Lecture Demos

M3-42 FABRY-PEROT INTERFEROMETER – SODIUM
M4-25 INTERFERENCE IN LARGE SOAP FILM - SODIUM AND WHITE
N1-14: REFLECTION GRATING – LARGE

L4-02: REFRACTION - BEER MUG IN WATER
L4-03: REFRACTION - ROD IN WATER
L4-06: REFRACTION IN CLOUDY WATER

L5-13: PLEXIGLASS SPIRAL WITH LASER
L5-11: LASER WATERFALL

L6-09: REAL IMAGE OF CONVERGING LENS
  combine with above:
  (L6-14): IMAGE OF CONVEX LENS - WITH AND WITHOUT BAFFLE

L3-16: FOCUSING OF HEAT WAVES BY MIRRORS
L3-18: FOCUSING OF HEAT WAVES - OVERHEAD PROJECTOR

L3-23: IMAGE ON SCREEN USING CONCAVE MIRROR
L3-31: GIANT MIRROR - CONCAVE AND CONVEX

Change of Class room: See schedule on website

Where:
Chemistry building
(attached to Physics building)
Room # 1402

When:
October: 8, 13, 20, 27, and 29

Exam I – Will be graded and posted by Tuesday next week

Problem 1 - B and E transformation between moving frames
Quiz #3b, Hwk #35.5

Problem 2 - Biot-Savart law from current Arc
example done in class, Hwk problem 34.46, quiz #1a and #1d

Problem 3 - Solenoid - very similar to Hwk # 34.40
a) derivation in class and in book, one of the few examples of the utility of ampere's law
b) RHR for direction of B-field from current
c) E-field inside solenoid very similar to quiz #3a
d) E-field direction application of Lenz's law (lots of homework)

Problem 4 - E&M traveling wave
Derived in class and in book (eq 35.24), wave direction ~ S ~ E x B, B=E/c, S is intensity, meaning of "plane wave"

Problem 5 - RLC circuit -
Hwk problem 36.8, and strongly related to 36.7

Problem 6 - displacement current between parallel capacitors
Quiz #3d, Hwk problem 35.38

Different limits for light behavior

Three limits for observing properties of light:

1. Physical optics – light as a wave

Energy of photon, $\hbar\omega \ll$ resolution of detector

size of objects $\lesssim \lambda$

2. Ray optics --- light

Energy of photon, $\hbar\omega \ll$ resolution of detector

size of objects $\gg \lambda$

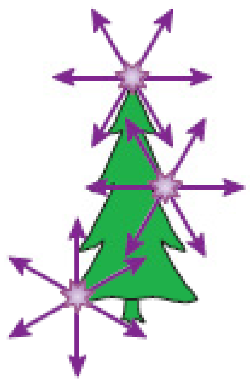
3. quantum regime

Energy of photon, $\hbar\omega \gtrsim$ resolution of detector

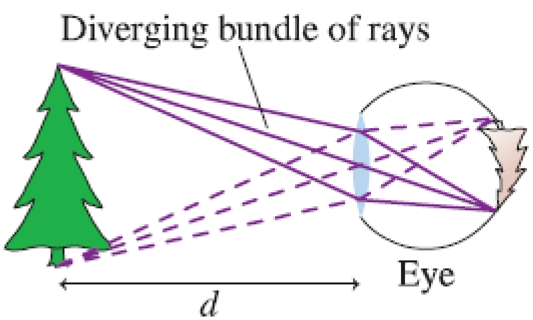
Ray optics -- Light travels in straight lines in direction of Poynting vector

Light Rays

Ray optics -- Light travels in straight lines in direction of Poynting vector



An object is a source of light rays, emanating from every point in all directions --- scattered light and light sources

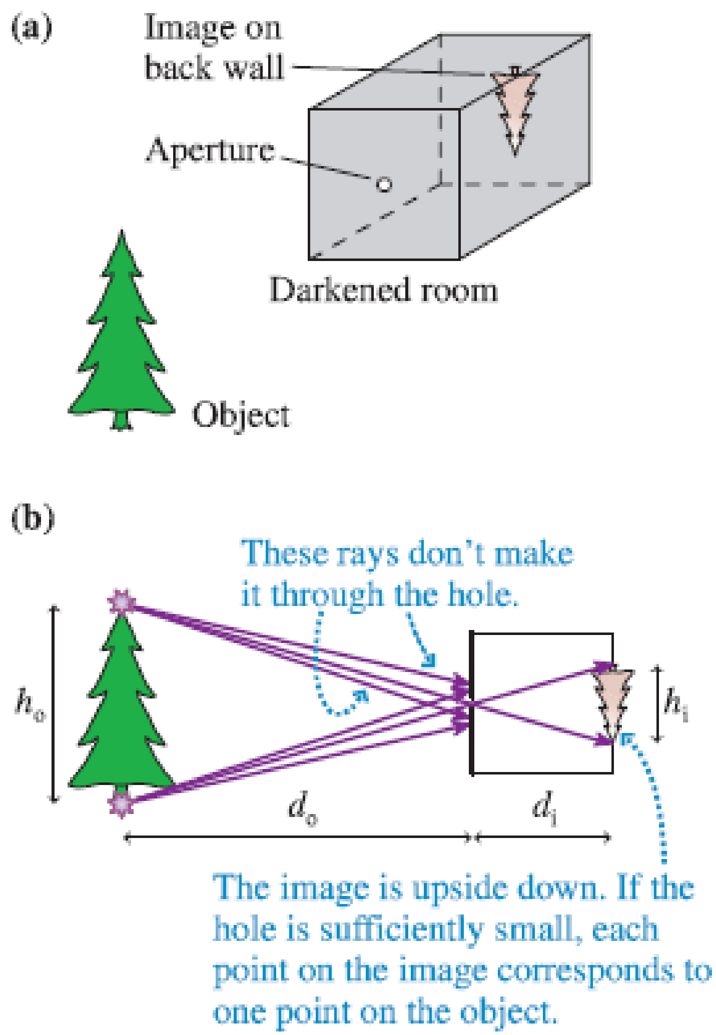


The eye is sensitive to how much the rays are diverging to give a sense of where object is located in space (eye separation is the main mechanism, not just from one eyeball).

Think of this as triangulating back to the source of the diverging rays to find where source is located.

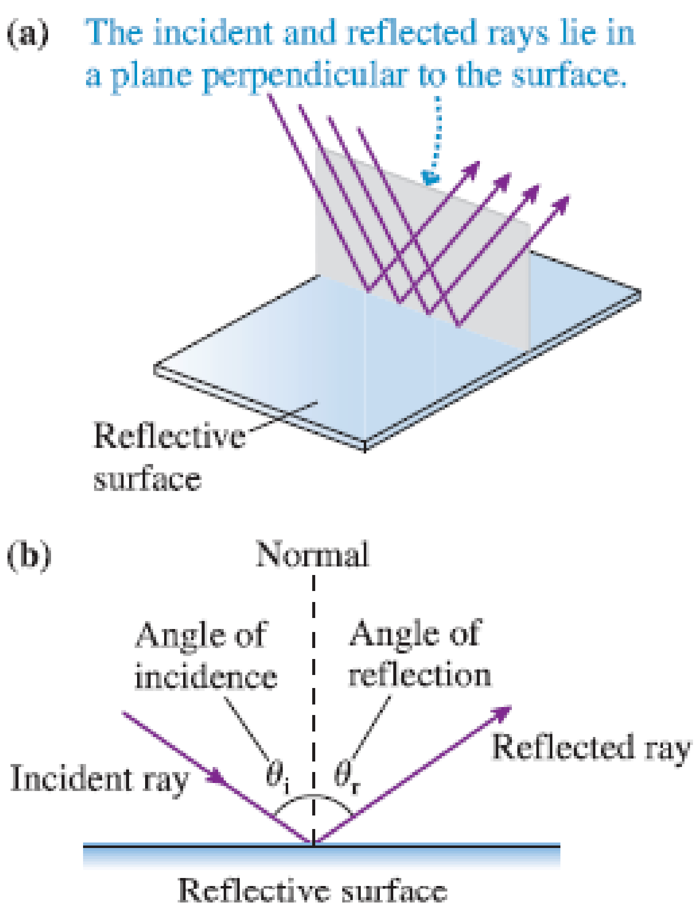
Ray diagram

FIGURE 23.5 A camera obscura.



Law of reflection (specular)

FIGURE 23.7 Specular reflection of light.

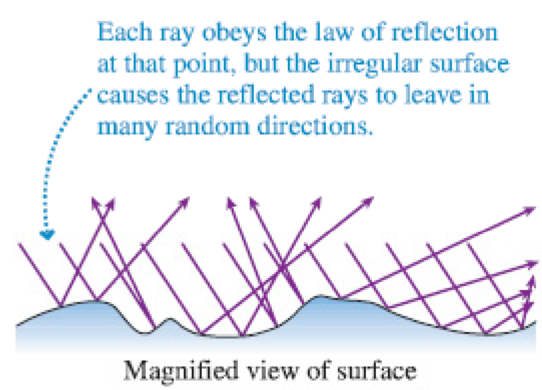


Specular reflection (object smooth and flat over an area large compared to wavelength)

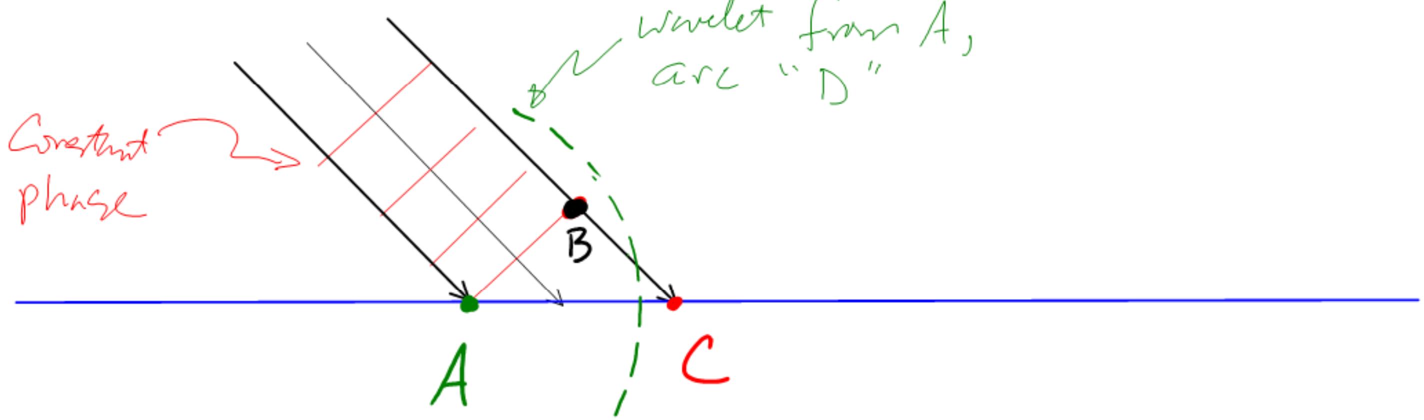
For large flat mirror:
Angle of incidence = angle of reflection

Diffusive reflection (object not smooth, but locally obeys the law of reflection)

FIGURE 23.9 Diffuse reflection from an irregular surface.

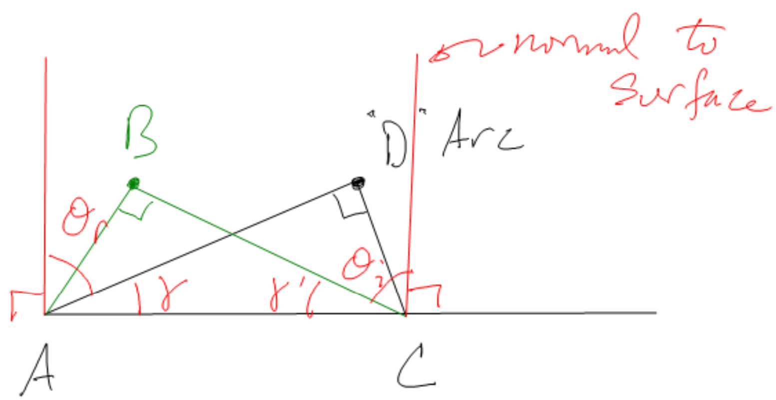


Law of Reflection Derivation from Huygen's Principle:



$\overline{BC} = c\Delta t$, $\overline{AD} = c\Delta t \Rightarrow \overline{BC} = \overline{AD}$

New wavefront tangent to "D" Arc & connects to pt. C.
Note that new reflected wave front is plane wave (sum of many wavelets from surface)



Two Right triangles where $\overline{AD} = \overline{BC}$

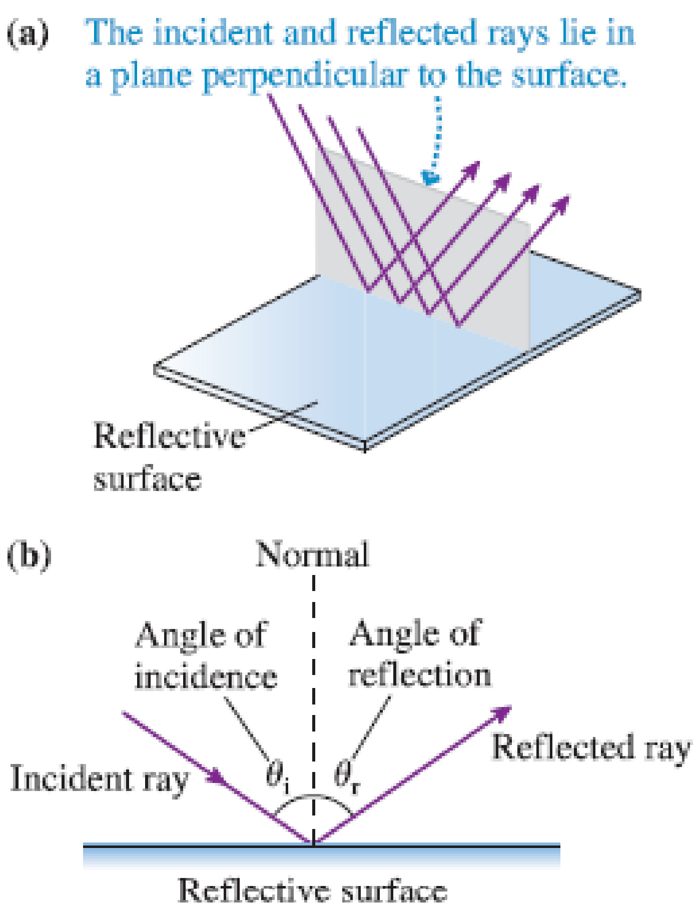
& Same hypotenuse, $\overline{AC}$

$\Rightarrow \gamma = \gamma'$

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

Law of reflection (specular)

FIGURE 23.7 Specular reflection of light.



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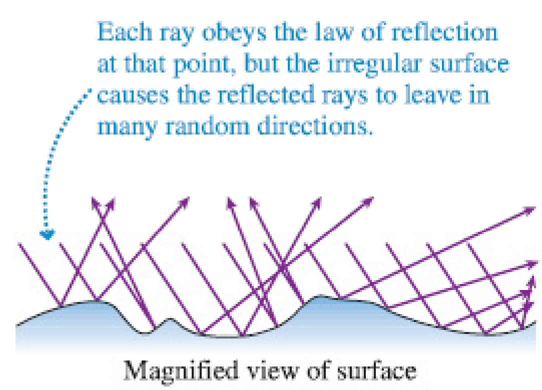
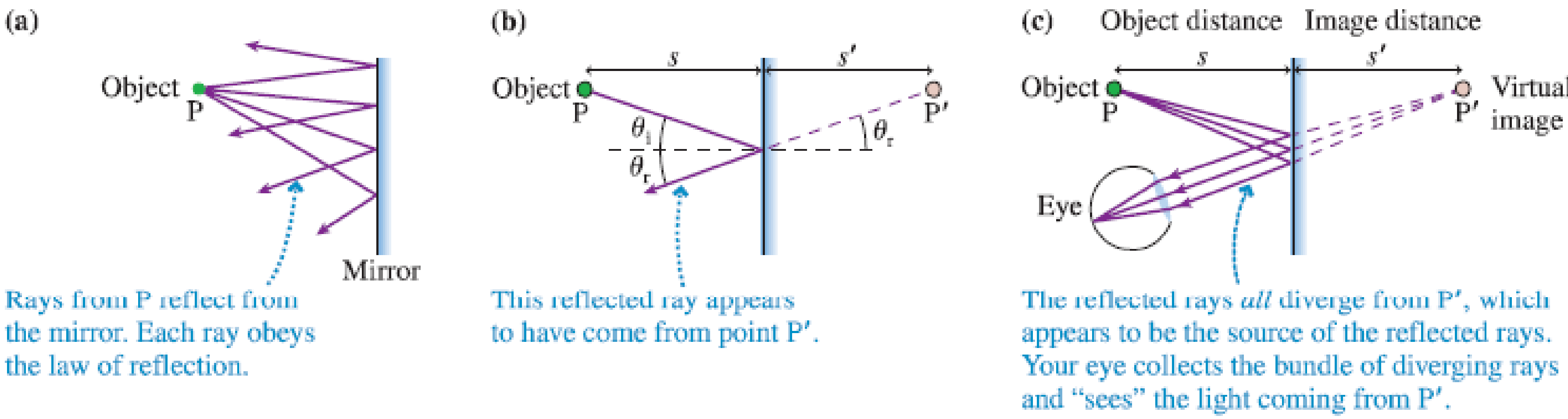


Law of reflection

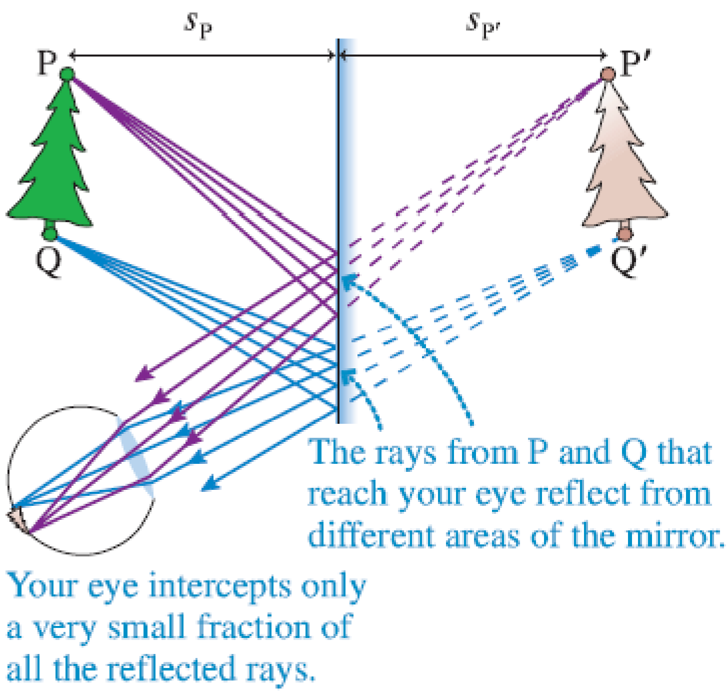
FIGURE 23.10 The light rays reflecting from a plane mirror.



$$s' = s \qquad \text{(plane mirror)}$$

Law of reflection

FIGURE 23.11 Each point on the extended object has a corresponding image point an equal distance on the opposite side of the mirror.

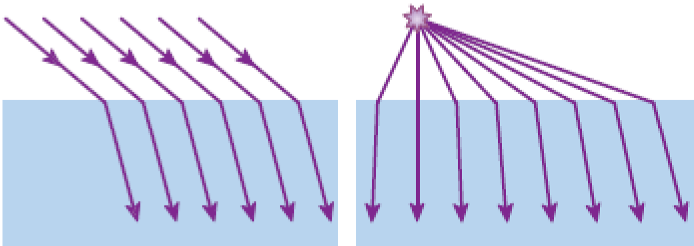


Virtual image – light rays do not physically pass through image.

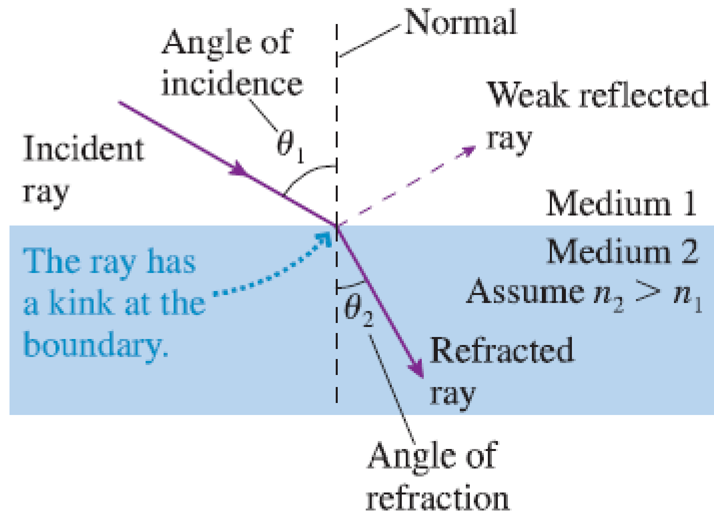
Eye perceives the rays diverging from the image location

1. Rays from each point on the object spread out in all directions and strike *every point* on the mirror. Only a very few of these rays enter your eye, but the other rays are very real and might be seen by other observers.
2. Rays from points P and Q enter your eye after reflecting from *different* areas of the mirror. This is why you can't always see the full image of an object in a very small mirror.

Refraction



Refraction of a parallel beam of light and of rays from a point source



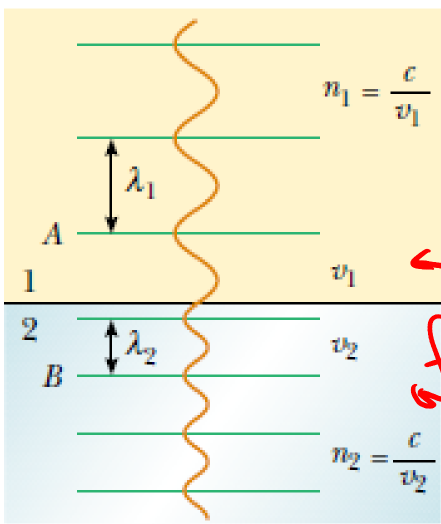


Figure 35.14 As a wave moves from medium 1 to medium 2, its wavelength changes but its frequency remains constant.

f the same
(Recall Fresnel Coef. "t")

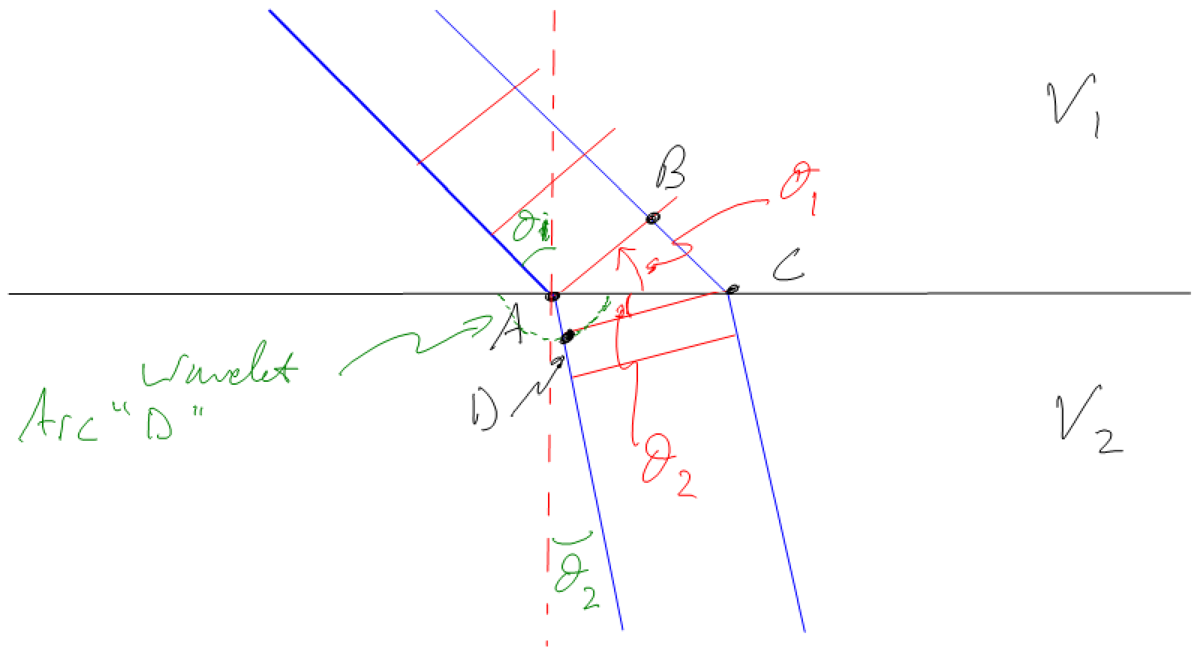
$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad \text{(Snell's law of refraction)}$$

$$n = \frac{c}{v_{\text{medium}}}$$

$$v_{\text{medium}} = c/n$$

$$\lambda f = v = \frac{c}{n} \text{ \& } \lambda_0 f = c \Rightarrow \lambda = \frac{\lambda_0}{n}$$

Proof of Snell's Law: Assume $V_2 < V_1$



Distance A to arc "D" = $V_2 \Delta t$

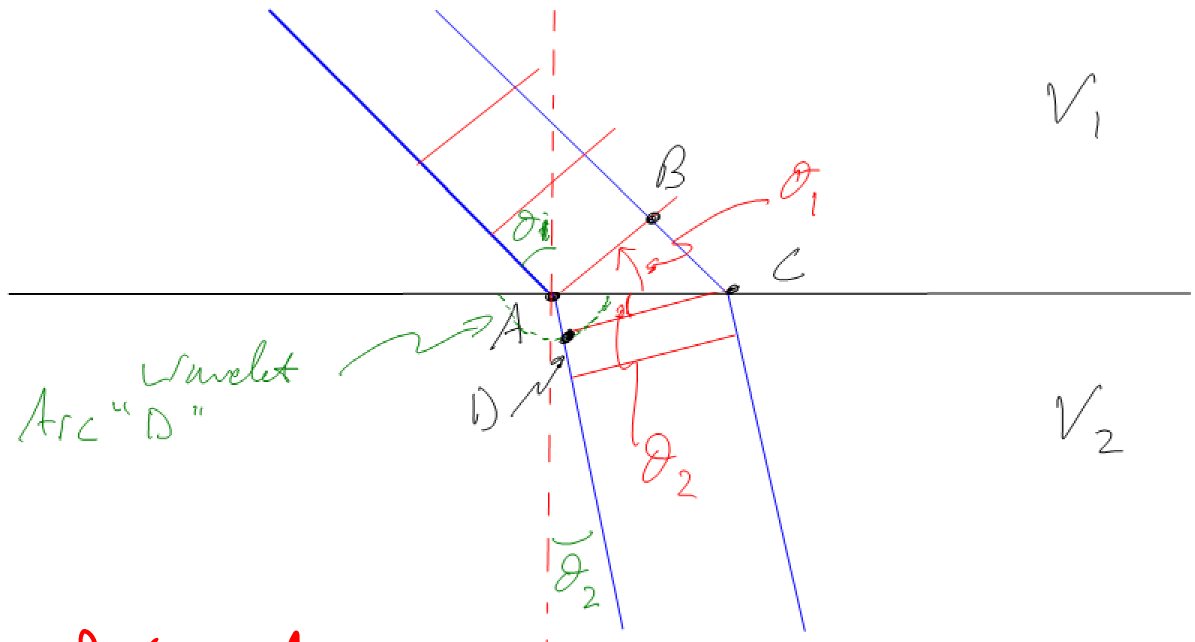
$\overline{BC} = V_1 \Delta t$

Bunch of wavelets along surface $\longrightarrow$ plane wave in medium 2 whose wavefront is tangent to wavelet

ΔABC + ΔADC have same hypotenuse

+ $$\frac{BC}{V_1} = \frac{AD}{V_2}$$

Proof of Snell's Law: Assume $V_2 < V_1$



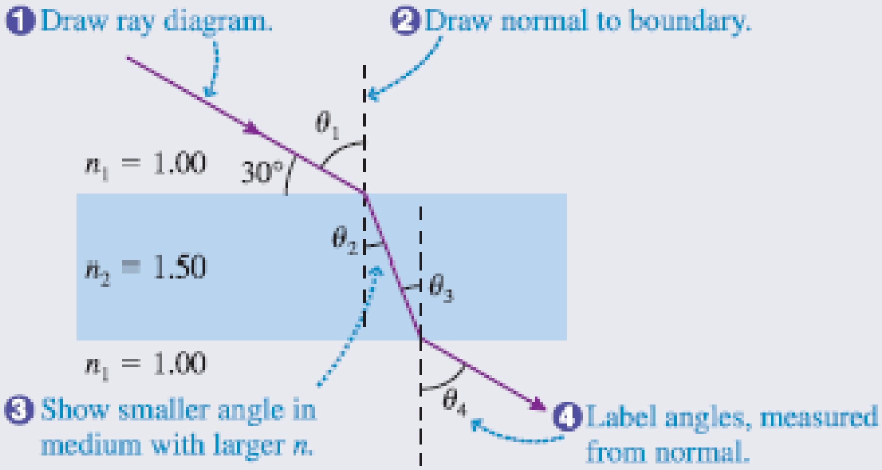
$$\frac{BC}{V_1} = \frac{AD}{V_2}$$

$$\sin\theta_1 = \frac{BC}{AC}, \quad \sin\theta_2 = \frac{AD}{AC}$$

$$\Rightarrow \quad \frac{\sin\theta_1}{\sin\theta_2} = \frac{BC}{AD} = \frac{V_1}{V_2} \quad ; \quad n_1 \equiv \frac{c}{V_1}, \quad n_2 \equiv \frac{c}{V_2}$$

$$\Rightarrow \quad n_1 \sin\theta_1 = n_2 \sin\theta_2$$

FIGURE 23.17 The ray diagram of a laser beam passing through a sheet of glass.



SOLVE a. Snell's law, the final step in the Tactics Box, is $n_1 \sin\theta_1 = n_2 \sin\theta_2$. Using $\theta_1 = 60°$, we find that the direction of travel in the glass is

$$\theta_2 = \sin^{-1}\left(\frac{n_1 \sin\theta_1}{n_2}\right) = \sin^{-1}\left(\frac{\sin 60°}{1.5}\right)$$
$$= \sin^{-1}(0.577) = 35.3°$$

b. Snell's law at the second boundary is $n_2 \sin\theta_3 = n_1 \sin\theta_4$. You can see from Figure 23.17 that the interior angles are equal: $\theta_3 = \theta_2 = 35.3°$. Thus the ray emerges back into the air traveling at angle

$$\theta_4 = \sin^{-1}\left(\frac{n_2 \sin\theta_3}{n_1}\right) = \sin^{-1}(1.5 \sin 35.3°)$$
$$= \sin^{-1}(0.867) = 60°$$

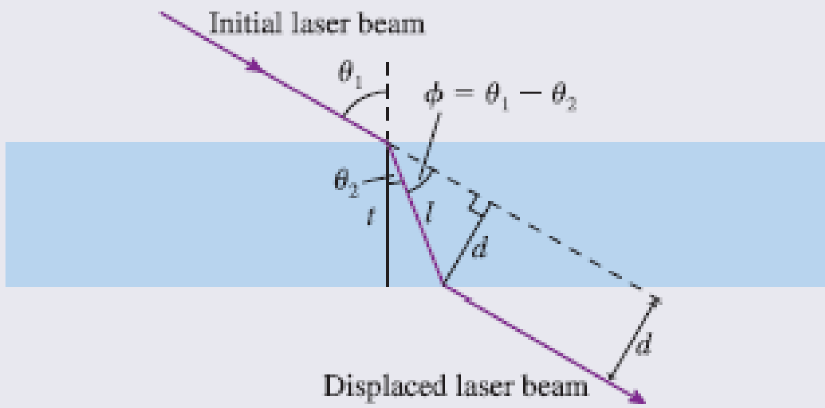
This is the same as θ_1, the original angle of incidence. The glass doesn't change the direction of the laser beam.

c. Although the exiting laser beam is parallel to the initial laser beam, it has been displaced sideways by distance d. FIGURE 23.18 shows the geometry for finding d. From trigonometry, $d = l \sin\phi$. Further, $\phi = \theta_1 - \theta_2$ and $l = t/\cos\theta_2$, where t is the thickness of the glass. Combining these gives

$$d = l \sin\phi = \frac{t}{\cos\theta_2}\sin(\theta_1 - \theta_2)$$
$$= \frac{(1.0 \text{ cm}) \sin 24.7°}{\cos 35.3°} = 0.51 \text{ cm}$$

The glass causes the laser beam to be displaced sideways by 0.51 cm.

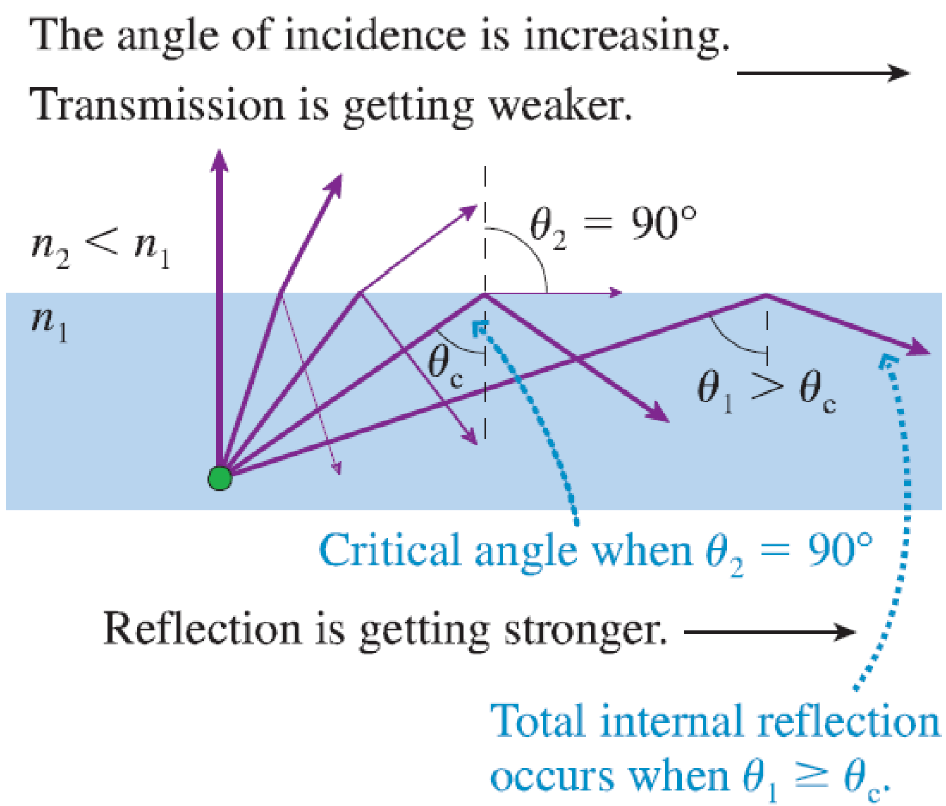
FIGURE 23.18 The laser beam is deflected sideways by distance d.



ASSESS The laser beam exits the glass still traveling in the same direction as it entered. This is a general result for light traveling through a medium with parallel sides. Notice that the displacement d becomes zero in the limit $t \to 0$. This will be an important observation when we get to lenses.

Total Internal Reflection

FIGURE 23.22 Refraction and reflection of rays as the angle of incidence increases.



$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$\theta_2 \Rightarrow 90°, \; \theta_1 \equiv \theta_c$$

$$\Rightarrow n_1 \sin\theta_c = n_2$$

$$\text{or} \quad \sin\theta_c = \frac{n_2}{n_1}$$

Total Internal Reflection – Fiber optics

FIGURE 23.25 Light rays are confined within an optical fiber by total internal reflection.

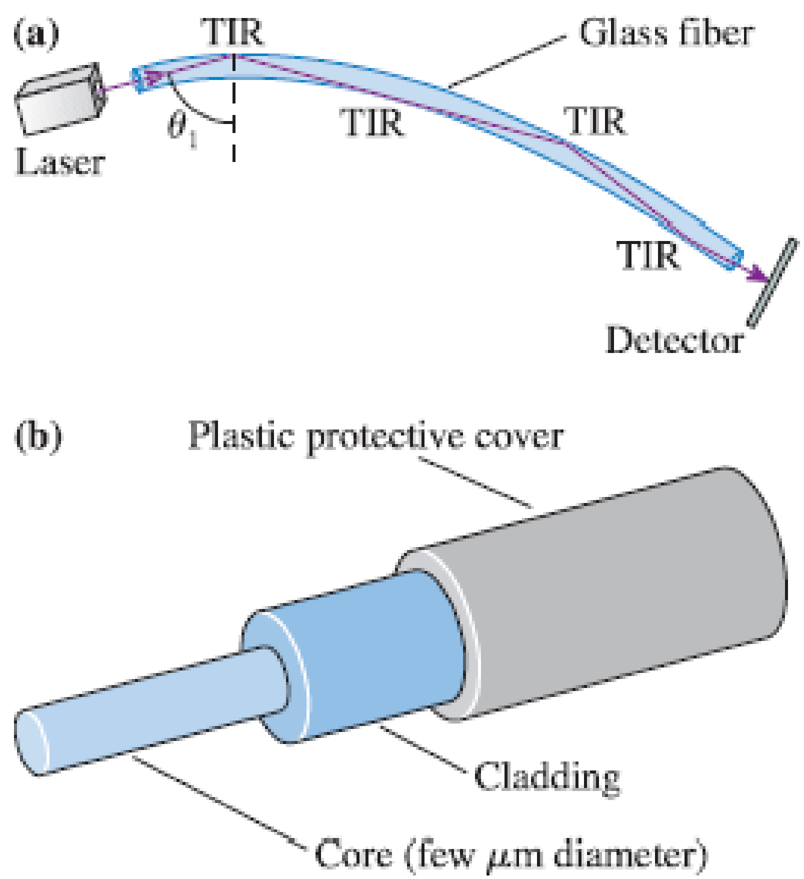


Image formation by Refraction

line perpendicular to the boundary is called the **optical axis**

s is called the **object distance** s', the **image distance**

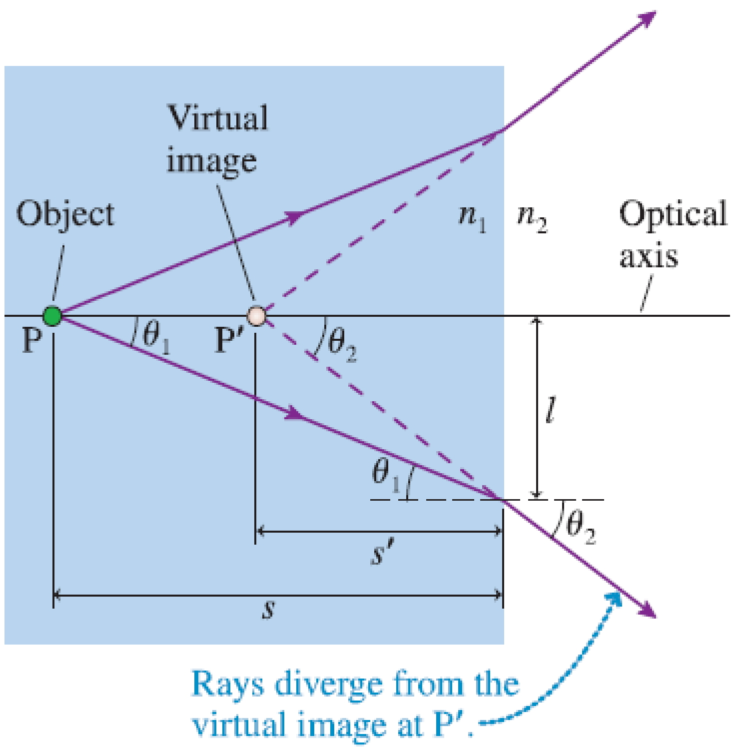


FIGURE 23.27 Finding the virtual image P′ of an object at P. We've assumed $n_1 > n_2$.

$$l = s\tan\theta_1 = s'\tan\theta_2$$

$$s' = \frac{\tan\theta_1}{\tan\theta_2}s$$

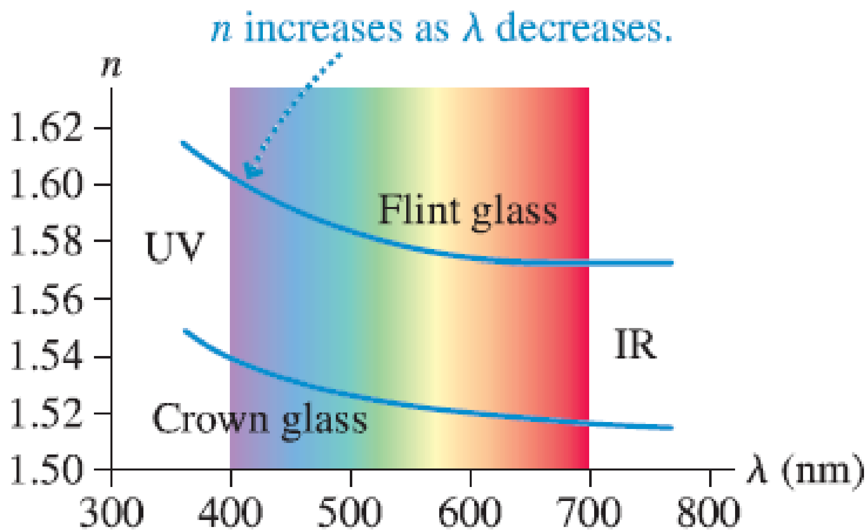
Snell's law $$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

paraxial rays $$\sin\theta \approx \tan\theta \approx \theta$$

$$\frac{\tan\theta_1}{\tan\theta_2} \approx \frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

$$s' = \frac{n_2}{n_1}s$$

Dispersion



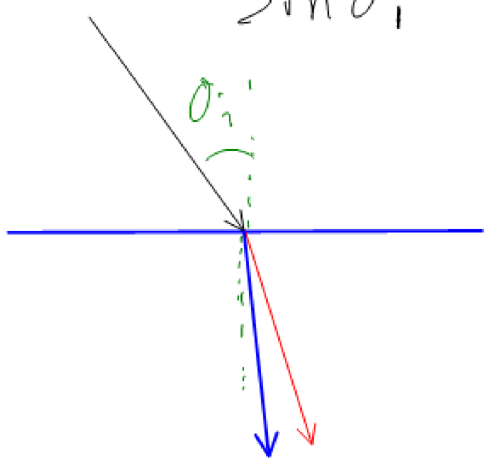
Color	Approximate wavelength
Deepest red	700 nm
Red	650 nm
Green	550 nm
Blue	450 nm
Deepest violet	400 nm

Index of refraction can be a function of frequency (or wavelength). Therefore, different frequencies will diffract to different angles via Snell's law:

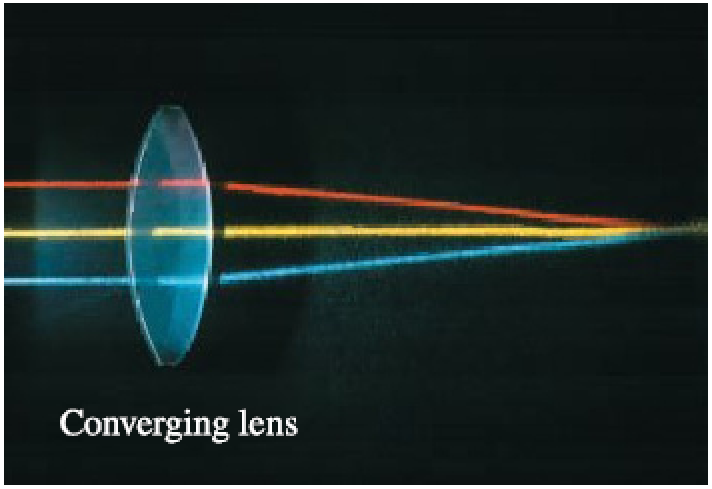
Consider Air into media of index $n(\omega)$:

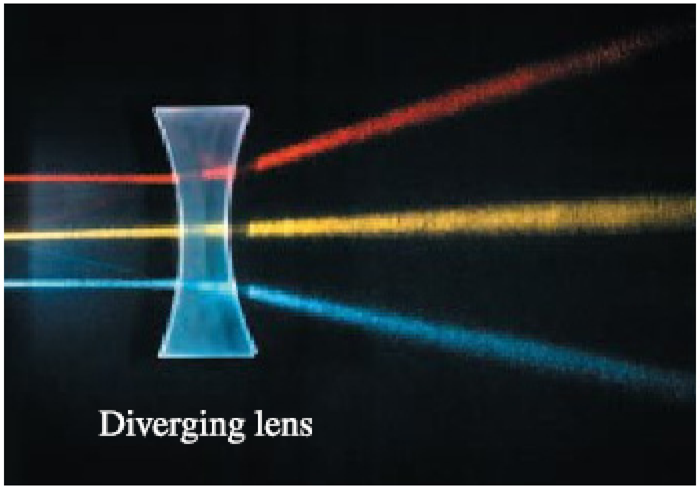
$$\sin\theta_1 = n(\omega)\sin\theta_2 \Rightarrow$$

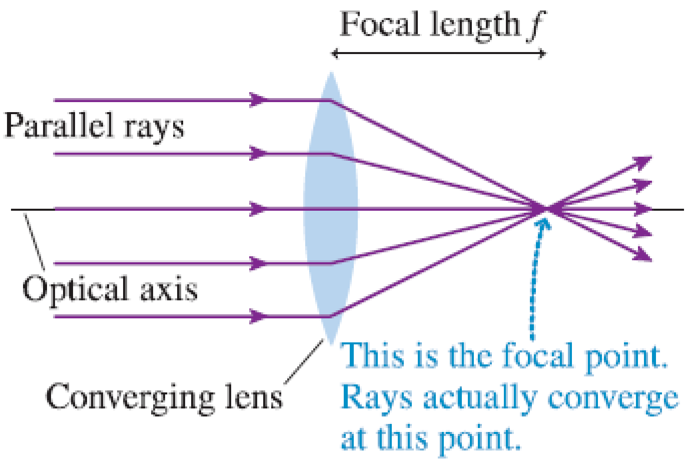
$$\theta_2(\omega) = \sin^{-1}\left(\frac{\sin\theta_1}{n(\omega)}\right)$$

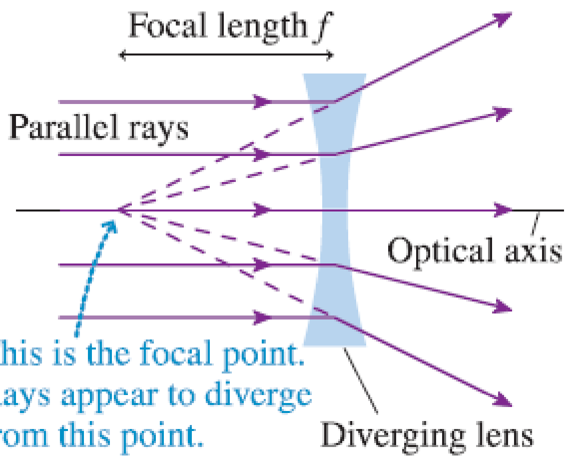


Thin Lenses -- Intro

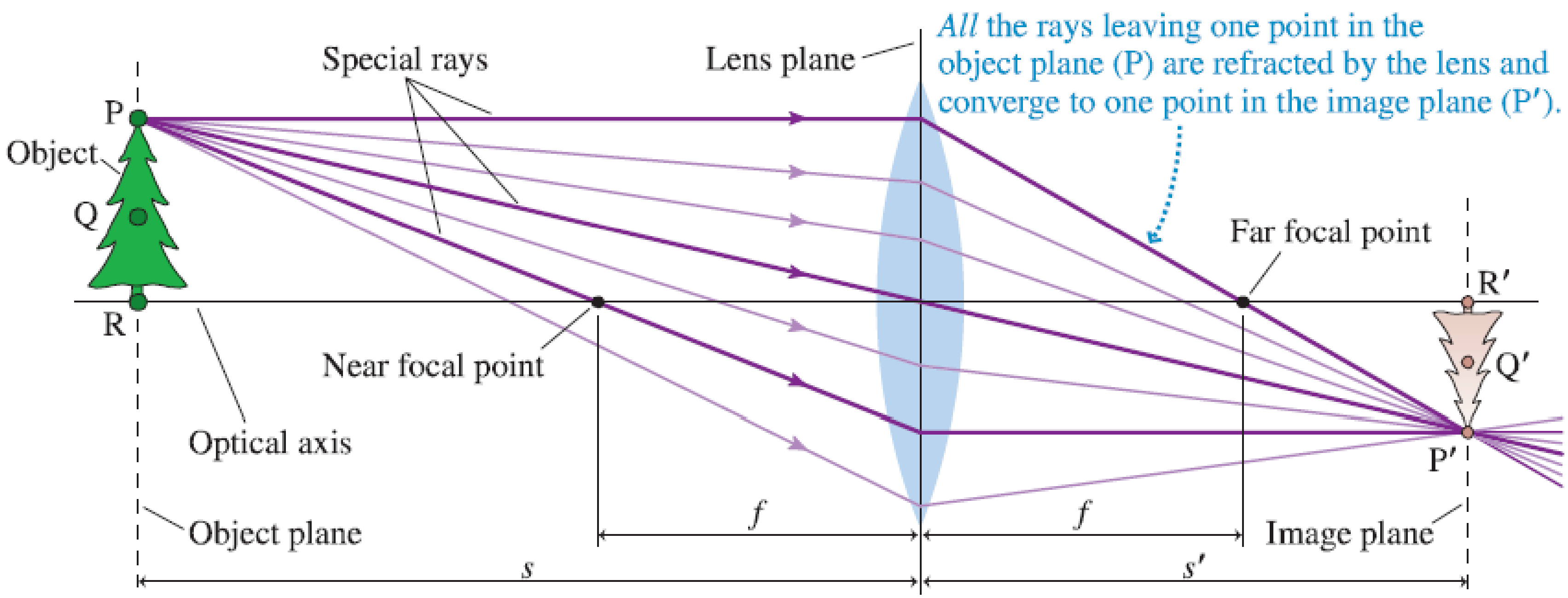








Thin Lenses -- Intro

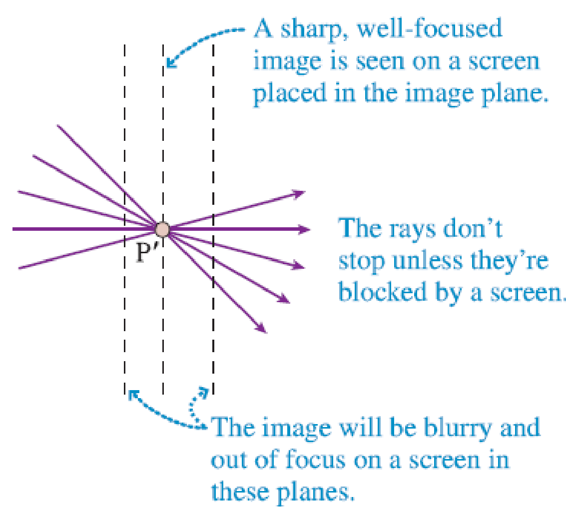


All points on the object that are in the same plane, the **object plane**.

image points in the **image plane.**

P′ a **real image**

inverted image,



Thin Lenses -- Intro

FIGURE 23.39 Rays from an object at distance $s < f$ are refracted by the lens and diverge to form a virtual image.

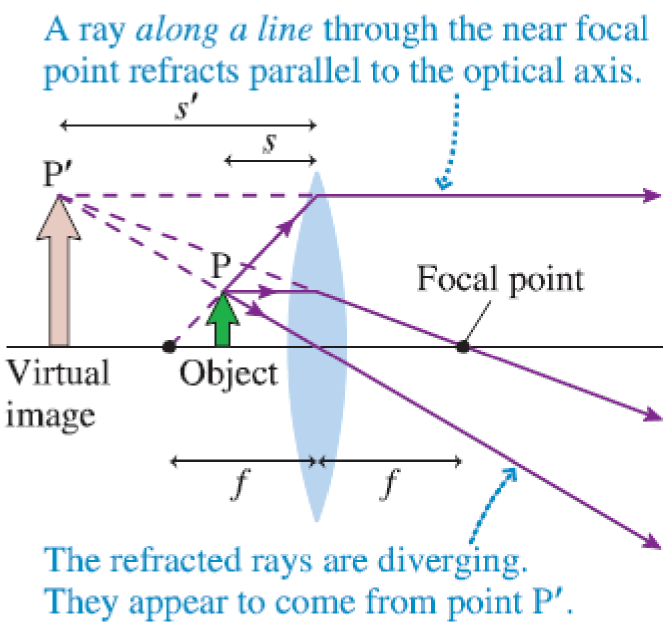
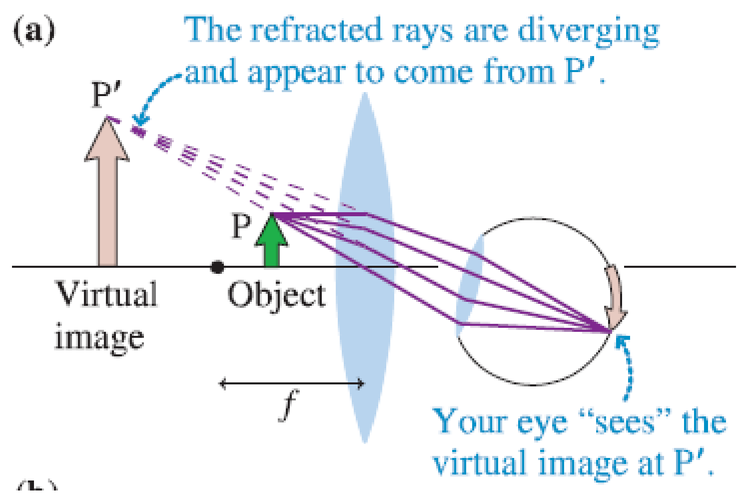
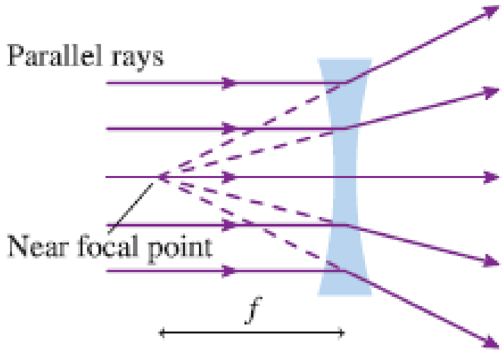


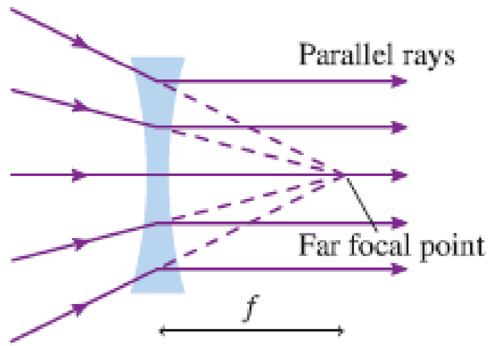
FIGURE 23.40 A converging lens is a magnifying glass when the object distance is less than f.



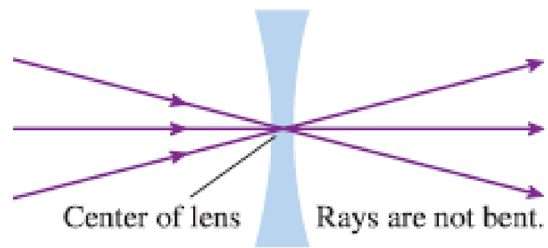
Thin Lenses, Diverging Lens -- Intro



Any ray initially parallel to the optical axis diverges along a line through the near focal point.

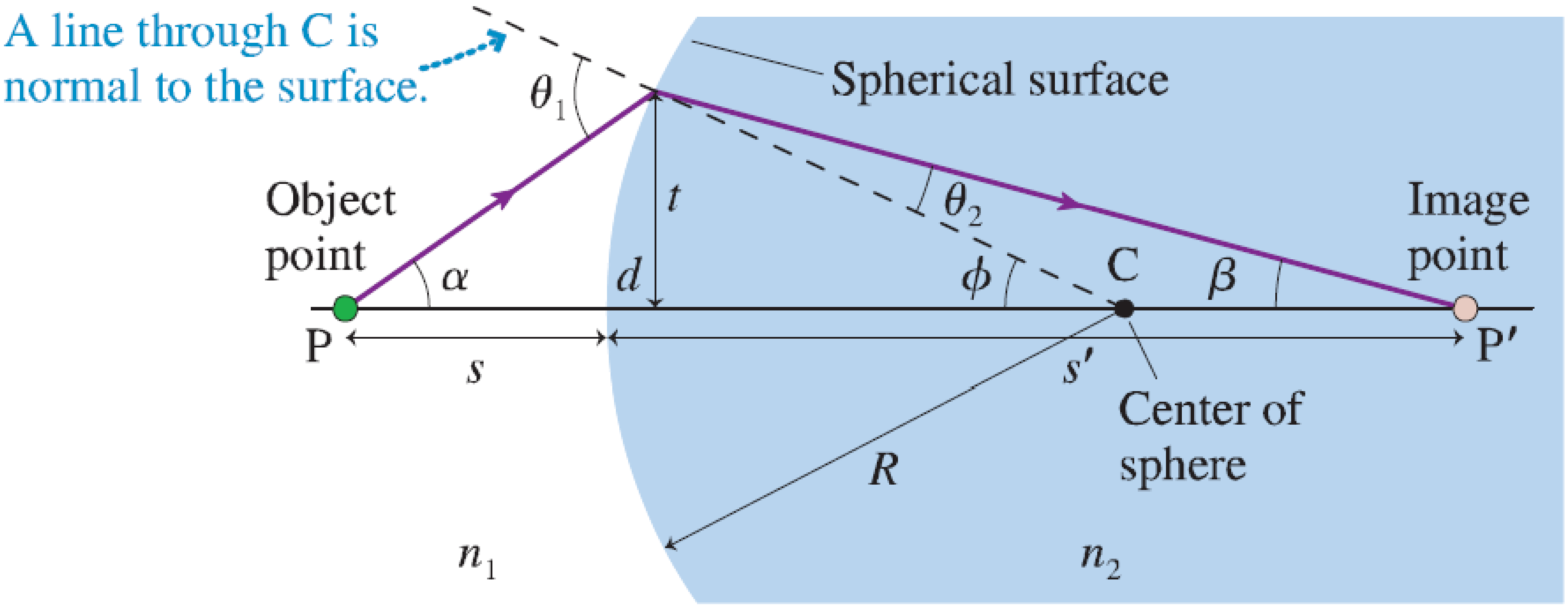


Any ray directed along a line toward the far focal point emerges from the lens parallel to the optical axis.



Any ray directed at the center of the lens passes through in a straight line.

Imaging at refractory surface



$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$n_1\theta_1 = n_2\theta_2$$

$$\theta_1 = \alpha + \phi$$

$$\theta_2 = \phi - \beta$$

$$n_1(\alpha + \phi) = n_2(\phi - \beta)$$

$$\tan\alpha \approx \alpha = \frac{t}{s + d} \qquad \tan\beta \approx \beta = \frac{t}{s' - d} \qquad \tan\phi \approx \phi = \frac{t}{R - d}$$

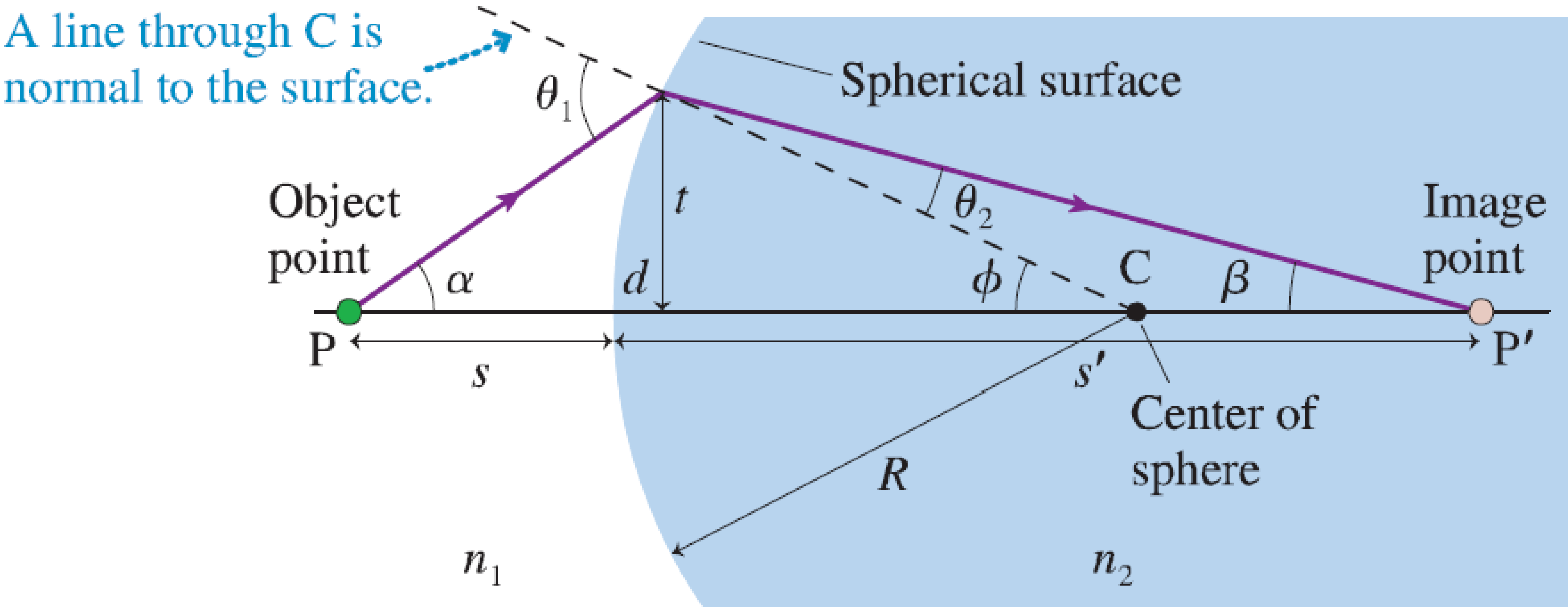
But $d \to 0$ for paraxial rays, thus

$$\alpha = \frac{t}{s} \qquad \beta = \frac{t}{s'} \qquad \phi = \frac{t}{R}$$

$$n_1\left(\frac{t}{s} + \frac{t}{R}\right) = n_2\left(\frac{t}{R} - \frac{t}{s'}\right)$$

$$\boxed{\frac{n_1}{s} + \frac{n_2}{s'} = \frac{n_2 - n_1}{R}}$$

Imaging at refractory surface – Convex



Assumed $s > 0, s' > 0, R > 0$

$$\frac{n_1}{s} + \frac{n_2}{s'} = \frac{n_2 - n_1}{R}$$

Imaging at refractory surface – Concave

$$n_1 \theta_1 = n_2 \theta_2 \quad , \quad \begin{array}{l} \beta + \theta_2 + (\pi - \phi) = \pi \Rightarrow \theta_2 = \phi - \beta \\ \alpha + \theta_1 + (\pi - \phi) = \pi \Rightarrow \theta_1 = \phi - \alpha \end{array}$$

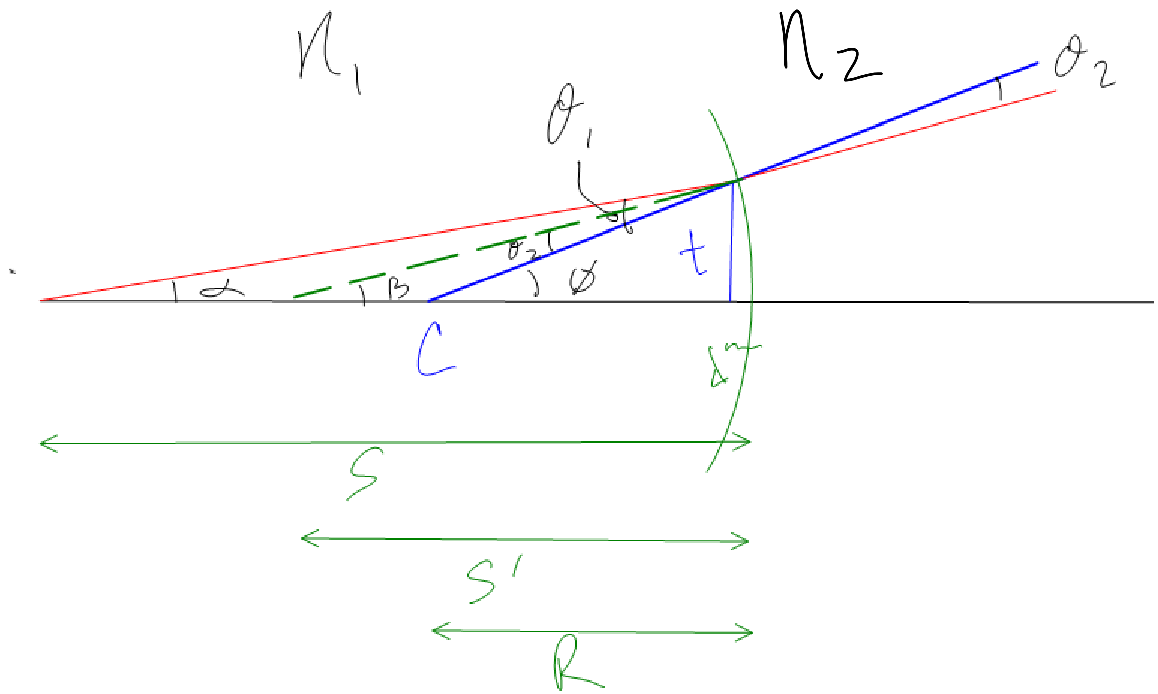
$$\phi \approx \frac{t}{R-d} \; , \; \beta = \frac{t}{s'-d} \; , \; \alpha = \frac{t}{s-d}$$

$$\Rightarrow \quad n_1(\phi - \alpha) = n_2(\phi - \beta)$$

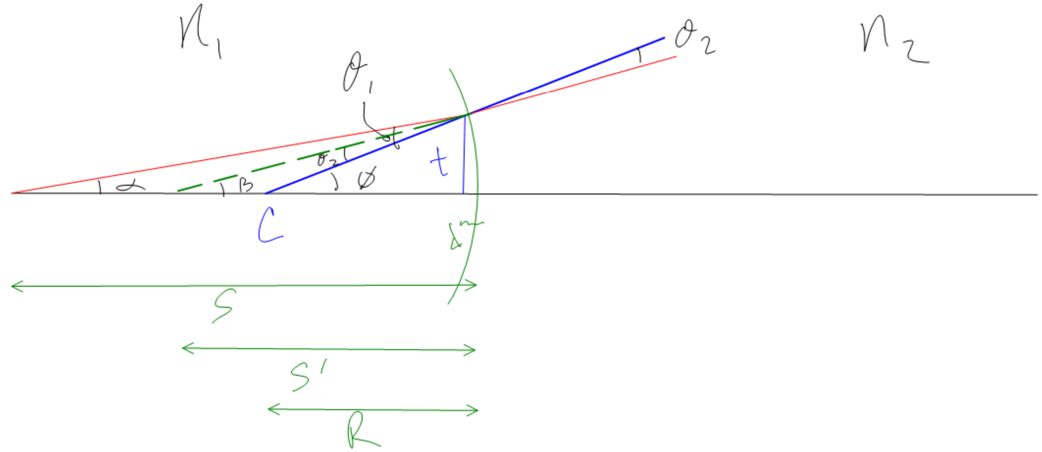
$$\Rightarrow \quad n_2 \beta - n_1 \alpha = (n_2 - n_1)\phi$$

$$\Rightarrow \quad \frac{n_2}{s'} - \frac{n_1}{s} = \frac{n_2 - n_1}{R}$$

$$\Rightarrow \quad \frac{n_1}{s} - \frac{n_2}{s'} = -\frac{n_2 - n_1}{R}$$



Imaging at refractory surface – Concave



$$\Rightarrow \quad \frac{n_1}{s} - \frac{n_2}{s'} = -\frac{n_2 - n_1}{R}$$

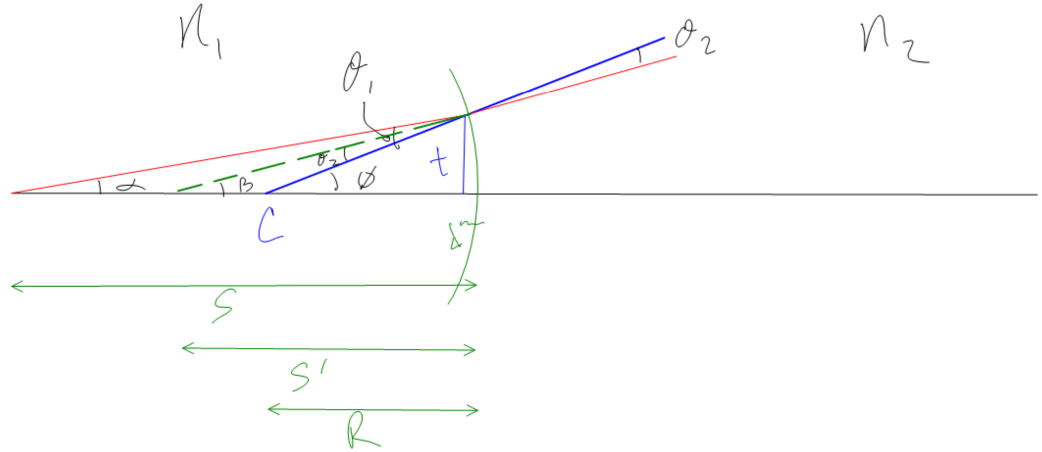
$\therefore$ Let $R < 0$ when on left side of concave interface

& $s' < 0$ " " " " " " "

$$\Rightarrow \quad \boxed{\frac{n_1}{s} + \frac{n_2}{s'} = \frac{n_2 - n_1}{R}}$$

looks like formula above provided we remember signs! ($R < 0$, $s' < 0$)

Imaging at refractory surface – Flat



$$\Rightarrow \quad \boxed{\frac{n_1}{s} + \frac{n_2}{s'} = \frac{n_2 - n_1}{R}}$$

looks like formula above provided we remember signs! ($R < 0$, $s' < 0$)

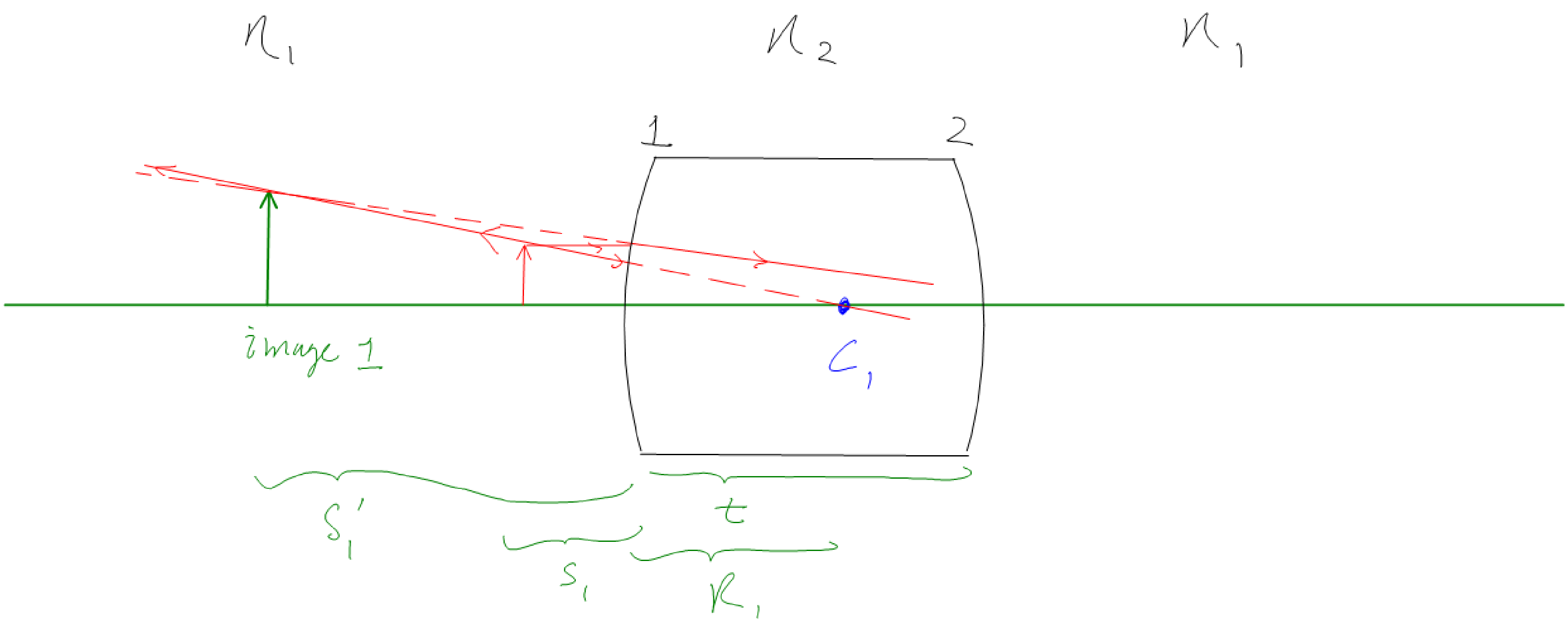
for a planar interface, let $R \to \infty$

$$\Rightarrow \quad s' = -\frac{n_2}{n_1} s$$

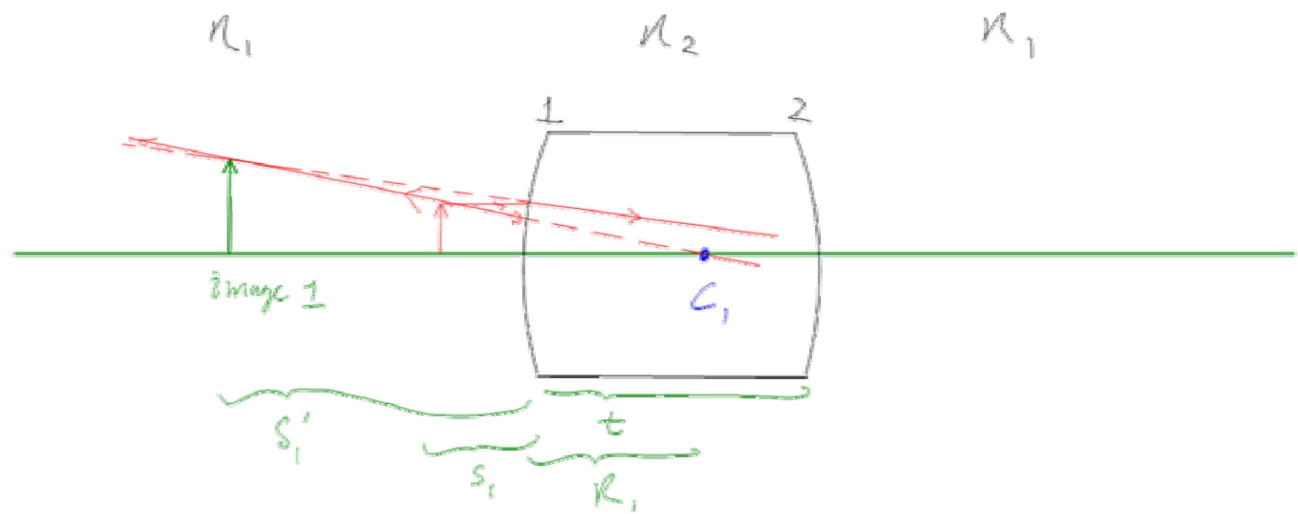
Consider a <u>thick</u> lens with two surfaces:

Image of surface 1 becomes object of surface 2

Case I: image 1 to <u>left</u> of surface 2:



$S_1 > 0$, $R_1 > 0$, $S_1' < 0$



① $$\frac{n_1}{S_1} + \frac{n_2}{S_1'} = \frac{n_2 - n_1}{R_1}$$

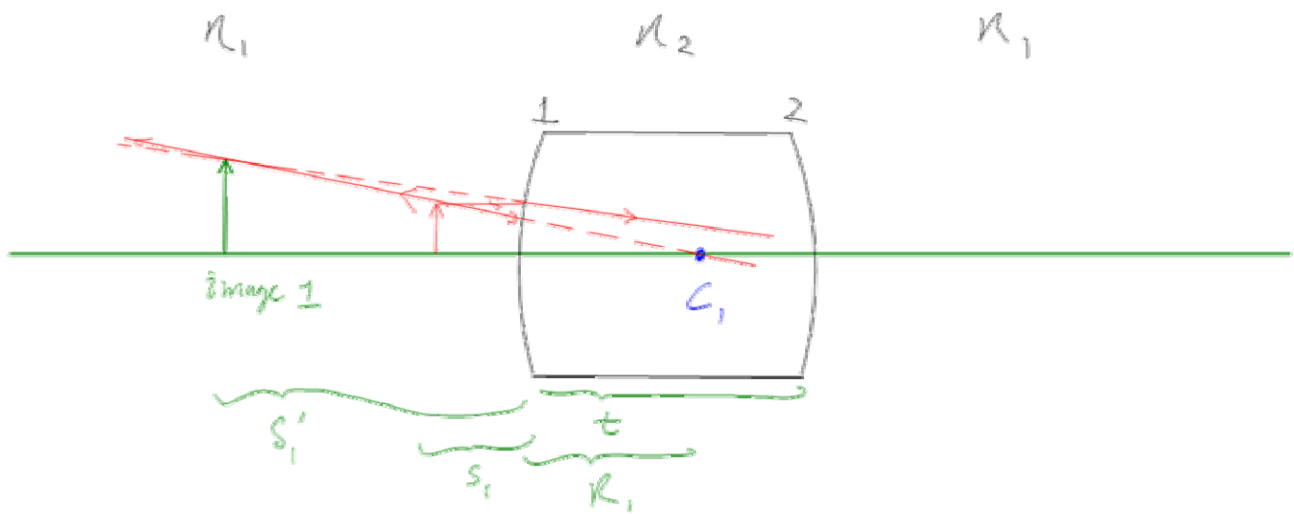
② $S_2 = t + |S_1'| = t - S_1'$ since $S_1' < 0$

③ $$\frac{n_2}{S_2} + \frac{n_1}{S_2'} = \frac{n_1 - n_2}{R_2}$$ where $R_2 < 0$, $\cancel{S_2' > 0}$, $S_2 > 0$

Lim $t \to 0$ (thin lens limit): $S_2 = -S_1'$ ④

③+④ $$\frac{n_2}{-S_1'} + \frac{n_1}{S_2'} = \frac{n_1 - n_2}{R_2}$$

① $\Rightarrow$ $$\frac{n_1}{S_1} - \frac{n_2 - n_1}{R_1}$$

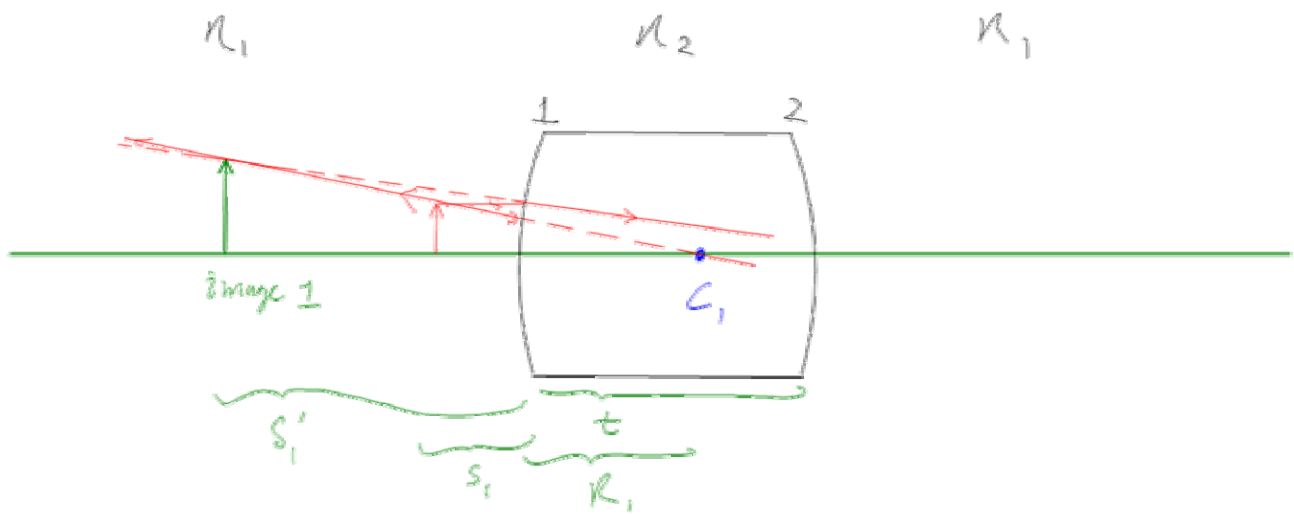


③ + ④ $$\frac{n_2}{-s_1'} + \frac{n_1}{s_2'} = \frac{n_1 - n_2}{R_2}$$

① $\Rightarrow$ $$\frac{n_1}{s_1} - \frac{n_2 - n_1}{R_1}$$

$$\Rightarrow \frac{n_1}{s_1} - \frac{n_2 - n_1}{R_1} + \frac{n_1}{s_2'} = \frac{n_1 - n_2}{R_2}$$

$$\Rightarrow \frac{n_1}{s_1} + \frac{n_1}{s_2'} = (n_2 - n_1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$



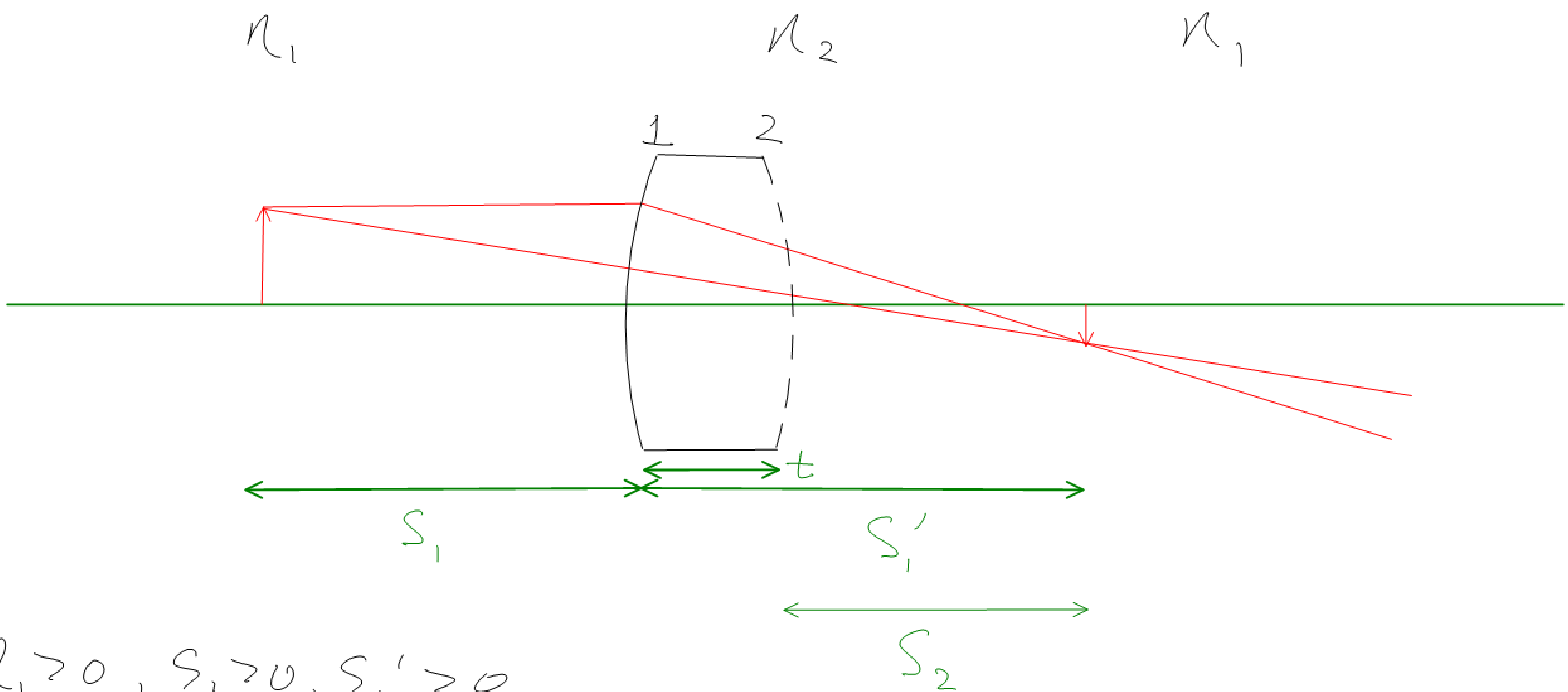
$$\Rightarrow \quad \frac{n_1}{S_1} + \frac{n_1}{S_2'} = (n_2 - n_1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

$n_1 = 1$ for air or vacuum

$$\Rightarrow \quad \frac{1}{S} + \frac{1}{S'} = (n_2 - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

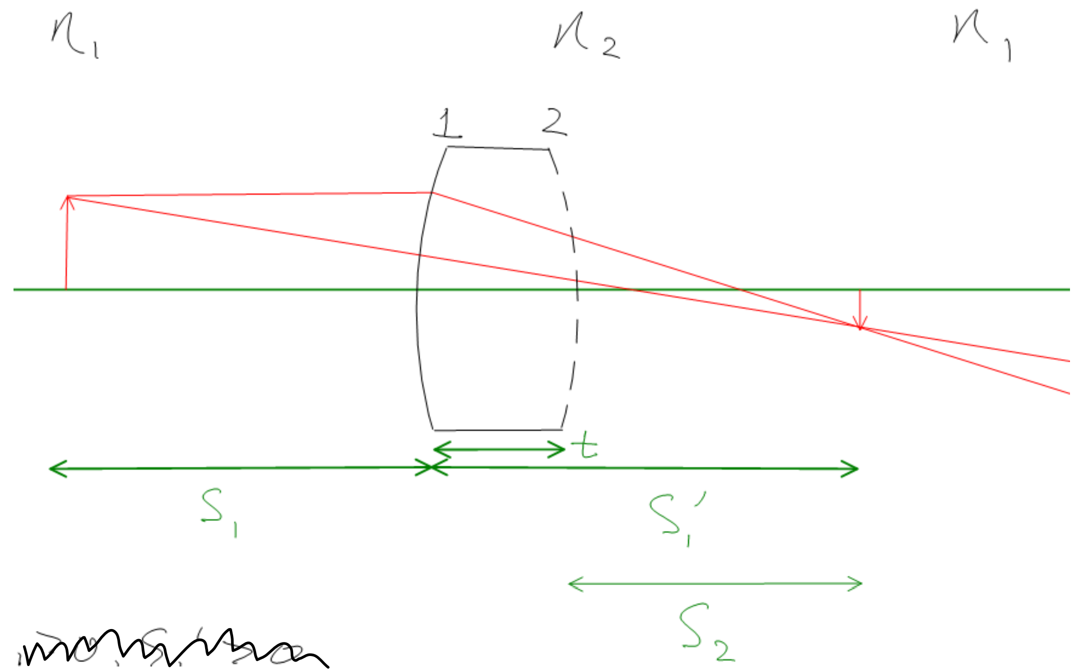
$S_1 > 0, \; R_1 > 0, \; S_1' < 0, \; R_2 < 0$

Case II: S_1' to the Right of surface 2



$R_1 > 0$, $S_1 > 0$, $S_1' > 0$

$S_2 < 0$



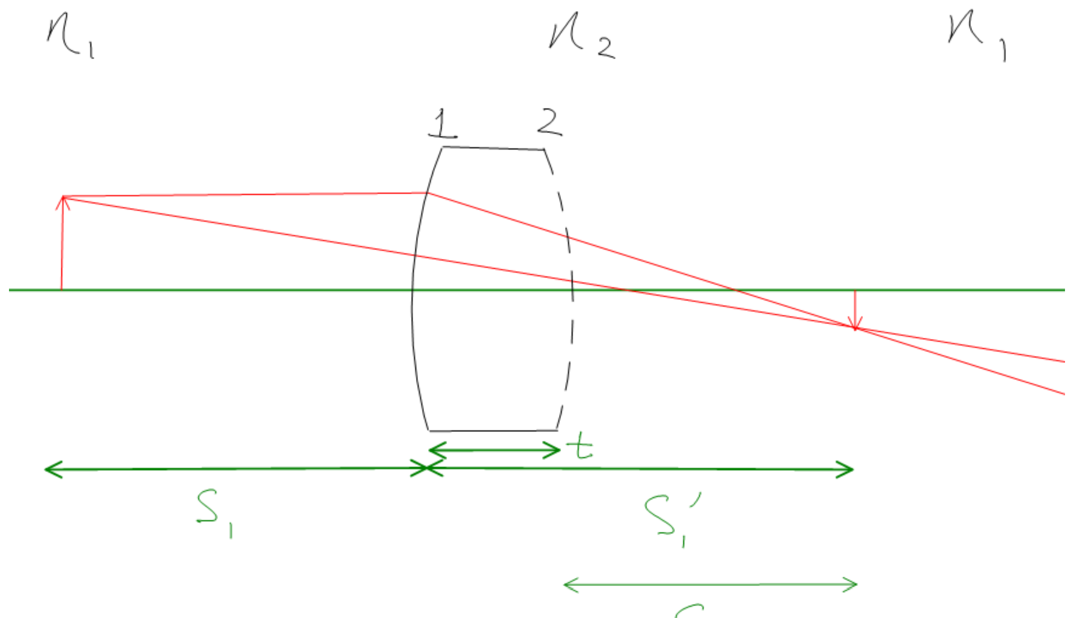
$$\frac{n_1}{S_1} + \frac{n_2}{S_1'} = \frac{n_2 - n_1}{R_1} \; ; \quad S_2 - t = |S_1'| \Rightarrow S_2 = t - S_1'$$

$$\& \lim_{t \to 0} \Rightarrow S_2 = -S_1'$$

$$\& \quad \underbrace{\frac{n_2}{S_2}} + \frac{n_1}{S_2'} = \frac{n_1 - n_2}{R_2} \qquad \text{where } R_2 < 0$$

$$= -\frac{n_2}{S_1'} = \frac{n_1}{S_1} - \frac{n_2 - n_1}{R_1}$$

$$\Rightarrow \frac{n_1}{S_1} + \frac{n_1}{S_2'} = (n_2 - n_1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$



$, > 0 \, . \, S_1' > 0$

$$\Rightarrow \quad \frac{n_1}{S_1} + \frac{n_1}{S_2'} = (n_2 - n_1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

$\therefore$ in Both Cases (using our sign Conventions!)

$$\frac{n_1}{S} + \frac{n_1}{S'} = (n_2 - n_1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

Thin Lens Formula:

$\therefore$ in Both Cases (using our Sign Conventions!)

$$\frac{n_1}{s} + \frac{n_1}{s'} = (n_2 - n_1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

Let $s \to \infty$ to find focal point s':

$$\Rightarrow \quad \frac{1}{s'} \equiv \frac{1}{f} = \frac{n_2 - n_1}{n_1}\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

if in air, $n_1 = 1 \Rightarrow$

$$\boxed{\frac{1}{s} + \frac{1}{s'} = \frac{1}{f} \quad \text{where} \quad \frac{1}{f} = (n_2 - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)}$$

thin Lens formula

Provided we use the following Sign Convention:

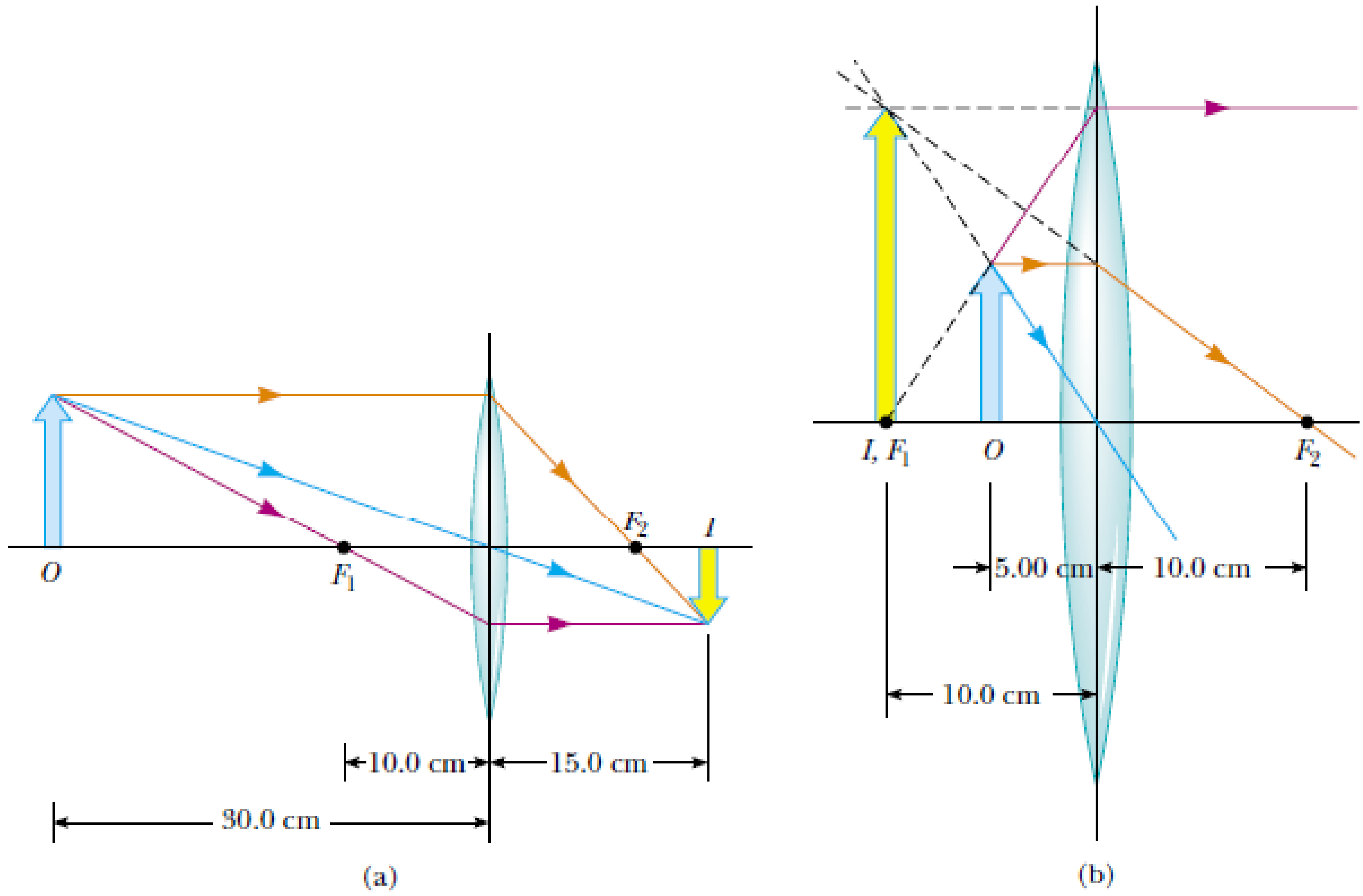
$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f} \quad \text{where} \quad \frac{1}{f} = (n_2 - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

6

Sign Conventions for thin Lenses:

	Positive	Negative
s	object in "front" of Lens	object in "back" of Lens
s'	real image	Virtual image
R_1 & R_2	Center of Curvature in "back"	Center of Curvature in "front"
f	Converging Lens	Diverging Lens
	image upright	image inverted

Thin Lens – Ray tracing Converging Lenses



Thin Lens – Ray tracing Diverging Lenses

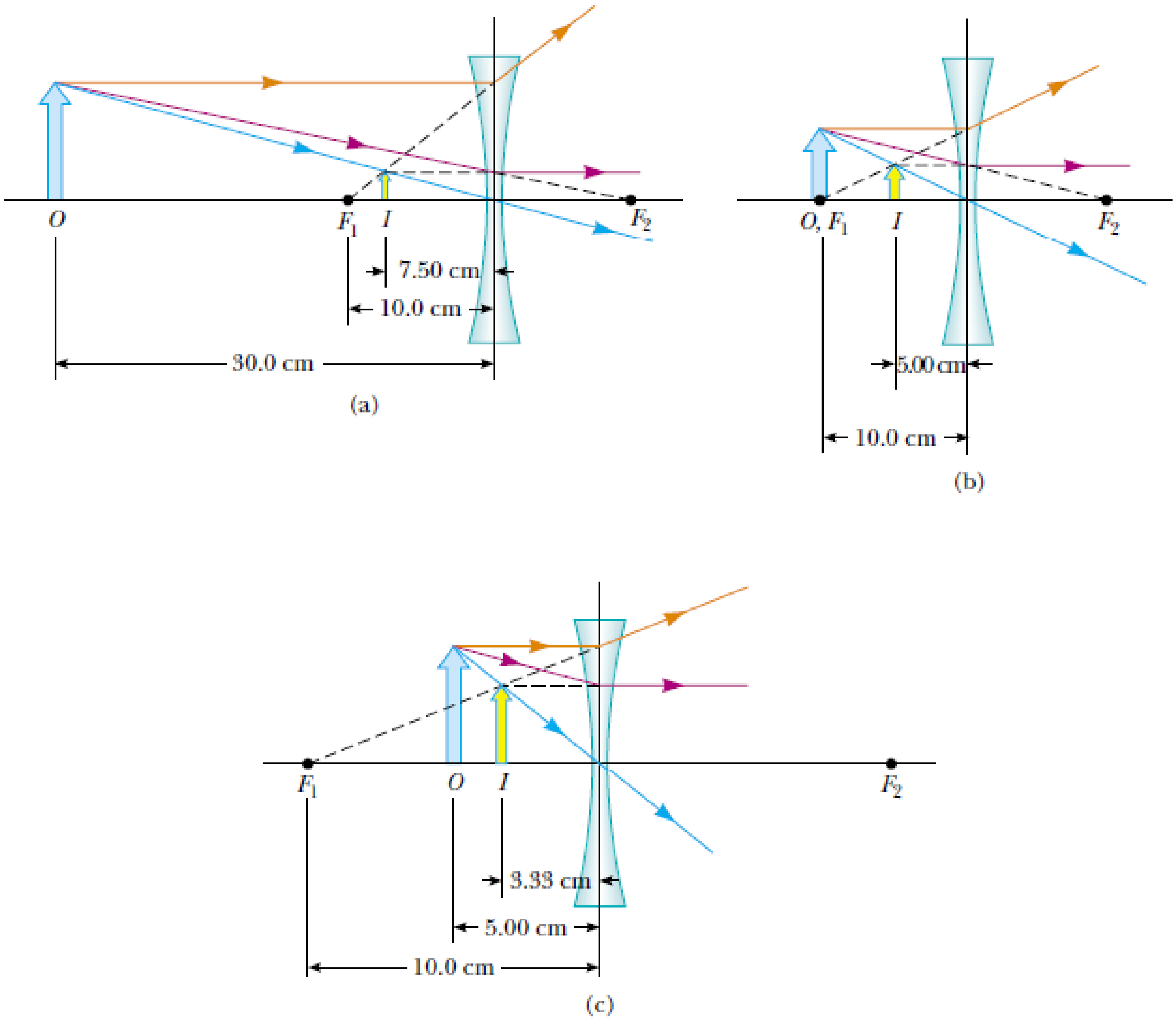
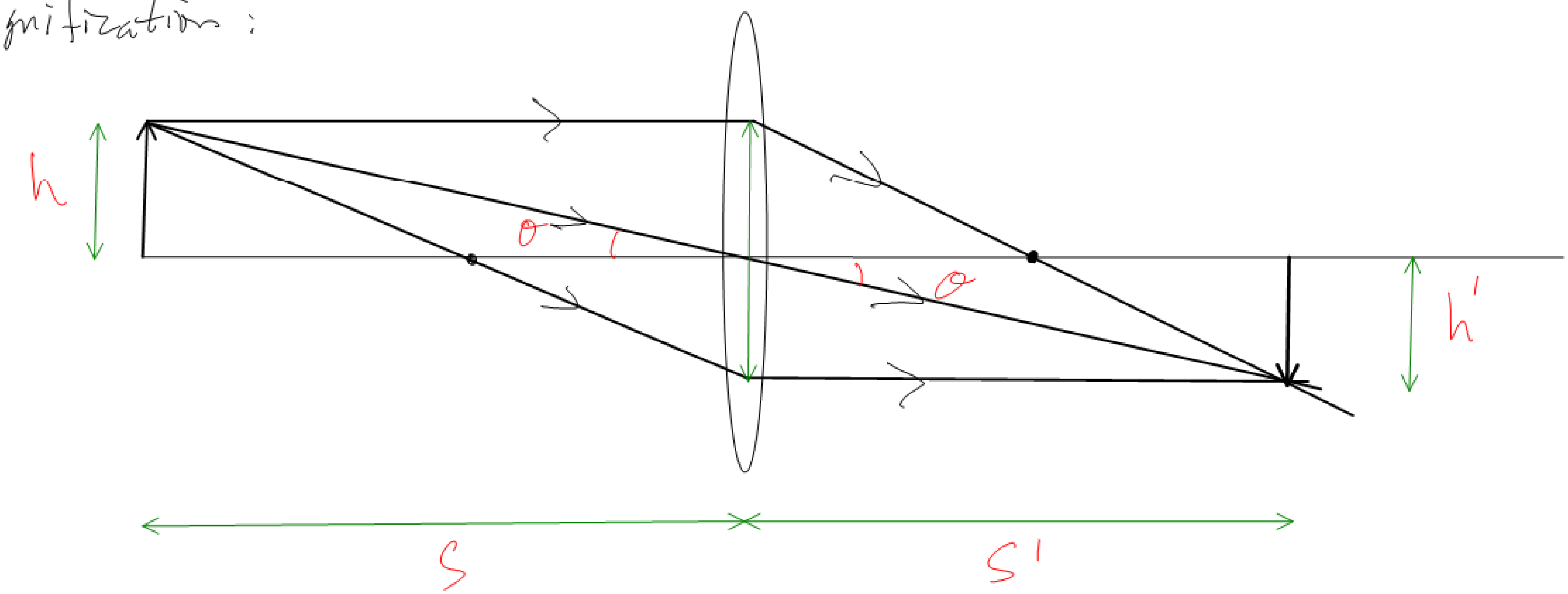


Figure 36.31 (Example 36.10) An image is formed by a diverging lens. (a) The object is farther from the lens than the focal point. (b) The object is at the focal point. (c) The object is closer to the lens than the focal point.

Magnification :

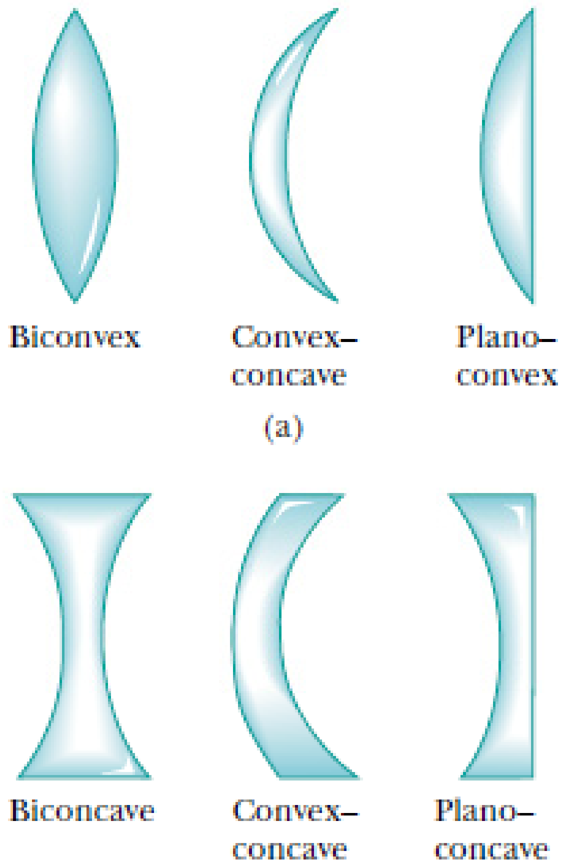


$$\tan\theta = \frac{h}{s} = \frac{h'}{s'} \Rightarrow \text{Magnification, } m = \frac{h'}{h} = \frac{s'}{s}$$

Define m to be negative for inverted images

$$\Rightarrow m = -\frac{s'}{s}$$

Various shaped lenses



(a) Converging lenses have a positive focal length and are thickest at the middle. (b) Diverging lenses have a negative focal length and are thickest at the edges.

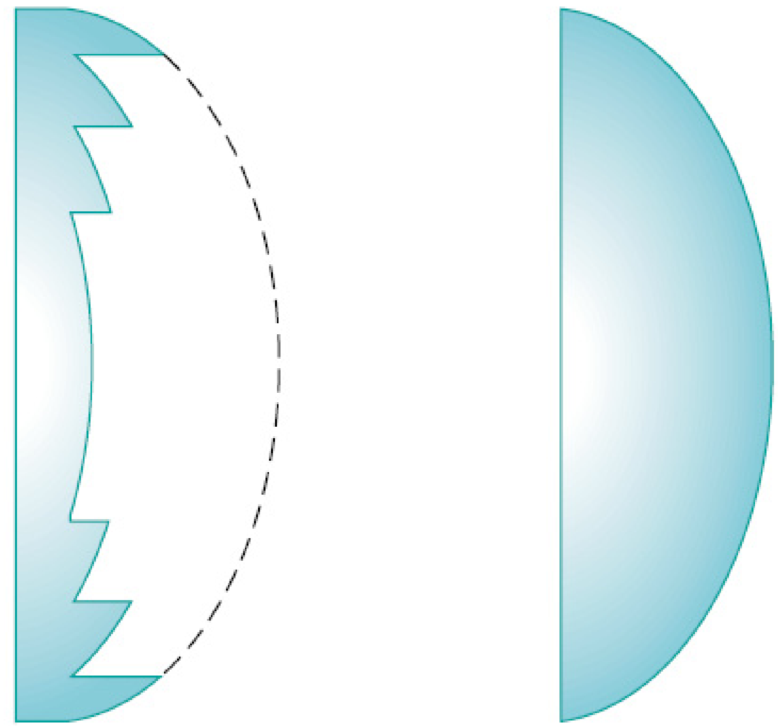
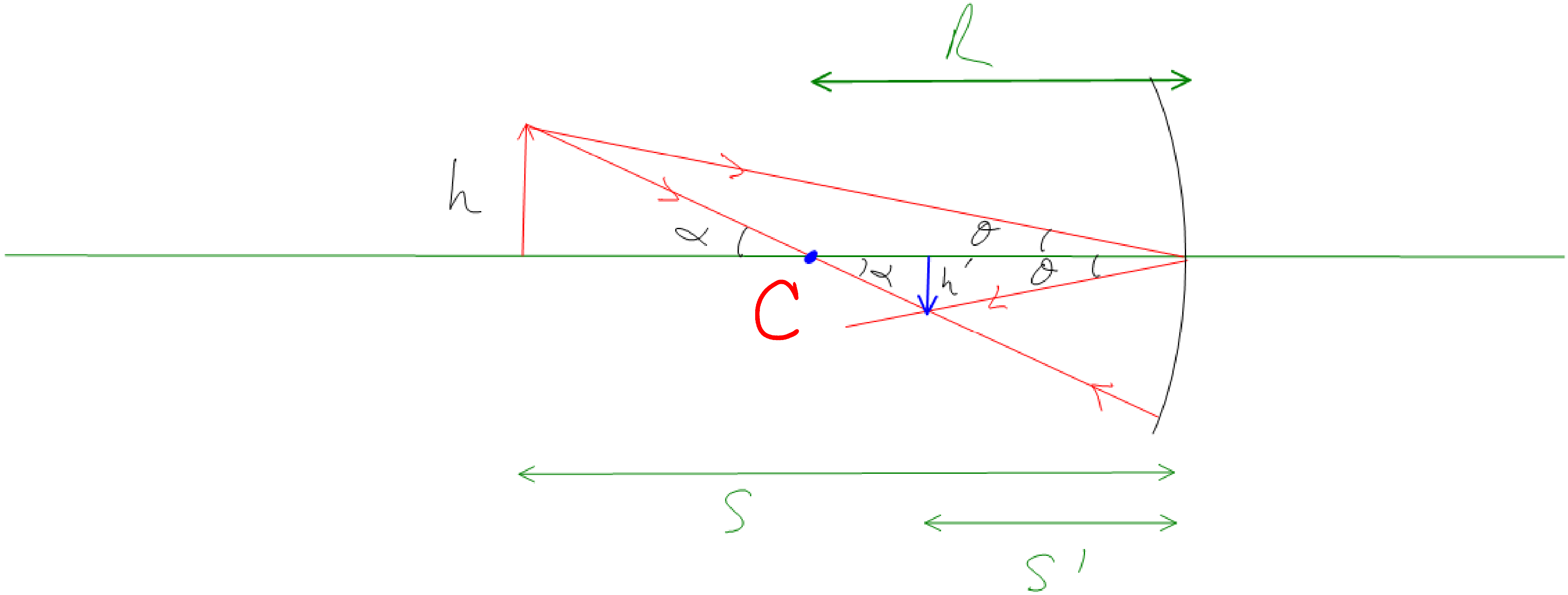
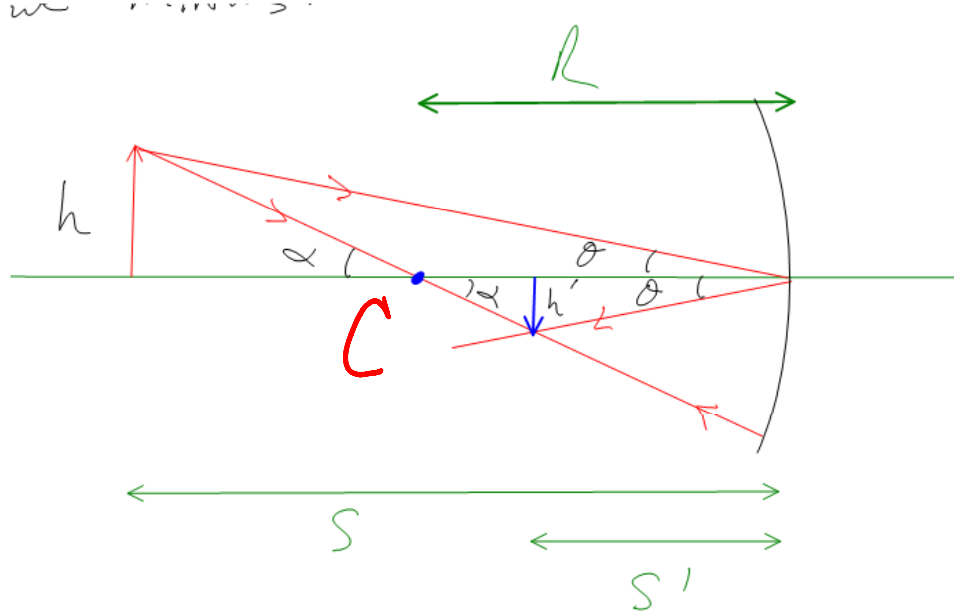


Figure 36.29 The Fresnel lens on the left has the same focal length as the thick lens on the right but is made of much less glass.

Spherical Mirrors:

Case I: Concave Mirrors:



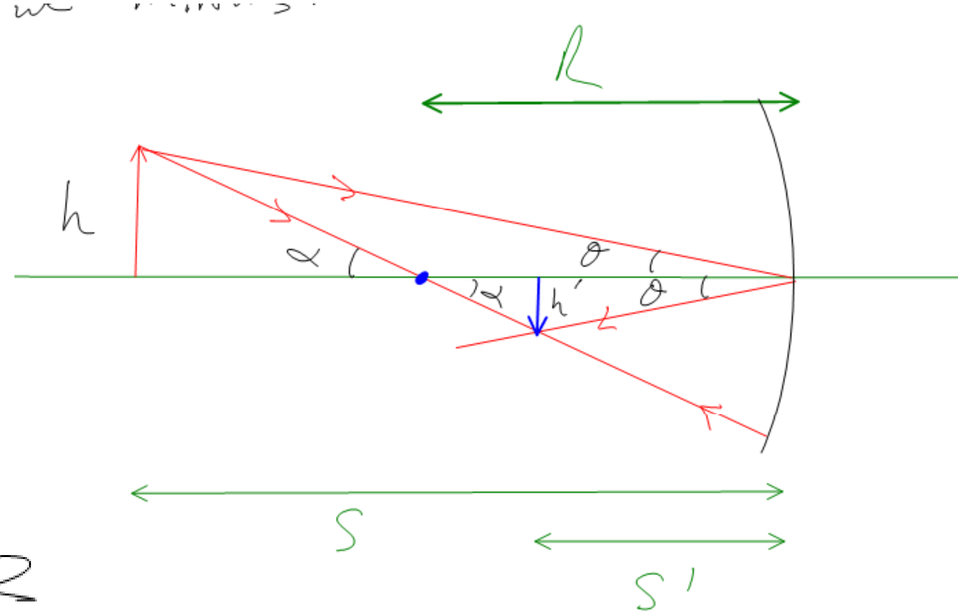


$$\tan\theta = \frac{h}{S} = \frac{-h'}{S'}$$ defining $h' < 0$ when upside down

$$\therefore\ M = \frac{h'}{h} = -\frac{S'}{S}$$ (1) Same as lenses

$$\tan\alpha = \frac{-h'}{R-S'} = \frac{h}{S-R} \Rightarrow \frac{h'}{h} = \frac{S'-R}{S-R} \overset{(1)}{=} -\frac{S'}{S}$$

$$\therefore\ \frac{S'-R}{S'} = \frac{R-S}{S} \Rightarrow 1 - \frac{R}{S'} = \frac{R}{S} - 1 \Rightarrow \frac{1}{S} + \frac{1}{S'} = \frac{2}{R}$$



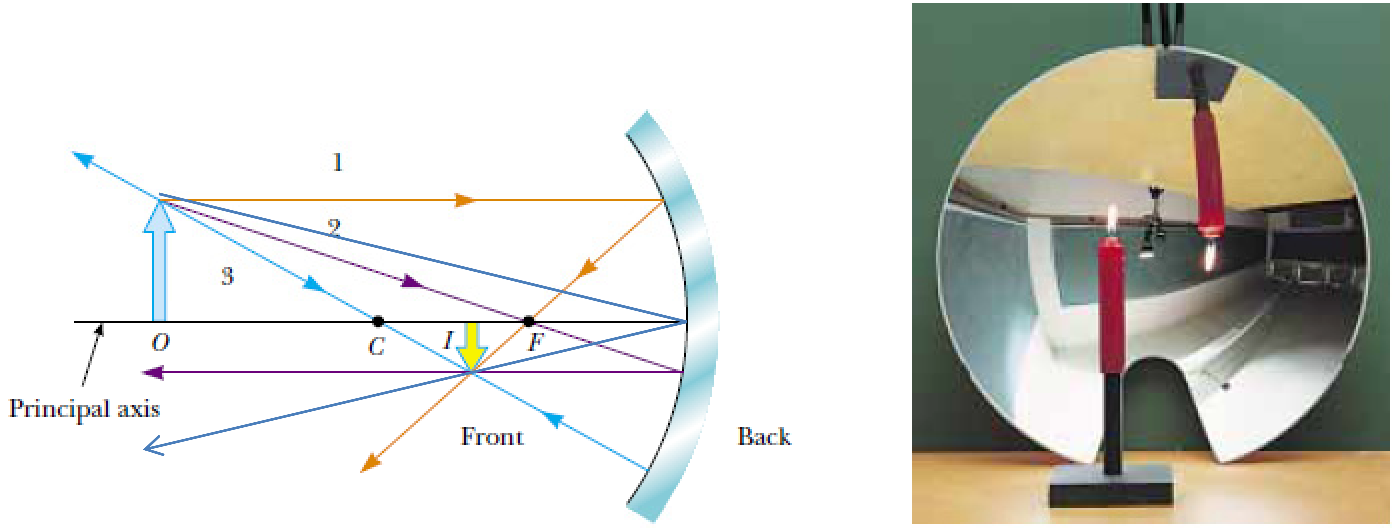
$$\frac{1}{S} + \frac{1}{S'} = \frac{2}{R}$$

Let $S \to \infty$, then $S' \to f$

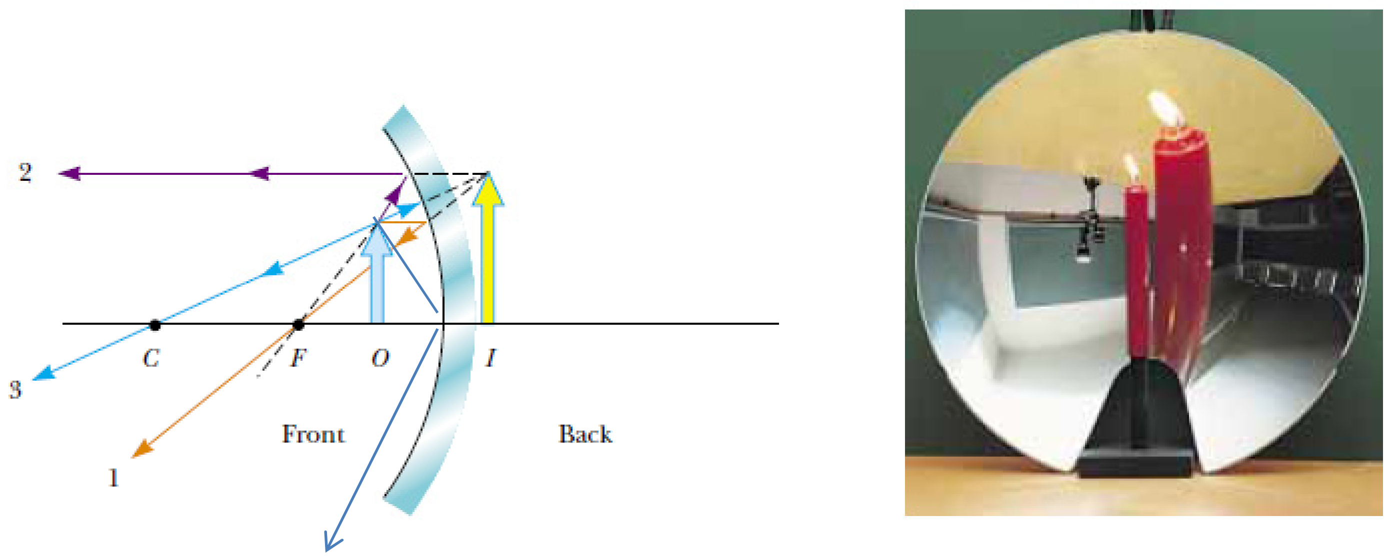
$$\Rightarrow \boxed{\frac{1}{f} = \frac{2}{R} \quad \& \quad \frac{1}{S} + \frac{1}{S'} = \frac{1}{f}} \quad \text{or} \quad \underline{\underline{f = \frac{R}{2}}}$$

We have defined $R > 0$, $S > 0$, $S' > 0$ $\Rightarrow f > 0$

Spherical Mirrors – Ray tracing Concave Mirrors

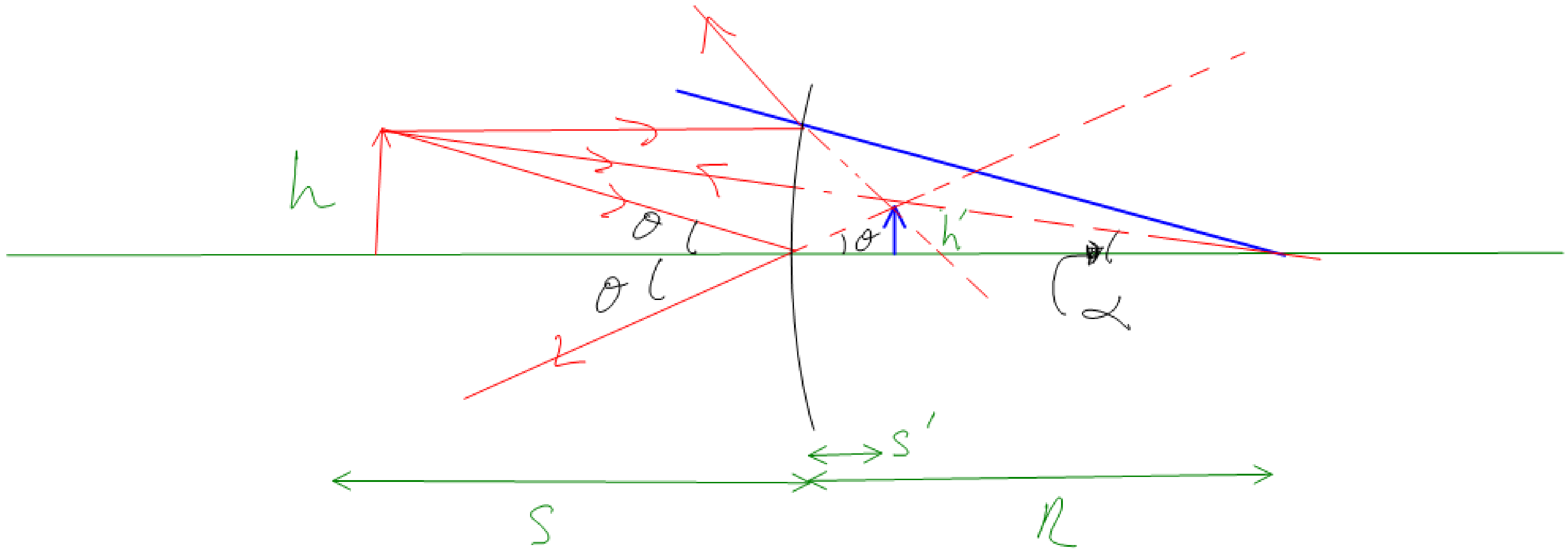


(a)



(b)

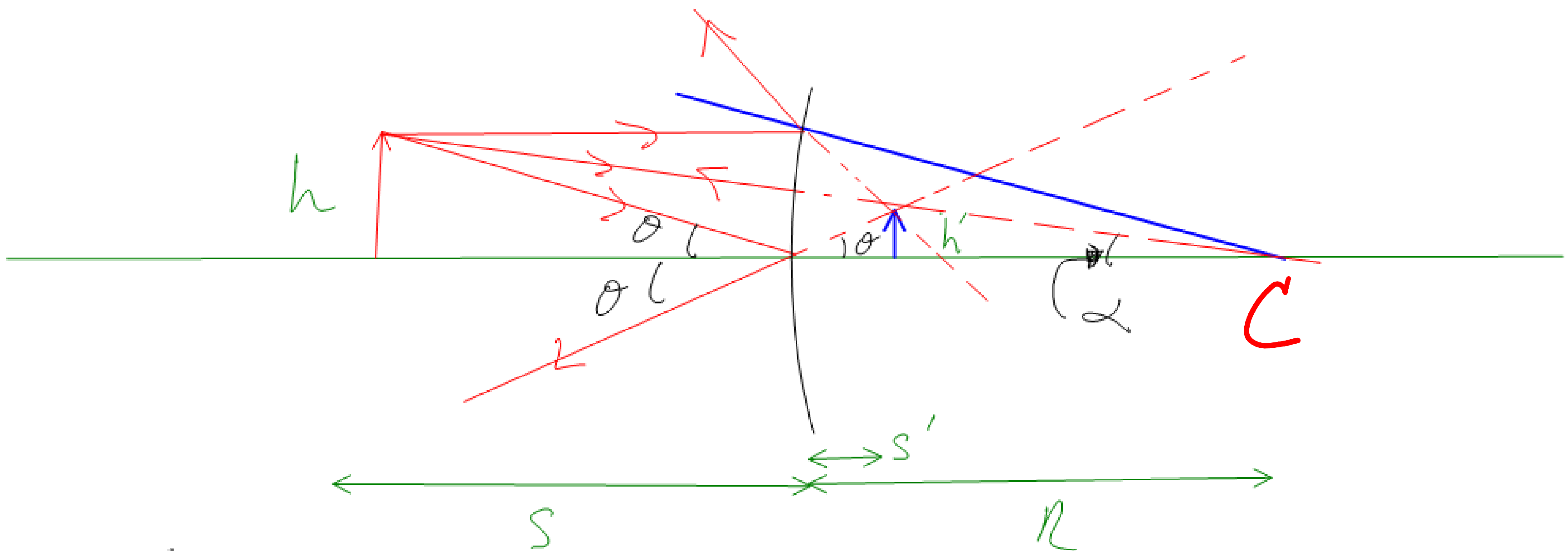
Case II: Convex Mirrors:



To derive the same "looking" formula as Convex case,

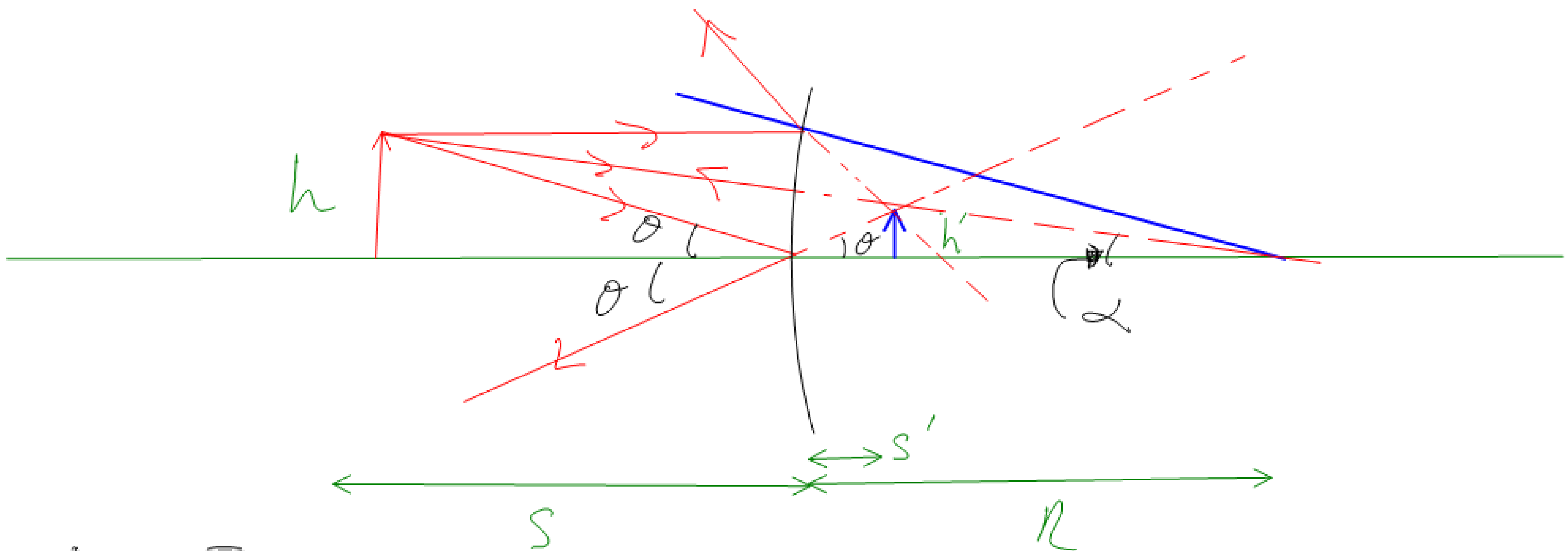
Define $s' < 0$ + $R < 0$ when "behind" mirror

$$\tan\theta = \frac{h}{s} = \frac{h'}{-s'} \Rightarrow m = \frac{h'}{h} = -\frac{s'}{s} \quad \text{Same}$$



$$\tan\alpha = \frac{h'}{\underbrace{-R}_{<0}+\underbrace{S'}_{<0}} = \frac{h}{S-\underbrace{R}_{<0}} \Rightarrow \frac{h'}{h} = \frac{S'-R}{S-R} = -\frac{S'}{S}$$

$$\therefore \quad \frac{S'-R}{S'} = \frac{R-S}{S} \Rightarrow 1-\frac{R}{S'} = \frac{R}{S}-1 \Rightarrow \frac{1}{S}+\frac{1}{S'} = \frac{2}{R}$$



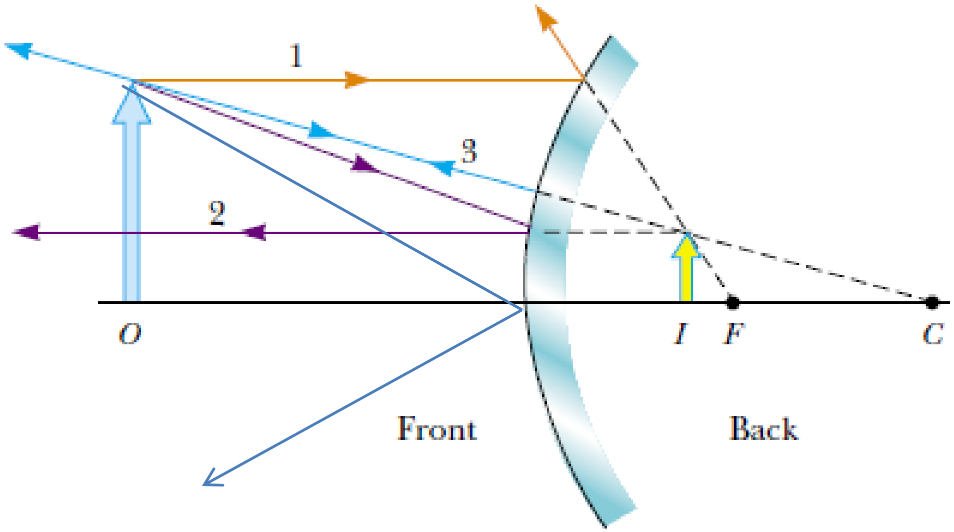
$$\frac{1}{s} + \frac{1}{s'} = \frac{2}{R}$$

Let $s \to \infty$, then $s' \to f$

$$\Rightarrow \boxed{\frac{1}{f} = \frac{2}{R} \quad \& \quad \frac{1}{s} + \frac{1}{s'} = \frac{1}{f}} \quad \text{or} \quad f = \frac{R}{2}$$

have defined $R < 0$, $s > 0$, $s' < 0 \Rightarrow f < 0$

Spherical Mirrors – Ray tracing Convex Mirrors



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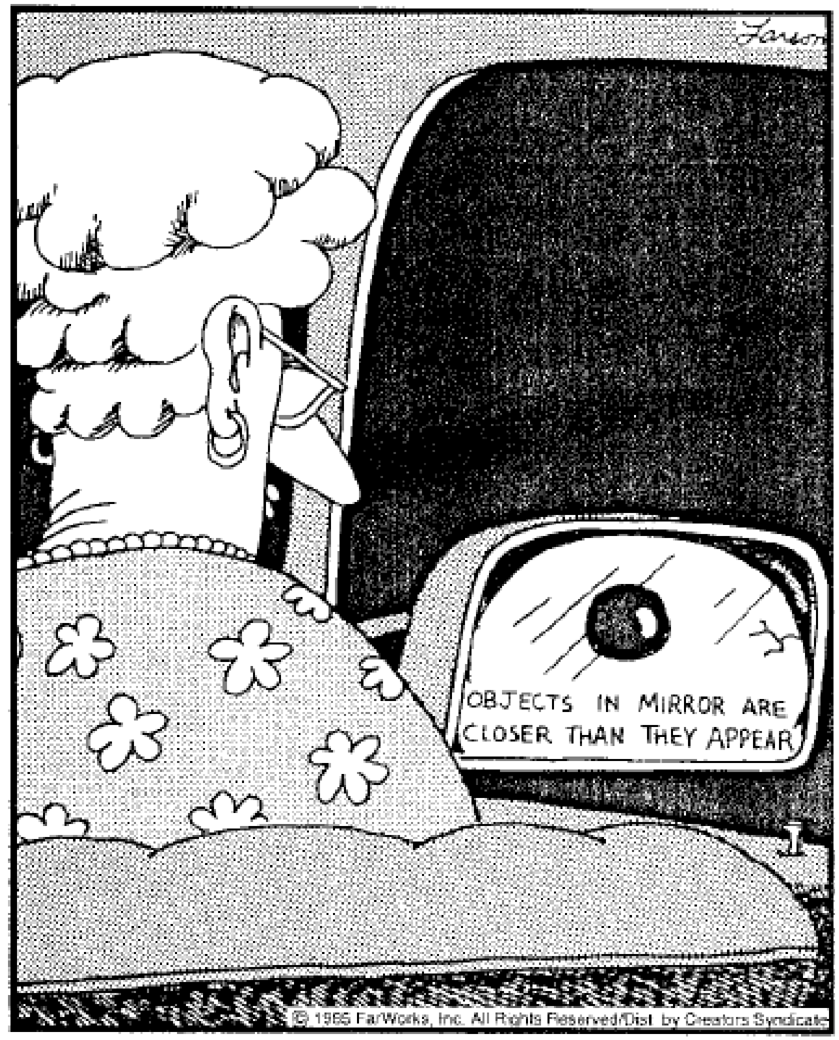


Spherical Mirrors – Sign convention

$$\boxed{\frac{1}{f} = \frac{2}{R} \quad \& \quad \frac{1}{S} + \frac{1}{S'} = \frac{1}{f}}$$

	Positive	Negative
S	in "front" of mirror	in "back" of mirror
S'	real image	virtual image
h', m	upright	upside down
f, R	Concave	Convex

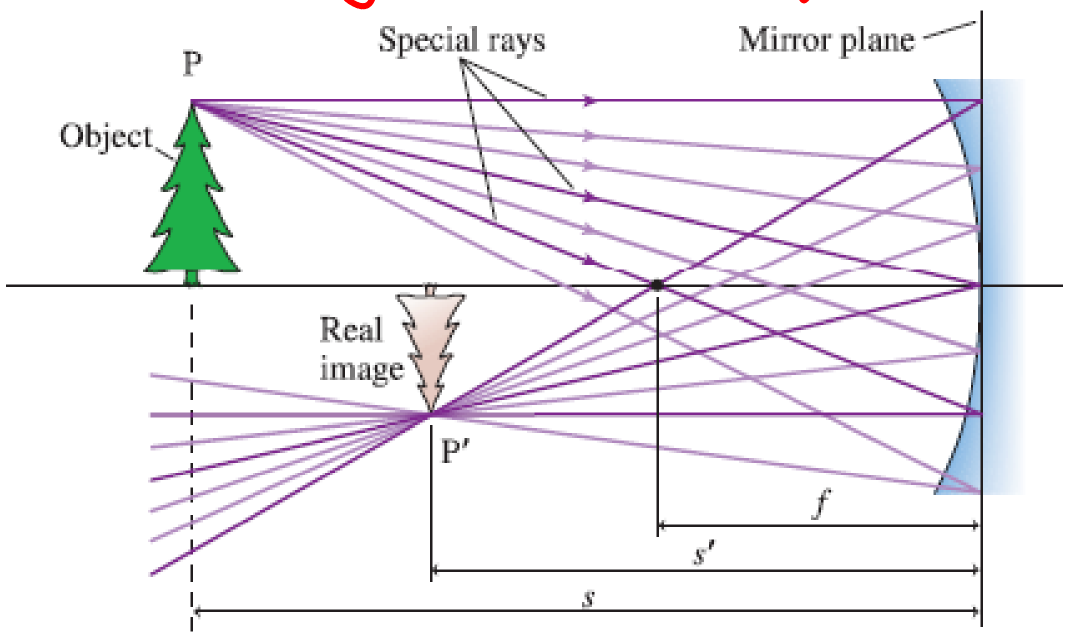
Ray Tracing:

Concave ① Top of object ∥ to principle axis & passes through f

② Top of object, through f, & becomes ∥ to principle Axis

③ Top of object, through C, & reflected back on itself

④ Top of object, to center of lens, $\theta_i = \theta_r$



Convex ① Top of object, ∥ to principle axis, passes away from f

② Top of object, directly toward f, reflected ray becomes ∥ to principle axis

③ Top towards C, reflected back on itself

④ Top of object, to center of lens, $\theta_i = \theta_r$