Interference of Light Wave Optics

Photonics- a rapidly emerging branch of Physics

But the exact nature of light is yet to be understood.

Conventionally Optics divides itself in to three branches

Ray-Optics	*Reflection, Total internal reflection, Refraction, Double refraction etc.*
Wave-Optics	*Interference, Diffraction and Polarization*
Quantum-Optics	*Photoelectric effect, Optoelectronics, Lasers etc*

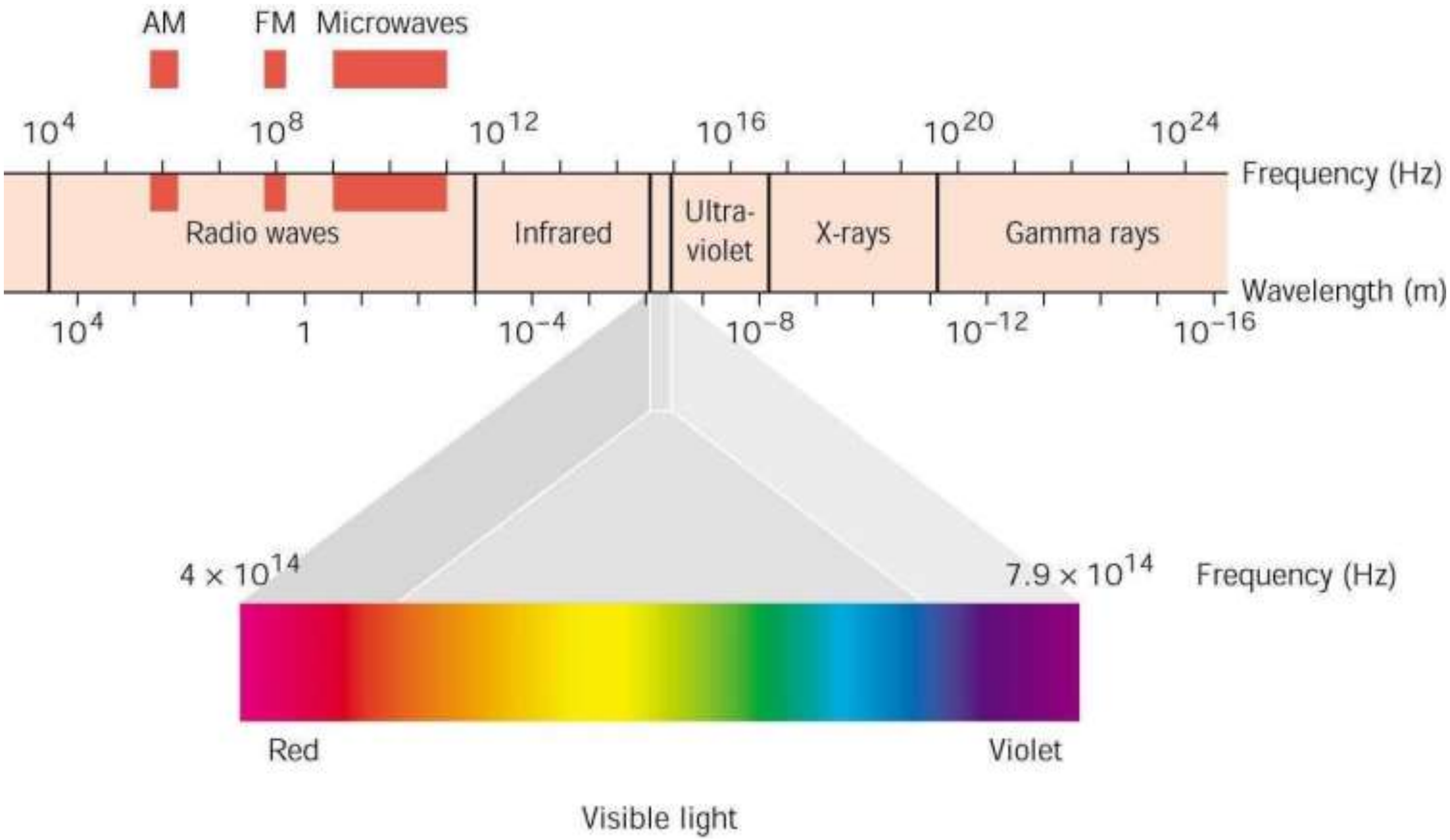
Interestingly, the oily films spread on the roads in rainy days, or the soup bubbles show beautiful colors. The pattern changes when viewed at different angles. This is due to thin film interference, where the thin film behaves like a ‘natural interferometer’.

The colors in many of a hummingbird's feathers are not due to pigment. The iridescence that makes the brilliant colors that often appear on the throat and belly is due to an interference effect caused by structures in the feathers. The colors will vary with the viewing angle.

The bright colors of peacock feathers are also due to interference

In both types of birds, <u>structures in the feathers</u> <u>split and recombine visible</u> <u>light so that interference occurs for certain colors</u>.

The Electromagnetic Spectrum



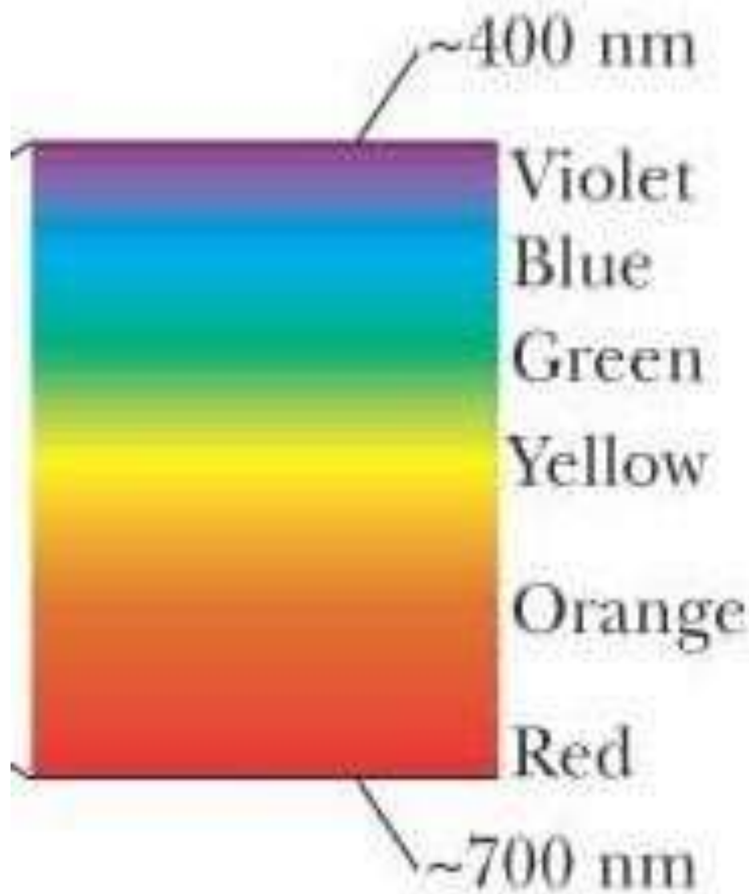
What is light?

Newton (*Opticks*, 1704). **Light is made of particles.** This accounts for straight rays and sharp shadows.

Huygens (*Traité de la lumière,*1690). **Light is made of waves.** Like water waves, light beams cross without interacting. Waves come from every part (A, B, C) of a candle and spread like water ripples. A little distance from the candle they seem like spheres centred on the candle.

Visible Light

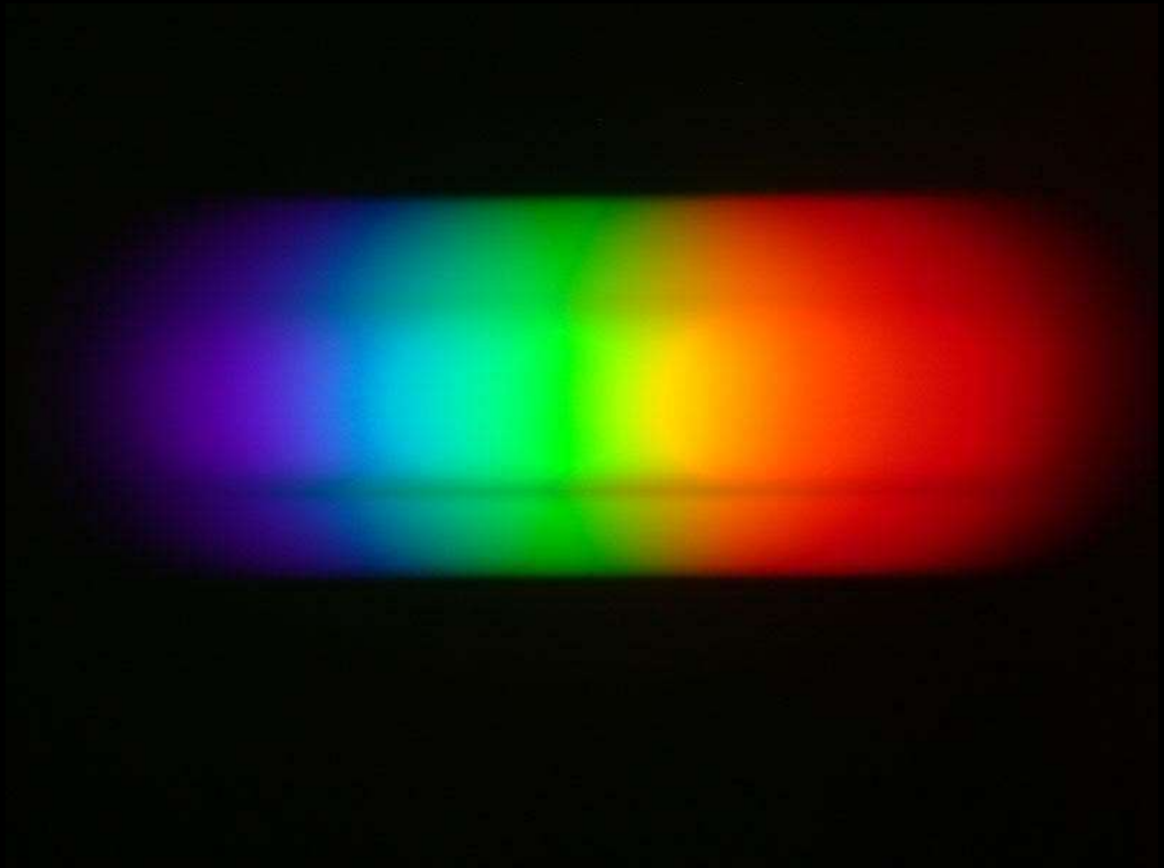
- Different wavelengths correspond to different colors
- The range is from red ($\lambda \sim 7 \times 10^{-7}$ m) to violet ($\lambda \sim 4 \times 10^{-7}$ m)



Incandescent Light Bulb

Full Spectrum of Light

All frequencies excited!



Periodic Waves

A periodic wave repeats the same pattern over and over.

For periodic waves: $\mathbf{v = \lambda f}$

v is the wave's speed

f is the wave's frequency

λ is the wave's wavelength

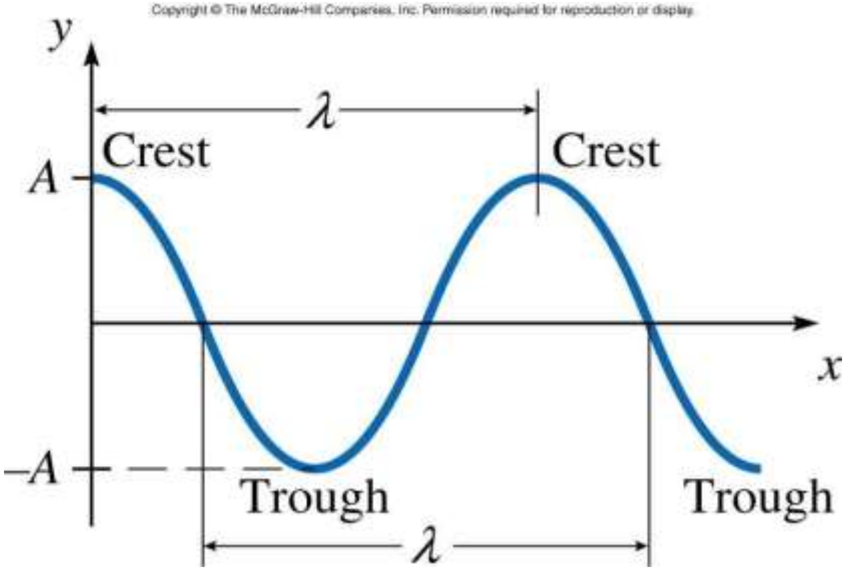
The period T is measured by the amount of time it takes for a point on the wave to go through one complete cycle of oscillations.

The frequency is then $\mathbf{f = 1/T}$

Periodic Waves

One way to determine the wavelength is by measuring the distance between two consecutive crests.

The maximum displacement from equilibrium is amplitude (A) of a wave.



Phase difference

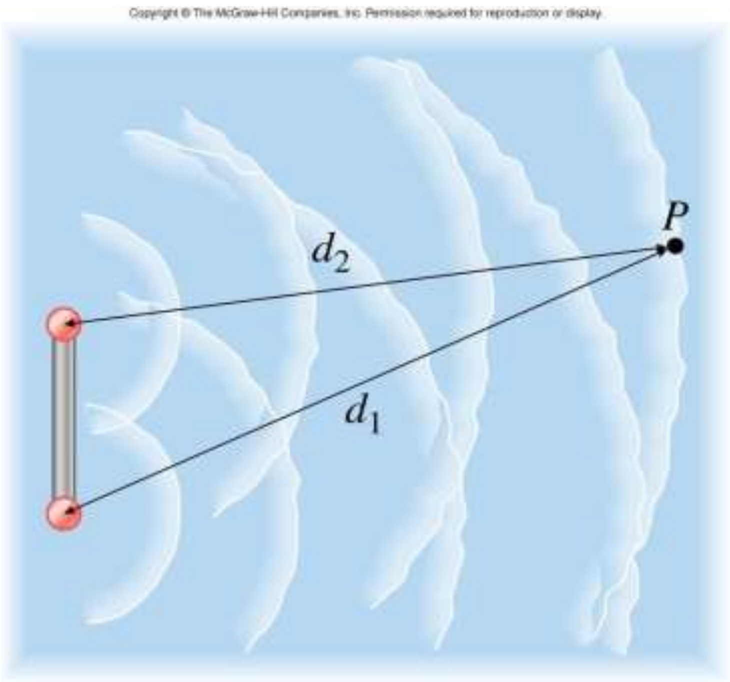
Particles in the medium are oscillating.
‘Phase’ = stage in their repeating cycle.

With two different path lengths to a point

- ‘In phase’– two waves are doing same things at same moments. No phase difference.
- ‘In antiphase’ - two waves are doing opposite things at same moments.
- A continuous range of phase relationships is possible.

AP experiments: *Path difference and phase differences, Superposition of microwaves*

Phase Difference

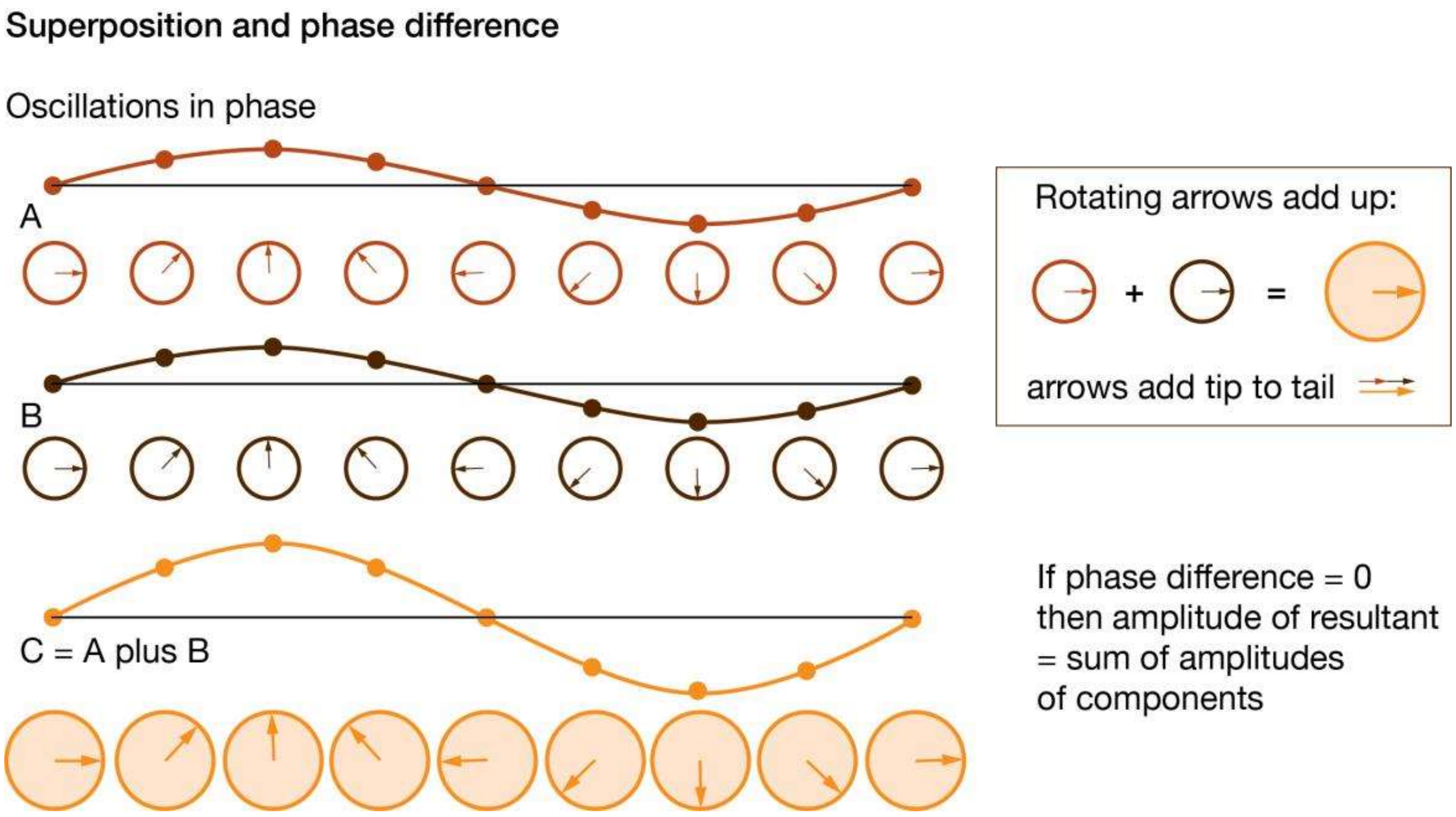


When two waves travel different distances to reach the same point, the phase difference is determined by:

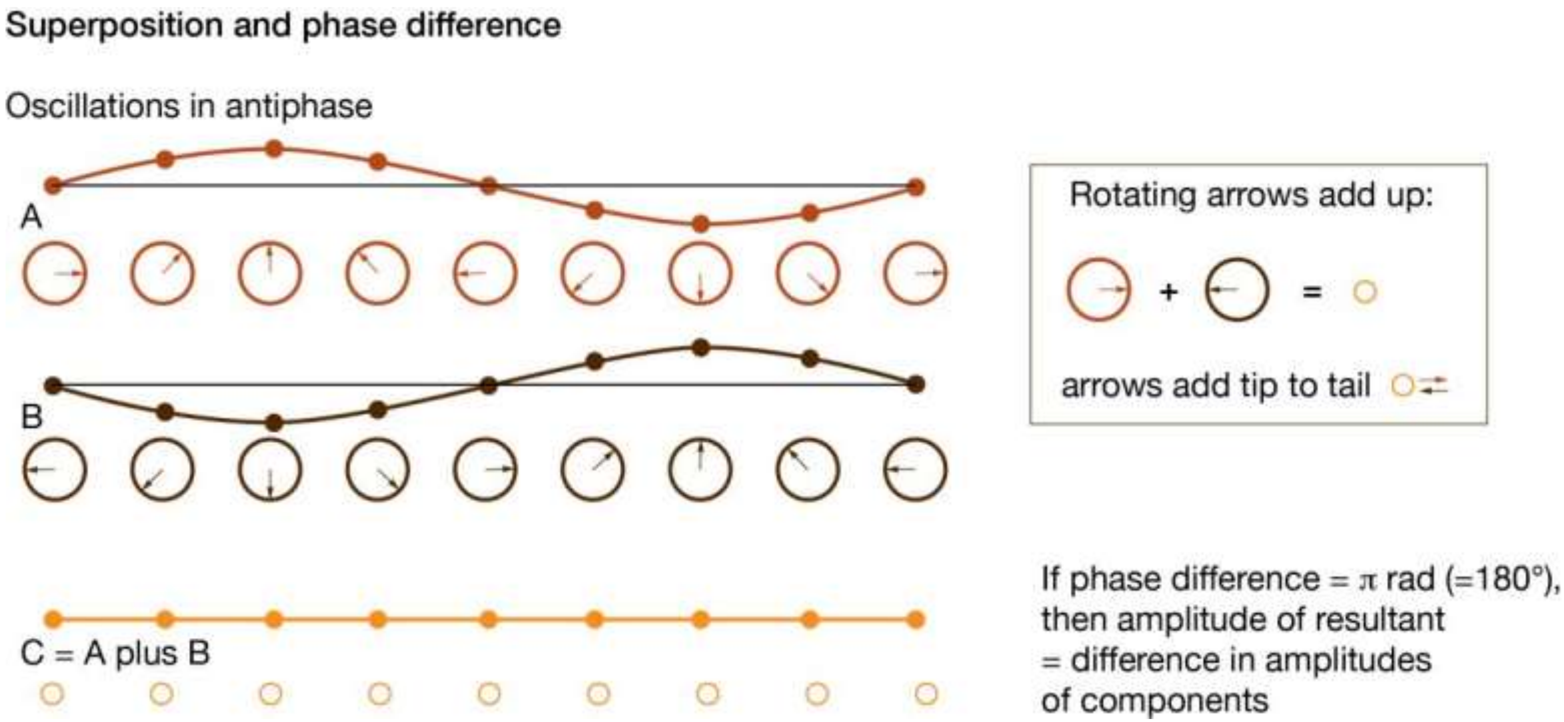
$$\frac{d_1 - d_2}{\lambda} = \frac{\text{phase difference}}{2\pi}$$

Note: This is a ratio comparison. λ is not equal to 2π

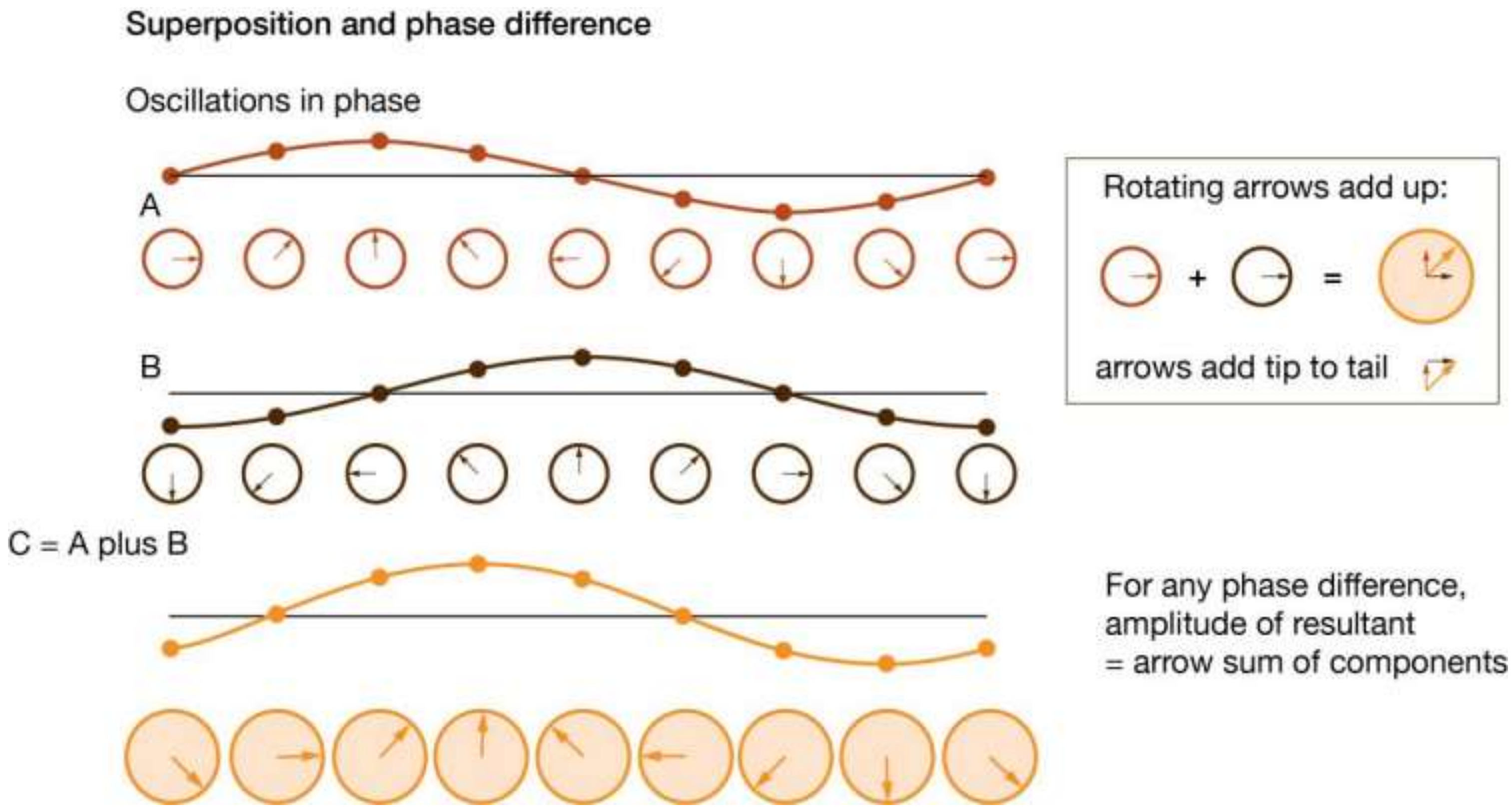
In phase


Superposition and phase difference
Oscillations in phase
A
B
C = A plus B
Rotating arrows add up:
+
=
arrows add tip to tail
If phase difference = 0
then amplitude of resultant
= sum of amplitudes
of components

In antiphase



Phase difference π/2

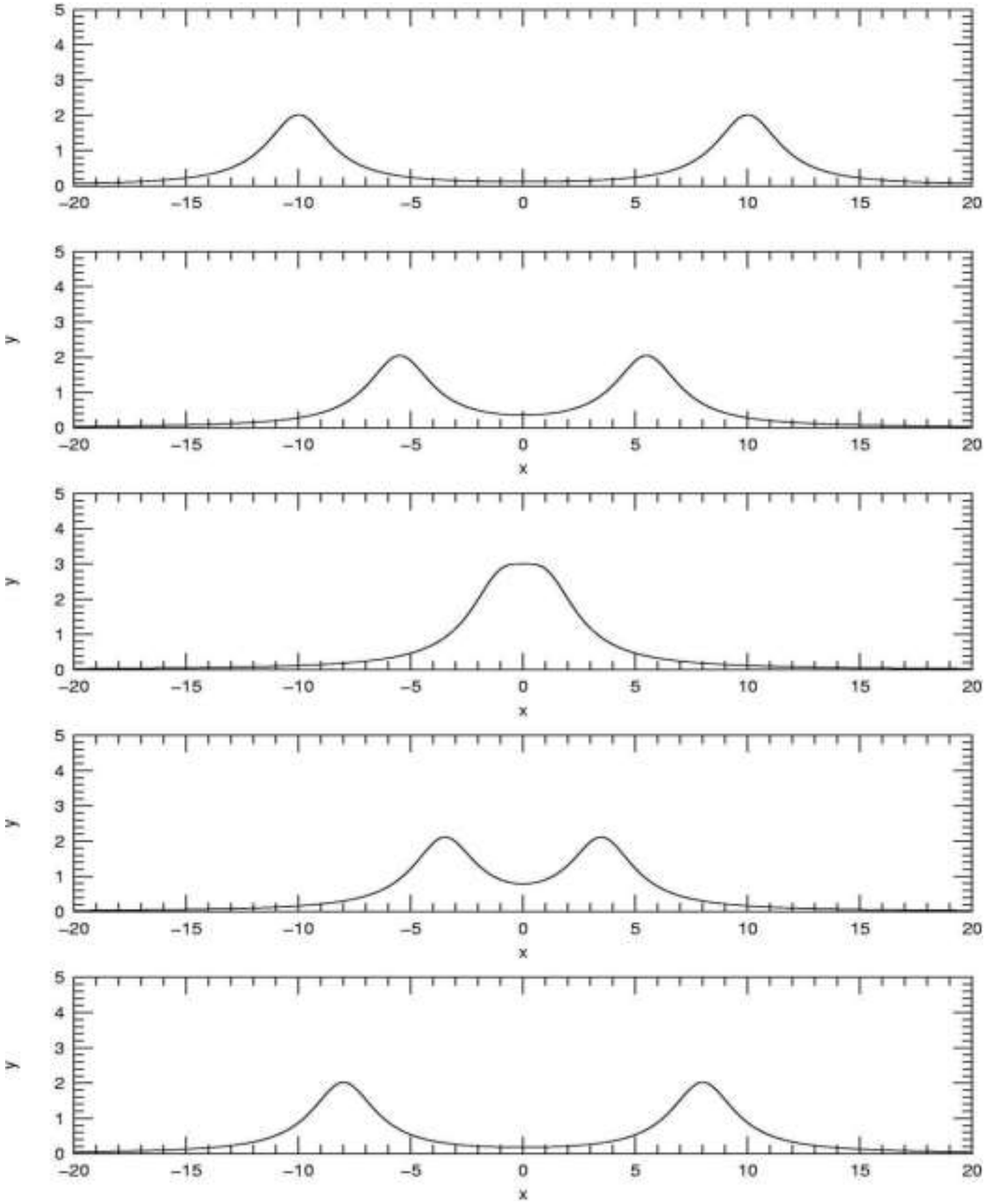


The Principle of Superposition

For small amplitudes, waves will pass through each other and emerge unchanged.

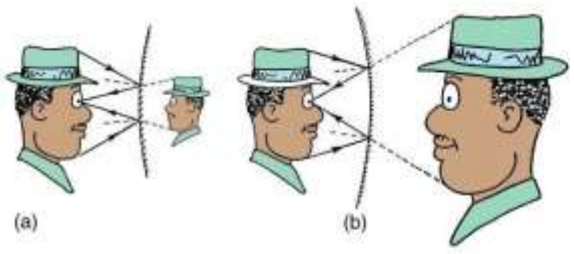
Superposition Principle: When two or more waves overlap, the net disturbance at any point is the sum of the individual disturbances due to each wave.

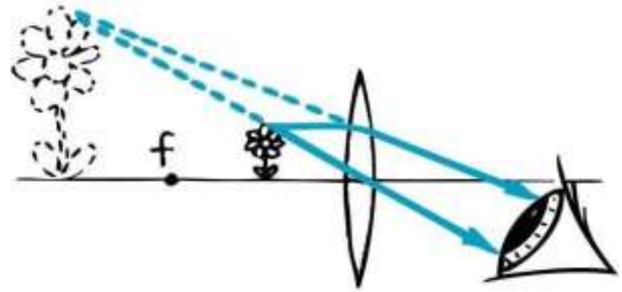
A steady interference pattern is created only if the waves have a fixed phase difference over a period of time.



Two traveling wave pulses: left pulse travels right; right pulse travels left.

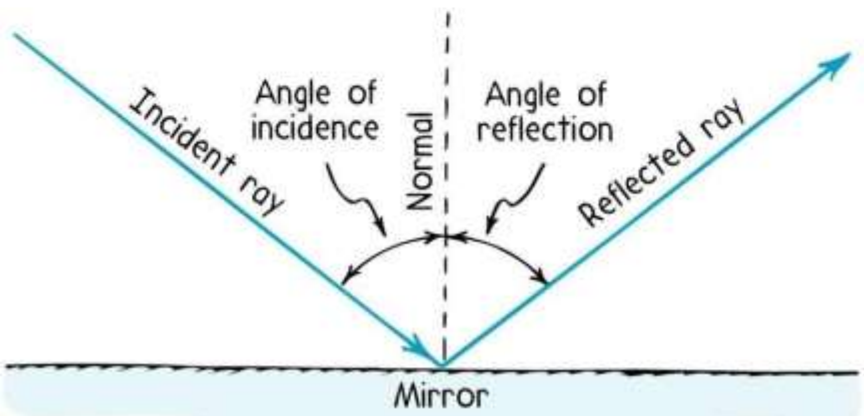
Geometric RAY Optics

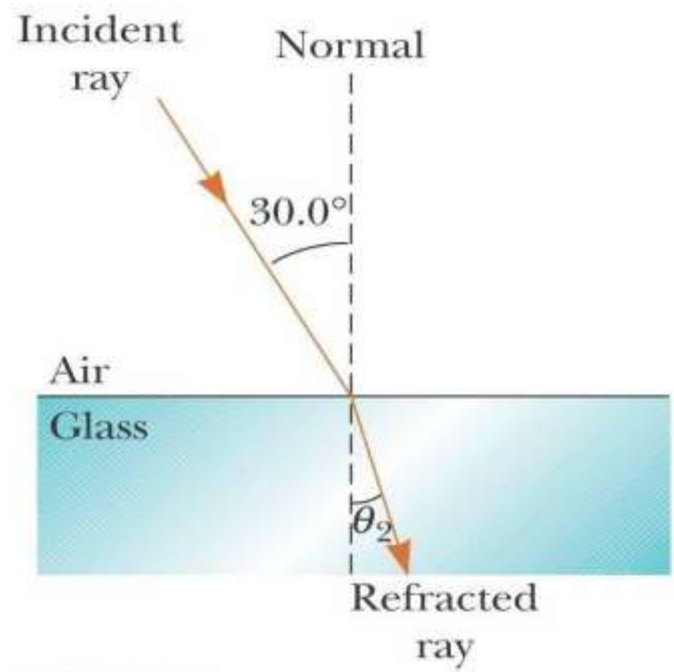




$$\boxed{\theta_i = \theta_r}$$

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





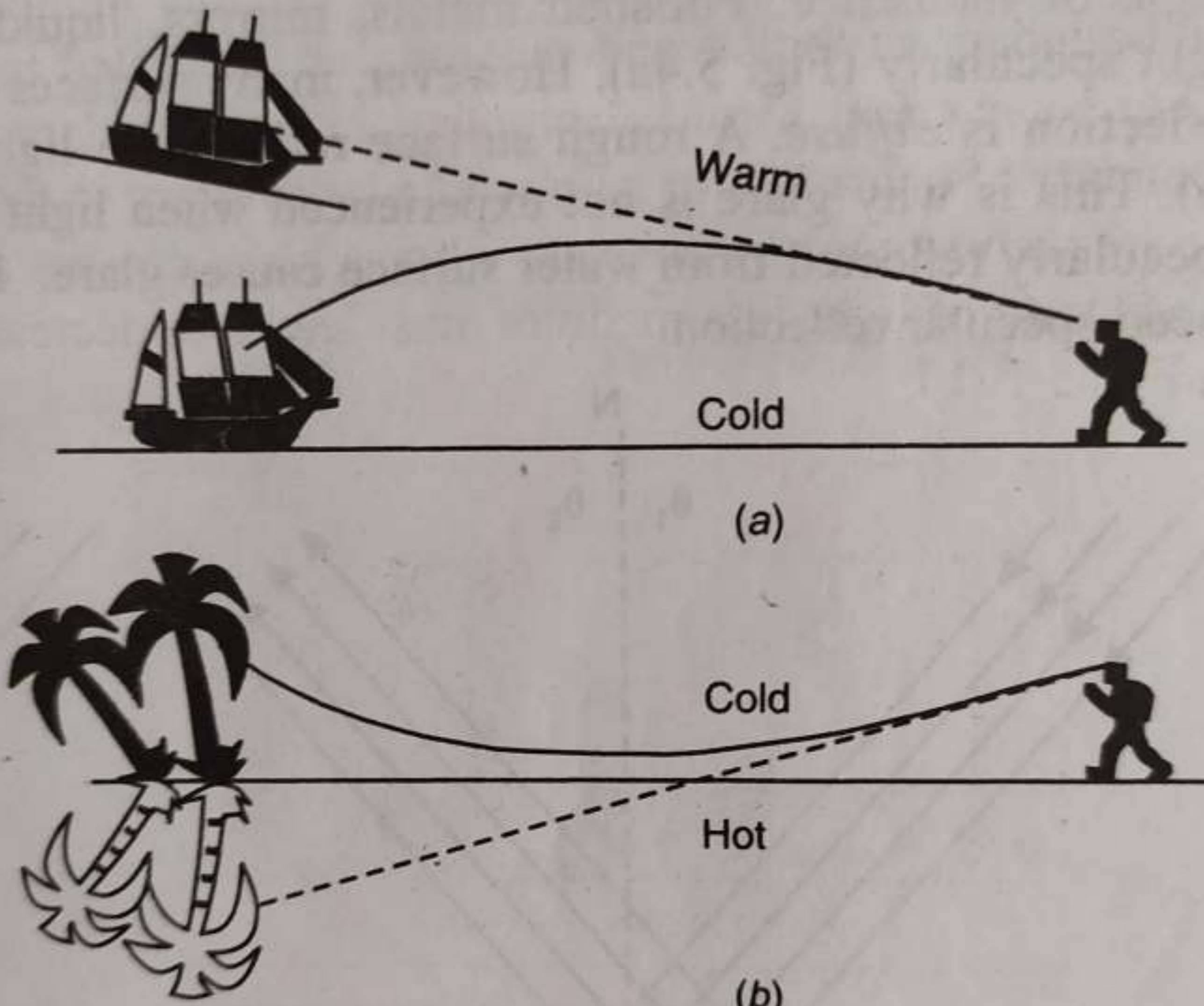


Fig. 5.2: Optical effects due to inhomogeneous nature of atmosphere (a) looming (b) mirages

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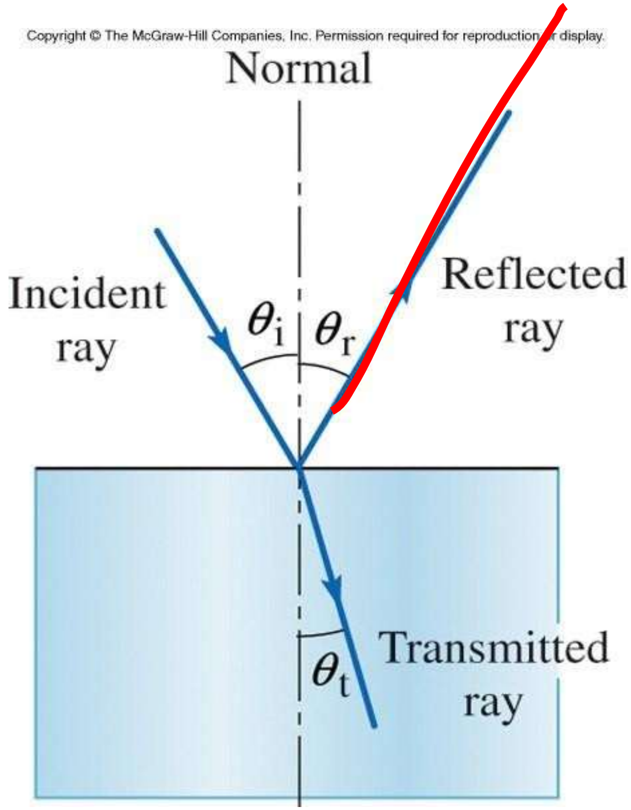
Reflection and Refraction

At an abrupt boundary between two media, a reflection will occur. A portion of the incident wave will be reflected backward from the boundary.

A portion of the incident wave will be transmitted through the media. This is the refracted ray.

Reflection and Refraction



When a wave is incident on the boundary between two different media, a portion of the wave is reflected, and a portion will be transmitted into the second medium. Reflected ray is 180^o out of phase.

The Frequency is Constant

The **frequency** of the transmitted wave **remains the same**. However, both the wave's speed and wavelength are changed such that:

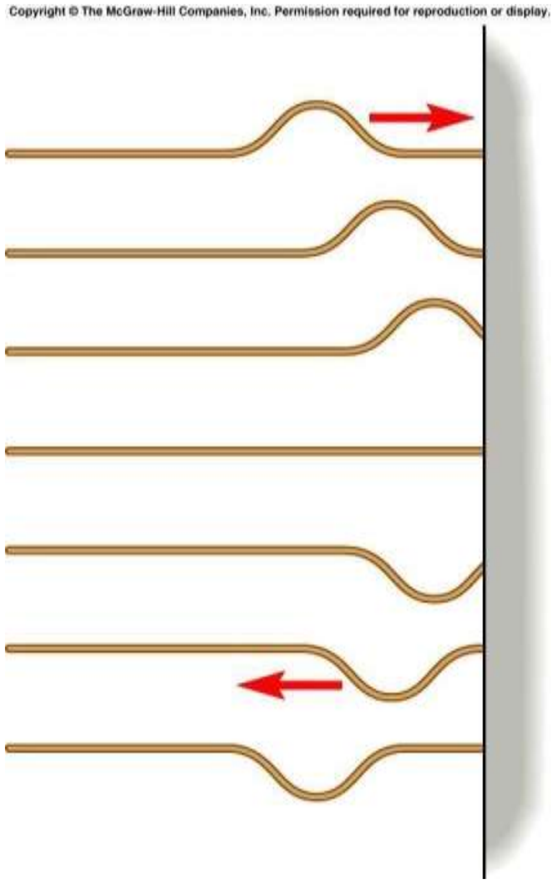
$$f = \frac{v_1}{\lambda_1} = \frac{v_2}{\lambda_2}$$

The transmitted wave will also suffer a change in propagation direction (**<u>refraction</u>**).

The Reflected Wave & Phase Change

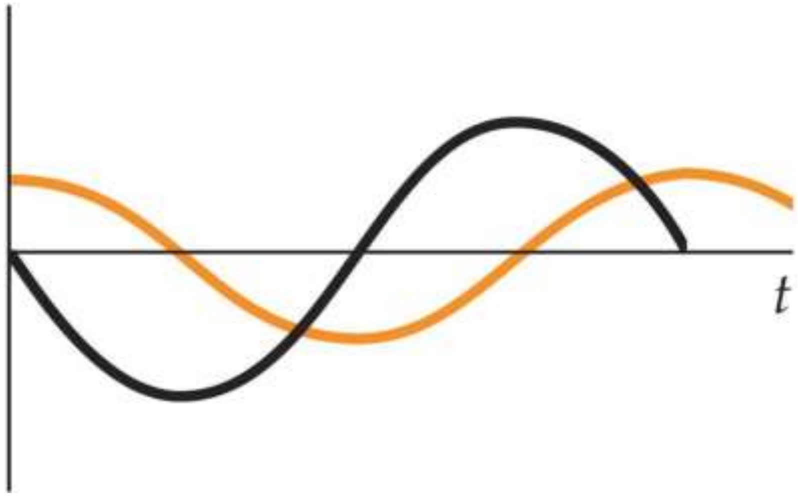
When you have a wave that travels from a “low density” medium to a “high density” medium, the reflected wave pulse will be inverted. (180^{o} phase shift.)

The frequency of the reflected wave remains the same.



Interference

Two waves are considered **coherent** if they have the same frequency and maintain a fixed phase relationship.



Two coherent waves. The black wave is $\pi/4$ radians behind the orange wave.

Two waves are considered **incoherent** if the phase relationship between them varies randomly.

Ray Optics: Ignores Diffraction and Interference of waves!

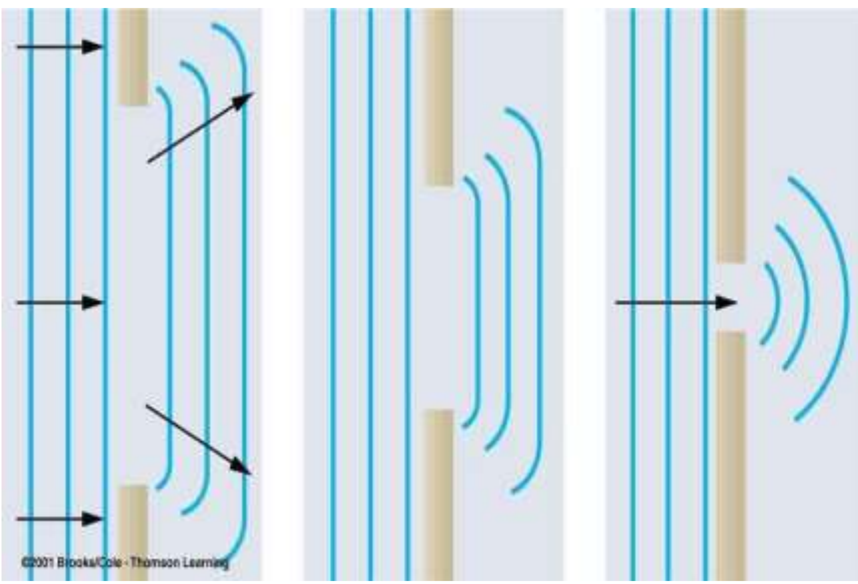
Diffraction depends on SLIT WIDTH: the smaller the width, relative to wavelength, the more bending and diffraction.

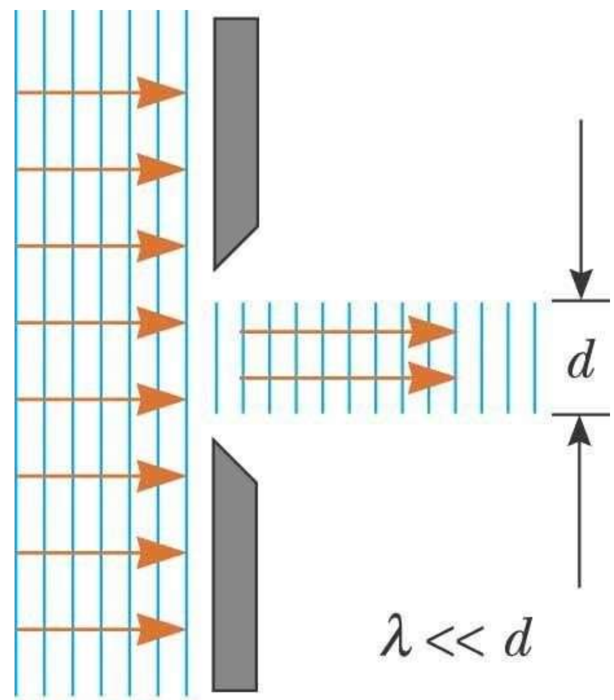
Ray Optics assumes that $\lambda \ll d$, where d is the diameter of the opening.

This approximation is good for the study of mirrors, lenses, prisms, etc.

Wave Optics assumes that $\lambda \sim d$, where d is the diameter of the opening.

This approximation is good for the study of interference.



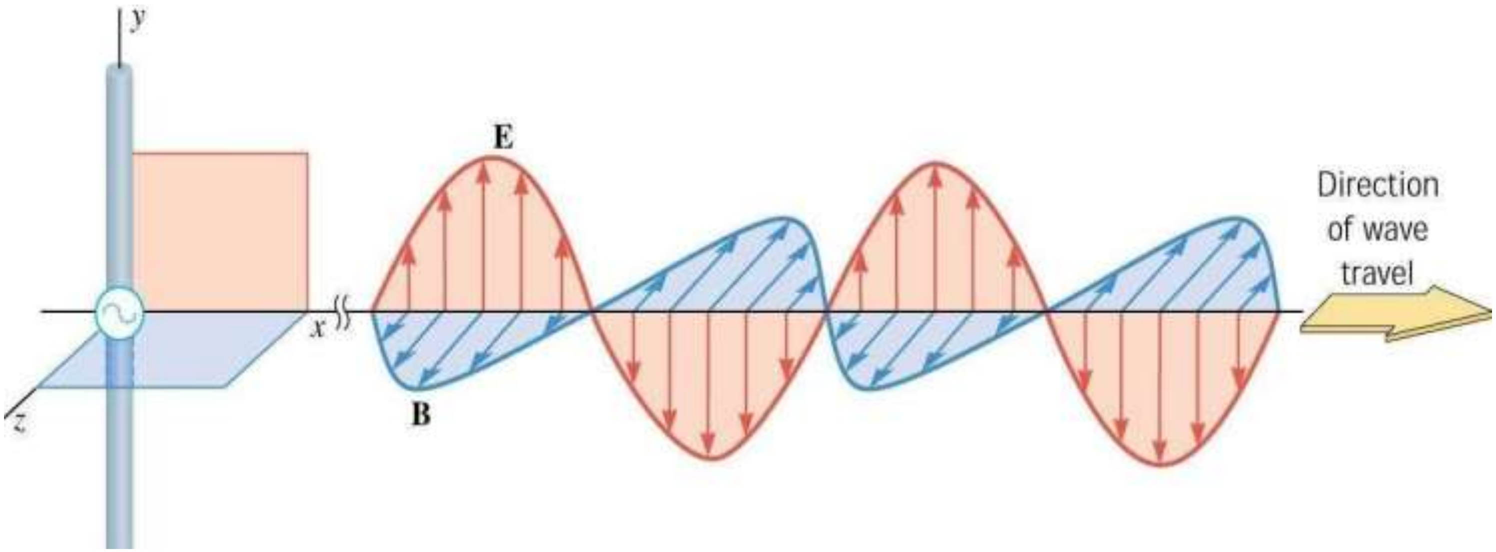


James Clerk Maxwell
1860s

Light is wave.

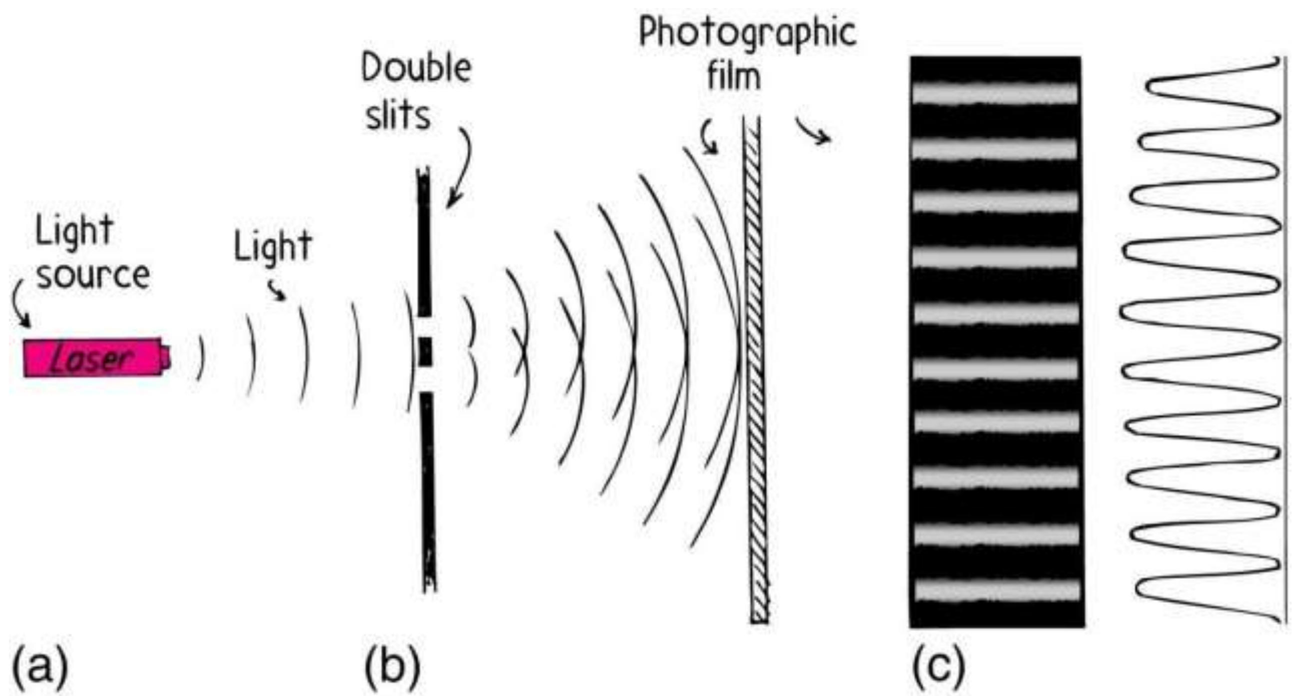
$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_o}} = 3.0x10^8 m/s$$

Speed of Light in a vacuum:
186,000 miles per second
300,000 kilometers per second
3 x 10^8 m/s



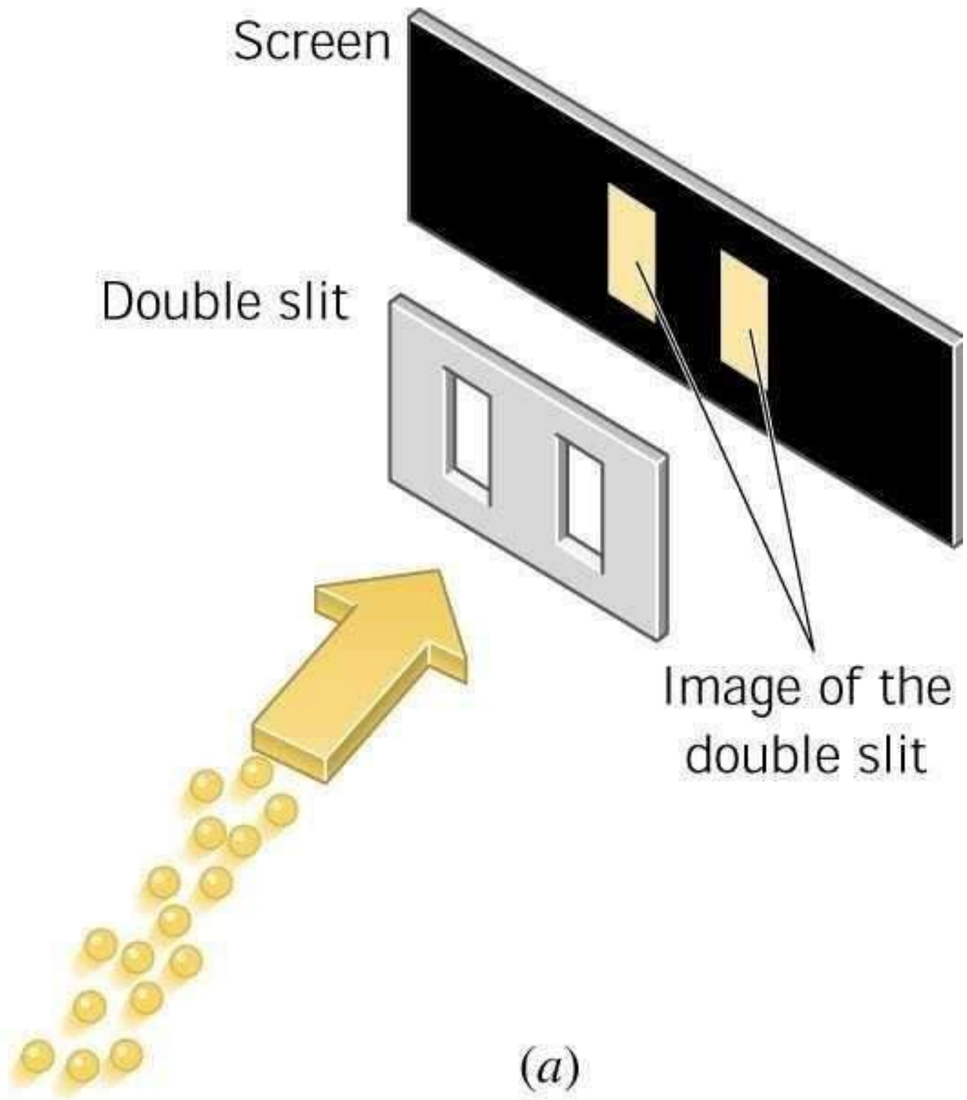
Double Slit

Double Slit is VERY IMPORTANT because it is evidence of waves. Only waves interfere like this.



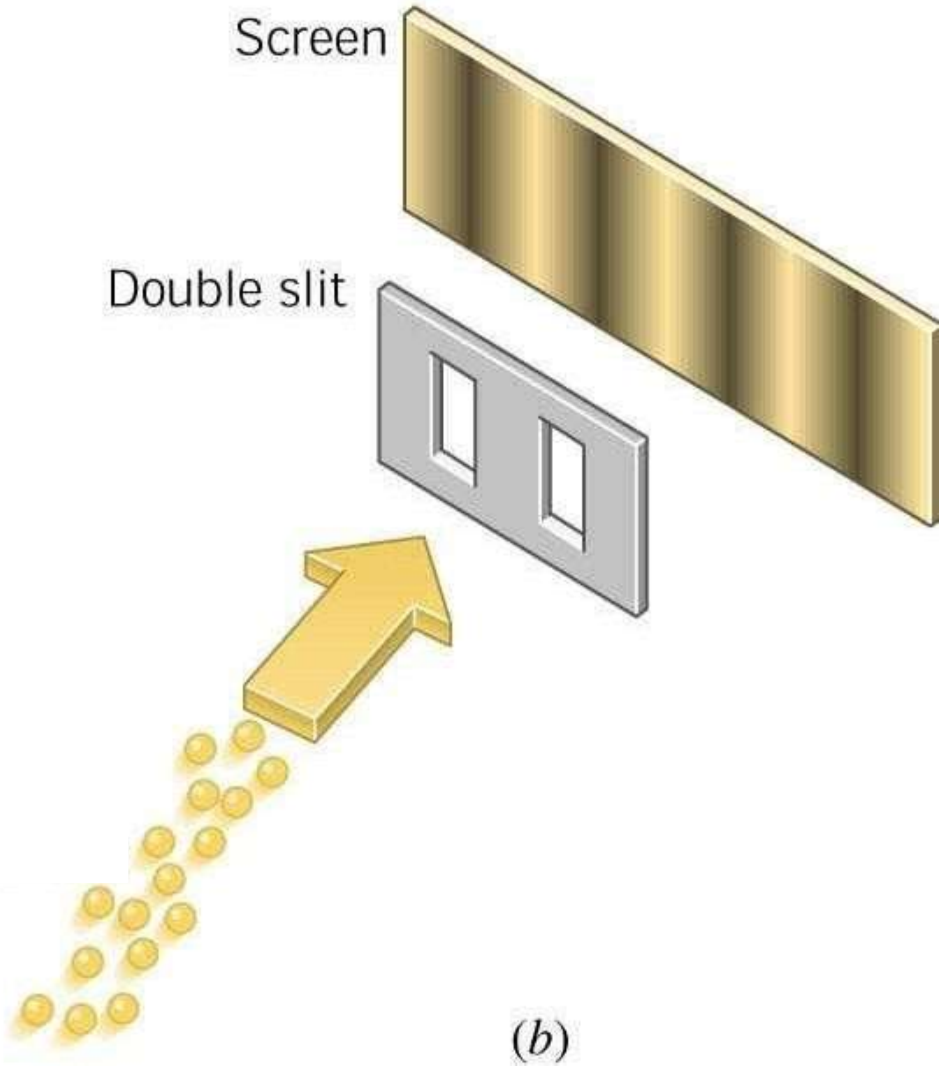
Particle Picture

If light were made of hard bullets, there would be no interference pattern.



(a)

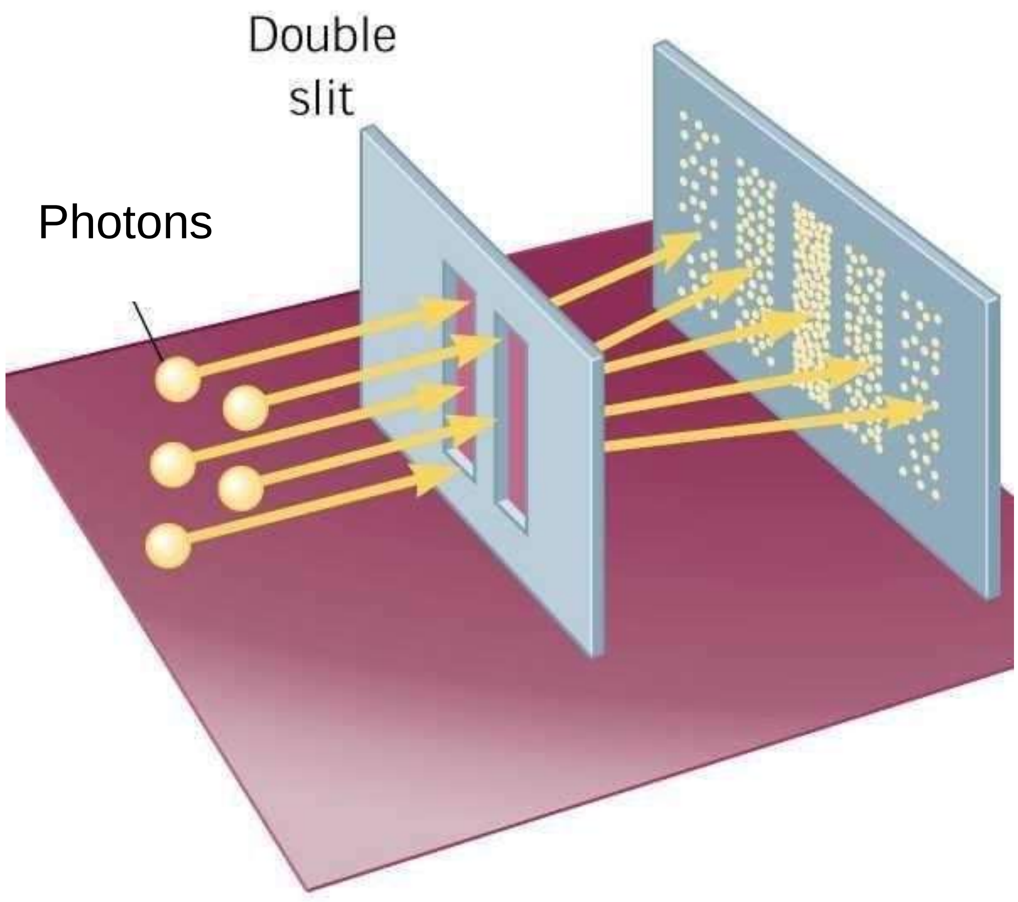
Wave Picture



In reality, light does show an interference pattern.

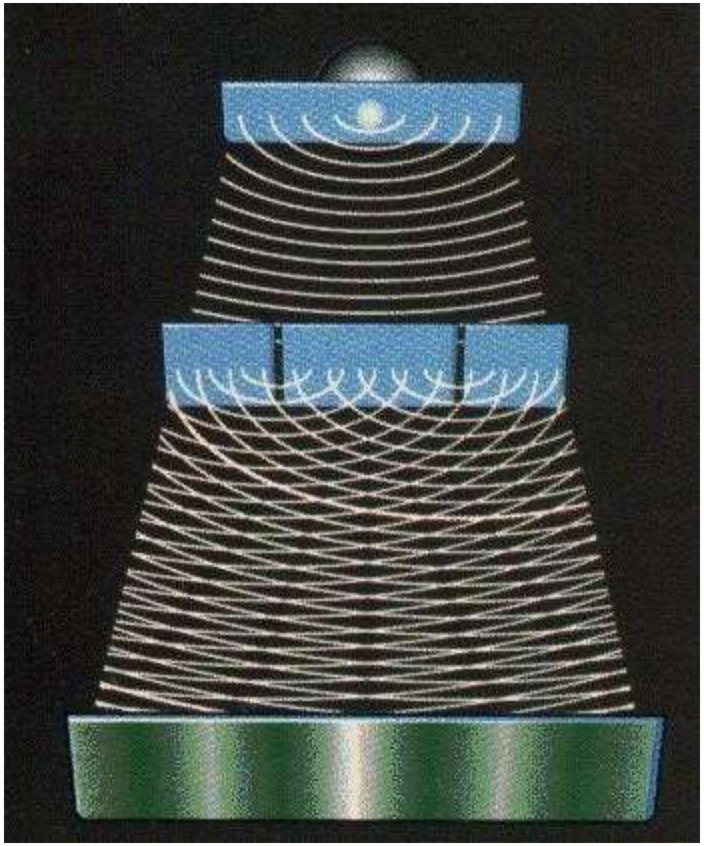
Particle-Wave Picture

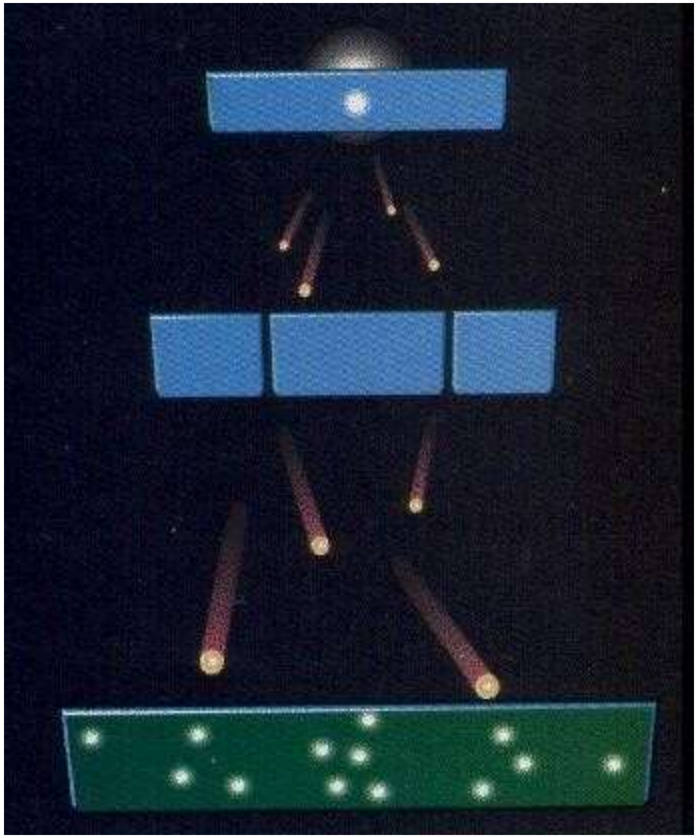
Light acts like a wave going through the slits but arrive at the detector like a particle.



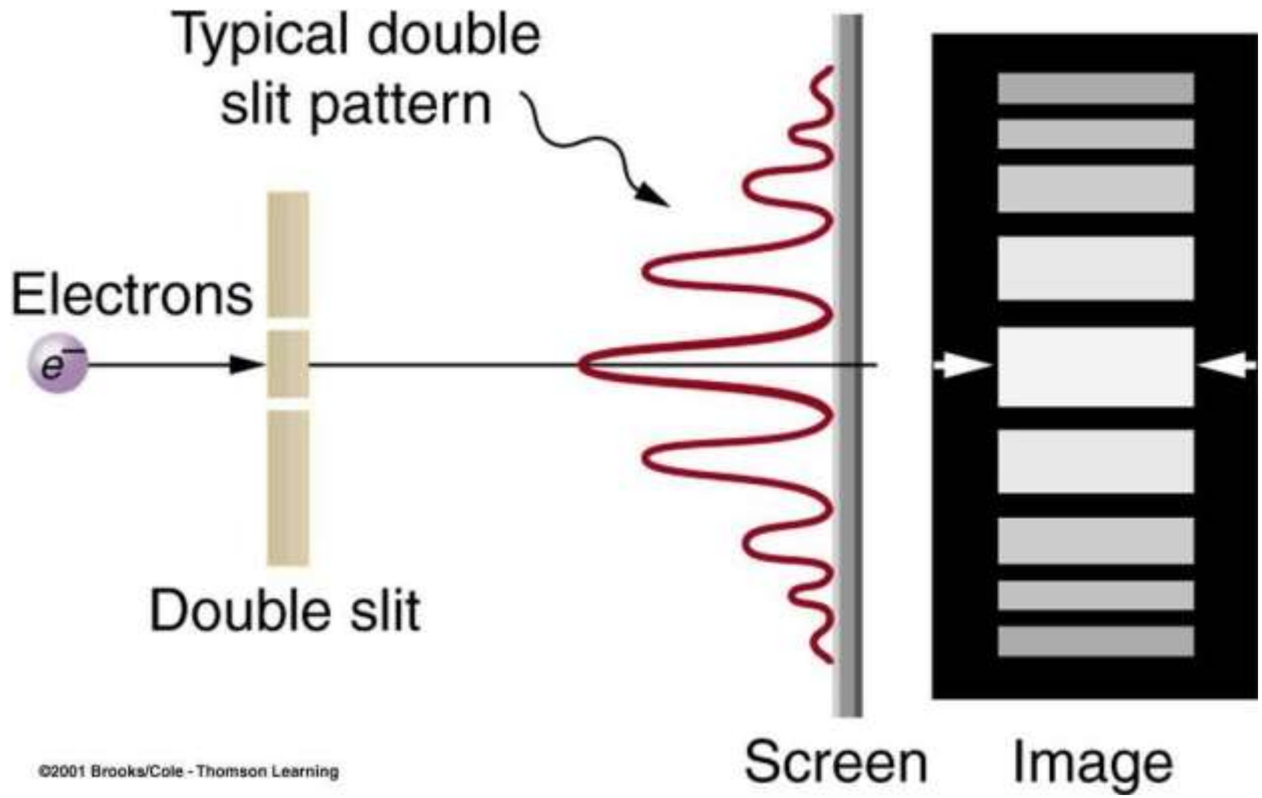
(a)

Particle Wave Duality





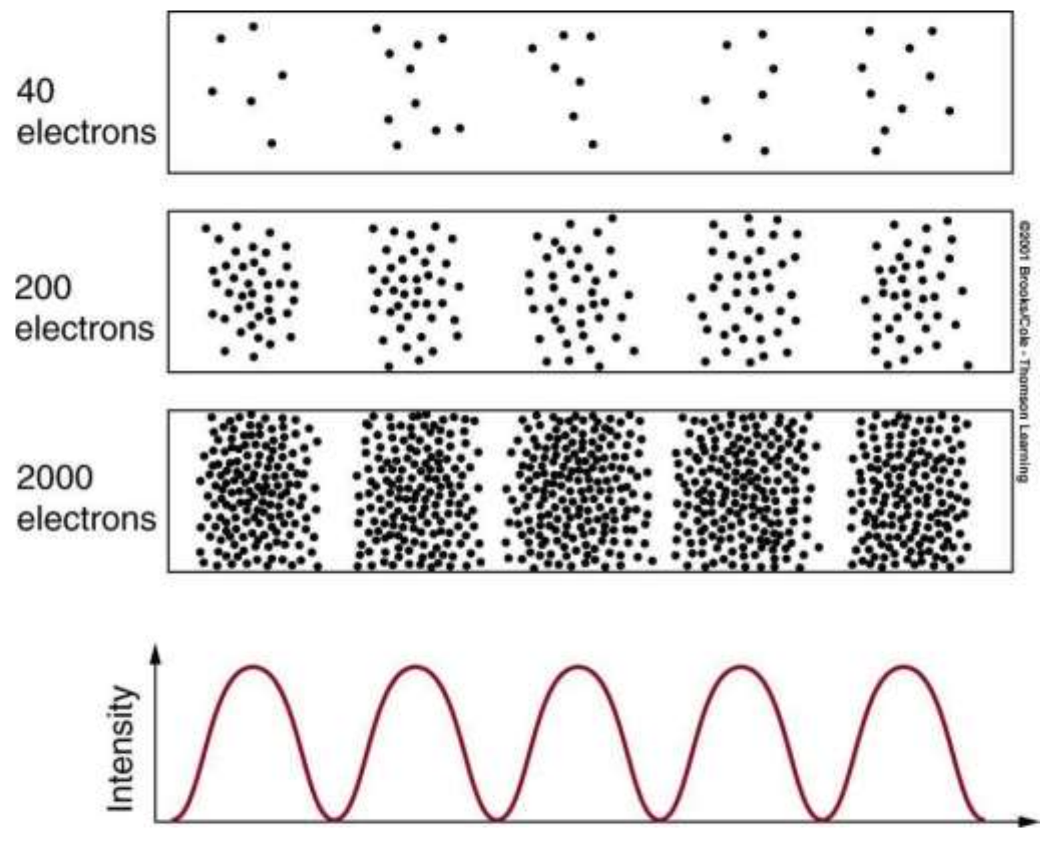
Double Slit for Electrons shows Wave Interference! Key to Quantum Theory!



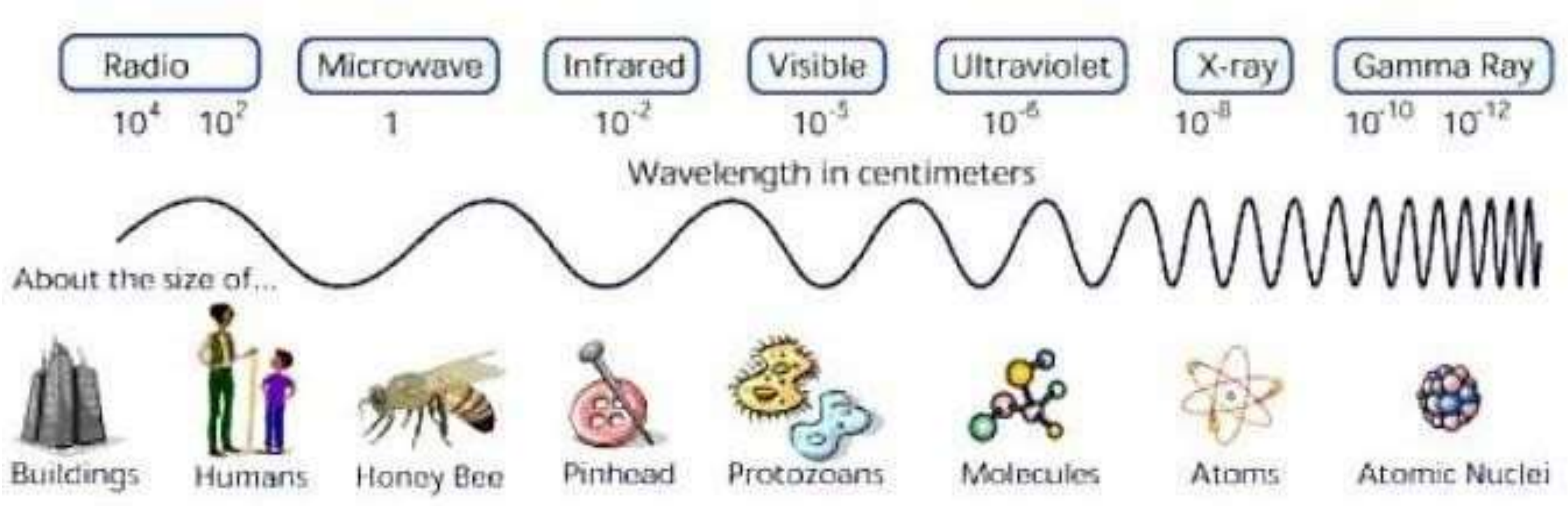
Interference pattern builds one electron at a time.

Electrons act like waves going through the slits but arrive at the detector like a particle.

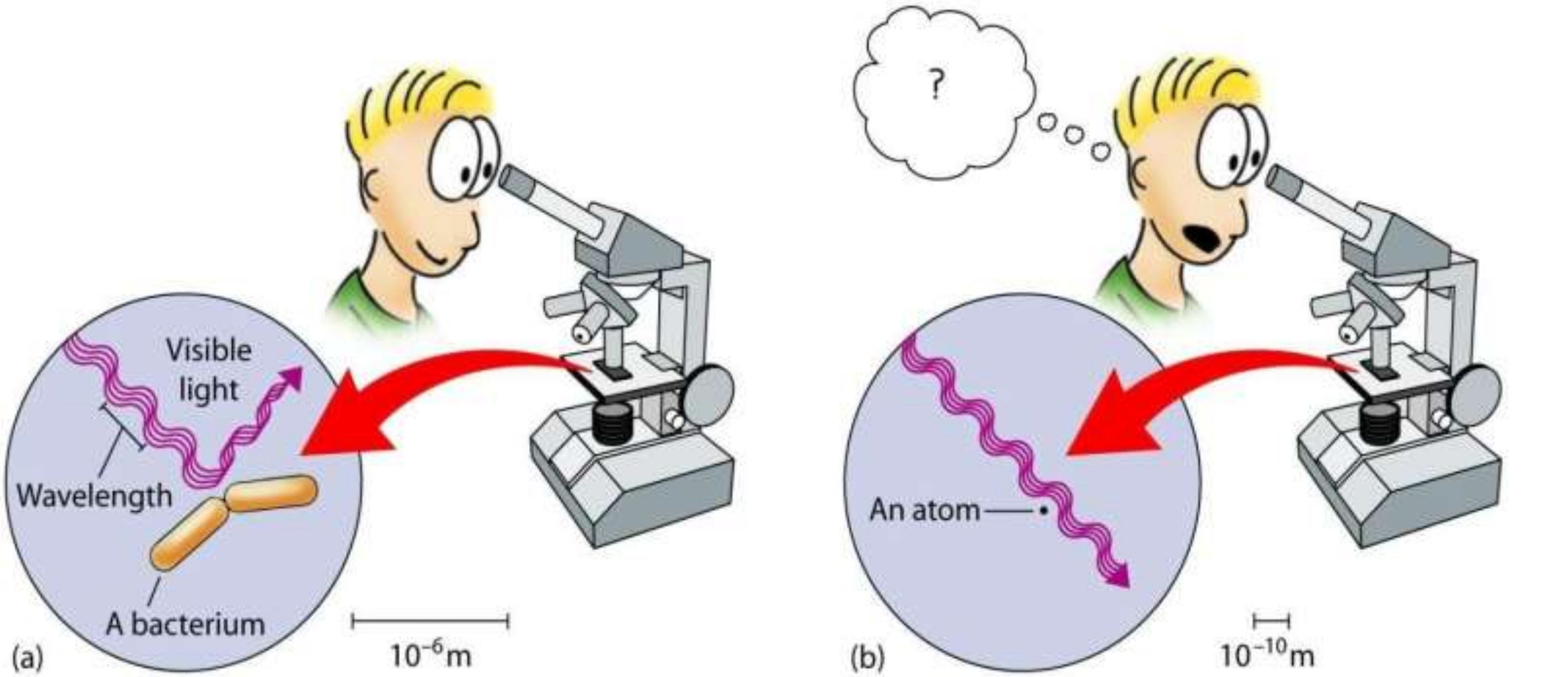
$$\lambda_e = 2.4x10^{-11}\,m$$



Limits of Vision

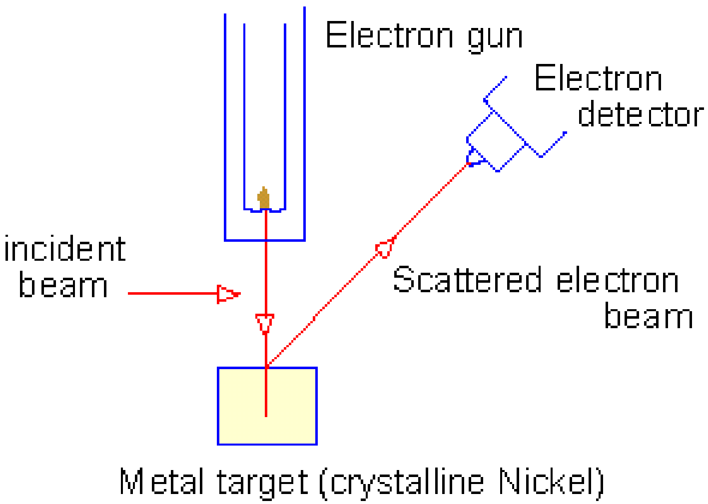


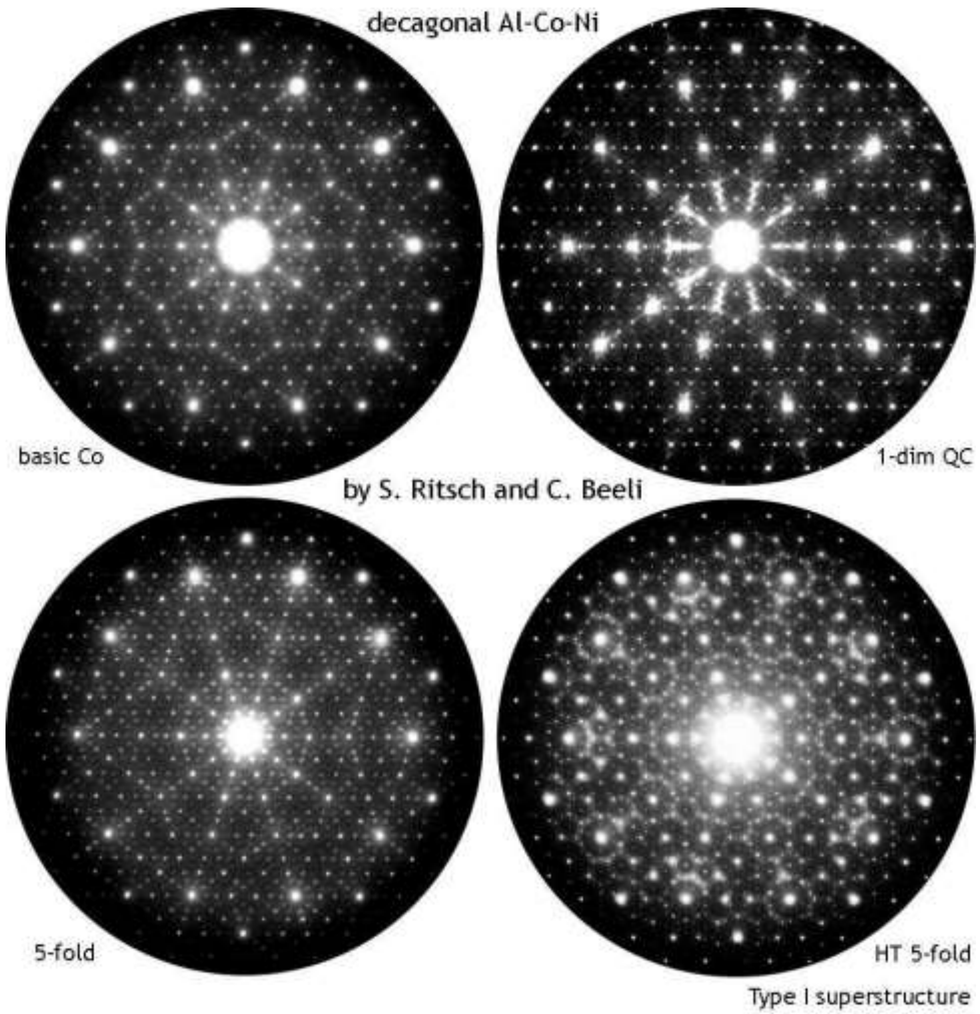
Limits of Vision



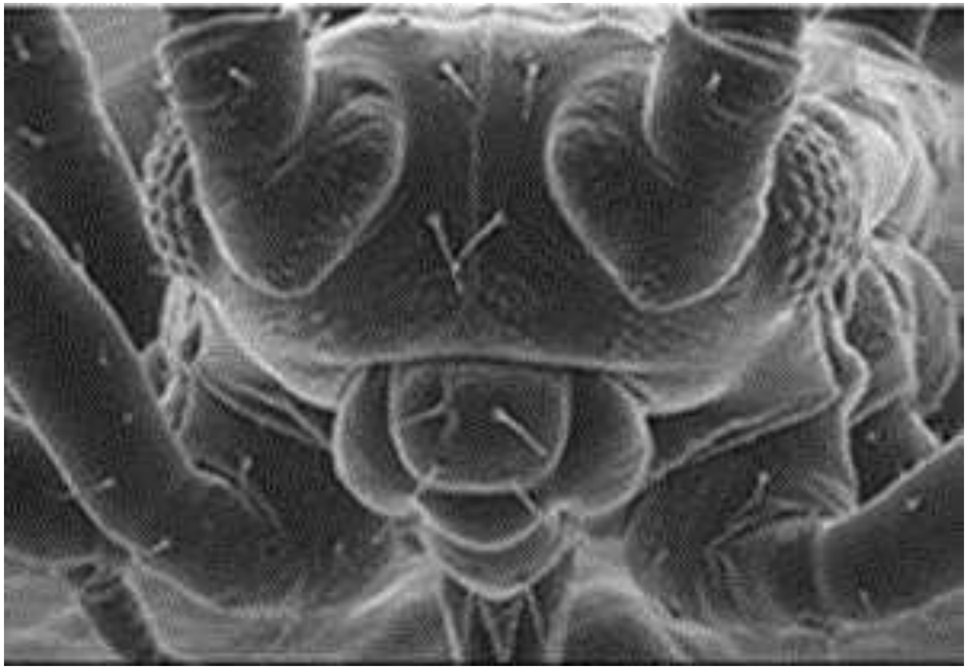
$\boxed{\text{Electron Waves}}$ $\lambda = 2.4\times10^{-11} m$

Electron Diffraction with Crystals





Electron Microscope



Electron microscope picture of a fly.

The resolving power of an optical lens depends on the wavelength of the light used. An electron-microscope exploits the wave-like properties of particles to reveal details that would be impossible to see with visible light.

When waves are in phase, their superposition gives **constructive interference**.

When waves are one-half a cycle out of phase, their superposition gives **destructive interference**.

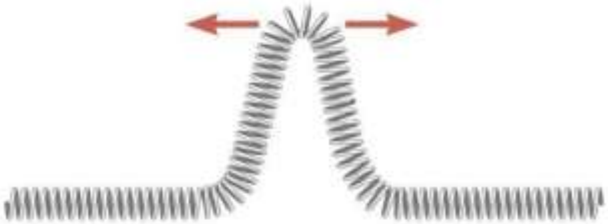
This is referred to as:

"exactly out of phase" or "180^o out of phase."

Constructive Interference

(Slinky Example)

(*a*) Overlap begins

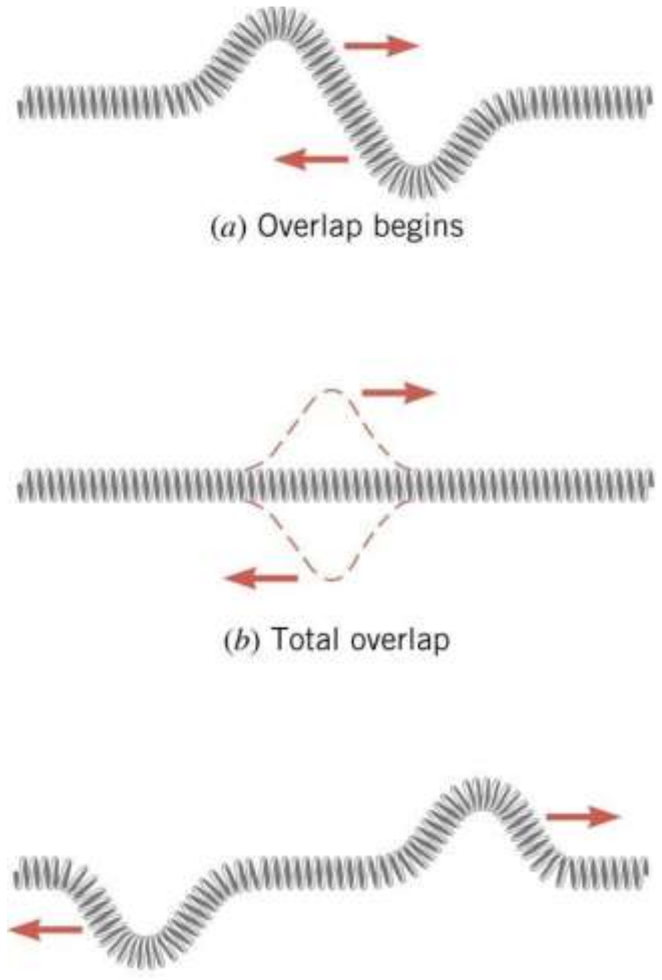


(*b*) Total overlap; the Slinky has twice the height of either pulse

(*c*) The receding pulses

Destructive Interference

(Slinky Example)



(a) Overlap begins

(b) Total overlap

(c) The receding pulses

Constructive Interference. Means that the waves ADD together and their amplitudes are in the same direction

Destructive Interference. Means that the waves ADD together and their amplitudes are in the opposite directions.

Special Condition for a Steady Optical Interference Pattern

- **The sources must be coherent—that is, they must maintain a constant phase with respect to each other.**
- **The sources should be monochromatic—that is, of a single wavelength**
- **There must be a path difference.**
- **There should be a systematic and gradual variation of the path difference**
- **Phase difference should be independent of time**
- **There should be Same wavelength and frequency**
- **Amplitudes approximately equal**
- **There should be Same polarization**

These conditions are most easily achieved by deriving the interfering light from the same source.

Interference Due to Phase Differences

Phase Differences Result from

- Optical Path Differences
- Phase Shifting

$$\Delta\textit{(Phase)} = \Delta\textit{(Optical Path Length)} + \Delta\textit{(Phase Shift)}$$

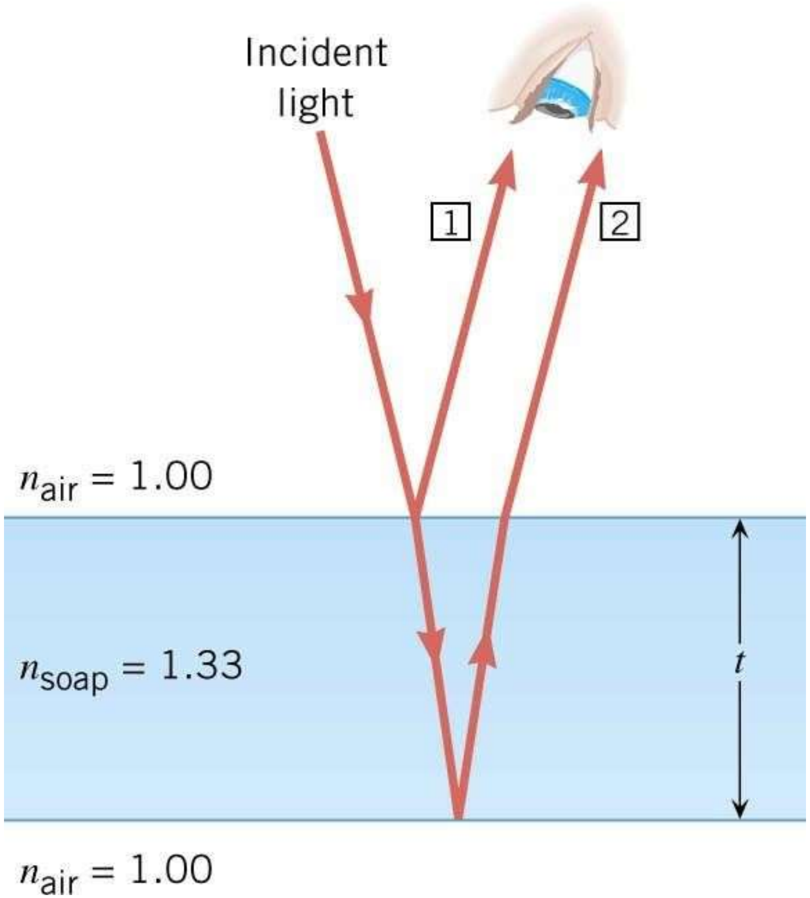
Phase Shifting Upon Reflection

Ray 1 is *<u>phase shifted</u>* by $\lambda/2$ at the air-film interface

Ray 2 is *<u>not phase shifted</u>* at the film-air interface

<u>Extra Conditions:</u>

- Monochromatic light
- Nearly normal incidence

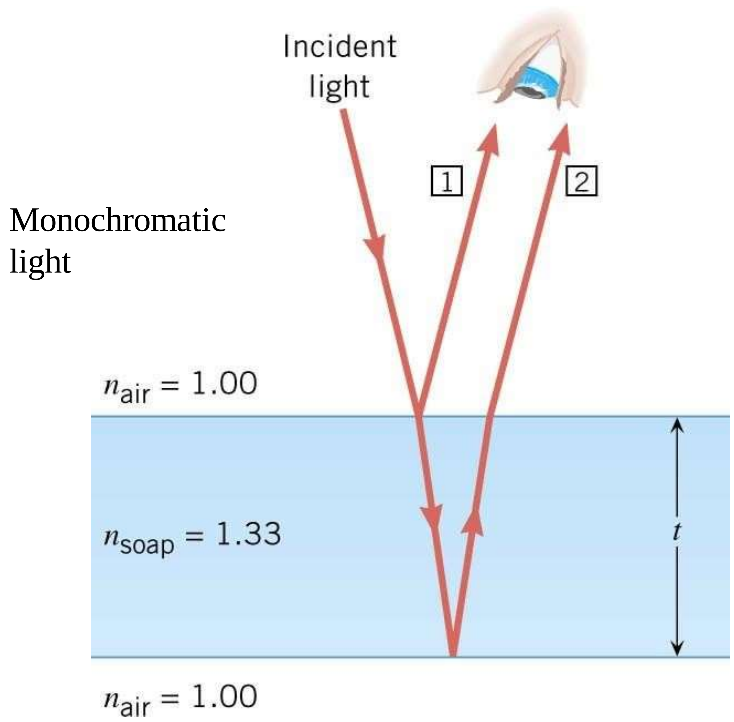


Constructive Interference

Ray 1 is *phase shifted* by $\lambda/2$ at the air-film interface

Ray 2 is *not phase shifted* at the film-air interface

The difference in the optical path length is the distance the 2nd ray travels in the soap film.



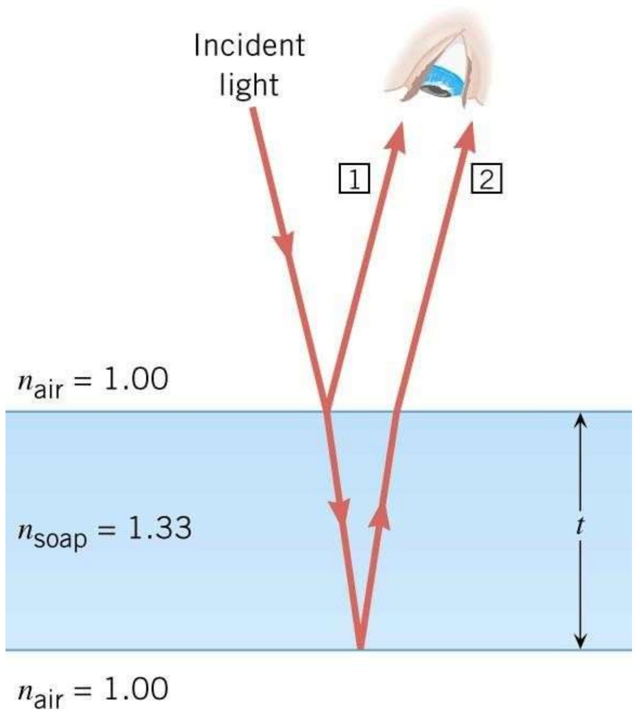
Looking for constructive interference. This requires that the phase difference of 1 and 2 are an integral number of wavelengths.

Constructive Interference

$$\Delta(Phase) = \Delta(OpticalPathLength) + \Delta(PhaseShift)$$

Constructive interference requires that the phase difference of 1 and 2 be equal to *either zero* or an *integral number of wavelengths*.

Constructive interference requires a minimum phase difference equivalent to
one wavelength = λ



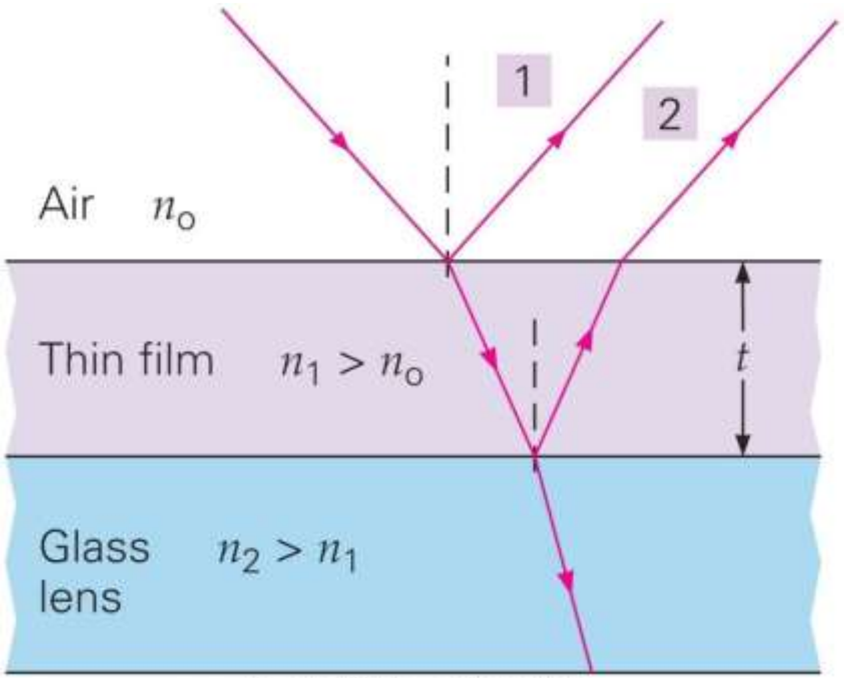
$$\delta = d \sin\theta_{\text{bright}} = m\lambda \qquad (m = 0, \pm 1, \pm 2, \ldots)$$

Destructive Interference

$$\Delta(Phase) = \Delta(OpticalPathLength) + \Delta(PhaseShift)$$

Ray 1 is *phase shifted* by $\lambda/2$ at the air-film interface

Ray 2 is *also phase shifted* by $\lambda/2$ at the film-glass interface



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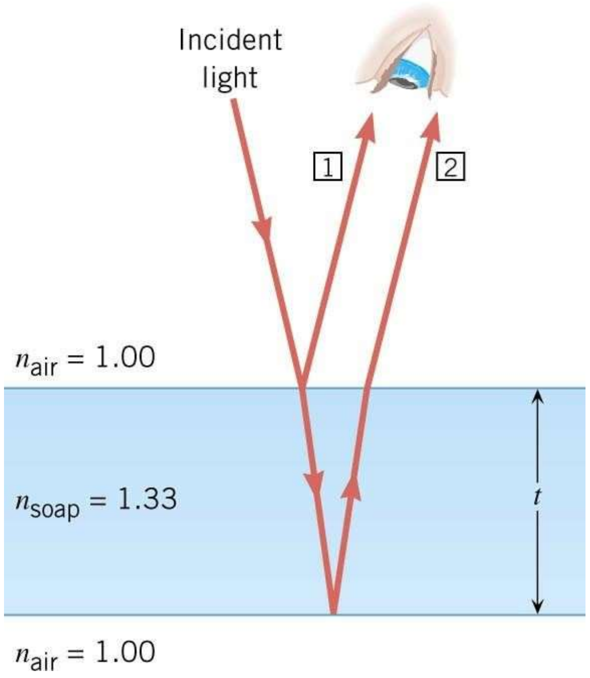
Destructive Interference

$$\Delta(Phase) = \Delta(OpticalPathLength) + \Delta(PhaseShift)$$

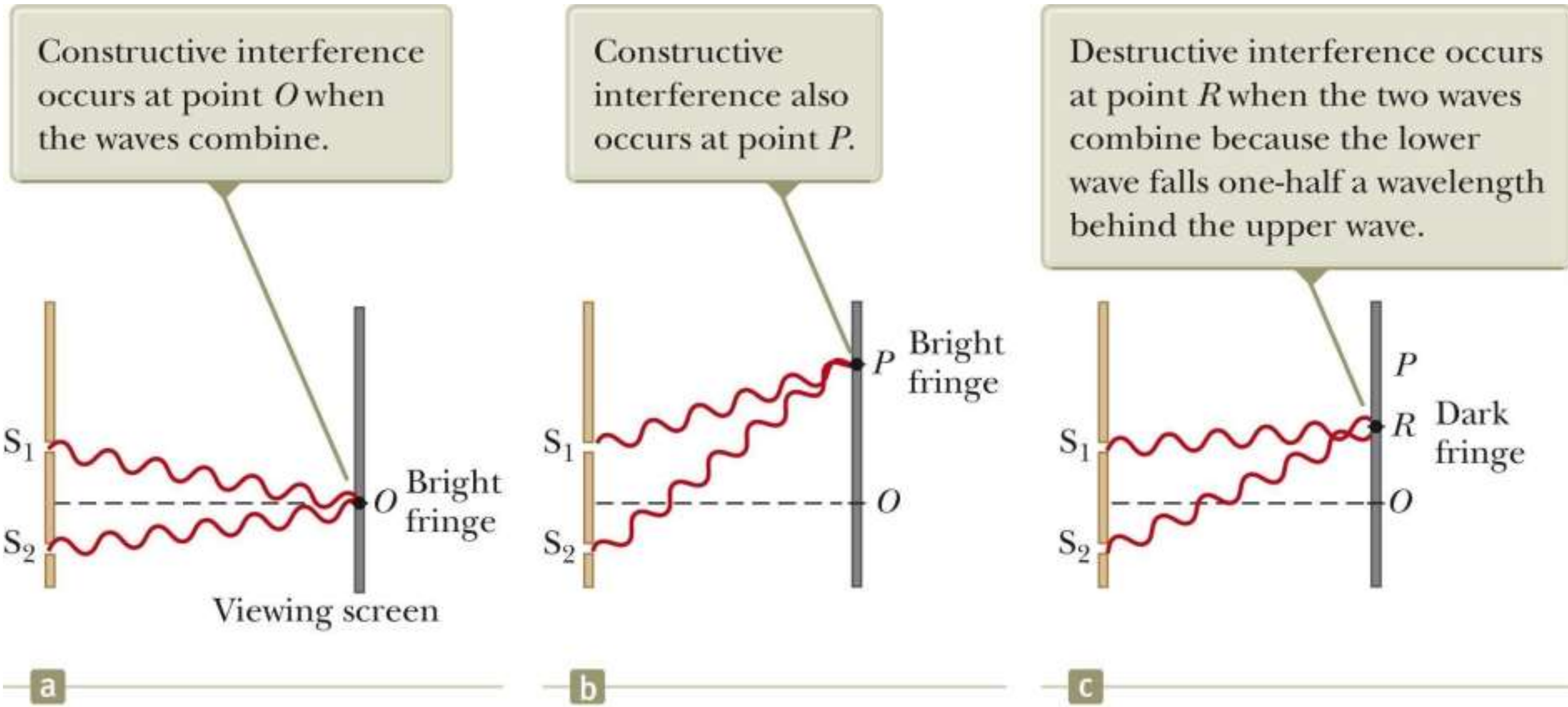
Destructive interference requires that the phase difference of 1 and 2 be equal to an *odd multiple of half wavelengths.*

Destructive interference requires a minimum phase difference equivalent to
one-half wavelength = λ/2



$$d \sin\theta_{dark} = (m + \tfrac{1}{2})\lambda \qquad (m = 0, \pm1, \pm2, \ldots)$$

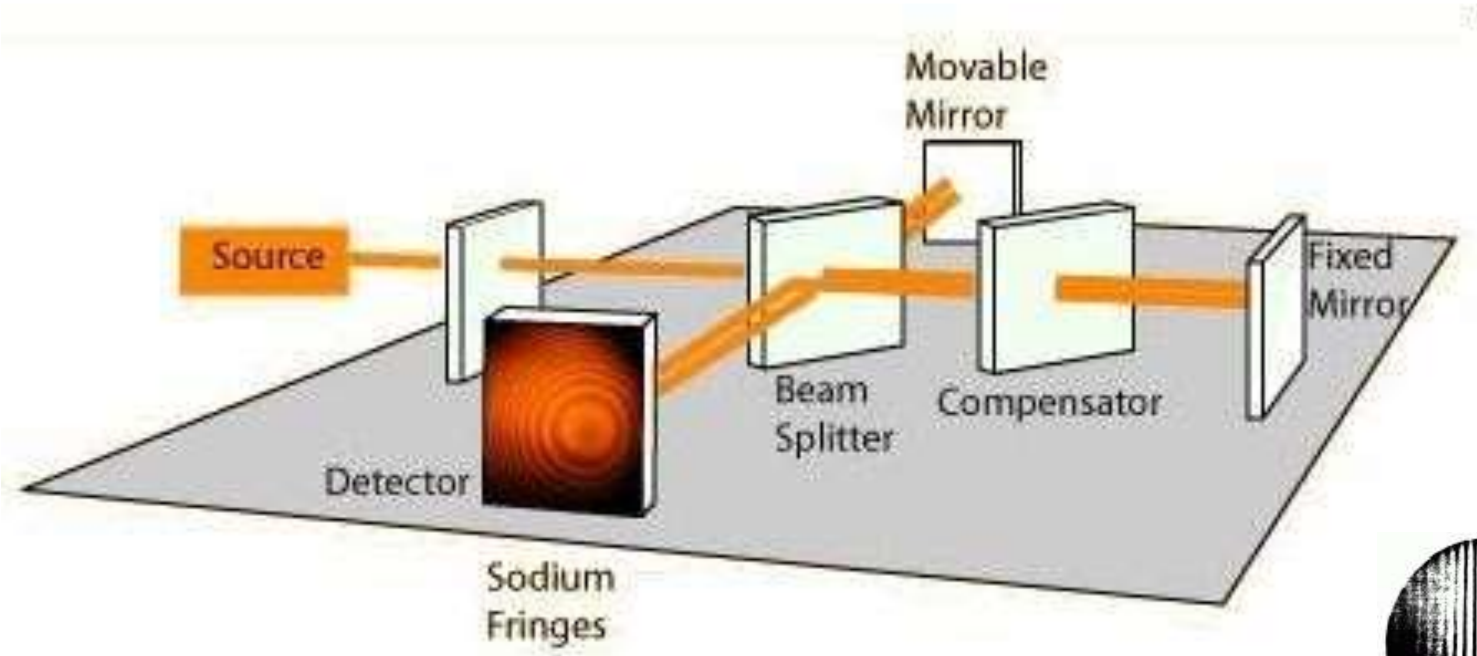
Phase Difference at P: $\Delta\phi = \frac{2\pi}{\lambda}\Delta r$

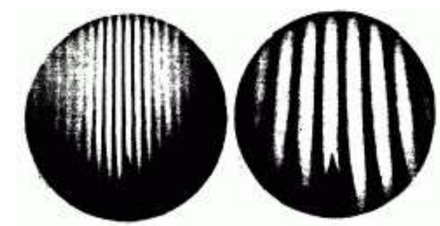


Constructive : $\Delta\phi = 2m\pi, \quad \Delta r = m\lambda, \quad m = 0,1,2,3...$

Destructive : $\Delta\phi = (2m+1)\pi, \quad \Delta r = (m+\frac{1}{2})\lambda, \quad m = 0,1,2,3...$

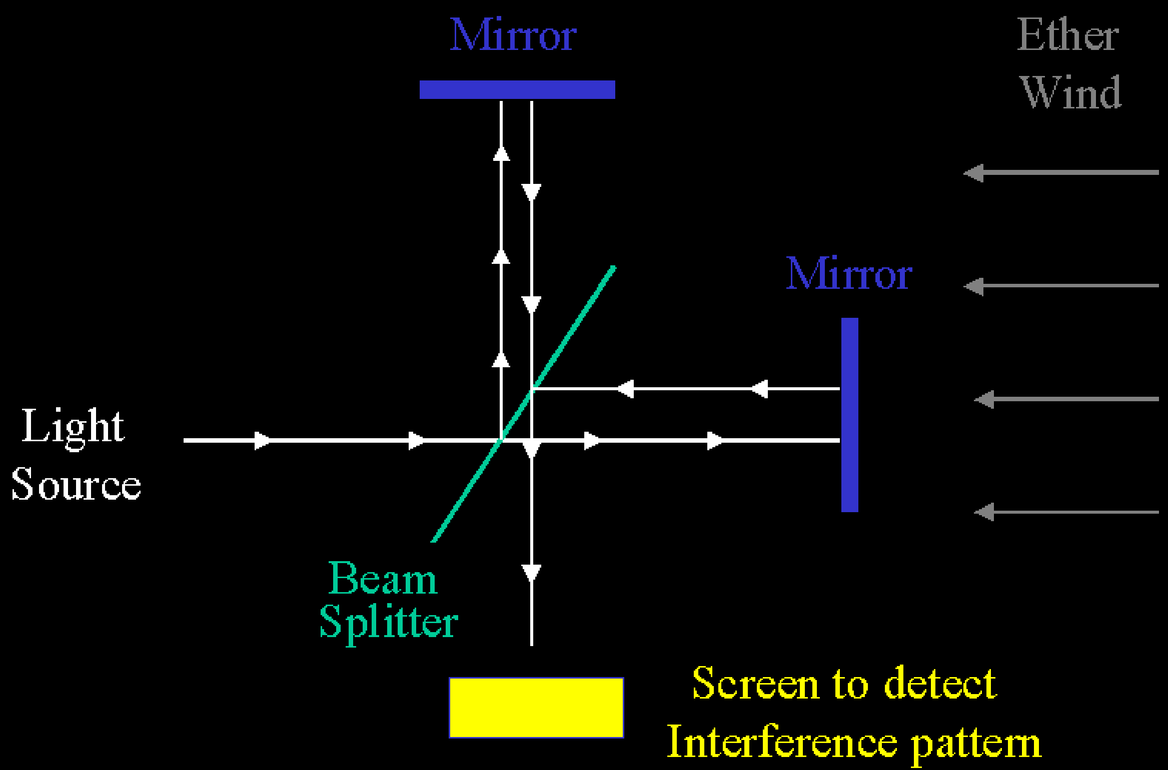
Michelson Interferometer

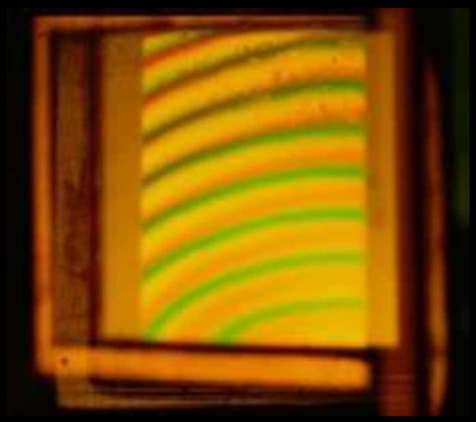




The fringe pattern shifts by one-half fringeeach time $M1$ is moved a distance $\lambda/4$

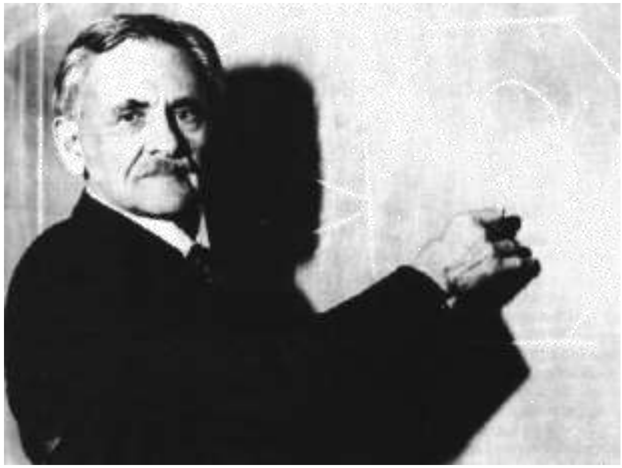
Michelson-Morley Experiment





Rotate arms to produce interference fringes and find different speeds of light caused by the Ether Wind, due to Galilean Relativity: light should travel slower against the Ether Wind. From that you can find the speed of the wind.

Michelson-Morely Experiment 1887



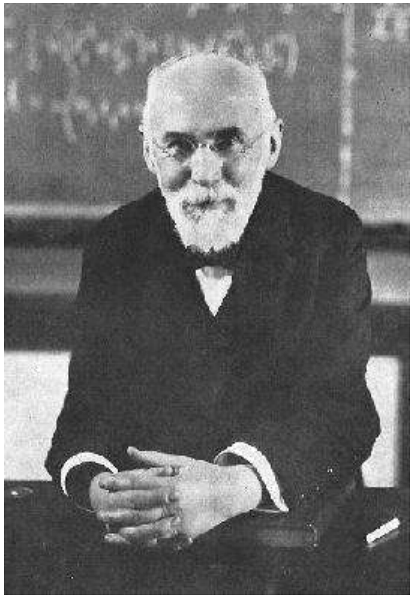
The speed of light is independent of the motion and is always c. The speed of the Ether wind is zero.

OR….

Lorentz Contraction

The apparatus shrinks by a factor :

$$\sqrt{1 - v^2 / c^2}$$




Time is Relative!
Space is Relative!
Only the *SPEED OF LIGHT* is Absolute!

The prime condition for interference is coherence

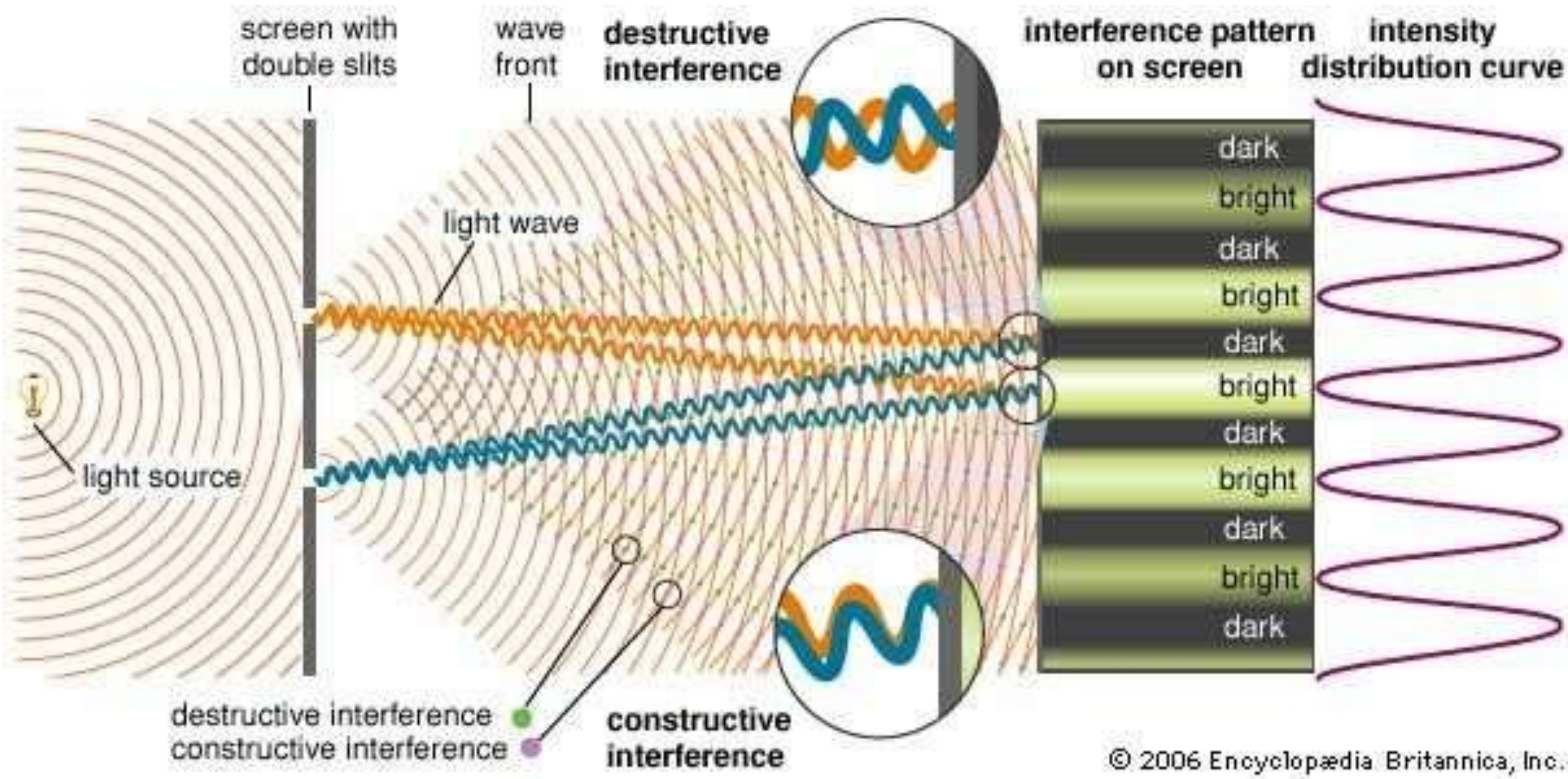
Two independent sources of light can be monochromatic but not coherent (laser is an exception).

Coherence is possible when the two sources are derived from the same source.

This can be done by using two techniques –

(i) Division of Wave-front (ii) Division of Amplitude

(i) Technique of Division of Wave-front used in Young's Double slit experiment.

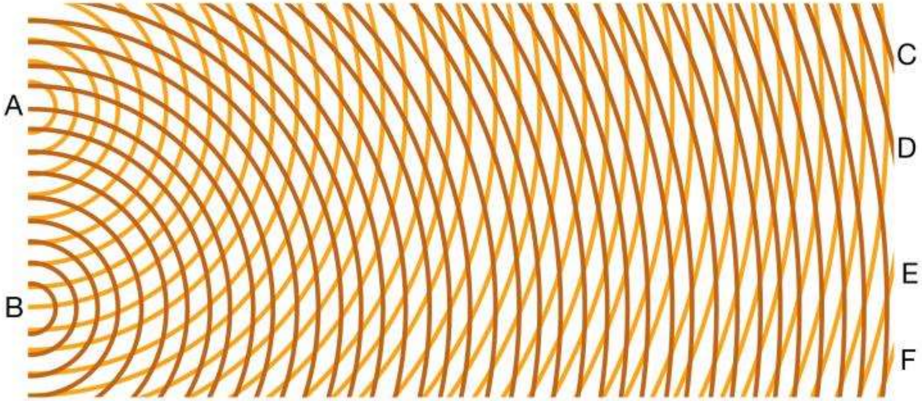


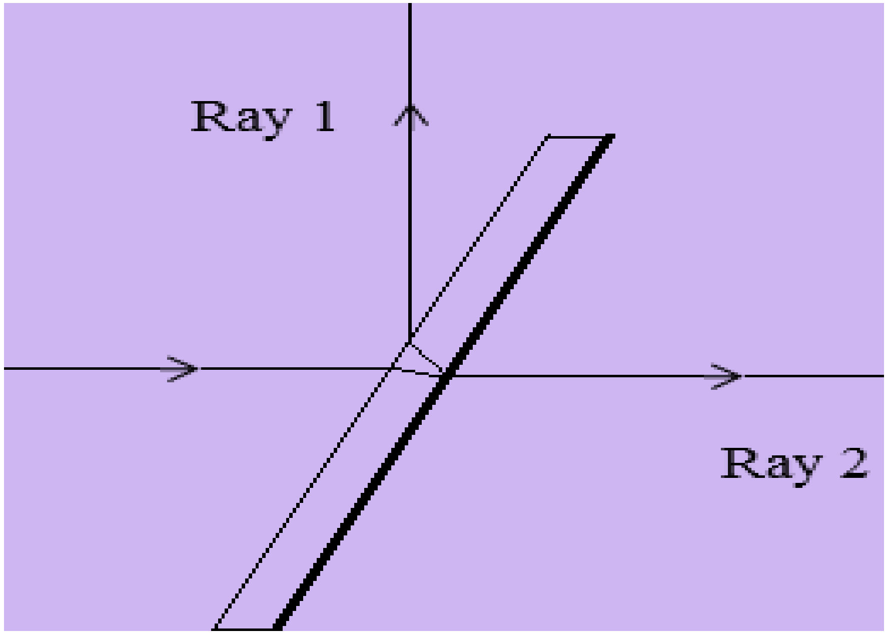
Young's double-slit experiment

Thomas Young gave 91 lectures at the Royal Institution 1801-03.

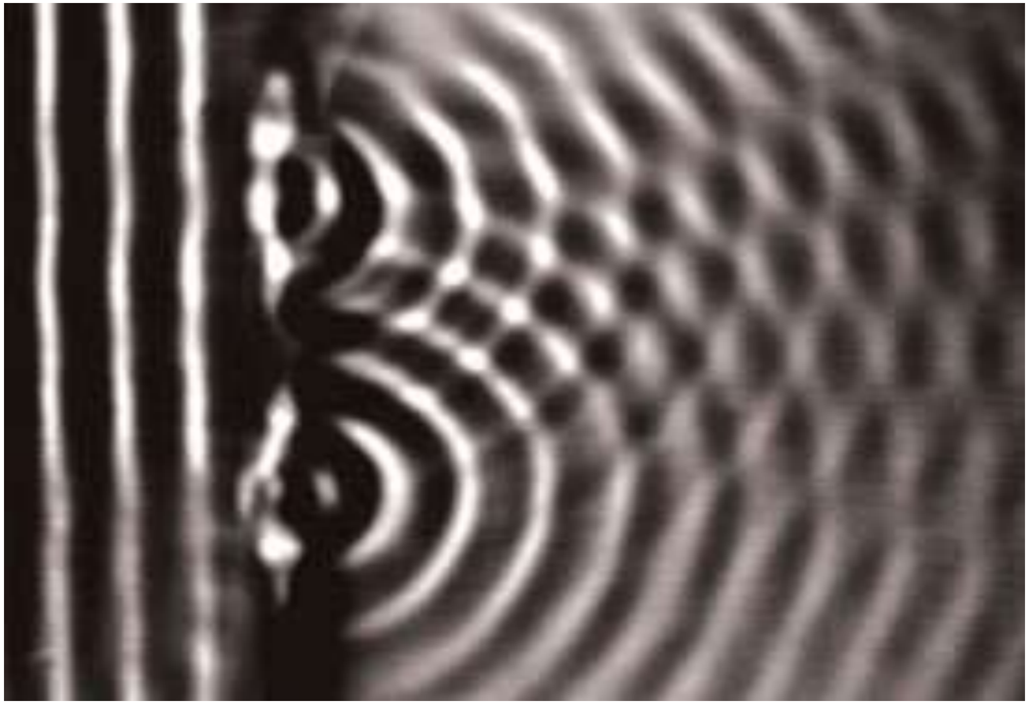
The musical phenomenon of *beats*, used to tune instruments, inspired Young to think that beams of light too might interfere.

He invented the ripple tank to illustrate double slit interference, because water waves can be simply visualised.





In a ripple tank



In a swimming pool

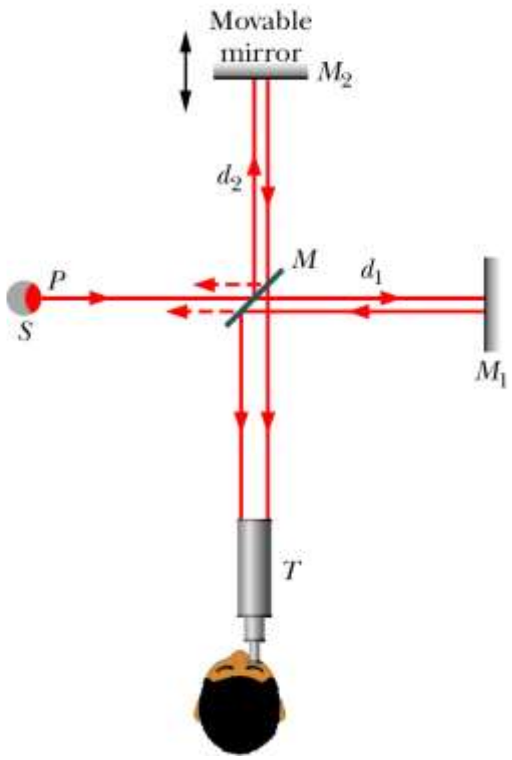
Credit: ESO/M. Alexander

(ii) Technique of Division of Amplitude used in Thin film interference, Newton's rings experiment and Michelson's interferometer.

Apart from these two techniques, Refraction and Reflection are also used to obtain coherent sources.

Fresnel's biprism and Lloyds mirror are based on these principles.

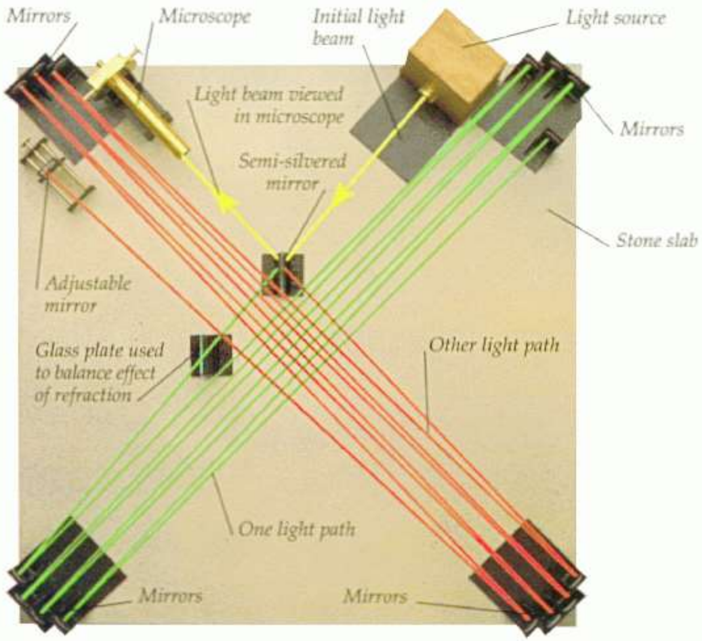
Michelson Interferometers:

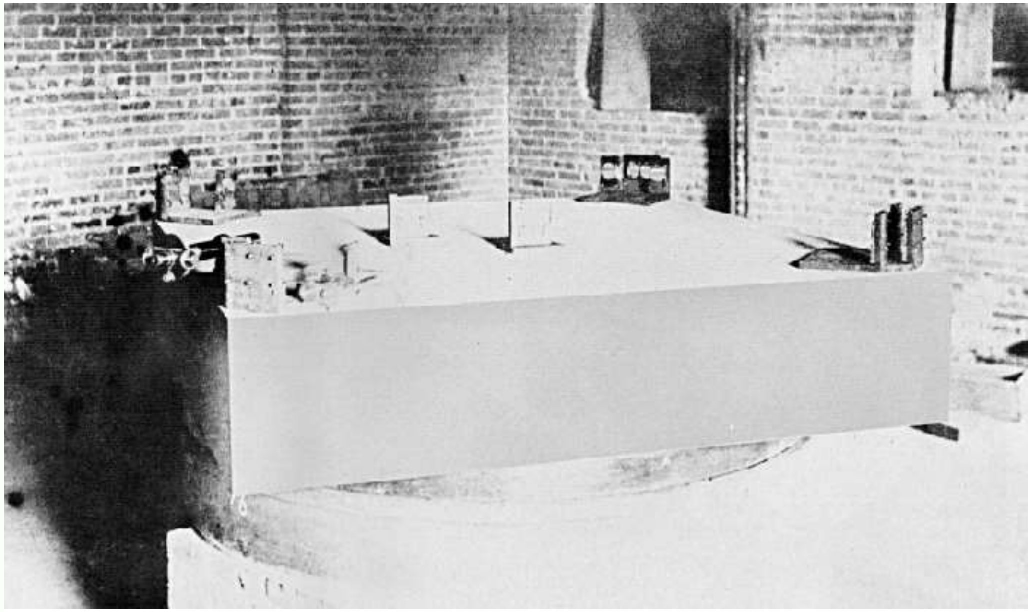


In the Michelson interferometer, light from a source (at the left, in the picture) hits a semi-plated mirror. Half of it goes through to the right and half goes upwards. The two halves are bounced back towards the half plated mirror, interfere, and the interference can be seen by the observer at the bottom. The observer will see light if the two distances travelled d_1 and d_2 are equal, and will see darkness if they differ by half a wavelength.

Michelson-Morley Experiment

Michelson won the Nobel prize in 1907, "for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid"





"The interpretation of these results is that there is no displacement of the interference bands. ... The result of the hypothesis of a stationary ether is thus shown to be incorrect." (A. A. Michelson, Am. J. Sci, 122, 120 (1881))

The largest Michelson interferometer in the world is in Livingston, LA, in LSU owned land (it is operated by a project funded by the National Science Foundation run by Caltech and MIT, and LSU collaborates in the project).

Mirrors are suspended with wires and will move
detecting ripples in
the gravitational field due to
astronomical events.

http://www.ligo-la.caltech.edu

Thank you