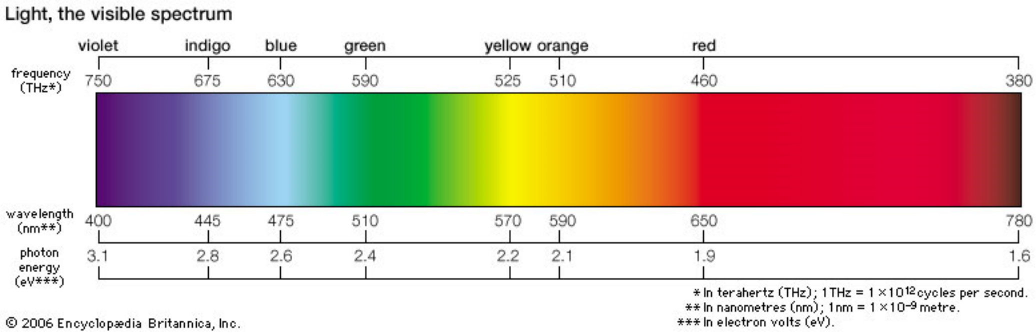
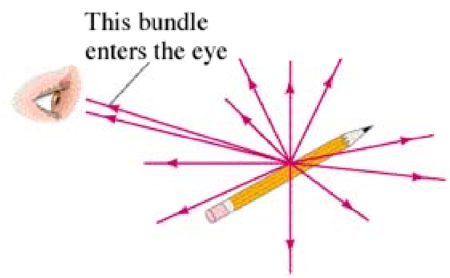
AP* Physics B
OPTICS

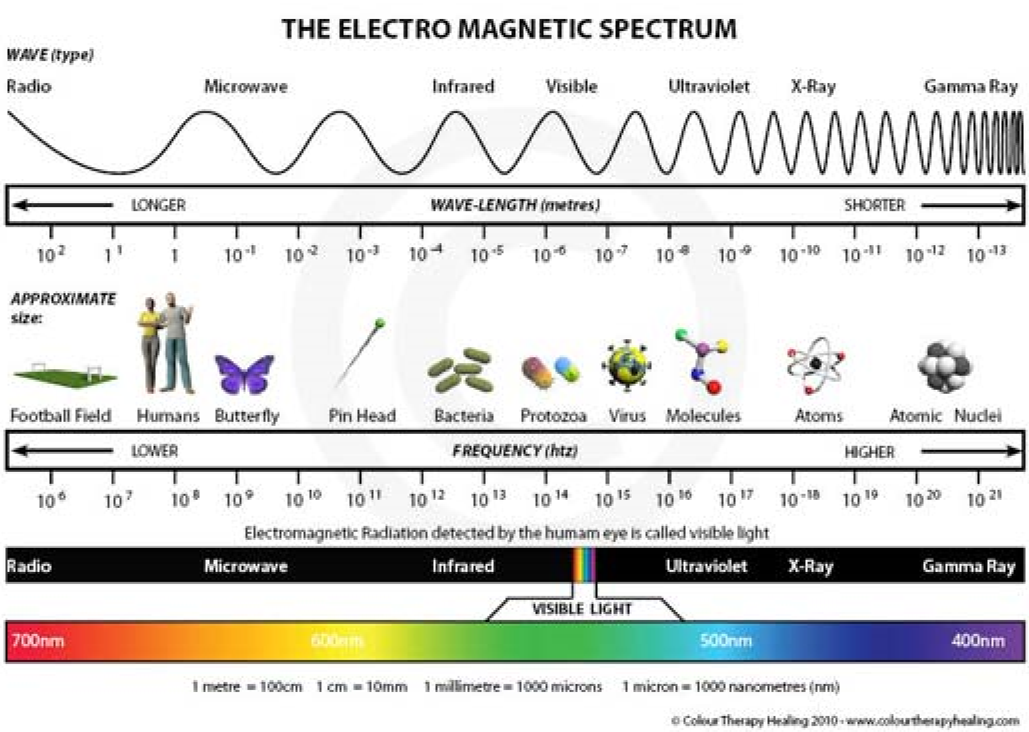
FACTS OF LIGHT

- Visible LIGHT--range of the electromagnetic spectra that stimulates the retina with $\lambda = 400 \rightarrow 700$



- ROY G.BIV sorts by frequency; the cones of your eyes are responsible for color vision; dogs are color blind since they have no cones in their eyes
- light travels in straight lines in a vacuum or uniform medium
- EM spectrum is far, far greater than the tiny slice humans are able to see. The RAY MODEL utilizes the assumption that light travels in straight lines through a vacuum or a constant medium (air, glass, etc). It ignores the wave nature of light.





SPEED OF LIGHT

- Before people were enlightened (Get it?) in the 1700's --light was thought to be instantaneous
- Galileo—1st to say light had finite speed & developed a method of determining speed but alas, too fast for him!!
- Ole Roemer--Danish astronomer (1644-1710)--1st to determine light traveled with measurable speed. 1668-1674 ☞ 70 measurements of one moon of Jupiter named Io (pronounced as "I owe" as in "I owe my physics teacher many thanks for illuminating the more difficult concepts in physics".) were made with a standard deviation of 14 seconds. In 1676 Roemer calculated 22 minutes to cross Earth's diameter ☞ less than 1 second to cross entire Earth
- 1926--Albert Michelson measured time light required to make a round trip through a pipe between 2 mountains in California, 35 km apart ☞ $2.997996 \pm 0.00004 \times 10^8$ m/s

  ☺ Michelson was the FIRST AMERICAN TO WIN THE NOBEL PRIZE (in 1907)
- 1960's--lasers ☞ better method of measuring the speed of light $v = c = f\lambda$ using time recorded by atomic clocks!! The measurement was refined in 1983 ☞ 299 792 458 m/s

  You can continue to use 3.00×10^8 m/s

SOURCES OF LIGHT

luminous--body emits light
illuminated--body reflects light
incandescent--glows HOT; luminous; W (that would be tungsten's chemical symbol) wire is heated by electricity and glows inside a light bulb
luminous flux, P--rate at which light is emitted from a source
lumen--lm--unit of flux 100W bulb = 1750 lm
illuminance, E--lm/m^2 or lux, lx; For a sphere with a 1.0 m radius; $E = \dfrac{1750 \text{ lx}}{4\pi \text{ m}^2}$

If you double the sphere's radius

$E = \dfrac{1750 \text{ lm}}{4\pi (2\text{m})^2} = \dfrac{1750 \text{ lx}}{16\pi}$

candela,cd--measures luminous intensity $\dfrac{1750 \text{ lx}}{4\pi} = 139$ cd

increased illumination is caused by either:
increase flux of alternate source
or decrease distance between source and surface

illuminance $= E = \dfrac{P}{4\pi d^2}$

perpendicular line between source and surface
point sources

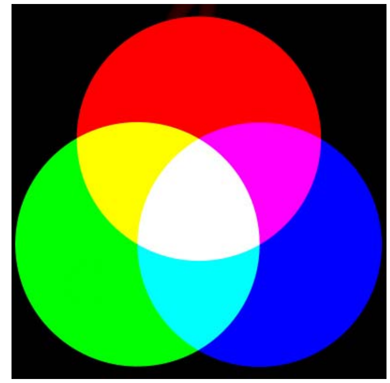
LIGHT AND MATTER

Words often used to describe light's attempt to travel through an object:
transparent--through; transmitted
translucent—sort of through; sort of transmitted; foggy
opaque--not through; absorbed/reflected all light; no transmission

COLOR (red is my favorite!)

- 1666—Newton (very busy guy)--"spectrum" from prism--each color different λ
- Primary colors of *light* (not the crayons or paint pigments you learned as primary colors of *pigments*)

    - red + green + blue light = white light, therefore these are the three primary colors of light
    - Once upon a time, there was only black and white TV (gasp!), and when “personal” computers came out, the monitors were also only black and white.
    - When “color” monitors came available for purchase, computer geeks rejoiced! The monitors were universally called “RGB” monitors since the primary colors of light were systematically “blended” to create 32 (cheap) or 256 (expensive) colors of light. We were so easy to please back then!



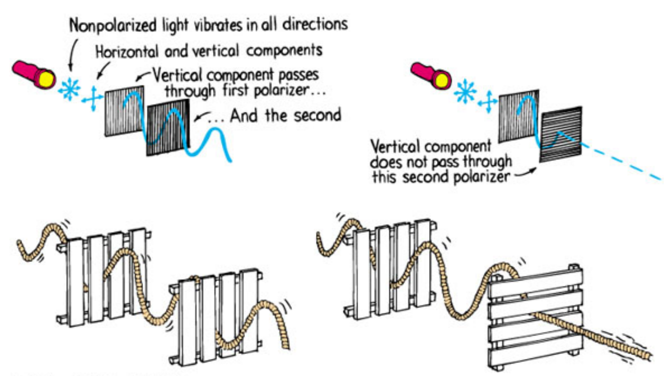
- Secondary colors of light:

    r + g = <u>yellow</u>
    b + g = <u>cyan</u>
    r + b = <u>magenta</u>
    y + b = white; yellow is complementary to blue: y:b c:r m:g
    black--absorption or reflected light

- PIGMENTS--colored material
    - <u>dye</u>—molecules usually containing an element with unpaired *d* electrons (it’s a long sordid chemistry explanation) such as: titanium(IV) dioxide ⇨ white; chromium(III) oxide ⇨ green; cadmium sulfate (Cd only makes +2 ions and you’re supposed to just know that, so it is deprived of a Roman numeral indicating its charge…in case you were curious.) ⇨ yellow
    - pigments mix to form suspensions NOT solutions ⇨ subtractive process
    - primary pigments absorb 1 color from white light--yellow, cyan, magenta
    - secondary pigments absorb 2 colors and reflect one--red, green, blue
    - primary pig. = secondary light   secondary pig. = primary light
    - y + b = black--all light is absorbed, none reflected
    - y:b, c:r, m:g ⇨ complementary pigments

POLARIZATION of Light

- only transverse waves can be polarized
- ordinary light contains EM waves vibrating in every direction perpendicular to travel. Each wave can be resolved into 2 perpendicular components
- <u>polarizer</u>--½ light waves pass through ⇨ intensity decreases by ½ (Go, figure!)
- repeat process ⇨ perpendicular no light through ⇨ parallel most light transmitted



Hewitt, *Conceptual Physics*, Ninth Edition.
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FIGURE 24–41 Crossed Polaroids completely eliminate light.

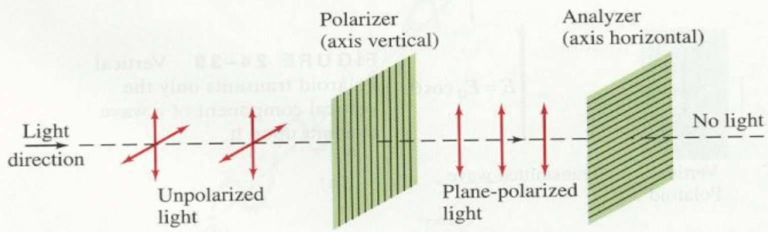
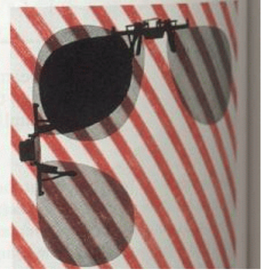
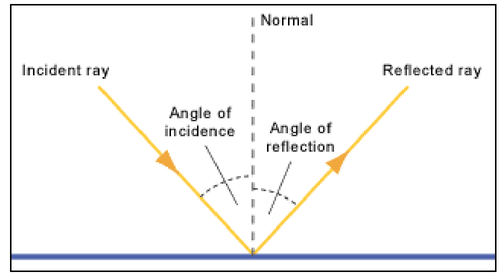


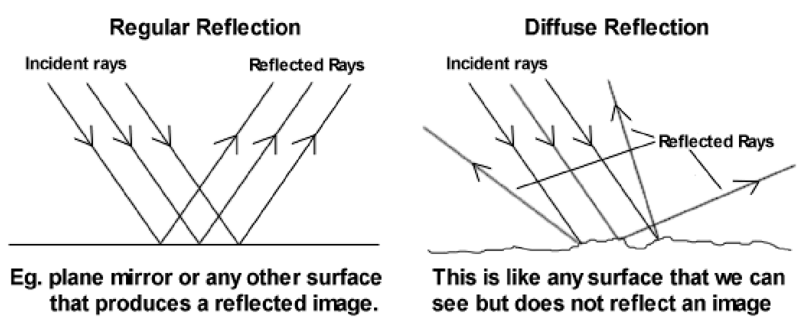
FIGURE 24–42 Crossed Polaroids. When the two polarized sunglass lenses overlap, with axes perpendicular, almost no light passes through.



HOW LIGHT BEHAVES AT A BOUNDARY



- LAW OF REFLECTION: angle of incidence = angle of reflection, ∠i = ∠r   or $\theta_i = \theta_r$
- both ∠'s measure from normal and *n*, ray i, ray r all lie in the *same* plane
  - diffuse reflection--reflection off rough surface
  - regular reflection--reflection off smooth surface



- REFRACTION OF LIGHT--light travels at different speeds in different media
- optically dense--media that slows light's speed; light bends/changes direction if ∠i ≠ 0 at the boundary between media as rays enter more dense media (travel slower) refraction TOWARD the normal
  ☞ ∠ref smaller than ∠ incidence; as rays enter less dense media (travel faster) refraction AWAY from the normal
  ☞ ∠ref smaller than ∠ incidence

Index of refraction

TABLE 23–1
Indices of Refraction†

Medium	$n = c/v$
Vacuum	1.0000
Air (at STP)	1.0003
Water	1.33
Ethyl alcohol	1.36
Glass	
Fused quartz	1.46
Crown glass	1.52
Light flint	1.58
Lucite or Plexiglas	1.51
Sodium chloride	1.53
Diamond	2.42

† λ = 589 nm

- ***Snell's Law***
  Willebrord Snell (1591-1626) Dutch:
  $n_i \sin\theta_i = n_r \sin\theta_r$

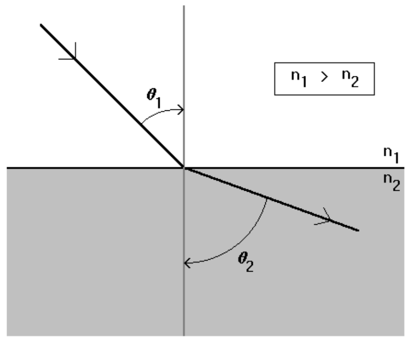
  a ray of light bends so ratio of
sin∠i : sin ∠r   is a constant

- Index of Refraction--when light travels from a vacuum to a new medium the constant is
  $$n = \frac{\sin\theta_i}{\sin\theta_r}$$

INDEX OF REFRACTION AND THE SPEED OF LIGHT

Refraction occurs because the speed of light depends on medium through which it travels

$n_s = \frac{c}{v_s}$ AND $n = \frac{\sin\theta_i}{\sin\theta_r}$ Can you feel some problems coming on?



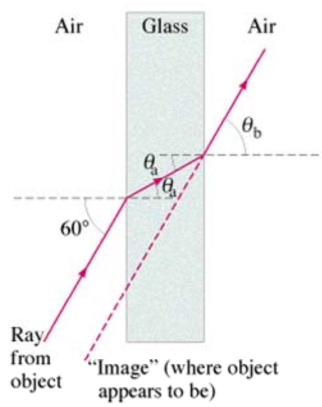
Example 7 (yeah, it's a bit out of order starting with #7--humor me!)

Calculate the speed of light in diamond. (Table of indices of refraction given on previous page.)

Example 8

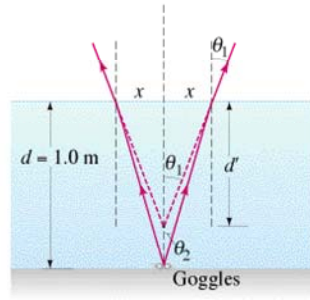
Light strikes a flat piece of glass at an incident angle of 60°.
If the index of refraction of the glass is 1.50

a) What is the angle of refraction θ_A in the glass.



b) What is the angle θ_B at which the ray emerges from the glass?

Example 9
A swimmer has dropped her goggles in the shallow end of a pool, marked at 1.0 m deep. But the goggles don't look that deep. Why? How deep do the goggles appear to be when you look straight down into the water?



APPLICATIONS OF REFLECTED AND REFRACTED LIGHT

Total Internal Reflection--light does not emerge! Best practical application? Fiber optic technology.
As light moves into a medium that is more dense ⇨ refraction is away from normal ⇨ ∠ref larger than ∠i

when this ∠ is HUGE, there is *NO REFRACTED RAY* ∴ total internal reflection.

The ∠ref = 90° and light <u>cannot</u> escape!!

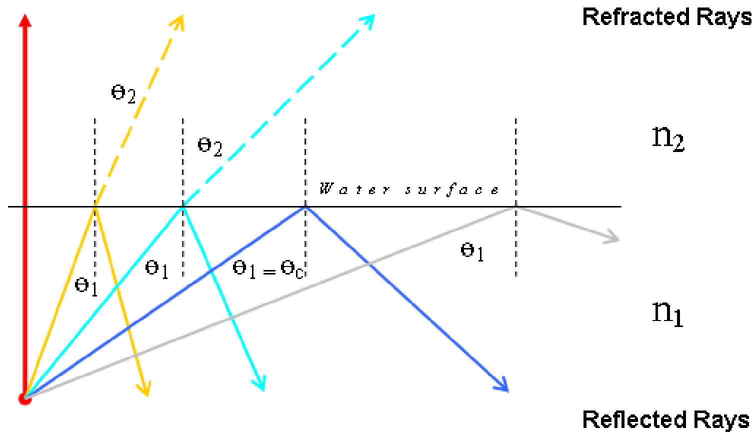
$n_i \sin \theta_i = n_{ref} \sin \theta_{ref}$

$n_{water} \sin \theta_i = n_{air} \sin \theta_{ref}$

$(1.33)\sin \theta_i = (1.00)\sin \theta_{ref}$

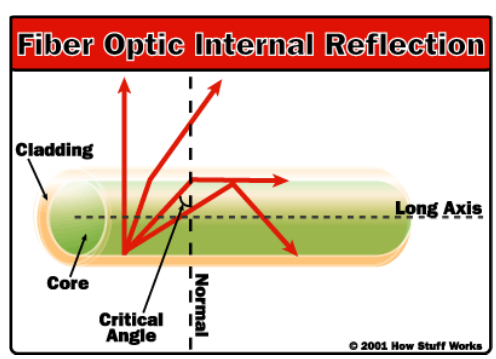
$\sin \theta_i = \dfrac{(1) \sin 90°}{1.33}$

$\therefore \theta_i = 48.8° = \theta_c$



θ_c is the critical ∠. Use Snell's law and set $\theta_i = \theta_c$; $n_{ref} = 1.000$ & $\theta_{ref} = 90.0°$

ANY ray reaching the boundary at θ_c *or above* causes total internal reflection



FIBER OPTICS--used to transmit information with light instead of electricity

Television, TV, radio ☞ vary the amplitude of the signal
as binary bits--0's and 1's to communicate information
☞ 13 = 1,1,0,1 and 3 = 0,0,1,1
1 ☞ on 0 ☞ off ⇨ creates pulses of light for communication

EFFECTS OF REFRACTION

Mirages--change in n_{air} due to temperature gradient. Ray aimed at road encounters smaller n, bent away from normal ⇨ you see light reflected from the sky which looks like light reflected from a puddle

Shift in position of object in a liquid--appears closer to surface than it is
sunset/sunrise--sunlight is refracted by Earth's atmosphere

- DISPERSION OF LIGHT

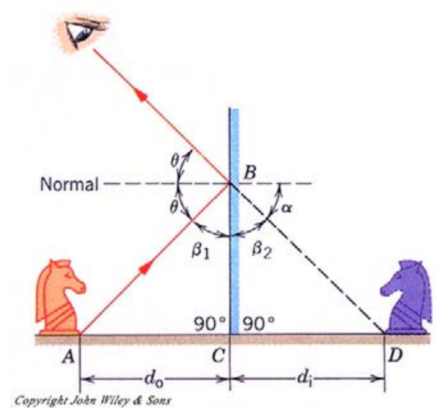
n_s depends on λ of incident light
In glass--red fastest, smallest n, therefore bent least. Violet slower, largest n, therefore bent most.

- o <u>dispersion</u>--separation into a spectrum by refraction
- o different light sources ☞ different spectra
- o rain droplets and sunshine ☞ rainbow!! Back of droplet light undergoes total internal reflection while out of droplet (front) light is refracted and dispersed red light = 42° & blue light = 40° w/respect to sun's rays

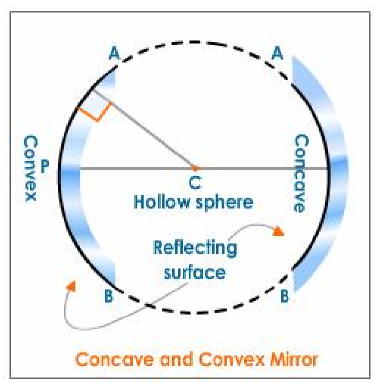
- OBJECTS AND THEIR IMAGES IN MIRRORS

PLANE MIRROR--flat, smooth, regular reflection, f/b or lft/rt reversed image

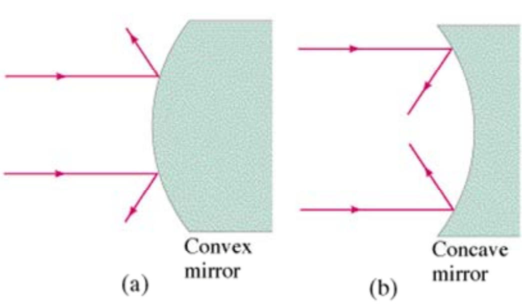
- o <u>object</u>--source of diverging light rays; luminous or illuminated
- o <u>image</u>--point where extended rays apparently intersect
- o <u>virtual image</u>--no source is really there; rays appear to diverge w/o doing so
- o <u>real image</u>--rays from object converge
- o <u>upright↑ inverted↓</u>

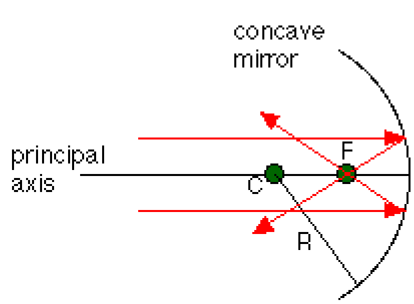


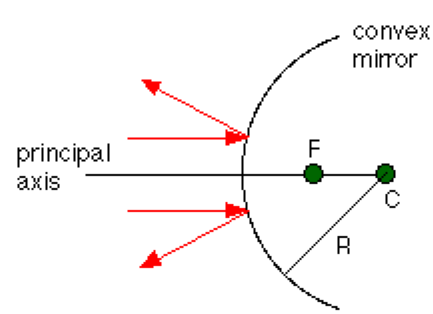
CONCAVE MIRRORS--reflects light from inner surface
part of hollow sphere
radius ⇨ r
geometric center of sphere ⇨ C
<u>principal axis</u>--CA, straight ⊥ line to surface of mirror
<u>focal point</u> ⇨ F--where light rays converge on principal axis ☞ occurs at midpoint of CA for small angles of incidence
<u>focal length</u> ⇨ f— ½ radius of curvature



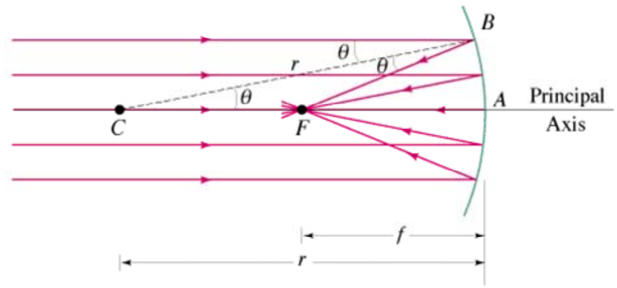
Concave and Convex Mirror







- **SPHERICAL ABERRATION**
  - o || rays converge @ F <u>only</u> if close to principal axis
  - o Farther rays converge @ point closer to mirror ∴ image is a disk; NOT a point (fuzzy image)
  - o Parabolic mirrors have NO SA ☞ used to focus rays from distant stars to a sharp focus in telescopes; ☹Hubble telescope ☺ flashlights



REAL vs. VIRTUAL IMAGES

<u>real</u>--light rays actually converge and pass through the image. Can be projected onto paper or a screen
<u>virtual</u>--rays diverge; cannot be projected or captured on paper/screen since rays DO NOT converge

IMAGES BY CONCAVE MIRRORS

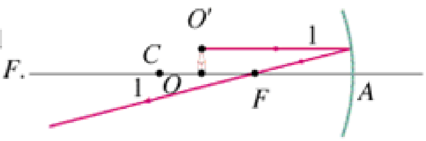
❶ rays$_i$ || to PA (principal axis) reflect thru *F*

❷ rays$_i$ passing thru *F* are reflected || to PA

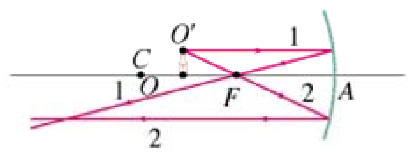
❸ rays$_i$ pass ⊥ to mirror, reflects back upon itself and goes through *C*.

- o If the object is "beyond *C*"--obj. farther from mirror than *C*--image is real, inverted and reduced
- o As object → *C*, images move ← toward *C*, real, inverted, reduced
- o An object at *C*, image at *C*--real inverted, same size
- o An object inside *C*, toward *F*-- image out beyond *C*, real, inverted, enlarged

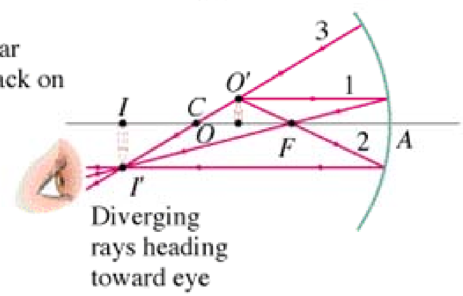
Ray 1 goes out from *O′* parallel to the axis and reflects through *F*.



Ray 2 goes through *F* and then reflects back parallel to the axis.



Ray 3 heads out perpendicular to mirror and then reflects back on itself and goes through *C* (center of curvature)

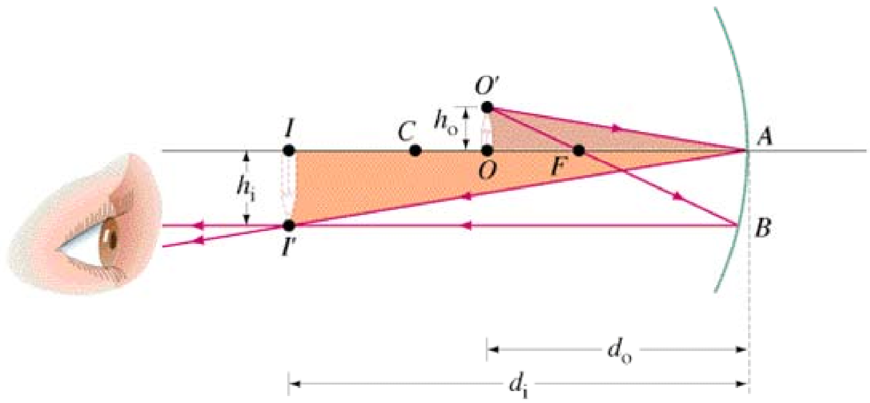


Also,

- o As object approaches *F*--image moves farther out
- o An object at *F*--all reflected rays are ||, image at infinity
- o An object between *F* & mirror--no real image exists, virtual image behind mirror

Things Are Not Always As They Appear!

With plane mirrors, there is no distortion of the image (as long as the surface is smooth). But curved mirrors are a different story! Examine the diagram below. How does the height of the image compare to the height of the original object? How does the distance of the image from the mirror compare to the distance the original object was from the mirror?



Mirrors and Lenses (as you will soon see) can magnify or reduce images. We use ray diagrams to illustrate the locations of objects and images relative to the principal axis, mirror (or lens) and focal point. If the drawings are done carefully and to scale, we can graphically determine the height of the image, etc. But, we can also solve for quantities algebraically.

Mirror & Lens Equation

$\frac{1}{f} = \frac{1}{d_i} + \frac{1}{d_o}$ where d_i and d_o are assigned positive values if real and negative values if virtual **AND** *f* is assigned a positive value if the mirror or lens is concave and a negative value if the mirror or lens is convex

Caution: Silliness approaching! It's easy to remember this equation since saying it out loud gives: "1 over *f* equals 1 over "die" plus one over "doh" (the last of which needs to be uttered in your best Homer Simpson voice).

Magnification Equation (*m*)

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

Caution: Yet more silliness approaching! Also easy to remember since saying it out loud gives: "Magnification equals "hi" over "ho" *and* equals NEGATIVE "die" over "doh"!

Quit sniggering… "Ho" as in Santa's battle cry, not a lady of ill repute, and once again, the last part should be uttered in your best Homer Simpson voice.

Example 3
A 1.50 cm-high diamond ring is placed 20.0 cm from a concave mirror whose radius of curvature is 30.0 cm.
A) Determine the position of the image

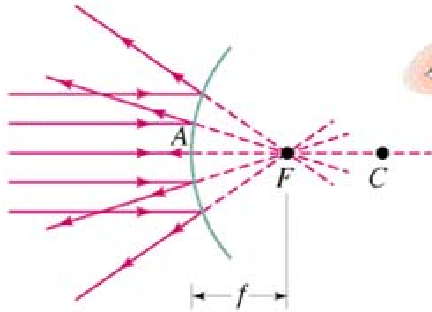
b) Determine the size of the image

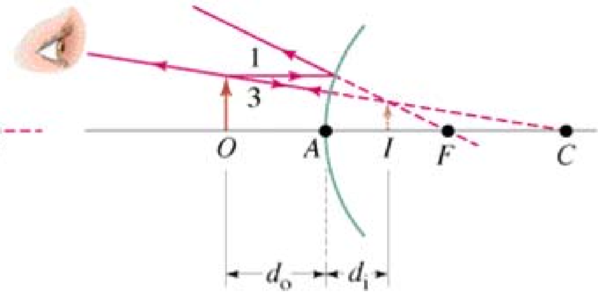
Example 5 (Yeah, I skipped #4)
A 1.00 cm-high object is placed 10.0 cm from a concave mirror whose radius of curvature is 30.0 cm.
a) Draw a ray diagram to locate the position of the image.

b) Determine the position of the image and the magnification analytically.

VIRTUAL IMAGES FORMED BY CONVEX MIRRORS

- Convex mirrors--reflected light from outer surface--rays diverge--virtual images; *F* is behind the mirror, ½ distance to the center of curvature--*f* is *negative*

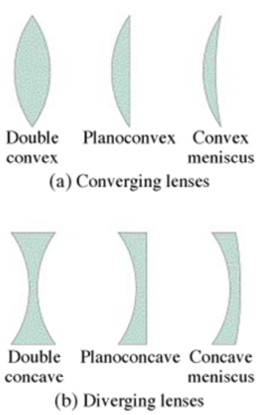




  - object in front of the mirror--image virtual, upright, reduced in size. Reflect an enlarged field of view—convenience stores, rearview mirrors, etc.

Example 6
A convex rearview car mirror has a radius of curvature of 40.0 cm. Determine the location of the image and its magnification for an object 10.0 m from the mirror.

Lenses

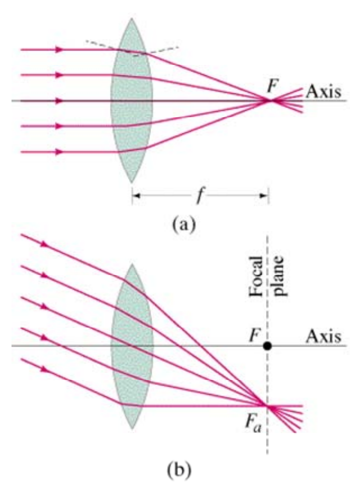


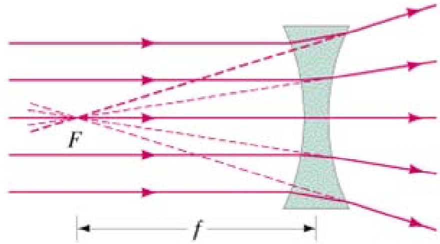
Lenses have been around since about the 13th century. In 1610 Galileo used 2 lenses to make a telescope; then came Leuwenhoek's microscopes and early cameras, eyeglasses, etc.

There are many types of lenses as shown right. Lenses can be made of glass or plastic as long as the substance has an index of refraction greater than 1.0.

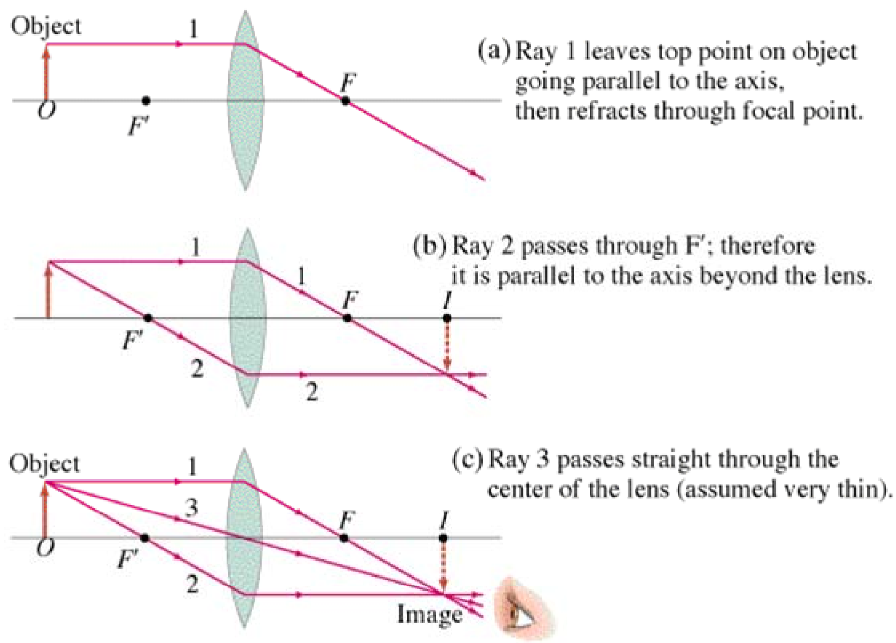
convex--thicker at the center than the edges; converging; refract light rays so they meet

concave--thinner at center than edges; diverging



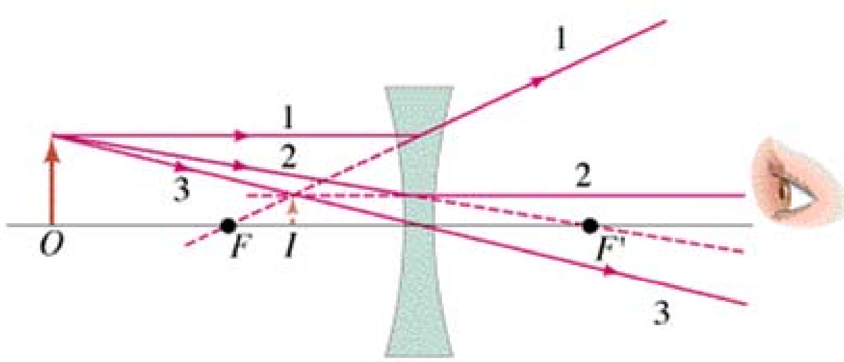


Real Images Formed By Convex Lenses



- Beyond 2*F*--image real, inverted, and reduced
- Approaching F--image real, inverted enlarged
- At 2*F*--image inverted, same size
- Virtual Images formed by Convex Lenses
- object at *F*--rays emerge in a parallel beam
- object between *F* and lens--rays DO NOT converge on opposite side of lens ∴ image is virtual, upright and enlarged

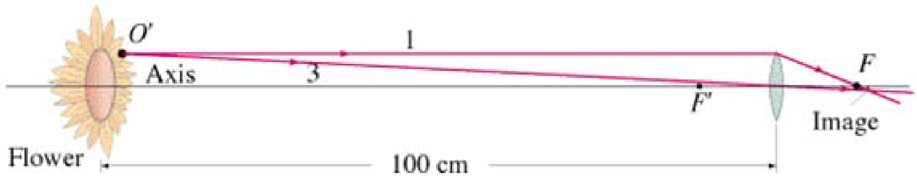
Virtual Images Formed By Concave Lenses



- concave ☞ *ALL RAYS DIVERGE*
- image virtual, upright, reduced no matter how far from the lens the object is located
- *F* is negative; corrects near sightedness

Example 11

What is a) the position and b) the size of the image of a large 7.6 cm-high flower placed 1.00 m from a +50.0 mm-focal-length camera lens?



a)

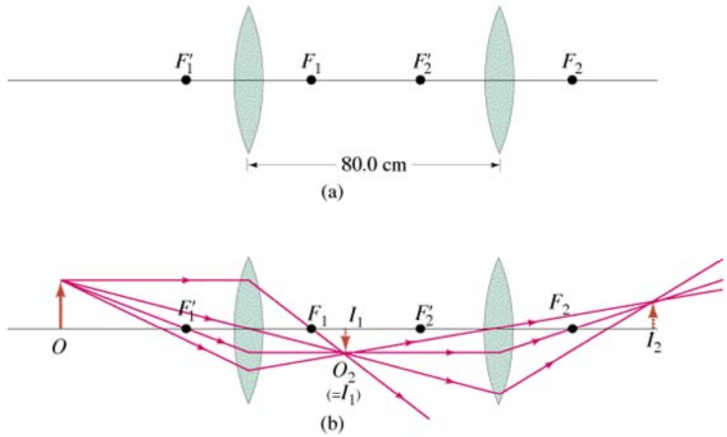
b)

Example 12
An object is placed 10 cm from a 15-cm-focal-length converging lens. Determine the image position and size
a) analytically

b) using a ray diagram

Example 13
Where must a small insect be placed if a 25-cm-focal-length diverging lens is to form a virtual image 20 cm in front of the lens?

A TWO LENS SYSTEM

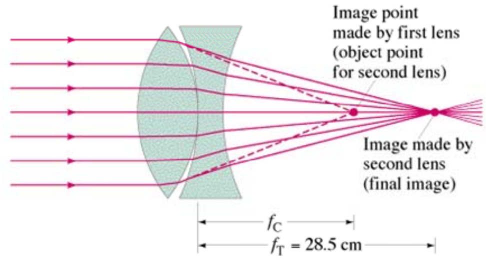


Example 14
Two converging lenses, with focal lengths f_1 = 20.0 cm and f_2 = 25.0 cm, are placed 80.0 cm apart, as shown above. An object is placed 60.0 cm in front of the first lens as shown. Determine
a) the position of the final image formed by the combination of the two lenses.

b) the magnification of the final image formed by the combination of the two lenses.

Example 15

To measure the focal length of a diverging lens, a converging lens is placed in contact with it. The Sun's rays are focused by this combination at a point 28.5 cm behind the lenses as shown. If the converging lens has a focal length f_c of 16.0 cm, what is the focal length f of the diverging lens?

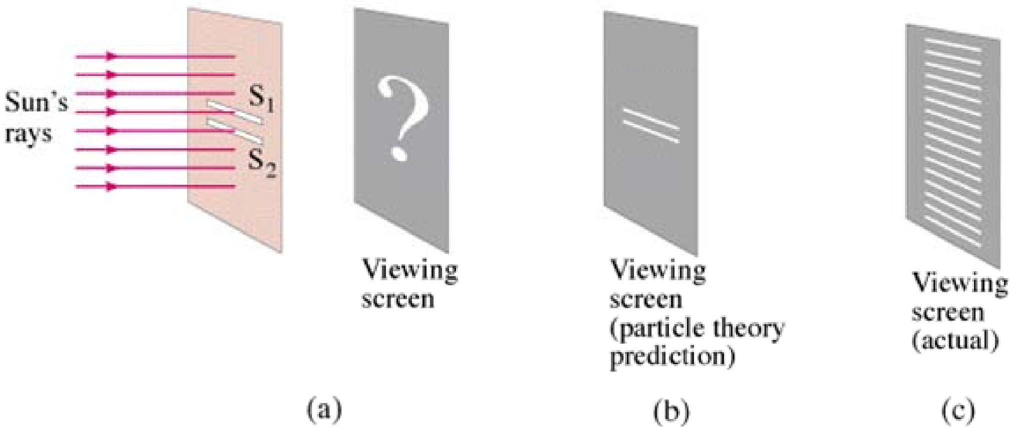


Chromatic Aberration & Optical Instruments

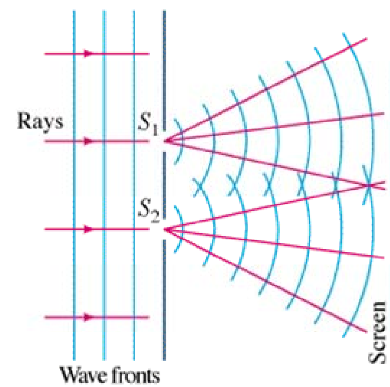
- Edges of lens resemble prism--objects ringed w/ color when viewed through a lens reduced by joining convex w/ concave ☞ achromatic lens
- All precision optical instruments use achromatic lenses
- Optical Instruments
  - Images focused on retina
  - most refraction occurs @ the curved surface of the cornea and muscles change shape of lens and thus *f*
    - relaxed ☞ distant object is focused on retina
    - contract ☞ f shortened, images 25 cm or closer focused on retina
    - myopic--near sighted--*f* is too short ☞ images of distant object formed in front of retina
      - concave lens correct by : diverging light rays, increasing d_i , placing image on retina
    - hyperopic--far sighted--*f* is too long ☞ image falls behind retina; at about 45 yrs. old--lens becomes rigid--muscles cannot shorten *f* enough
      - convex lens correct by: virtual image farther from eye than object
    - astigmatism--eye shapes NOT spherical -- vertical lines in focus, horizontal lines are not in focus
    - contacts--most refraction occurs at air/lens surface where change in refractive index is greatest
    - microscopes--at least 2 convex lenses; virtual enlarged
    - refracting telescope--2 convex lenses; virtual, enlarged, inverted image

INTERFERENCE: YOUNG'S DOUBLE-SLIT EXPERIMENT
(A favorite topic on the AP Exam!)

In 1801 Englishman Thomas Young obtained convincing evidence for the wave nature of light AND was even able to measure the λ's of visible light. Light from a single source [Young used the Sun] falls on a screen containing two closely spaced slits, S_1 and S_2 (b) below:



IF light consists of tiny *particles*, then you'd expect to see two bright lines placed behind the slits as in (b) of the diagram above. BUT 'ya don't! Young observed a series of bright lines as seen in (c) on the diagram above.

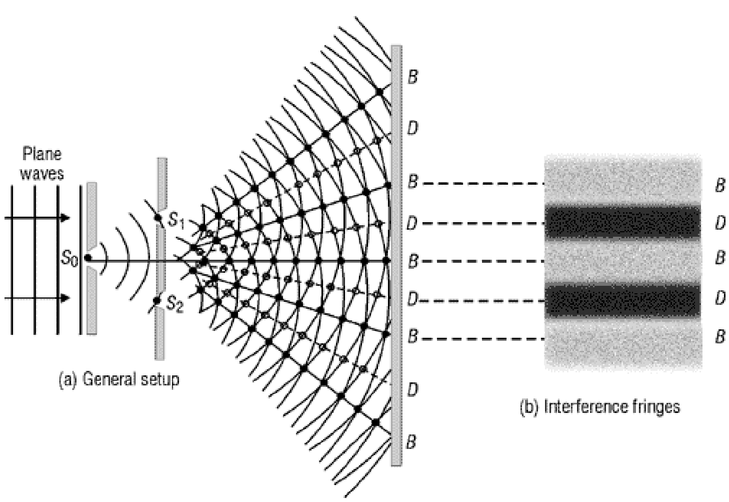


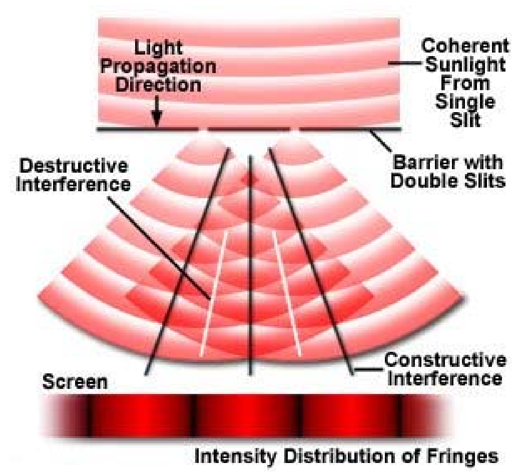
Young EXPLAINED this result as a wave-interference phenomenon. Imagine plane waves of light of a single λ, monochromatic, falling on the two slits as shown here at right.

Because of diffraction, the waves leaving the 2 small slits spread out [sort of like water waves if 2 rocks are thrown into a pond]

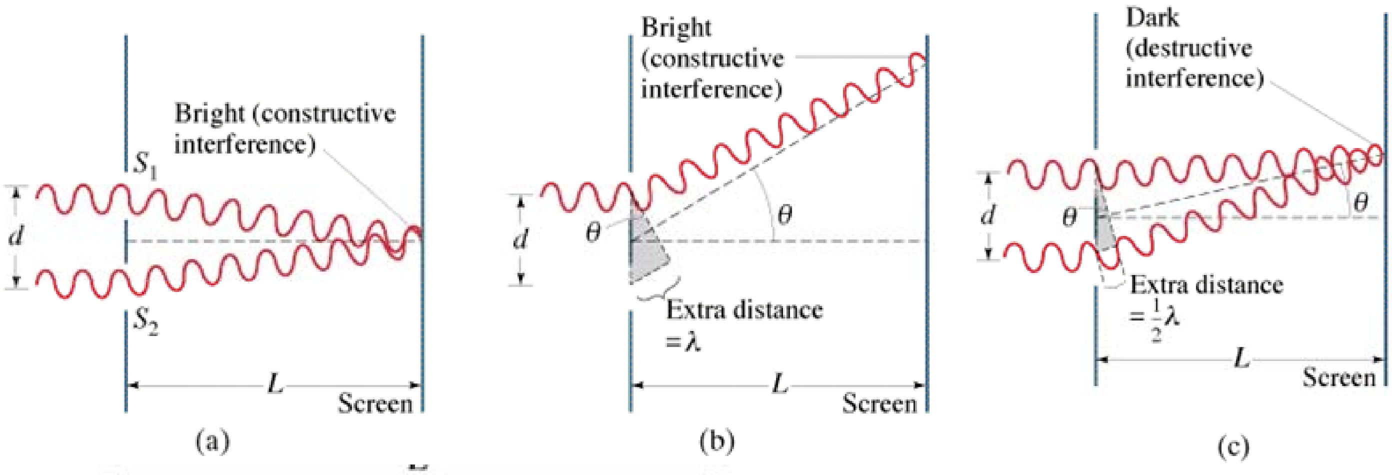
How is the interference pattern made on the screen? What is a bright line? What causes the dark lines?

Here are a few other visualization models of Young's observations:
The Bs & Ds mean "Bright" and "Dark" bands observed on the screen.





Look at the diagram below. Waves of wavelength λ are shown here entering the slits S_1 and S_2 which are a distance, *d*, apart

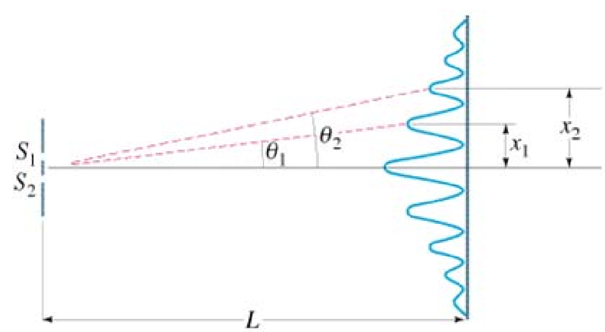


The waves spread out in all directions however, we are focusing on only three different angles:

- (a) The waves reaching the center of the screen [θ = 0] have traveled the same distance so are IN PHASE and interfere *constructively* ☞resulting in a bright spot.
- (b) Constructive interference occurs whenever the paths of 2 rays differ by any whole number of wavelengths.
- (c) IF one ray travels at a ½ λ [or 3/2 λ or 5/2 λ and so on] ☞*destructive* interference occurs and the screen is dark
- These interference patterns create a series of light and dark bands or fringes.

To determine WHERE the bright lines fall, notice the following about our diagram above. The distance *d* between the slits is small compared to *L* the distance to the screen. This makes the rays from each slit essentially parallel and θ is the angle they make with the horizontal. From the shaded right triangle in (b) above, we can see that the extra distance traveled by the lower ray is $d \sin \theta = m\lambda$,

What the heck is *m?* Where *m* is the *order* of the interference fringe and the central bright fringe (where θ = 0) is given an order of zero thus *m* = 0,1,2...etc,



Destructive interference occurs when the extra distance $d \sin \theta = (m + \frac{1}{2})\lambda$,

The INTENSITY of the bright fringes is greatest for the central fringe (*m* = 0) and decreases for higher orders

Example 16

A screen containing two slits 0.100 mm apart is 1.20 m from the viewing screen. Light of wavelength λ = 500 nm falls on the slits from a distant source. Approximately how far apart will the bright interference fringes be on the screen?

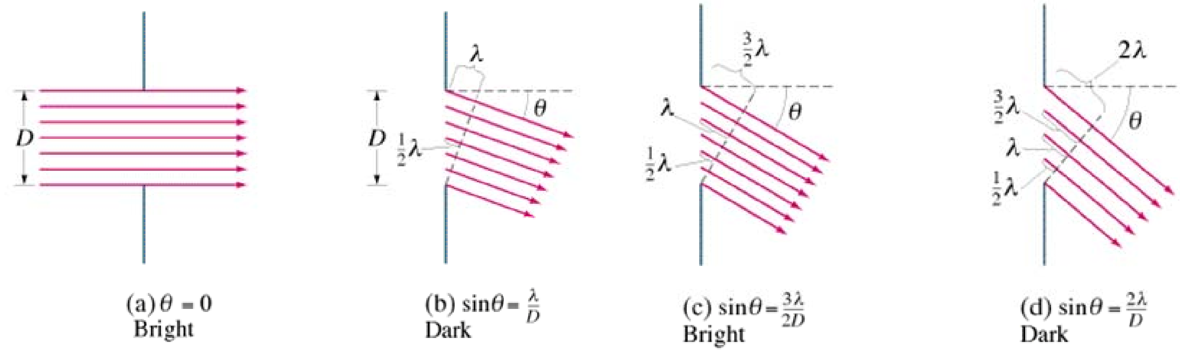
We can see that except for the zeroth-order fringe at the center, the position of the fringes depends on the λ. Consequently when white light falls on the 2 slits, as Young found in his experiments, the central fringe is white, BUT the first-and higher-fringes contain a spectrum of colors like the rainbow. Young could then determine the wavelengths of visible light.

Example 17

White light passes through two slits 0.50 mm apart and an interference pattern is observed on a screen 2.5 m away. The first-order fringe resembles a rainbow with violet light and red light at either end. The violet light falls about 2.0 mm and the red 3.5 mm from the center of the central white fringe. Estimate the λ's of the violet and red lights.

SINGLE SLIT DIFFRACTION (You knew it was coming, right?)

All the prior assumptions remain intact. Look! Another diagram to contemplate!



(a) Consider rays that pass straight through−all in phase so there is a bright spot on the screen

(b) Consider rays moving at an angle θ such that the ray from the TOP of the slit travels *exactly* one λ farther than the ray at the BOTTOM edge. The middle ray will therefore travel ½ λ and destructively interfere.

Similarly a ray above the bottom one will cancel a ray the same distance above the central one. English translation: each ray below the central one will cancel a ray above the central one as its "pair". The θ at which this occurs is when $\lambda = D \sin\theta$ so....
$\sin\theta = \lambda/D$ [first minimum]

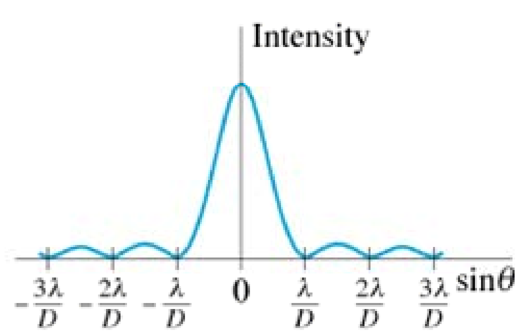
The light intensity is a max at $\theta = 0°$ and decreases to a minimum when
$\sin\theta = \lambda/D$

(c) Consider a larger θ such that the top ray travels 3/2 λ farther than the bottom ray. Now the rays from the bottom 1/3 of the slit cancel in pairs rays from the middle 1/3 since they will be ½ λ apart, leaving the top 1/3 of the rays to [you guessed it] hit the screen. A dim spot will be seen.

(d) Consider a larger θ still. One that the top ray travels 2 λ farther than the bottom ray. Rays in the bottom 1/4 will cancel in pairs those from the 1/4 just above it since their paths differ by ½ λ. The rays from the 1/4 just above the center will cancel the top 1/4 so darkness.

Minima occur at $D \sin\theta = m\lambda$, $m = 1,2,3...$ BUT not at $m = 0$−that's a maxima not a minima!!

Plot this puppy: notice the min for single slit is very similar to that for the max for double-slit interference.



Be sure and check out this Dr. Quantum explanation and animation. It's WAY better than these notes!
http://www.youtube.com/watch?v=DfPeprQ7oGc

Maybe I should have led with Dr. Quantum…

Example 18

Light of λ 750 nm passes through a slit 1.0×10^{-3} mm wide. How wide is the central maximum in

a) degrees

b) in centimeters, on a screen 20 cm away?