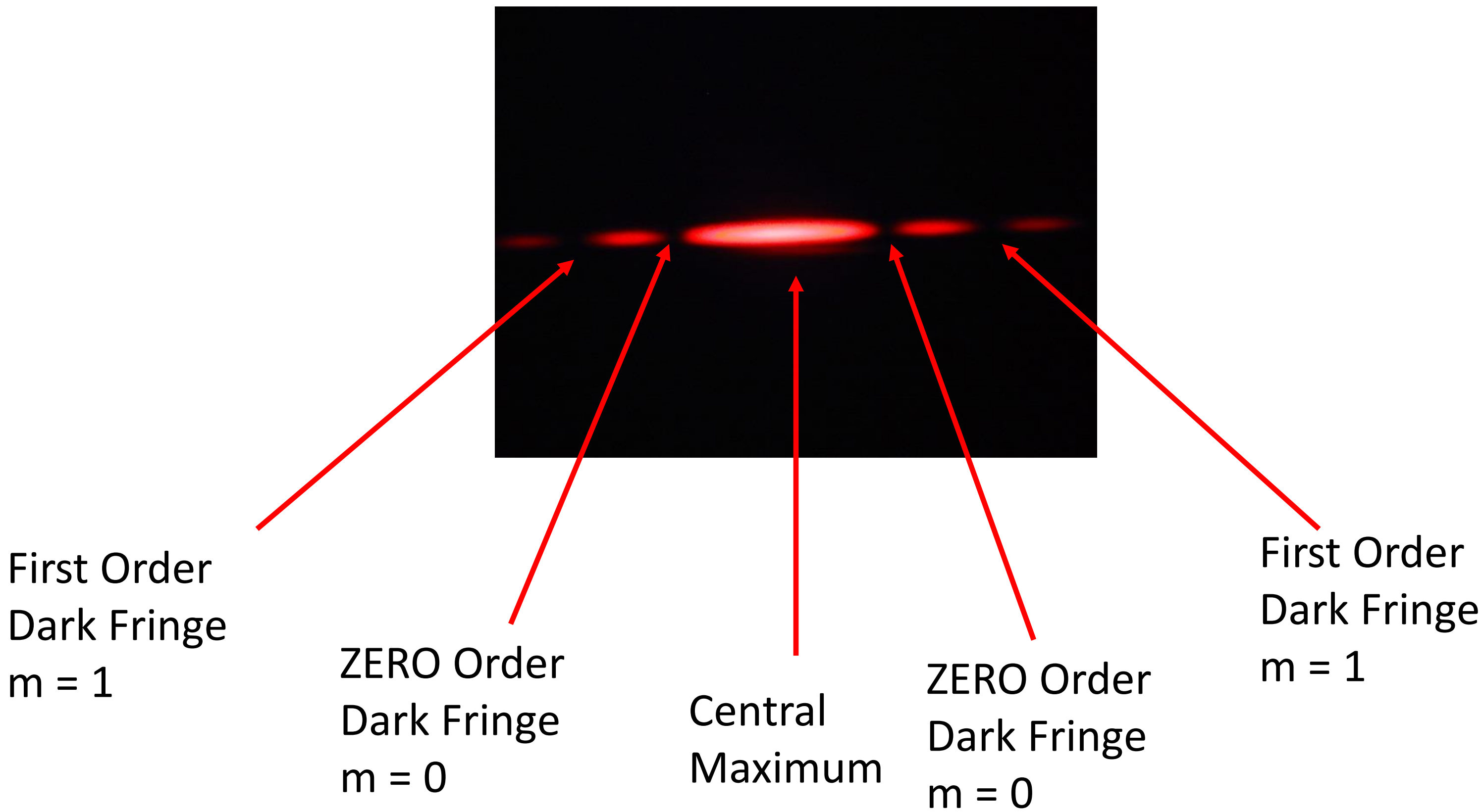
Central
Maximum

First Order
Bright Fringe
$m = 1$

Second Order
Bright Fringe
$m = 2$

It is important to understand that we see these bright fringes as a result of CONSTRUCTIVE INTERFERENCE.

Diffraction – Dark Fringes



It is important to understand that we see these dark fringes as a result of DESTRUCTIVE INTERFERENCE.

Experiment : Single Slit

- **Purpose**

The purpose of this experiment is to examine the diffraction pattern formed by laser light passing through a single slit and verify that the positions of the minima in the diffraction pattern match the positions predicted by theory.

Theory

When diffraction of light occurs as it passes through a slit, the angle to the minima in the diffraction pattern is given by

$a \sin \theta = m\lambda \ (m = 1,2,3...)$

where *a* is the slit width, θ is the angle from the center of the pattern to the m^{th} minimum, λ is the wavelength of the light, and *m* is the order (1 for the first minimum, 2 for the second minimum, . . . counting from the center out). See Figure 1.1.

Since the angles are usually small, it can be assumed

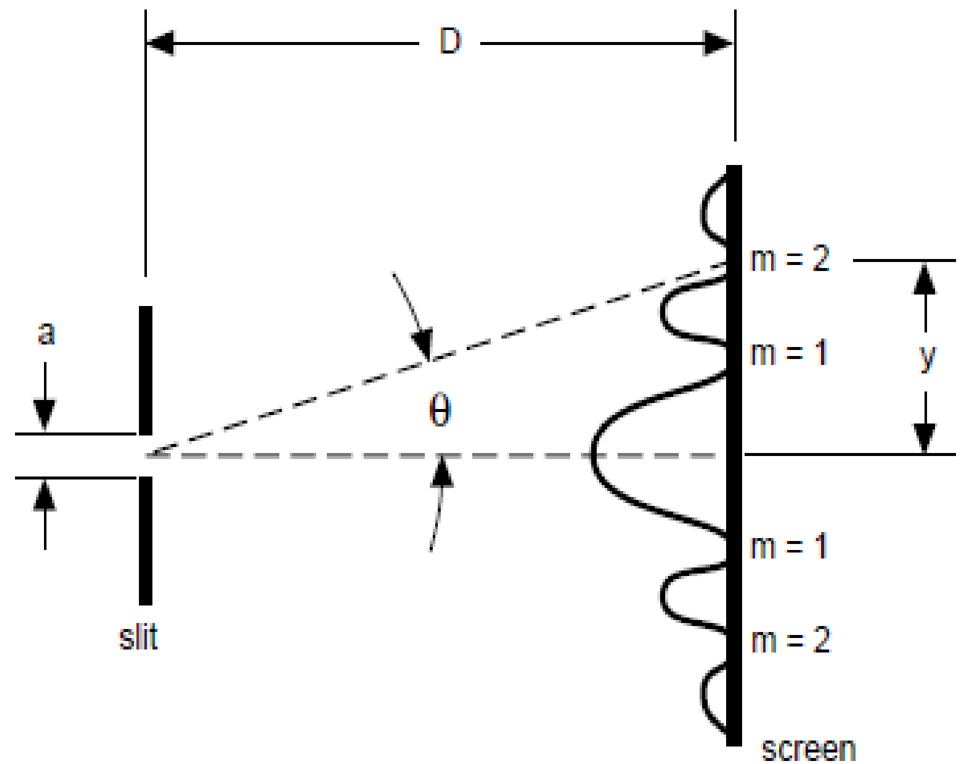
That

$\sin\theta \approx \tan\theta$

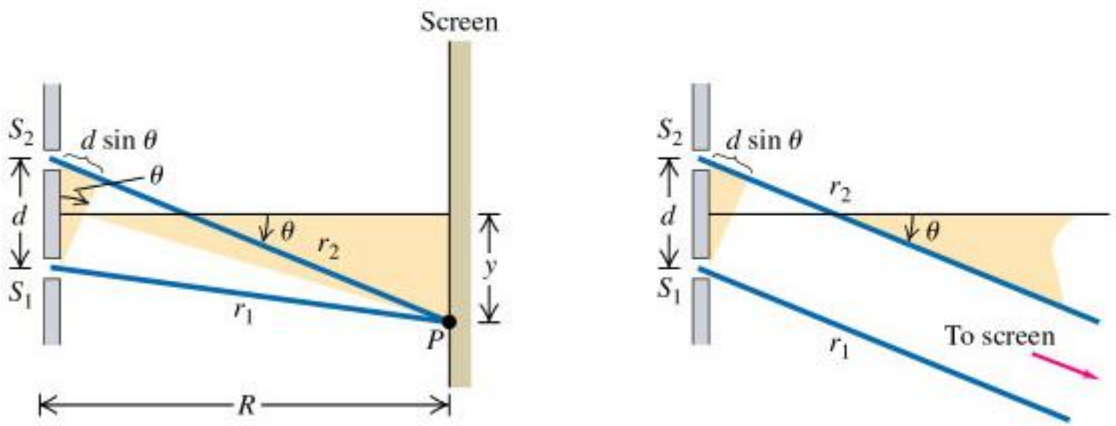
From trigonometry,

$\tan\theta = y/D$

where *y* is the distance on the screen from the center of the pattern to the m^{th} minimum and *D* is the distance from the slit to the screen as shown in Figure 1.1.



Young's Double Slit Experiment



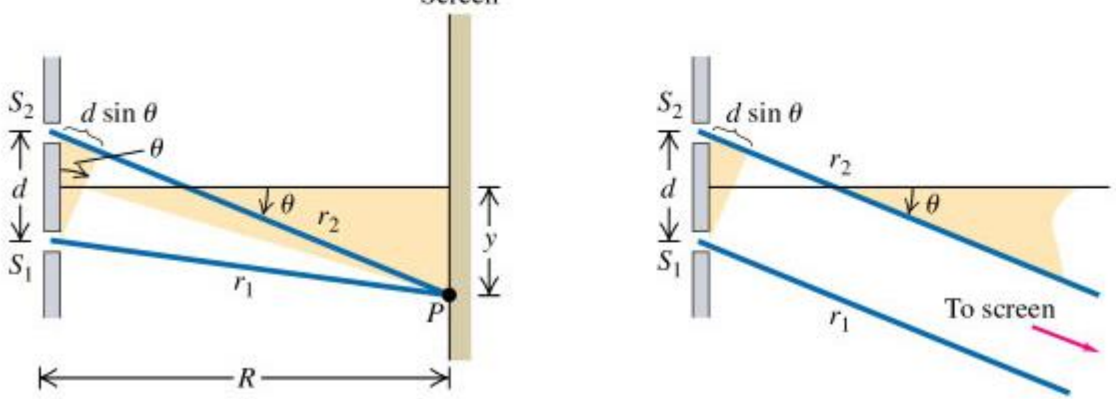
(b) Slits S_1 and S_2 are horizontal and seen from the side in cross section

(c) Same as (b), but with screen very far from slits (R much greater than d)

Constructive interference: $d \sin\theta = n\lambda$

Destructive interference: $d \sin\theta = \left(n + \frac{1}{2}\right)\lambda$

Young's Double Slit Experiment



(b) Slits S_1 and S_2 are horizontal and seen from the side in cross section

(c) Same as (b), but with screen very far from slits (R much greater than d)

Y-position of bright fringe on screen: $y_m = R\tan\theta_m$

Small θ, ie r_1, $r_2 \approx R$, so $\tan\theta \approx \sin\theta$

So, get bright fringe when:

$$y_m = R\frac{n\lambda}{d}$$

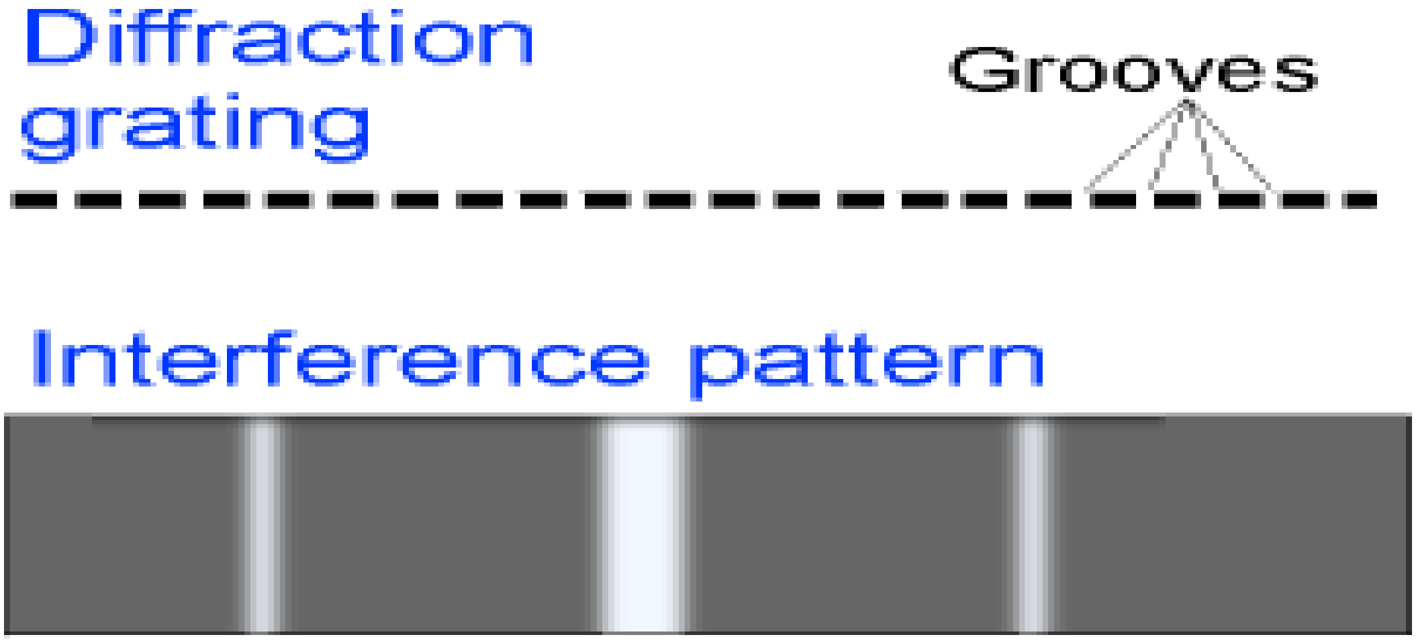
(small θ only)

Conditions for Observable Interference

- Coherent Sources
  - Coherent sources are those which emit light waves of the same wavelength or frequency and are always in phase with each other or have a constant phase difference.
- Polarization
  - The wave disturbance have the same polarization.
- Amplitudes
  - The two sets of wave must have roughly equal amplitude.
- Path Difference
  - The path difference between the light waves must not be too great.

Diffraction gratings

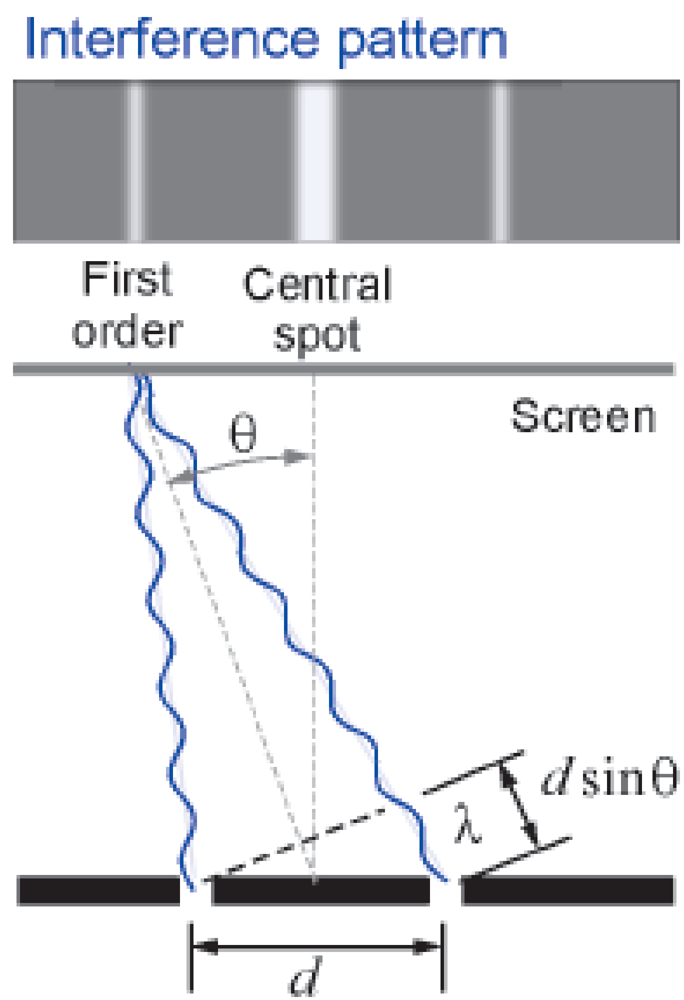
- A diffraction grating is a precise array of tiny engraved lines, each of which allows light through.
- The spectrum produced is a mixture of many different wavelengths of light.



How a Diffraction Grating Works

When you look at a diffracted light you see:

- the light straight ahead as if the grating were transparent.
- a "central bright spot".
- the interference of all other light waves from many different grooves produces a scattered pattern called a spectrum.



Diffraction – Putting it all together

Path difference is equal to the following:

- $m\lambda$
- $(m+1/2)\lambda$
- $d\sin\theta$

Constructive Interference

$$d\sin\theta = m\lambda$$

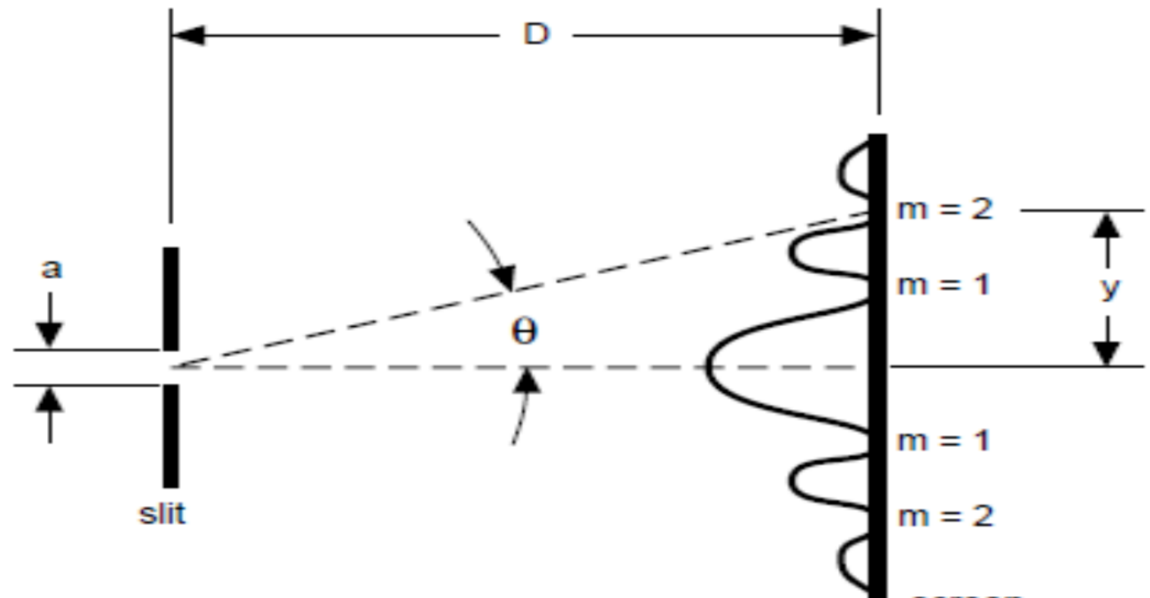
Destructive Interference

$$d\sin\theta = (m + 1/2)\lambda$$

Therefore, we can say:

$$Tan\,\theta = \frac{y}{L}$$

Will be used to find the angle!



Example

A viewing screen is separated from a double slit source by 1.2 m. The distance between the two slits is 0.030 mm. The second -order bright fringe (m=2) is 4.5 cm from the central maximum. Determine the wavelength of light.

$$L = 1.2m \quad d = 3.0x10^{-5} m$$

$$\theta = \tan^{-1}(\frac{y}{L}) = \tan^{-1}(\frac{0.045}{1.2}) =$$

2.15 degrees

$$m = 2 \quad y = 0.045 m$$

$$\text{"bright"} = \text{Constructive}$$

$$\lambda = ?$$

$$d \sin\theta = m\lambda$$

$$(3x10^{-5})\sin(2.15) = 2\lambda$$

$$\lambda =$$

$5.62x10^{-7}$ m

Example

A light with wavelength, 450 nm, falls on a diffraction grating (multiple slits). On a screen 1.80 m away the distance between dark fringes on either side of the bright central is 4.20 mm. a) What is the separation between a set of slits? b) How many lines per meter are on the grating?

$$\lambda = 450\,x10^{-9}\,m \quad L = 1.80\,m$$

$$y = 0.0021\,m \quad \theta = ?$$

$$d = ?$$

$$\theta = \tan^{-1}\left(\frac{0.0021}{1.8}\right) =$$ **0.067 degrees**

$$d \sin\theta = (m + 1/2)\lambda$$

$$d \sin(0.067) = (0 + 1/2)450\,x10^{-9}$$

$d =$ **0.0001924 m**

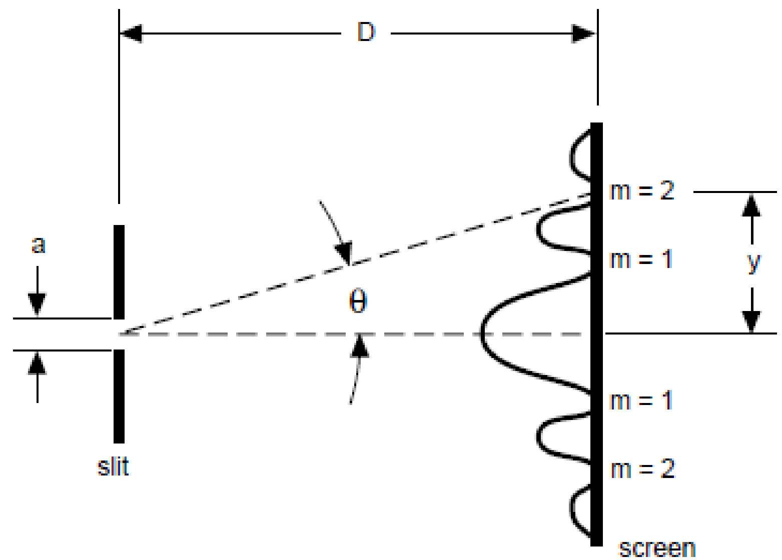
$$d = \frac{meters}{line}$$

$$\frac{lines}{meter} = d^{-1} \; or \; \frac{1}{d} =$$ **5197.2 lines/m**

http://www.youtube.com/watch?v=NqqWKwO9xdw

The diffraction equation can thus be solved for the slit width:

$$a = \frac{m\lambda D}{y}\left(m = 1,2,3,\right)$$



Some Vocabulary Terms

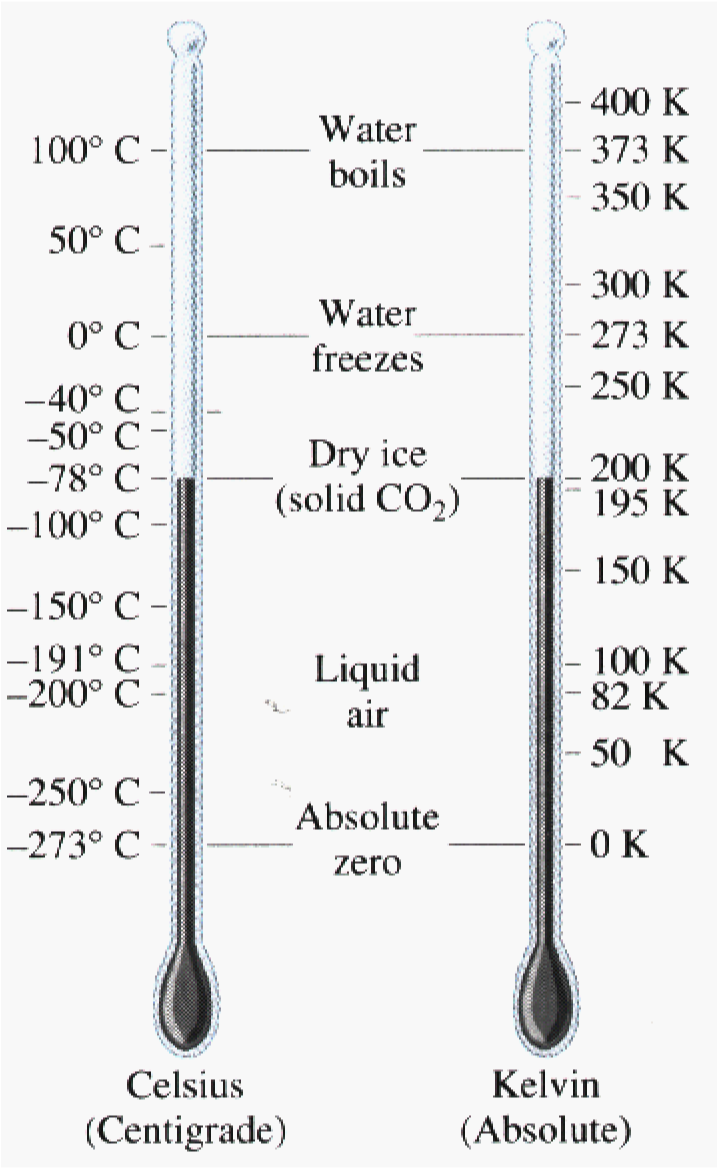
- **x-ray**
- **spectrum**
- **microwave**
- **index of refraction**
- **electromagnetic wave**
- **spectrometer**
- **gamma ray**
- **radio wave**
- **transmission axis**
- **diffraction grating**
- **Radiation**
- ***Period***
- ***Frequency***
- **interference**
- **ultraviolet**
- **infrared**
- **speed of light**
- **constructive interference**
- **visible light**
- **Wavelength**
- **Diffraction**
- **Single slit**
- **Double slit**
- **Young's Experiment**
- ***Wavelength***
- ***Amplitude***

Wavelengths of Light - Visible

- Red light has an approximate wavelength of 7.0×10^{-7} m and a frequency of 4.3×10^{14} Hz
- Violet light has an approximate wavelength of 4.0×10^{-7} m and a frequency of 7.5×10^{14} Hz
- When dealing with such small numbers for wavelength, astronomers often use a new unit called the angstrom
  - 1 angstrom = 1×10^{-10} m
    - Red light has a wavelength of about 7000 angstroms
- When dealing with large numbers for frequency, we often use the traditional prefixes
  - Kilo = 10^3, Mega = 10^6, Giga = 10^9
    - Red light has a frequency of about 430,000 GHz

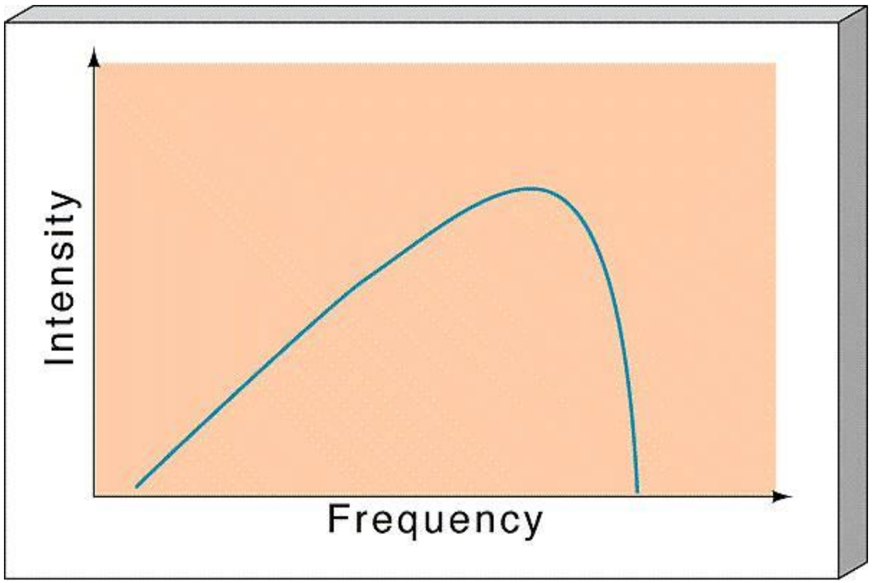
Measuring Temperature from Light

- Astronomers can use the light from an object to measure its temperature
- Astronomers also use a different unit for temperature, the Kelvin
- Water boils at 373 K and freezes at 273 K
  - Most stars have a temperature in the 1000's of Kelvin
- The coldest possible temperature (absolute zero) corresponds to 0 Kelvin

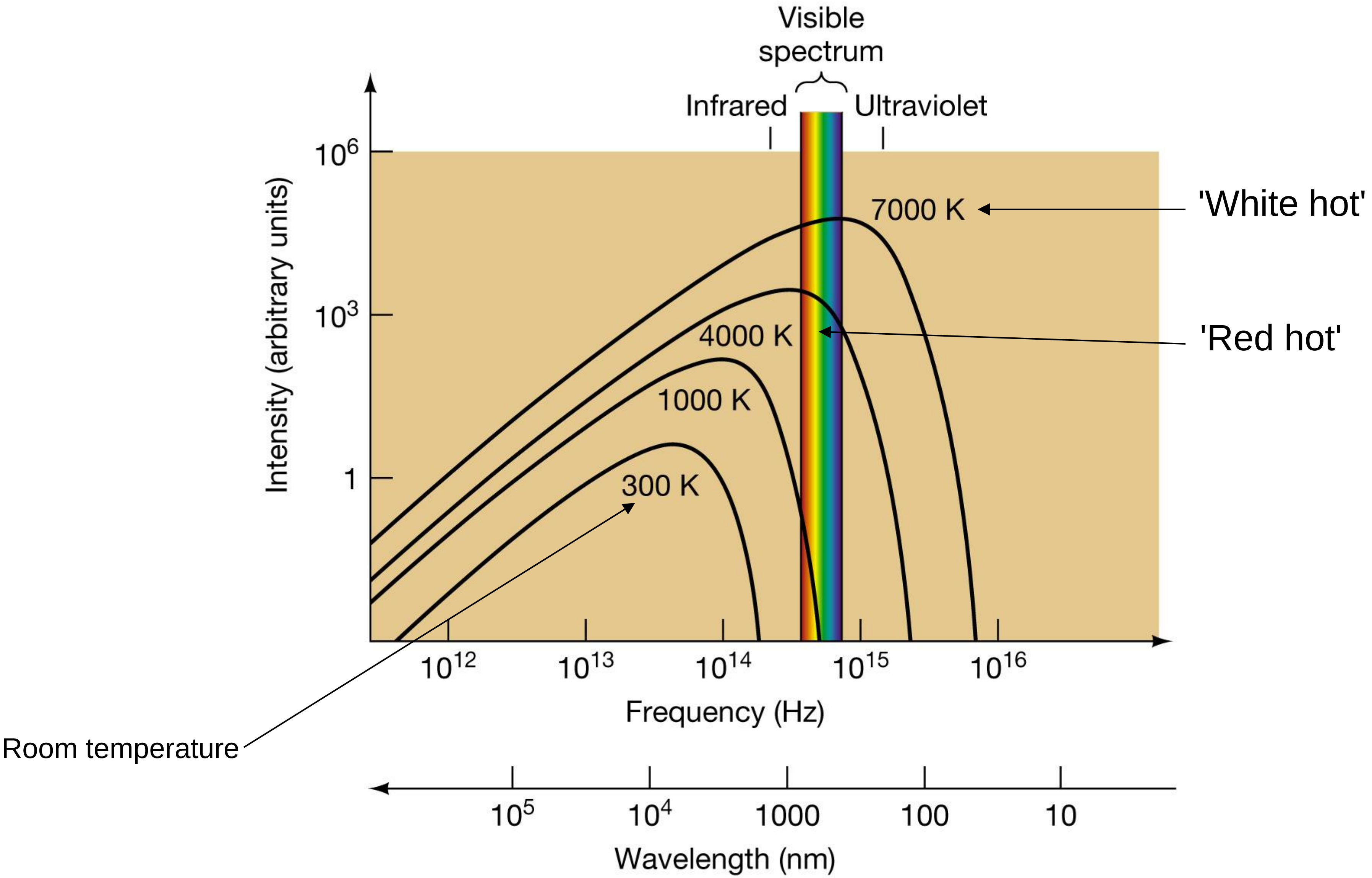


Blackbody Radiation

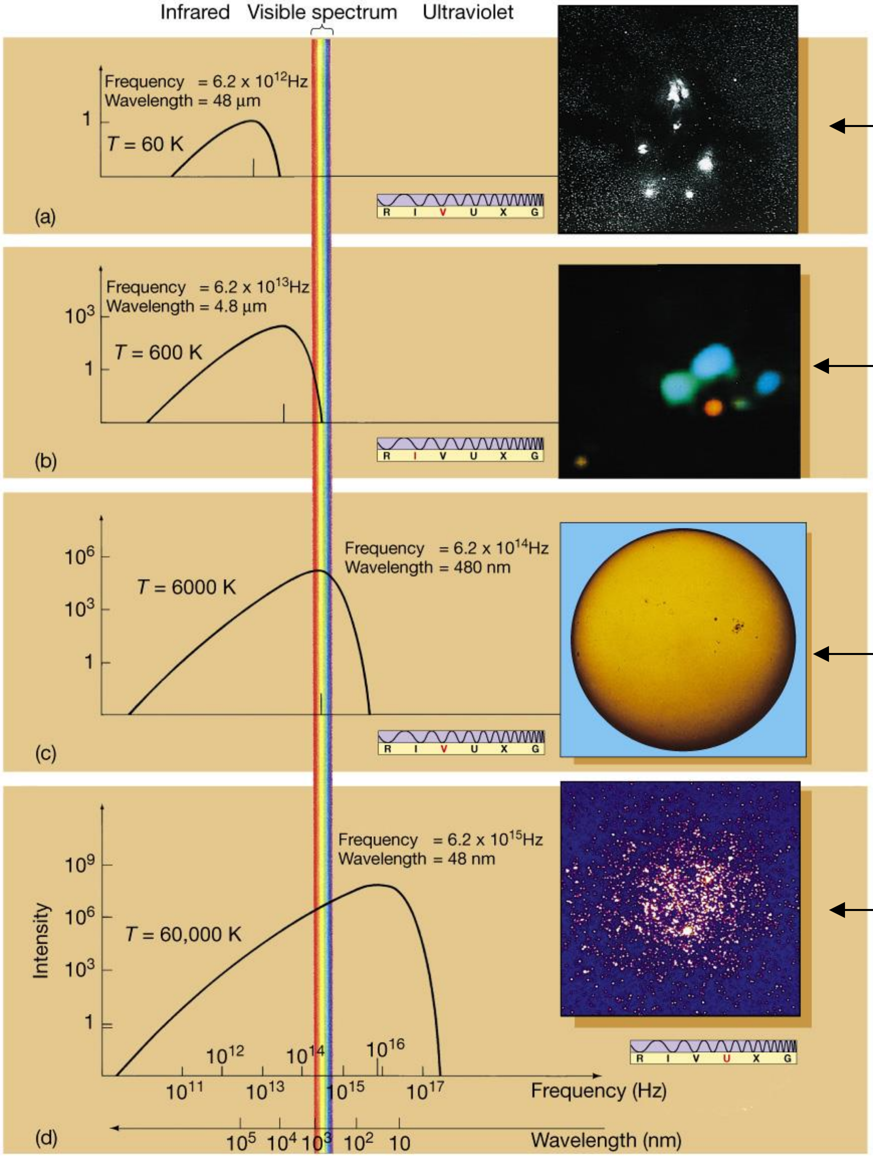
- Every object radiates energy
- This energy is emitted at different wavelengths (or frequencies) of light
- The distribution of this energy is called a blackbody curve
- The size and shape of a blackbody curve changes with an object's temperature



Blackbody Radiation



Blackbody Radiation

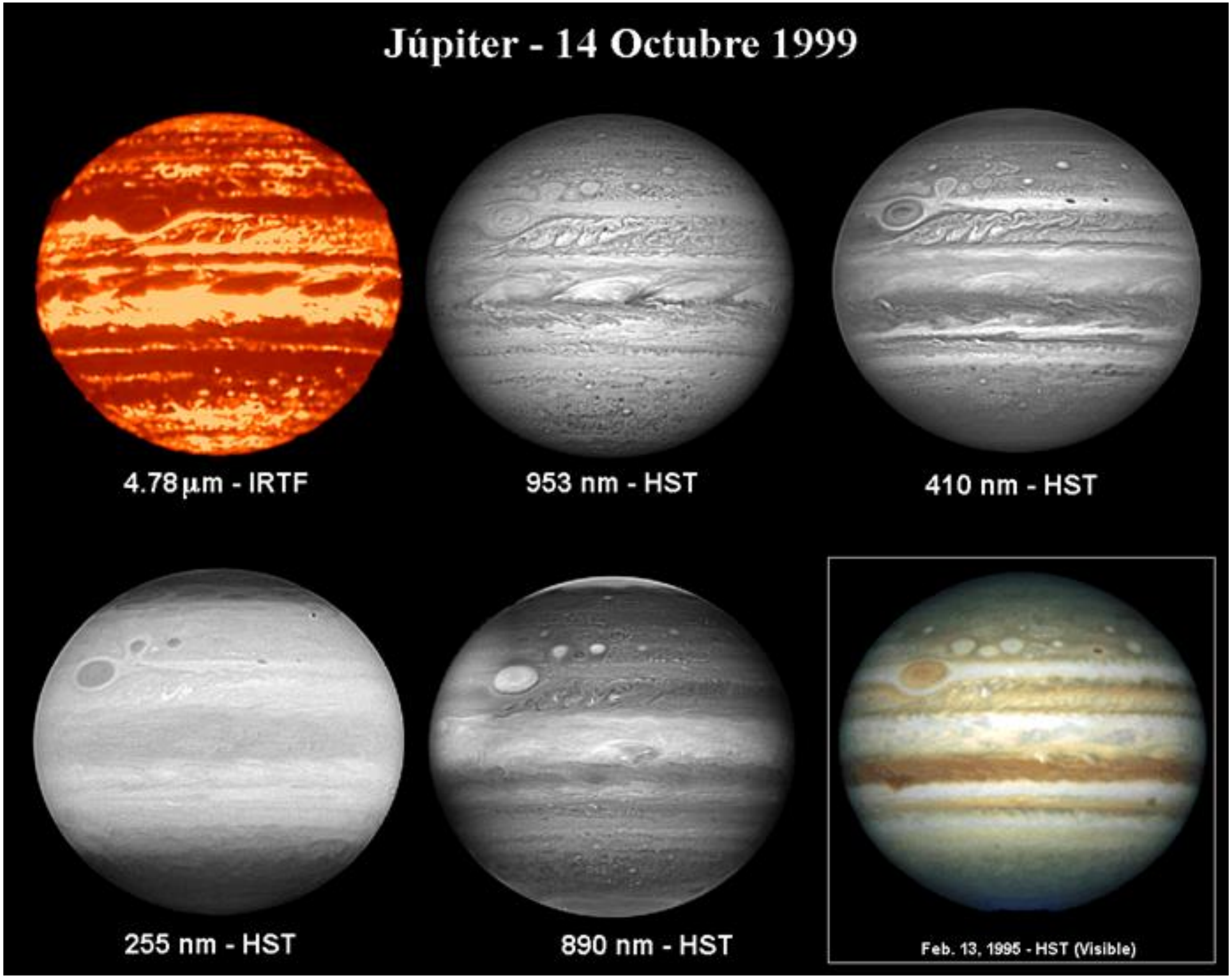


Cool gas (~60K)

Young star (~600K)

The Sun (~6000K)

Hot stars in a cluster (~60,000K)



Jupiter seen at different wavelengths of light