Phys 153: Fundamentals of Physics III

Unit #1 – Ray Optics & Image Formation

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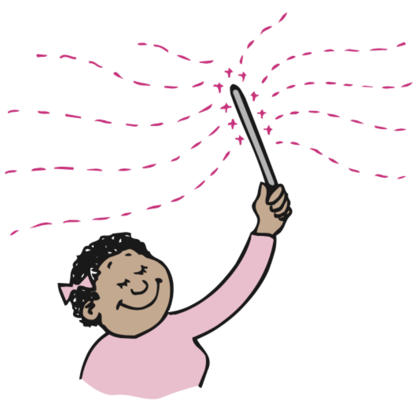
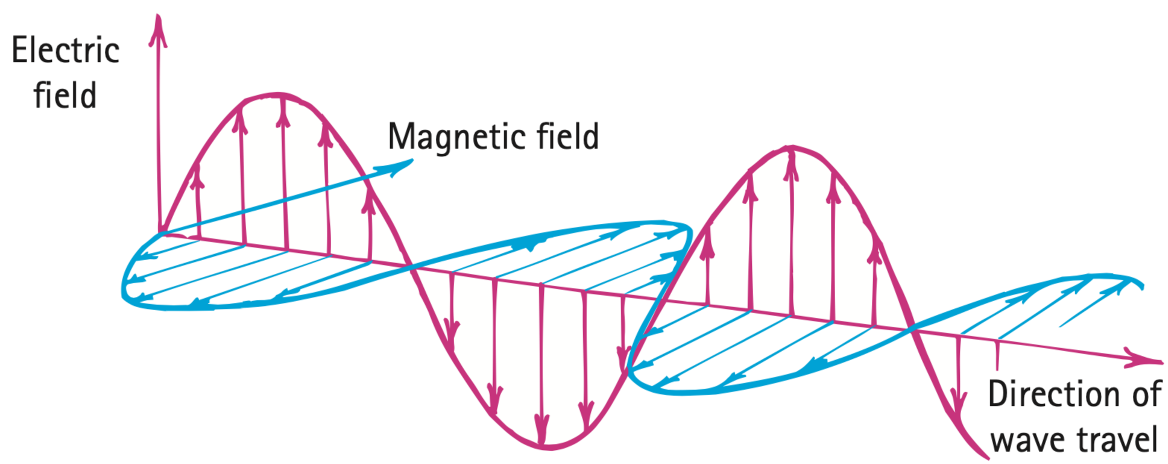
Recommended Reading

- Please read the following sections carefully and skim the rest:
  - 34.2-34.7, 35.1-35.2 & 35.4

Light as an Electromagnetic Wave

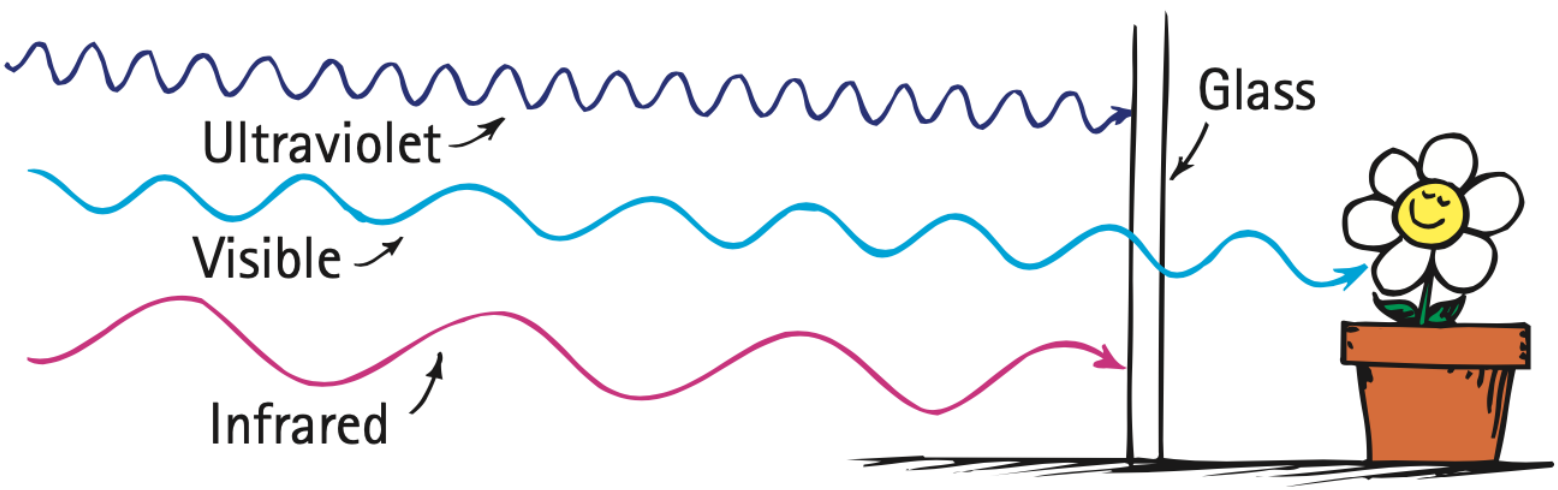
- By 1887, many aspects of light could be understood by the electromagnetic wave model.
- Key properties of all electromagnetic (EM) waves:
    - EM waves can travel through a vacuum and do so with a definite and unchanging speed $c = 299\,792\,458$ m/s.
    - EM waves are **transverse**: $\vec{E}$ and $\vec{B}$ are perpendicular to each other and to the direction of propagation, which is given by $\vec{E} \times \vec{B}$ (vector cross product).
    - At any instant, $|\vec{E}| = c|\vec{B}|$





Light-Matter Interactions

- Transmission, absorption, and emission of light by a material are largely *resonance phenomena*.
- Materials respond differently to different frequencies of light. For instance, glass is transparent to visible light but opaque to ultraviolet and infrared.
    - Materials are transparent if the incident light is “off resonance” and opaque if the incident light is “on resonance.”



Reflection from a Mirror

- We say incident light is **reflected** when it is absorbed and reemitted back into the medium it came from.
- When light strikes an ideal mirror (a perfect conductor), the electric field drives free electrons into oscillation. The oscillating electrons emit (reflect) EM waves with the same frequency and amplitude.
  - The incident and reflected waves combine in such a way that $E = 0$ inside the conductor!

Transmission of Light

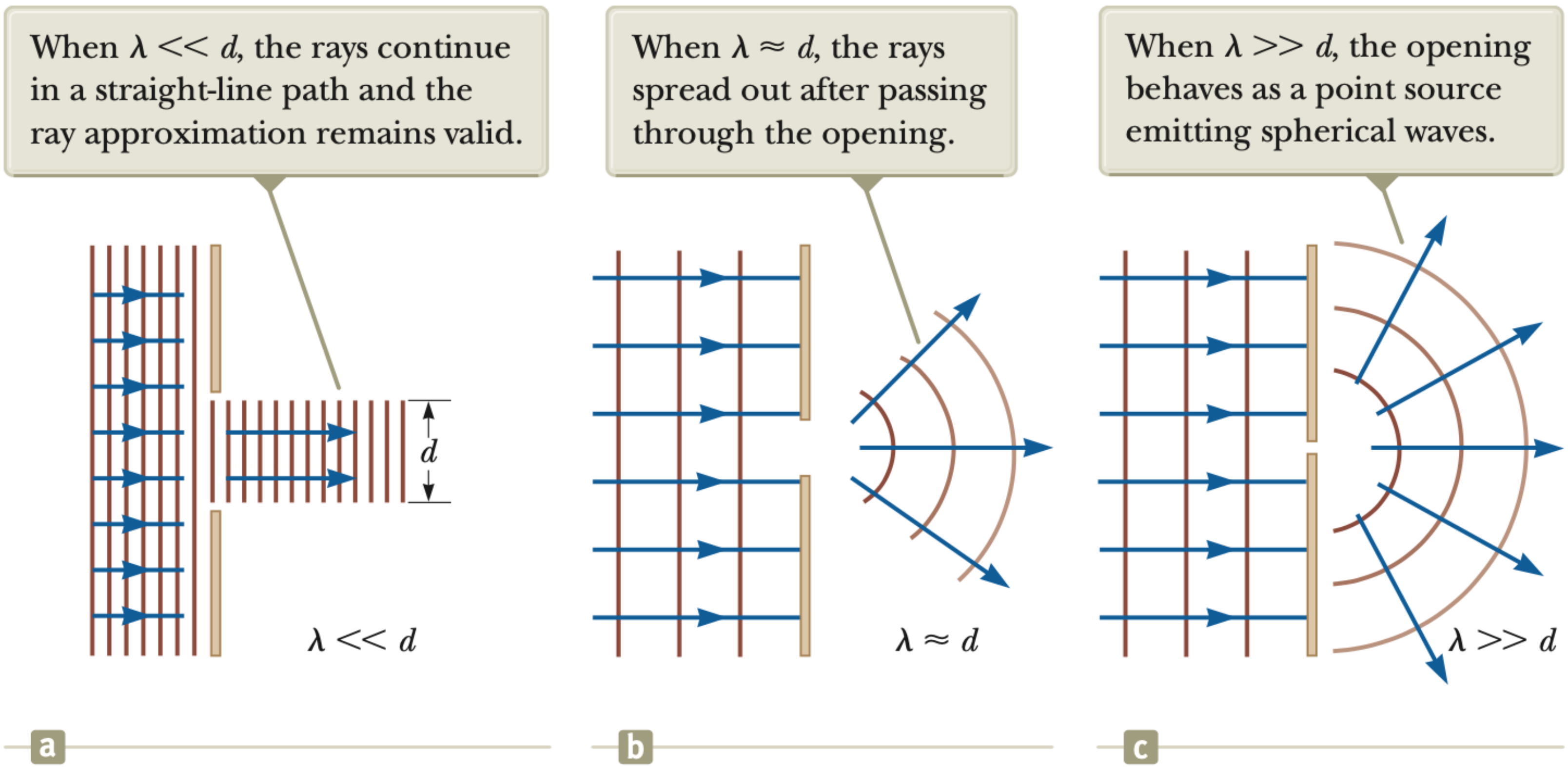
- For most real metals and dielectrics, incident light is partially reflected and partially transmitted (although it doesn't travel very far into most metals).
- Light that is transmitted through a transparent material will nearly always have the same frequency as the incident light—think of the incident light as a periodic driving force.
- There is a small frequency-dependent time delay as atoms absorb light energy and reemit light. This time delay leads to a speed of light less than c in all transparent materials.
  - Technically, light still travels at c between atoms and combines with the light reemitted by the atoms to produce an overall light wave that is slower on average.
- The speed of light in a medium depends not only on the medium but also the frequency of light.

Some Properties of Waves

- A **wave** is any disturbance that travels through space and time, carrying energy without necessarily transporting matter.
- The **phase** of a wave specifies where in its oscillation the wave is at a particular point and time.
  - Points with the same phase oscillate in step—they reach max and min at the same time.
  - Points that are 180° out of phase oscillate out of step—one point is at max while the other is at min.
- A **wavefront** is a surface connecting all points that share the same phase at a given instant.
  - For a plane wave, the wavefronts are parallel planes.
  - For a spherical wave, the wavefronts are concentric spheres centered on the source.

Ray Approximation

- The **rays** of a wave are straight lines perpendicular to the wavefronts.
- In the **ray approximation**, a wave moving through a uniform medium travels in a straight line in the direction of its rays.



Principle of Least Time

- The idea that light takes the quickest path in going from one place to another is called **Fermat's principle of least time.**
- The principle of least time provides a link between **ray optics** and **wave optics**. It can be derived from Maxwell's equations.
- We can treat light as a collection of rays if the obstacles encountered by the wave are much larger than the wavelength.

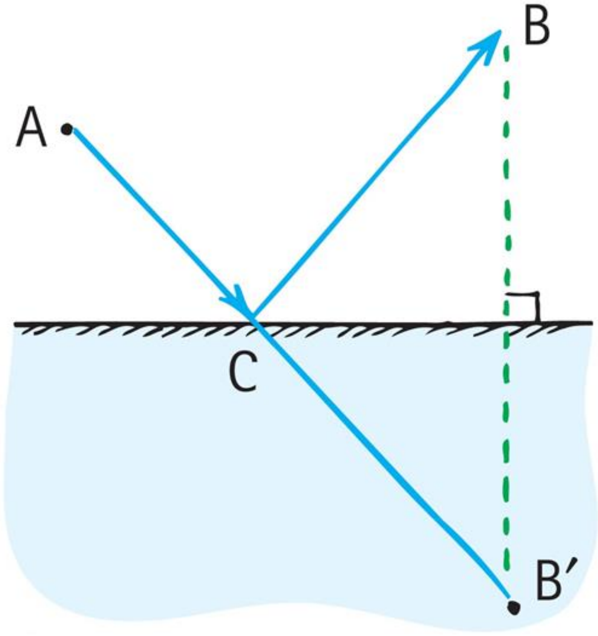
Pierre de Fermat

Fermat's principle states that the path taken by a ray between two given points is the path that can be traveled in the least amount of time.

Quickest Path for Reflection

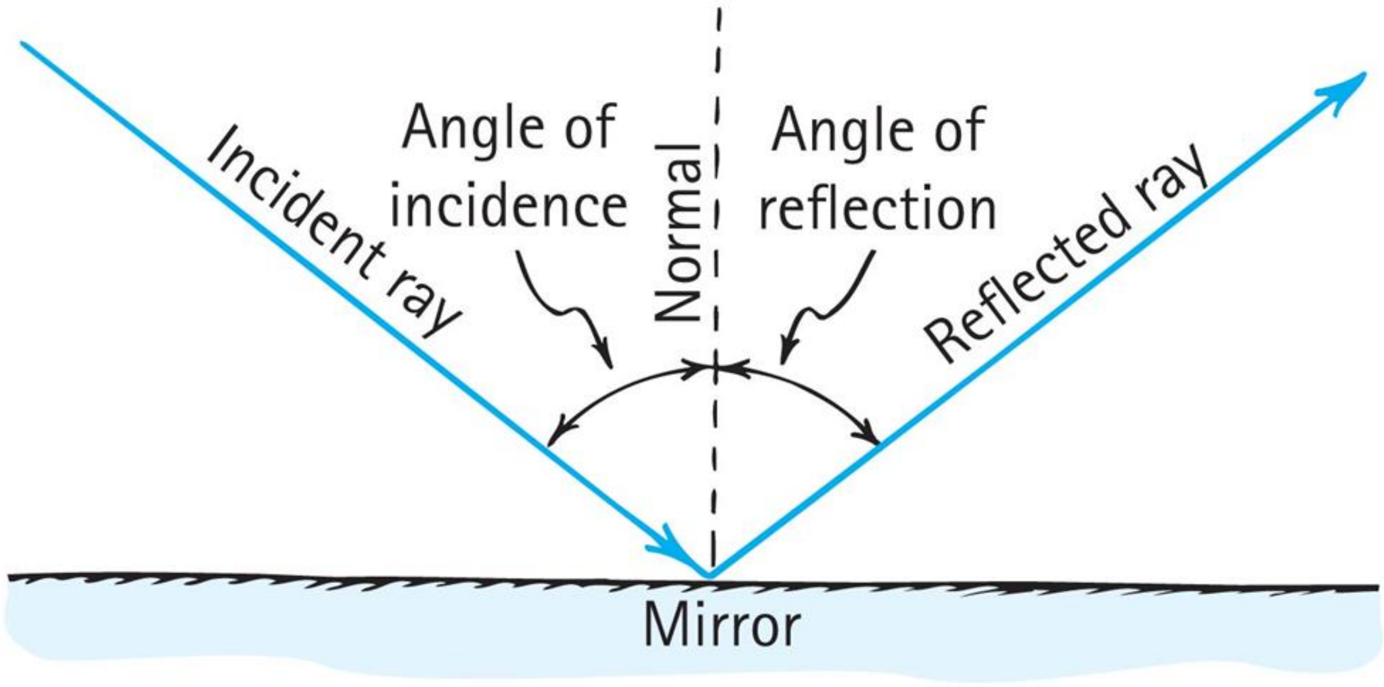
Finding the shortest time for light to go from A to B by reflecting off the mirror:

- Construct, on the opposite side of the mirror, an artificial point B', which is the same distance below the mirror as the point B is above the mirror.
- The shortest distance between A and B' is a straight line and $\overline{AB'} = \overline{AB}$ by symmetry.
- This straight line intersects the mirror at a point C, the precise point of reflection for least time from A to B.



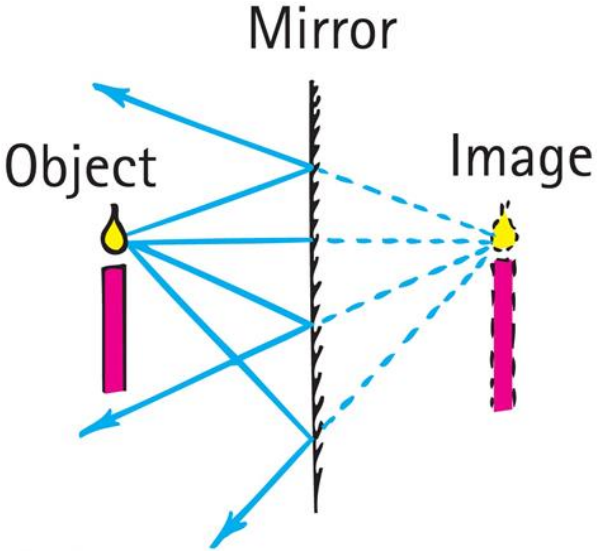
Law of Reflection

The angle of reflection equals the angle of incidence.



Plane Mirrors

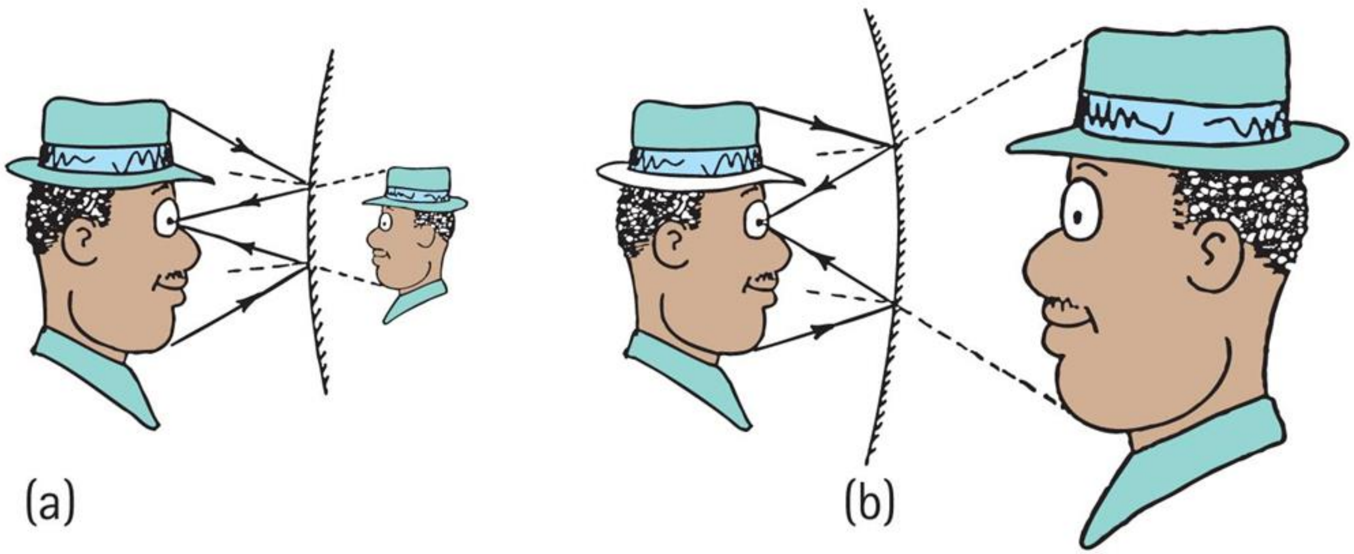
- A plane mirror creates a **virtual image** that is
  - is the same size as the object, formed behind a mirror, and located at the position where the extended reflected rays converge.
  - is as far behind the mirror as the object is in front of the mirror.



How does the mirror know?

Curved Mirrors

- Convex mirror (that curves outward): Virtual image is always smaller and closer to the mirror than the object.
- Concave mirror (that curves inward): Virtual image of a **close object** is larger and farther away than the object.



Concave Mirrors

Conceptual Question 1

Light reflecting from a smooth surface undergoes a change in

A. frequency.

B. speed.

C. wavelength.

D. None of the above is correct.

Conceptual Question 2

If you wish to take a picture of your image while standing 5 m in front of a plane mirror, for what distance should you set your camera to provide the sharpest focus?

A. 5 m

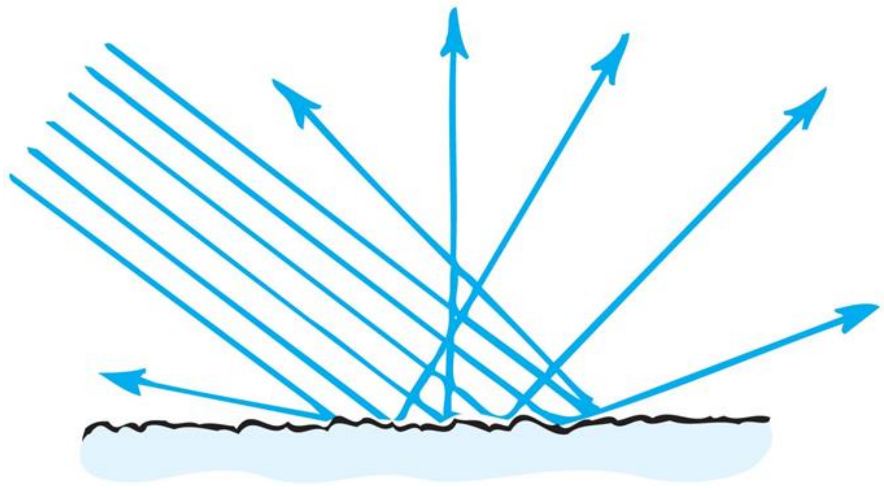
B. 10 m

C. Any distance will work

D. Not enough information

Diffuse Reflection

- Diffuse reflection
  - occurs when light strikes a rough or an irregular surface and reflects in many directions.
  - is what allows us to see most objects from various angles.



Conceptual Question 3

Diffuse reflection occurs when the sizes of surface irregularities are

A. small compared with the wavelength of reflected radiation.

B. large compared with the wavelength of reflected radiation.

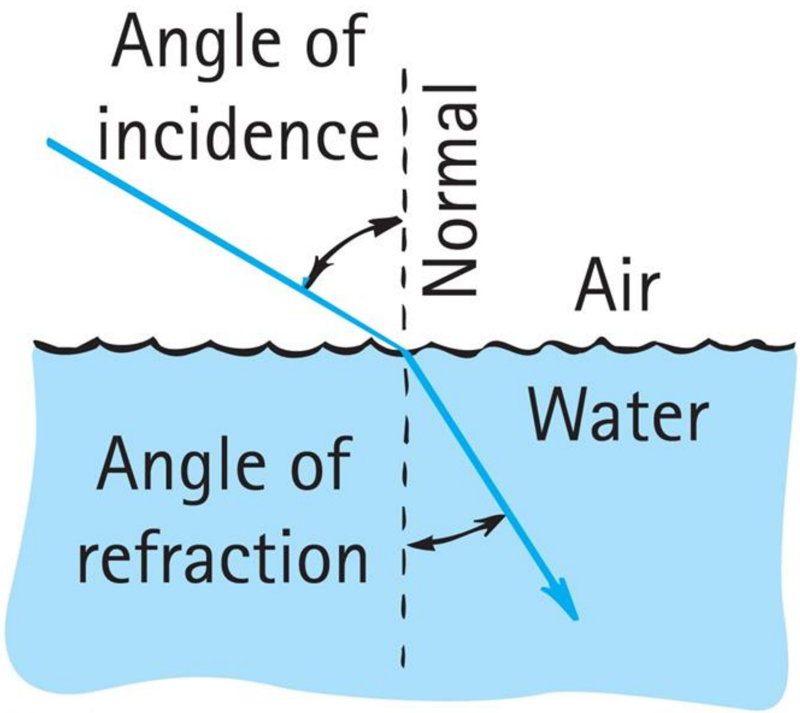
C. Both A and B are correct.

D. None of the above is correct.

Hikaru Dorodango

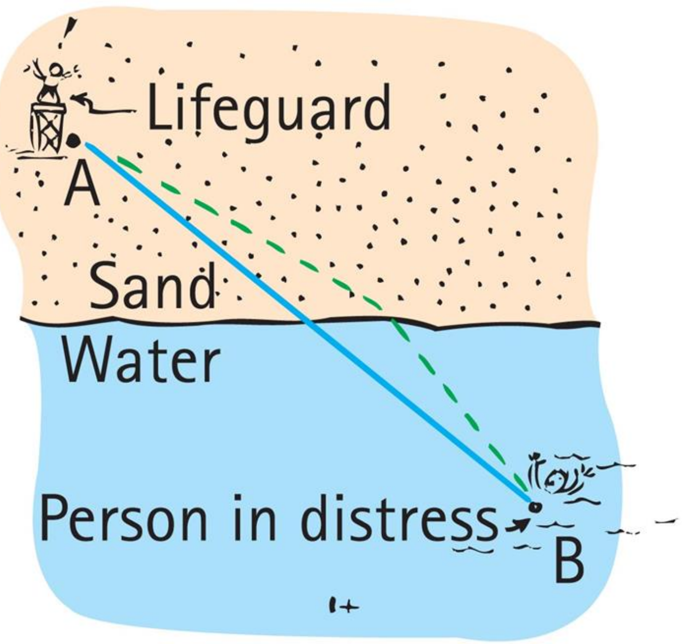
Refraction

Refraction is the bending of light rays after passing obliquely from one medium to another.



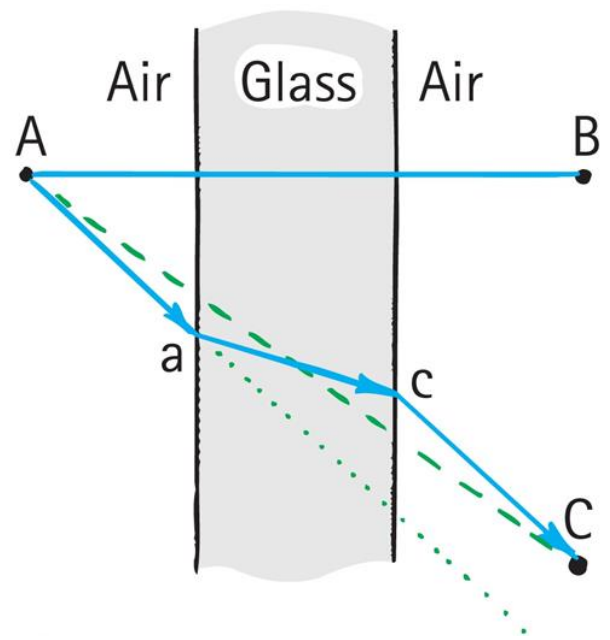
Quickest Path for Refraction

- Refraction occurs to minimize the time taken for light to travel from A to B, using a different light speed in different media.
- Similarly: To save someone from drowning, the quickest path would not be the straight line—it would be the dashed path shown. Presumably, the lifeguard moves quicker on the sand than in the water.



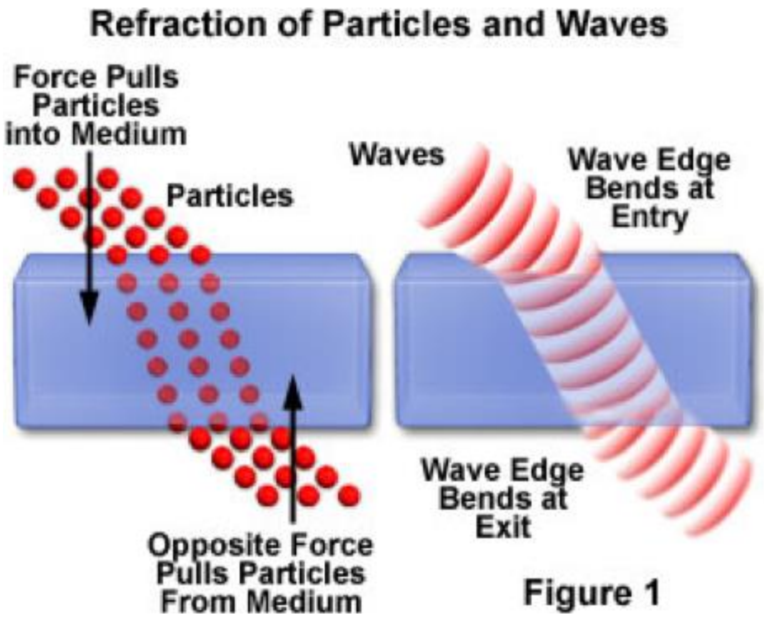
Refraction by Glass

- Light travels slower in glass than in air, so it bends when passing from *a* to *c*, to minimize the time it spends in the glass.



Newton’s Corpuscular Model

- Newton’s corpuscular model proposed that light consists of tiny particles that speed up when entering a denser medium, like glass, due to an attractive force.
- This increase in speed causes the light to bend toward the normal, explaining refraction. Later experiments showed that **light actually slows down in denser media**, contradicting Newton’s model.



Conceptual Question 4

Refracted light that bends toward the normal is light that has

A. slowed down.

B. sped up.

C. nearly been absorbed.

D. diffracted.

Conceptual Question 5

Refracted light that bends away from the normal is light that has

A. slowed down.

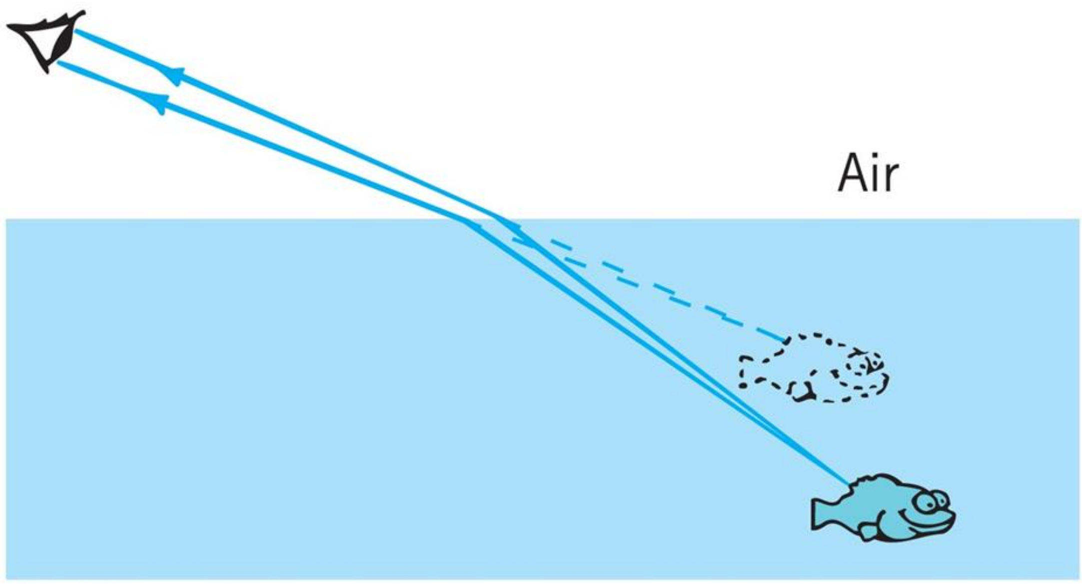
B. sped up.

C. nearly been absorbed.

D. diffracted.

Illusions caused by refraction

- **Objects submerged in water appear closer to the surface.**
- Objects such as the Sun seen through air are displaced because of atmospheric refraction.
- Atmospheric refraction is the cause of mirages.



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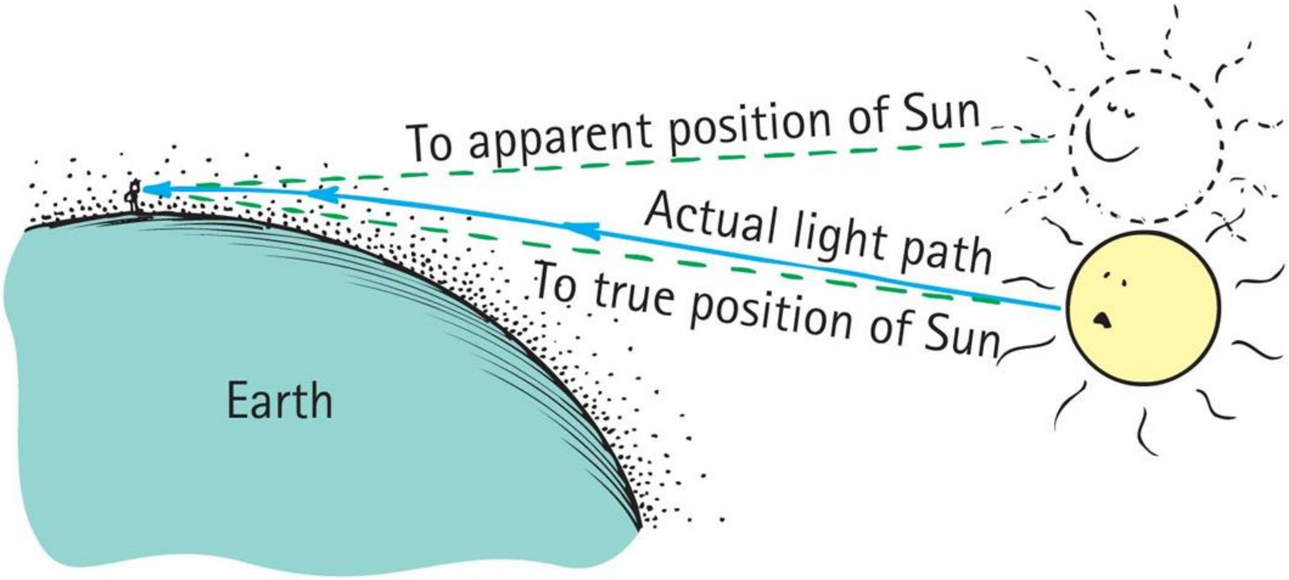

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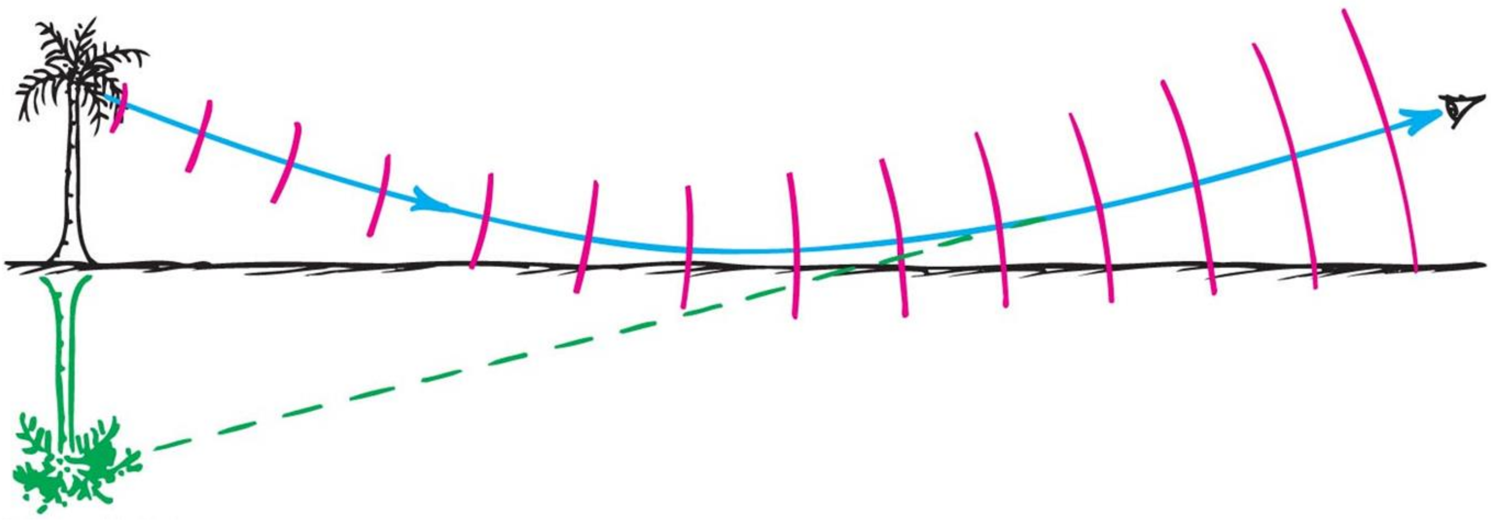


Index of Refraction

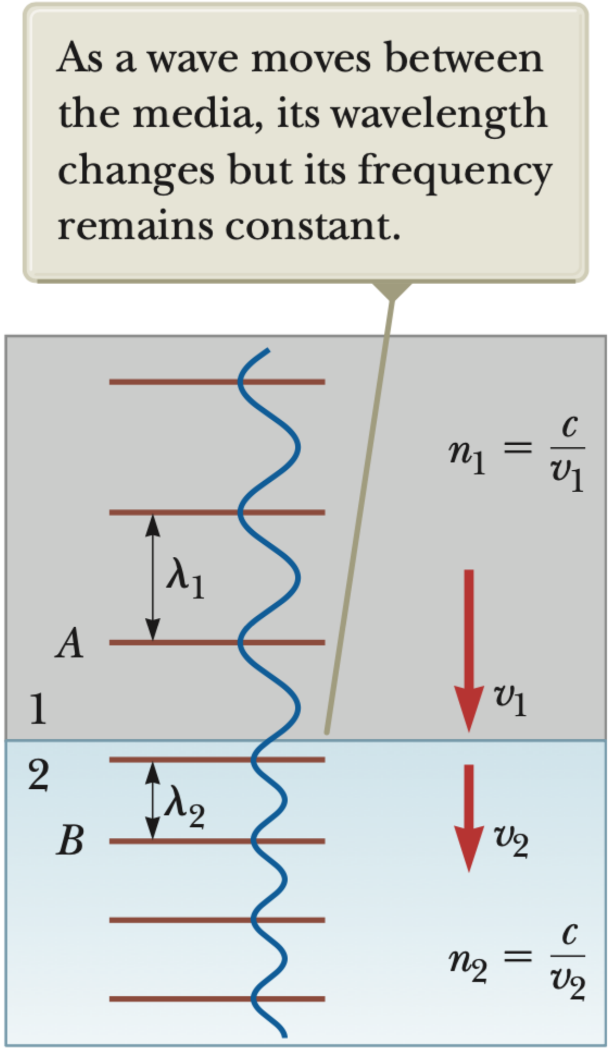
- The **refractive index (index of refraction)** of a material
  - is the ratio of speed of light in vacuum to the speed of light in the material.
  - determines the extent of bending of refracted light rays.
  - Medium with a high index means high bending effect and greatest slowing of light.

$$n = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}}$$

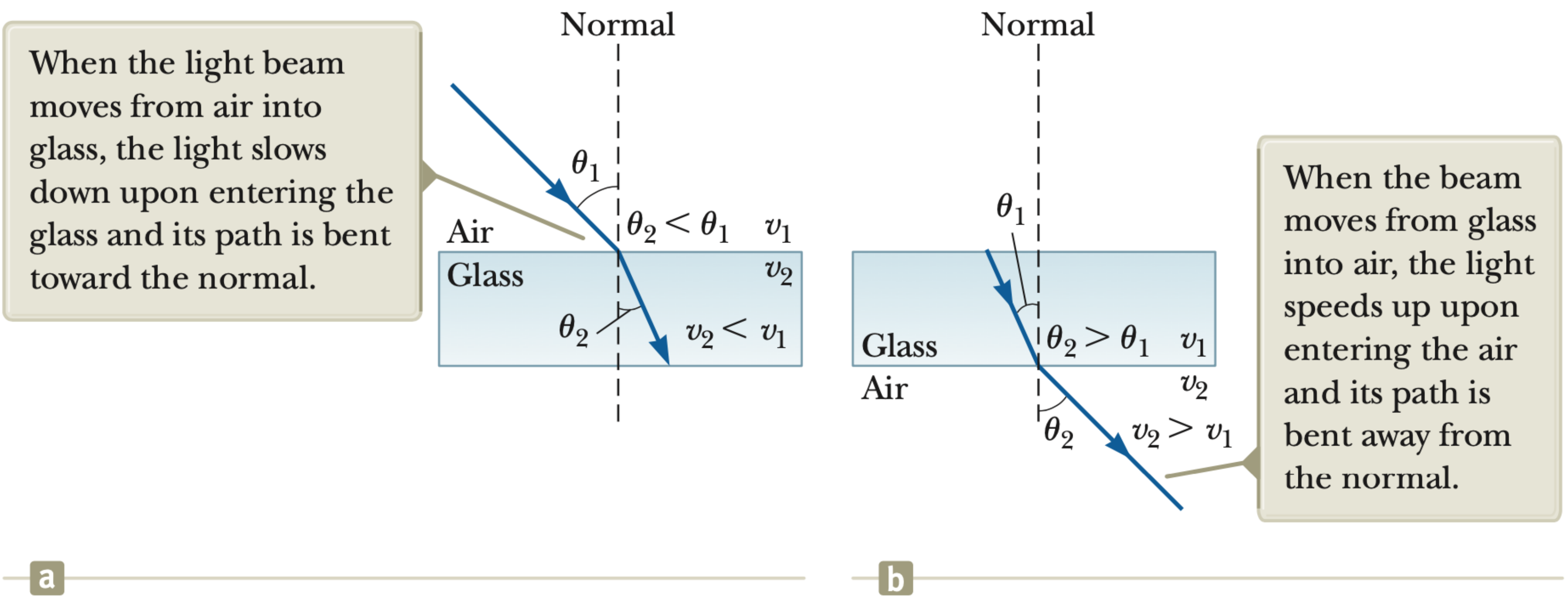
Refracted Wavelength

- For a monochromatic EM wave $v = \lambda f$. When light enters a material, the speed changes but the frequency stays the same, so the wavelength must change.

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$



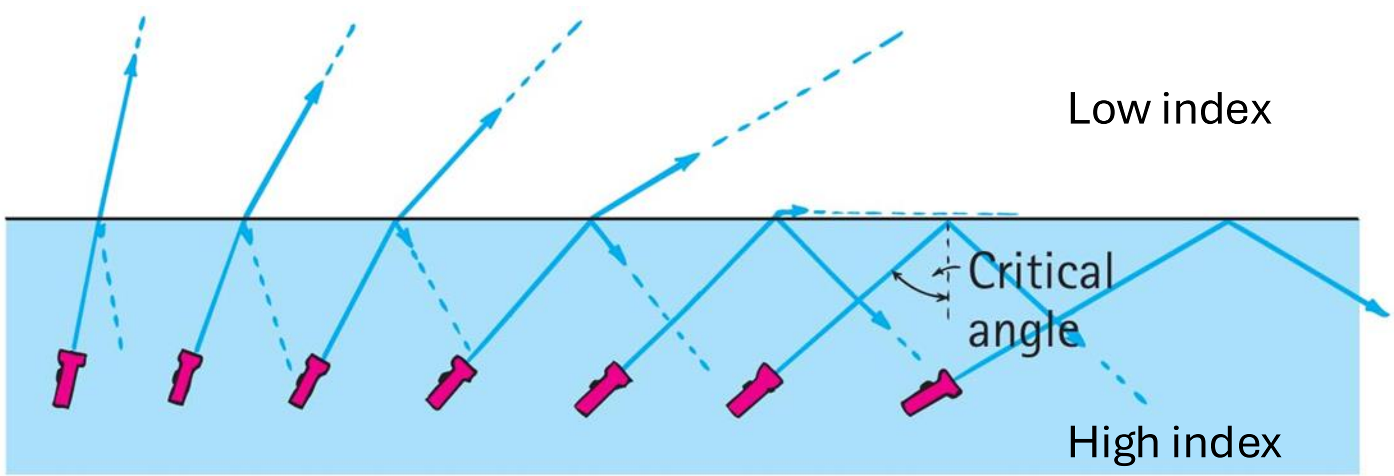
Law of Refraction (Snell's Law)



$$\boxed{n_1 \sin\theta_1 = n_2 \sin\theta_2}$$

Total Internal Reflection

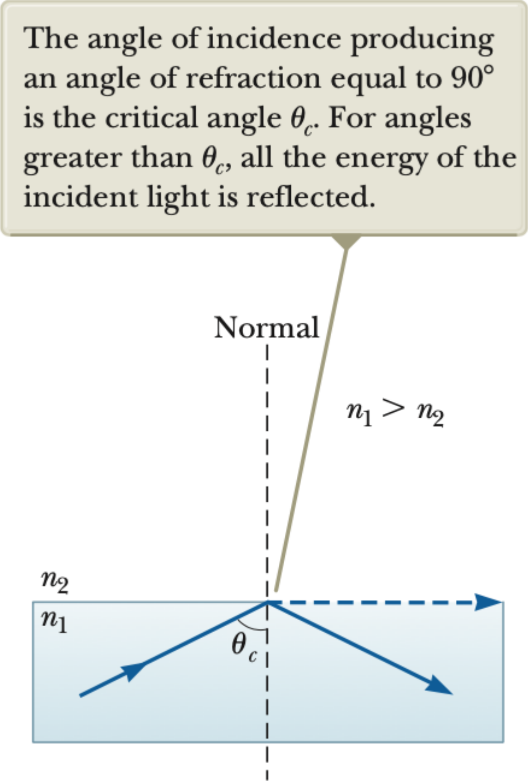
- Total internal reflection is total reflection of light traveling within a high-index medium that strikes the boundary of another low-index medium at an angle at, or greater than, a critical angle.



Critical Angle

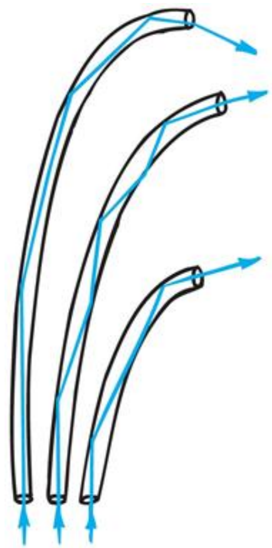
- Critical angle for light rays beneath the air/medium interface
  - minimum angle at which a light beam does not emerge into the air above the surface
  - varies for different materials

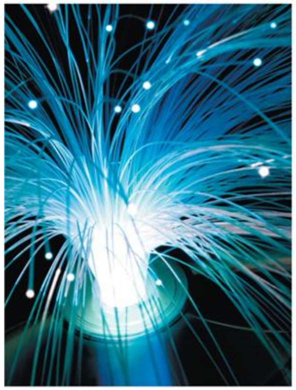
$$\sin\theta_c = \frac{n_2}{n_1} \quad (\text{for } n_1 > n_2)$$



Optical Fibers

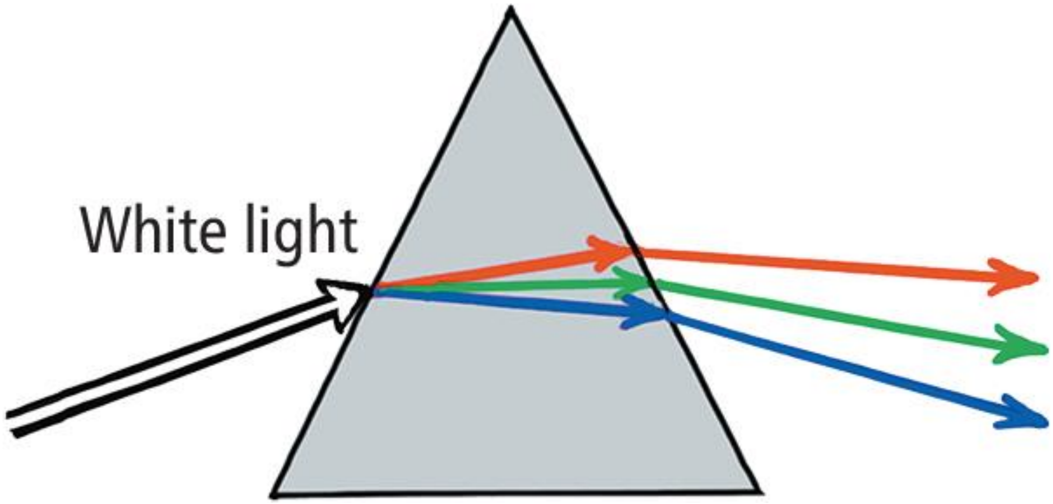
- Optical fibers or light pipes:
  - Thin, flexible rods of special glass or transparent plastic.
  - Light from one end of the fiber is total internally reflected to the other end, resulting in nearly the same brightness of light emerging as entering
- Used in
  - illuminating instrument displays
  - concentrating light in dental procedures
  - viewing of inaccessible regions of organs and other devices
  - communications





Dispersion

- Separation of light into colors arranged by frequency
- Dispersion is ultimately a resonance effect—some frequencies of light move slower than others because they interact more with the material.



Conceptual Question 6

Compared to the speed of green light passing through a prism, red light passing through the same prism

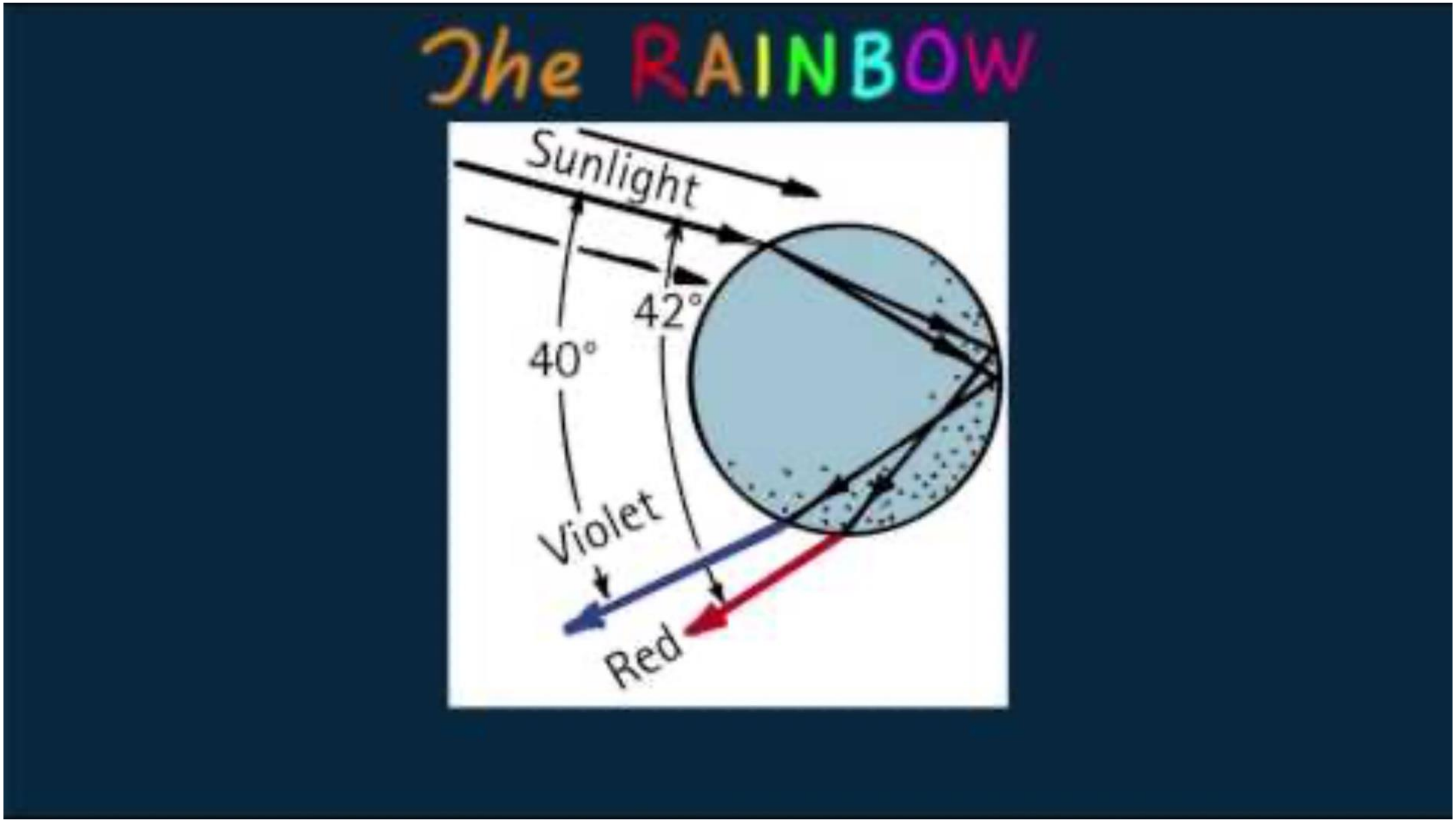
A. Moves faster

B. Moves slower

C. Moves at the same speed

D. Need more information

The Physics of Rainbows



Conceptual Question 7

Compared with the primary rainbow, the secondary bow

A. is dimmer.

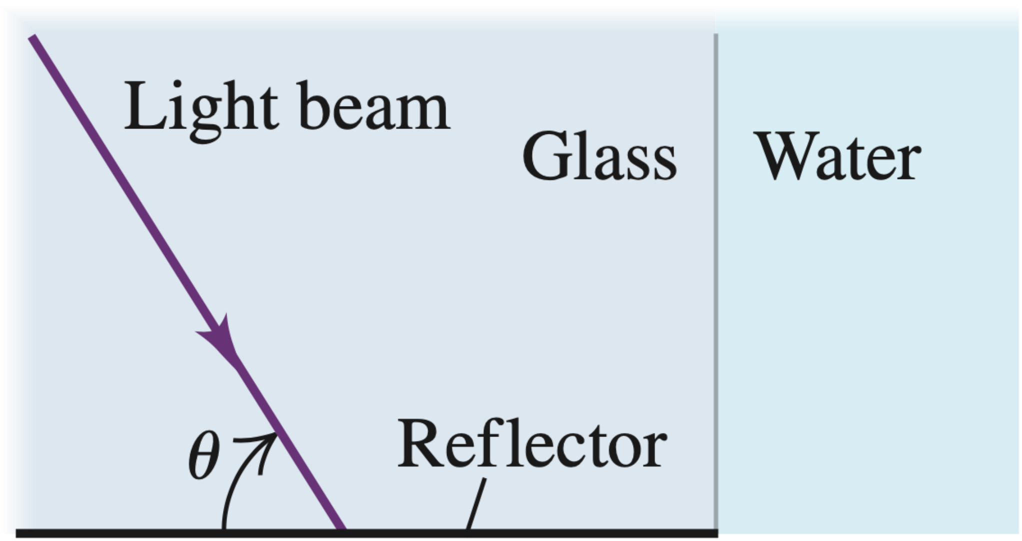
B. has colors reversed.

C. is caused by two internal reflections.

D. All of the above are correct.

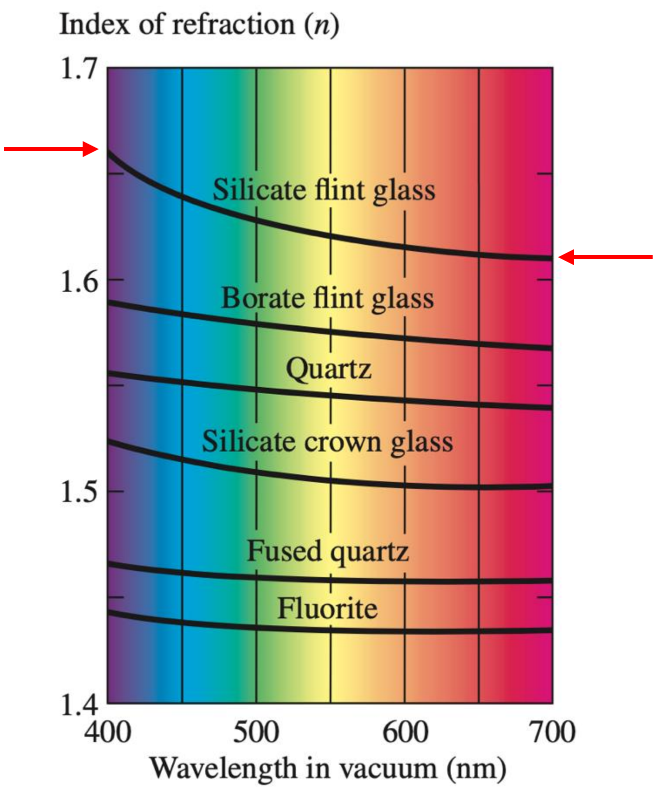
Example 1: Total Internal Reflection

The figure shows a rectangular glass block that has a metal reflector on one face and water on an adjoining face. A light beam strikes the reflector as shown. You gradually increase the angle θ of the light beam. If $\theta \geq 59.2°$, no light enters the water. What is the speed of light in this glass?



Example 2: Dispersion

A narrow beam of white light strikes one face of a slab of silicate flint glass. The light is traveling parallel to the two adjoining faces, as shown in the figure below. For the transmitted light inside the glass, through what angle $\Delta\theta$ is the portion of the visible spectrum between 400 nm and 700 nm dispersed? Use the information in the figure on the right.



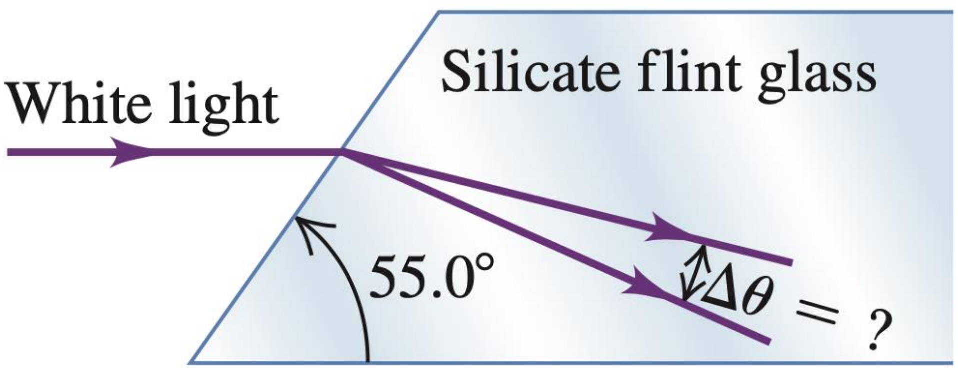
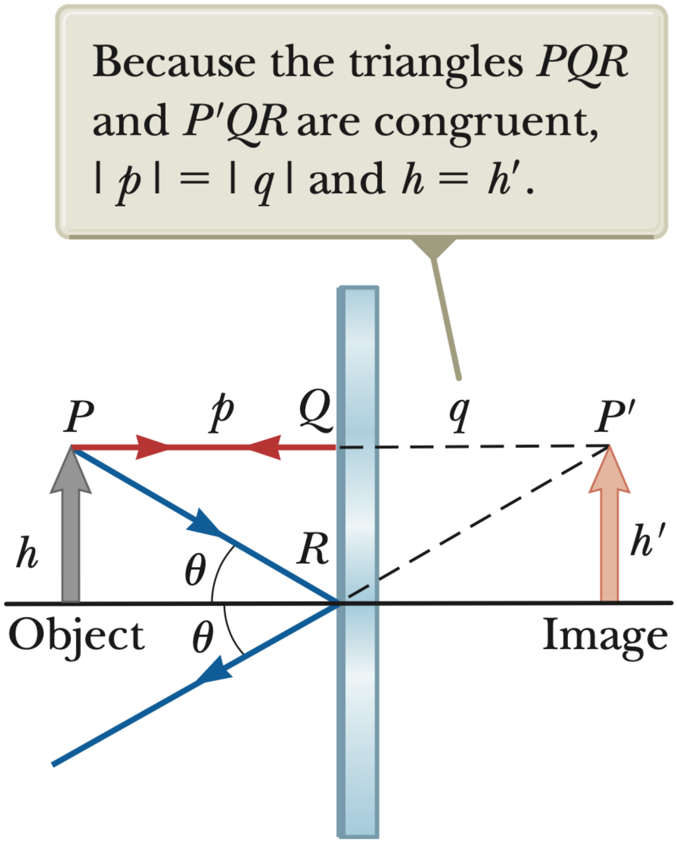


Image Formation

- An **image** is a pattern of light rays emerging from an optical system that carry information about an object's shape and position.
- Geometrically, we locate the image at the point or region from which these rays actually diverge (for a real image) or appear to diverge (for a virtual image).
- The image's position and size depend on how mirrors, lenses, or other optical elements reflect or refract the light.

Flat Mirrors

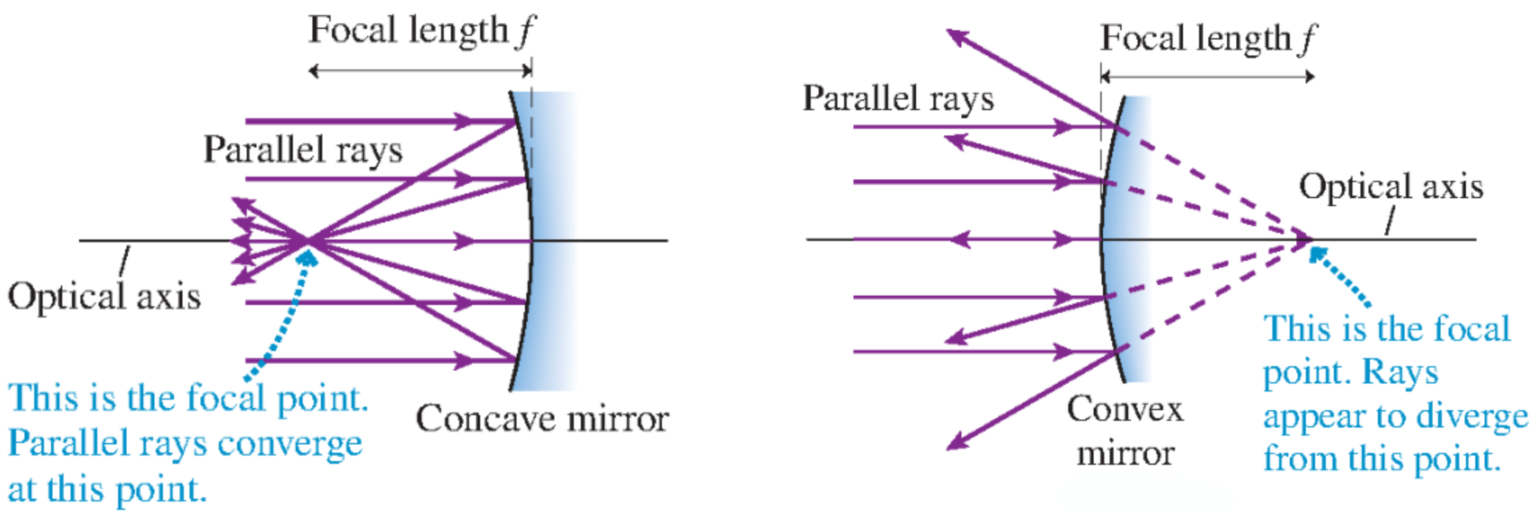


Lateral magnification

$$M = \frac{\text{image height}}{\text{object height}} = \frac{h'}{h}$$

$M = +1$ for a flat mirror

Spherical Mirrors



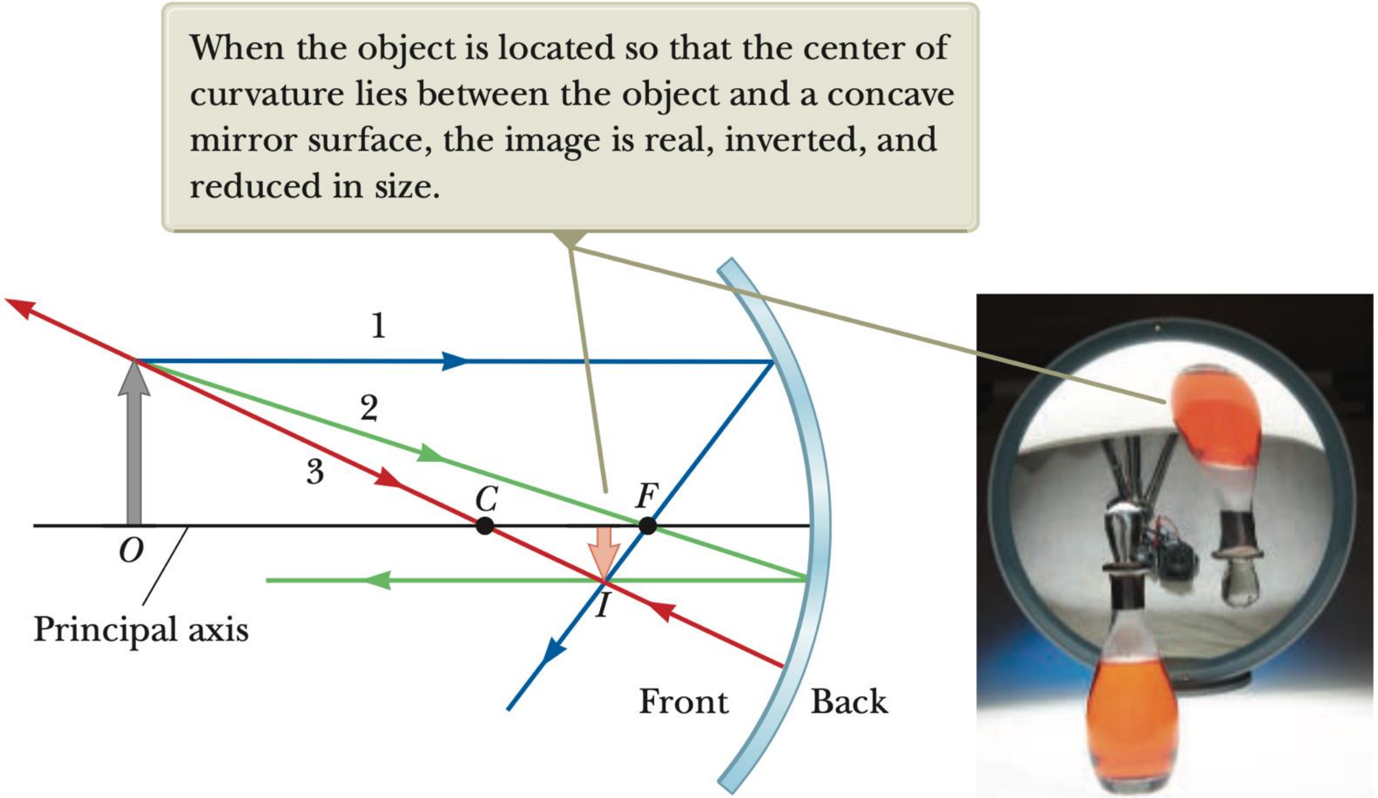
For paraxial rays, the focal length of a spherical mirror is half its radius of curvature.

$$f = \frac{R}{2}$$

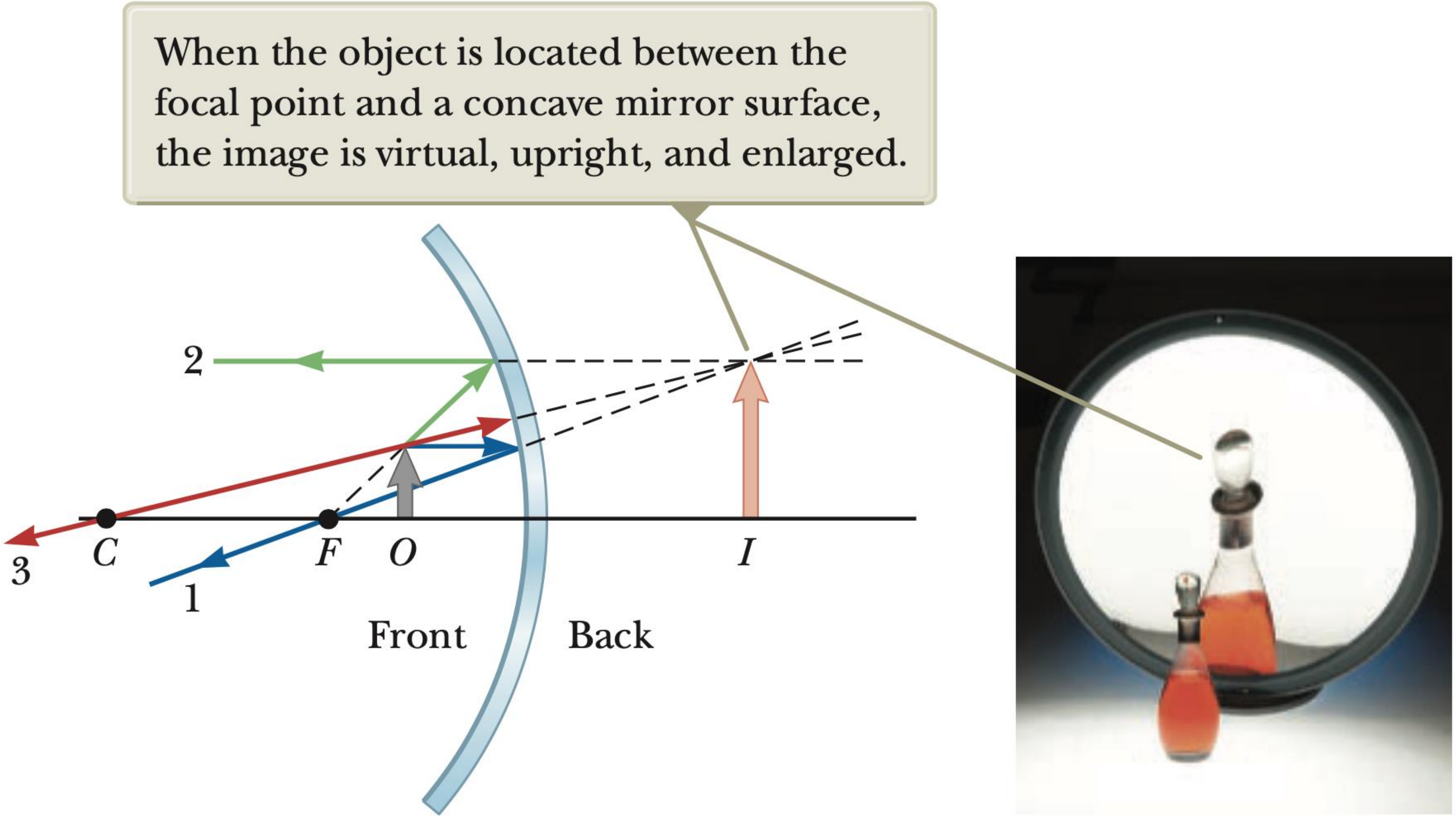
Ray Tracing for Spherical Mirrors

1. Center the mirror on the optical axis and indicate the focal point at distance f from the mirror's surface.
2. Represent the object with an upright arrow drawn from the axis at distance p from the mirror's surface.
3. Draw three special rays from the tip of the arrow. All reflections occur at the mirror plane.
    a. Ray #1 is parallel to the axis and reflects through (concave) or away from (convex) the focal point.
    b. Ray #2 passes through (concave) or away from (convex) the focal point reflects parallel to the axis.
    c. Ray #3 passes through the center of the sphere and reflects back on itself.
    d. Alternatively, you could choose Ray #4 that strikes the center of the mirror and reflects at an equal angle on the opposite side of the optical axis.
4. Extend the rays until they converge at the image point.

Concave Mirror ($p > f$)

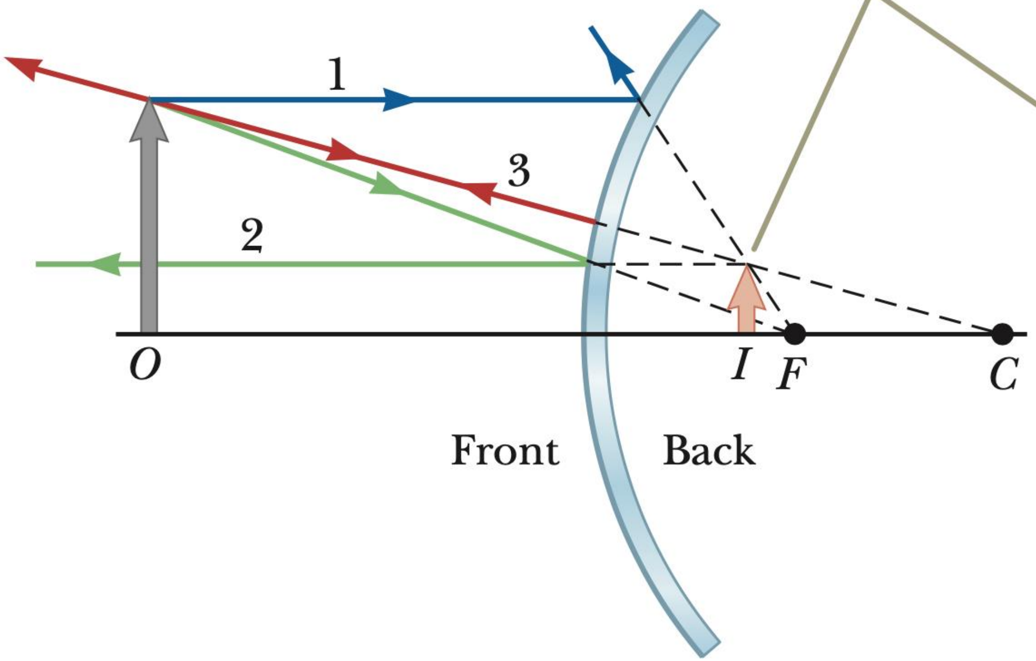


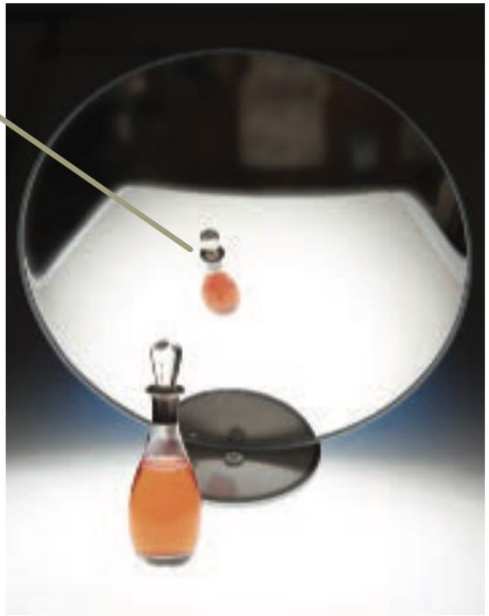
Concave Mirror ($p < f$)



Convex Mirror

When the object is in front of a convex mirror, the image is virtual, upright, and reduced in size.





Mirror Equation & Sign Conventions

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

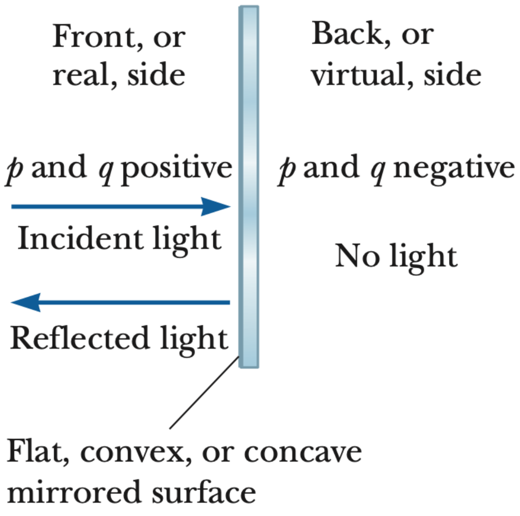


TABLE 35.1 Sign Conventions for Mirrors

Quantity	Positive When . . .	Negative When . . .
Object location (p)	object is in front of mirror (real object).	object is in back of mirror (virtual object).
Image location (q)	image is in front of mirror (real image).	image is in back of mirror (virtual image).
Image height (h')	image is upright.	image is inverted.
Focal length (f) and radius (R)	mirror is concave.	mirror is convex.
Magnification (M)	image is upright.	image is inverted.

Conceptual Question 8

A concave mirror of focal length f produces an image of the moon. Where is the image located?

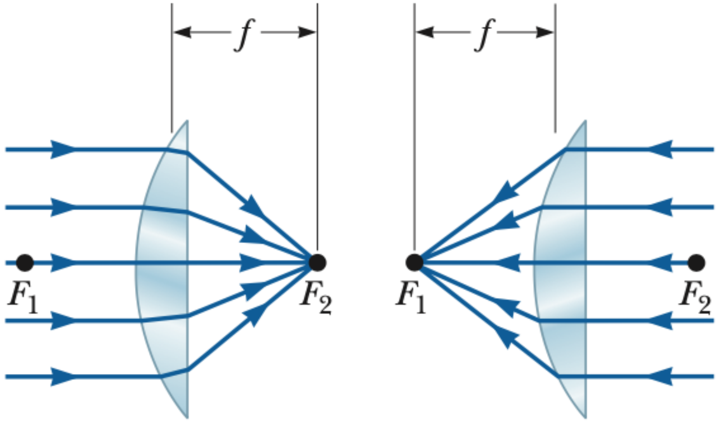
A. At the moon's surface.

B. Almost exactly a distance f behind the mirror.

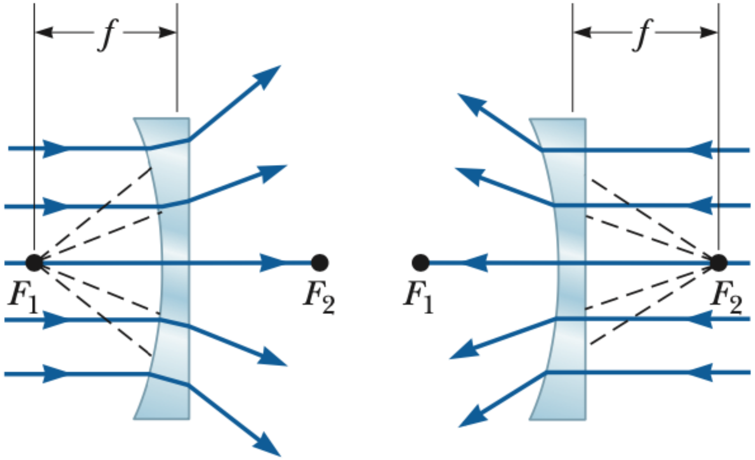
C. Almost exactly a distance f in front of the mirror.

D. At a distance behind the mirror equal to the distance of the moon in front of the mirror.

Converging and Diverging Lenses



Converging Lens



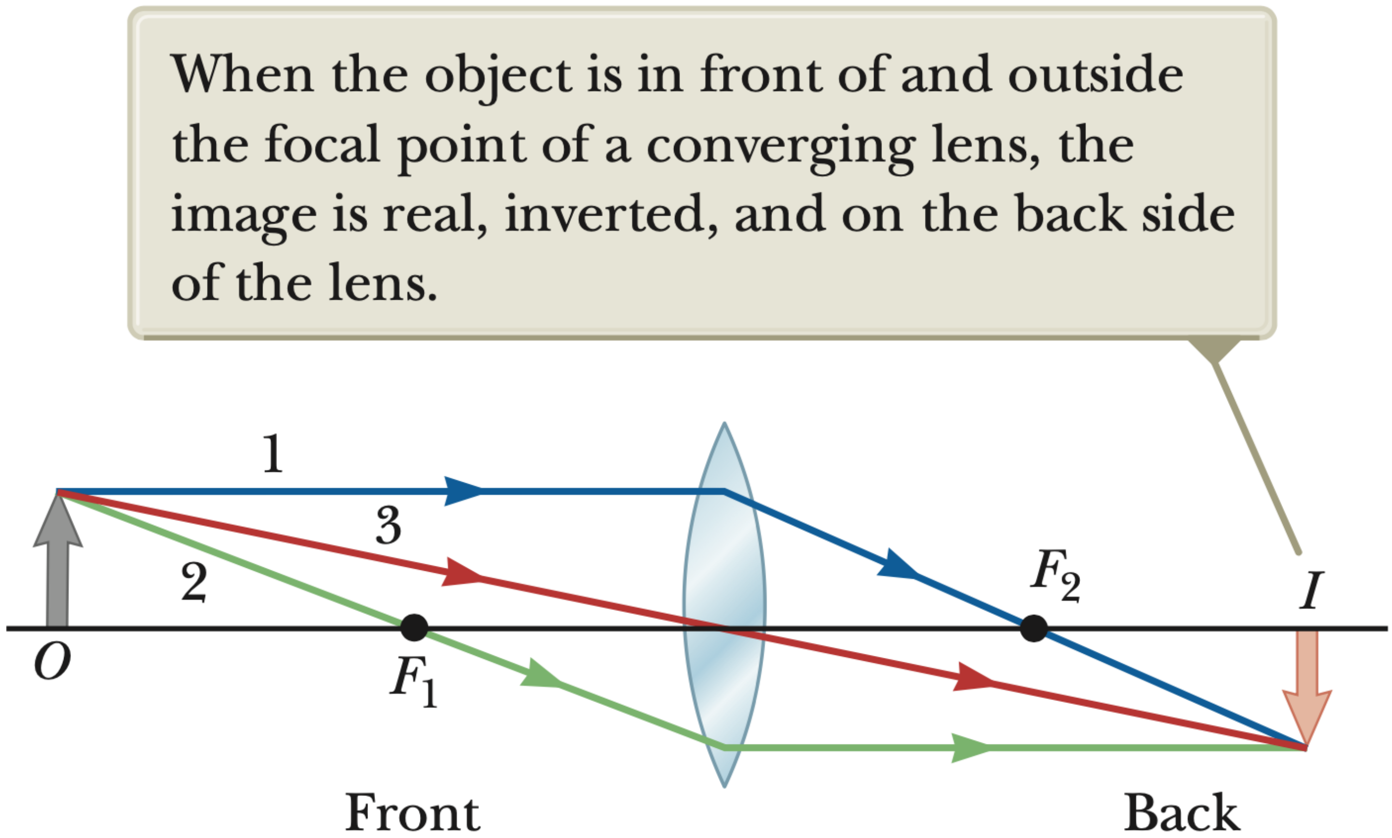
Diverging Lens

Ray Tracing for Thin Lenses

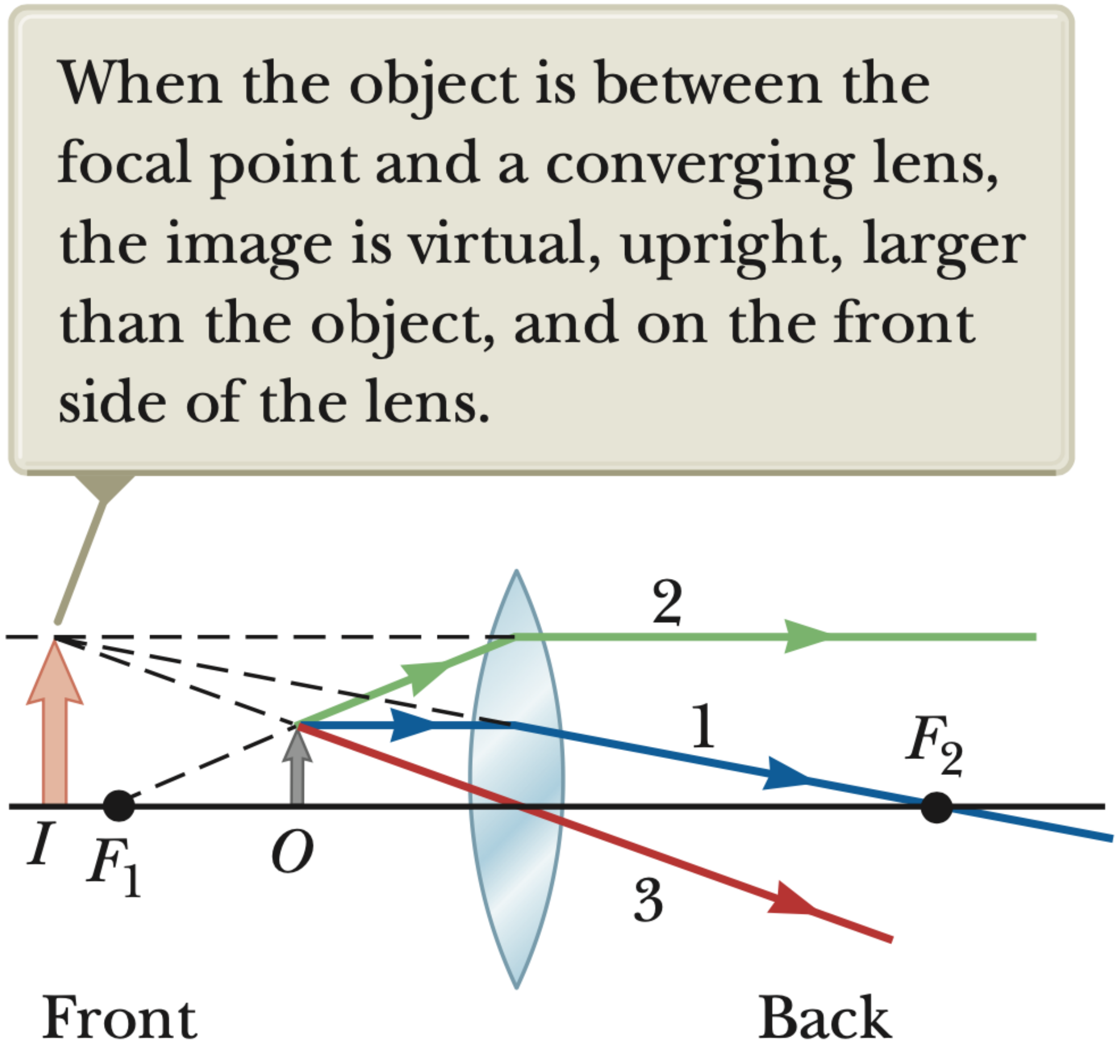
1. Ray #1 is parallel to the axis and refracts through the focal point.
2. Ray #2 passes through the focal point (or as if it comes from the focal point) and refracts parallel to the axis.
3. Ray #3 passes through the center of the lens and continues in a straight line.

Extend the rays until they converge to find the image point.

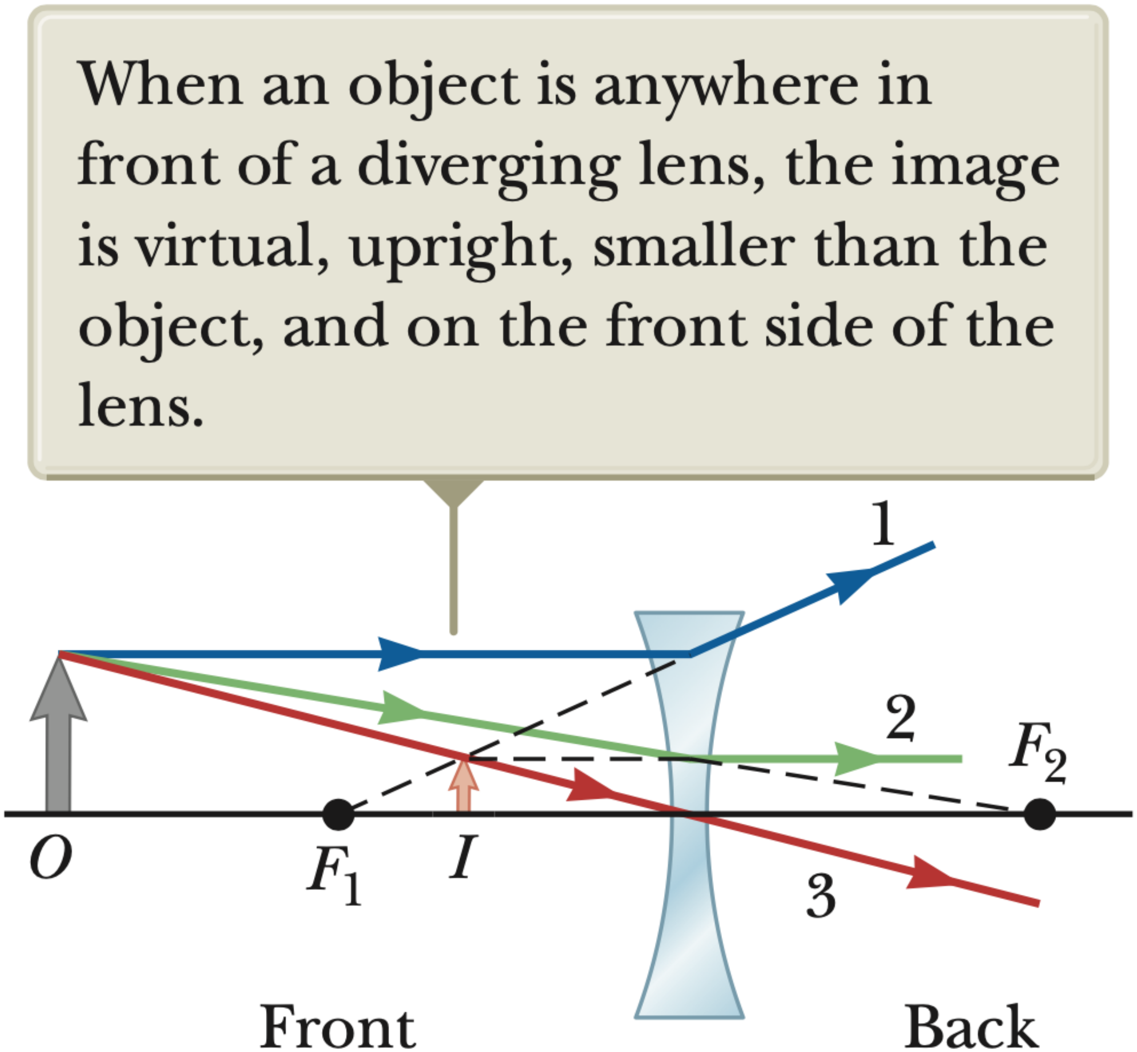
Converging Lens ($p > f$)



Converging Lens ($p < f$)



Diverging Lens



Thin Lens Equation & Sign Conventions

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

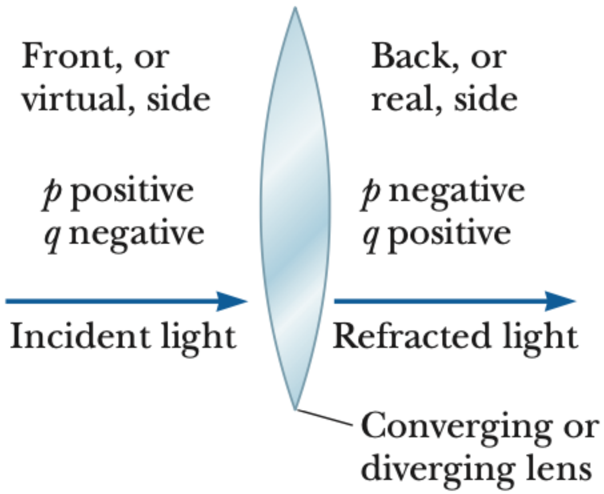


TABLE 35.3 Sign Conventions for Thin Lenses

Quantity	Positive When . . .	Negative When . . .
Object location (p)	object is in front of lens (real object).	object is in back of lens (virtual object).
Image location (q)	image is in back of lens (real image).	image is in front of lens (virtual image).
Image height (h')	image is upright.	image is inverted.
R_1 and R_2	center of curvature is in back of lens.	center of curvature is in front of lens.
Focal length (f)	a converging lens.	a diverging lens.

Conceptual Question 9

A lens produces a sharply focused, inverted image on a screen. What will you see on the screen if the lens is removed?

A. The image will be inverted and blurry.
B. The image will be upright and blurry.
C. The image will be upright and sharp.
D. The image will be upright but otherwise unchanged.
E. There will be no image at all.