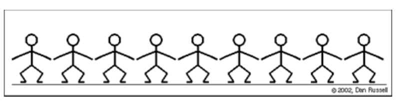
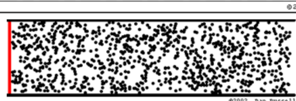
Wave - Susanne Nilsson (Attribution-ShareAlike 2.0 Generic)

What is a wave?

- A disturbance that travels in a medium (or vacuum for electromagnetic waves) transferring energy and momentum from one place to another.



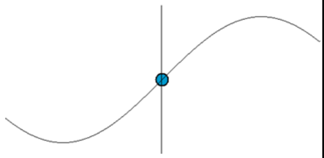


Animations courtesy of Dr. Dan Russell, Grad. Prog. Acoustics, Penn State

Types of Waves

- Mechanical waves
  - Require a material medium to travel through
  - Sound, water
- Electromagnetic waves
  - Can travel through a vacuum
  - Light

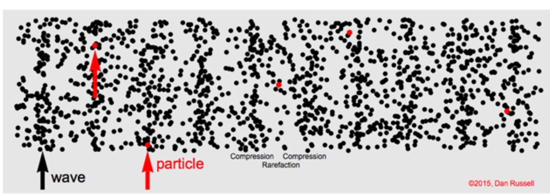
- Transverse
  - The particles move perpendicular to the wave motion



[Animation courtesy of Dr. Dan Russell, Grad. Prog. Acoustics, Penn State]

Evil saltine (public domain)

- Longitudinal
  - The particles move parallel to the wave motion



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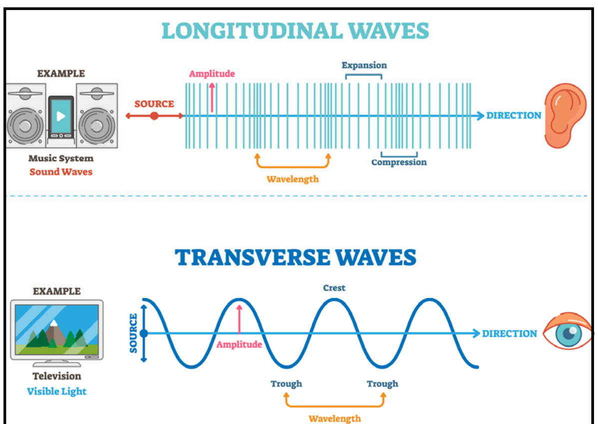

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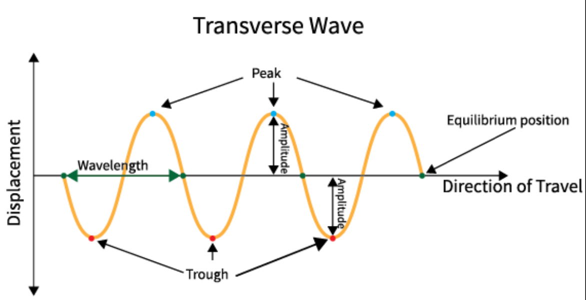
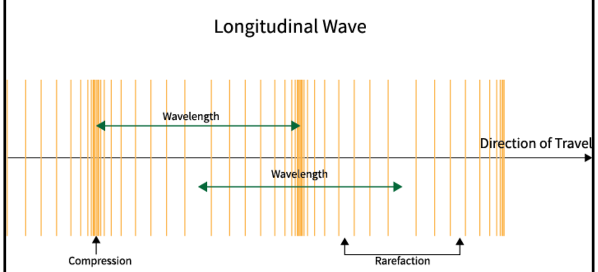
Describing Waves

- Wavelength (λ)
  - Shortest distance between two points that are in phase on a wave
- Amplitude (A)
  - Maximum displacement of a wave from its rest (equilibrium) position



doethion (Adobe Stock)



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- Frequency (f)
  - Number of vibrations per second
  - Number of crests passing a fixed point per second
- Period (T)
  - Time for one complete wavelength to pass a given point
  - Time for a particle to undergo one complete oscillation

Wave Equation

- When a source of a wave undergoes one complete oscillation the wave it produces moves forward one wavelength (λ)
- Since there are f oscillations per second, the wave progresses $f\lambda$ during this time
- Therefore, the velocity of a wave (c) is given by

$$c = f\lambda$$

Intensity of a Wave

- The loudness of a sound wave or the brightness of a light depends on the amount of energy that is received by an observer
- The intensity (energy) is proportional to the square of the amplitude

$$I \propto A^2$$

- Loudness and brightness are intensities perceived by the observer and are related to frequency
- The intensity of the wave decreases as the distance between the source and the observer increases

$$I \propto x^{-2}$$

Sound Waves

- Sound waves are produced by vibrations
- The vibrating source moves the nearby air particles sending a disturbance through the surrounding medium as a longitudinal wave

Speed of Sound

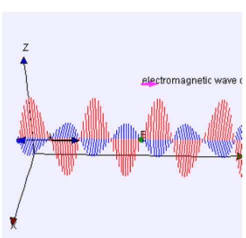
- The speed of sound depends on two things:
  - The medium it is traveling in
    - Sound travels faster in a denser medium
  - The temperature of the medium
    - Sound travels slower as the temperature decreases
      - Air (20°C) = 343 m/s
      - Air (0°C) = 331 m/s
      - Air (-20°C) = 319 m/s

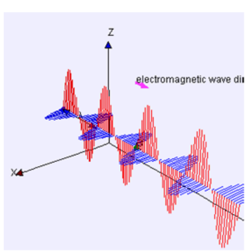
Speed of Sound in Different Media at 25°C

State	Substance	Speed in m/s
Gas	Air	346
	Oxygen	316
	Helium	965
Liquid	Distilled Water	1498
	Sea Water	1531
	Ethanol	1207
Solid	Aluminum	6420
	Steel	5690
	Glass	3980

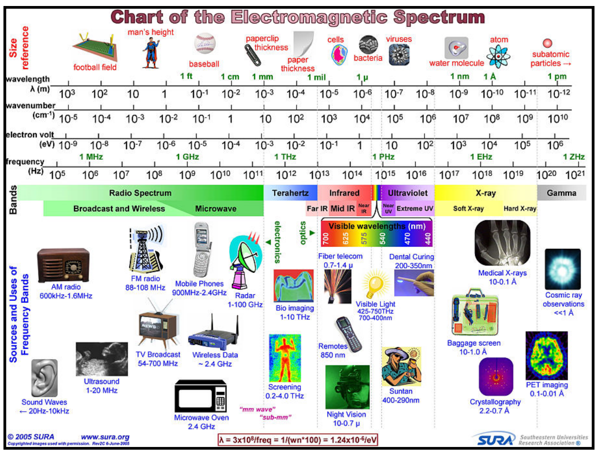
Electromagnetic Waves

- Produced when electrons undergo an energy change
  - Radio waves are produced by accelerating electrons through an antenna
  - Gamma rays are produced by particle decays or other annihilation events
- Velocity = 3.0×10^8 ms^{-1}
- Consist of a time-varying electric field and its associated time-varying magnetic field





- The human eye is sensitive to the electric field component
- Therefore, the amplitude of an electromagnetic wave is usually taken as the wave's maximum electric field strength



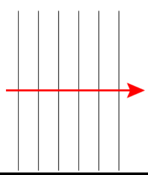
Electromagnetic Spectrum

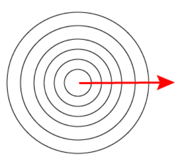
- Radio (λ~1mm-100km)
- Microwave (λ~1mm-30cm)
- Infrared (λ~1μm-1000μm)
- Visible (λ~440nm-700nm
- Ultraviolet (λ~100nm-400nm)
- X-ray (λ~30pm-3nm)
- Gamma (λ<1pm)

Wave Characteristics

Representing Waves in Two Dimensions

- Wavefront
  - A surface that travels with a wave and is perpendicular to the direction in which it travels
- Ray
  - A line showing the direction in which a wave transfers energy and is perpendicular to the wave front





Reflection (1D)

- Fixed/Hard Boundary
- Free/Soft Boundary

- Pulse is inverted
- Pulse is not inverted

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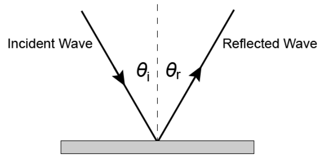
Reflection (2D)

- The angle of reflection equals the angle of incidence.

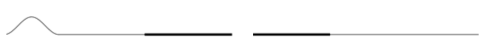
$$\theta_r = \theta_i$$



The angles are measured relative to the normal to the surface at the point where the ray strikes the surface.

Refraction

- A wave traveling from one medium into another



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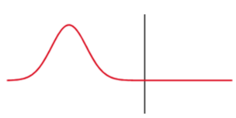

Oleg Alexandrov [Public domain]

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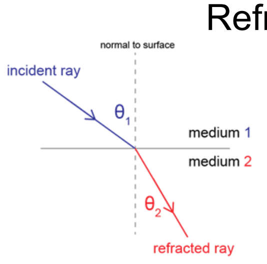
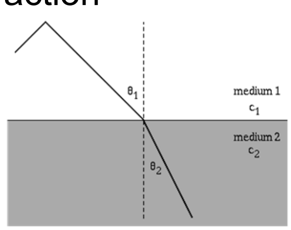
Refraction

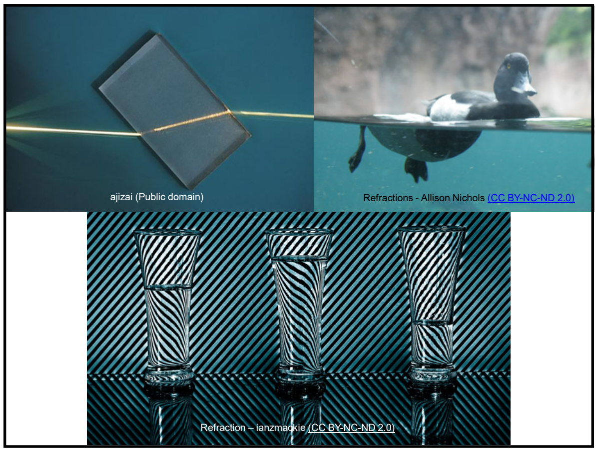




Snell's Law: $\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$

(*n* is the index of refraction)

Animation courtesy of Dr. Dan Russell, Grad. Prog. Acoustics, Penn State



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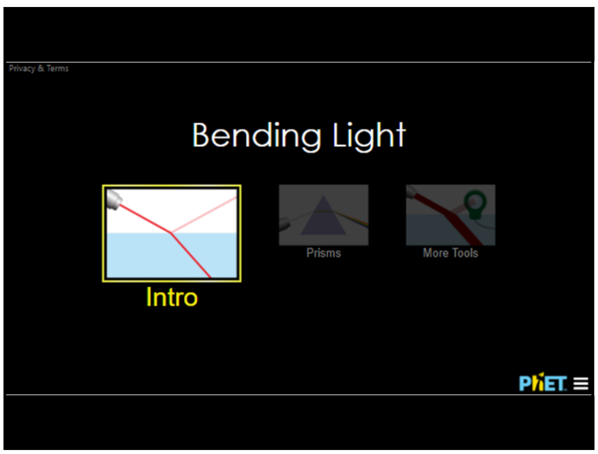
Refractions - Allison Nichols (CC BY-NC-ND 2.0)

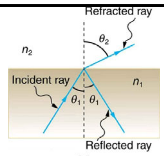
Refraction – ianzmackie (CC BY-NC-ND 2.0)



Total Internal Reflection

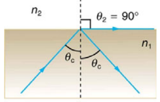
- As we increase the angle of incidence, the angle of refraction will also increase.
- At some point the angle of refraction will become 90°.
- If we continue to increase the angle of incidence, the wave will stop refracting and instead will reflect off the surface.
- This is called total internal reflection.

Image credit: Wolfe, Gregg, et al. "Huygens's Principle: Diffraction." In *College Physics for AP® Courses*. Houston, TX: OpenStax, 2015. https://openstax.org/books/college-physics-ap-courses/pages/25-4-total-internal-reflection (CC BY 4.0)



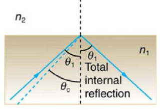
(a)

Wave is refracted (and partially reflected).



(b)

The refracted wave is now at 90°. The refracted wave is not visible.



(c)

No refraction occurs. There is total internal reflection.

- The angle at which the refracted ray is 90° (total internal reflection begins) is referred to as the critical angle, θ_c.
- Total internal reflection can only occur if $n_1 > n_2$.

Example

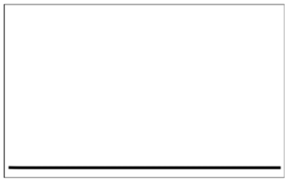
- A light is shone under water in a swimming pool. Calculate the critical angle required for total internal reflection. $(n_{water} = 1.33)$

$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} \qquad \theta_2 = 90°$$

$$\theta_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}\frac{1}{1.33} = 48.8°$$

Superposition

- When two waves meet, they pass through each other and continue their path as if nothing happened.



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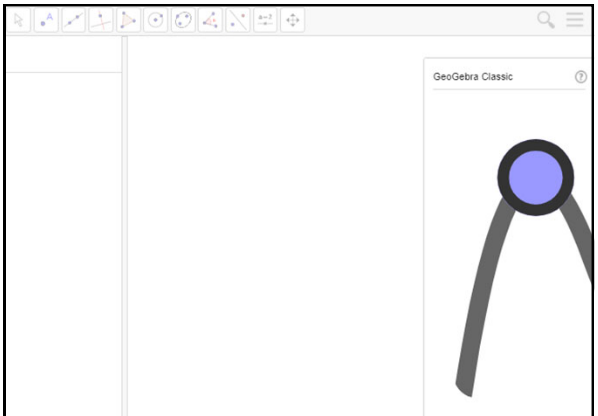

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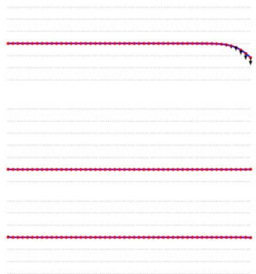
Principle of Superposition

- When two (or more) waves meet at some point in space the displacement at that point is the algebraic sum of the individual displacements



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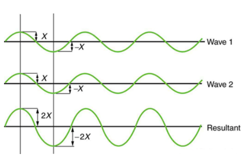
Interference

- Constructive
  - Resulting amplitude is greater
- Destructive
  - Resulting amplitude is smaller



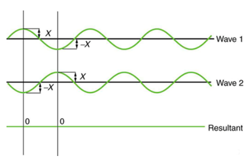


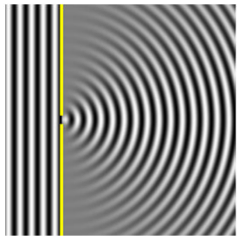
Image credit: Wolfe, Gregg, et al. "Superposition and Interference." In *College Physics for AP® Courses*. Houston, TX: OpenStax, 2015. https://openstax.org/books/college-physics-ap-courses/pages/16-10-superposition-and-interference (CC BY 4.0)

Diffraction

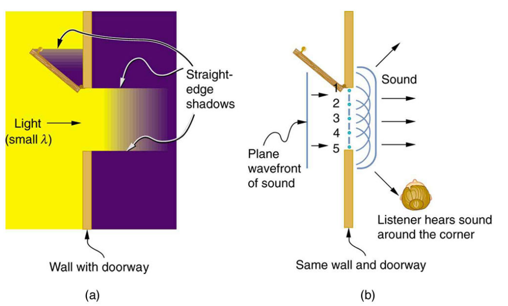
- Italian priest Francesco Grimaldi published the first detailed observation and description of diffraction in 1665 (two years after his death).

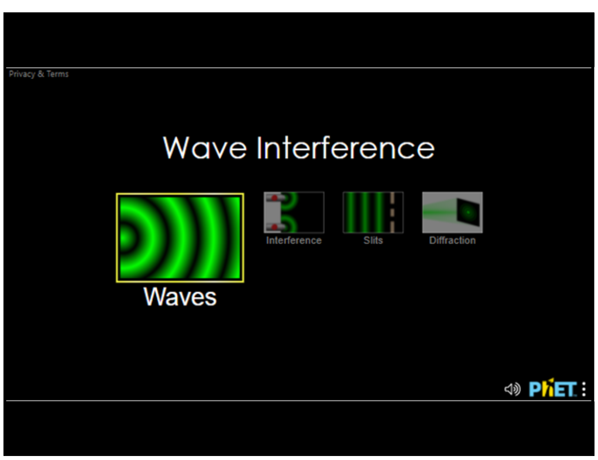
Portrait of Francesco Maria Grimaldi – Unknown (public domain)

- When waves pass through a narrow gap or slit, or when their path is partially blocked by an object, the waves spread out into what one would expect to be a shadow region.

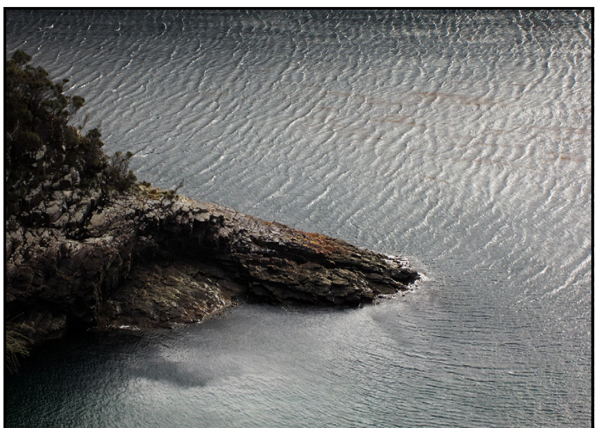


- Waves will only diffract if the wavelength is larger than the barrier or opening.





Diffraction – Mauro Orlando (CC BY-NC-ND 2.0)

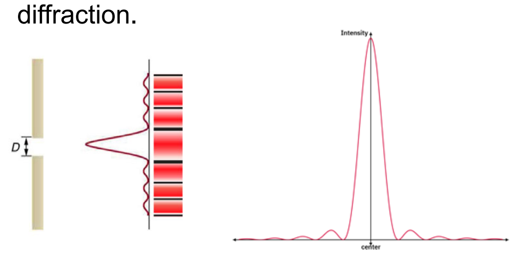


Fluted Cape Diffraction – ccdoh1 (CC BY-NC-ND 2.0)

wave diffraction and interference – Richard Droker (CC BY-NC-ND 2.0)

Roberto Lo Savio (Adobe Stock Photo)

- A distinctive pattern of a bright spot in the middle with alternating dark and bright spots on either side results from diffraction.



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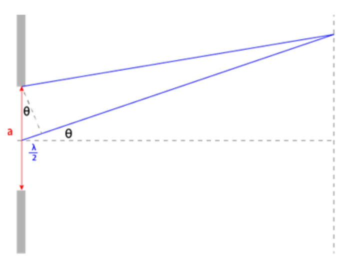
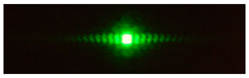
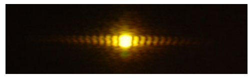
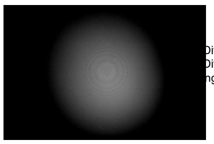
- This happens because the paths of the wave from each end of the slit (or side of the barrier) are different lengths than the path from the middle resulting in areas of constructive and destructive interference



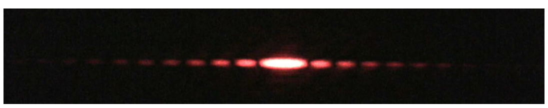






Diffraction - ~546nm – Eli Brody (CC BY-NC 2.0)
Diffraction - ~579nm – Eli Brody (CC BY-NC 2.0)
ngs in a pinhole camera – Darron Birgenheier (CC BY-SA 2.0)

laser.physics.sunysb.edu/~mkorn/lecture/



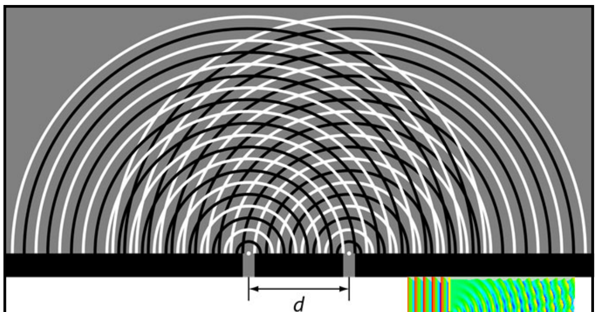
interventions-mesures-physiques-evreux.e-monsite.com/pages/optique/diffraction-par-une-fente.html

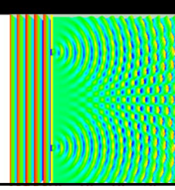
Path Difference

- When the path length of two coherent waves differs by **one-half wavelength**, the result will be total **destructive interference**.
- When the path length of two coherent waves differs by **one wavelength**, the result will be total **constructive interference**.

Double Slit Interference

- If a wave passes through two slits, then the wave will diffract through both slits resulting in two coherent waves.
  - The waves are in phase and traveling in the same direction.
- These two waves will overlap creating areas of constructive and destructive interference.





Diffraction on two slits – Center for Images in Science and Art _ University of Lisbon (CC BY-NC-SA 2.0)
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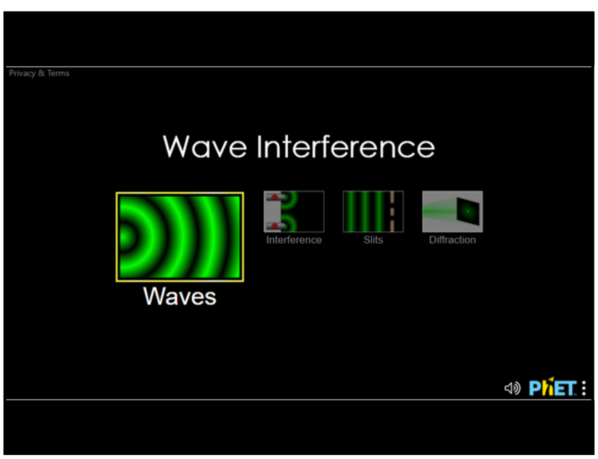
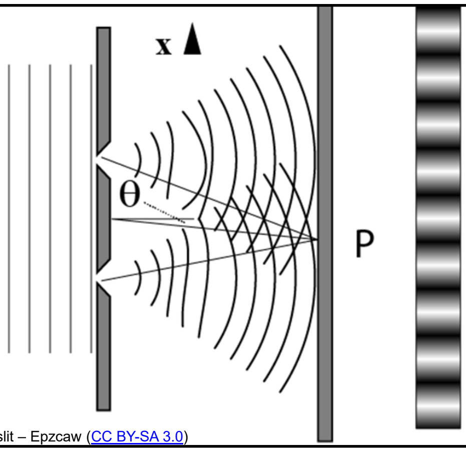


- Thomas Young (British, 1773 – 1829)
  - "Experiments and Calculations Relative to Physical Optics" (1804)
  - Demonstrated that light will diffract and cause areas of constructive and destructive interference when passed through two slits.

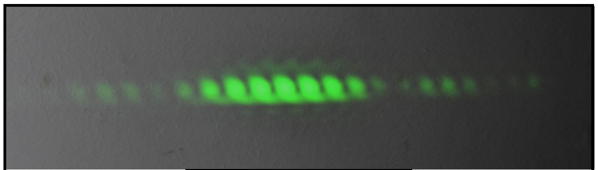
Henry Briggs (public domain)

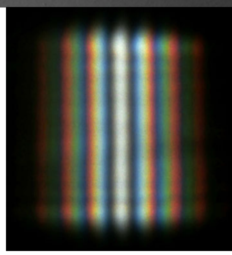


Double slit – Epzcaw (CC BY-SA 3.0)

I made a small hole in a window-shutter, and covered it with a piece of thick paper, which I perforated with a fine needle. For greater convenience of observation I placed a small looking-glass without the window-shutter, in such a position as to reflect the sun's light in a direction nearly horizontal upon the opposite wall, and to cause the cone of diverging light to pass over a table on which were several little screens of card-paper. I brought into the sunbeam a slip of card about one-thirtieth of an inch in breadth, and observed its shadow, either on the wall or on other cards held at different distances. Besides the fringes of color on each side of the shadow, the shadow itself was divided by similar parallel fringes of smaller dimensions, differing in number according to the distance at which the shadow was observed, but leaving the middle of the shadow always white.

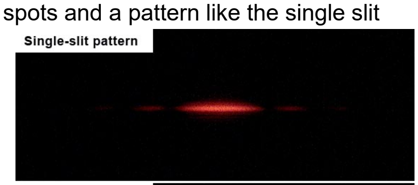
Thomas Young. Experiments and Calculations Relative to Physical Optics. A Bakerian Lecture. Read November 24, 1803. Philosophical Transactions. 1804.

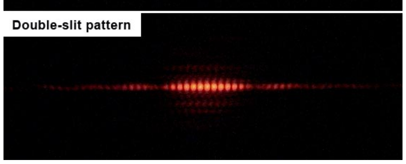




Young's slits – Graham Beards (CC BY-SA 4.0)
Double-slit interference of sunlight – Aleksandr Berdnikov (CC BY-SA 4.0)

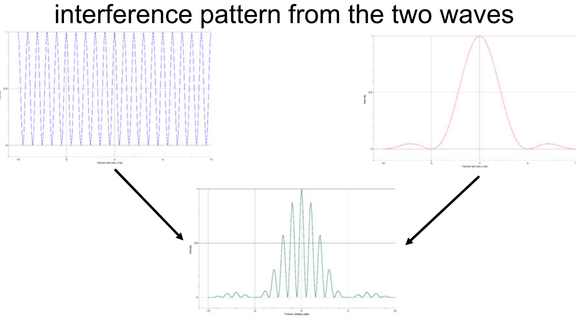
- Two patterns exist
  - A series of equally spaced bright and dark spots and a pattern like the single slit

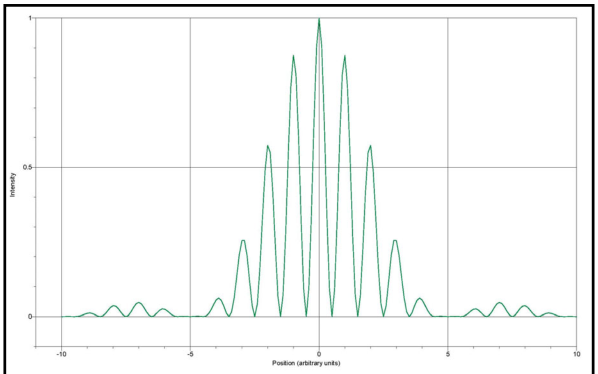


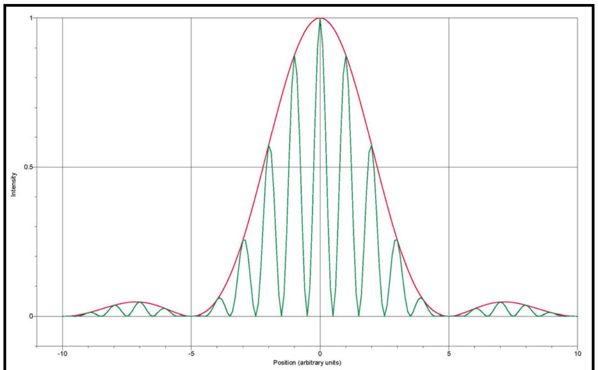


jordgette (CC BY-SA 3.0)

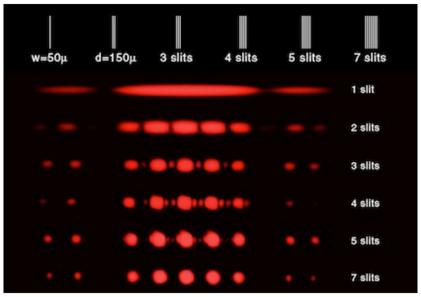
- This happens because there is still a diffraction pattern from each slit and this pattern is superimposed on the interference pattern from the two waves







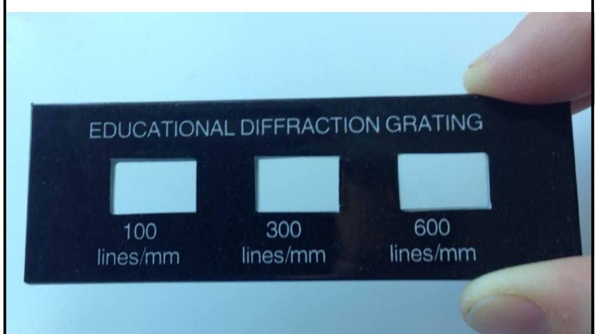
- If we add more slits the bright fringes get narrower



www.unistudyguides.com/wiki/Interference_and_Diffraction

Diffraction Grating

- A diffraction grating is a natural consequence of the effect on the interference pattern when the number of slits is increased
- Diffraction gratings are used to produce optical spectra
- Typically contain 600 slits (or lines) per mm with very small spacing between the slits

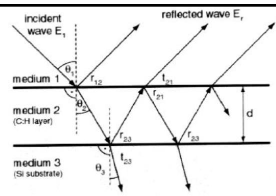


Diffraction grating – Magdalena Wiklund (CC BY-ND 2.0)

https://youtu.be/iQPntUPNDIQ

Thin Films

- When light is incident on a thin film (oil, soap) part of the light reflects off the surface and some of the light is refracted into the film
- When the refracted light hits the bottom of the film it is once again both reflected and refracted
- This process can occur several times for the same incident wave



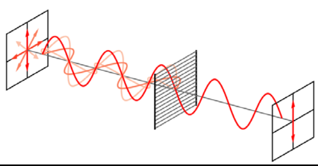
www.ualberta.ca/~pogosyan/teaching/PHYS_130/FALL_2010/lectures/lect34/lecture34.html

- When the light reflects off the top of the film it undergoes a phase shift of 180° (or π radians)
- Depending on the thickness of the film this will result in either constructive or destructive interference at the surface

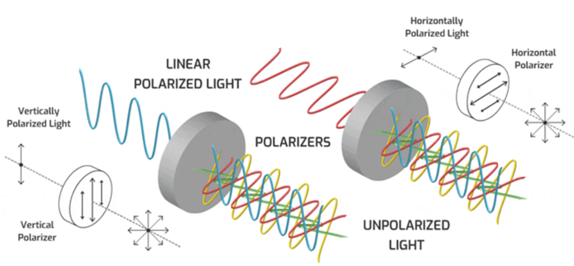
CD – chrysics (CC BY-NC 2.0)
Peacock – mika (CC BY-NC-ND 2.0)
Diffraction of a fly wing 1 – roger mepsted (CC BY-NC-ND 2.0)

Polarization

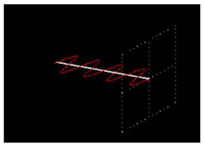
- Transverse waves have a unique property call polarization
- Polarization of a transverse wave restricts the direction of the oscillations to a plane perpendicular to the direction of propagation

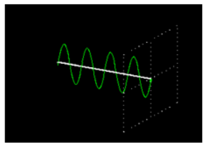


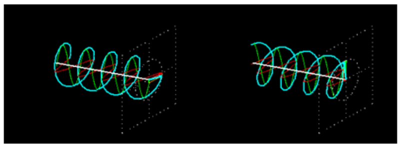
Fffred



https://thinklucid.com/tech-briefs/polarization-explained-sony-polarized-sensor/

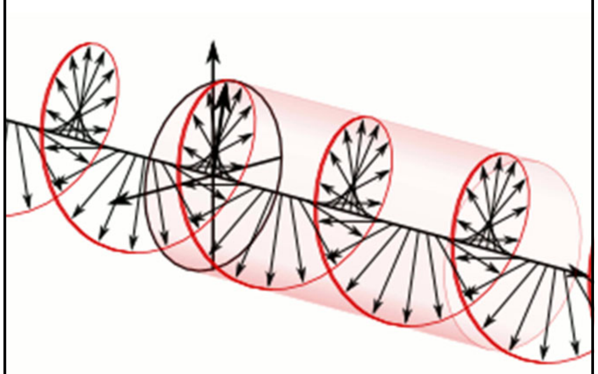






https://www.microwaves101.com/encyclopedias/polarization

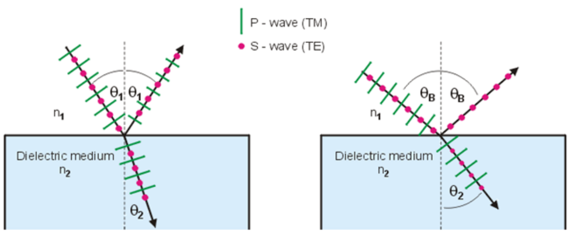
Circular Polarization



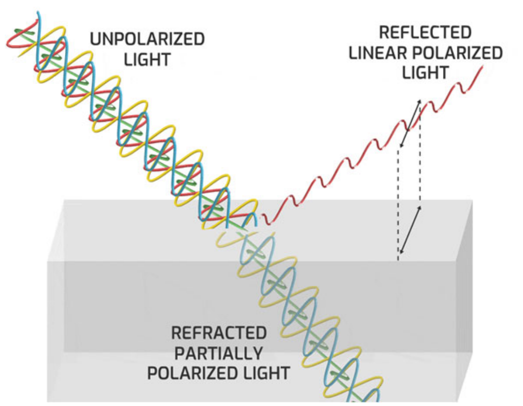
Dave3457 (public domain)

Polarization of Light

- Étienne-Louis Malus (1809) showed that when unpolarized light reflected off a glass plate it could be polarized
- Sir David Brewster (1812) showed that when unpolarised light was incident on an optically dense surface (like glass) at a specific angle (called Brewster’s angle), the light is completely polarized



www.ryerson.ca/~kantorek/ELE884/Polarization.htm



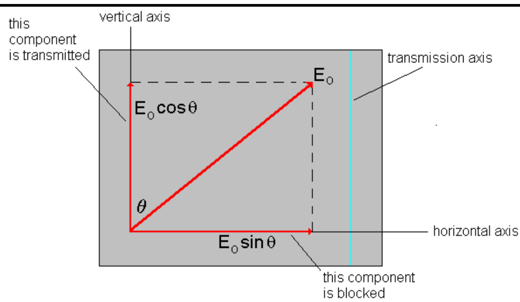
https://thinklucid.com/tech-briefs/polarization-explained-sony-polarized-sensor/

- Edwin Land (1928) developed a material with a molecular structure that only allows a specific orientation of the electric field to go through (called a Polaroid J sheet)

Library of Congress, Prints & Photographs Division, photograph by Bernard Gotfryd, [Reproduction number LC-DIG-gtfy-02233]

Malus's Law

- Consider polarized light whose electric field E_o makes an angle θ with the transmission axis of a second polarizer (analyser)
- We can split the electric field into its horizontal and vertical components



- In this case only the vertical component can pass through giving

$$E = E_o \cos\theta$$

- Transmitted intensity is proportional to the square of the electric field so…

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

I_o - Incident intensity

Practical Uses of Polarizers

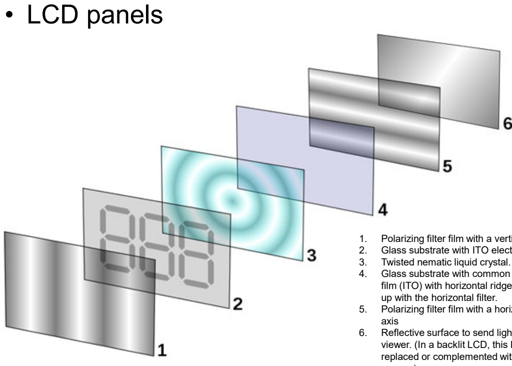
- Sunglasses

Practical Uses of Polarizers

- Polarized filter (photography)

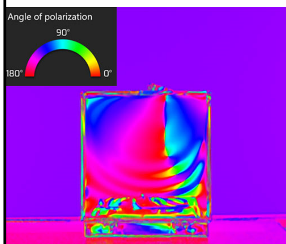
Without polarizing filter | With polarizing filter

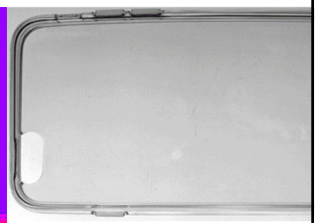
- LCD panels



1. Polarizing filter film with a vertical axis
2. Glass substrate with ITO electrodes
3. Twisted nematic liquid crystal.
4. Glass substrate with common electrode film (ITO) with horizontal ridges to line up with the horizontal filter.
5. Polarizing filter film with a horizontal axis
6. Reflective surface to send light back to viewer. (In a backlit LCD, this layer is replaced or complemented with a light source.)

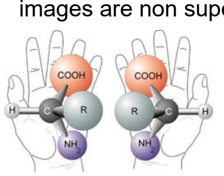
- Stress and scratch analysis

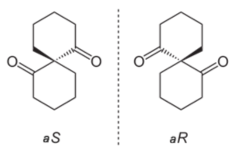




https://thinklucid.com/tech-briefs/polarization-explained-sony-polarized-sensor/

- Some chiral molecules are optically active
  - A Chiral molecule has a mirror image that cannot line up with it perfectly- the mirror images are non superimposable.





  - Tartaric acid, sugar, almost all amino acids, ascorbic acid (vitamin C)

Images: Pareja, Kristeen and Ifemayowa Aworanti. Fundamentals of Chirality. Organic Chemistry. LibreTexts. https://chem.libretexts.org/Bookshelves/Organic_Chemistry/Supplemental_Modules_(Organic_Chemistry)/Chirality/Fundamentals_of_Chirality

https://youtu.be/GchTURvBz68