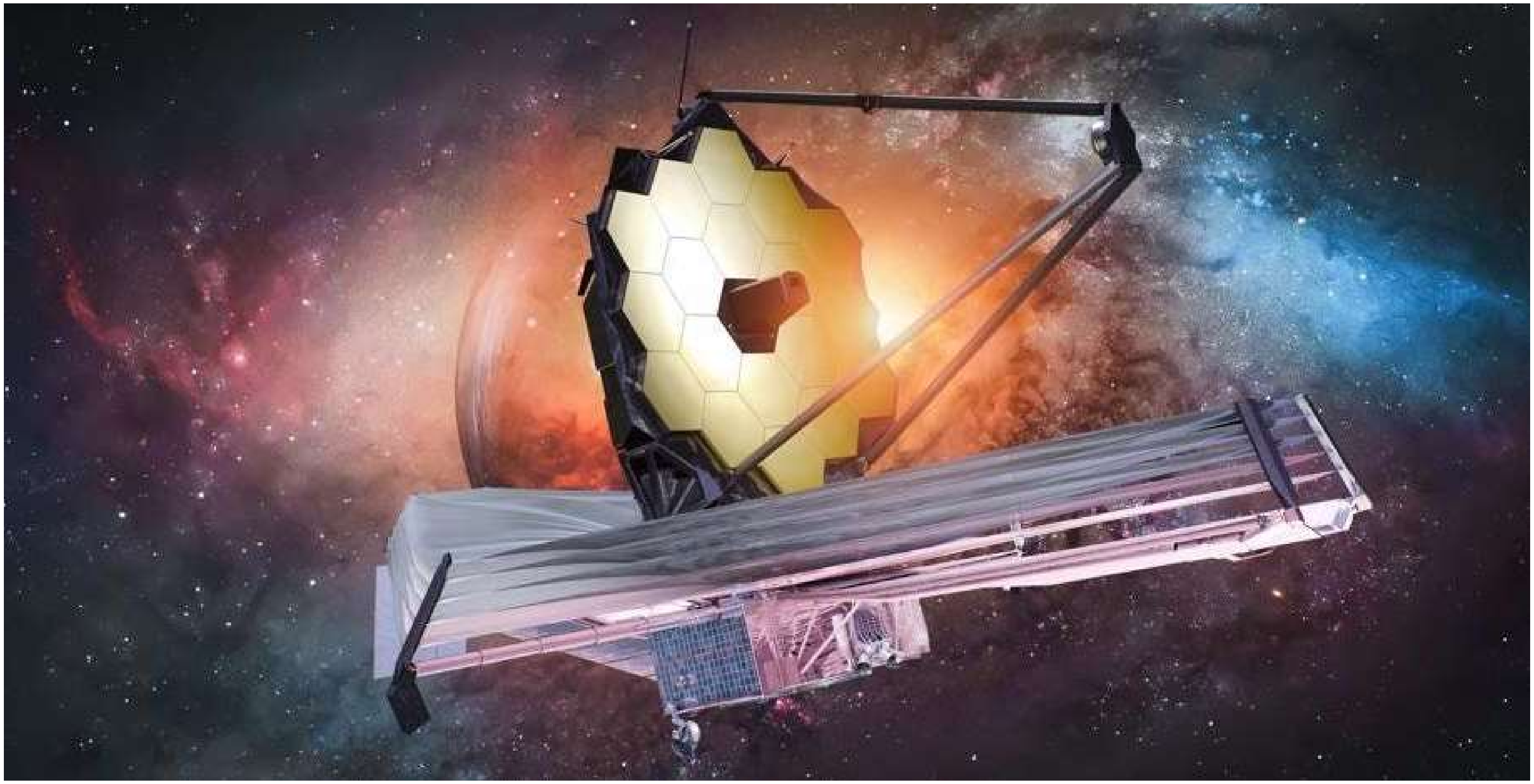

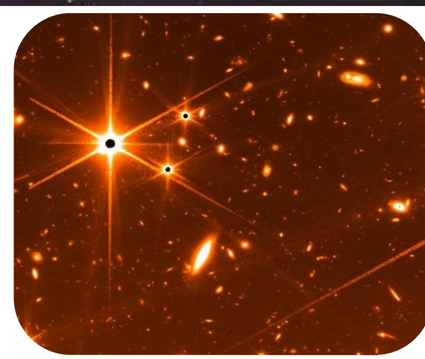


# Chapter 32
# Light: Reflection and Refraction

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# Chapter 32 - Light: Reflection and Refraction

- **32-0 Introduction**
  - Camera obscura
  - Optics a game with light
- **32-1 The Ray Model of Light**
- **32-2 Reflection; Image Formation by a Plane Mirror**
  - Law of reflection
  - Law of reflection with a rough surface
  - Example 32-1: Reflection from flat mirrors.
  - Virtual vs Real images
  - Example 32-2: How tall must a full-length mirror be?
- **32-3 Formation of Images by Spherical Mirrors**
  - Introduction
  - Focal length & Focal point
  - Aberration
  - Ray diagrams
  - Mirror Equation and Magnification
  - Conceptual Example 32-5: Reversible rays.
  - Example 32-6: Object closer to concave mirror
- **32-5 Convex Mirrors**
  - Problem-Solving: Spherical Mirrors
  - Example 32-7: Convex rearview mirror.
- **32- 6 Index of Refraction**
- **32-7 Refraction: Snell's Law**
  - Snell's law
  - Example 32-8: Refraction through flat glass.
  - Example 32-9: Apparent depth of a pool
- **32-8 Visible Spectrum and Dispersion**
  - Spectrum and prism
  - Conceptual Example 32-10: Observed color of light under water:
- **32-9 Total Internal Reflection; Fiber Optics**
- **32-10 Refraction at a spherical surface**
  - Convex surface
  - Concave surface
  - Example 32-12: Apparent depth II.



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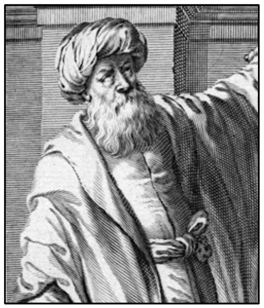
# Camera Obscura



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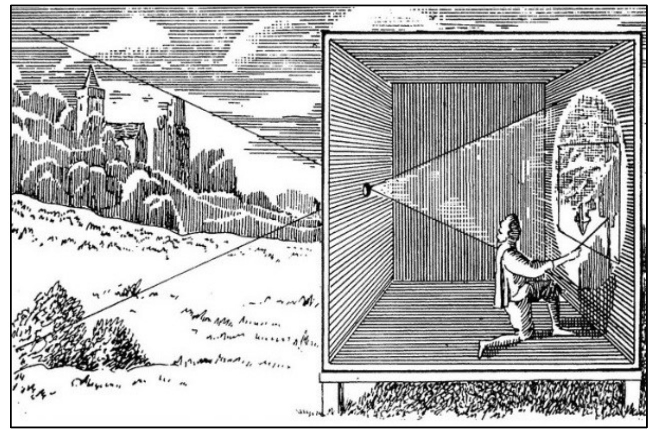
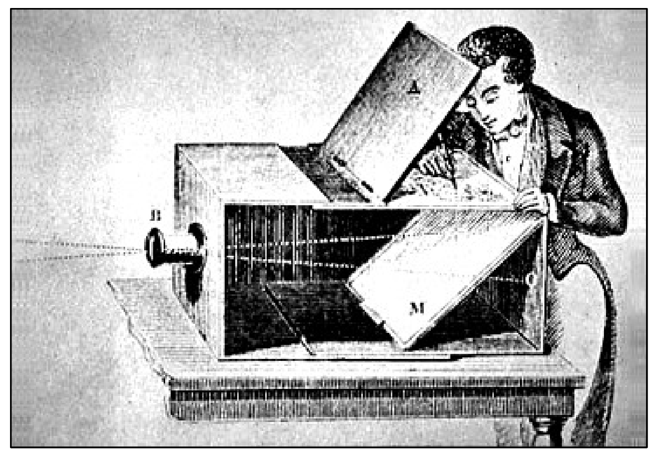
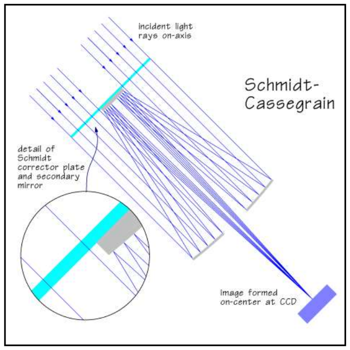


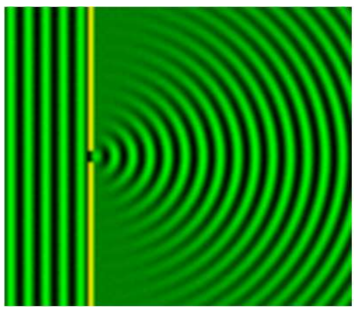
Proof that light travels in straight lines

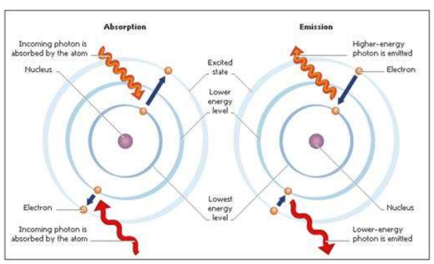
→ « Camera obscura »



# Optics: a game with light







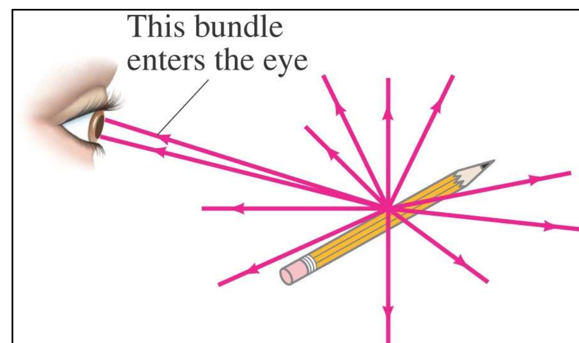

- Designing an optical instrument doesn't only mean the use the geometrical optics.
- Light can be considered as:
  - **a ray** → geometrical optics limits
    - Reflective optics
    - Refractive optics
  - **a wave** → diffractive optics
    - Grating description
    - Effect of the pupil
    - Interferometry
    - Scattering
  - **A particle**/ energy quanta
    - Light-matter Interaction
    - Spectroscopic process (interaction with atoms/molecules)
    - Light-Detector Interaction → conversion photon to electron

# 32-1 The Ray Model of Light

- Light travels in straight lines -> ray model of light (geometrical optics limit)
- Therefore, we represent light using rays as extremely narrow beams.
- Light rays leave each point of an object in all directions (if scattering)
- A small bundle (only) of rays enters the eye or detector
- This model is an idealization, but is very useful for geometric optics, describing :

  Reflection, Refraction, Image Formation by mirrors and lenses, …



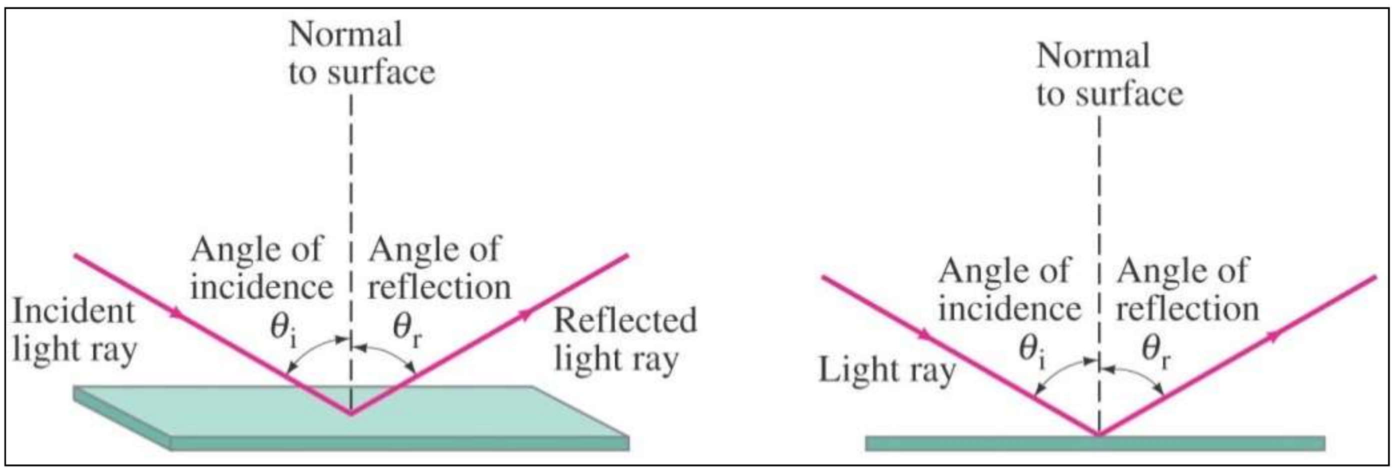



# 32-2 Reflection - Image Formation by a Plane Mirror

**Law of reflection:**

- **The angle of reflection (that the ray makes with the normal to a surface) equals the angle of incidence.**
- **Incident ray, normal to the surface and reflected ray are all in the same plane**

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

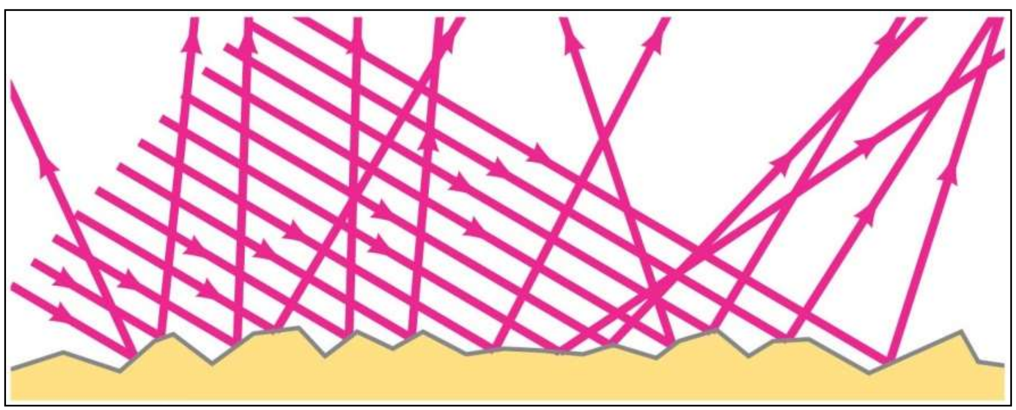


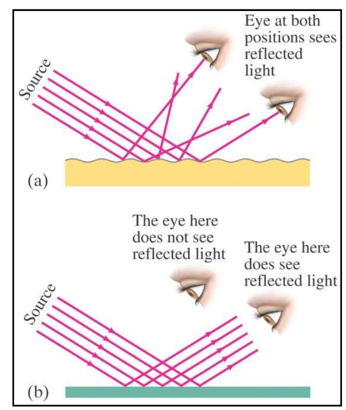
# 32-2 Reflection - Image Formation by a Plane Mirror

**Law of reflection with a rough surface:**

- **When light reflects from a rough surface (irregular), *the law of reflection still holds* (in first approximation), but now at each small section of surface separately. This is called diffuse reflection or scattered light.**
- **With diffuse reflection, an object can be seen at many different angles. With specular reflection (e.g. from a mirror), your eye must be (only) in the correct position.**

*Remark: the full description of scattering needs Electromagnetism equations (Maxwell equations)*





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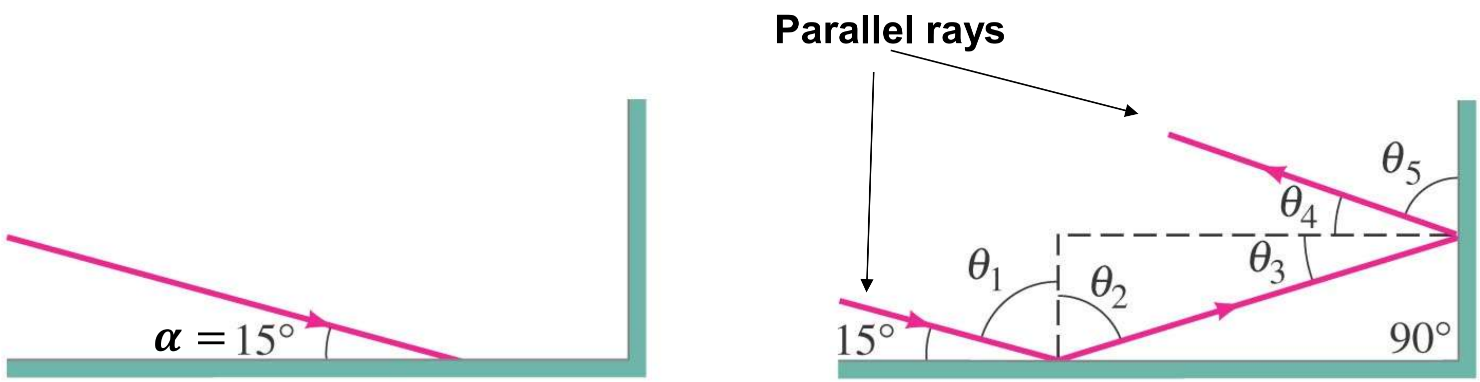
# 32-2 Reflection - Image Formation by a Plane Mirror

## Example 32-1: Reflection from flat mirrors.

Two flat mirrors are perpendicular to each other. An incoming beam of light makes an angle of 15° with the first mirror as shown.

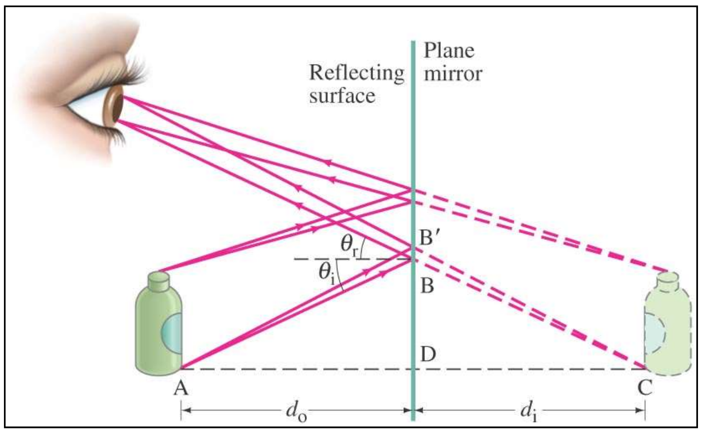
What angle will the outgoing beam make with the second mirror?




Prove: $\theta_5 = \frac{\pi}{2} - \alpha$

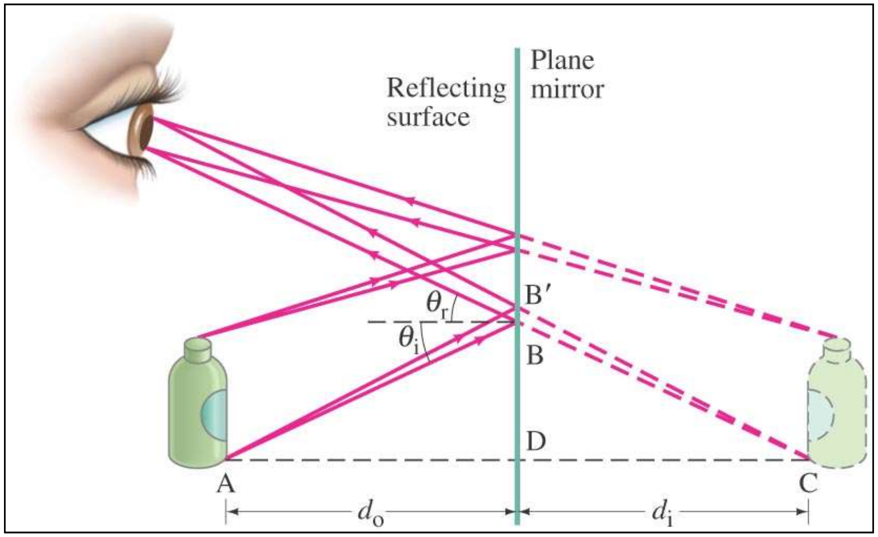
# 32-2 Reflection - Image Formation by a Plane Mirror

- What you see when you look into a plane (flat) mirror is an image, which appears to be behind the mirror?




- **Rays leave each point on object in all directions**
- **only those two that enclose the bundle that enter the eye are shown**
- **They appear to come from a point behind the mirror**

# 32-2 Reflection - Image Formation by a Plane Mirror




- This is called a virtual image, *as the light does not go through it.*
- The distance of the ***virtual*** image from the mirror is **equal** to the distance of the object from the mirror.

**Is it obvious?**

**We can see both real and virtual images, as long as diverging rays enter our eyes**

# 32-2 Reflection - Image Formation by a Plane Mirror

## Virtual vs Real images

- A **real image** is the collection of focus points made by **converging rays** (where the rays cross), while a **virtual image** is the collection of focus points made by **extensions of diverging rays**.

- In other words, a virtual image is found by **tracing real rays** that emerge **from an optical device** (lens, mirror, or some combination) **backwards** to perceived or apparent origins of ray divergences.

***Remark:*** *In diagrams of optical systems, **virtual rays** are conventionally represented by **dotted lines**, to contrast with the solid lines of real rays.*



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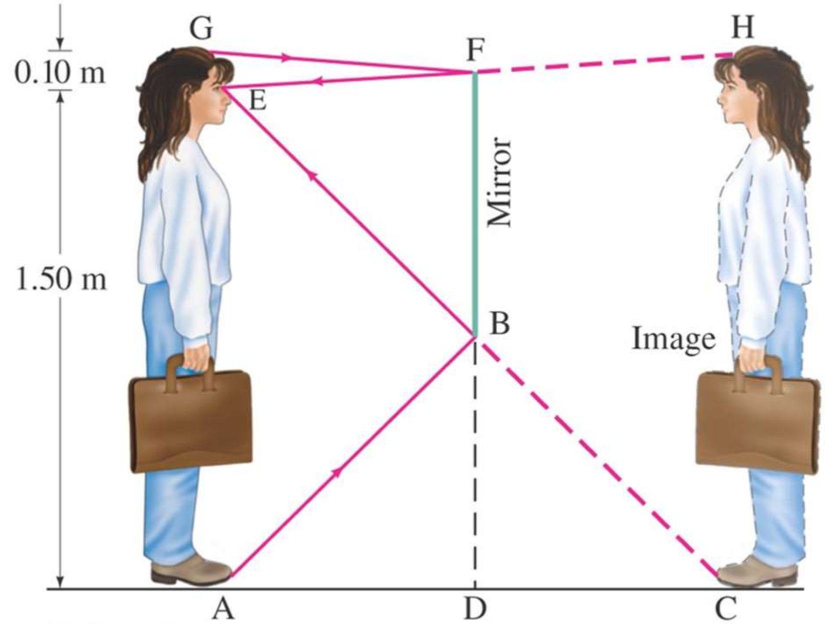
# 32-2 Reflection - Image Formation by a Plane Mirror

## Example 32-2: How tall must a full-length mirror be?

A woman 1.60 m tall stands in front of a vertical plane mirror.

- What is the minimum height of the mirror, and how close must its lower edge be to the floor, if she is to be able to see her whole body?

- Does the result depend on the distance from the mirror?



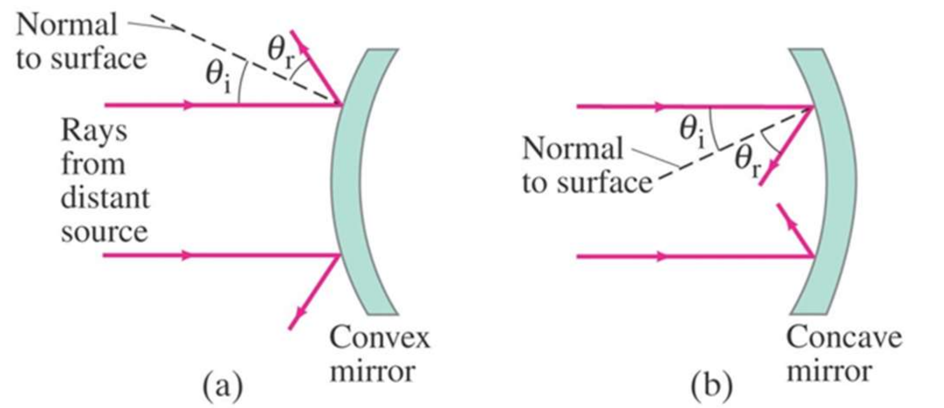
# 32-3 Formation of Images by Spherical Mirrors

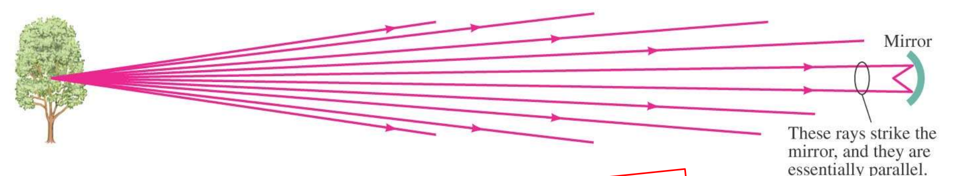
## Introduction

- Spherical mirrors are shaped like sections of a sphere and may be reflective on either the inside (concave) or outside (convex).

- Rays coming from an "infinitely" faraway object are effectively parallel.

- Angles arriving at an optical device are so small that we consider them parallel
  - Angle variation is so small that we consider this difference negligible.

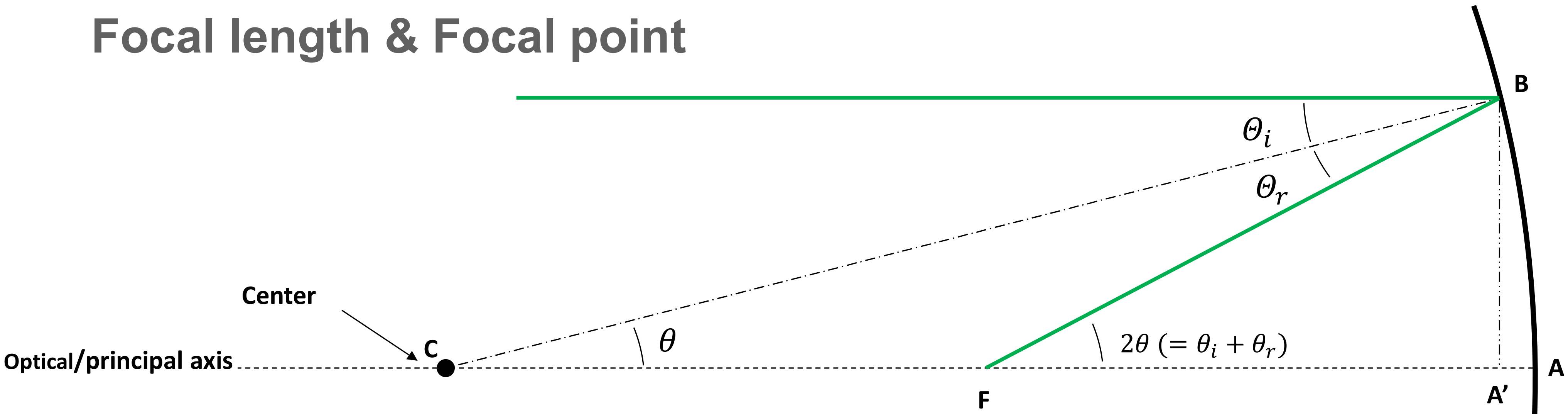



Stars are even farther

# 32-3 Formation of Images by Spherical Mirrors

## Focal length & Focal point




(1) $\boldsymbol{\theta_i = \theta_r = \theta}$

(2) $\dfrac{\overline{A'B}}{\overline{A'C}} = \boldsymbol{tan(\theta)}$

(3) $\dfrac{\overline{A'B}}{\overline{A'F}} = \boldsymbol{tan(2\theta)}$

(4) $\boldsymbol{x^2 + y^2 = r^2}$ **with** $\boldsymbol{r}$ **the radius of curvature** $(= \overline{CA})$

(5) $\boldsymbol{x = \overline{CA'} = \left|\left(\sqrt{r^2 - y^2}\right)\right|}$ **and** $\boldsymbol{y = \overline{A'B}}$

- If the size of the mirror is small compared to the radius of curvature ➔ $y^2 \ll r^2$, then $\overline{CA'} = \overline{CA} = r$.
- In addition, it leads to small $\theta$ ➔ $tan(\theta) \approx \theta$ (in rad.)
- Then we get with (2) and (3) and the approximation above:

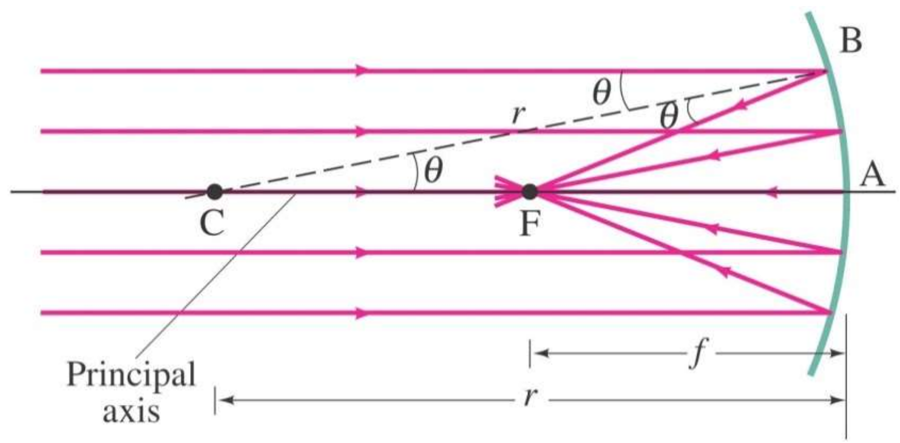
$\overline{AF} = \dfrac{\overline{AC}}{2}$ : is called the **focal distance (f)** of the mirror and **F the focal point**.

# 32-3 Formation of Images by Spherical Mirrors

- Paraxial rays : rays making a small angle with the principal axis of the mirror

- The focal point F is where all the rays parallel to the optical axis converge (or cross the optical axis) and $f$ is the focal length.

- Using simple geometry (and the approx. FB = FA), we find that the focal length is half the radius of curvature of the sphere : $f = \frac{r}{2}$



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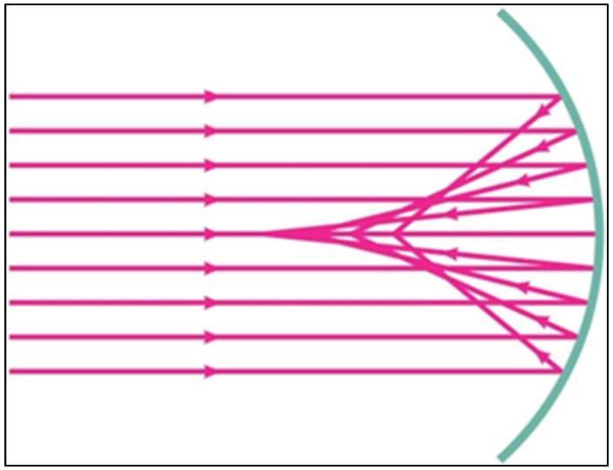
# 32-3 Formation of Images by Spherical Mirrors:

## Aberration

What if the paraxial approximation is not met?

Then if $\overline{CA'} \neq \overline{CA}$



- Parallel rays striking a spherical mirror do not all converge at **exactly** the same place if the curvature of the mirror is large; this is called **spherical aberration**.

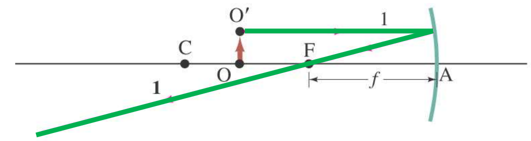
- Spherical aberration can be avoided by using a parabolic reflector
  - these are more difficult and expensive to make, and so are used only when necessary, such as in research telescopes.

# 32-3 Formation of Images by Spherical Mirrors:

## Ray diagrams

- We use ray diagrams to determine where an image will be. For mirrors, we use three key rays, all of which begin on the object:
    1. **A ray parallel to the axis; after reflection it passes through the focal point.**
    2. **A ray through the focal point; after reflection it is parallel to the axis.**
    3. **A ray perpendicular to the mirror; it reflects back on itself.**
- The intersection of these three rays gives the position of the image of that point on the object. To get a full image, we can do the same with other points.

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

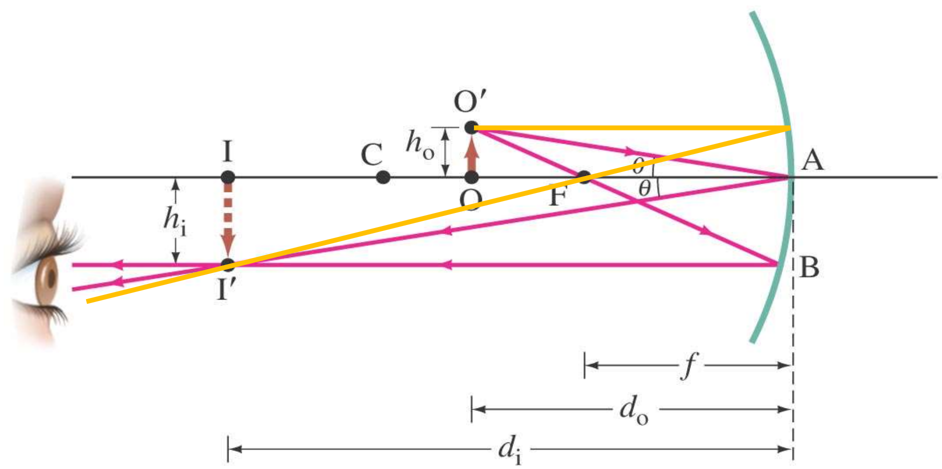



**In this example we obtain a real image. Can we see it ???**

**All other rays from this object point also pass through the image point!**

# 32-3 Formation of Images by Spherical Mirrors:

## Mirror Equation and Magnification




- Geometrically, we can derive an equation that relates the object distance, image distance, and focal length of the mirror:
- Similarities of $O'AO$ and $I'AI$ $\rightarrow \frac{h_0}{h_i} = \frac{d_o}{d_i}$
- Use of triangle $\mathrm{O'FO}$ and $AFB$ $\rightarrow \frac{h_0}{h_i} = \frac{d_o - f}{f}$

$$\boxed{\frac{1}{\mathrm{d}_0} + \frac{1}{\mathrm{d}_\mathrm{i}} = \frac{1}{\mathrm{f}}}$$



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# 32-3 Formation of Images by Spherical Mirrors:

- We can also find the magnification (ratio of **image height** to **object height**):

$$\boxed{m = \frac{h_i}{h_0} = -\frac{d_i}{d_0}}$$

- The negative sign indicates that the image is inverted (convention).
- This object is between the centre of curvature and the focal point, and its image is *larger, inverted, and real*.

- Convention:
  - The image height $h_i$ is positive if the image is upright, and negative if inverted relative to the object
  - $d_i$ or $d_o$ is positive if image or object is in front of the mirror if either the image or the object is behind the mirror, the corresponding distance is negative.

**Study example 32-4 yourself !**



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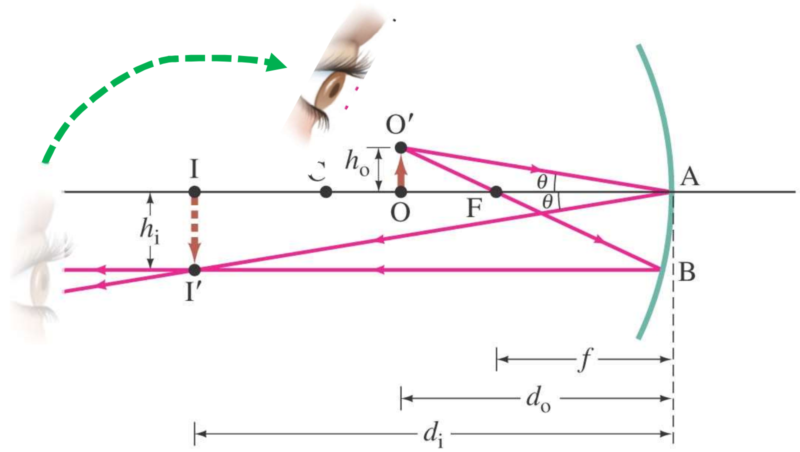
# 32-3 Formation of Images by Spherical Mirrors:

## Conceptual Example 32-5: Reversible rays.

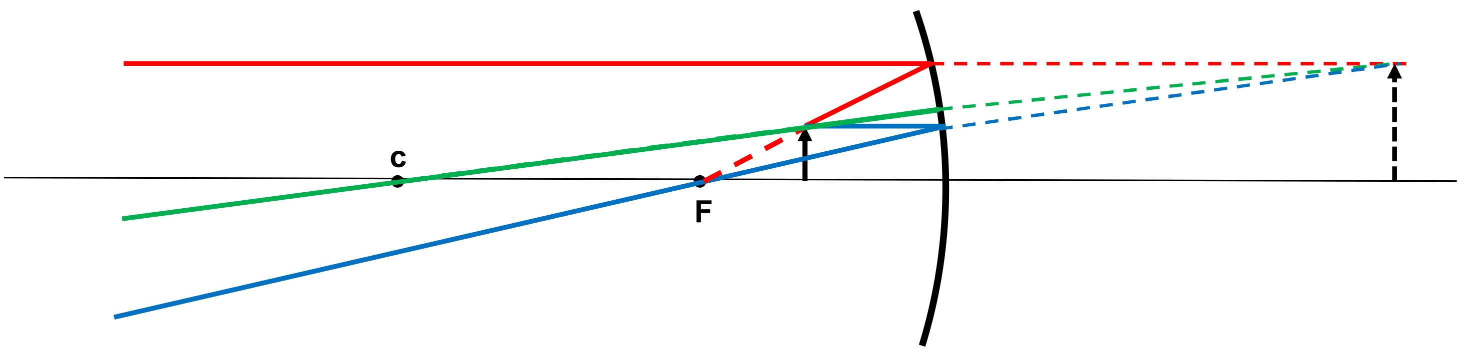
- If the object in this figure is placed where the image is, where will the new image be?




- The new image will be where the old object was (indeed only reverse the direction of the rays).

# 32-3 Formation of Images by Spherical Mirrors:

## Example 32-6: Object closer to concave mirror



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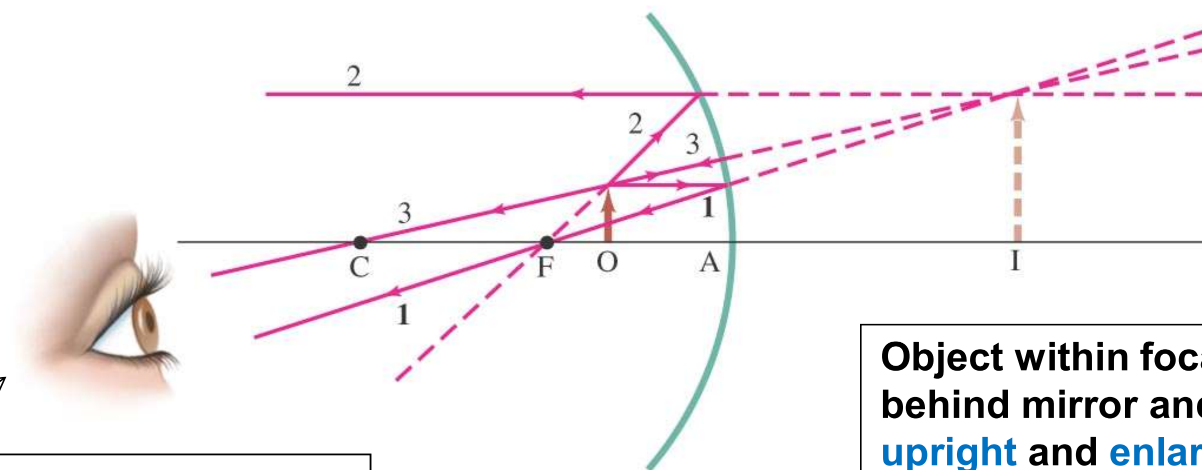
# 32-3 Formation of Images by Spherical Mirrors:

## Example 32-6: Object closer to concave mirror

- A 1-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 (approximately) the position of the image. (b) Determine the position of the image and the magnification analytically.




**Object within focal point: Image is behind mirror and is thus virtual. It is upright and enlarged.**

**Here we can see the virtual image, as diverging rays enter our pupil.**

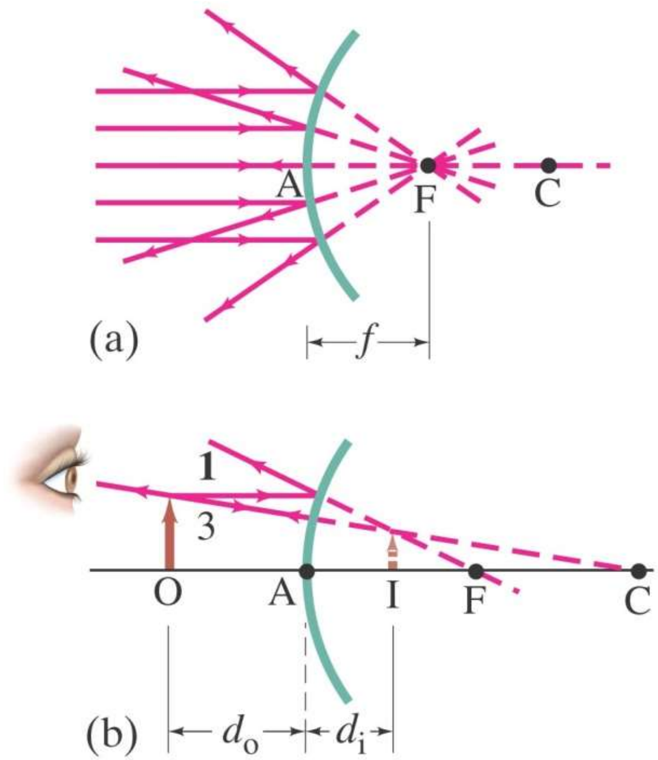
**The cornea + crystalline of the eye act as relay optics to create a real image on the retina**

**$d_i$ = -30 cm < 0**

**Magnification = -(-30 cm)/10 cm = + 3**

# 32-5 Convex Mirrors

- For a convex mirror (f < 0), the image is always virtual, upright, and smaller.
- **Problem Solving: Spherical Mirrors**
  1. Draw a ray diagram; the image is where the rays intersect.
  2. Apply the mirror and magnification equations.
  3. Sign conventions: if the object, image, or focal point is on the reflective side of the mirror, its distance is positive, and negative otherwise. Magnification is positive if image is upright, negative otherwise.
  4. Check that your solution agrees with the ray diagram.

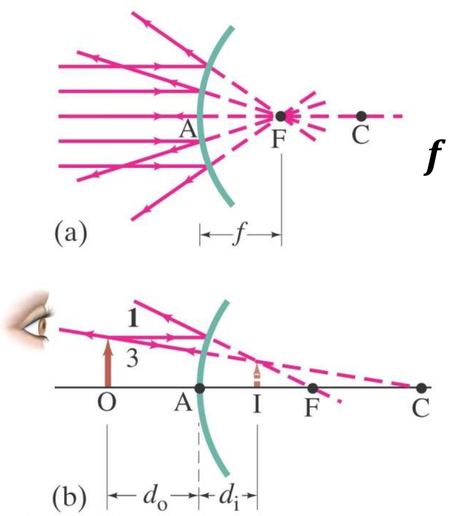


# 32-5 Convex Mirrors

## Example 32-7: Convex rearview mirror.

- An external rearview car mirror is convex with a radius of curvature of 0.8 m. Determine the location of the image and its magnification for an object 10.0 m from the mirror.

- This is the situation:




$$f = -0.4\,m$$

$$d_0 = 10\,m$$

$$\longrightarrow \quad d_i = -0.38\,m \text{ and } m = +0.038$$

# 32- 6 Index of Refraction

- **Light is an electromagnetic wave**
  - In vacuum, the speed of light is $c = 2.99792458\ x\ 10^8$ m/s
    $(\approx 3.0\ 10^8\ m/s)$
  - In other transparent materials (f.i. glass, water,…) the speed of light is always lower.
  - The index of refraction is a measure of the speed of light ratio in vaccum compared to materials :

$$\boxed{n = \frac{c}{v}}$$

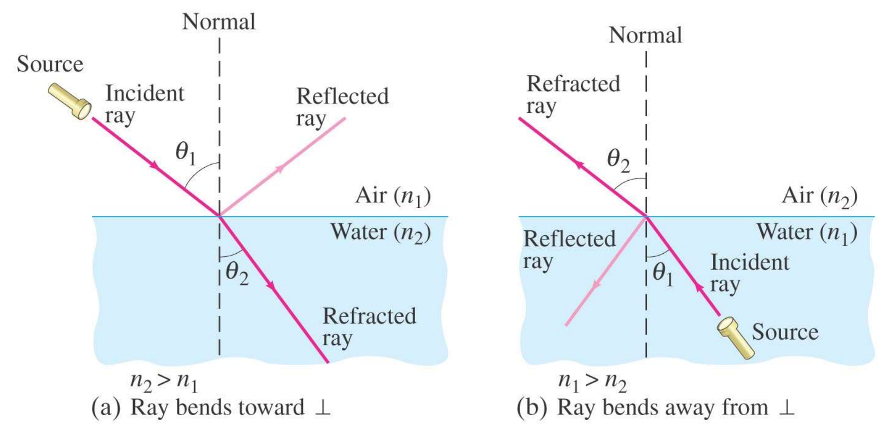
**TABLE 32–1 Indices of Refraction**[†]

| Material | $n = \frac{c}{v}$ |
|---|---|
| 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 flin | .58 |
| Lucite or Plexiglas | 1.51 |
| Sodium chloride | 1.53 |
| Diamond | 2.42 |

[†] $\lambda = 589$ nm.

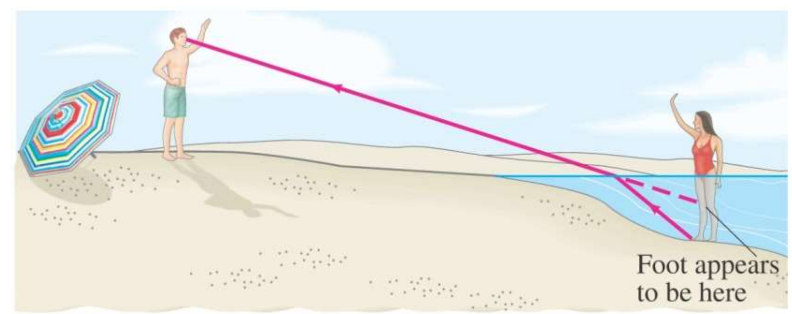
# 32-7 Refraction: Snell's Law

- Light changes direction when crossing a boundary from one medium to another (interface). This is called refraction, and the angle the outgoing ray makes with the normal is called the angle of refraction.




- The angle of refraction depends on the indices of refraction, and is given by Snell's law:

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



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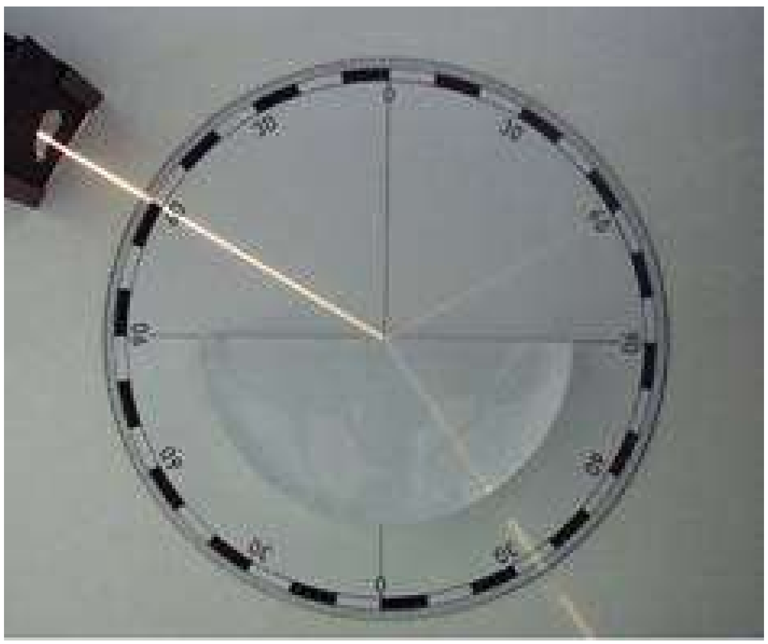
# 32-7 Refraction: Snell's Law

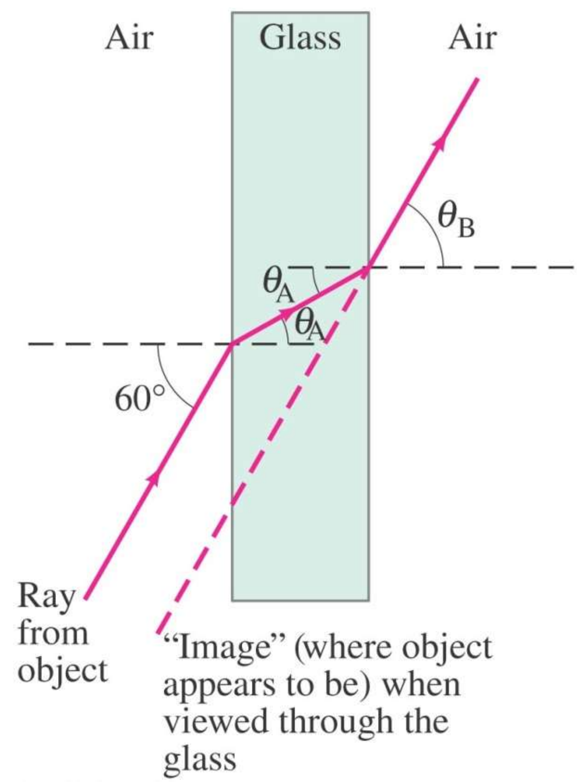


$$\boxed{n_1 \sin(\theta_1) = n_2 \sin(\theta_2)}$$

# 32-7 Refraction: Snell's Law

## Example 32-8: Refraction through flat glass.

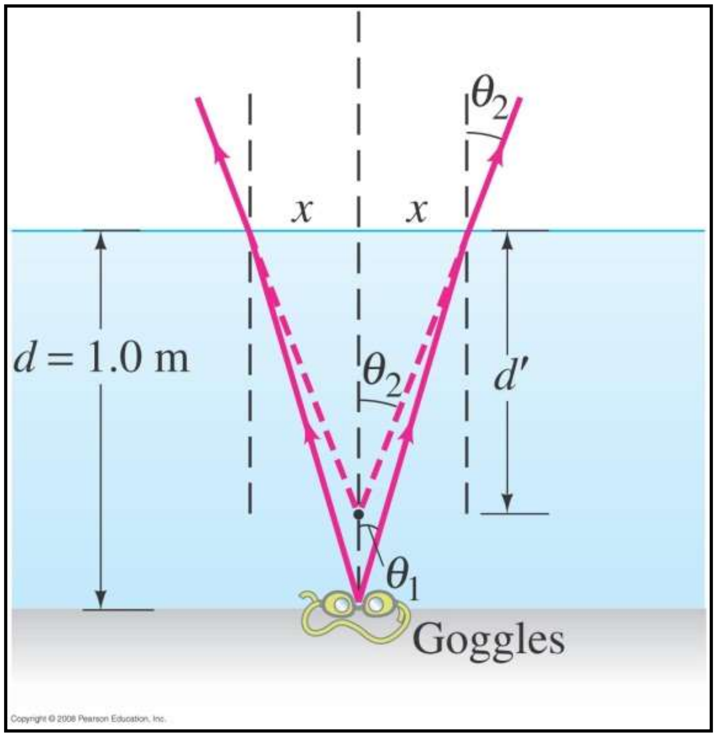
- Light travelling in air strikes a flat piece of uniformly thick glass at an incident angle of 60°, as shown. If the index of refraction of the glass is 1.5.
- What is the angle of refraction $\theta_A$ in the glass?
- what is the angle $\theta_B$ at which the ray emerges from the glass?




**Remark: a ray that will enter into a parallel plate will always emerge out of that plate with the same angle**

# 32-7 Refraction: Snell's Law

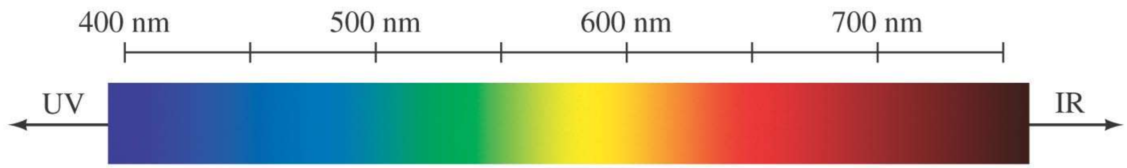
## Example 32-9: Apparent depth of a pool



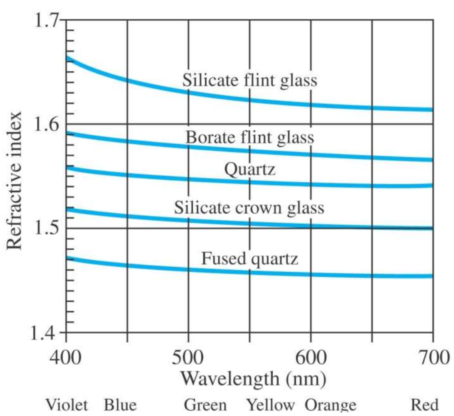

**Practice with Snell's law!**

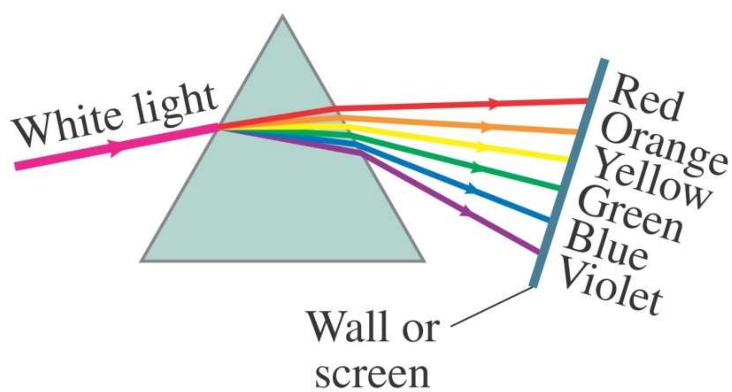
# 32-8 Visible Spectrum and Dispersion

- The visible spectrum contains the full range of wavelengths of light that are visible to the human eye.




- The index of refraction of many transparent materials, such as glass and water, varies slightly with wavelength. This is how prisms and water droplets create rainbows from sunlight.



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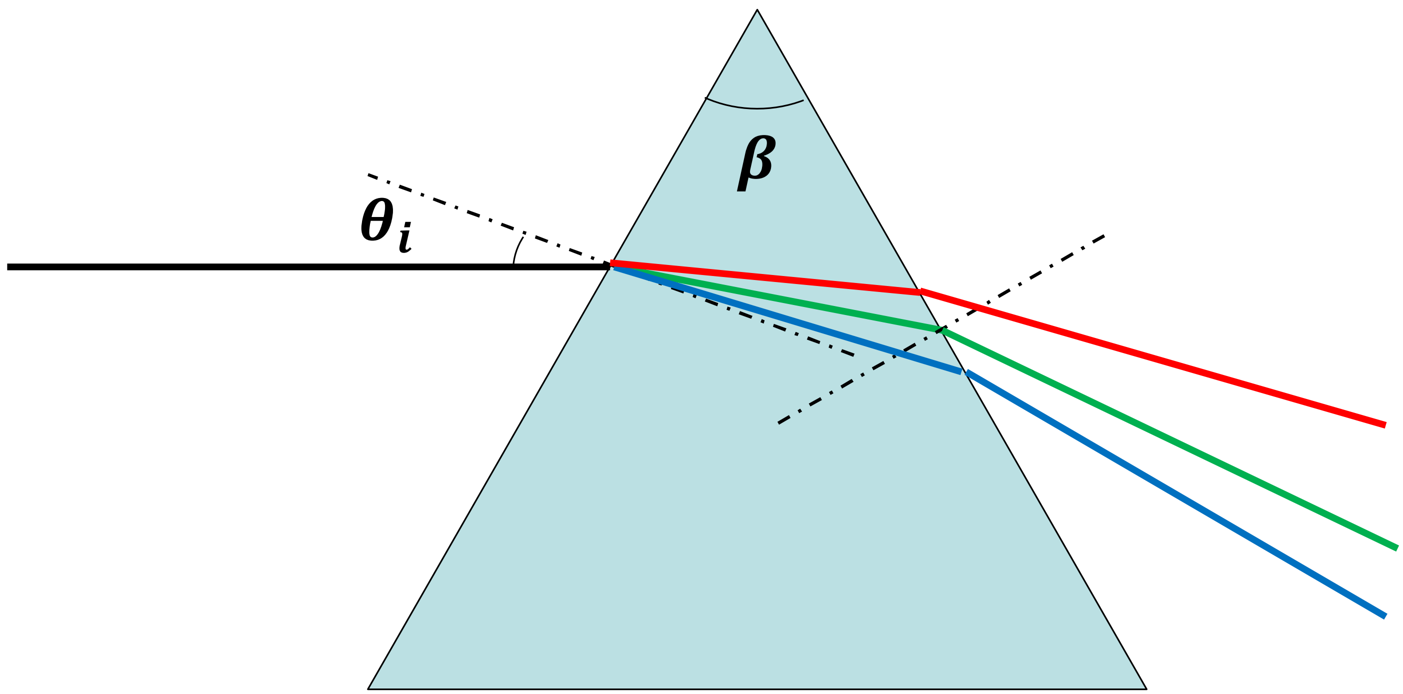
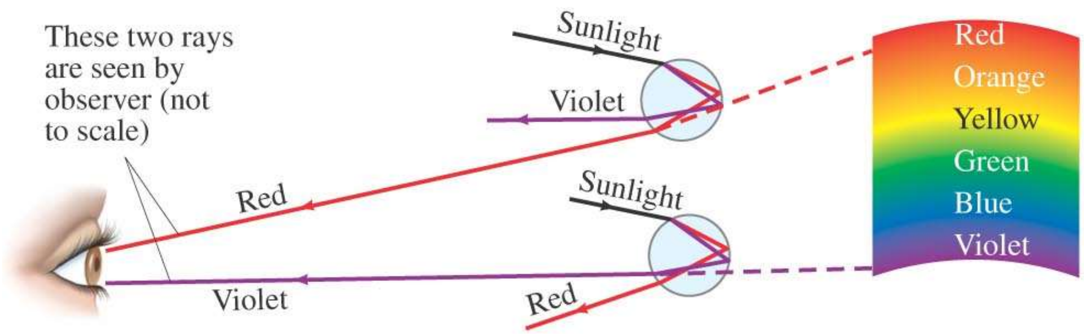
# 32-8 Visible Spectrum and Dispersion



# 32-8 Visible Spectrum and Dispersion




- When a wave travels from one material into another, the **frequency does not change**, but the **wavelength does**. If light goes from air to a material with refractive index n, then the wavelength becomes:

$$\lambda_n = \frac{v}{f} = \frac{c}{nf} = \frac{\lambda}{n}$$



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# 32-8 Visible Spectrum and Dispersion

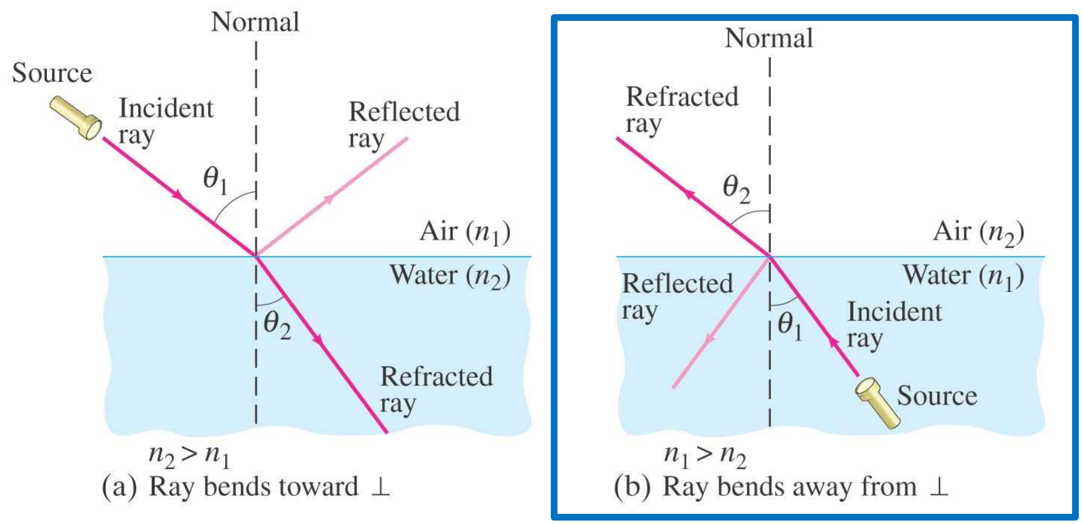
Conceptual Example 32-10: Observed color of light under water:

– We said that color depends on wavelength. For example, for an object emitting 650 nm light in air, we see red. But this is true only in air. If we observe this same object when under water, it still looks red. But the wavelength in water λn is 650 nm/1.33 = 489 nm. Light with wavelength 489 nm would appear blue in air. Can you explain why the light appears red rather than blue when observed under water?

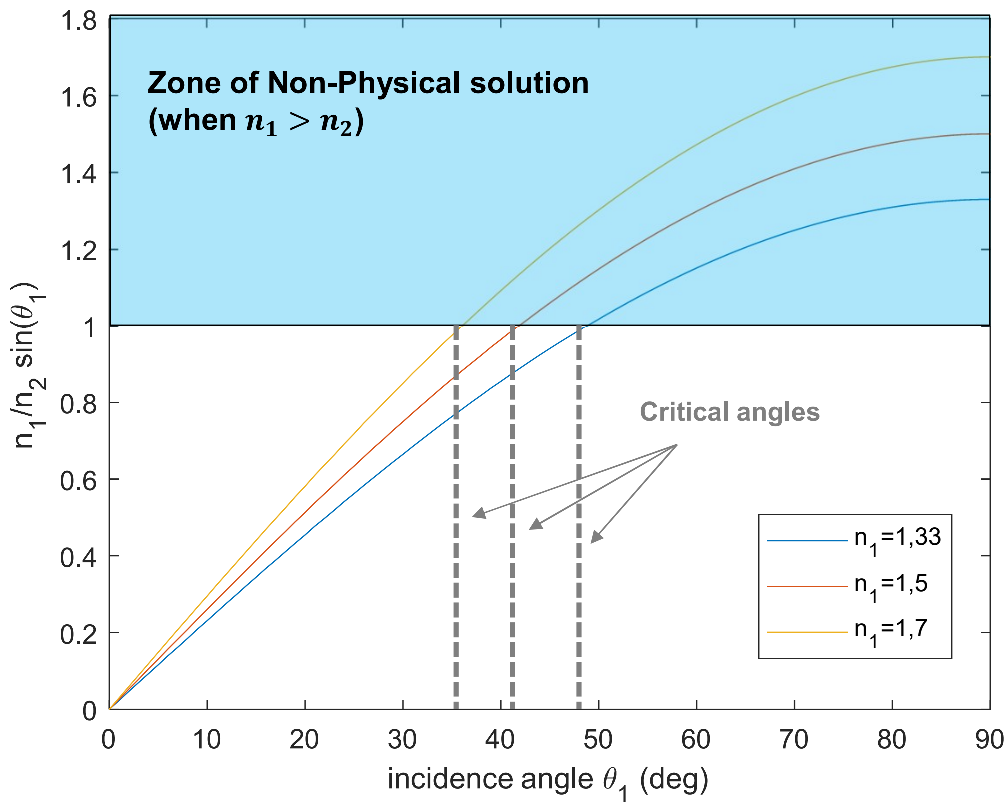
# 32-9 Total Internal Reflection; Fiber Optics

- Let's consider in deeper detail the second case:
  - The **source is IN a medium** with a higher index of refraction
  - $n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \rightarrow \left[\sin(\theta_2) = \frac{n_1}{n_2}\sin(\theta_1)\right] \leq \mathbf{1}$

**(by definition of the sine function)**



# 32-9 Total Internal Reflection; Fiber Optics

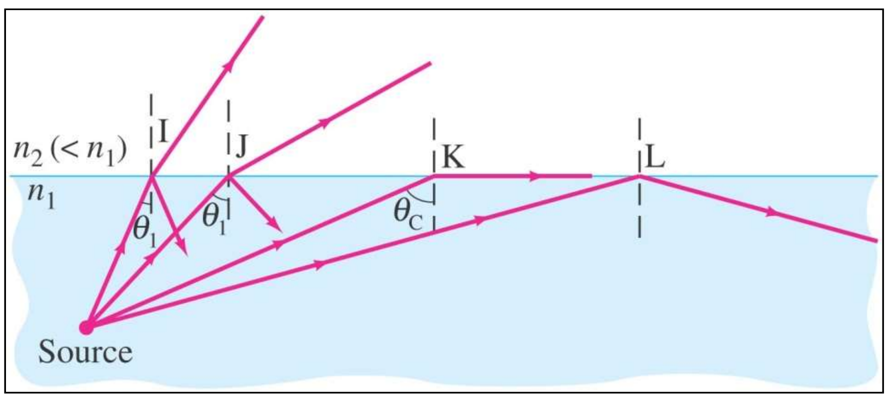


# 32-9 Total Internal Reflection; Fiber Optics

- If light passes into a medium with a smaller index of refraction, the angle of refraction is larger. There is an angle of incidence for which the angle of refraction will be 90°; the related incidence angle is called the **critical angle**.
- **Critical angle:**

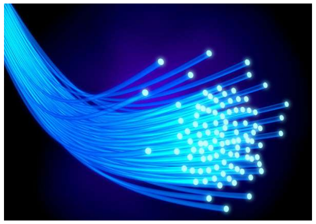
$$\boxed{\sin(\theta_c) = \frac{n_2}{n_1}\sin(90°) = n_2/n_1}$$

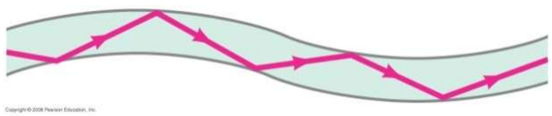
- if the angle of incidence is larger than this, no transmission occurs. This is called **Total Internal Reflection (TIR)**.



# 32-9 Total Internal Reflection; Fiber Optics

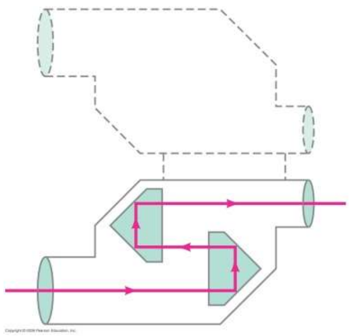
**Optical Fiber**





Optical fibers also depend on total internal reflection; they are therefore able to transmit light signals with very small losses (long distance).

**Prisms in binocular**



Binoculars often  use total internal reflection; this gives true 100% reflection, which even the best mirror cannot do.



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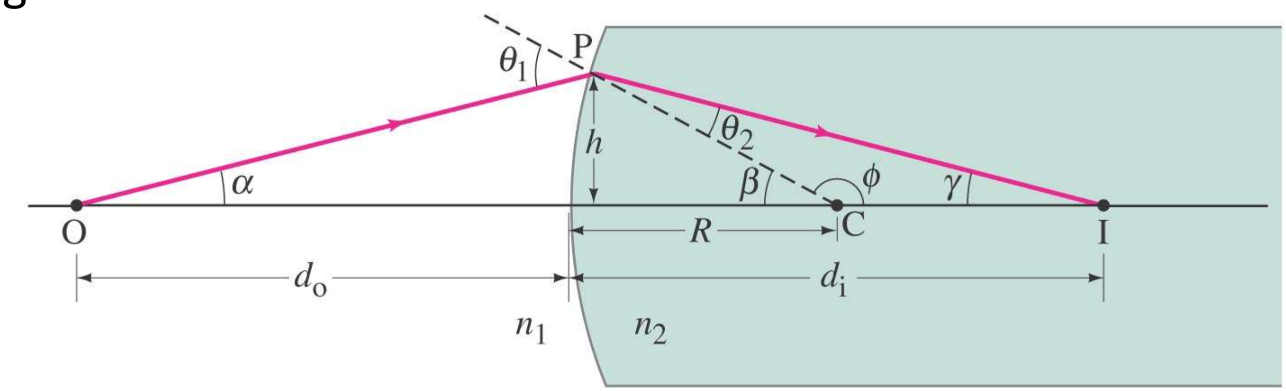
# 32-10 Refraction at a spherical surface

- Rays from a single point will be focused by a convex spherical interface with a medium of larger index of refraction to a single point, as long as the angles are not too large:



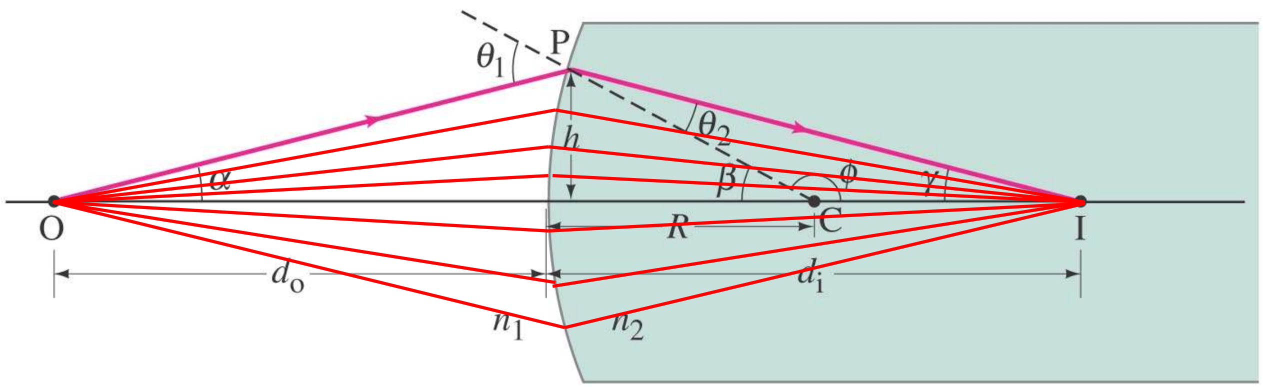

- Geometry gives the relationship between the indices of refraction, the object distance, the image distance, and the radius of curvature:

$$\boxed{\frac{n_1}{d_o} + \frac{n_2}{d_i} = \frac{n_2 - n_1}{R}}$$

# 32-10 Refraction at a spherical surface

## Convex surface

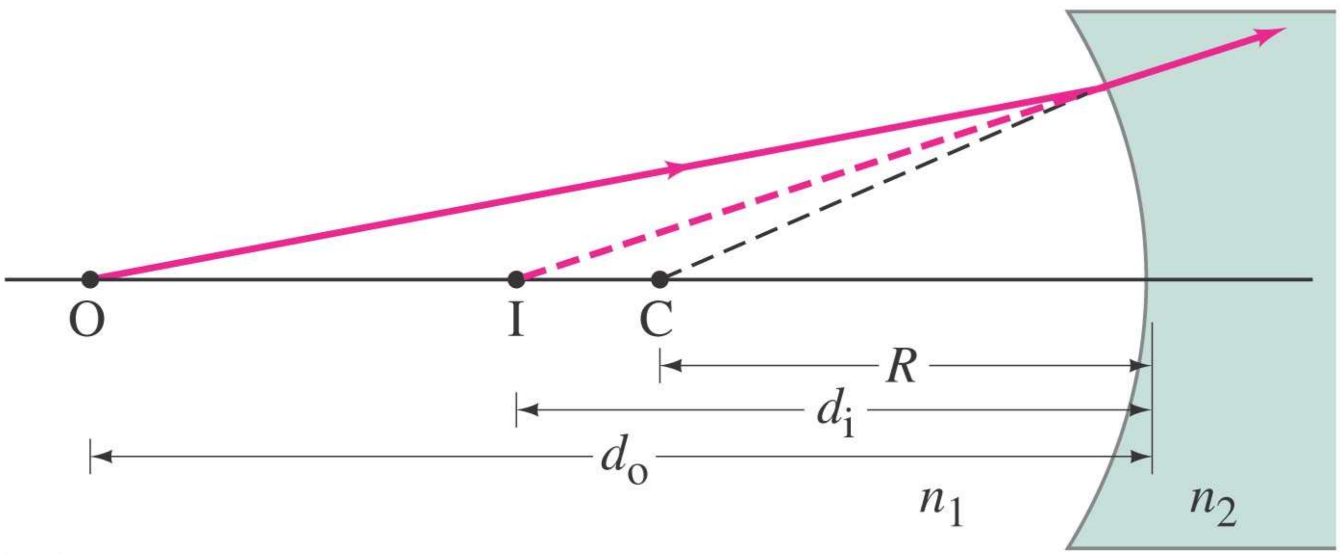
- As long as the angles stay small it is true for every $h$ → image formation.
- Otherwise → aberration (spherical aberration, for instance)



# 32-10 Refraction at a spherical surface

## Concave surface

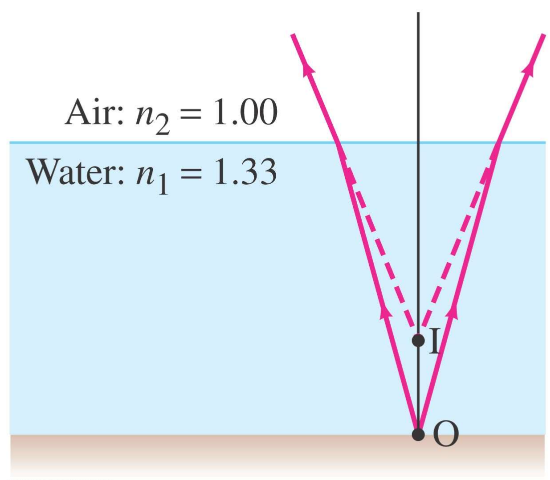
- For a concave spherical interface, the rays will diverge from a virtual image.



# 32-10 Refraction at a spherical surface

## Example 32-12: Apparent depth II.

– A person looks vertically down into a 1.0-m-deep pool. How deep does the water appear to be?




– The clue → consider $R = \infty$

# Summary of Chapter 32 (1 of 3)

- Light paths are called rays.
- Index of refraction: $n = \frac{c}{v}.$
- Angle of reflection equals angle of incidence.
- Plane mirror: image is virtual, upright, and the same size as the object.
- Spherical mirror can be concave or convex.
- Focal length of the mirror: $f = \frac{r}{2}.$



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# Summary of Chapter 32 (2 of 3)

- **Mirror equation:**

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}.$$

- **Magnification:**

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

# Summary of Chapter 32 (3 of 3)

- Law of refraction (Snell's law):

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

- Total internal reflection occurs when angle of incidence is greater than critical angle:

$$\sin\theta_C = \frac{n_2}{n_1}\sin 90^\circ = \frac{n_2}{n_1}.$$