Interference and Diffraction

Ken Intriligator's week 9+10 lectures, Dec.3-12, 2014

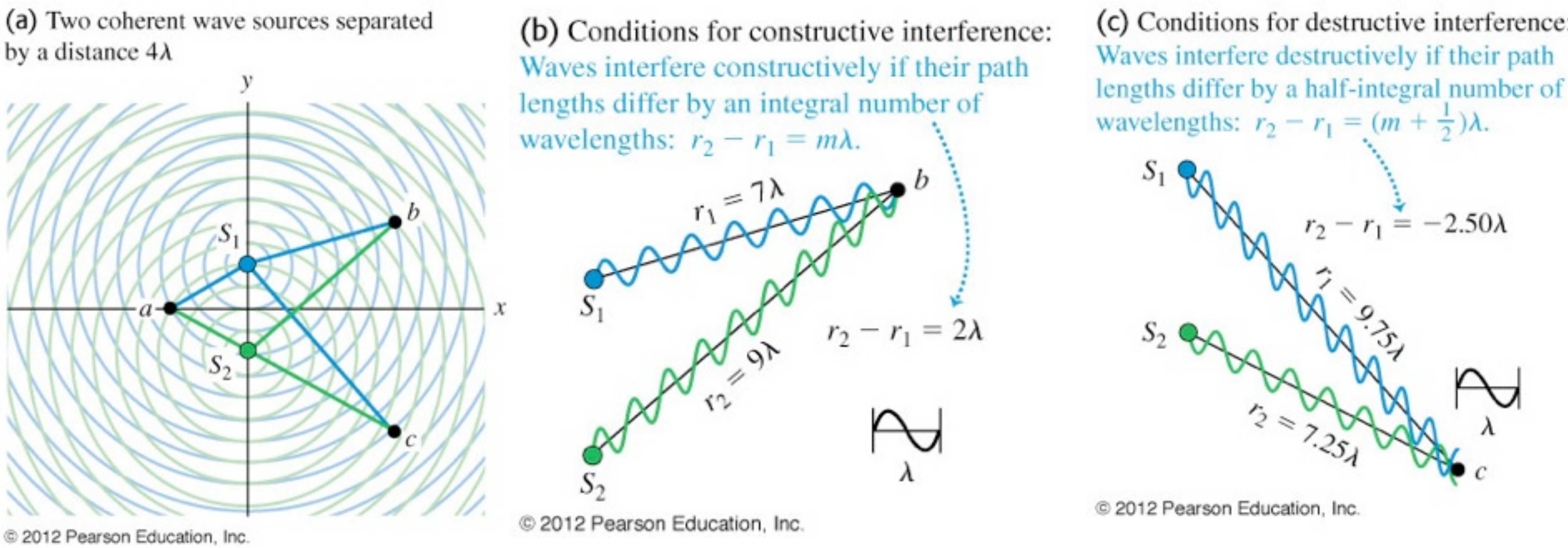
Same as with sound

Superposition with light: Maxwell's equations are linear equations for E and B, so we can simply add the E and B of different sources to get the total E and B. Do this for light sources. Intensity is proportional to E-squared. Depending on the location, sources can either add or subtract: i.e. constructive or destructive interference.

Constructive: E's peaks from two sources aligned.

Destructive: E's peaks from two sources anti-align.

Example:

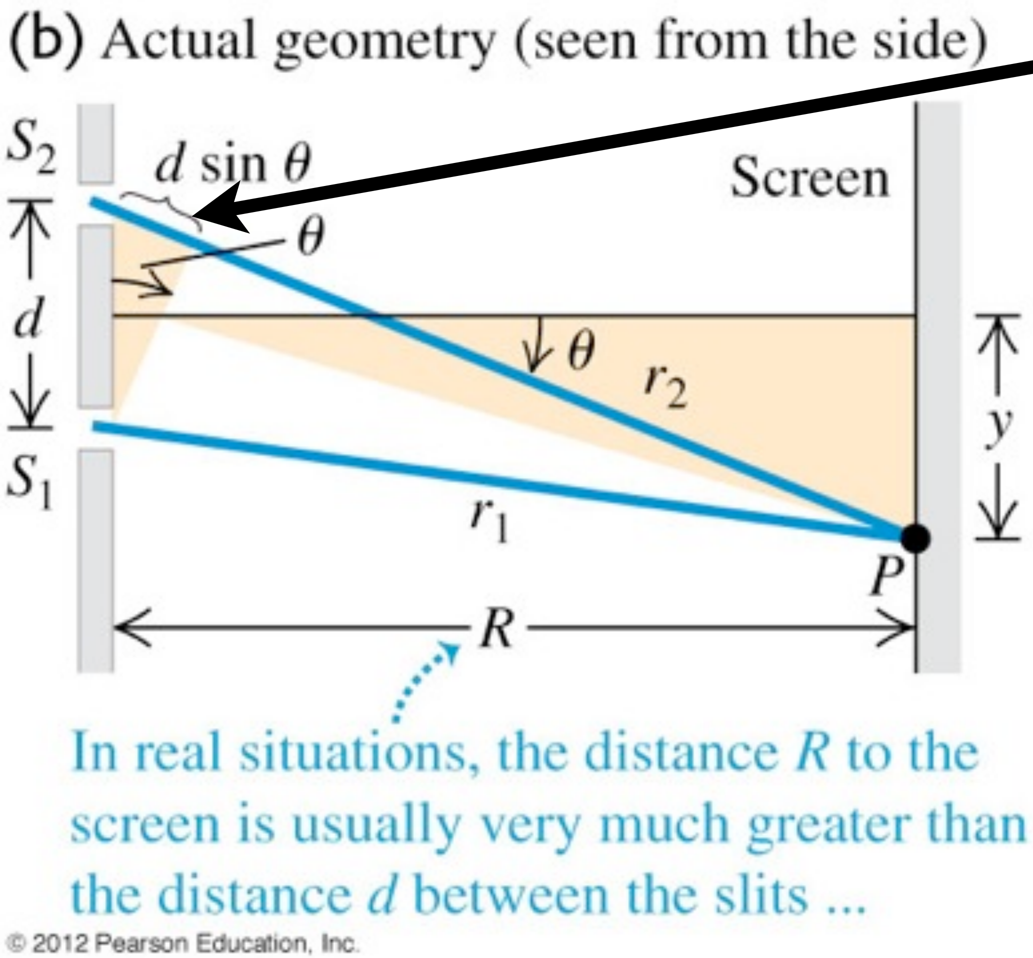


Constructive: $\Delta L = m\lambda$

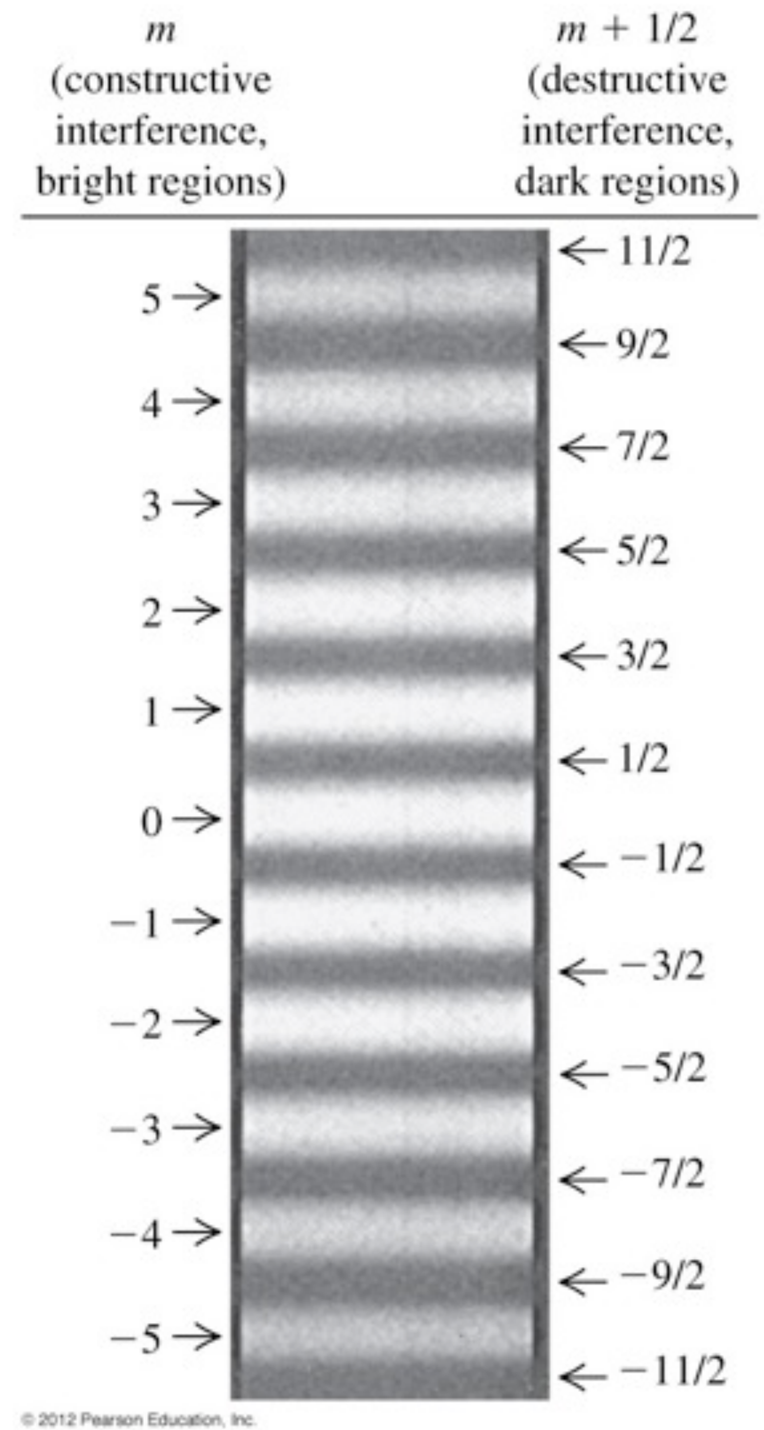
Destructive: $\Delta L = (m + \frac{1}{2})\lambda$

$m = 0, \pm 1, \pm 2, \ldots$

Two source geometry



$$\Delta L \approx d \sin \theta$$



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

Dark: $d \sin \theta = (m + \frac{1}{2})\lambda$

2 sources intensity

(coherent)

$$I \sim \langle E_{tot}^2 \rangle$$ (Time averaged)

Recall trig identity:

$$\cos a + \cos b = 2\cos(\frac{a+b}{2})\cos(\frac{a-b}{2})$$

source 1 wave   source 2 wave

$$E_{tot}/E_0 = \cos(kL - \omega t) + \cos(kL' - \omega t) = 2\cos(\frac{k\Delta L}{2})\cos(kL_{ave} - \omega t)$$

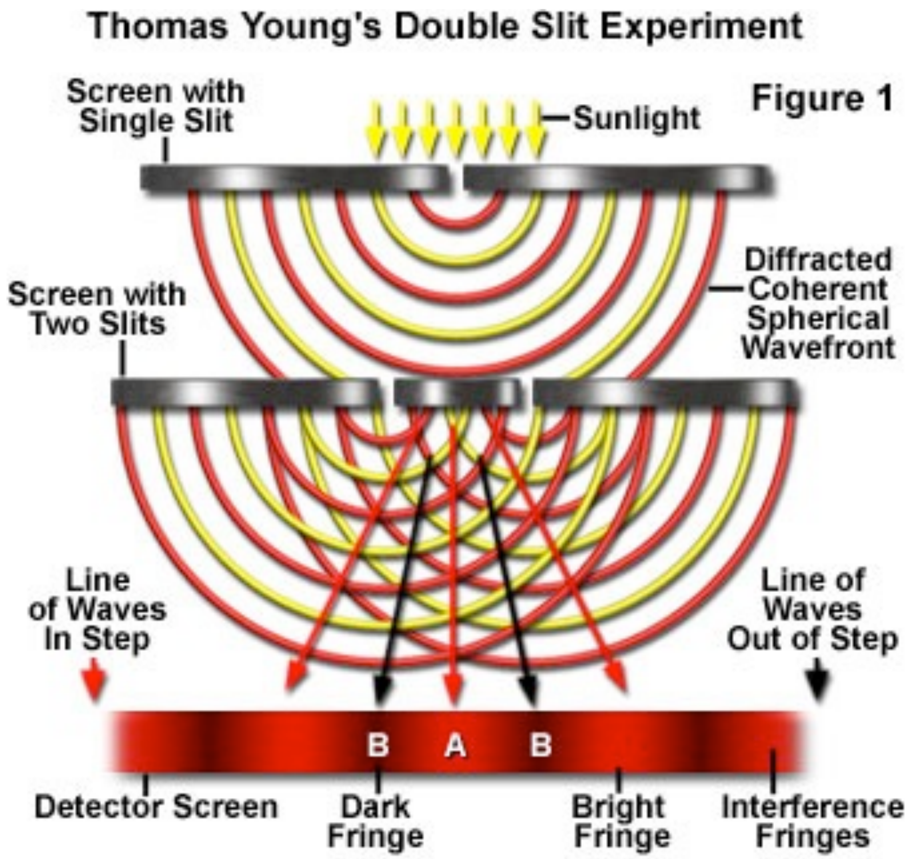
interference amplitude, square it for intensity.

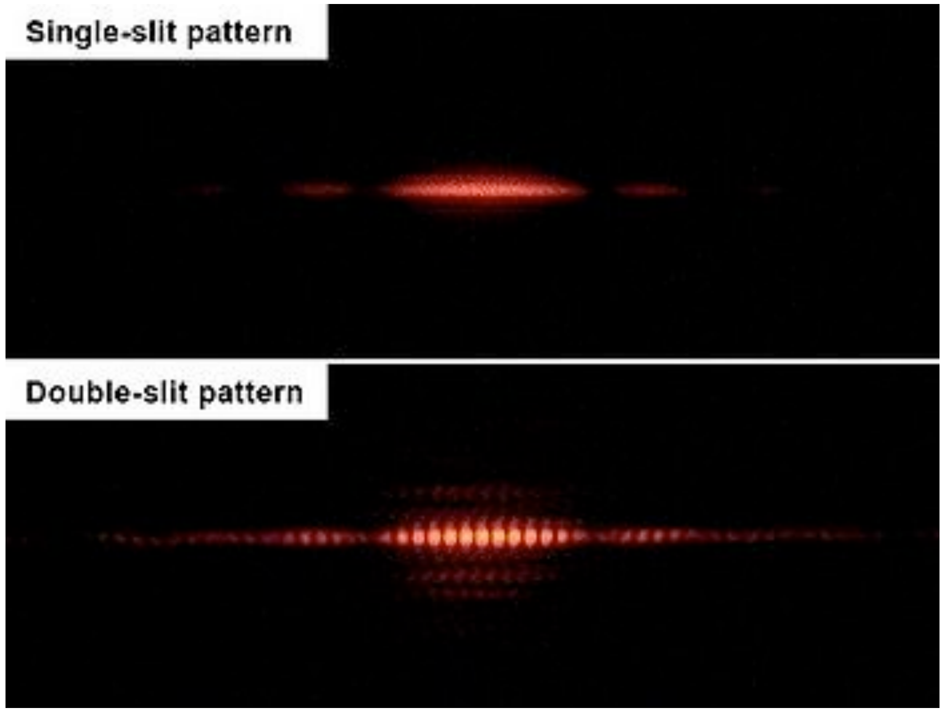
$$I_2 = 4I_1\cos^2(\frac{1}{2}k\Delta L) = 4I_1\cos^2(\pi\Delta L/\lambda)$$

Constructive intensity peaks from 2 sources is 4 times that of a single source. Averaging over space gives

$\overline{I_2} = 2I_1$ since $\overline{\cos^2\theta} = \frac{1}{2}$ Makes sense.

Young expt. (1801)





$$I_2 = 4I_1\cos^2(\frac{1}{2}k\Delta L) = 4I_1\cos^2(\pi\Delta L/\lambda)$$

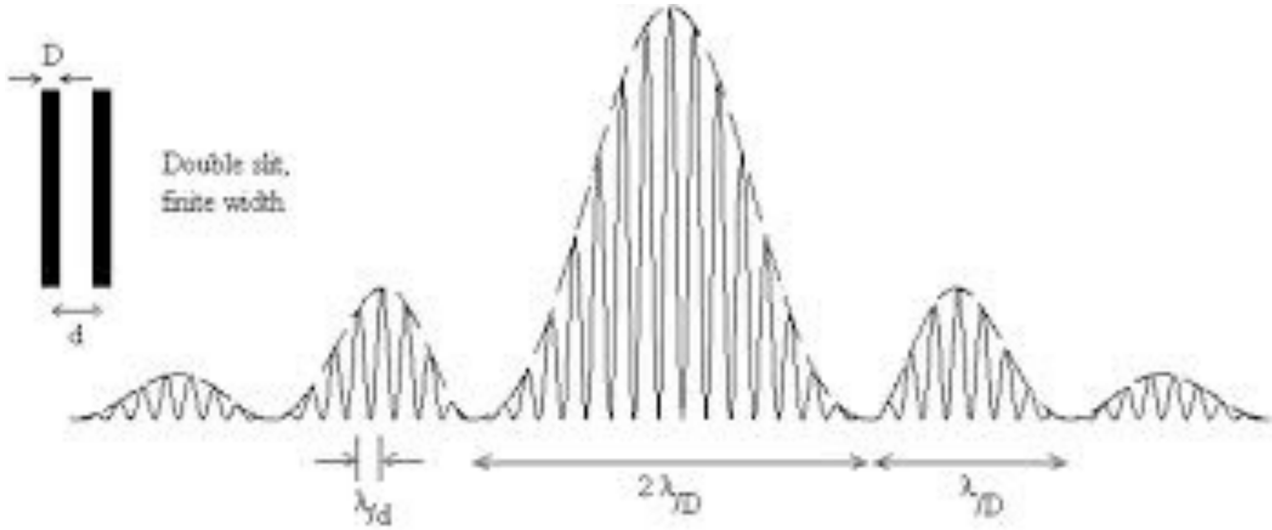
$$\Delta L = d\sin\theta$$

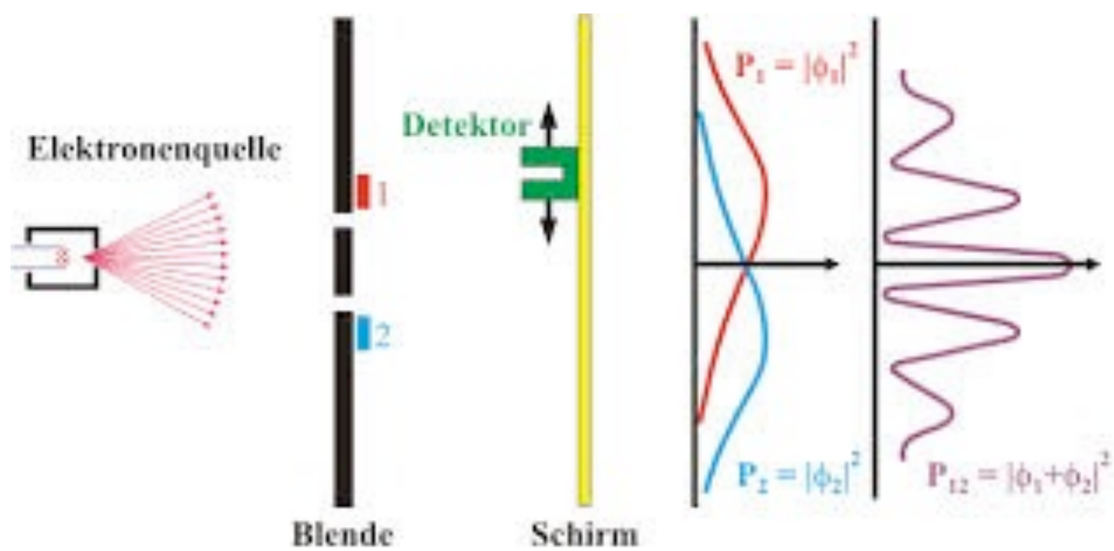
$$I(\theta) \propto \cos^2(\pi d\sin\theta/\lambda)$$

Shows light is a wave!

Actually small particles (e.g. electrons) behave same way (QM)!

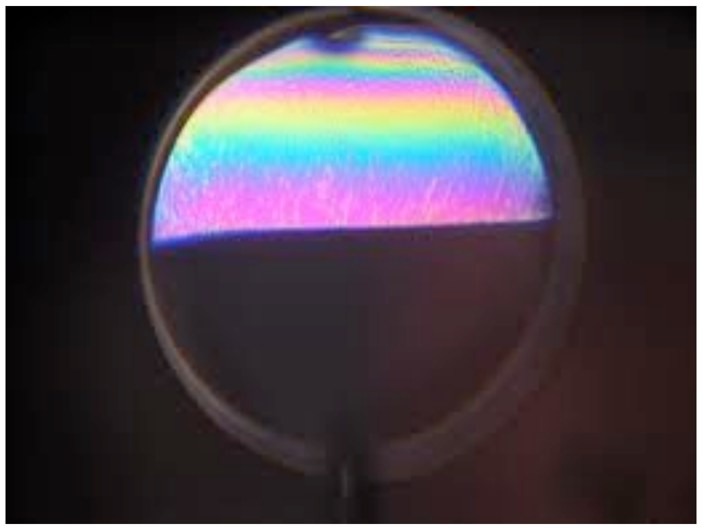
Double slit intensity

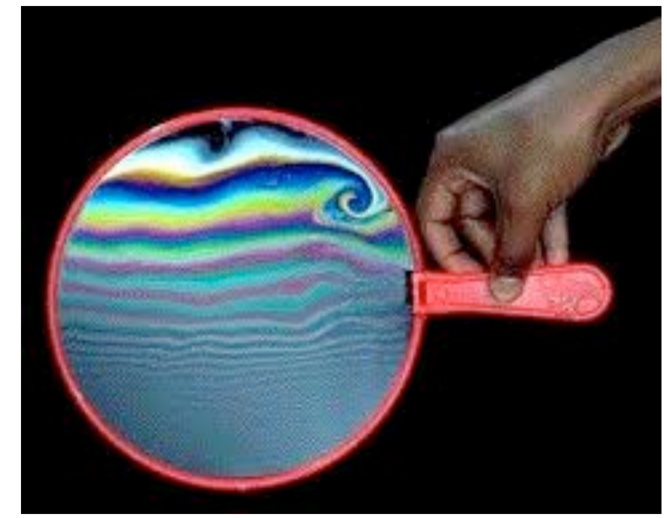


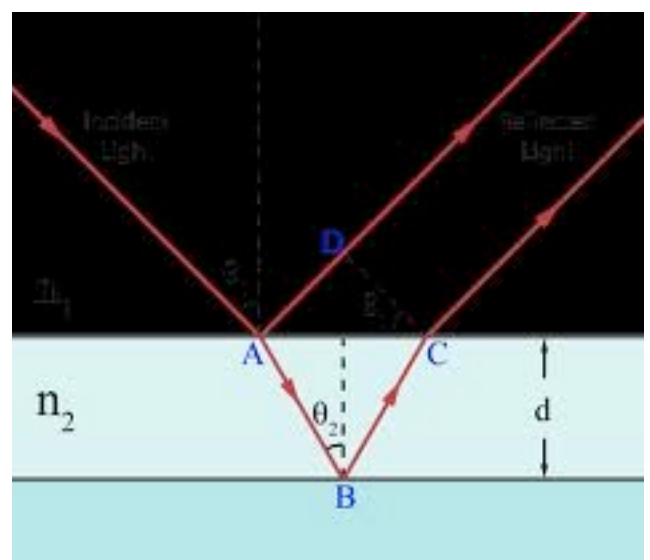


Actually small particles (e.g. electrons) behave same way (QM)!

thin films

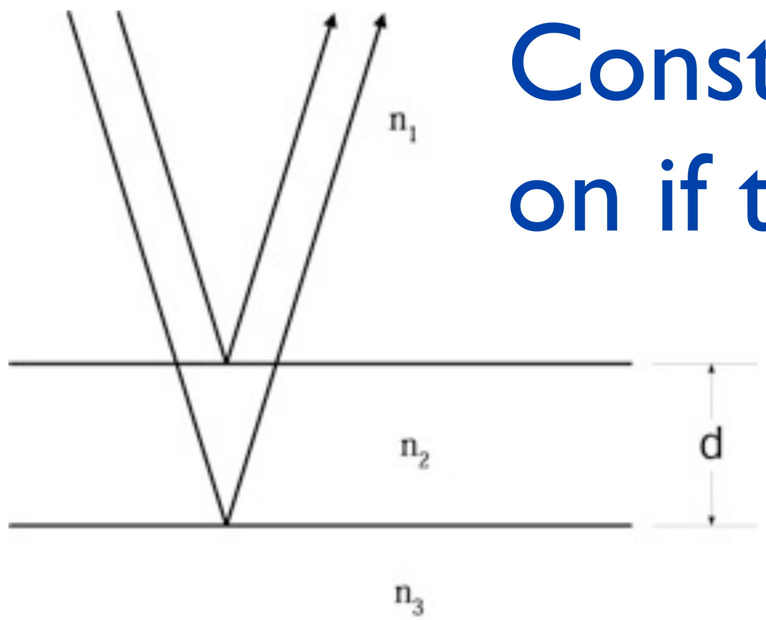






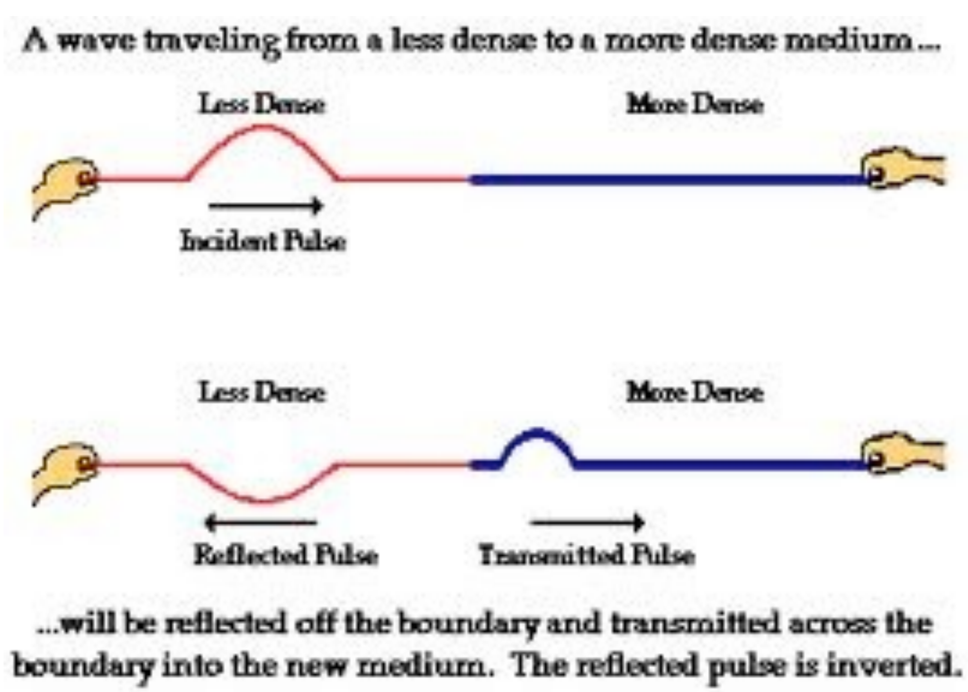
even some critters!

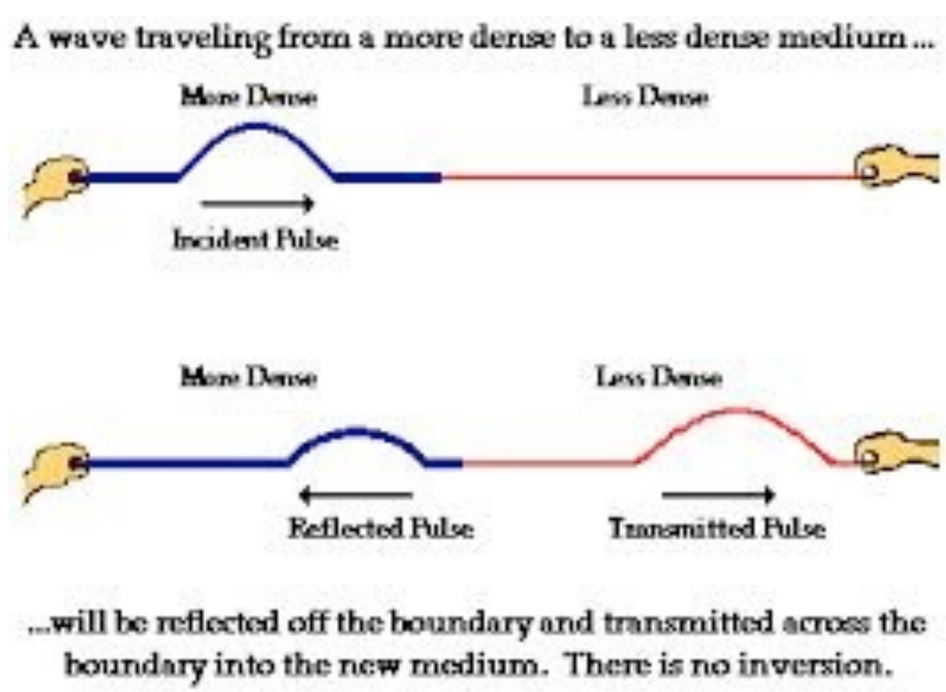
thin film interference



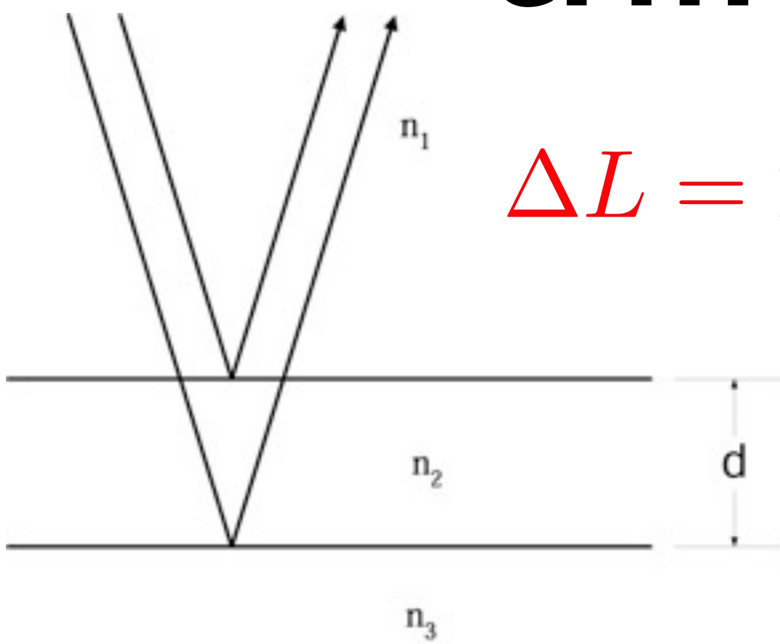
Constructive / destructive depending on if two waves are in / out of phase.

RPS: Reflected wave gets upside-down phase shifted if it hits bigger index n.





thin films, cont.



$\Delta L = 2d$ Length difference of two rays.

$\lambda_{n_2} = \lambda_{vac}/n_2$ in material 2

m= integer.

$$\Delta L = m\lambda_{n_2}$$

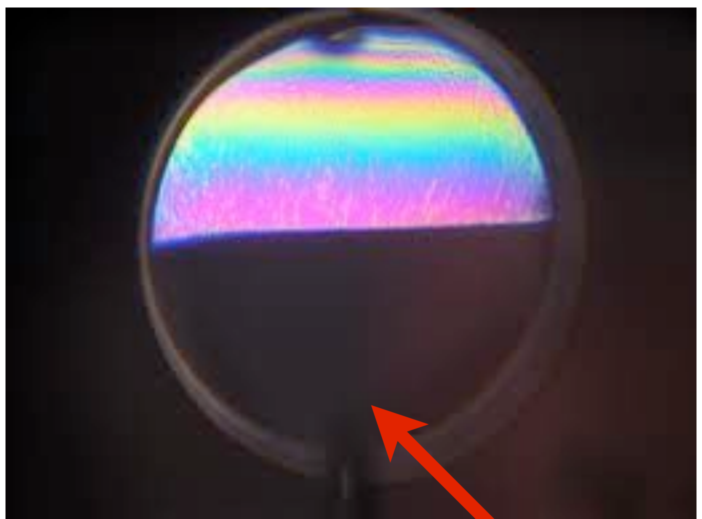
Constructive interference if 0 or 2 RPS's,
or destructive interference if 1 RPS.

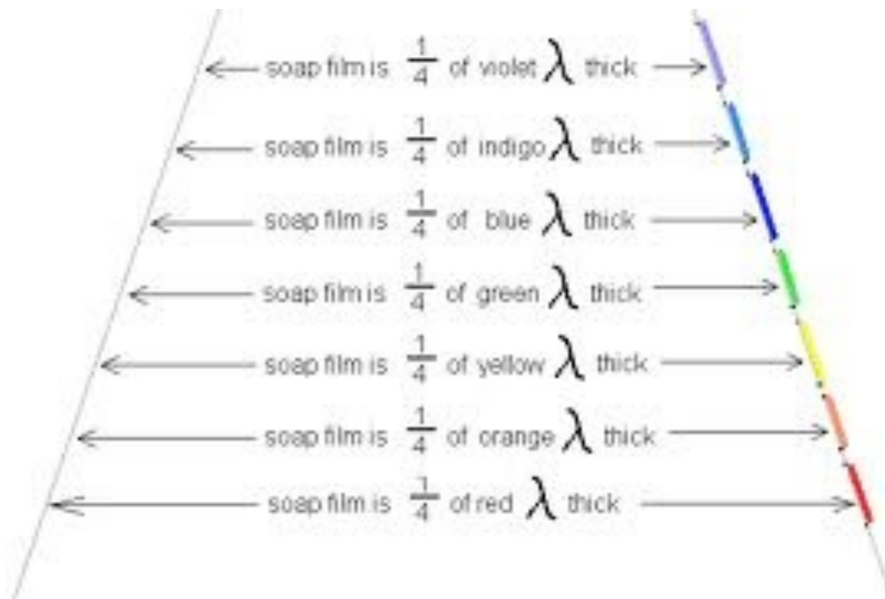
$$\Delta L = (m + \frac{1}{2})\lambda_{n_2}$$

Destructive interference if 0 or 2 RPS's,
or constructive interference if 1 RPS.

e.g. soap bubble

RPS from outer surface, not from inner surface.

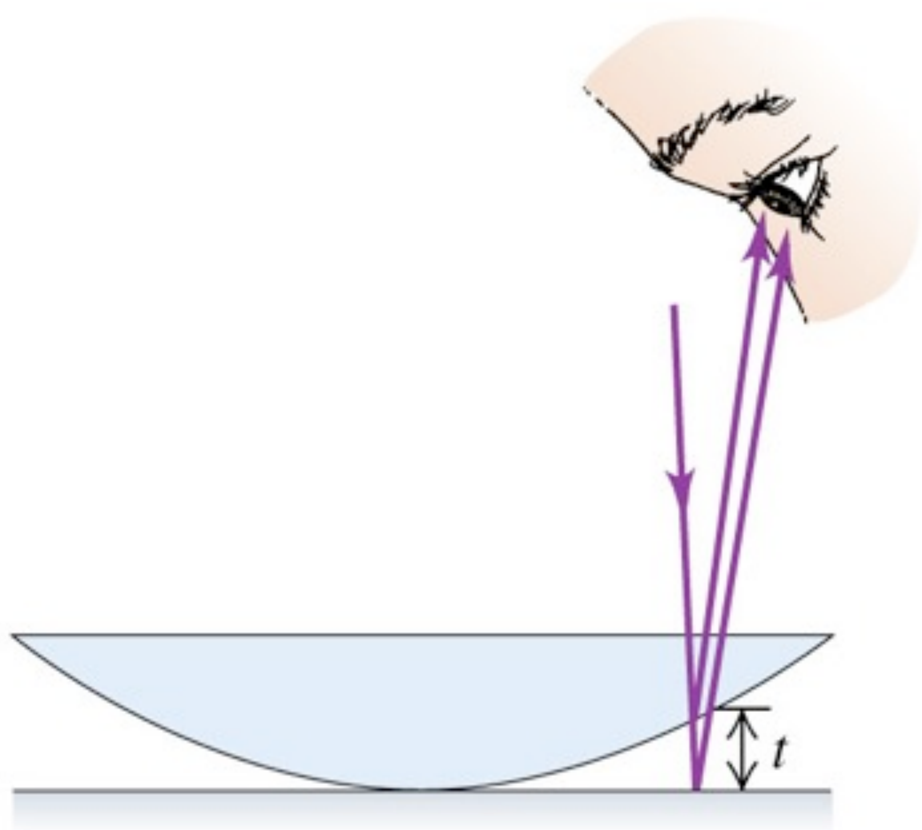




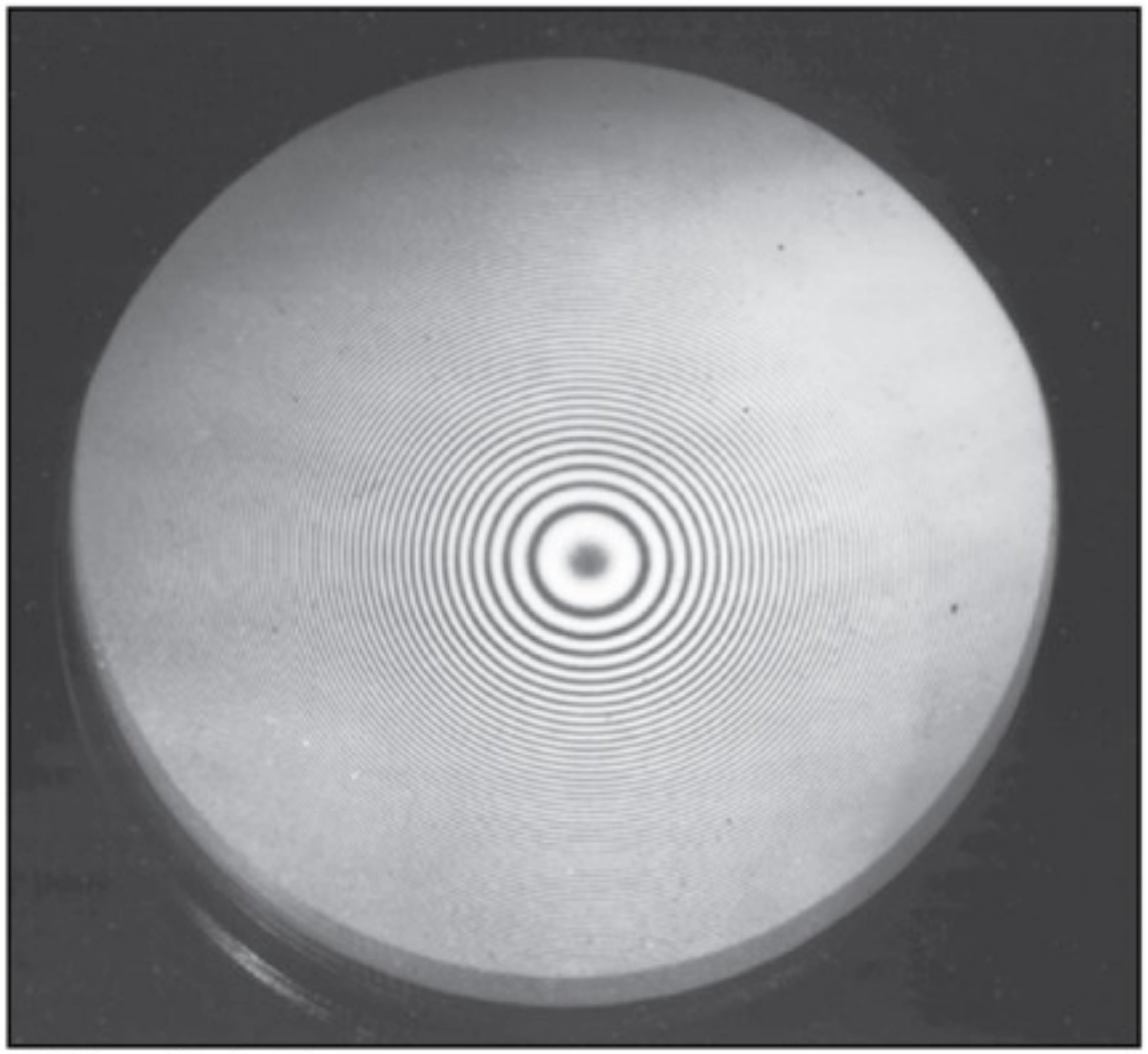
(Constructive interference outside of visible range here.)

Newton's rings

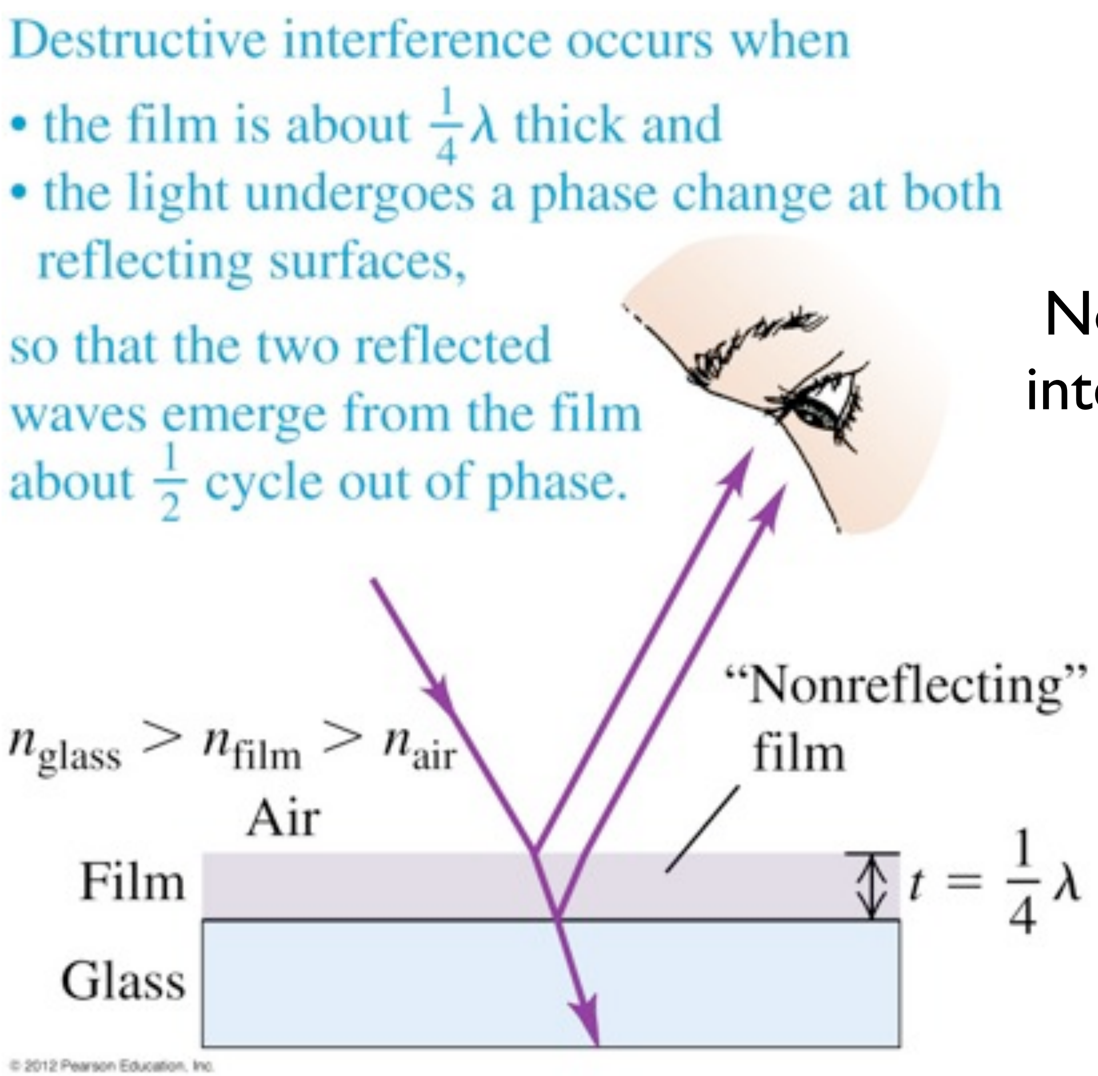
(a) A convex lens in contact with a glass plane



(b) Newton's rings: circular interference fringes

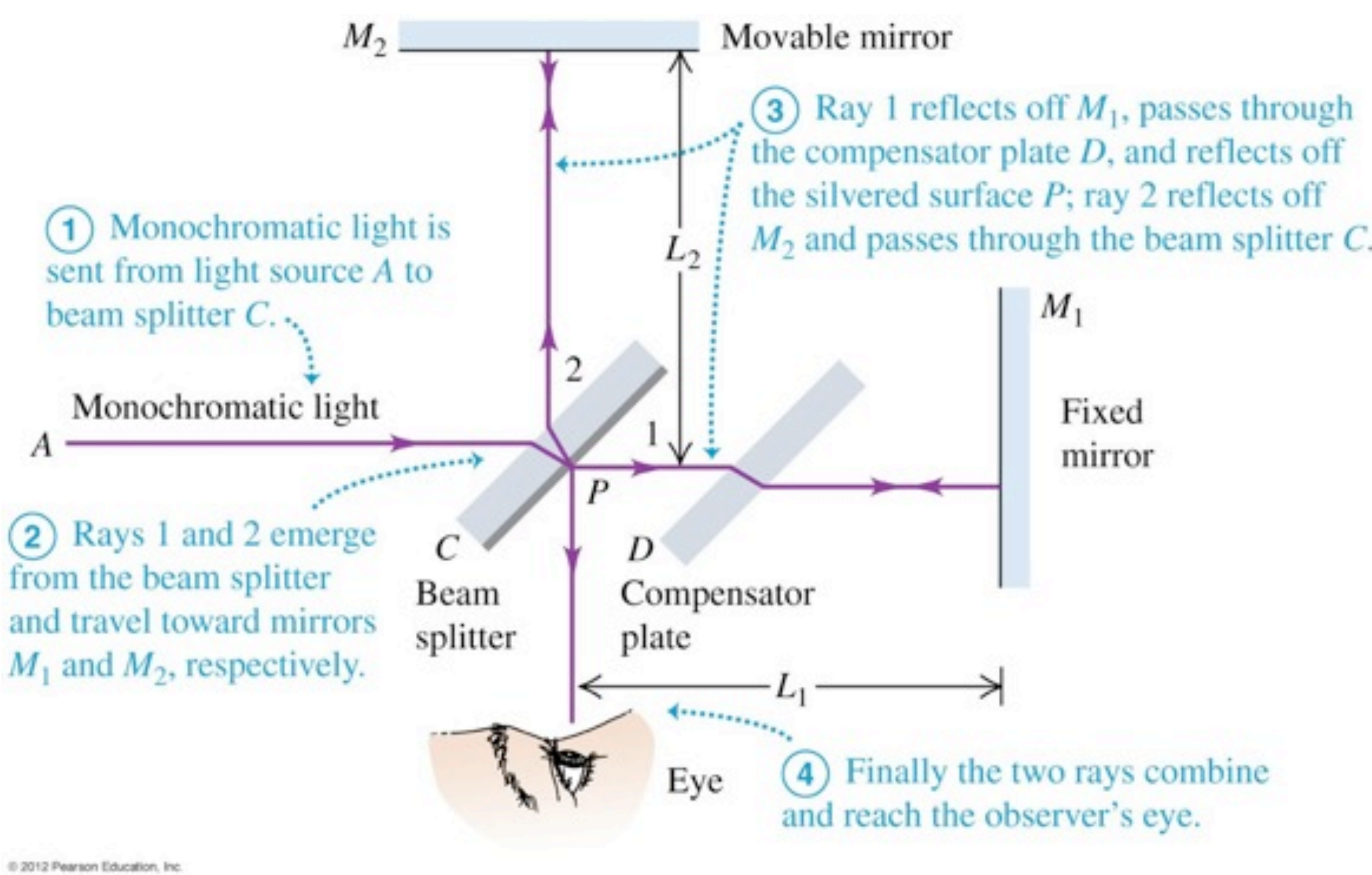


nonreflective coatings

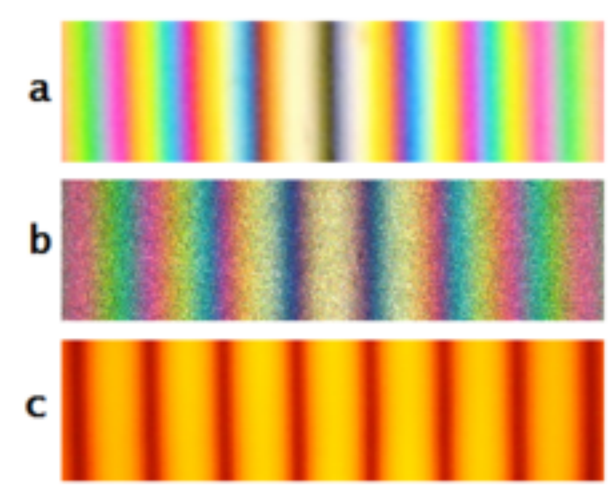


Note both reflections give a RPS, so destructive interference when the length difference is an odd number of half wavelengths.

Michelson interferometer



Two paths interfere, based on their length difference. If the lengths are changed, find interference fringes move. Can measure lengths, and wavelengths very accurately this way.



E.g. LIGO

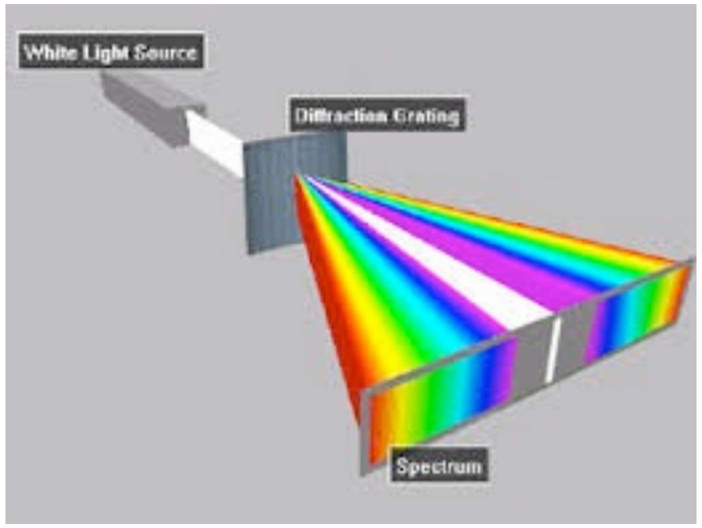
Huge laser interferometer, looking for tiny length changes from gravitational waves. Hope to get a new view of the sky, using gravitational wave detectors in addition to electromagnetic wave (light) telescope detectors. Fantastically difficult, because gravity is so much weaker than electromagnetism. Hope to see for example strong gravity effects, from sources like black holes and maybe some special events, like black hole collisions, and also in the early universe.

Michelson Morley Expt:

1887. Used Michelson's interferometer to try to see the effect of earth's motion through the "ether". "Ether" was the imagined stuff, filling all space, which allows light to propagate. Thought to be analogous to how sound waves require a medium, i.e. the air.

They did a careful experiment and found a negative result: no evident effect on the light from the earth's motion. Was explained by Einstein's 1905 theory of special relativity: there is no ether, and light's speed is unaffected by motion of the observer or source.

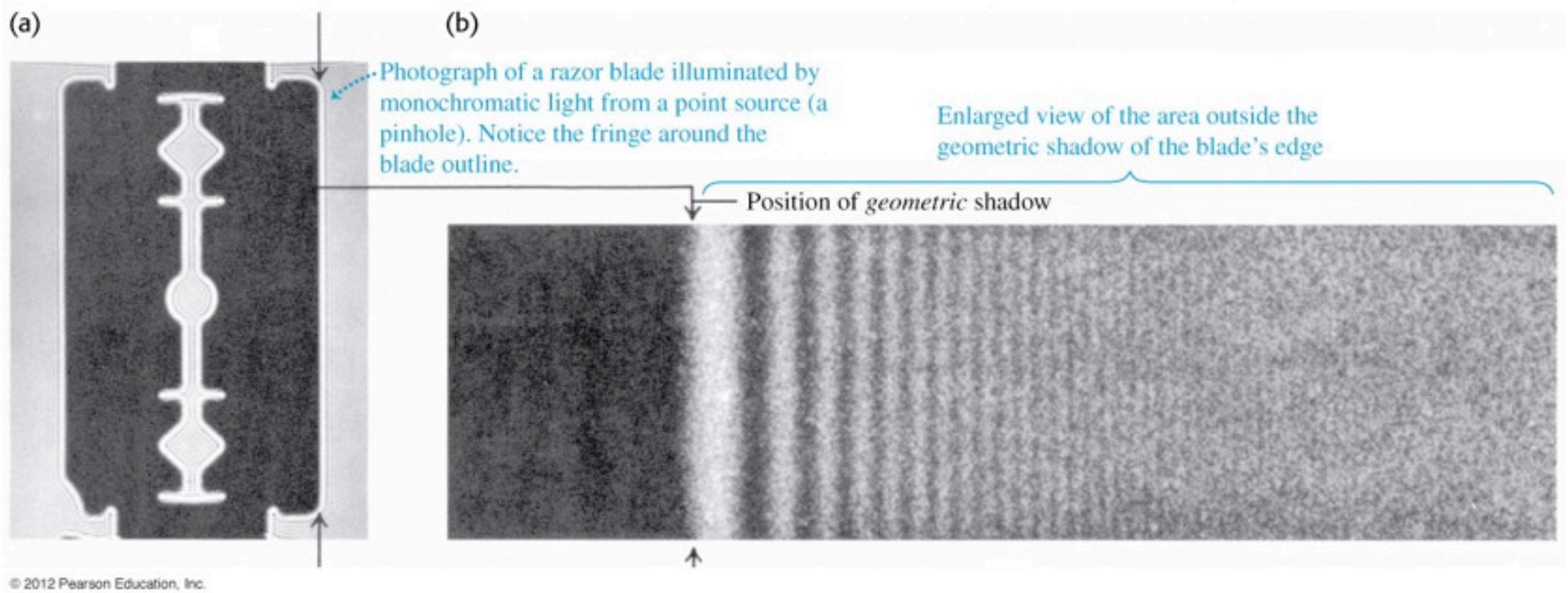
Diffraction*



* = various kinds of interference effects. For example why beams of light spread out. Colors on CDs. Diffraction gratings.

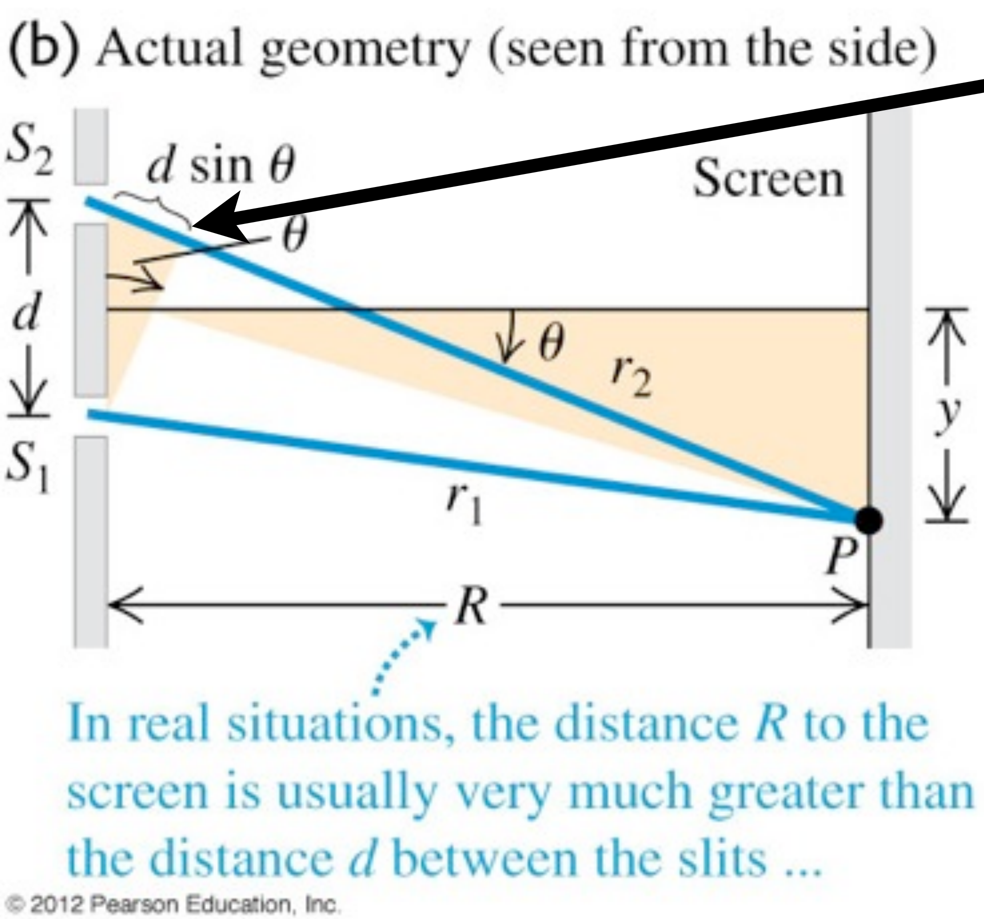
E.g. : Shadow edges

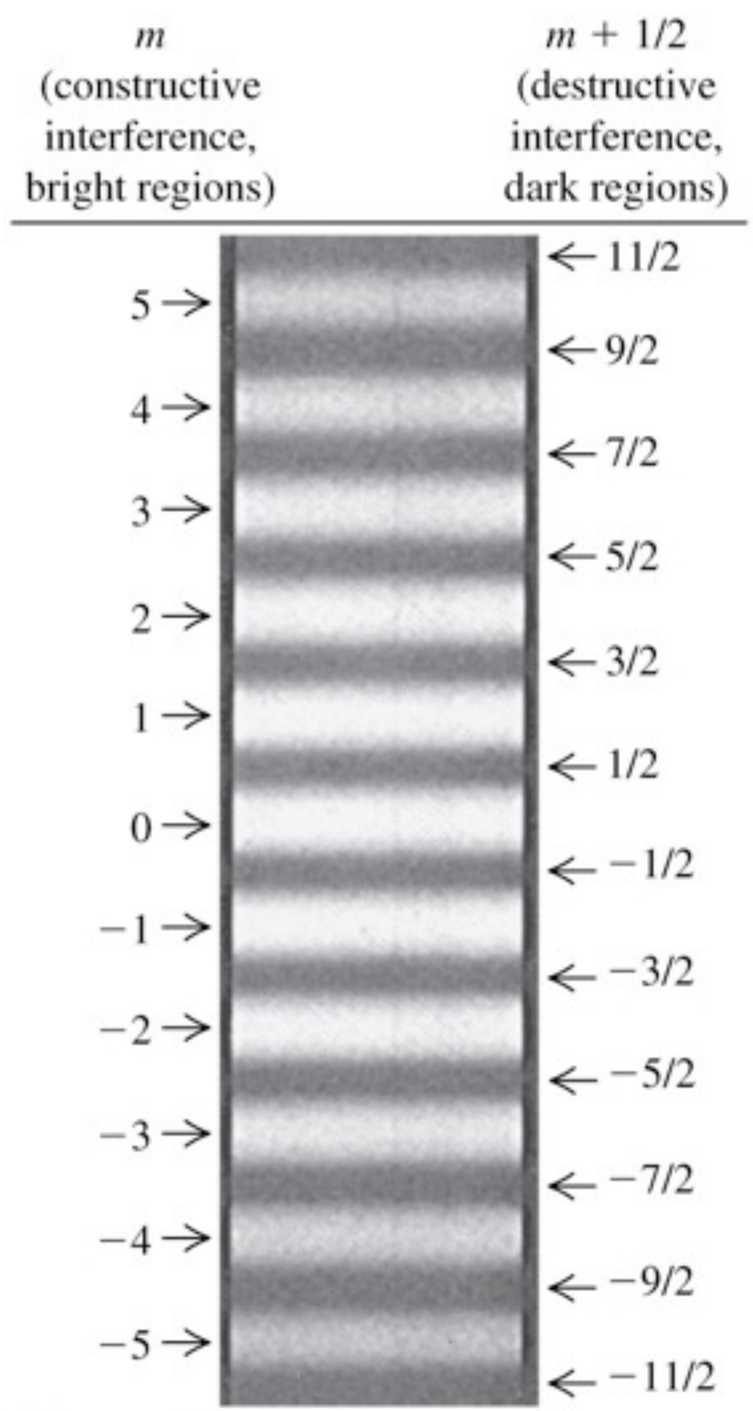
The edges of shadows can an interesting constructive / destructive interference pattern, related to the fact that light is a wave. Can see why from Huygen's principle: every point on light front acts as a point source for later light wave.



Recall 2slit interference

$$\Delta L \approx d \sin\theta$$





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

Dark: $d \sin\theta = (m + \frac{1}{2})\lambda$

Note: larger wavelength (redder) gives more spread-out fringes.

Recall 2-slit intensity

$$I \sim \langle E_{tot}^2 \rangle$$ (Time averaged)

trig identity: $$\cos a + \cos b = 2\cos(\frac{a+b}{2})\cos(\frac{a-b}{2})$$

source 1 wave　　source 2 wave

$$E_{tot}/E_0 = \cos(kL - \omega t) + \cos(kL' - \omega t) = 2\cos(\frac{k\Delta L}{2})\cos(kL_{ave} - \omega t)$$

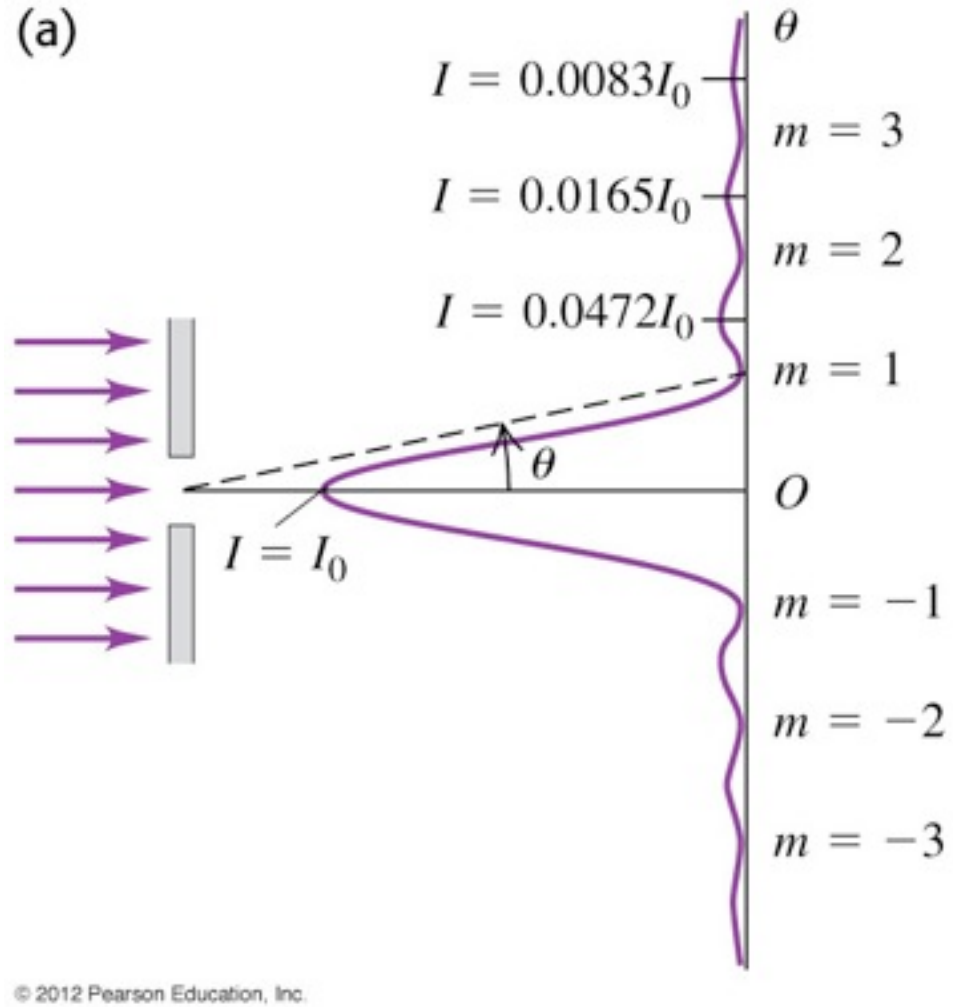
$$I_2 = 4I_1\cos^2(\frac{1}{2}k\Delta L) = 4I_1\cos^2(\pi\Delta L/\lambda)$$

Bright: $d\sin\theta = m\lambda$　　**Dark:** $d\sin\theta = (m+\frac{1}{2})\lambda$

This was for 2 point sources = slits of approximately zero width (i.e. small width compared to light's wavelength). We'll now consider diffraction from a **single slit** of general width a.

Single slit diffraction

Consider barrier with width a. Observe interesting light patterns, projected on the screen, depending on the relative size of the slit width and the light's wavelength.



Demo: show change with a.

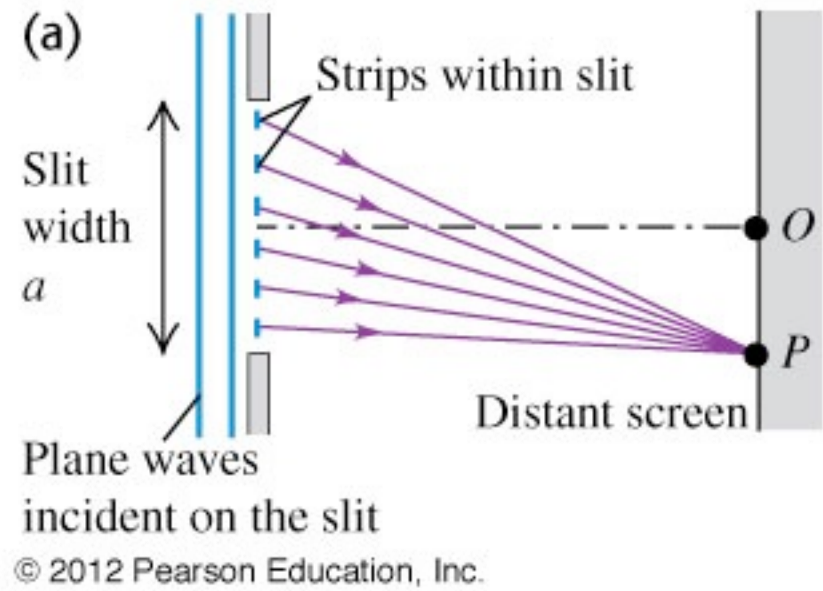
We'll now derive this from interference, thinking of each element of the slit as a point source and adding up their interference effect.

Single slit derivation

Consider interference from N point sources (tiny holes in the barrier), each separated by distance d:

Total:

$$E = A\sum_{i=1}^{N}\cos(kL_i - \omega t)$$



$$L_i = L_1 + (i-1)d\sin\theta$$

sum the series (using trig / tricks):

$$E = A\cos(kL_{ave} - \omega t)\frac{\sin(\frac{kNd\sin\theta}{2})}{\sin(\frac{kd\sin\theta}{2})}$$

Setting N=2 reduces to the 2-slit result from last week, by using trig identity: $\sin 2\beta = 2\sin\beta\cos\beta$

Constructive interference when $d\sin\theta = m\lambda$

Single slit deriv. cont.

$$E = A\cos(kL_{ave} - \omega t)\frac{\sin(\frac{kNd\sin\theta}{2})}{\sin(\frac{kd\sin\theta}{2})} \rightarrow I \sim E^2 = \delta I_0 \frac{\sin^2(\frac{\pi N d\sin\theta}{\lambda})}{\sin^2(\frac{\pi d\sin\theta}{\lambda})}$$

Now replace: $N \to \infty,\ d \to 0,\ Nd = a.$

So $\sin(\pi d\sin\theta/\lambda) \to \pi d\sin\theta/\lambda = \pi\frac{a}{N}\sin\theta/\lambda$

And call $N^2\delta I_0 \to I_0$

= Maximum intensity from N constructive sources

= N-squared times that of a single source.

Final result on next slide...

Single slit intensity

Single slit diffraction

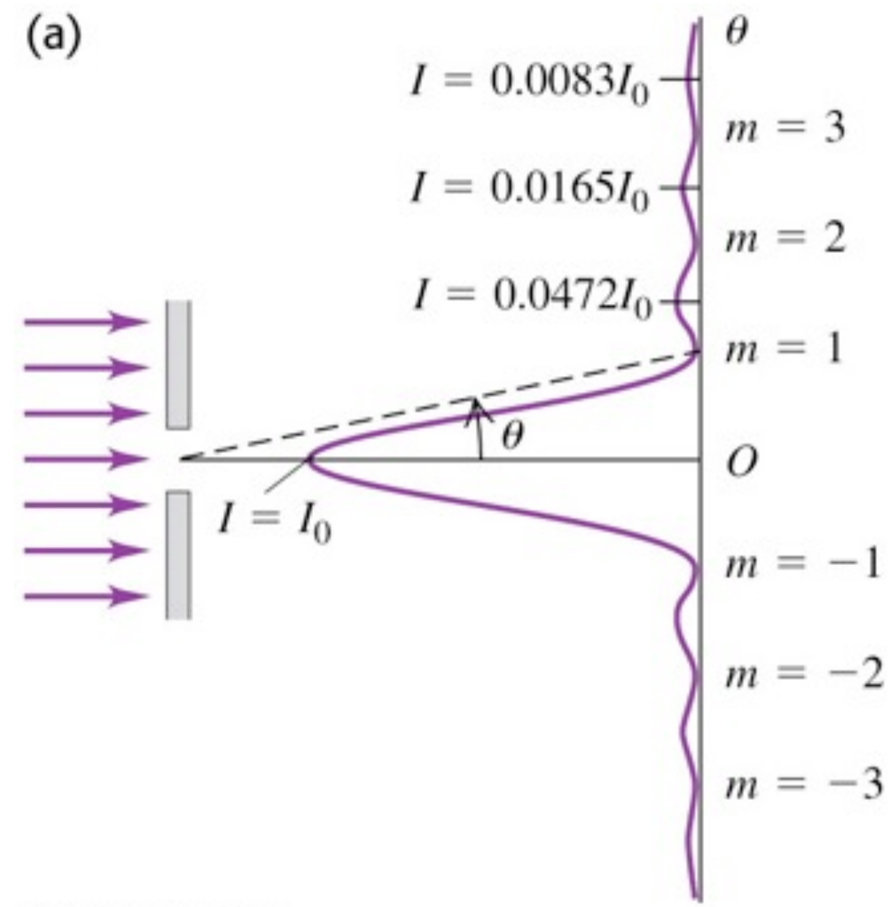
intensity result:

$$I \to I_0 \left[\frac{\sin\left(\frac{\pi a \sin\theta}{\lambda}\right)}{\left(\frac{\pi a \sin\theta}{\lambda}\right)}\right]^2$$

Maximum intensity, at

$\theta = 0$ The function of theta = one there.

The function of theta gives this shape for general angles theta:

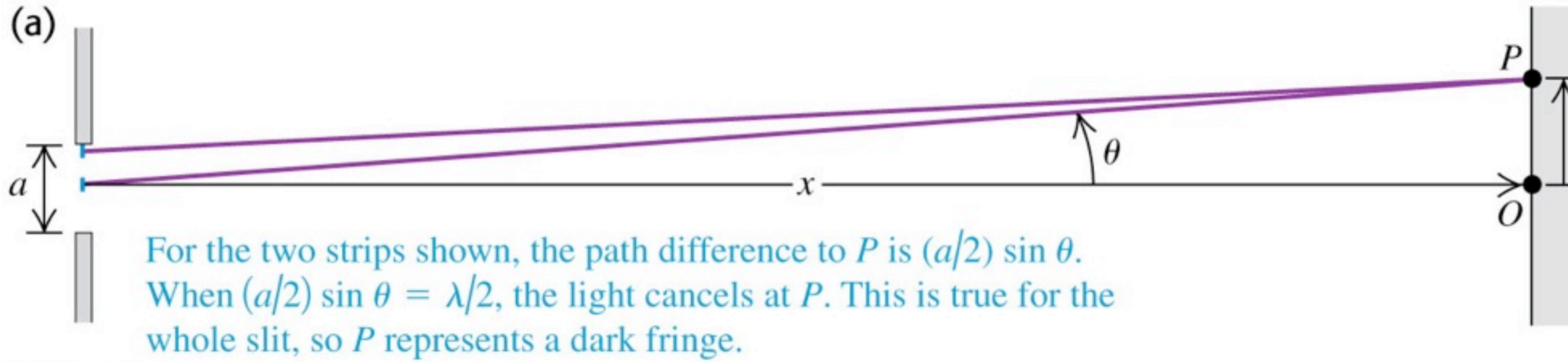


Zero intensity (dark fringes) at

$$\sin\theta = m\lambda/a, \;\; m = \pm 1, \pm 2, \ldots$$

Note larger wavelengths (redder) get wider pattern.
And for a=0, get constant intensity.

Beam spreading



First minimum of our intensity result (m=1) is at $\sin\theta = \lambda/a$

$\sin\theta \approx \tan\theta = \Delta y/D$ So $\Delta y \approx D\lambda/a$

$$\text{width} \approx \frac{D\lambda}{a} + a \approx \frac{D\lambda}{a}$$ for large D.

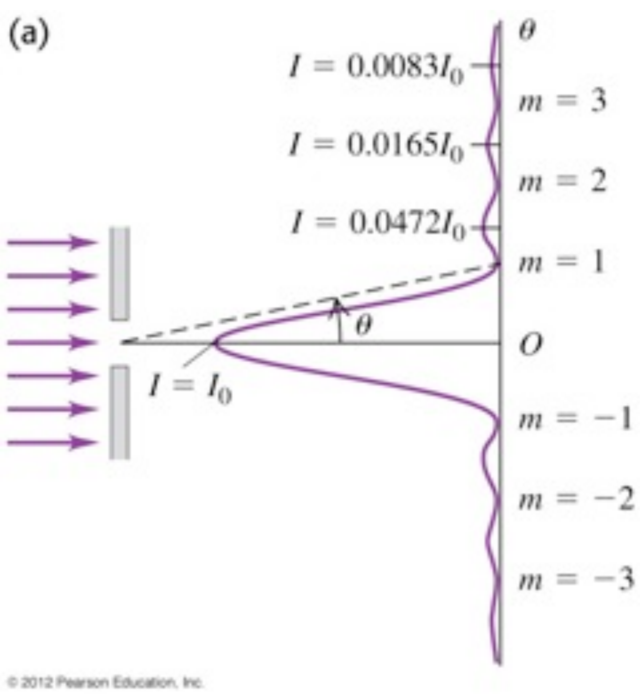
Aside: Related to property of Fourier transforms: $\Delta y \Delta k_y \geq 2\pi$

$$\Delta y = a$$
$$\Delta k_y = k\Delta\theta$$

Circular holes

Similar interference result, but the math is more complicated. Get some special functions (Bessel functions) beyond the scope of Physics 2C.

$$I = I_0[\frac{J_1(2\pi a \sin\theta/\lambda)}{2\pi a \sin\theta/\lambda}]^2$$



Function is different, but shape is qualitatively similar. First minimum at:

$$\sin\theta \approx 1.22\lambda/2R$$

R= radius of circular hole.

Resolvability

Raleigh: two spots are just barely resolvable if the central maximum of one is at the first minimum of the other. Their angular separation is then

$$\sin\theta_R = (1.22\lambda/d) \approx \theta_R$$

E.g. d is your pupil diameter and the angle is the minimum angle that you can visually resolve between stars. Bigger pupils (or telescope lenses) allow smaller angles to be resolved.

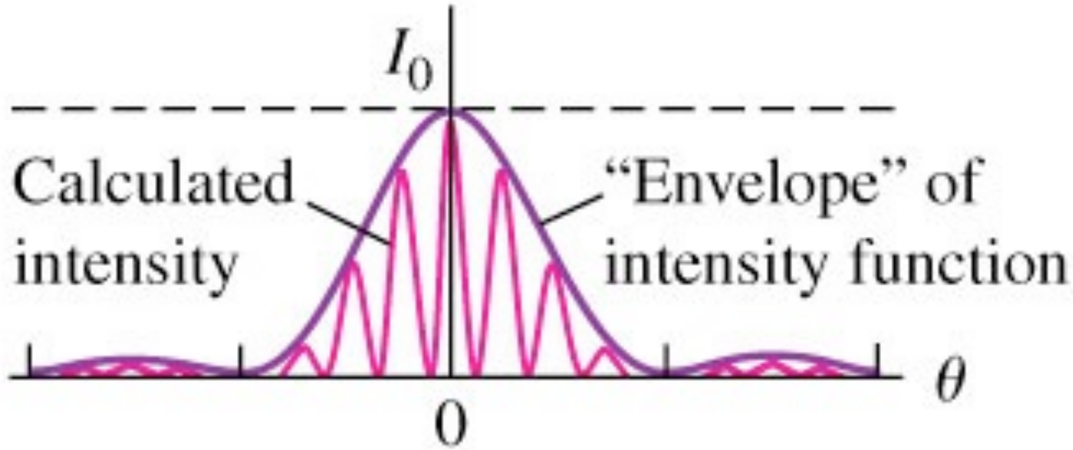
Two slits of width a

$$I = I_0 \cos^2(\frac{\pi d \sin\theta}{\lambda}) \left[\frac{\sin(\frac{\pi a \sin\theta}{\lambda})}{\frac{\pi a \sin\theta}{\lambda}} \right]^2$$

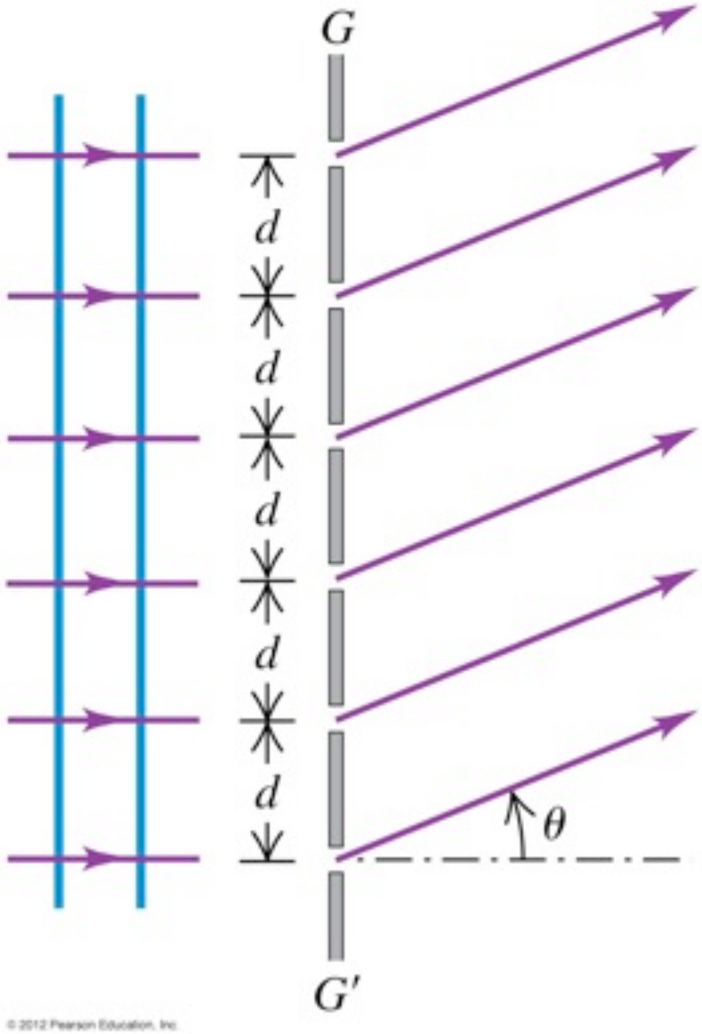
From the two slits.

From their width.

(c) Calculated intensity pattern for two slits of width a and separation $d = 4a$, including both interference and diffraction effects



Diffraction grating



Recall the N slit interference result:

$$E = A\cos(kL_{ave} - \omega t)\frac{\sin(\frac{kNd\sin\theta}{2})}{\sin(\frac{kd\sin\theta}{2})}$$

$$\rightarrow\ I \sim E^2 = \delta I_0 \frac{\sin^2(\frac{\pi N d\sin\theta}{\lambda})}{\sin^2(\frac{\pi d\sin\theta}{\lambda})}$$

Constructive interference when: $d\sin\theta = m\lambda$

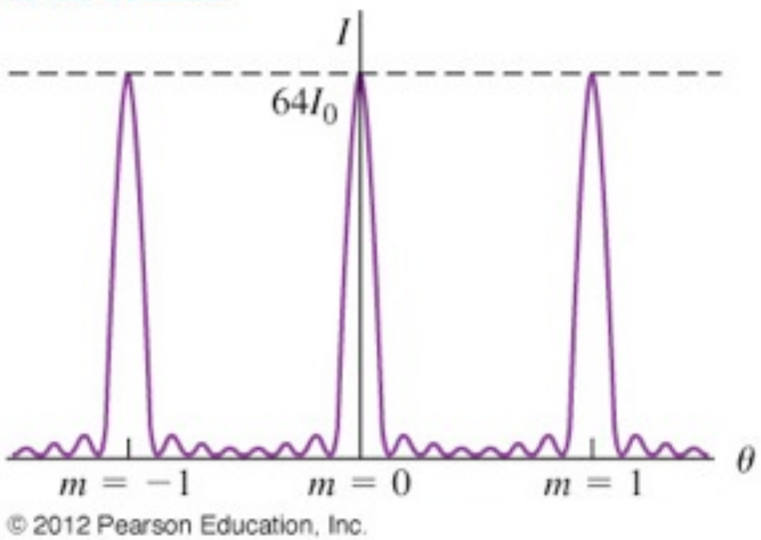
$$m = 0,\ \pm 1,\ \pm 2,\ \ldots$$

Increasing N makes the bright peaks taller and thinner.

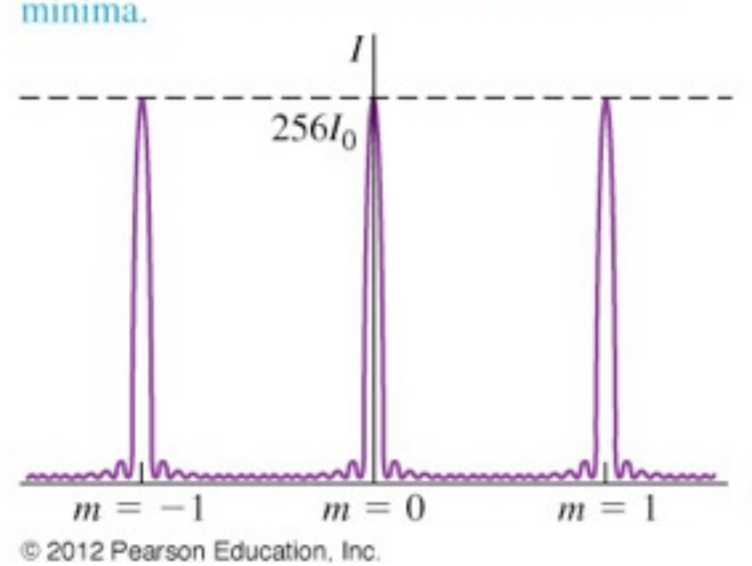
Diffraction grating cont.

$$I \sim E^2 = \delta I_0 \frac{\sin^2(\frac{\pi N d \sin\theta}{\lambda})}{\sin^2(\frac{\pi d \sin\theta}{\lambda})} \rightarrow \Delta\theta_{HW} = \lambda / N d \cos\theta$$

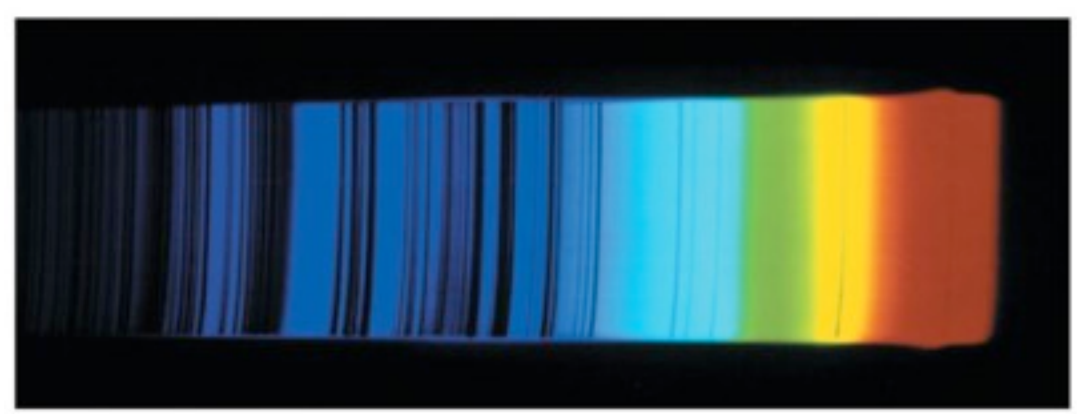
(b) $N = 8$: eight slits produce taller, narrower maxima in the same locations, separated by seven minima.



(c) $N = 16$: with 16 slits, the maxima are even taller and narrower, with more intervening minima.



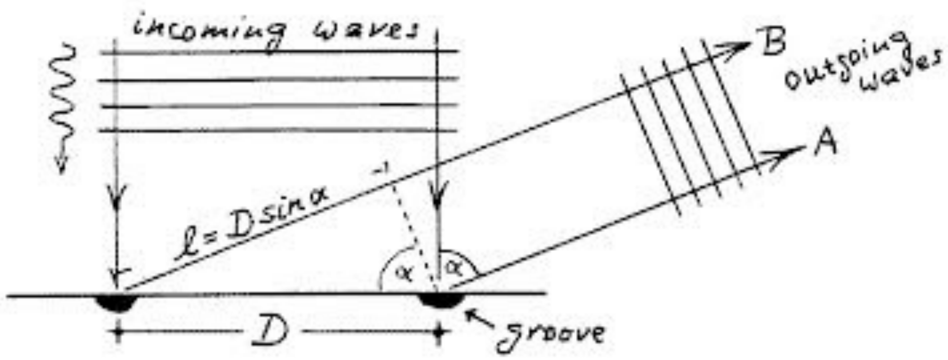
(b)

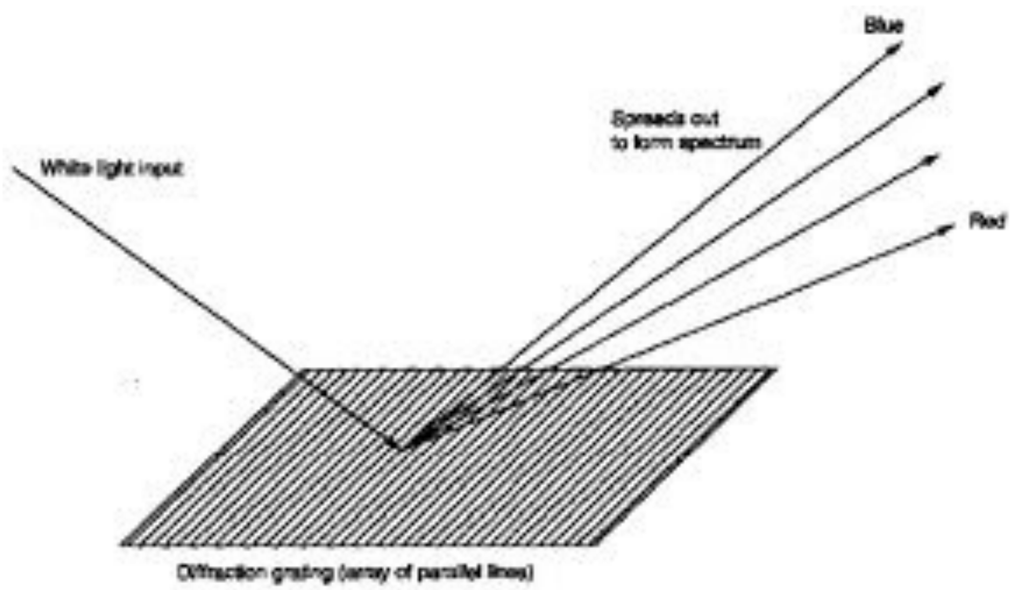


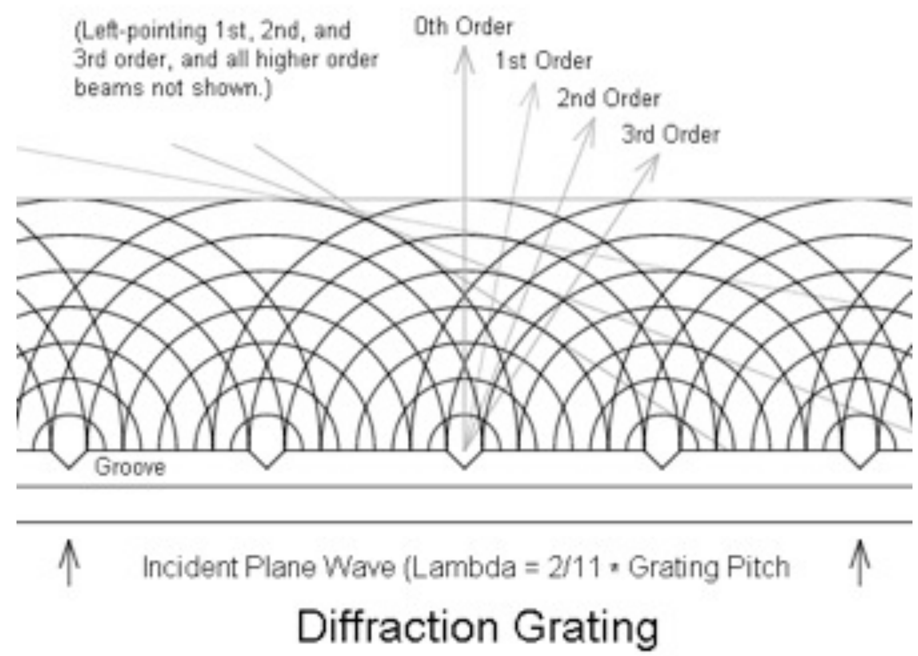
peaks @: $d\sin\theta = m\lambda$

So redder light at bigger angles theta for e.g. m=1:

CD's reflection ~ a diffraction grating







Diffr. Grating's R-power

$$R = \lambda/\Delta\lambda \qquad \Delta\theta_{HW} = \lambda/Nd\cos\theta$$

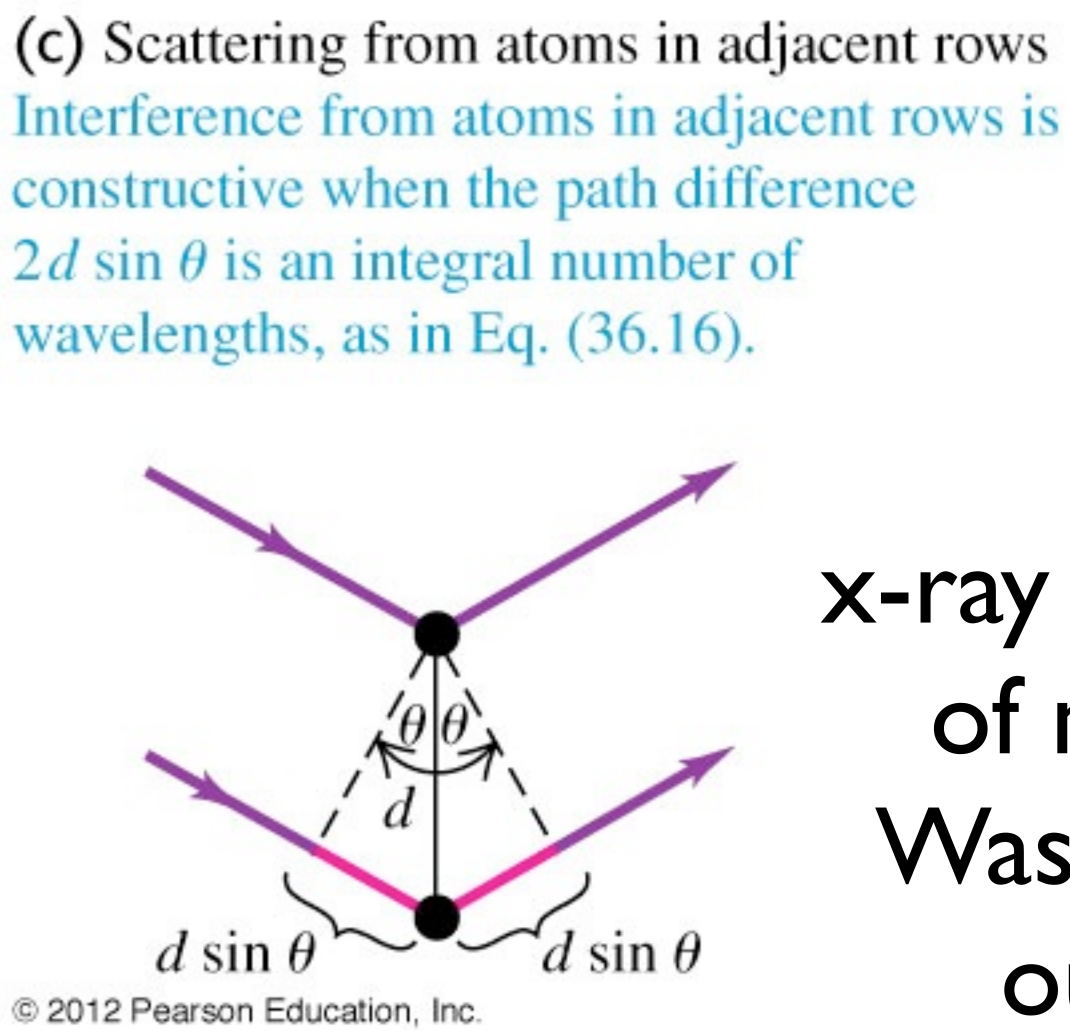
$$d\cos\theta\Delta\theta = m\Delta\lambda \quad \rightarrow \quad R = Nm$$

Can better resolve wavelengths for larger R, i.e. larger N and / or m.

Diffraction grating obs.:

Gasses of elements have a characteristic spectrum of quantized light frequencies / wavelengths (from quantum mechanics). Using a diffraction grating, can identify the glowing gas. Used to study stars' identity / characteristics. Also, see the effect of Doppler effect for light: distant stars are moving away, so their star's spectrum is red-shifted by the Doppler effect. Can be quantitatively measured using diffraction gratings, determines how fast distant starts are moving away from us. Measures the expansion of the Universe (Big Bang Cosmology / Inflation).

x-ray diffraction



constructive interference:

$$2d\sin\theta = m\lambda$$ Bragg peaks.

x-ray diffraction shows the structure of materials, crystals, DNA, etc.. Was & still is hugely important for our understanding of matter.

1927: Davisson & Germer found interference like this for electrons! Showed quantum wave-nature for matter.