山东大学 SHANDONG UNIVERSITY

Physics I: Introduction to Wave Theory
SDU Course Number: sd01232810 (Fall 2023)

Lecture 10: Interference and Diffraction

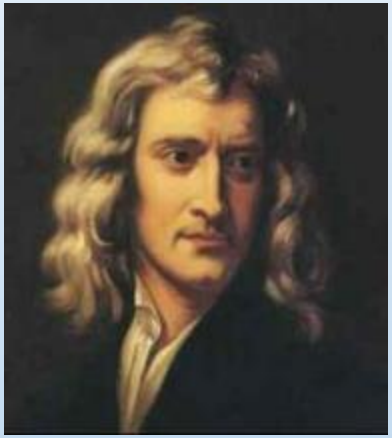
Outline

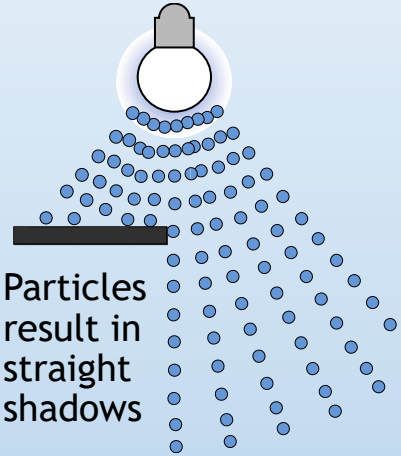
- Particles or Waves
- Young's Double-Slit Experiment
- Huygen's Principle
- Interference
- Diffraction

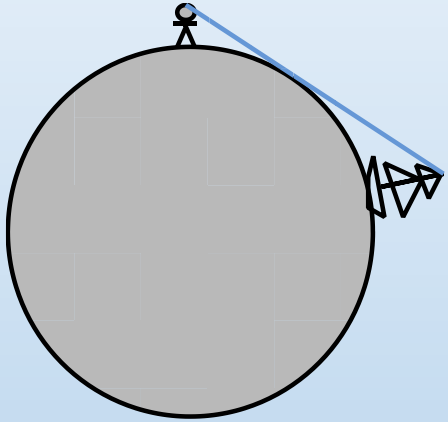
Are Photons Particles or Waves ?

Newton believed that light was particles:

- light travels in straight lines !

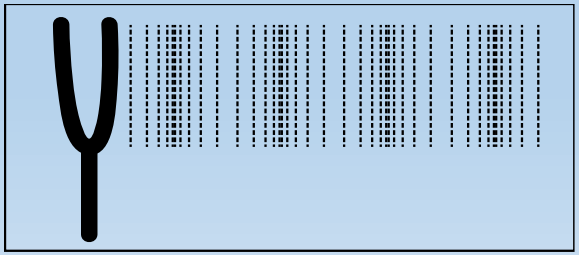




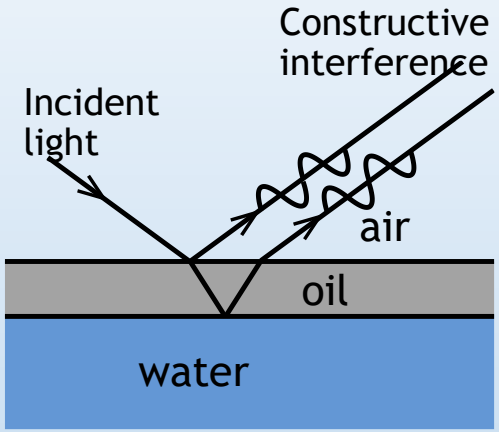


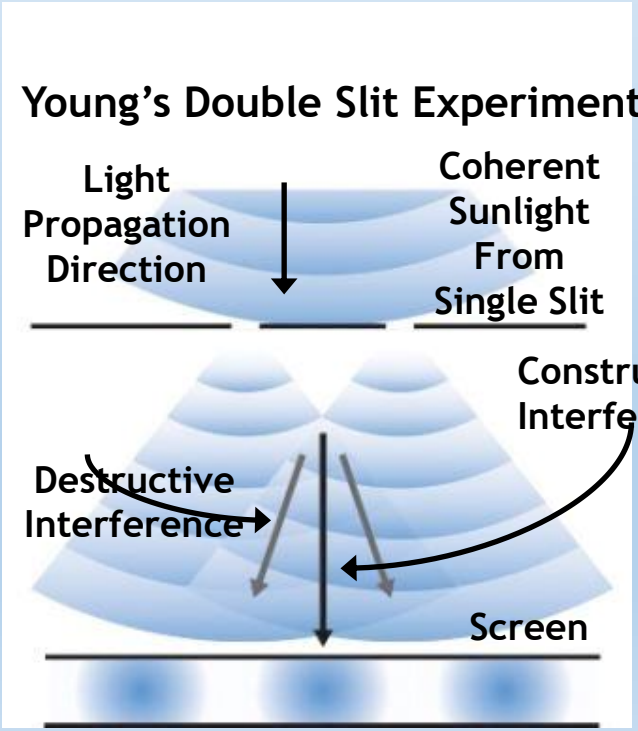
- what is ‘waving’ in an EM wave ?

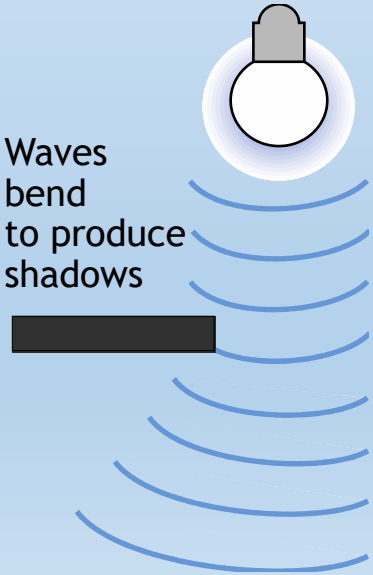
A wave is a vibration of some medium through which it propagates, e.g., water waves, waves propagating on a string



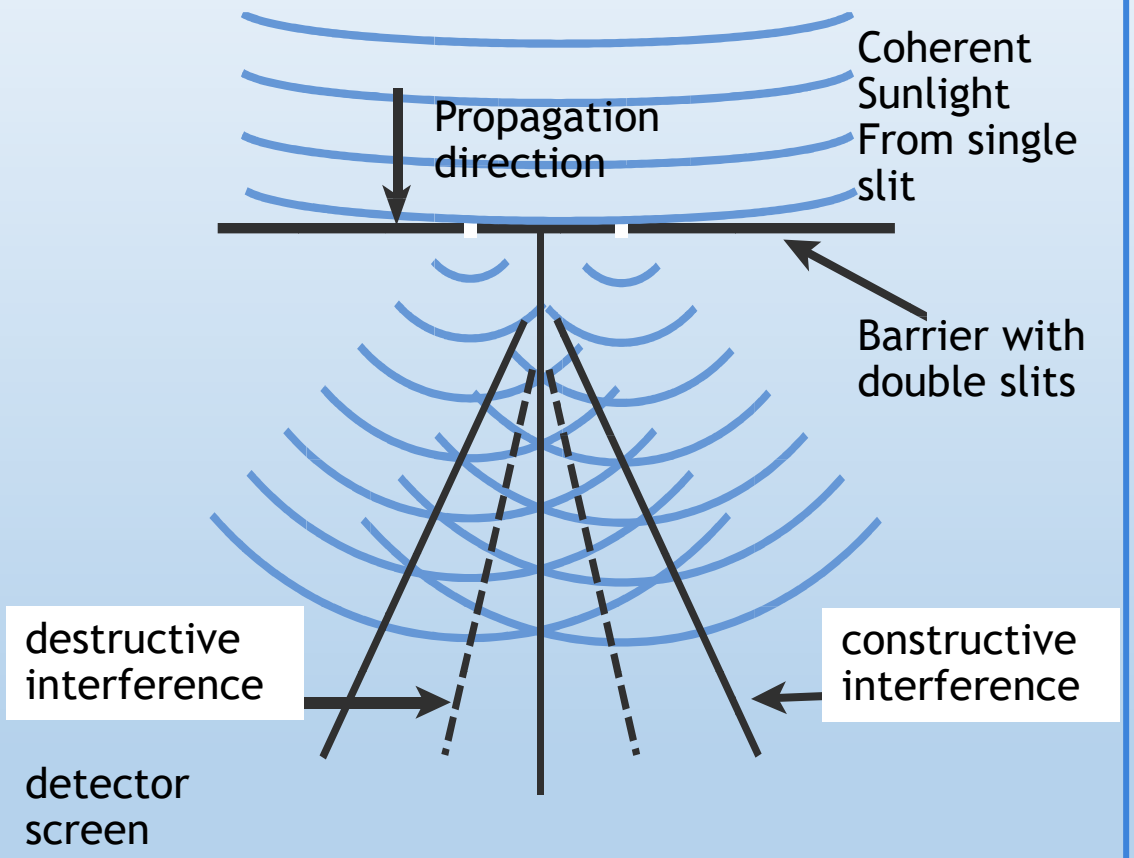
Are Photons Particles or Waves ?







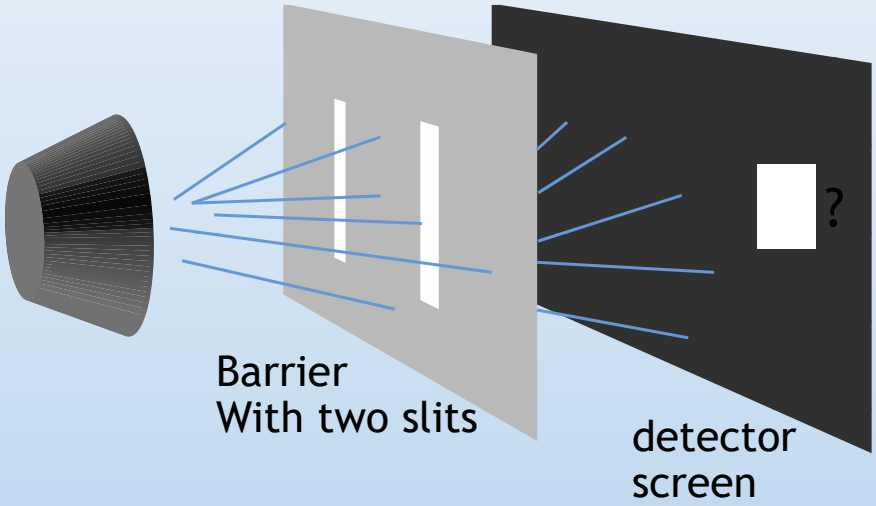
Thomas Young's Double Slit Experiment

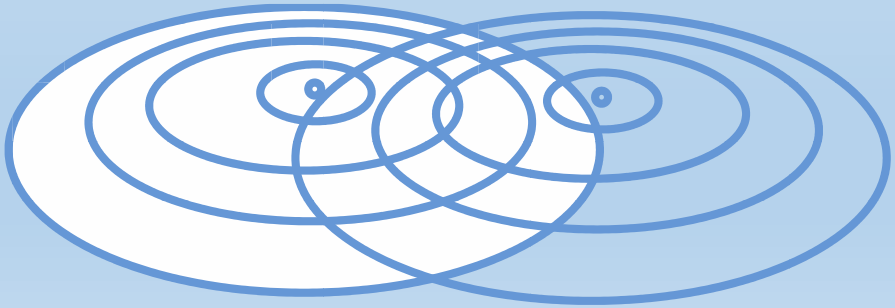


Historical Note:
When Thomas Young published his result in 1802 he encountered a great deal of criticism from the proponents of Newton's particle theory of light. One objection was that the interference experiment was inconsistent with the law of energy conservation (at points of constructive interference, the light intensity is twice the intensity calculated by adding the intensities associated with each individual slit).
- Is energy conservation violated ?

Young was discouraged by the criticism of his work, and gave up his research in optics for other endeavors.
(He made a major contribution to Egyptology by deciphering the Rosetta stone. His theory of color vision is widely cited today, so is his work on elasticity. He made pioneering contributions in studies of sound, tides, and human voice.)

Thomas Young's Double Slit Experiment





Interference is the defining characteristic of <u>waves</u>

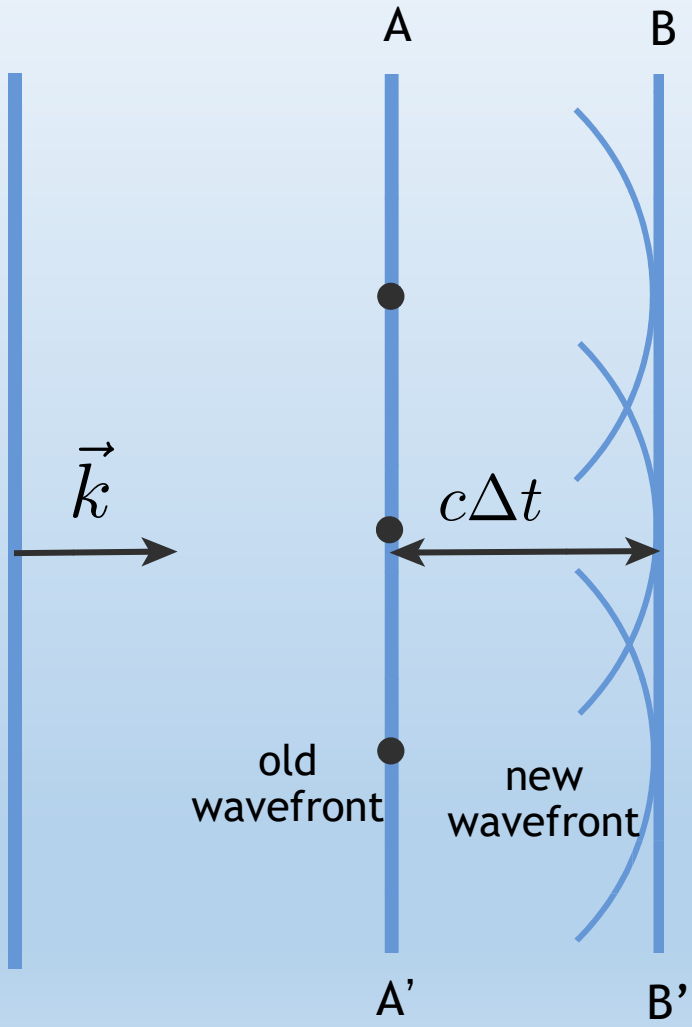
Huygen's Principle

- Huygen assumed that light is a form of wave motion rather than a stream of particles
- Huygen's Principle is a geometric construction for determining the position of a new wave at some point based on the knowledge of the wave front that preceded it
- All points on a given wave front are taken as point sources for the production of spherical secondary waves, called wavelets, which propagate in the forward direction with speeds characteristic of waves in that medium
  - After some time has elapsed, the new position of the wave front is the surface tangent to the wavelets

As you might expect, the heuristic idea of Huygens can be fully justified through various derivations associated with the Maxwell equations.

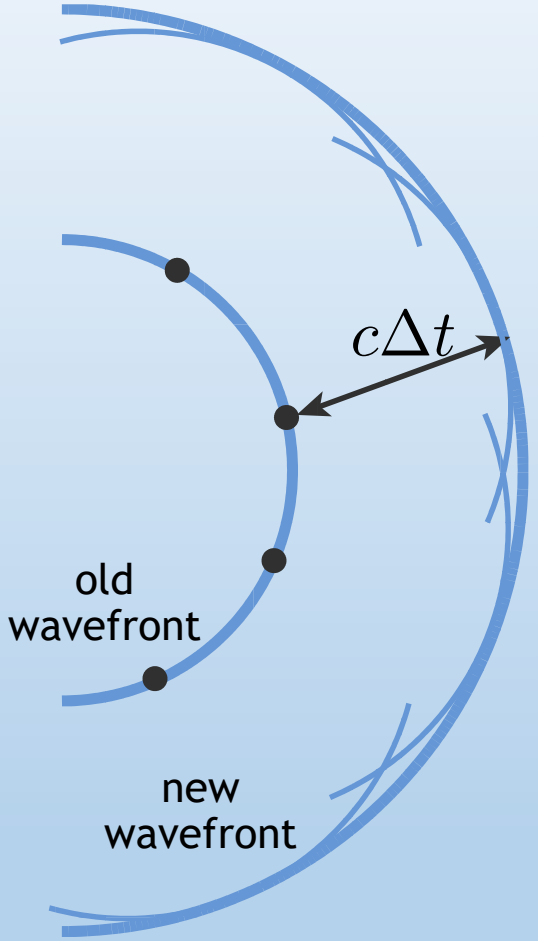
Huygen's Construction for a Plane Wave

- At t = 0, the wave front is indicated by the plane AA'
- The points are representative sources for the wavelets
- After the wavelets have moved a distance cΔt, a new plane BB' can be drawn tangent to the wavefronts

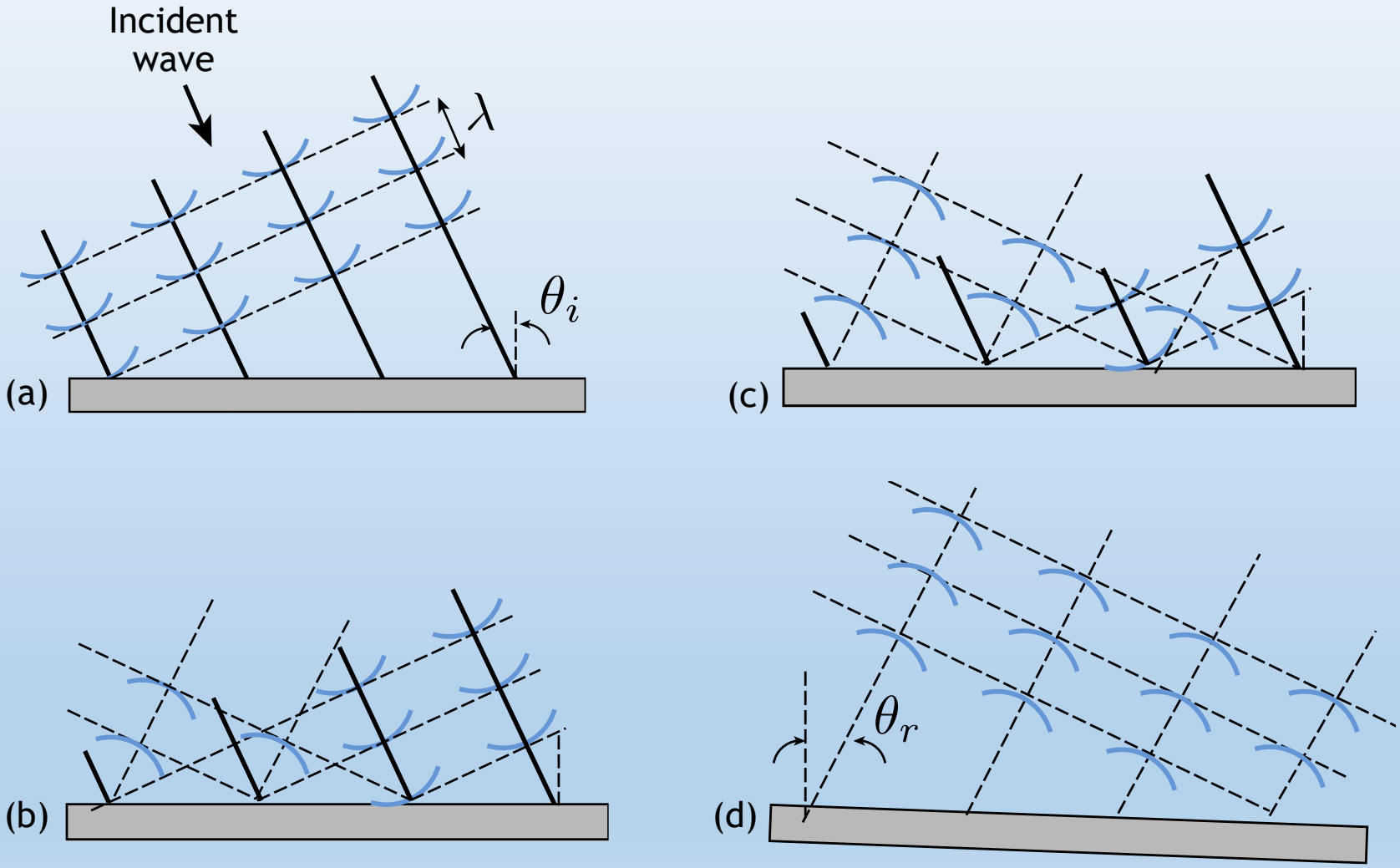


Huygen's Construction for a Spherical Wave

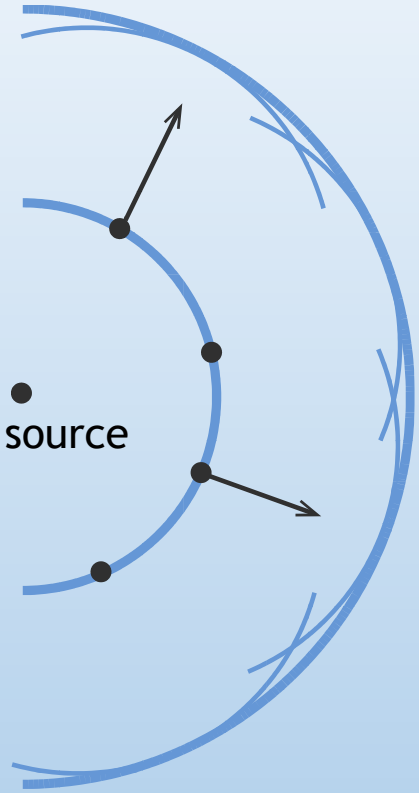
- The inner arc represents part of the spherical wave
- The points are representative points where wavelets are propagated
- The new wavefront is tangent at each point to the wavelet

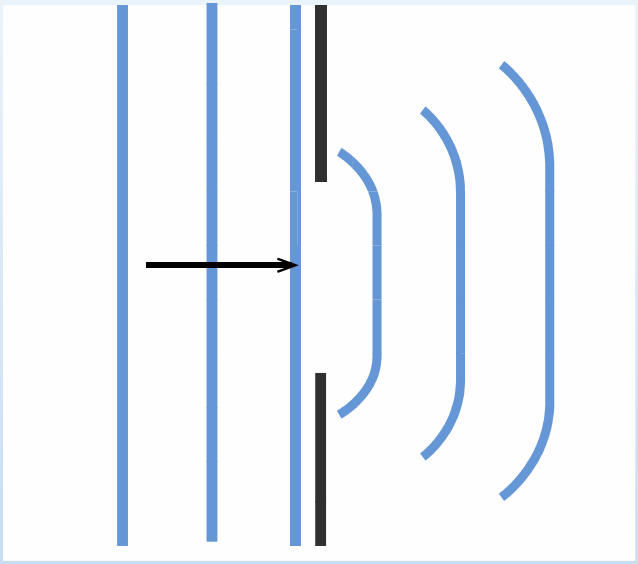


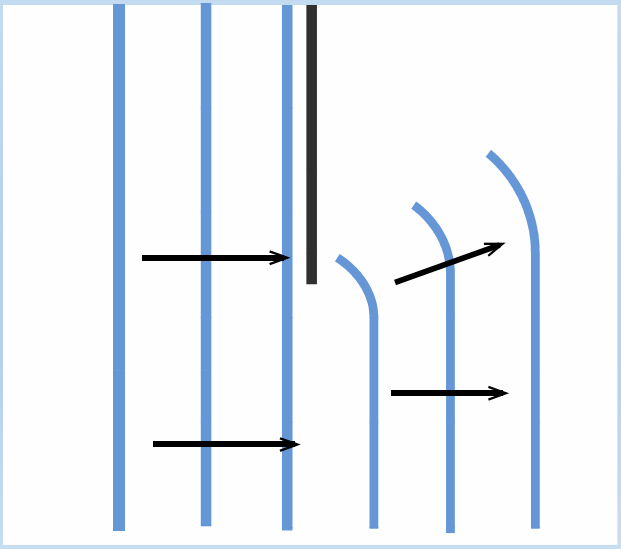
Huygen's Construction for a Reflection



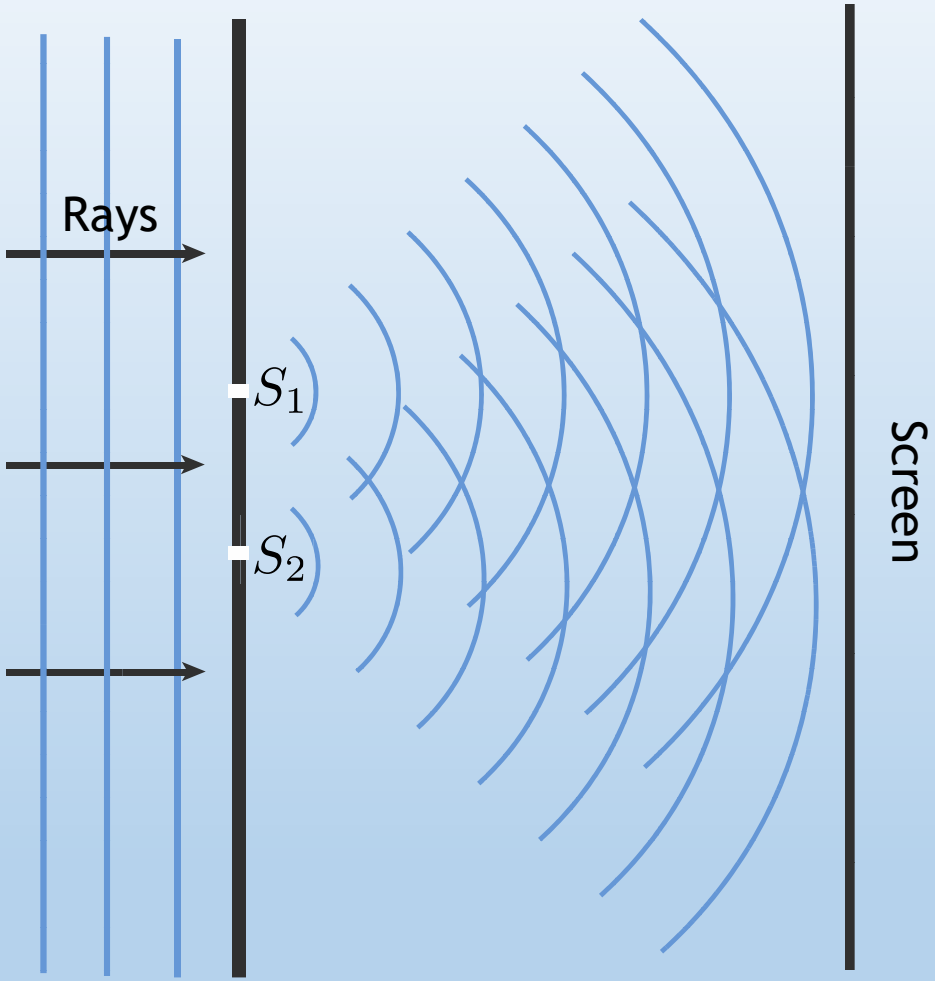
Huygens' Principle Explains Diffraction



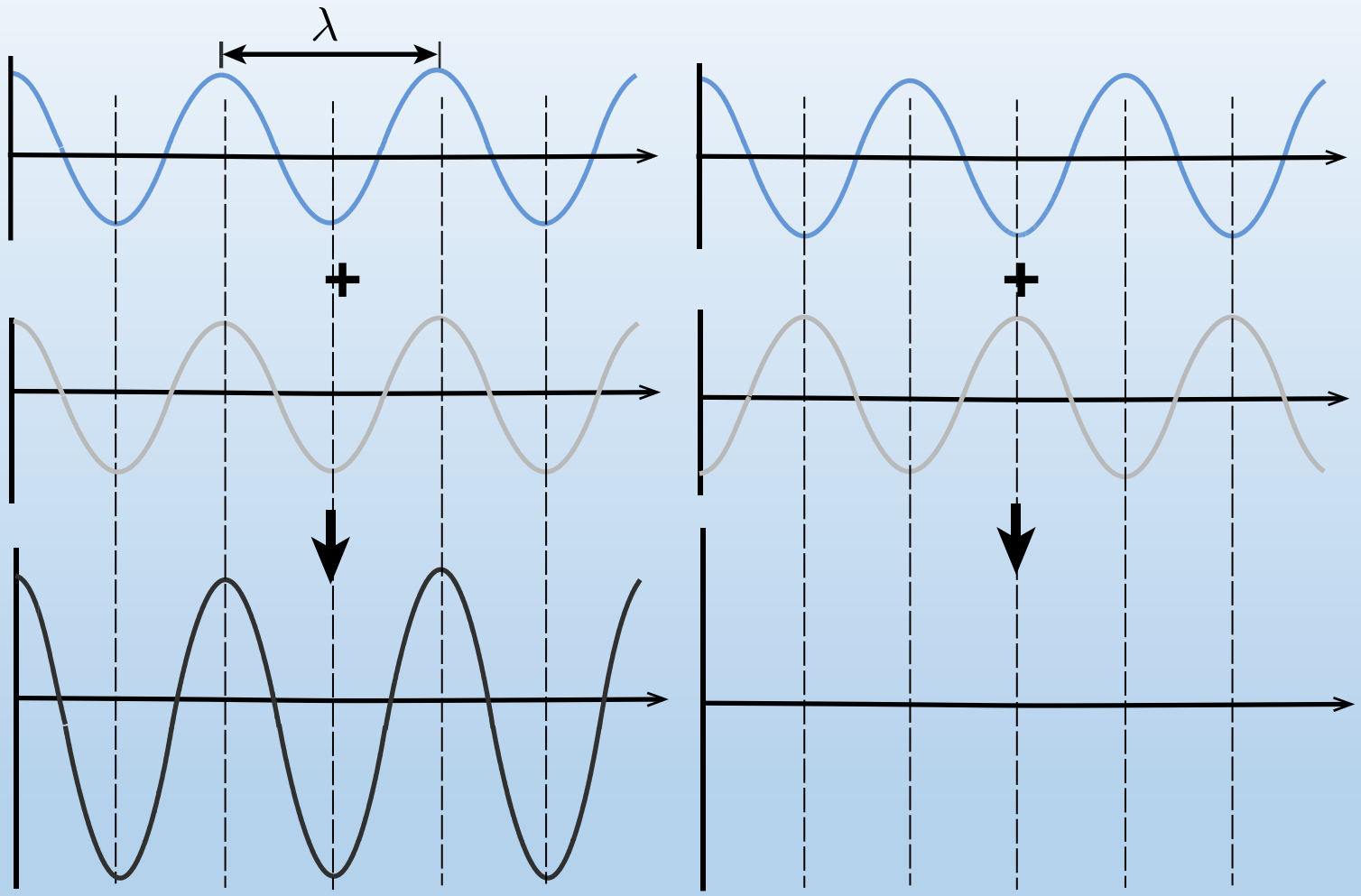




Applying Huygens' Principle to Two Slits



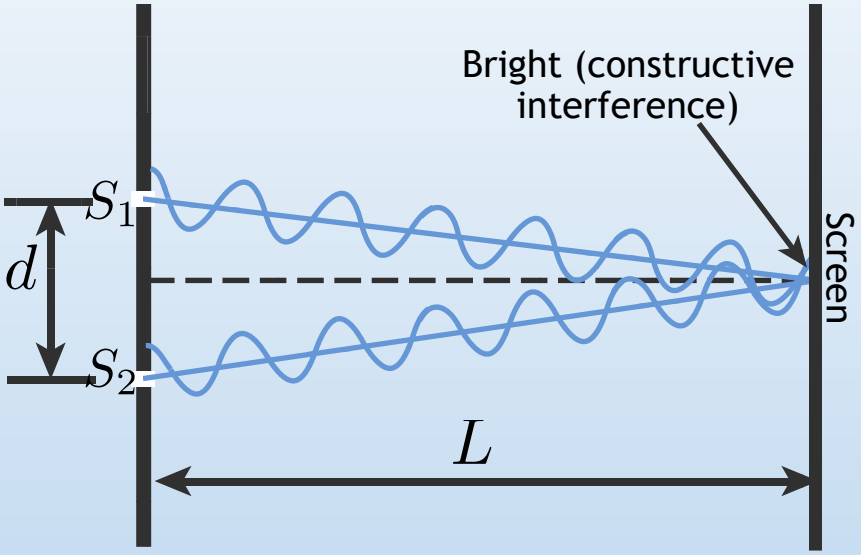
Wave Interference

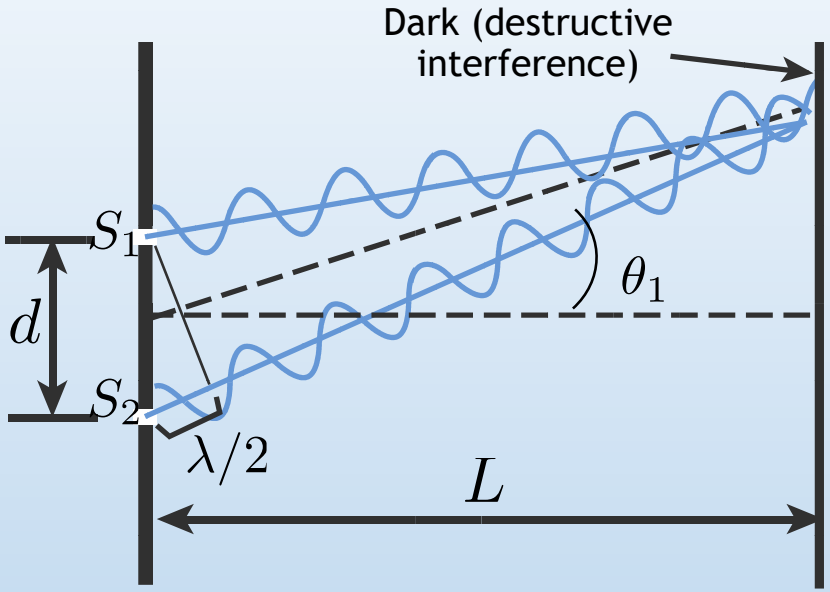


CONSTRUCTIVE

DESTRUCTIVE

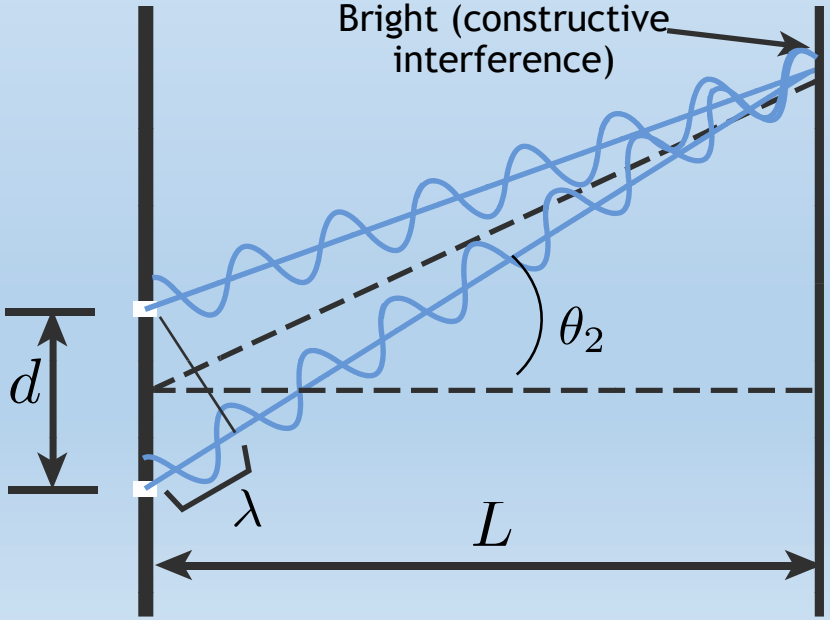
Interference: Double-Slit Experiment





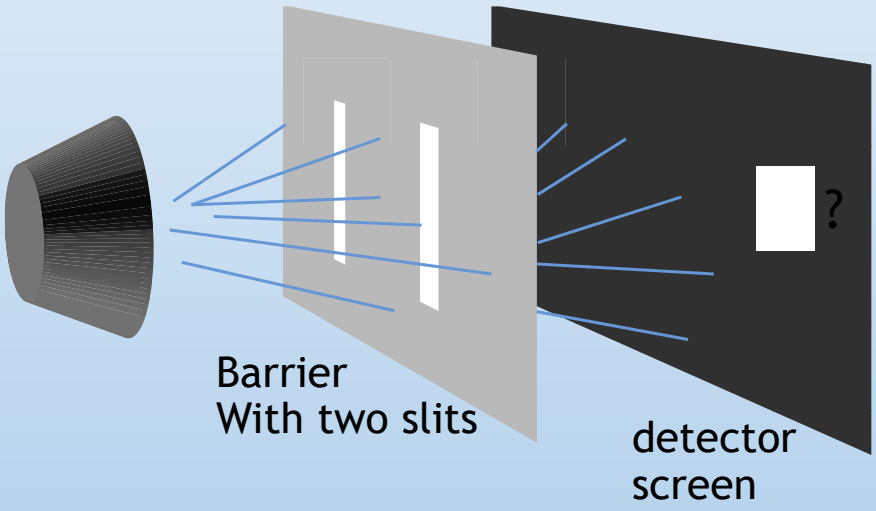
Waves at slits have to be *coherent* for interference to occur!

Two different light bulbs in front of each slit will not give interference pattern.



Young's Double-Slit Experiment

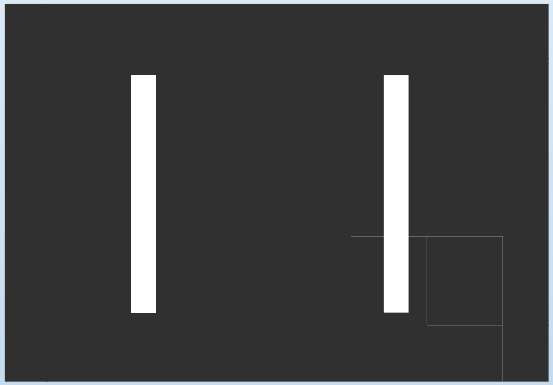
Light : Particles or Waves?



What should we see on the detector screen ?

we expect to see the following patterns for …

particles



waves

Interference Preconditions

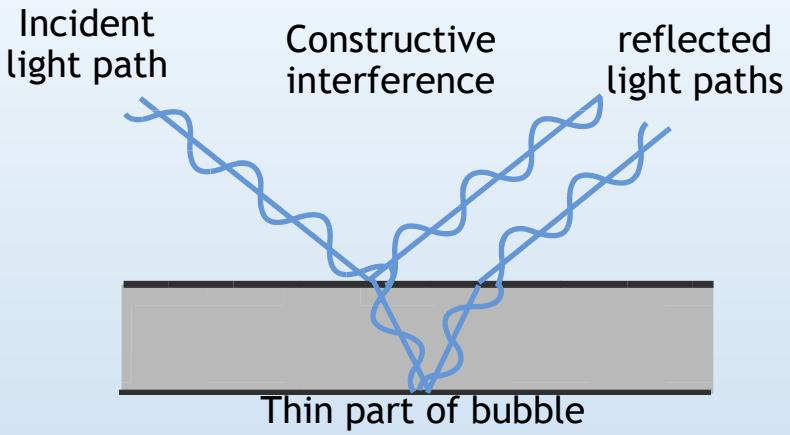
1. Light must be *monochromatic*, i.e., involve just a single frequency (single wavelength).

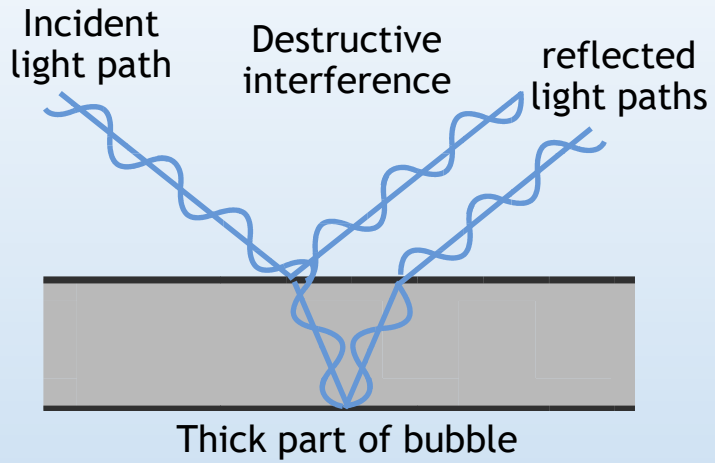
2. Light sources must be *coherent*, the relative phase is always the same.

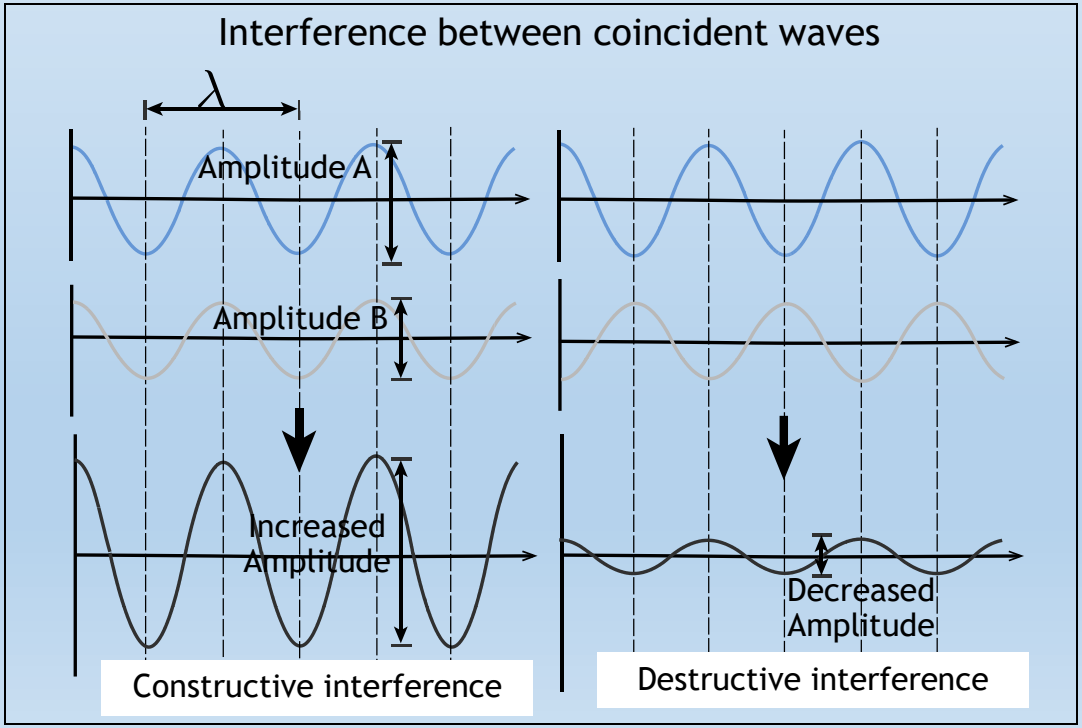
3. Light sources must have the *same amplitudes*.

If these conditions do not hold, one still gets constructive and destructive interference but the interference pattern can change with time or not be complete (destructive interference leads to a decrease in amplitude but not to zero amplitude).

Interference in Soap Bubbles







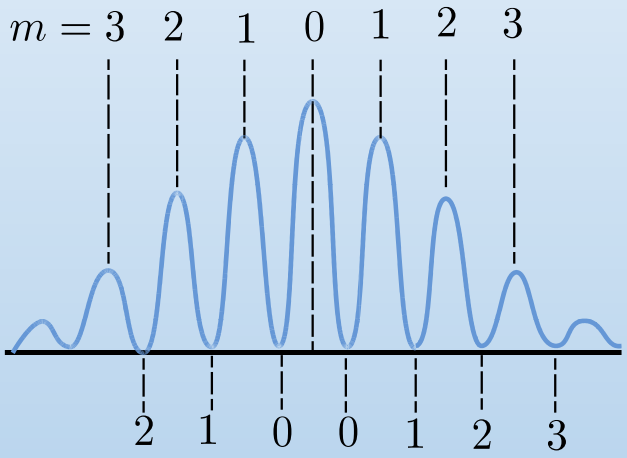
Interference Fringes

$$dsin(\theta) = m\lambda, \quad m = 0, \pm1, \pm2, \ldots \quad \text{Constructive}$$
$$dsin(\theta) = (m + 1/2)\lambda, \quad m = 0, \pm1, \pm2, \ldots \quad \text{Destructive}$$

m is the **order** of an interference fringe

constructive interference

destructive interference



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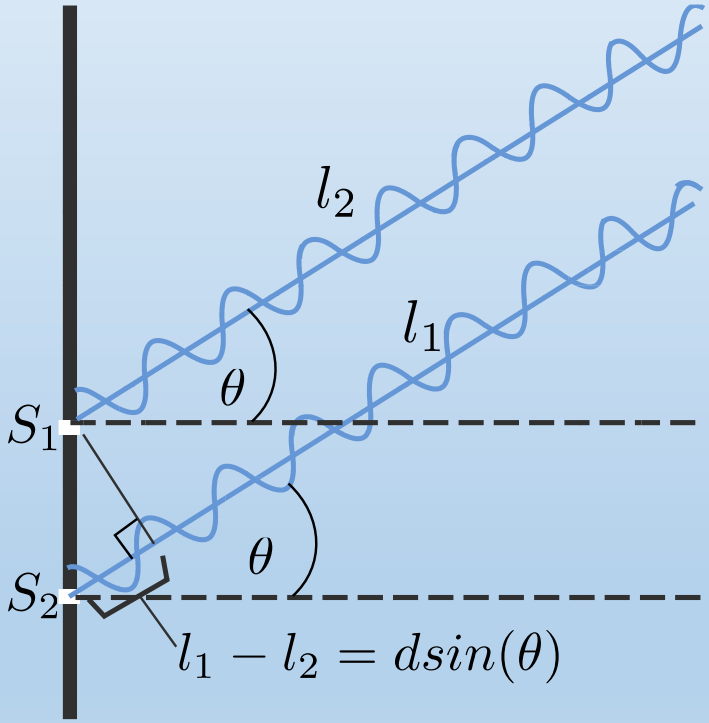

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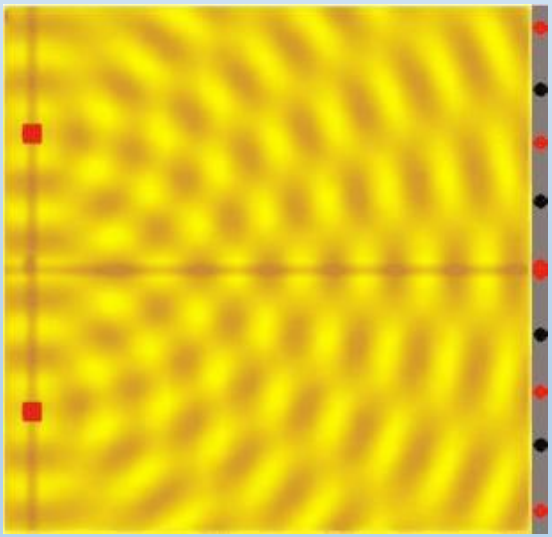
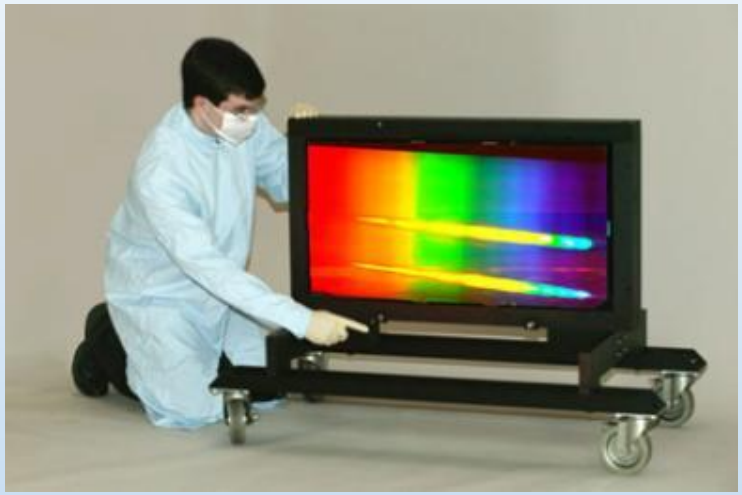
If distance *d* between slits is decreased,
then the angles corresponding to the bright fringes will …



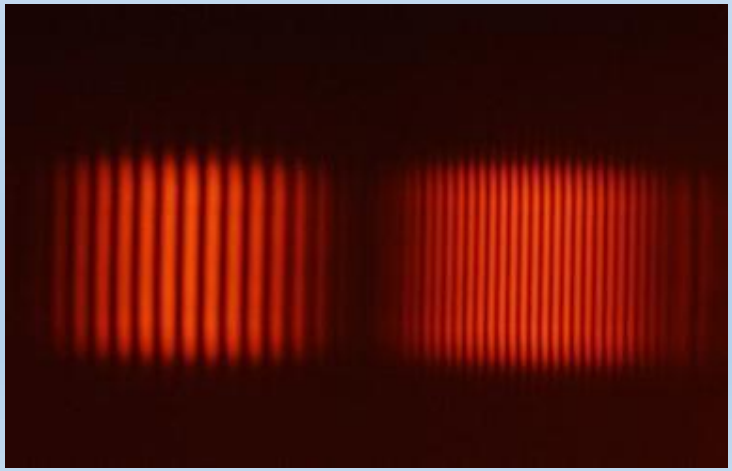
(Choose one)

1. all become smaller.
2. all become larger
3. some will become larger, some smaller.
4. remain unchanged but the fringes will all become dimmer.
5. remain unchanged but the fringes will all become brighter.

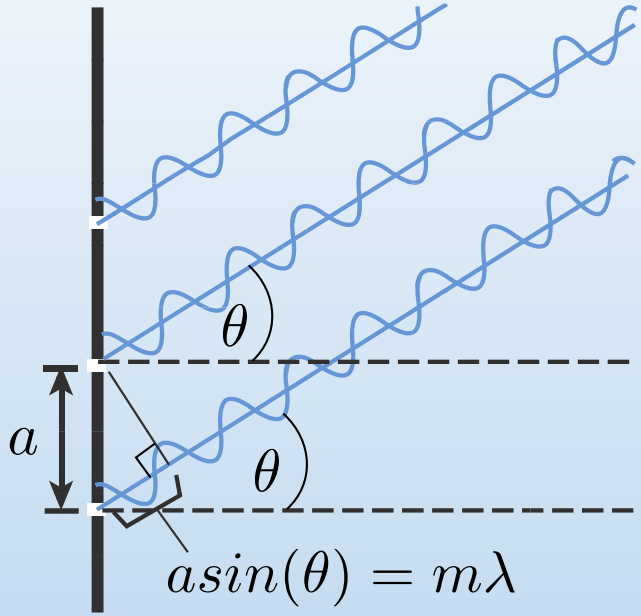
Diffraction of Light From Periodic Slit Source



One of world's largest multilayer dielectric diffraction gratings

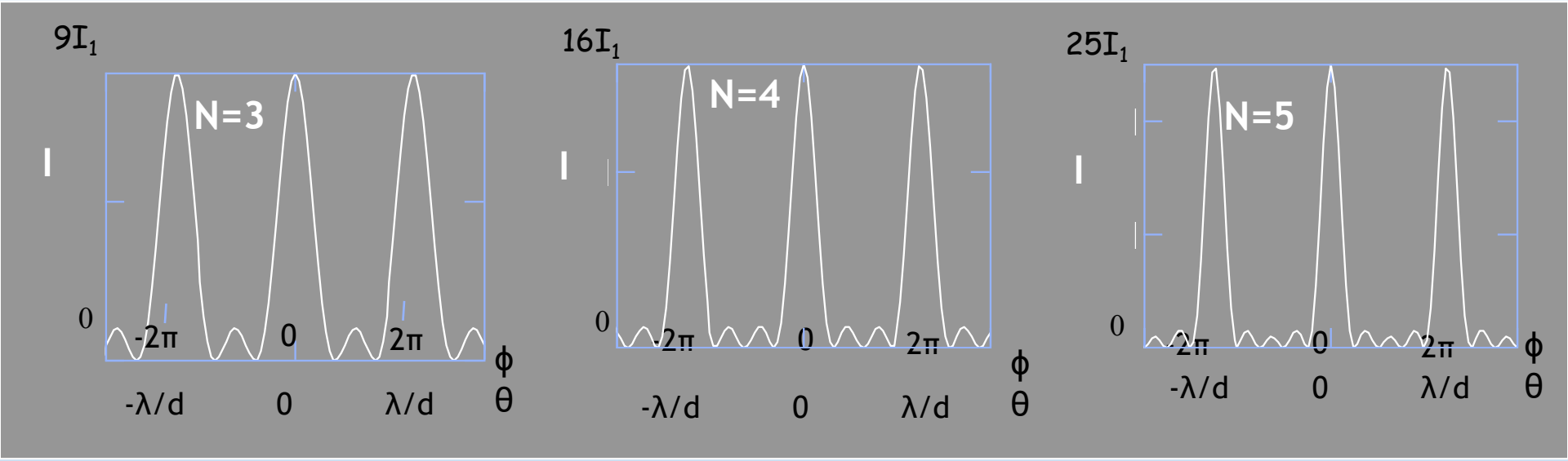


Double slit diffraction fringes with different slit separation



Maxima in the intensity occur if this path length difference is an integer number of wavelengths.

Diffraction of Light From Multiple Slits



The positions of the principal maxima occur at $\phi = 0, \pm 2\pi, \pm 4\pi, \ldots$ where ϕ is the phase between adjacent slits.

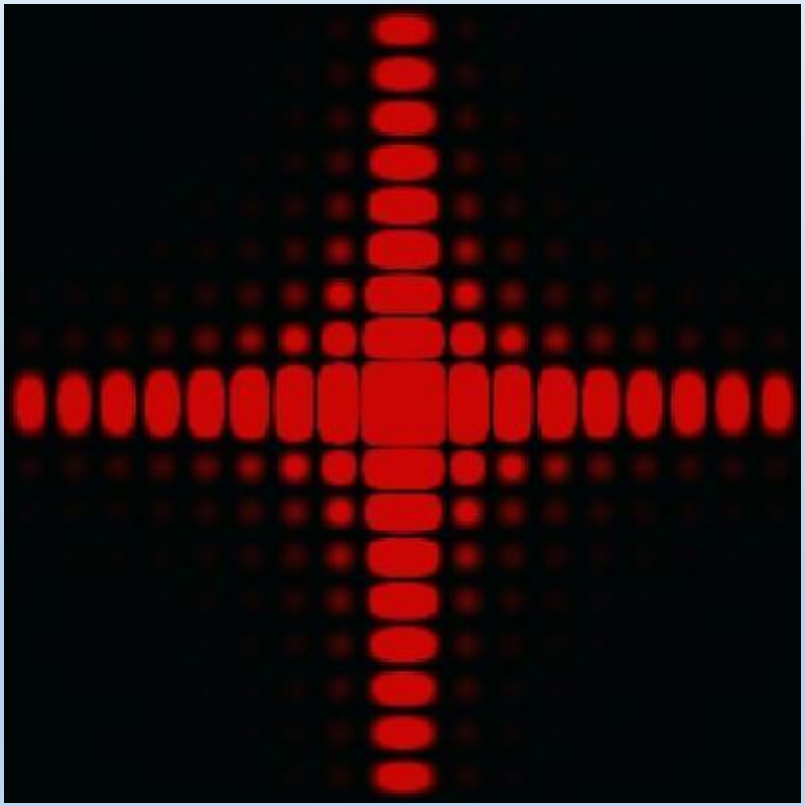
The intensity at the peak of a principle maximum goes as N^2.
3 slits: $A_{tot} = 3A_1 \rightarrow I_{tot} = 9I_1$. N slits: $I_N = N^2 I_1$.

Between two principle maxima there are N-1 zeros and N-2 secondary maxima → The peak width ~ 1/N.

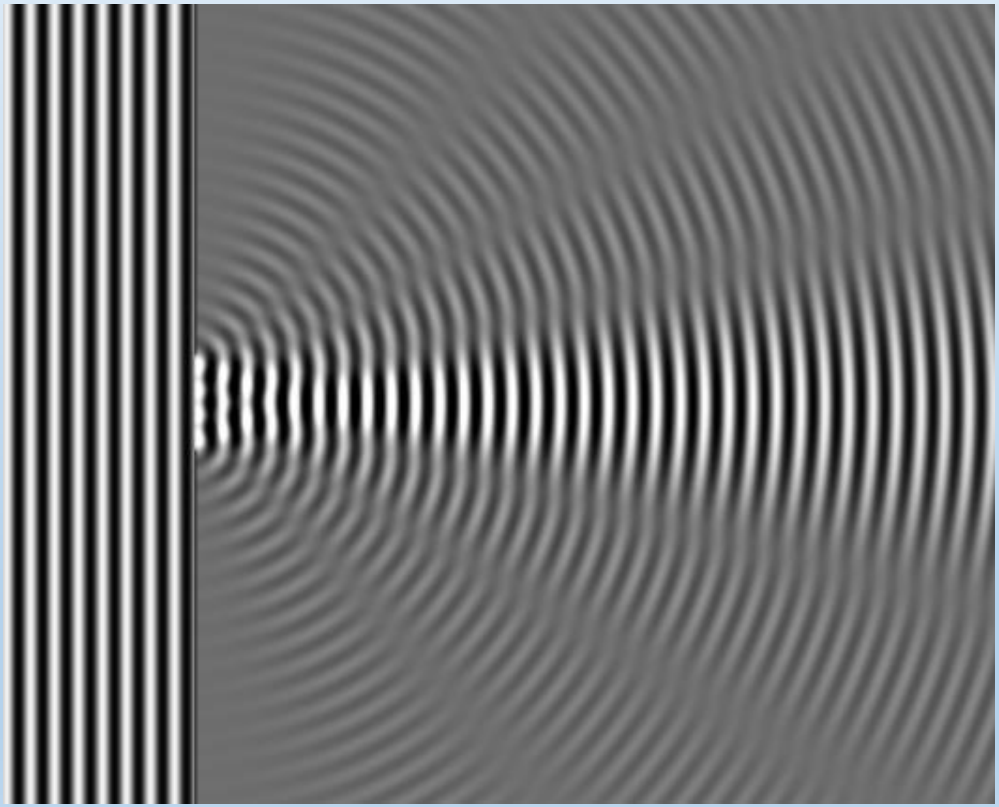
The total integrated power for a principle maximum goes as $N^2(1/N) = N$.

Diffraction Pattern from a Single Slit

The intensity pattern formed on a screen by diffraction from a single square aperture



Numerical approximation of diffraction pattern from a slit of width four wavelengths with an incident plane wave.



Key Takeaways

In 1802 Thomas Young's Double Slit Experiment demonstrated wave-nature of photons. (Much later, a similar double-slit experiment will be used to demonstrate wave nature of electrons, and of matter in general.)

Huygen's Principle is a geometric construction for determining the position of a new wave at some point based on the knowledge of the wave front that preceded it

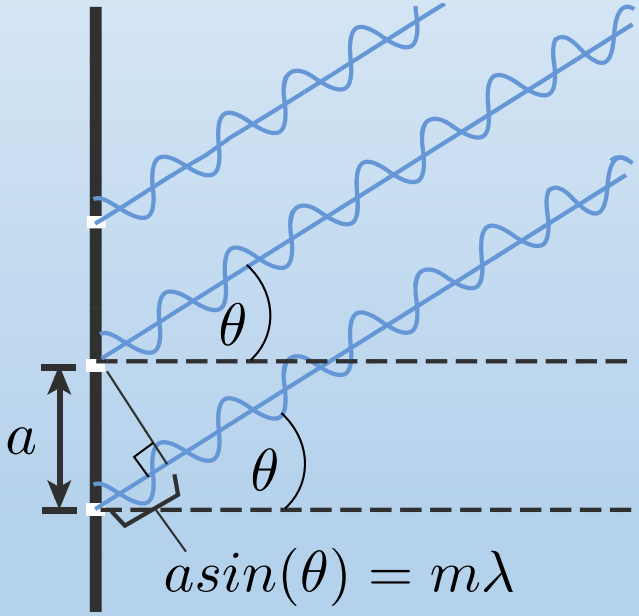


Image is in the public domain

$dsin(\theta) = m\lambda,$	$m = 0, \pm1, \pm2, ...$	Constructive
$dsin(\theta) = (m + 1/2)\lambda,$	$m = 0, \pm1, \pm2, ...$	Destructive

Thin Film Interference

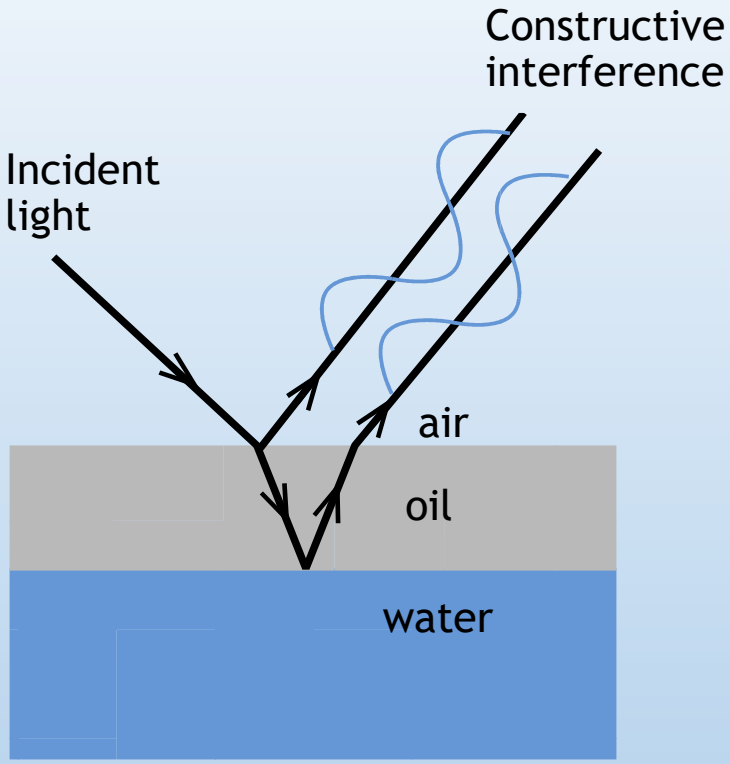
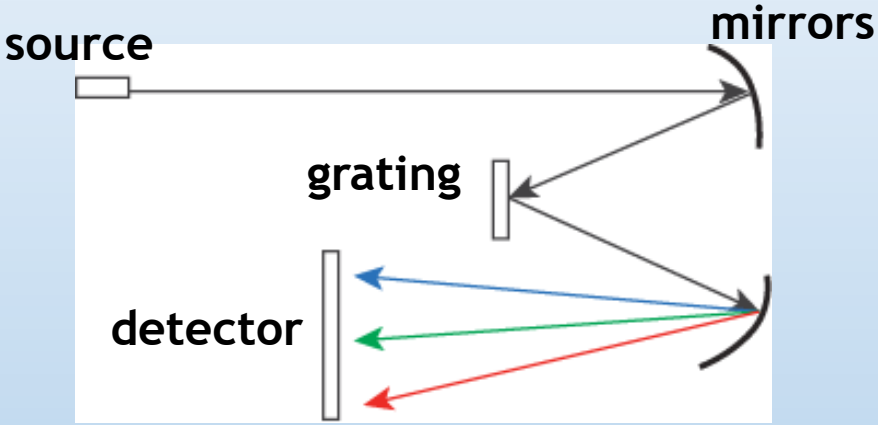


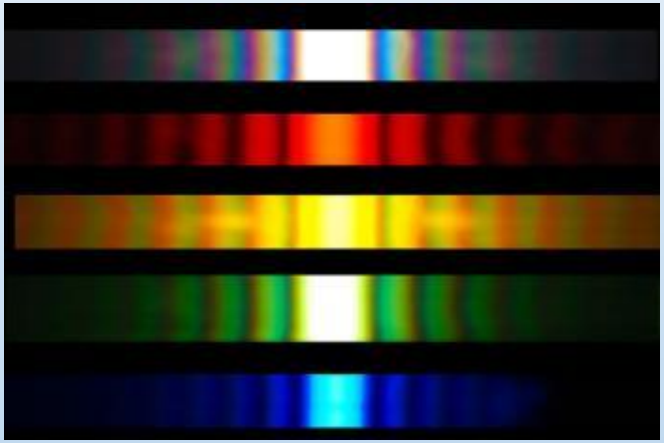
Image of Lord Rayleigh is in the public domain

Lord Rayleigh (1842 -1919) Repeated Franklin's oil on water experiment in 1890 and made a calculation of the thickness of the oil layer.

teaspoonful of oil ÷ half an acre of pond
= 2.4 nm

Application of Diffraction Gratings in Spectrometers





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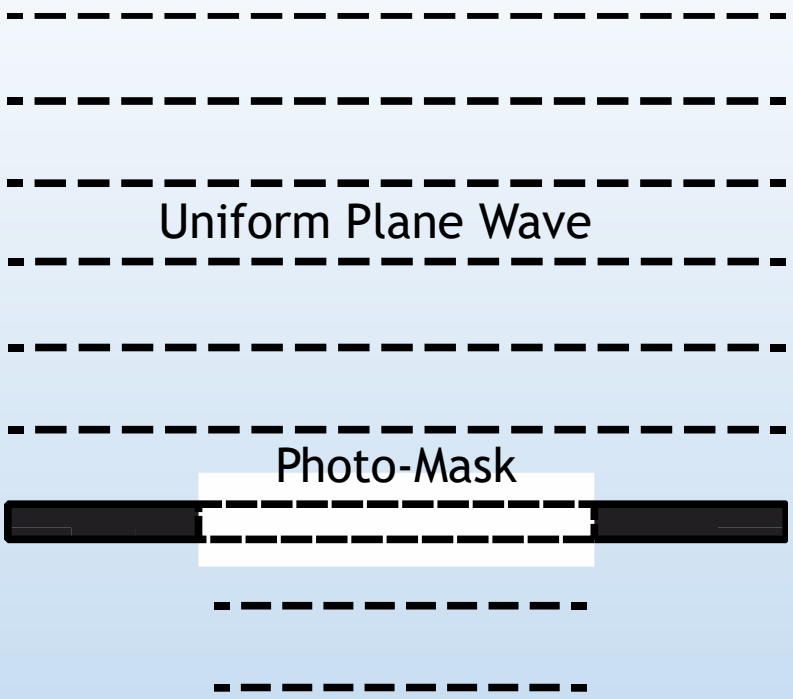
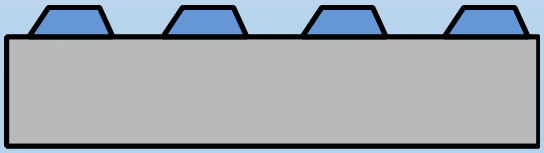
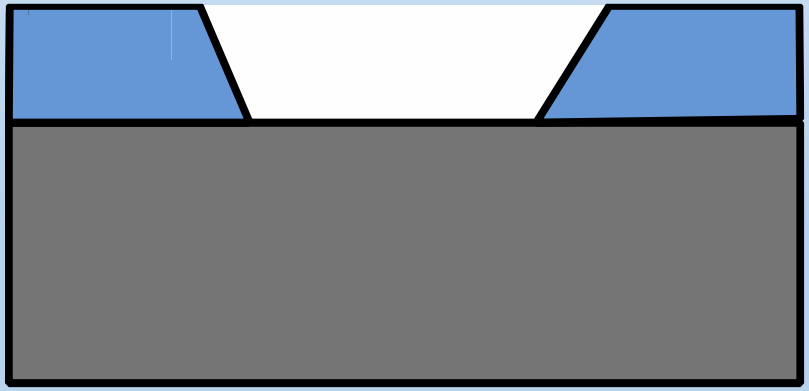
Making Diffraction Gratings via Photolithography



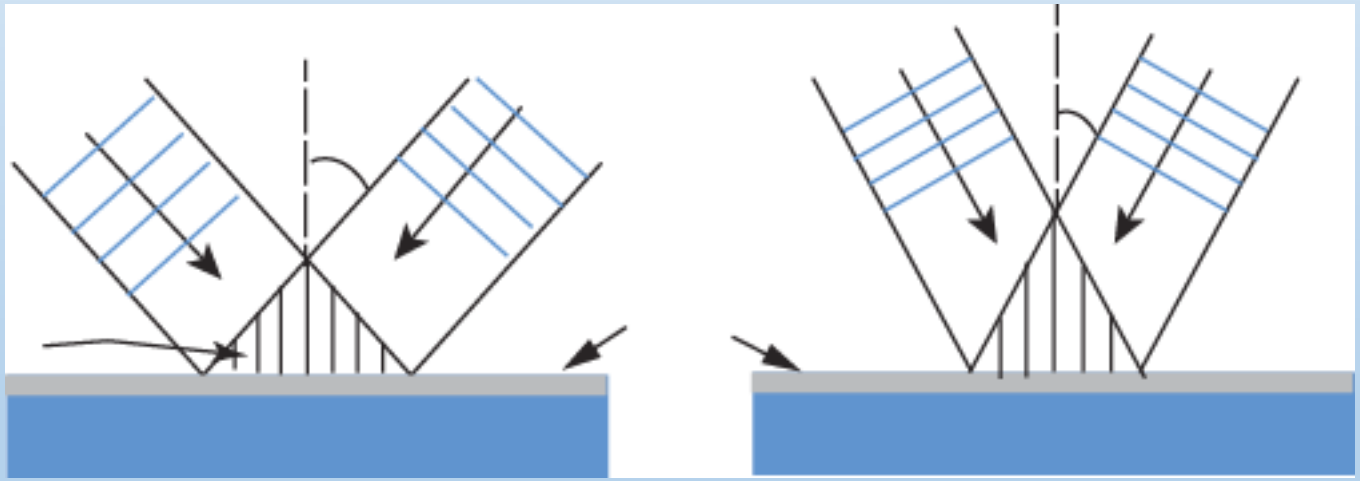




Making Diffraction Gratings

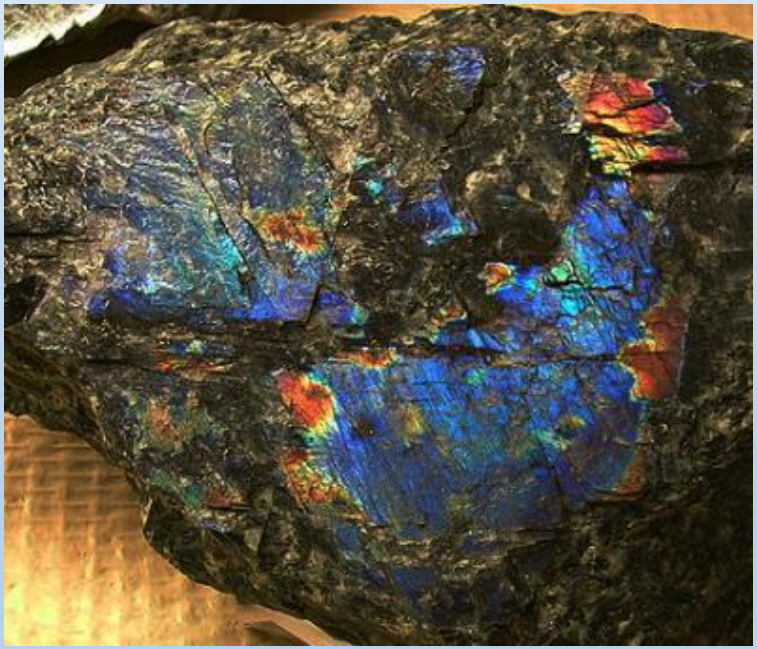
A lithographic technique is often used to produce diffraction gratings. This method relies on the interference pattern between two plane wave light sources. The grating period can be changed by changing the angle between the two.

$$P = \frac{\lambda}{2\,sin\,\theta}$$



Natural Diffraction Gratings

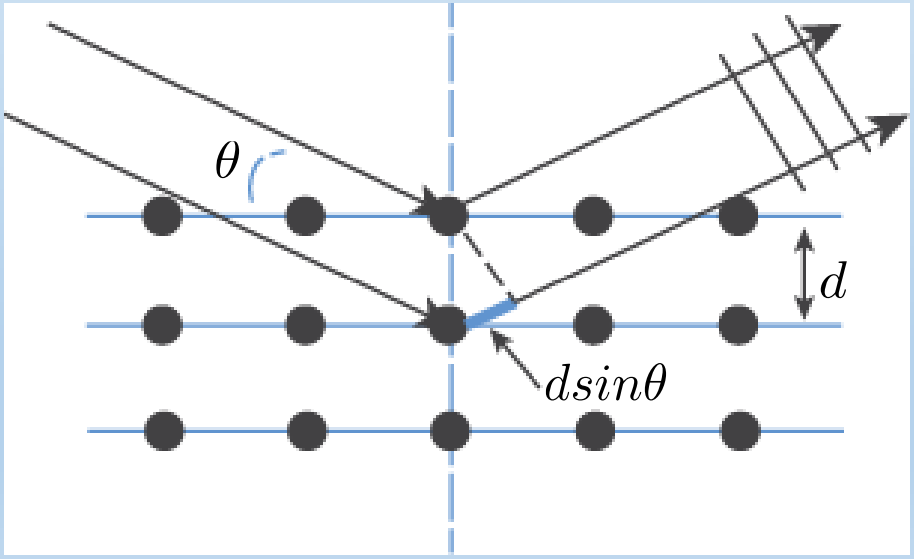
Structural color: color arising from the diffraction of light by the surfaces and interference in an object, rather than from any absorption of light by pigments.



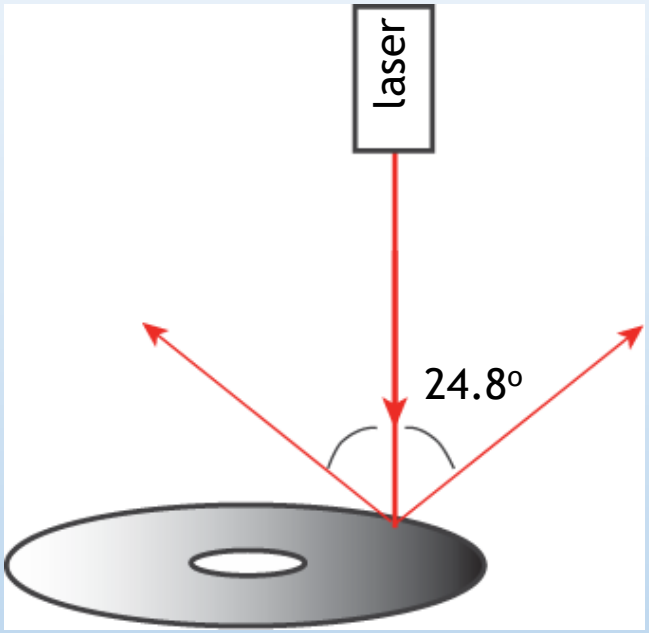
Applications of Diffraction

X-ray Crystallography

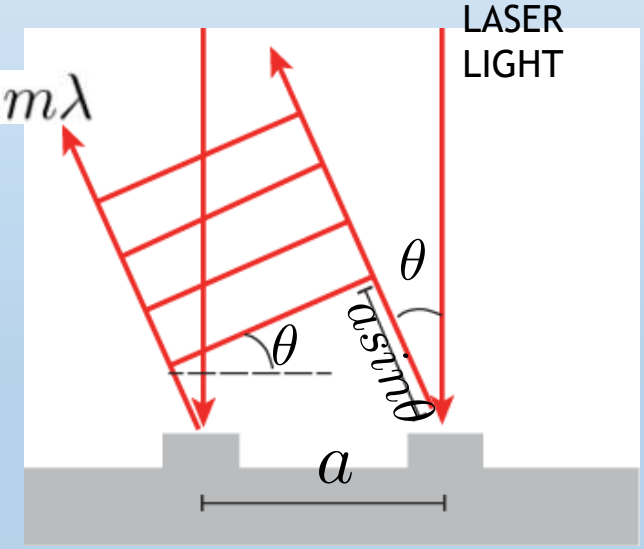
The incoming beam (coming from upper left) causes each scatterer to re-radiate a small portion of its energy as a spherical wave. If scatterers are arranged symmetrically with a separation d, these spherical waves will be in synch (add constructively) only in directions where their path-length difference 2d sin θ equals an integer multiple of the wavelength λ. In that case, part of the incoming beam is deflected by an angle 2θ, producing a reflection spot in the diffraction pattern.



Diffraction of Light a DVD



$$a \sin\theta = m\lambda$$



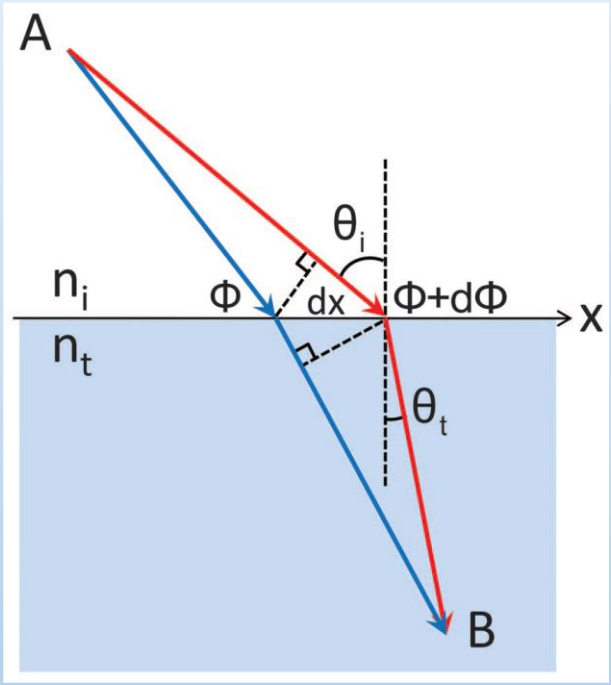
2 BUMPS on a CD/DVD SURFACE
are DISTANCE *a* APART

CD/DVD surface acts like a diffraction grating

How much information can the CD store?

Flat optics with Metasurfaces

Generalized laws of reflection and refraction



Assuming that the two paths are infinitesimally close to the actual light path, then the phase difference between them is zero.

$$k_0 n_i \sin(\theta_i)\,dx + (\Phi + d\Phi)$$
$$= k_0 n_t \sin(\theta_t)\,dx + \Phi$$

$$n_t \sin(\theta_t) - n_i \sin(\theta_i) = \frac{\lambda_0}{2\pi}\frac{d\Phi}{dx} \quad \textbf{(Refraction)}$$

$$\sin(\theta_r) - \sin(\theta_i) = \frac{\lambda_0}{2\pi n_i}\frac{d\Phi}{dx} \quad \textbf{(Reflection)}$$

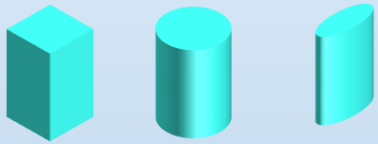
N. Yu et al., Science 334, 333–337 (2011).

Flat optics with Metasurfaces

An electromagnetic metasurface refers to a kind of artificial sheet material with sub-wavelength thickness. Metasurfaces have strong abilities to steer the flow of light by introducing phase discontinuities at the interface.

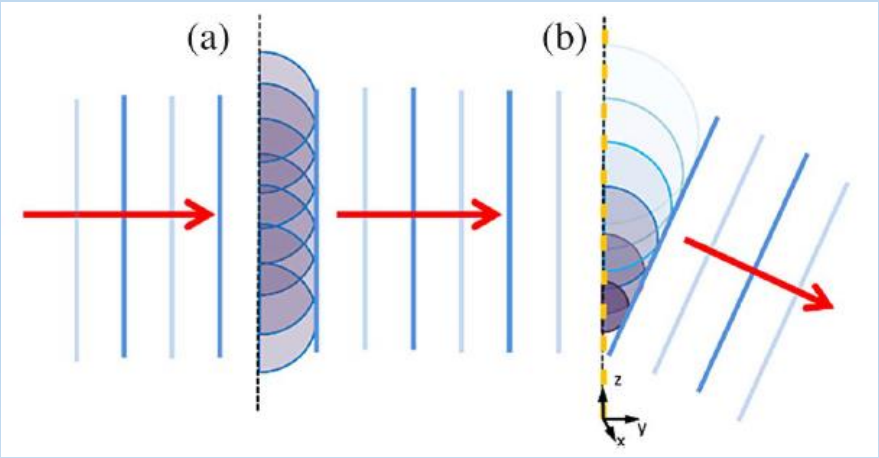
Metallic Meta-atoms
（Au、Ag、Al、Cu）

Dielectric Meta-atoms
（Si、SiO_2、TiO_2）



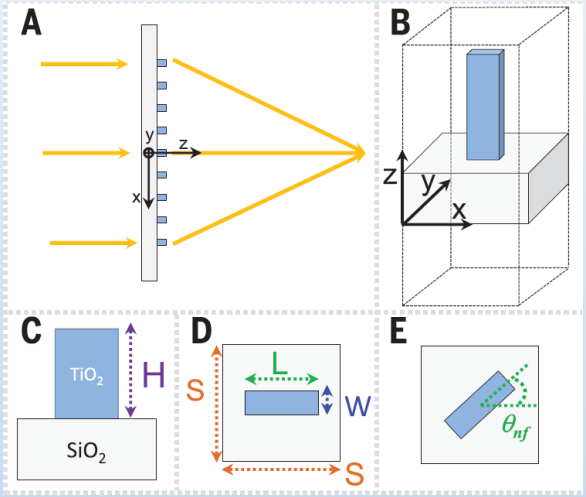
Wavefront Control

- **Phase Distribution**
- **Amplitude Distribution**

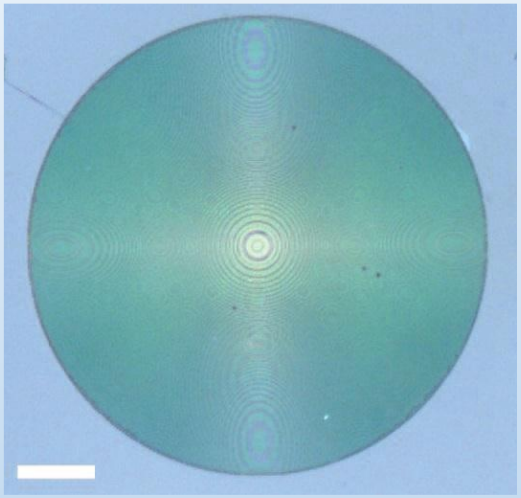


Metalenses

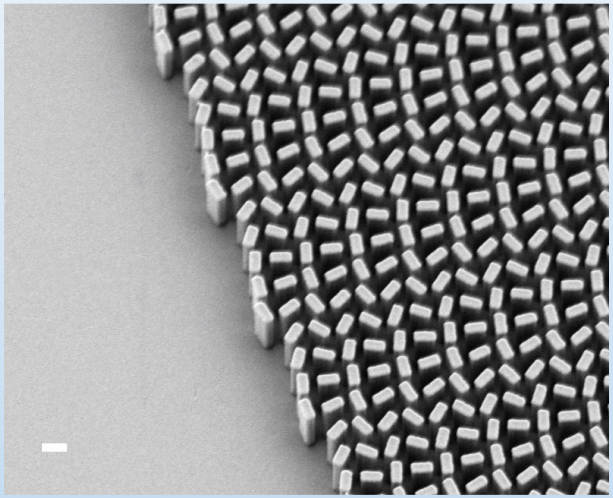
Schematic of the metalens



Optical image of the metalens

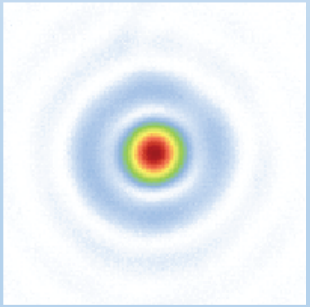


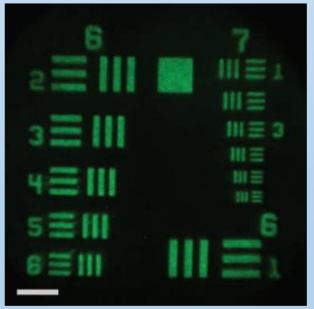
SEM micrograph



Phase Profile:

$$\Phi(x,y)=\frac{2\pi}{\lambda}\left(f-\sqrt{x^2+y^2+f^2}\right)$$





Selected as The Breakthrough of the Year in 2016, awarded by the journal of Science

Science 352, no. 6290 (2016): 1190-1194.