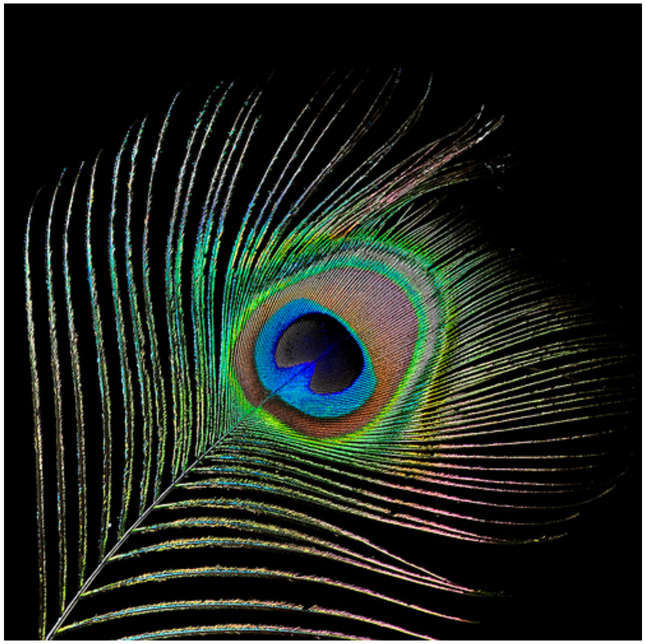
Lecture 14 (Giancoli Chapter 24)

The Wave Nature of Light



Lecture 12 Summary

- Four Consequences of the Wave nature of Light:
  - Dispersion
  - Interference
  - Diffraction
  - Polarization
- Huygens' principle: every point on a wavefront is a source of spherical wavelets
- Young's double-slit experiment.
- Rainbows, Anti-Reflection Coatings

Light as a Wave

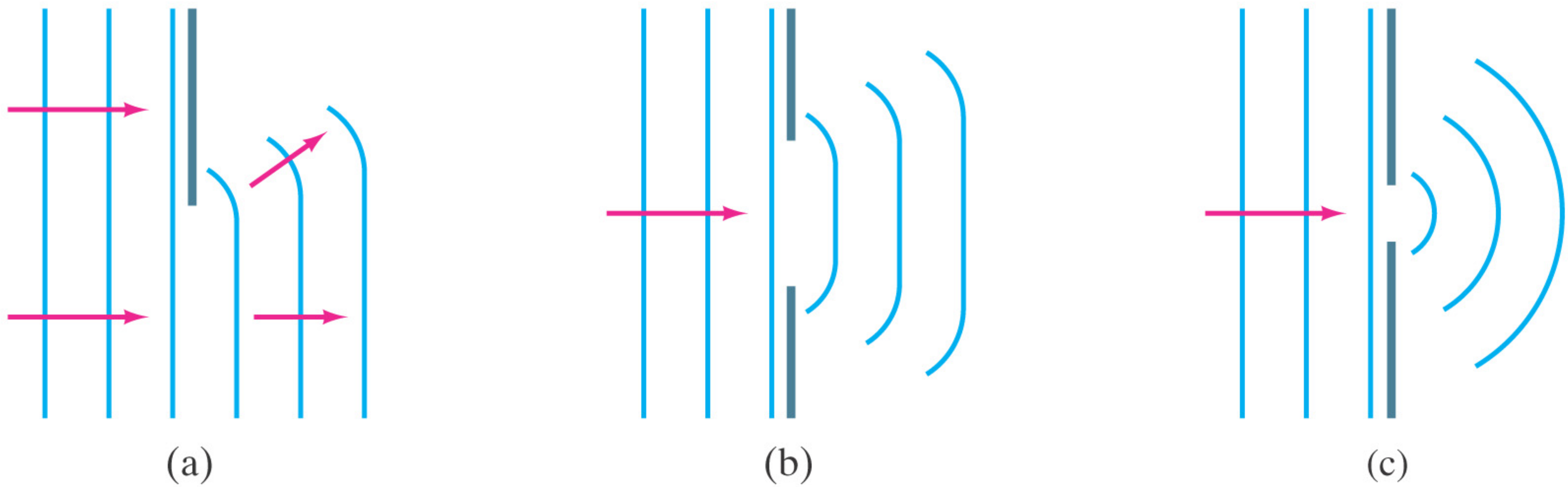
If Light is an electromagnetic wave, lets start by looking at how waves behave.

Ocean Waves entering a Cove

- Where the long ocean waves enter the opening of the cove, they spread out in rings, as if from a point.
- This phenomenon is called Diffraction
- Exactly the same thing happens to sound, and EM waves (light, radio, X-rays etc)

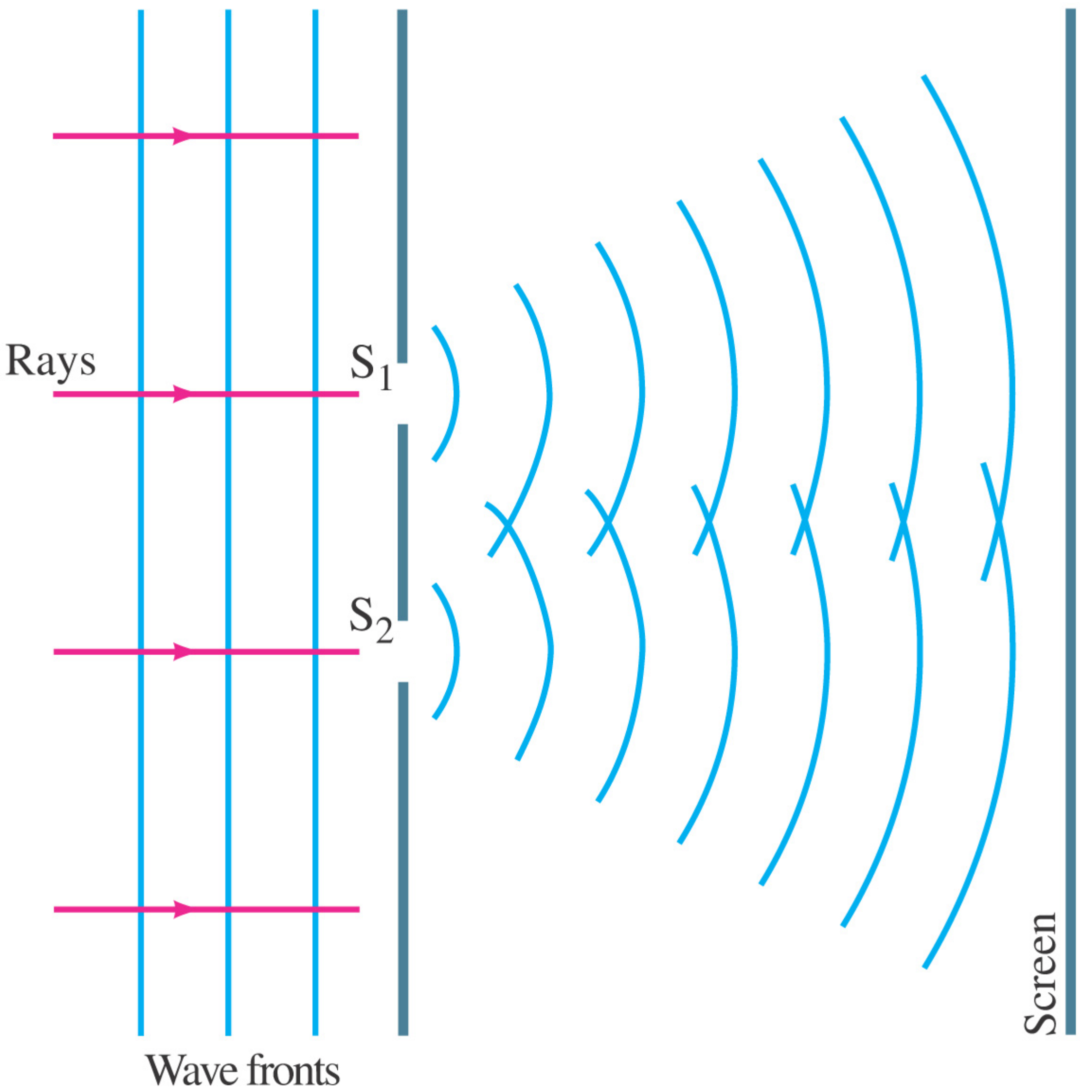
24.1 Huygens' Principle and Diffraction

Large aperture **Small aperture**



The smaller the aperture (or the more the waves are disturbed) the less information remains about the original direction of the waves.

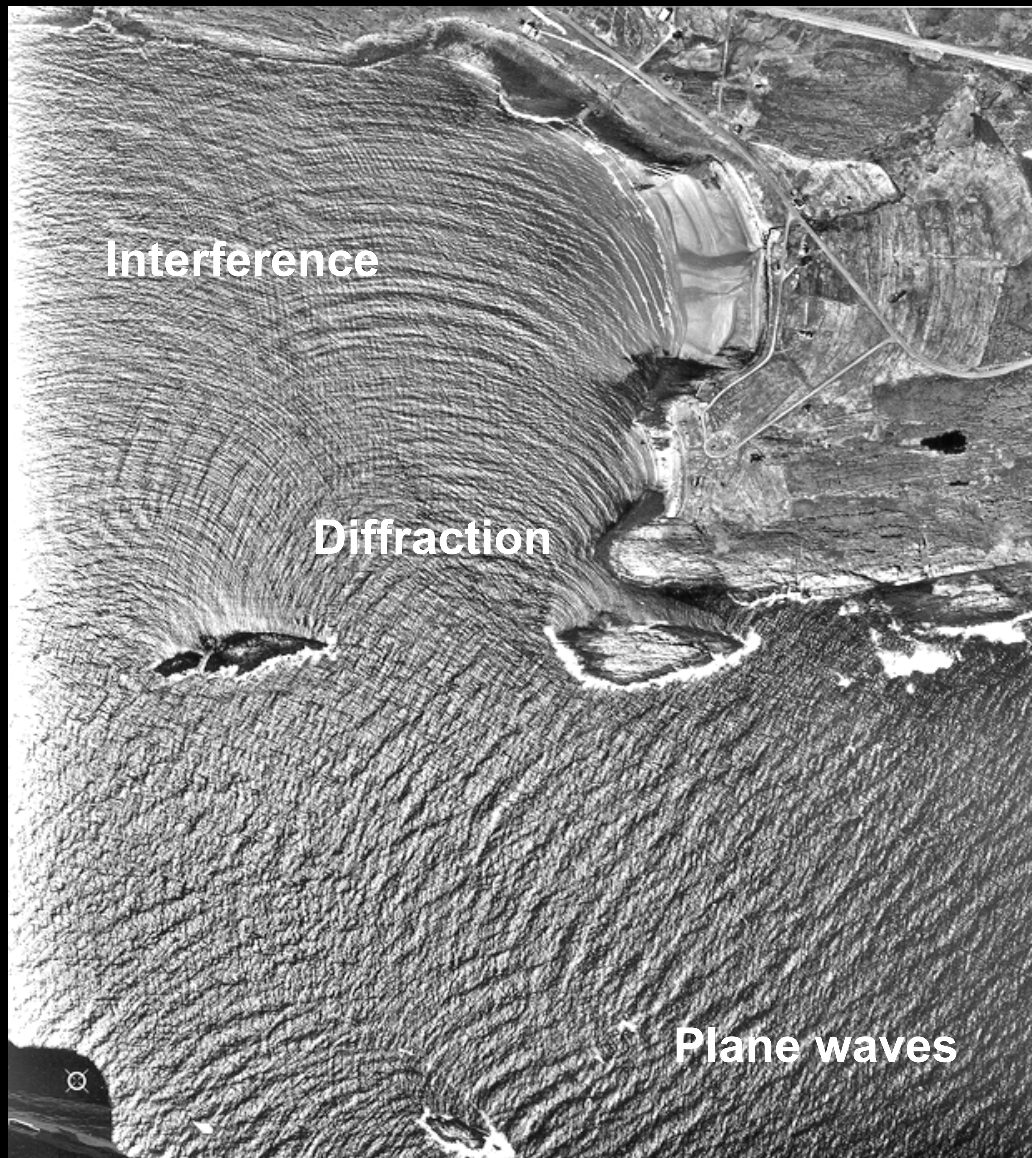
24.3 Interference – Young's Double-Slit Experiment



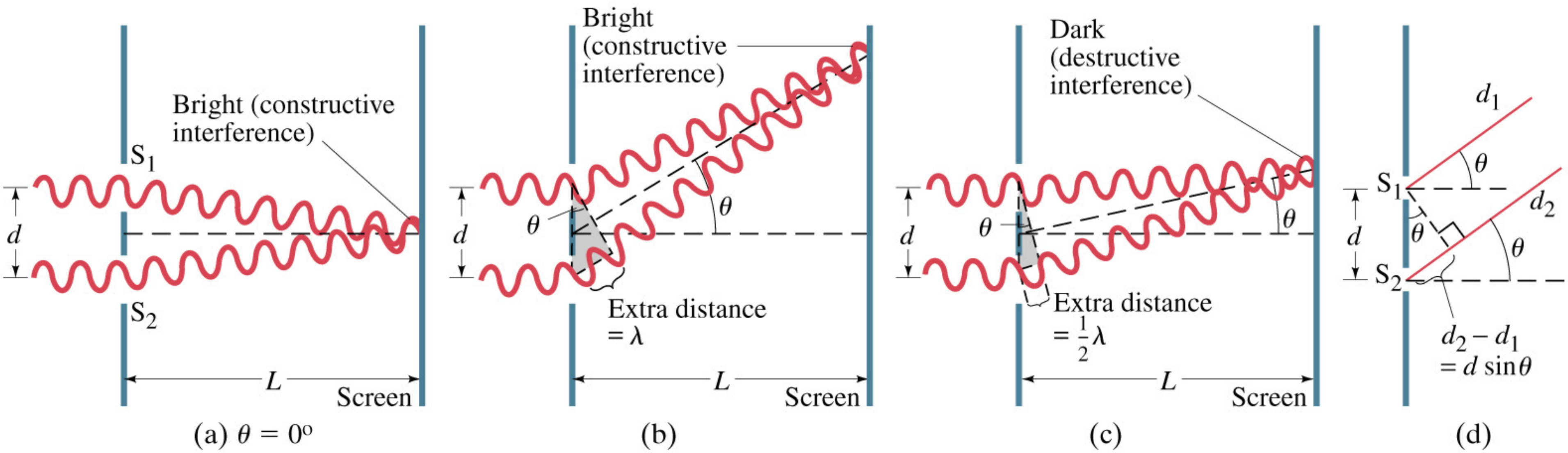
If light is a wave, there should be an interference pattern.

Need live demo
Or video followed by calculation

Long straight ocean waves Diffracting and creating Interference Patterns as they divide and recombine around an island-strewn coastline

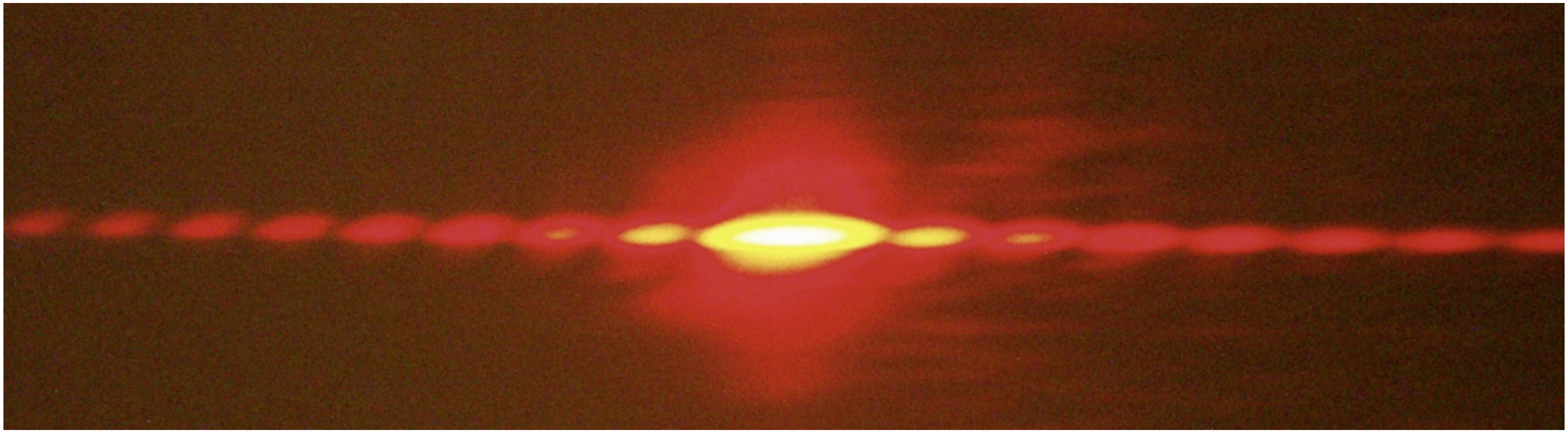


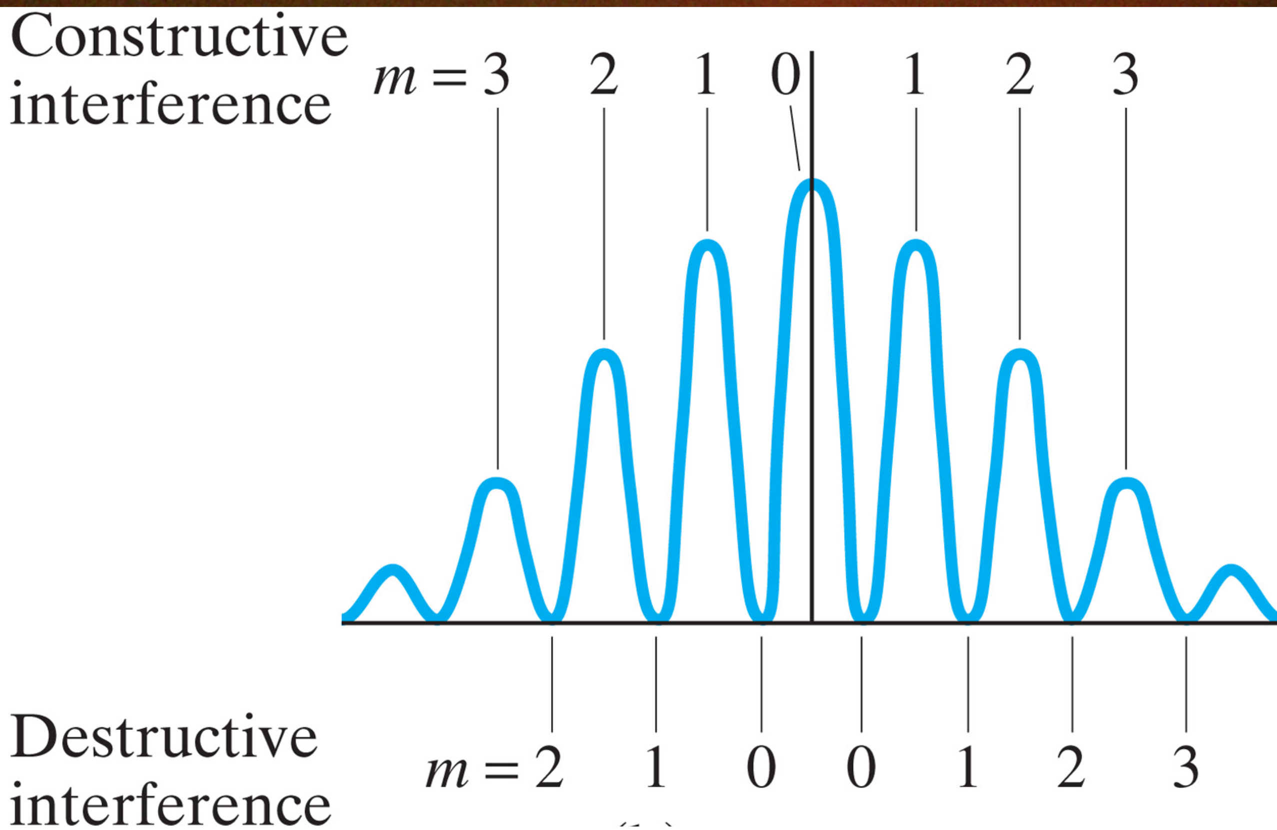
Constructive & Destructive Interference



- **The interference occurs because each point on the screen is not the same distance from both slits.**
- **Depending on the path length difference, the wave can interfere constructively (bright spot) or destructively (dark spot).**

Interference Pattern





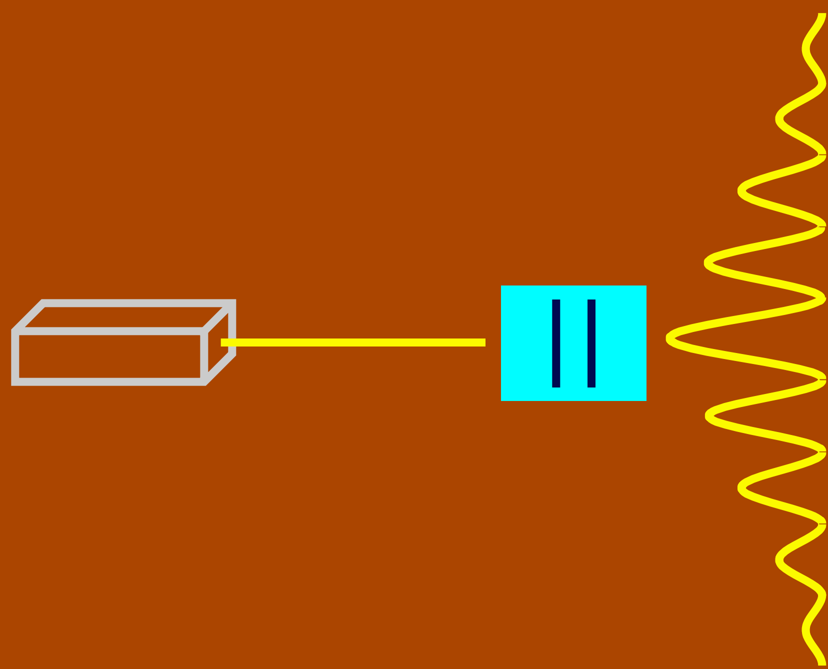
$$d \sin \theta = m\lambda,$$

ConcepTest 24.3b Double Slits II

If instead the **slits** are moved **farther apart** (without changing the wavelength) the interference pattern

1) spreads out
2) stays the same
3) shrinks together
4) disappears

Lets do the experiment and see who is right!



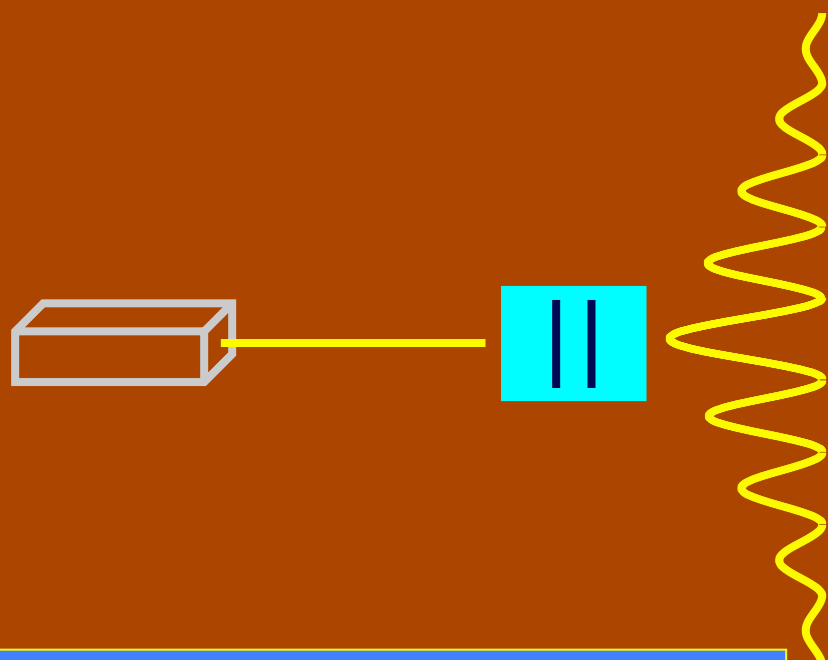
ConcepTest 24.3b Double Slits II

If instead the slits are moved farther apart (without changing the wavelength) the interference pattern

1) spreads out
2) stays the same
3) shrinks together
4) disappears

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

If d is increased and λ does not change, then θ must decrease, so the pattern shrinks together



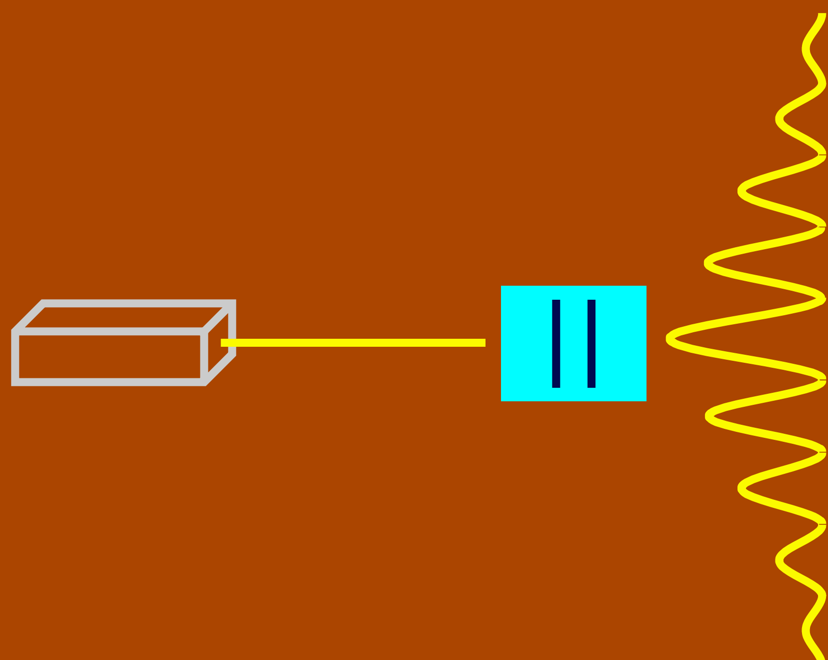
Follow-up: When would the interference pattern disappear?

ConcepTest 24.3a Double Slits I

In a double-slit experiment, when the **wavelength** of the light is **increased**, the interference pattern

1) spreads out
2) stays the same
3) shrinks together
4) disappears

I'd like to try, but my green laser is broken ☹



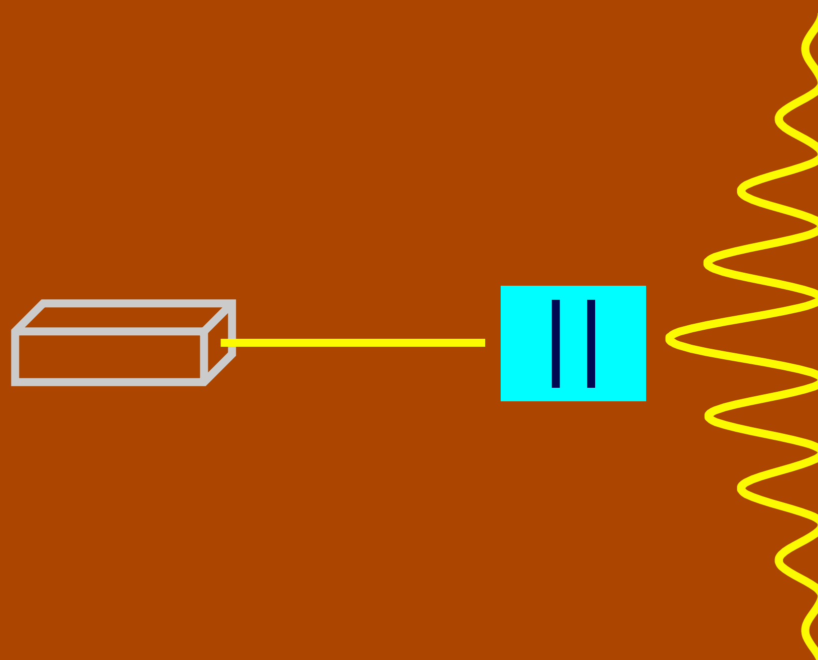
ConcepTest 24.3a Double Slits I

In a double-slit experiment, when the wavelength of the light is increased, the interference pattern

1) spreads out
2) stays the same
3) shrinks together
4) disappears

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

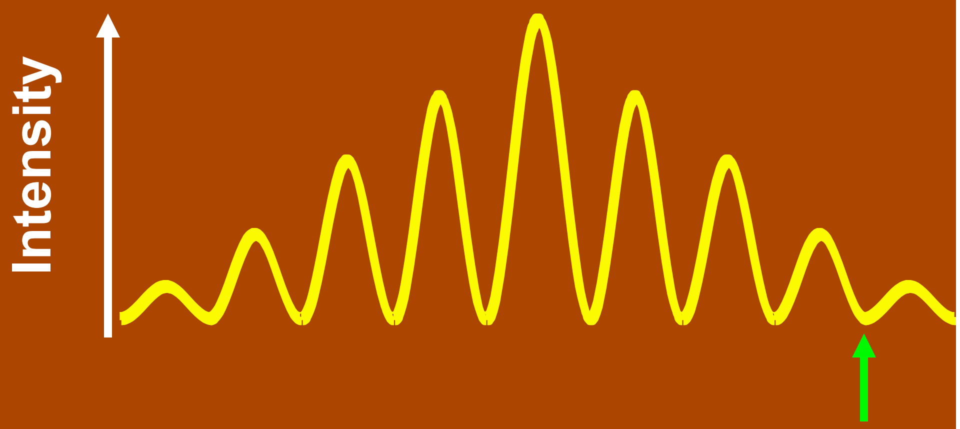
If λ is increased and d does not change, then θ must increase, so the pattern spreads out.



ConcepTest 24.4 Path Difference

In a double-slit experiment, what *path difference* have the waves from each slit traveled to give a minimum at the indicated position?

1) there is no difference
2) half a wavelength
3) one wavelength
4) three wavelengths
5) more than three wavelengths



ConcepTest 24.4 Path Difference

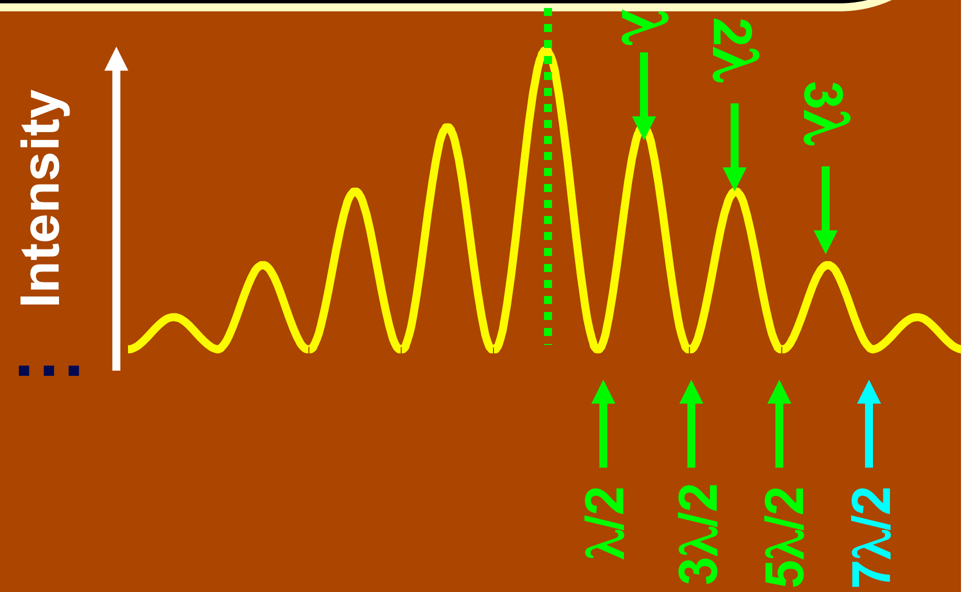
In a double-slit experiment, what *path difference* have the waves from each slit traveled to give a minimum at the indicated position?

1) there is no difference
2) half a wavelength
3) one wavelength
4) three wavelengths
5) more than three wavelengths

For Destructive Interference

$\delta = 1/2\ \lambda,\ 3/2\ \lambda,\ 5/2\ \lambda,\ 7/2\ \lambda,\ \ldots$

$= (m + 1/2)\ \lambda$

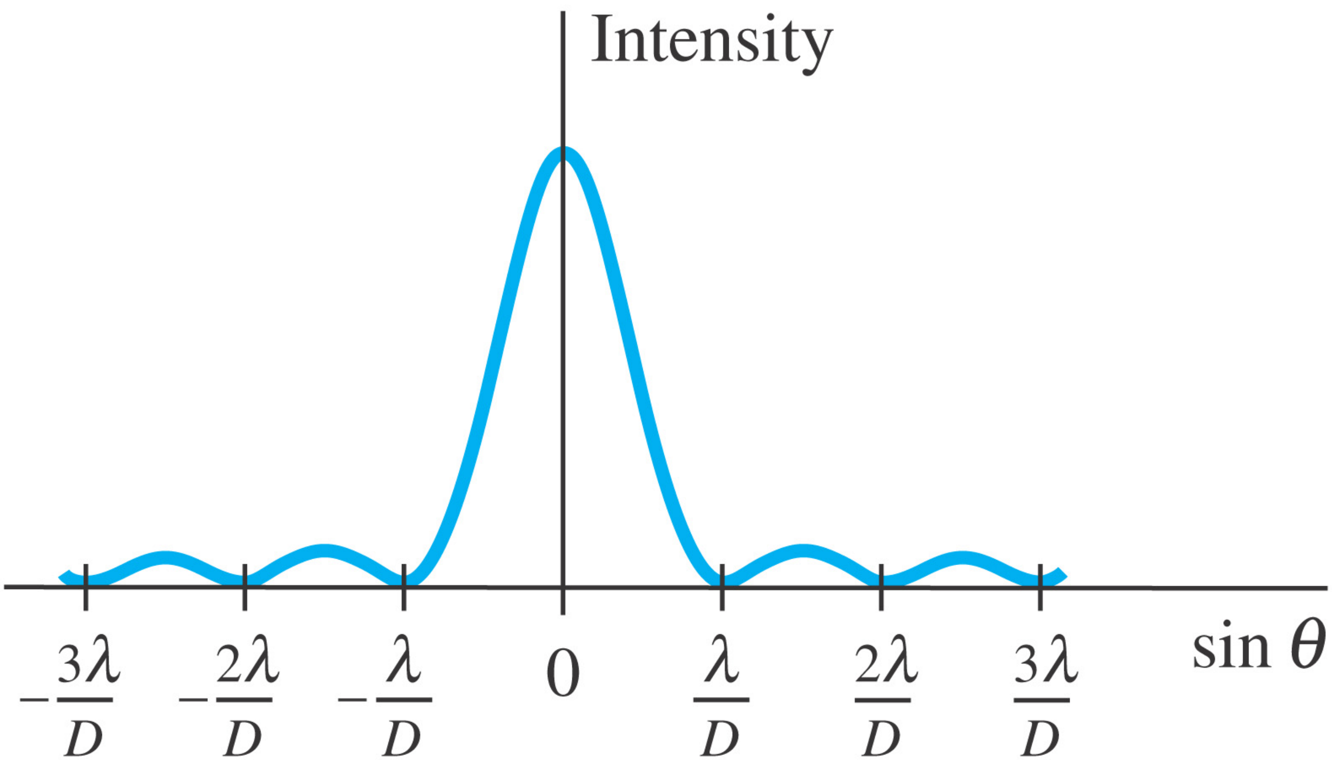


Diffraction by a Single Slit

- A diffraction pattern still arises because different points along a slit create wavelets that interfere with each other just as a double slit would.
- The minima of the single-slit diffraction pattern occur when

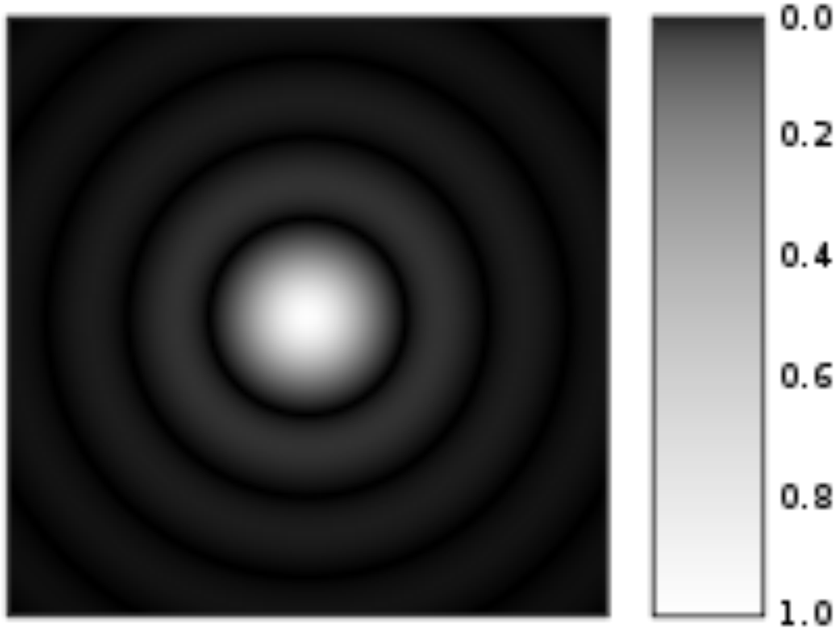
$$D \sin\theta = m\lambda, \qquad m = 1, 2, 3, \cdots$$

- Where D is now the diameter of the slit



Airey Pattern: Diffraction by a circular aperture

For a circular hole (for example your eye's pupil, or the aperture in a camera) the diffraction pattern is a central maximum, surrounded by concentric rings

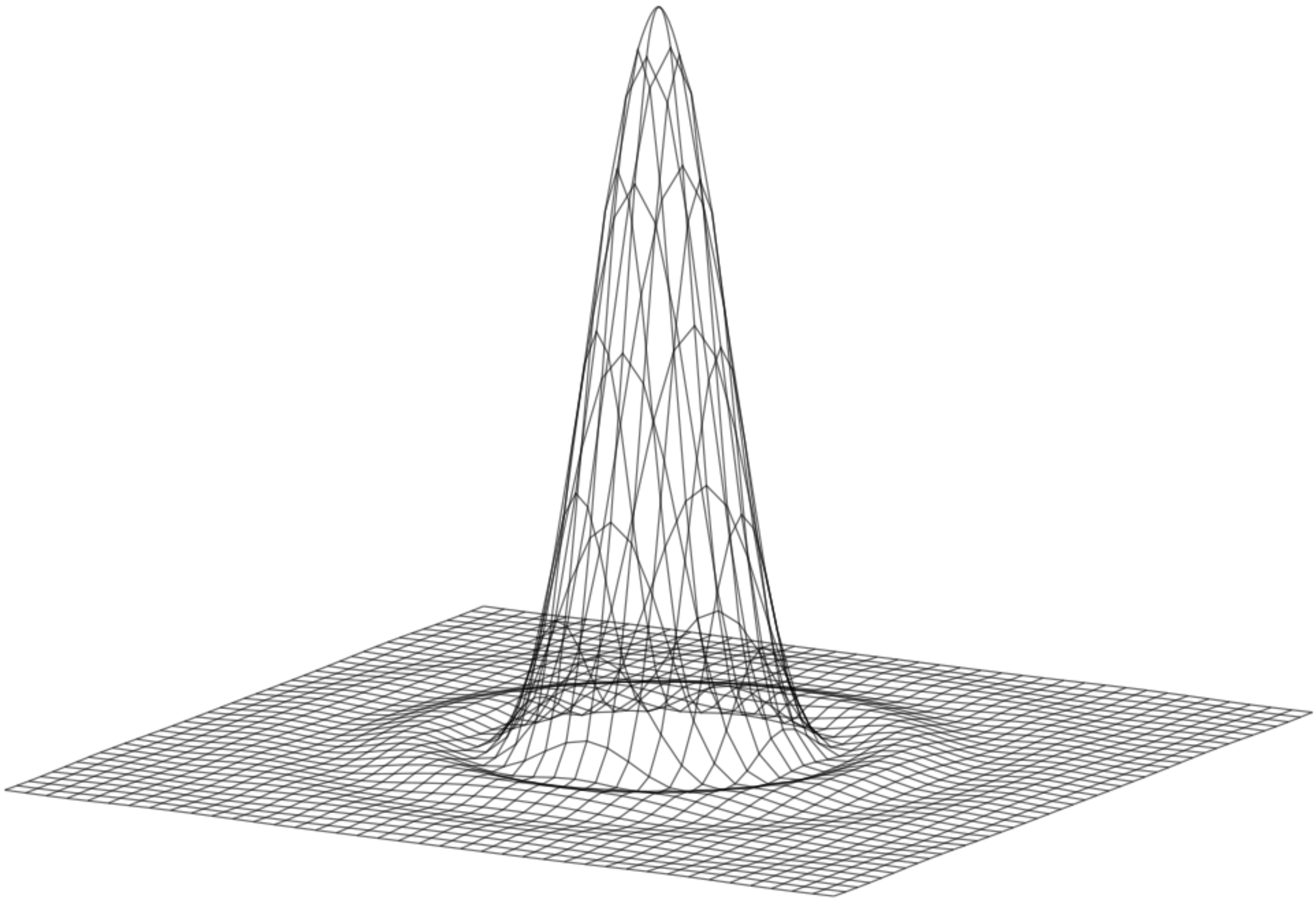


The angular diameter of the central spot (in radians) is

$$\theta_{min} = 1.22\lambda/D$$

Where D is the diameter of the aperture (in meters)

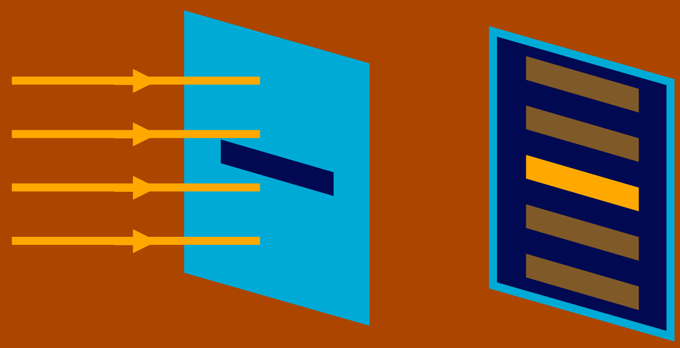
- **This fact is a fundamental limitation for ALL optical devices**
- **Nothing smaller than θ_{min} can be resolved, no matter what the magnification!**
- **More on this next Monday and in the Homework**



ConcepTest 24.5a Diffraction I

The diffraction pattern below arises from a single slit. If we would like to sharpen the pattern, i.e., make the central bright spot narrower, what should we do to the slit width?

1) narrow the slit
2) widen the slit
3) enlarge the screen
4) close off the slit



ConcepTest 24.5a Diffraction I

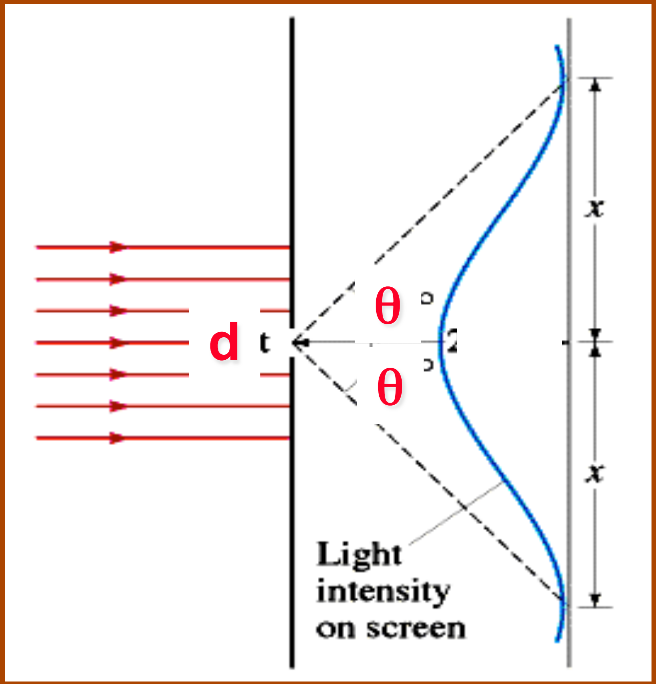
The diffraction pattern below arises from a single slit. If we would like to sharpen the pattern, i.e., make the central bright spot narrower, what should we do to the slit width?

1) narrow the slit
2) widen the slit
3) enlarge the screen
4) close off the slit

The angle at which one finds the first minimum is:

$$\sin\theta = \lambda / d$$

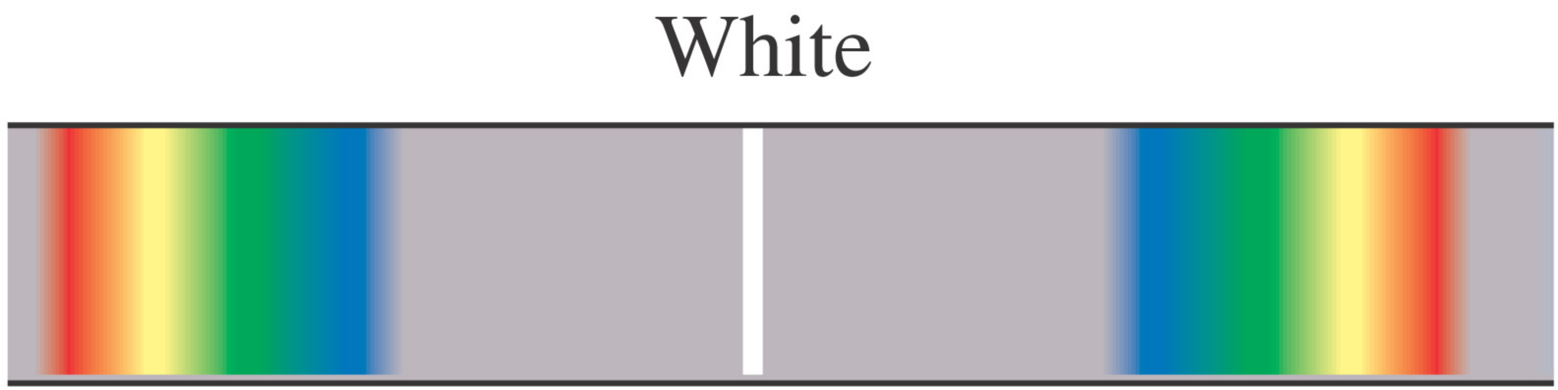
The central bright spot can be narrowed by having a smaller angle. This in turn is accomplished by widening the slit.



Diffraction Pattern for White Light

The position of the maxima (except the central one) depends on wavelength.

The first- and higher-order fringes contain a spectrum of colors.

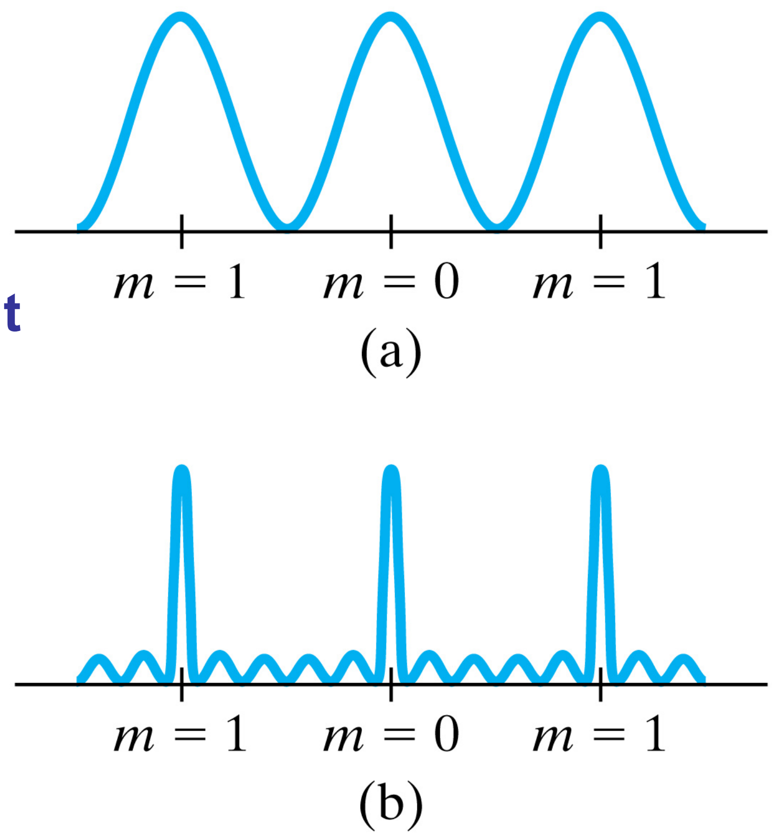


This is the principle used in a Spectrograph

Diffraction Gratings

A diffraction grating consists of a large number of equally spaced narrow slits or lines. A transmission grating has slits, while a reflection grating has lines that reflect light.

- The more lines or slits there are, the narrower the peaks. (greater spectral resolution)
- A normal CD or DVD is an excellent diffraction grating
- Gratings are more efficient than prisms and have largely replaced them
- The Bright Iridescent Colors of Birds' Feathers are due to Diffraction-Grating effects



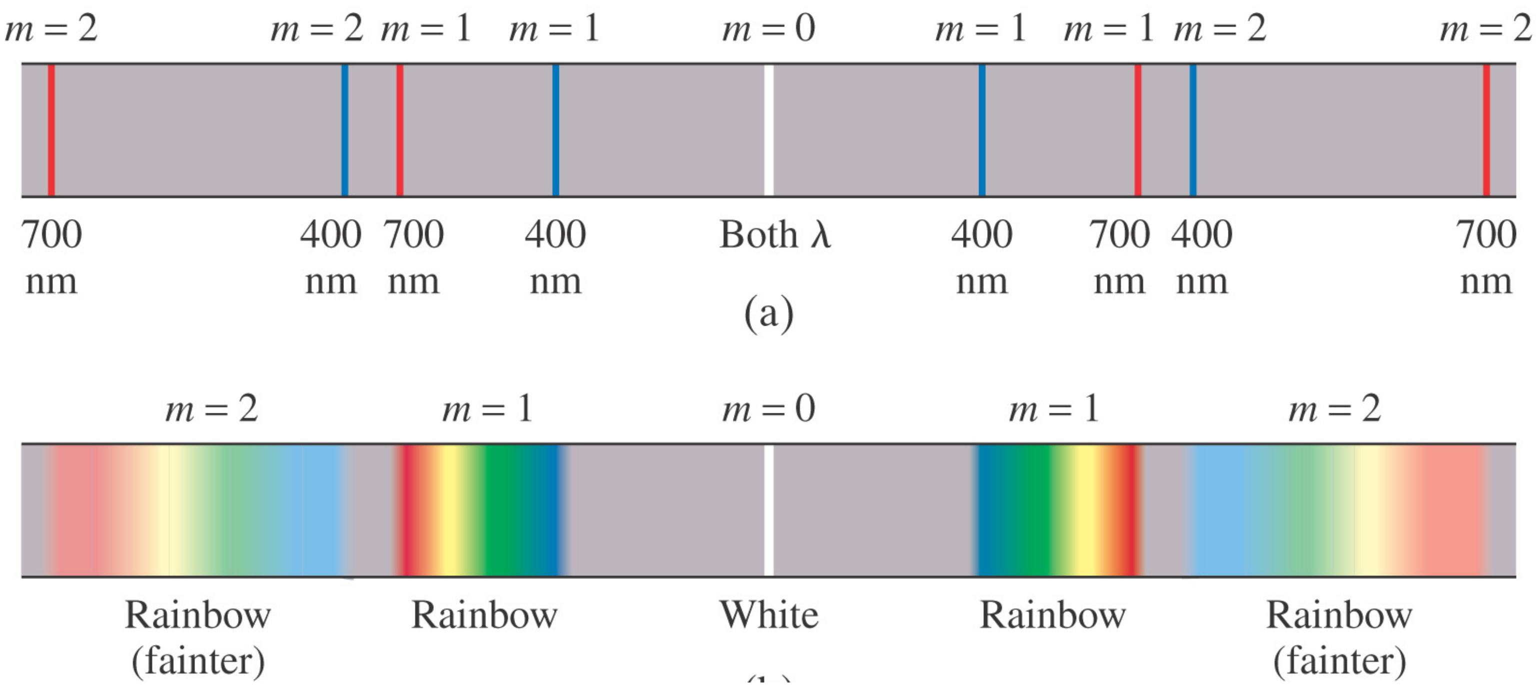
Diffraction Grating

- The maxima of the diffraction pattern are defined by

$$\sin\theta = \frac{m\lambda}{d}, \qquad m = 0, 1, 2,$$

- Where d is the line spacing, and m is called the “order”

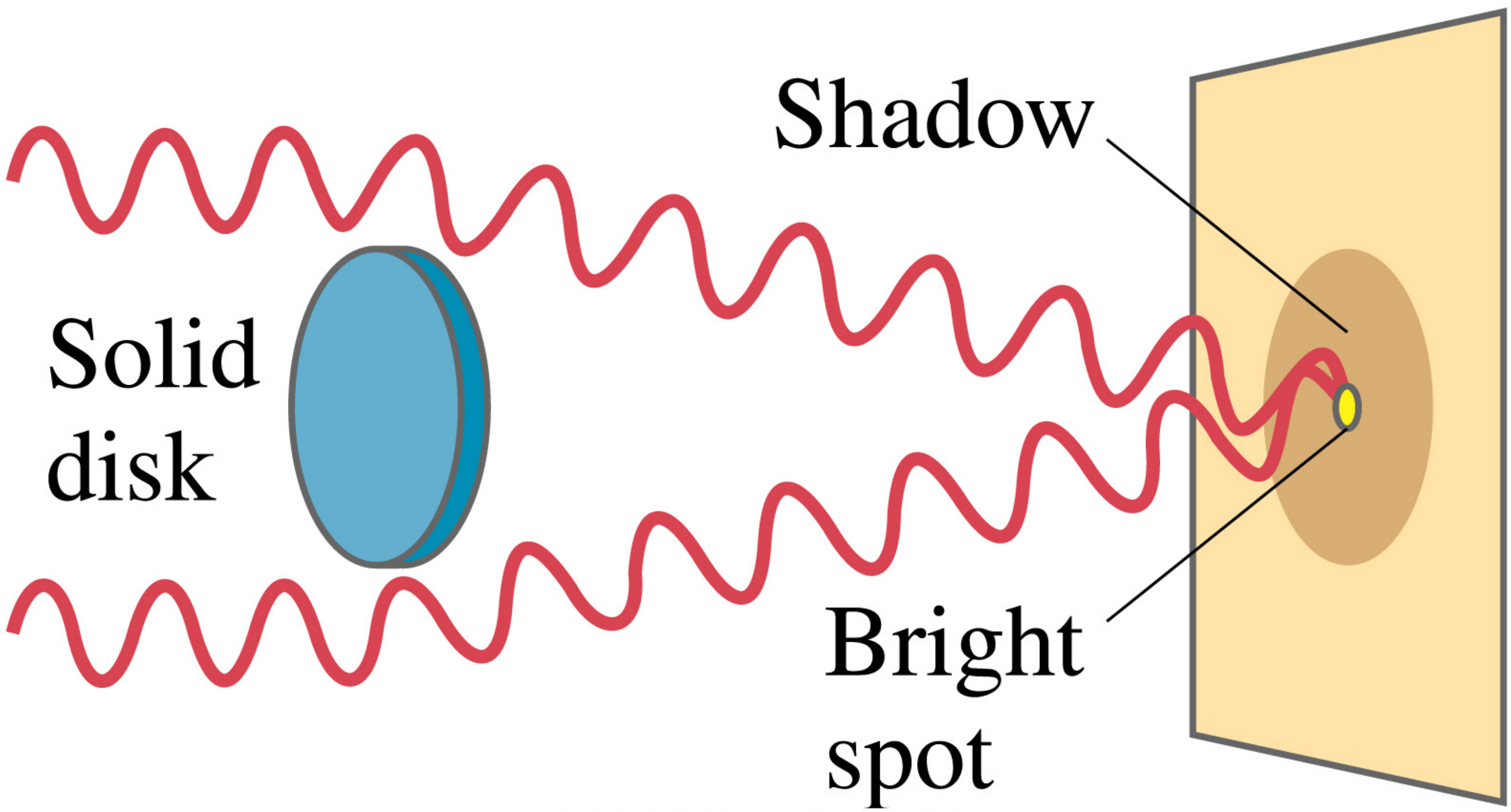
- The higher the order, the greater the dispersion, but the spectra get much fainter at the same time.



Lets use a diffraction grating to measure the wavelength of my laser pointer, and to examine the spectrum shown by a lamp

Diffraction by a Single Slit or Disk

Light will also diffract around a single slit or obstacle.



Polarization

• Light is polarized when its electric fields oscillate in a single plane.

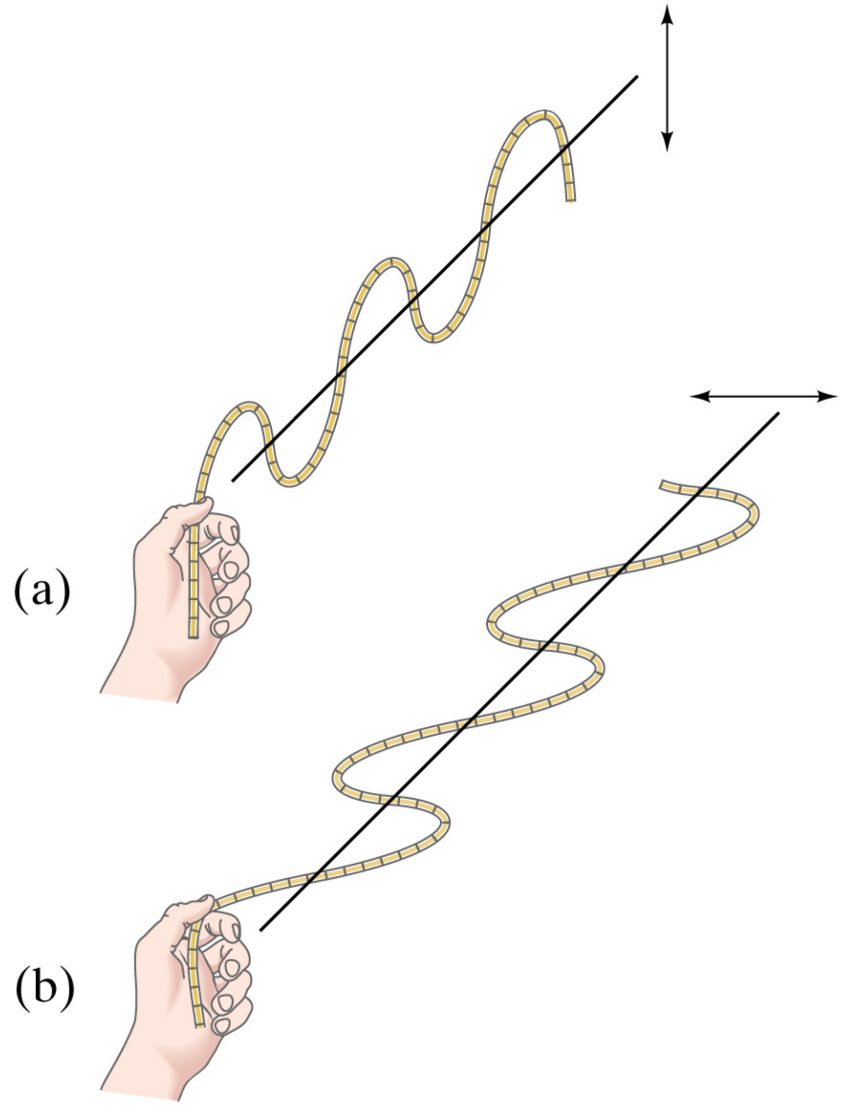
• Consequence of the direction of oscillation of electrons in atoms

• Light gets polarized when it reflects off surfaces, or is scattered by gases (e.g. the atmosphere)

• Any electromagnetic wave can be polarized.

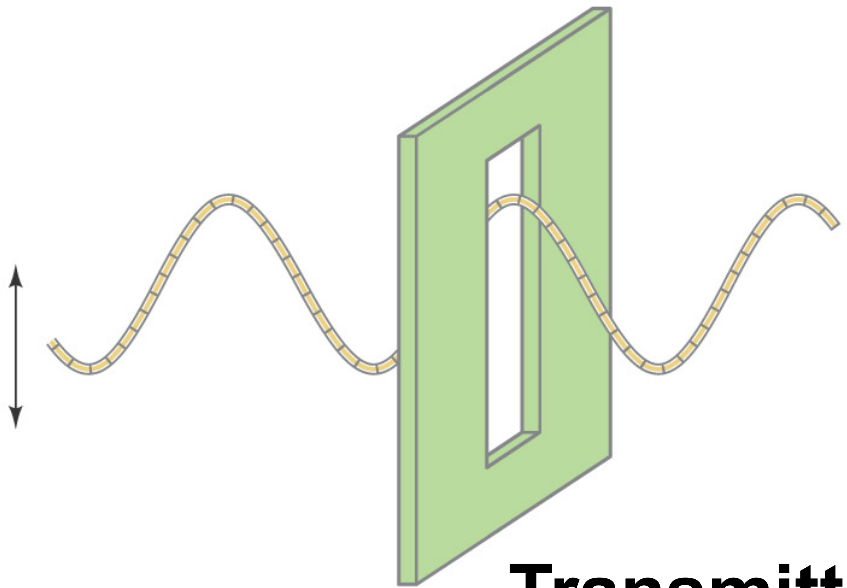
• Another important example is radio waves.

•Can sound waves be polarized?

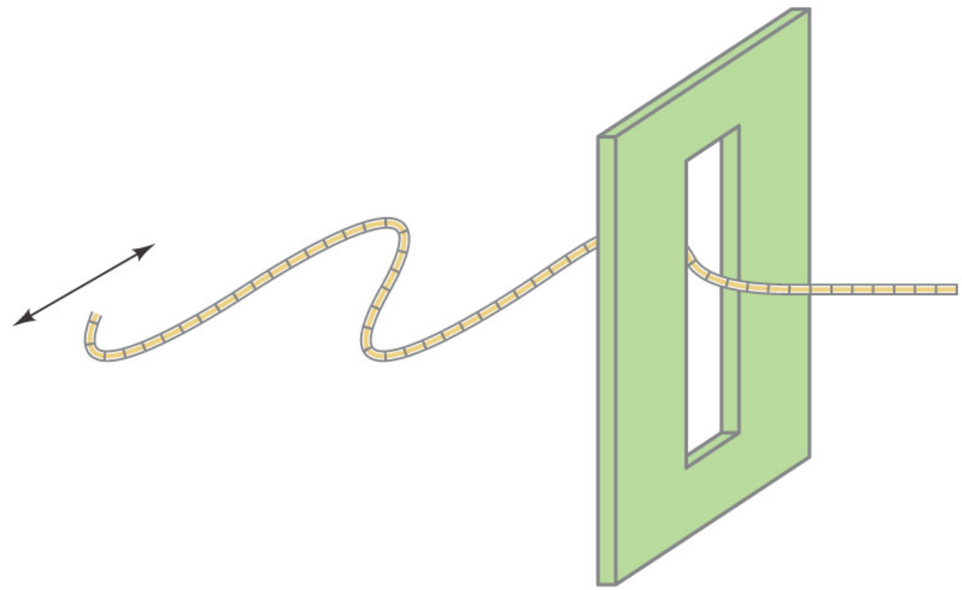


Polarizing Filters (polaroid)

- Polarized light will not be transmitted through a polarized film whose axis is perpendicular to the polarization direction.
- Polarizing filters are used in Photography, Sunglasses, Science Labs etc.
- Usually created by stressing plastics while they are still partially melted, creating a preferred direction of vibration for the molecules.



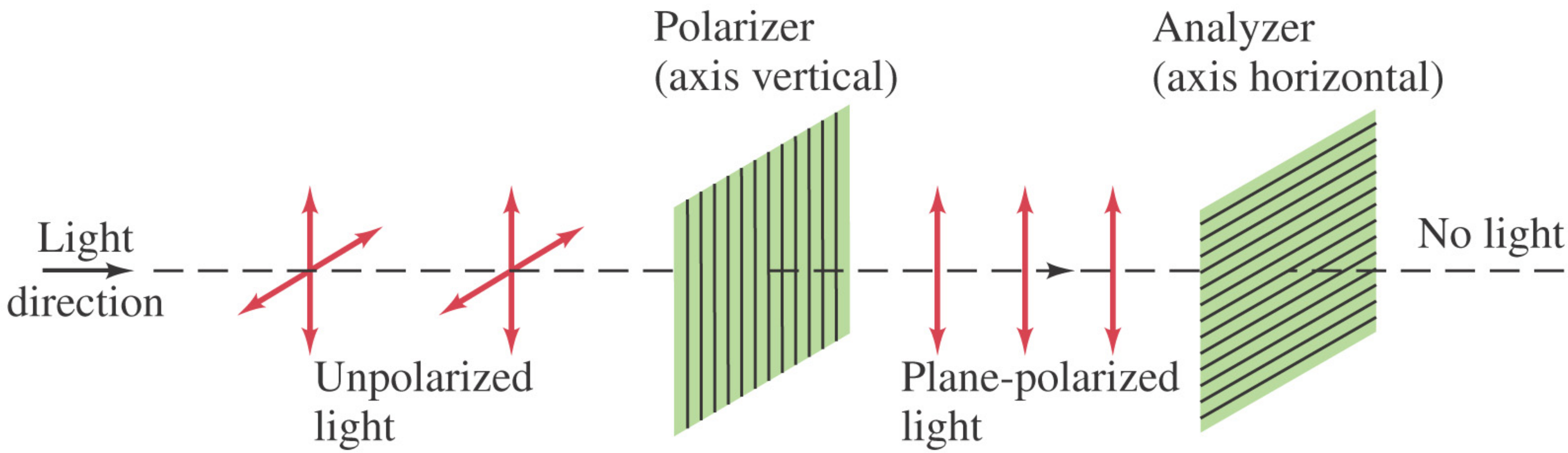
Transmitted



Blocked

Crossed Polarizers

If initially unpolarized light passes through crossed polarizers, no light will get through the second one.

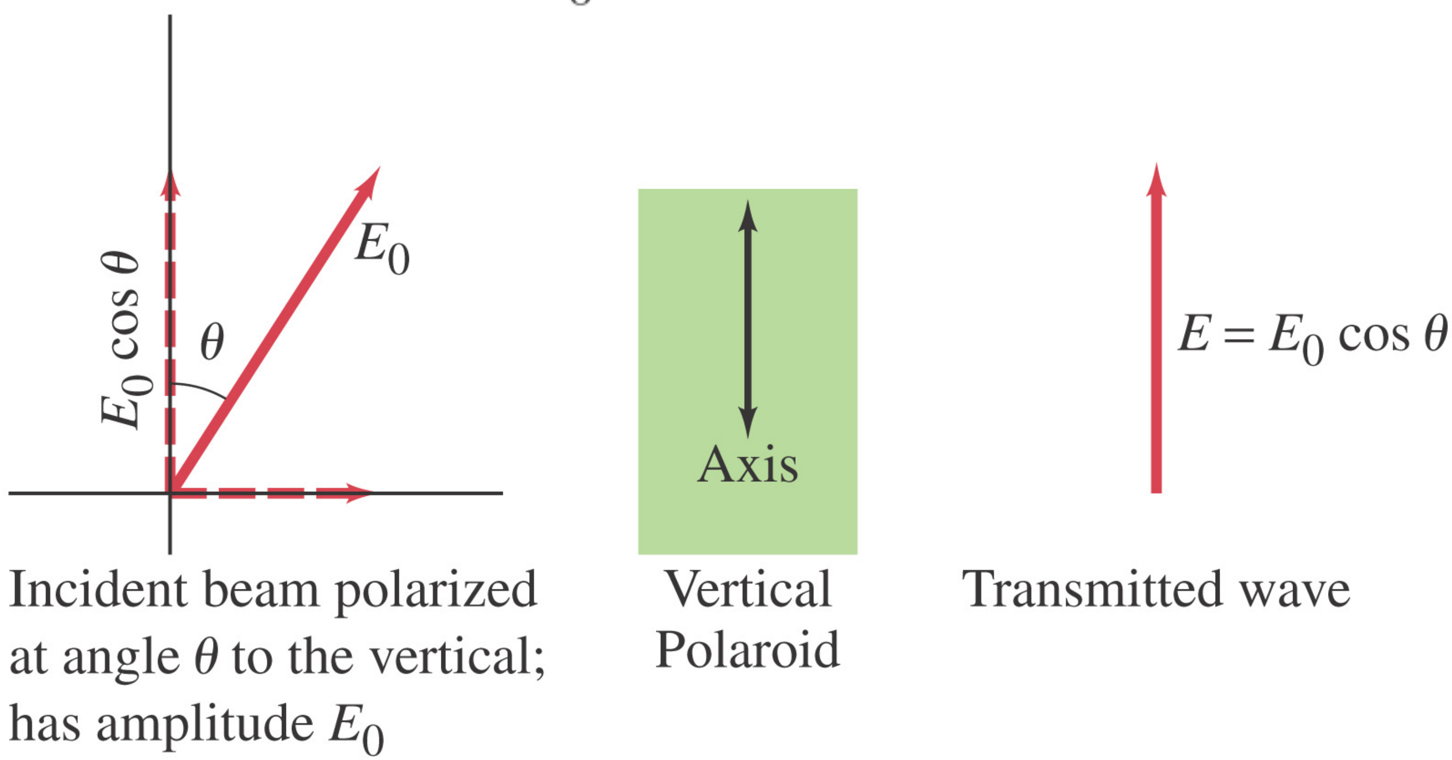


This can be very useful, as certain special materials can rotate the plane of polarization.

Polarization

When light passes through a polarizer, only the component parallel to the polarization axis is transmitted. If the incoming light is plane-polarized, the outgoing intensity is:

$$I = I_0 \cos^2 \theta$$



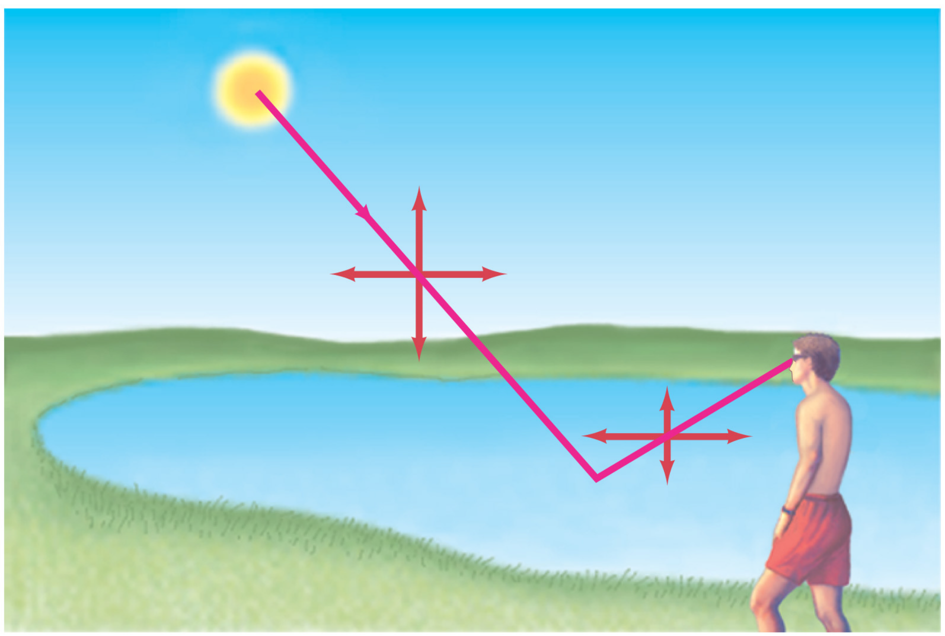
You are looking through a single polarizer at an unpolarized light.

What angle do you need to rotate a second polarizer (relative to the first) in order to block half of the remaining light?

A. 0 degrees
B. 30 degrees
C. 45 degrees
D. 90 degrees

Polarization upon Reflection

- Light is also polarized after reflecting from a nonmetallic surface.
- At a special angle, called the polarizing angle or Brewster's angle, the polarization is 100%.
- Reflected Light is Horizontally Polarized
- Incident waves that are vertically polarized get absorbed and so are not reflected



$$\tan \theta_p = \frac{n_2}{n_1} \quad (24\text{-}6a)$$

For light in air, reflecting off water, Brewster's angle is 53 degrees

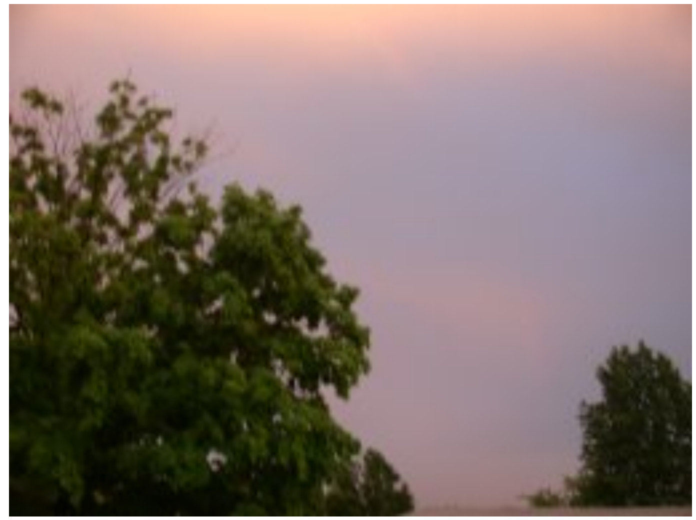
Use of Polarizer to remove Reflections and Glare in Photography (and Everyday life)

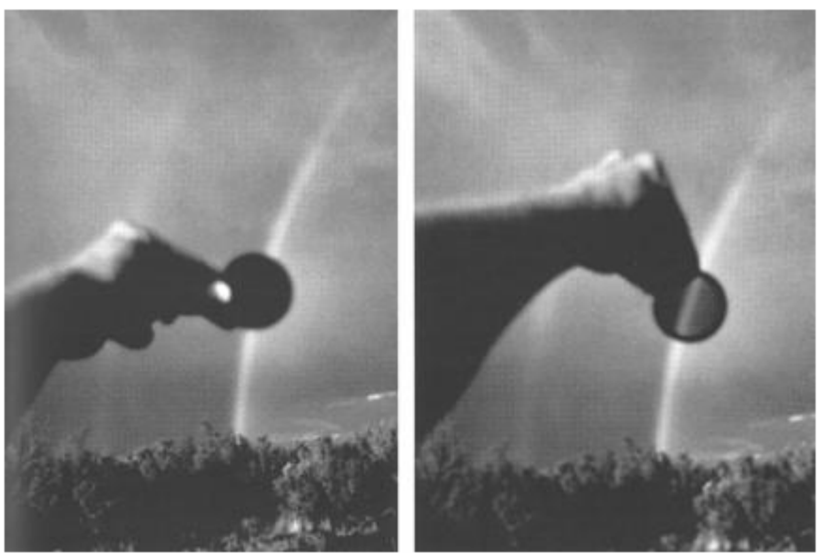
Without polarizer:
(or adjusted horizontally)

Reflections in surface of water

With Polarizer:
(adjusted vertically)
Reflections suppressed.
The leaves at the bottom of the pond are now visible

Polarization of rainbows

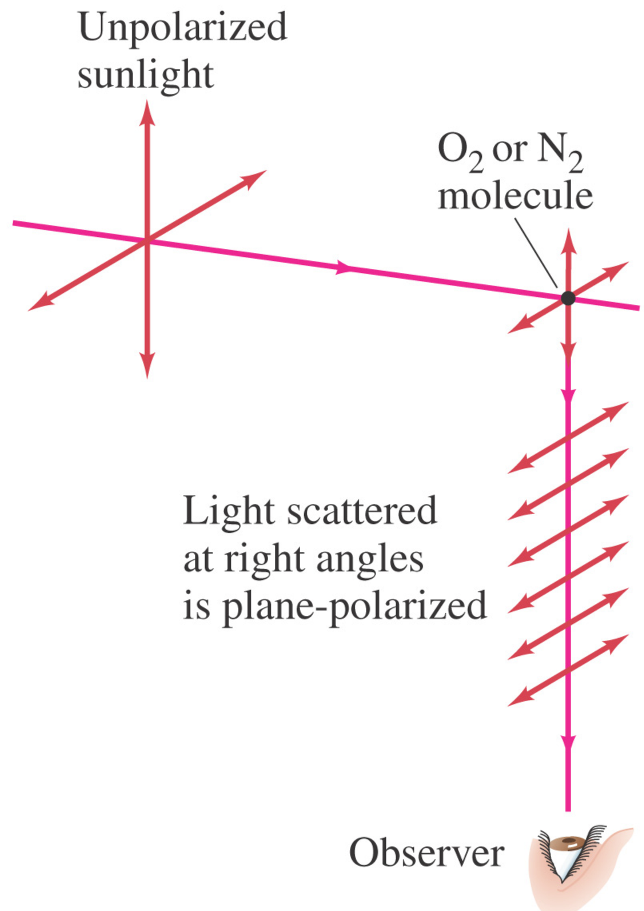




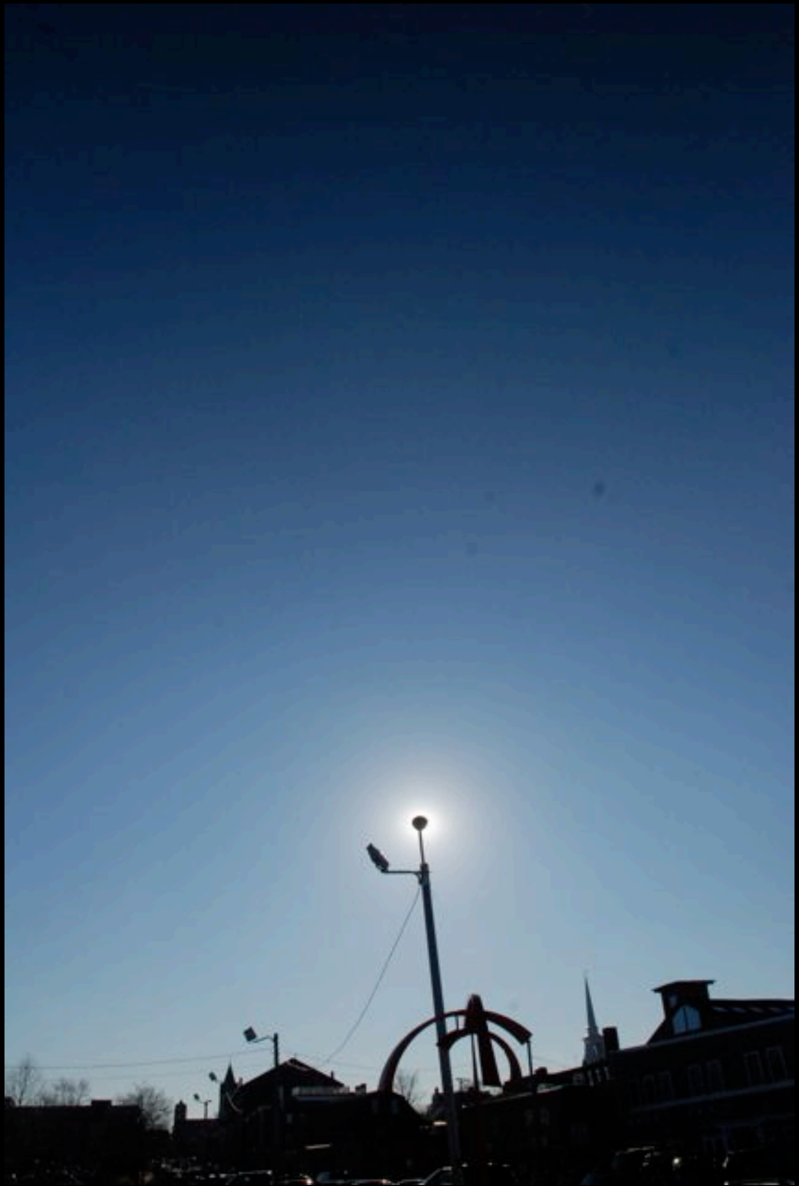
- **Rainbows involve reflection and refraction both inside and at the boundaries of the raindrops.**
- **The rainbow is 100% linearly polarized**
- **The polarization axis is radial to the bow**
- **Just rotate your head while wearing polarized sunglasses**

Why is the Sky Blue? and is it also Polarized?

- The clear sky is blue due to Scattering by air molecules.
- Scattering is a directional process.
- Examine the sky with polarized sunglasses!
- At 90 from the Sun, the polarization is upto 80%. -so it will look dark!



The blue sky is polarized



- Polarization of the sky reaches its maximum strength at 90 degrees from the sun
- Go see if you can observe the overall pattern for yourself
- Its very hard to photograph!

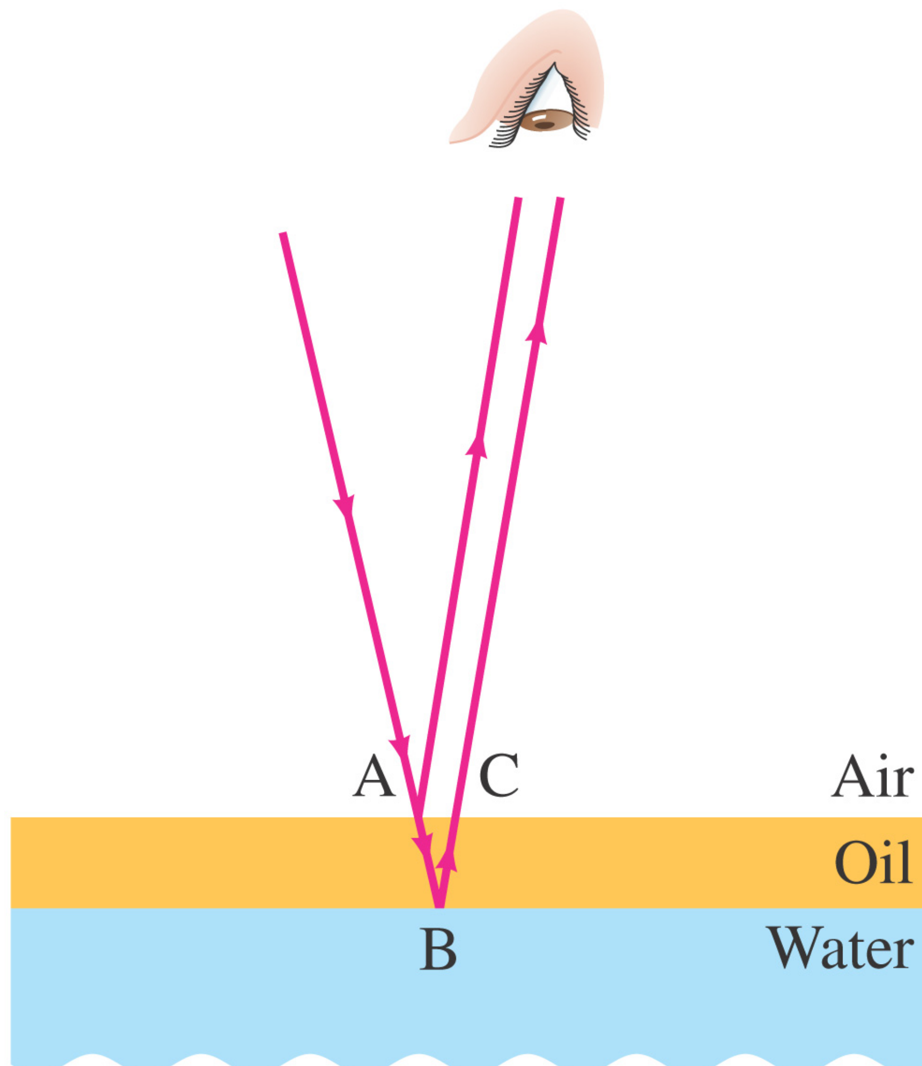
Interference by Thin Films: from Soap Bubbles to Anti-Reflection Coatings

- If there is a very thin film of material – a few wavelengths thick – light will reflect from both the bottom and the top of the layer, causing interference.
- This can be seen in soap bubbles and oil slicks, for example.
- The color seen depends on the thickness of the Film, and its refractive index
- Thin Coatings on Camera Lenses (etc) are used to prevent reflections
- But only for limited range of wavelength and incidence angle

Go play with some bubbles….. Can you notice something about their color as each bubble "ages" ?

Anti-Reflective Coatings

- When a light wave is reflected from a surface (A), it changes in phase by a 1/2 cycle.
- Usually some of the light is transmitted and some reflected
- A thin layer (film) of a material with intermediate refractive index is deposited on the surface
- Some light is reflected at this second boundary B.
- If the thickness of the film is just right, the reflected wave from B will arrive at the surface 1/2 cycle out of phase with the original reflection.
- The waves cancel out!
- A certain AR layer only works for a narrow wavelength range, (because it depends on the index)



Summary of Chapter 24

- In the double-slit experiment, constructive interference occurs when

$$\sin\theta = m\frac{\lambda}{d}$$

- and destructive interference when

$$\sin\theta = \left(m + \tfrac{1}{2}\right)\frac{\lambda}{d}$$

- Two sources of light are coherent if they have the same frequency and maintain the same phase relationship

Summary of Chapter 24

- Visible spectrum of light ranges from 400 nm to 750 nm (approximately)

- Index of refraction varies with wavelength, leading to dispersion

- Diffraction grating has many small slits or lines, and the same condition for constructive interference as for a pair of slits.

- Light bends around obstacles and openings in its path, yielding diffraction patterns

- Light passing through a narrow slit will produce a central bright maximum of width

$$\sin\theta = \frac{\lambda}{D}$$

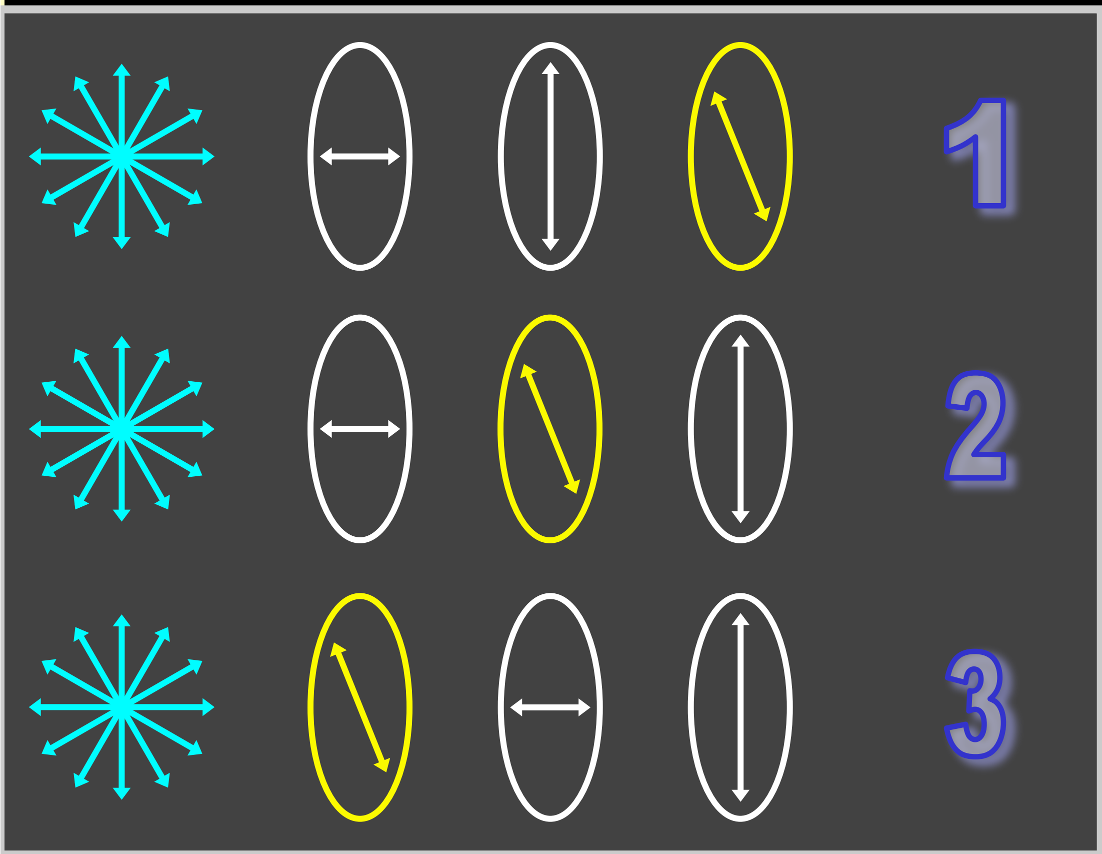
- Interference can occur between reflections from the front and back surfaces of a thin film, leading to iridescence and Anti-reflection coatings

- Light whose electric fields are all in the same plane is called plane polarized

ConcepTest 24.8 Polarization

If unpolarized light is incident from the left, in which case will some light get through?

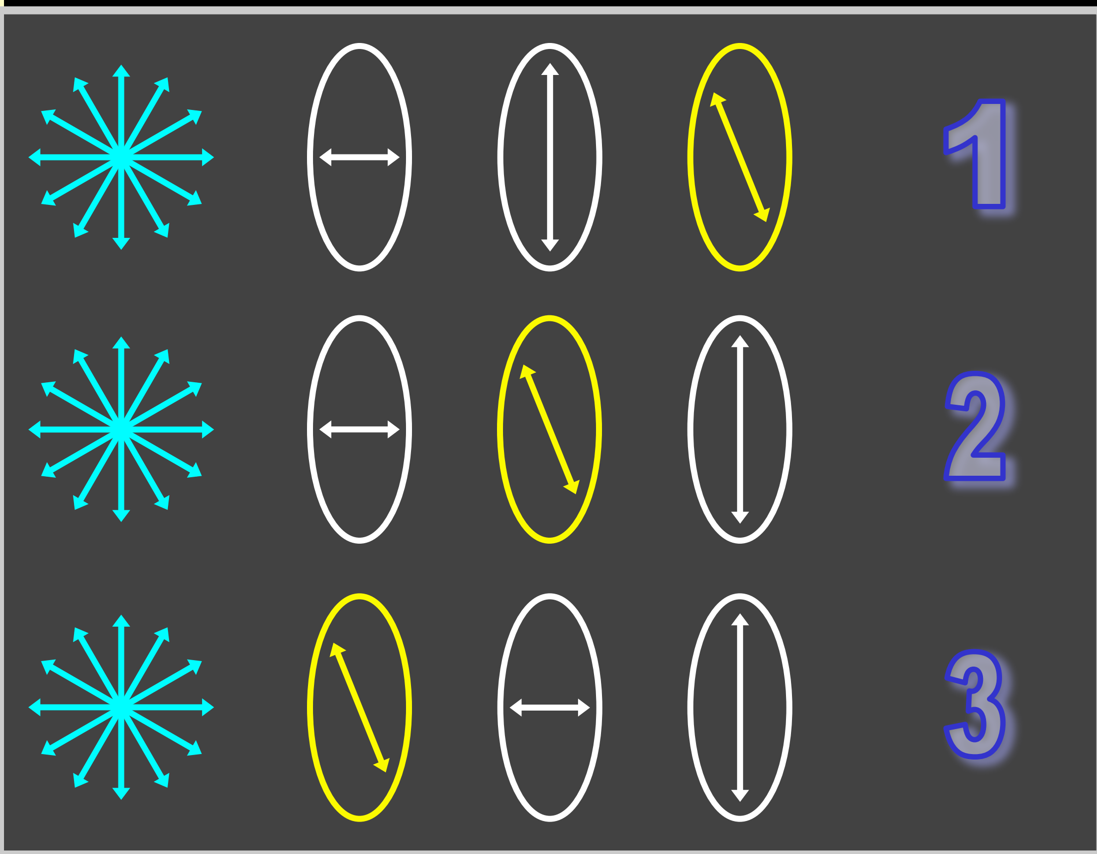
1) only case 1
2) only case 2
3) only case 3
4) cases 1 and 3
5) all three cases



ConcepTest 24.8 Polarization

If unpolarized light is incident from the left, in which case will some light get through?

1) only case 1
2) only case 2
3) only case 3
4) cases 1 and 3
5) all three cases

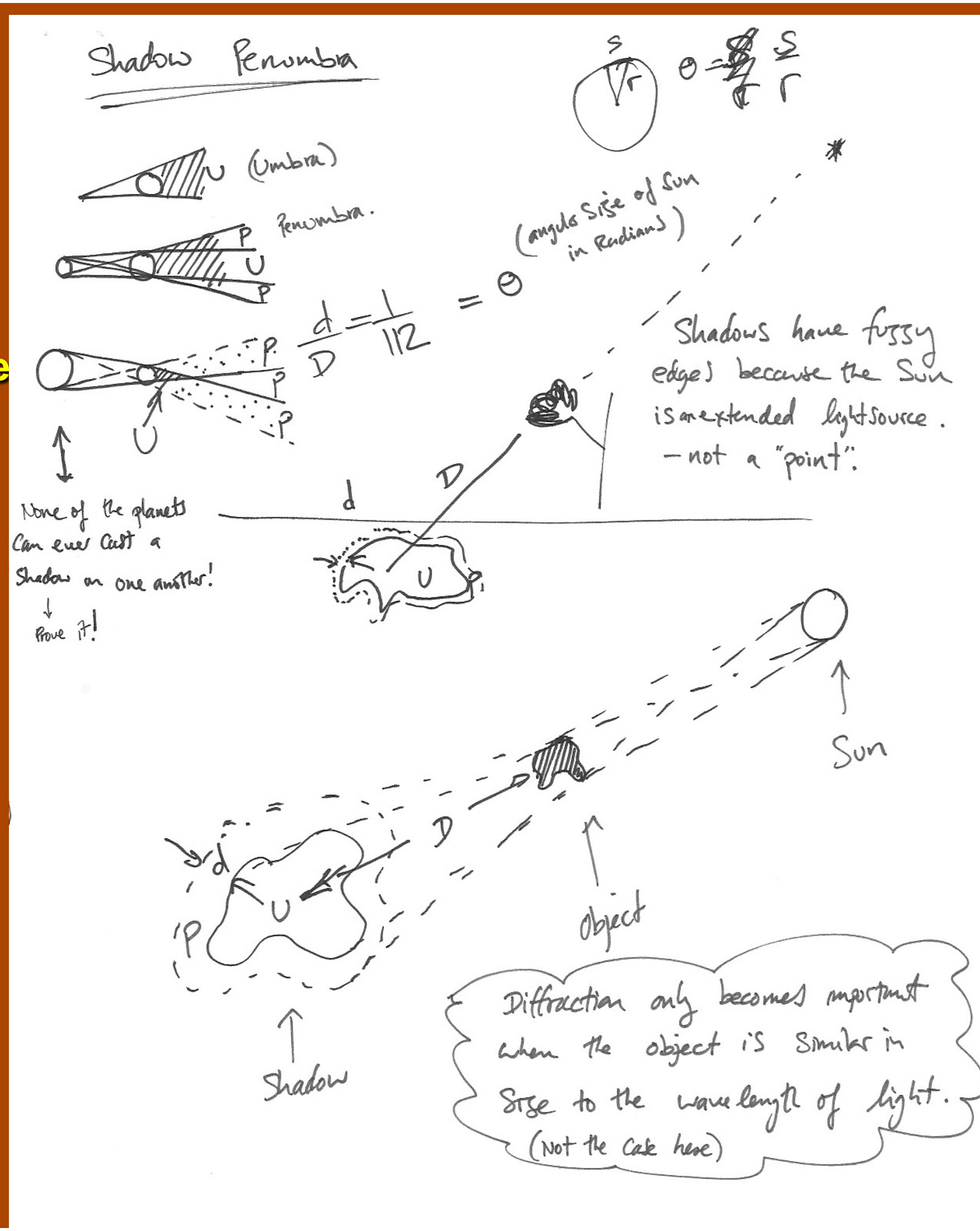


In cases 1 and 3, light is blocked by the adjacent horizontal and vertical polarizers. However, in case 2, the **intermediate 45° polarizer allows some light to get through** the last vertical polarizer.

Shadows

Umbra (dark area)

Penumbra
(partially shaded fuzzy edge



Why is it that your shadow cast by the sun, has a fuzzy edge?

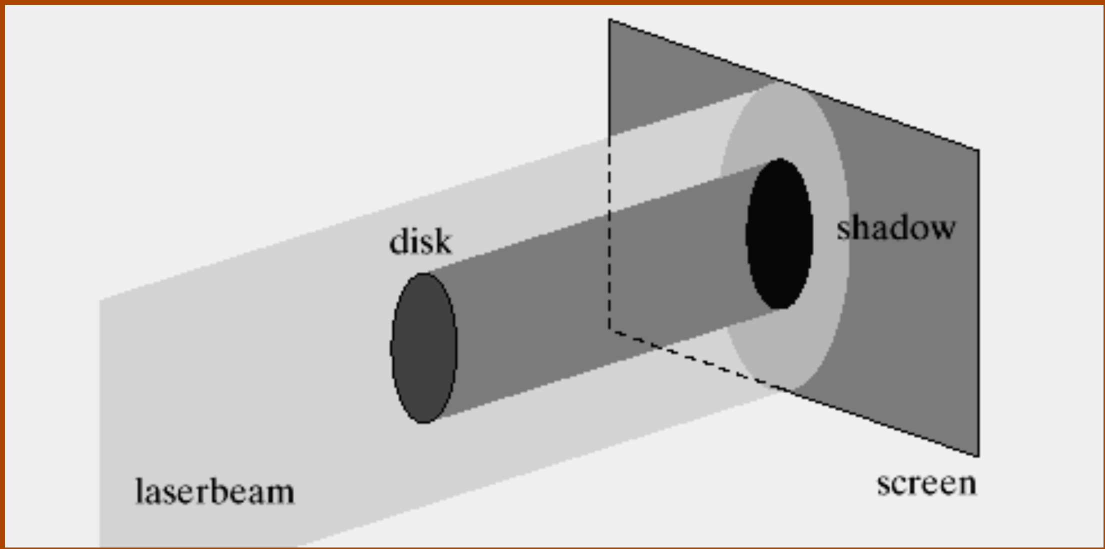
A. Diffraction

B. The Sun's disk is not a point

ConcepTest 24.6 Diffraction Disk

Imagine holding a circular disk in a beam of monochromatic light. If diffraction occurs at the edge of the disk, the center of the shadow is

1) darker than the rest of the shadow
2) a bright spot
3) bright or dark, depends on the wavelength
4) bright or dark, depends on the distance to the screen

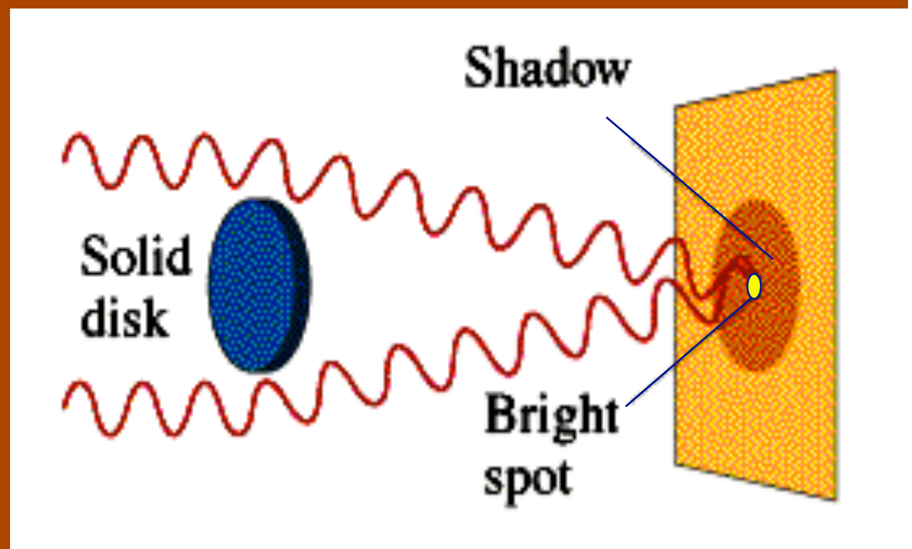


ConcepTest 24.6 Diffraction Disk

Imagine holding a circular disk in a beam of monochromatic light. If diffraction occurs at the edge of the disk, the center of the shadow is

1) darker than the rest of the shadow
2) a bright spot
3) bright or dark, depends on the wavelength
4) bright or dark, depends on the distance to the screen

By symmetry, all of the waves coming from the edge of the disk ***interfere constructively*** in the middle because they are all **in phase** and they all travel the **same distance** to the screen.



Follow-up: What if the disk is oval and not circular?