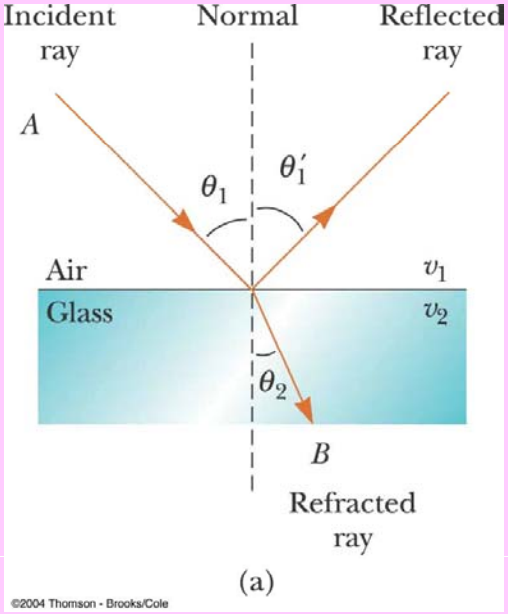
## The law of reflection:

$$\theta_1 = \theta_1'$$

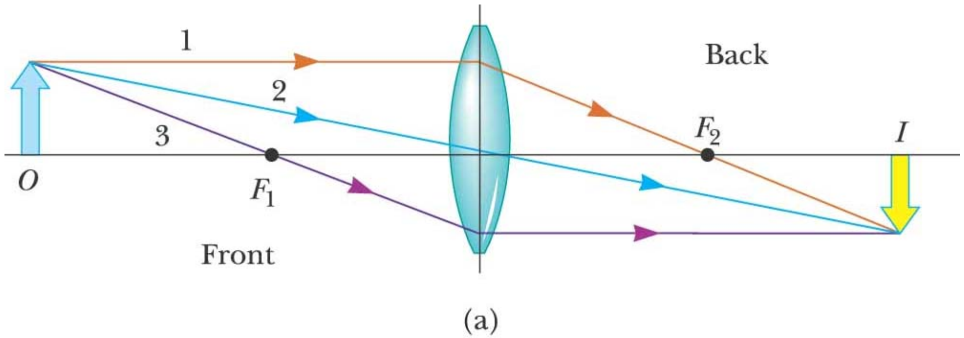
## The law of refraction:

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

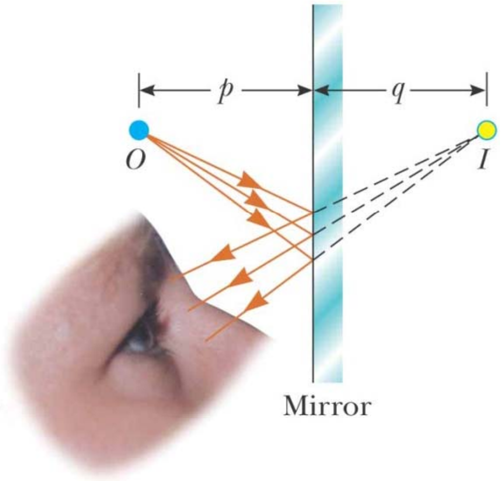
**Snell's Law**




## Image formation

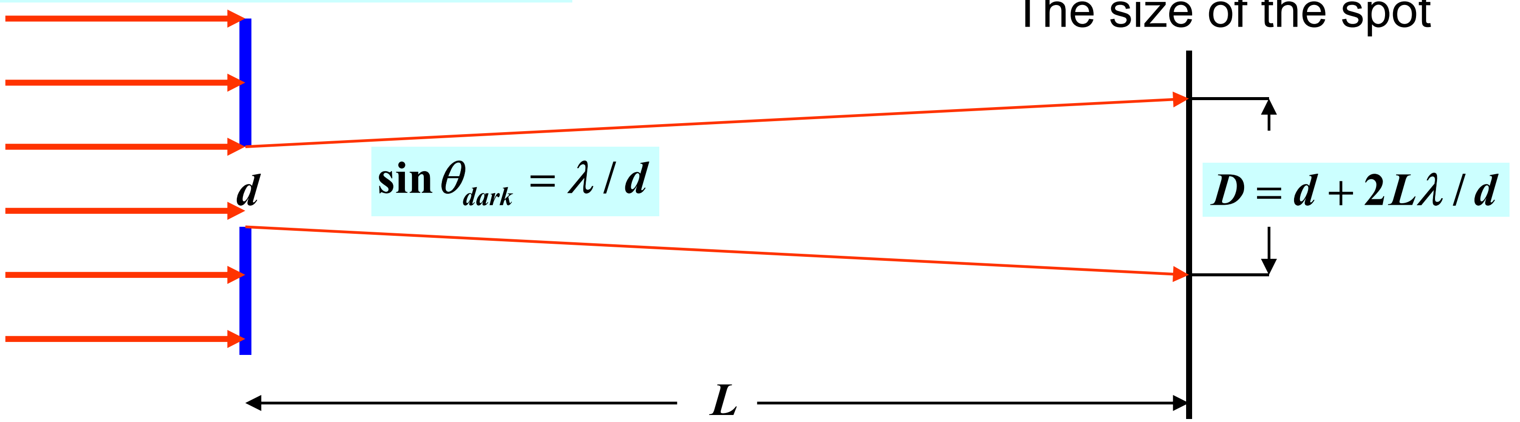


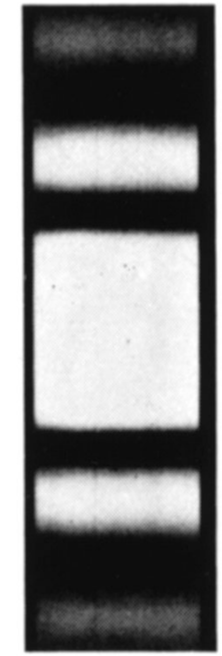


# Diffraction vs Ray Optics

$$I(\theta) = I_{\max}\left[\frac{\sin(\pi a \sin\theta / \lambda)}{\pi a \sin\theta / \lambda}\right]^2$$

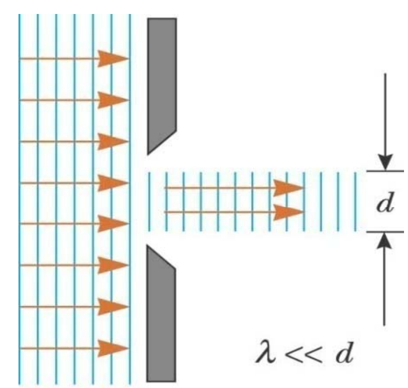



If $d << L\lambda / d$ then the size of the spot is $D = L\lambda / d$ - wave optics (diffraction)

If $d >> L\lambda / d$ then the size of the spot is $D = d$ - ray (geometric) optics

$$d^2 >> L\lambda$$



# Chapter 18

## Propagation of Light - Ray Optics

# Propagation of Light – Ray (Geometric) Optics

**Main assumption:**

- **light travels in a straight-line path in a uniform medium and**
- **changes its direction when it meets the surface of a different medium or**
- **if the optical properties of the medium are nonuniform**

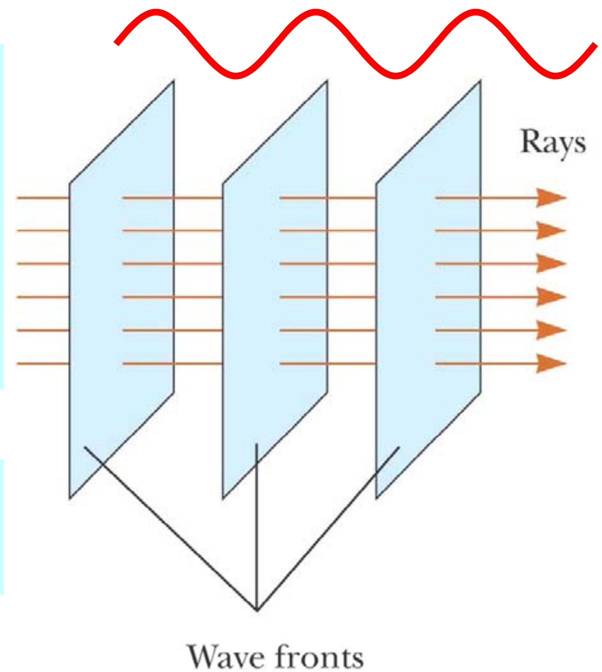
**The rays (directions of propagation) are straight lines perpendicular to the wave fronts**

**The above assumption is valid only when the size of the barrier (or the size of the media) is much larger than the wavelength of light**

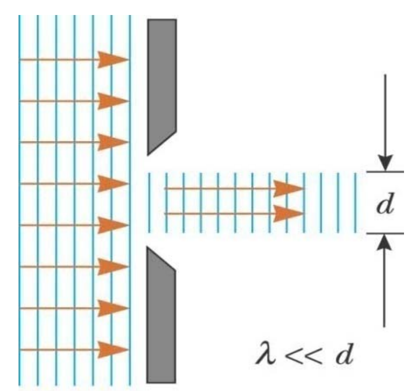
$$\lambda \ll d$$

**Main Question of Ray Optics:**

**What happens to light at the boundary between two media?**







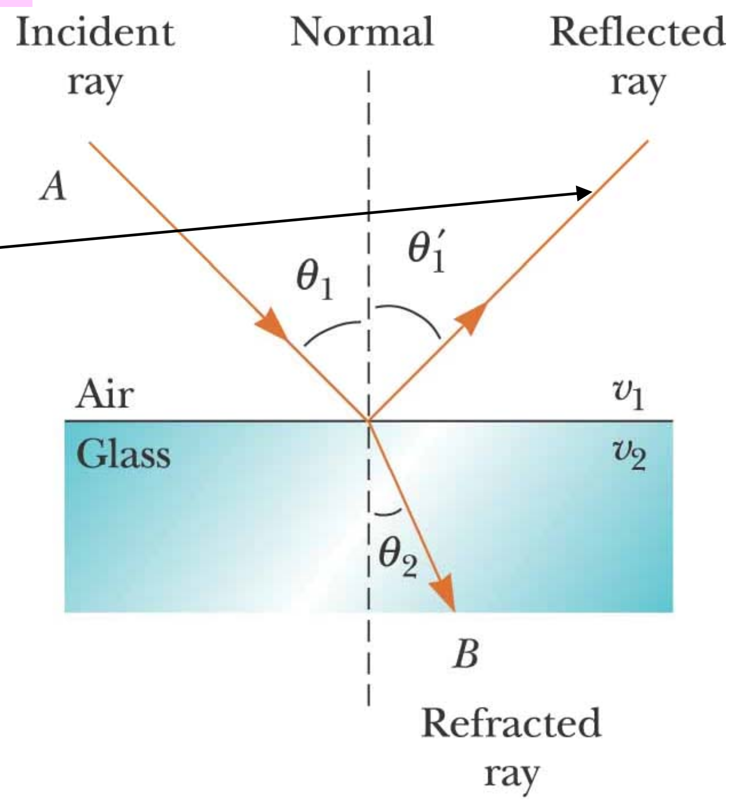
(a)

# Propagation of Light - Ray Optics

**What happens to light at the boundary between two media?**

**The light can be**

- **reflected or**
- **refracted (transmitted)**




(a)

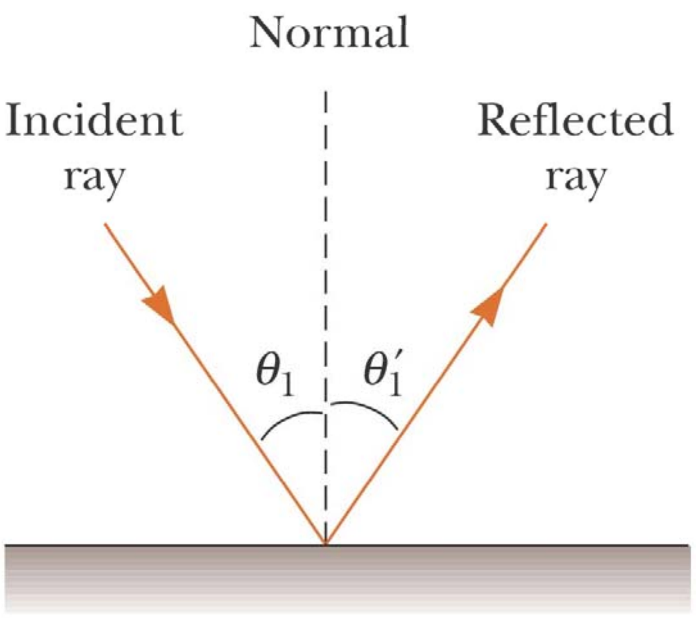
# Reflection of Light

**The law of reflection:**

**The angle of reflection is equal to the angle of incidence**

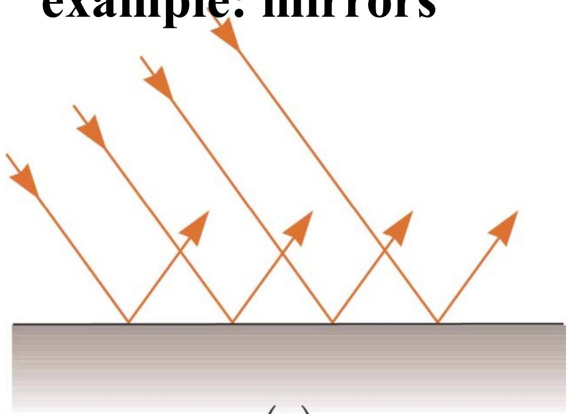
$$\theta_1 = \theta_1'$$

**The incident ray, the reflected ray and the normal are all in the same plane**



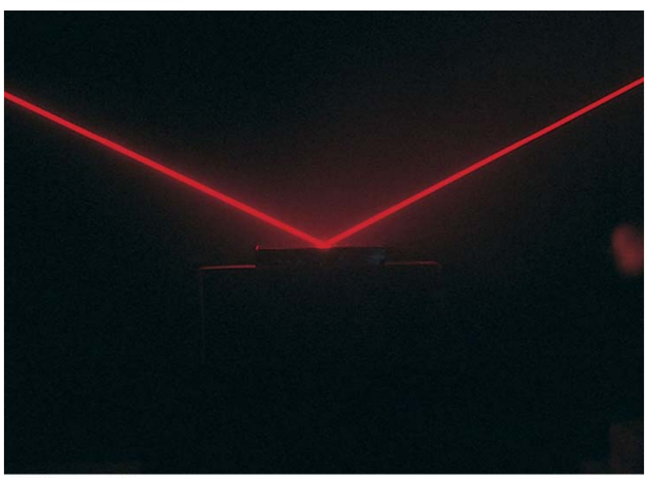
# Reflection of Light

***Specular reflection***
**(reflection from a smooth surface) – example: mirrors**



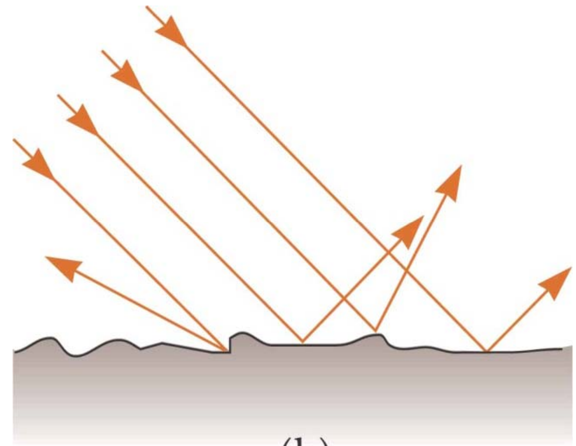
(a)



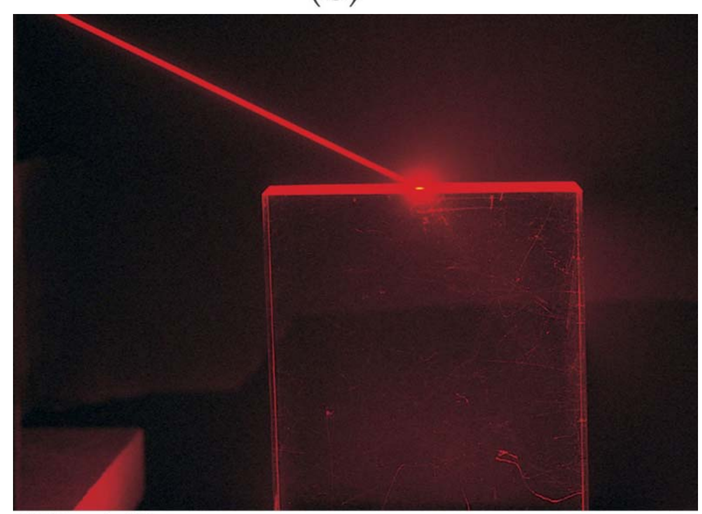




***Diffuse reflection***
**(reflection from a rough surface)**



(b)

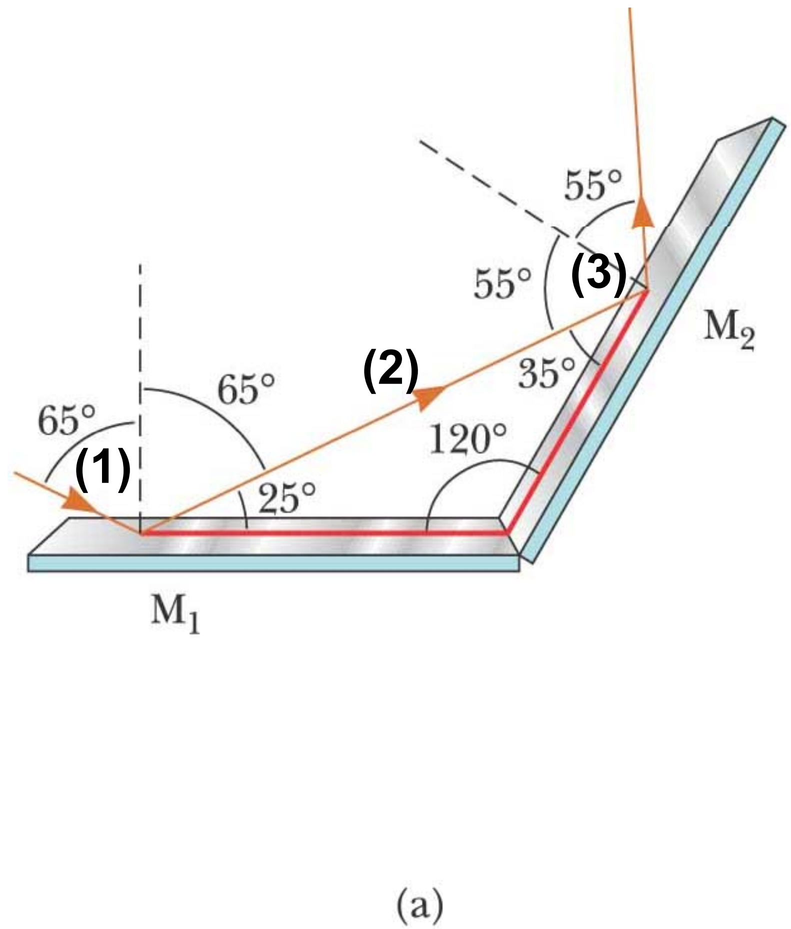


# Example: Multiple Reflection

(1) The incident ray strikes the first mirror

(2) The reflected ray is directed toward the second mirror

(3) There is a second reflection from the second mirror

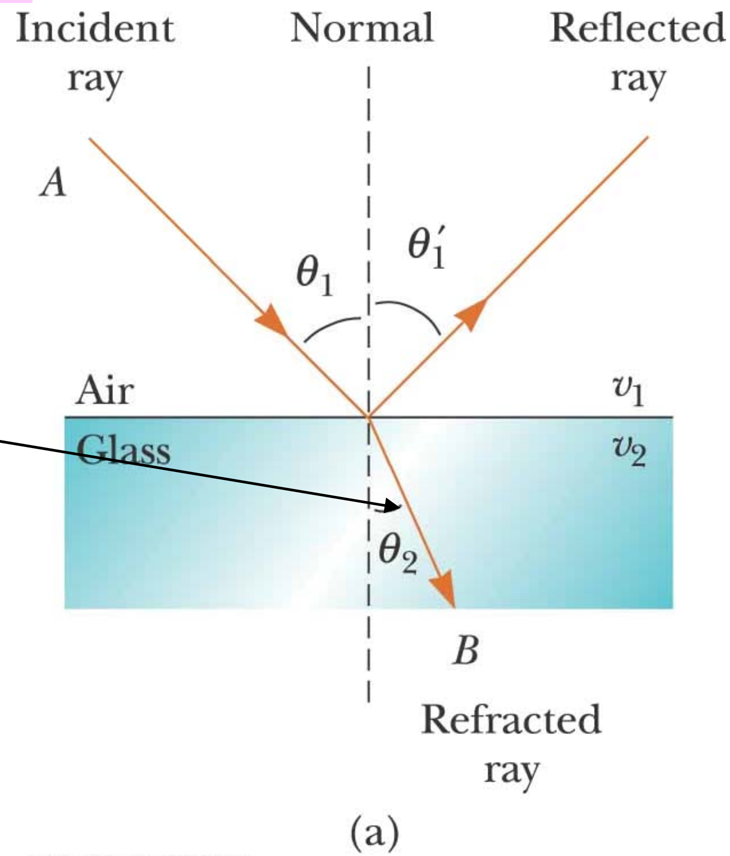


# Propagation of Light - Ray Optics

**What happens to light at the boundary between two media?**

**The light can be**

- **reflected or**
- **refracted (transmitted)**

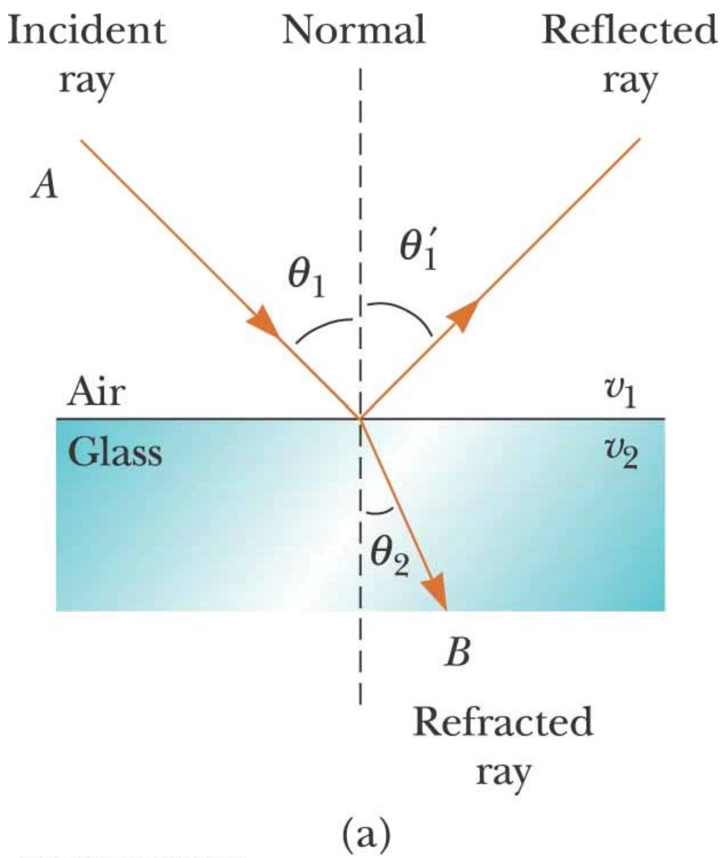


# Refraction – Snell's Law

- **The incident ray, the refracted ray, and the normal all lie on the same plane**
- **The angle of refraction is related to the angle of incidence as**

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$$

  - **$v_1$ is the speed of the light in the first medium and $v_2$ is its speed in the second**





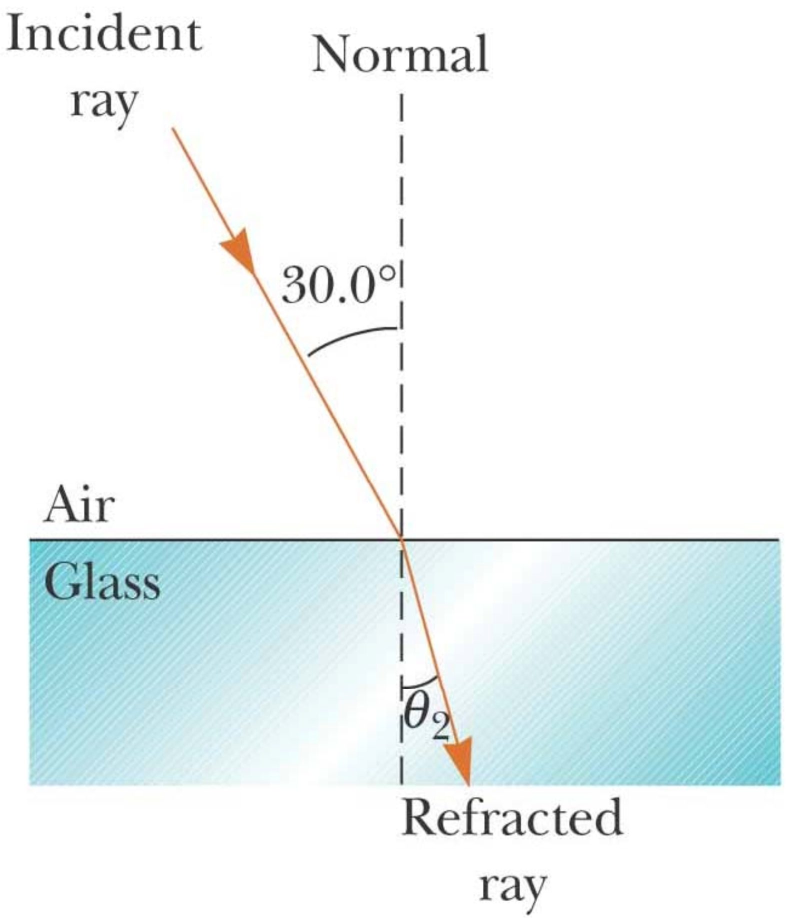
**Since** $v_1 = \dfrac{c}{n_1}$ **and** $v_2 = \dfrac{c}{n_2}$, **we get** $\dfrac{\sin\theta_2}{\sin\theta_1} = \dfrac{v_2}{v_1} = \dfrac{c/n_2}{c/n_1} = \dfrac{n_1}{n_2}$, **or** $n_2 \sin\theta_2 = n_1 \sin\theta_1$

**index of refraction**

**Snell's Law**

## Snell's Law: Example

- **Light is refracted into a crown glass slab**
- $\Theta_1 = 30.0^o$ , $\Theta_2 = ?$
- $n_1 = 1.0$ **and** $n_2 = 1.52$
- $n_1 \sin \Theta_1 = n_2 \sin \Theta_2$ **then**
- $\Theta_2 = \sin^{-1}[(n_1 / n_2) \sin \Theta_1] = 19.2^o$



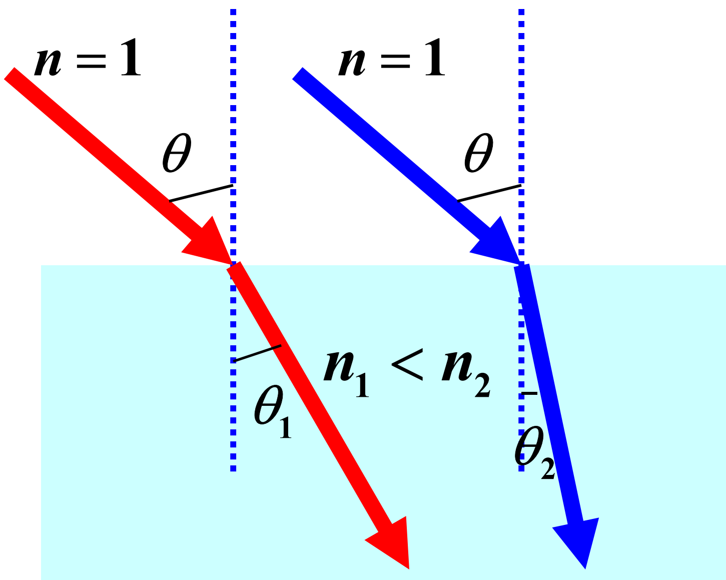
# Refraction in a Prism

# Variation of Index of Refraction with Wavelength

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

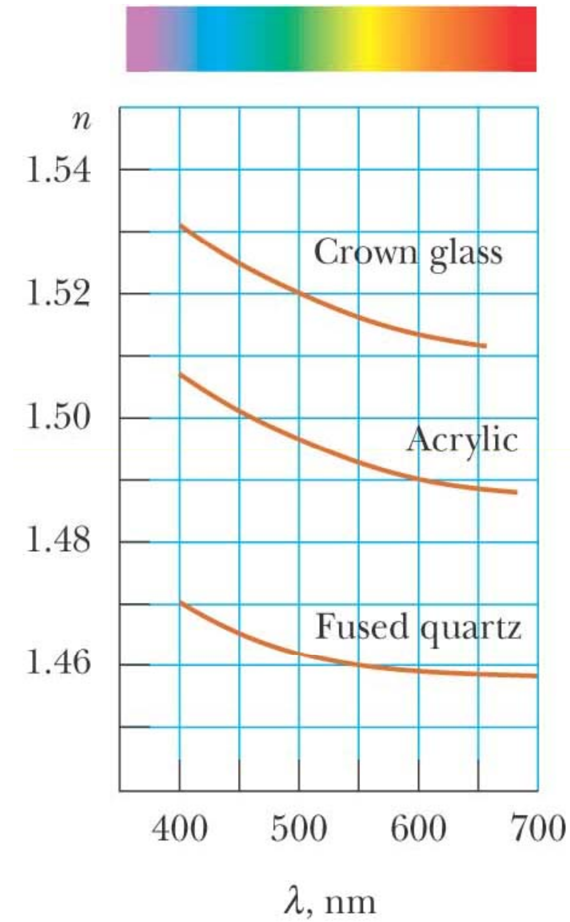
**Snell's Law**

- **The index of refraction depends on the wavelength (frequency)**
- **It generally decreases with increasing wavelength**




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

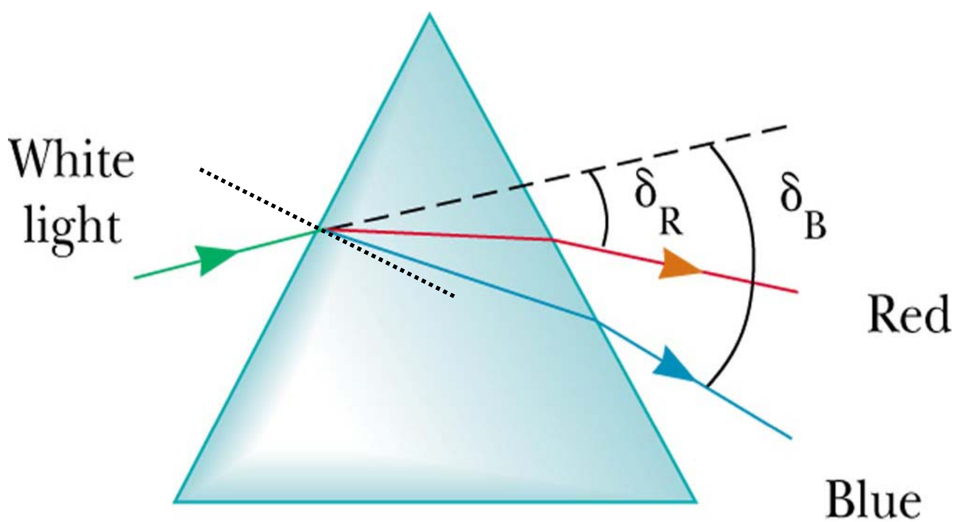
So $\theta_1 > \theta_2$



# Refraction in a Prism

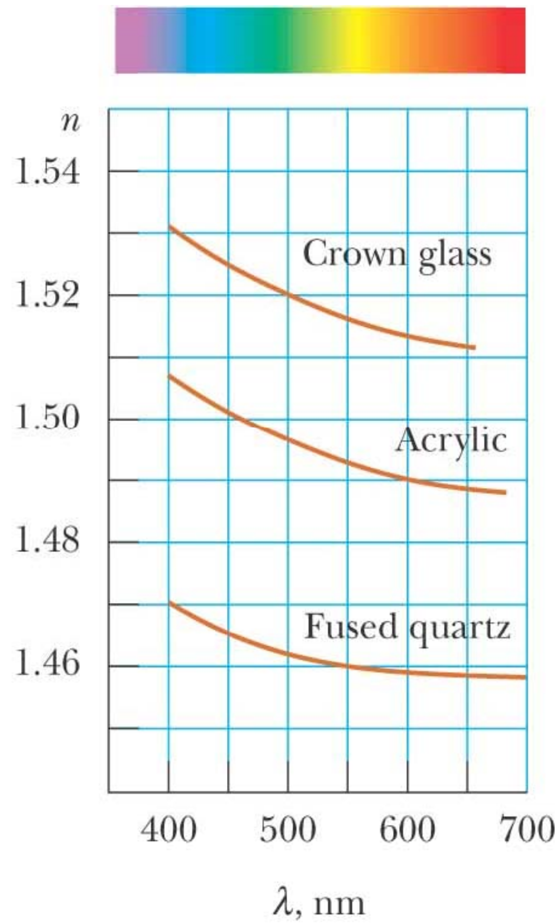
**Since all the colors have different angles of deviation, white light will spread out into a *spectrum***

- **Violet deviates the most**
- **Red deviates the least**
- **The remaining colors are in between**

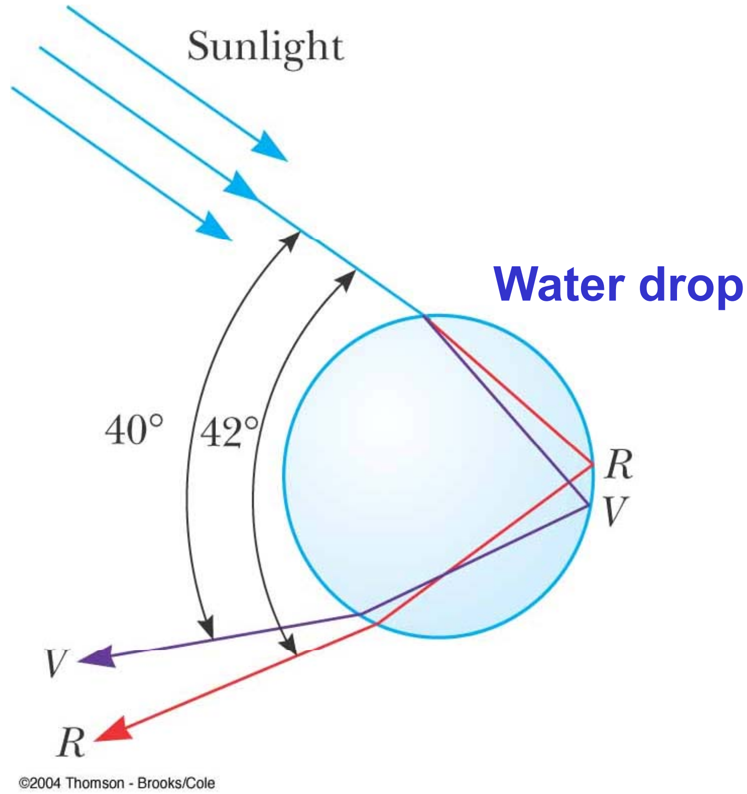


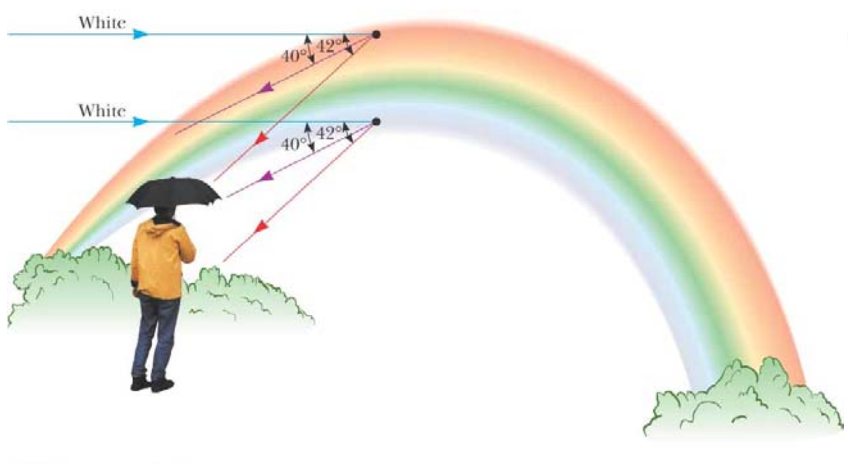

(b)





- The rays leave the drop at various angles
  - The angle between the white light and the most intense violet ray is 40°
  - The angle between the white light and the most intense red ray is 42°



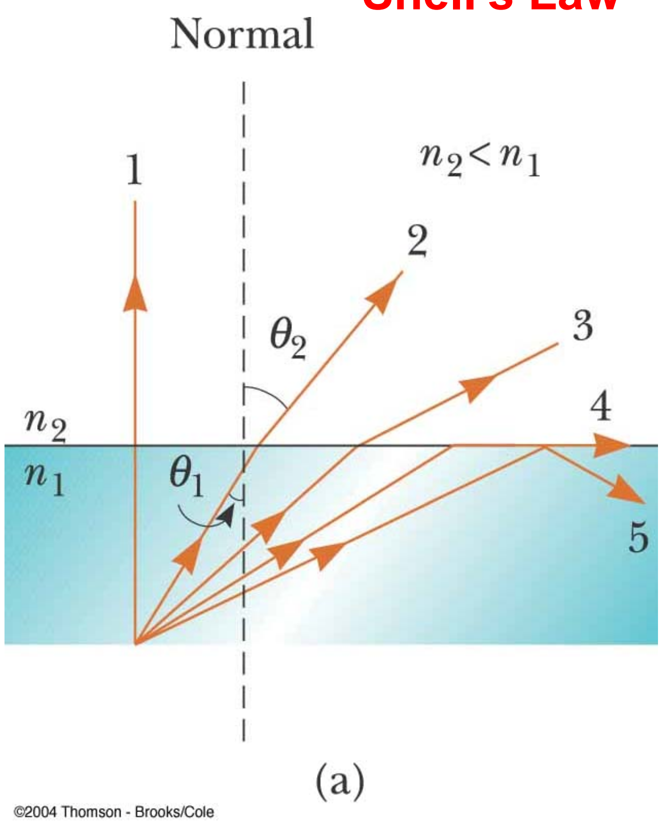
# Total Internal Reflection

# Possible Beam Directions: Total Internal Reflection

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

**Snell's Law**

- Possible directions of the beam are indicated by rays numbered 1 through 5
- The refracted rays are bent away ($\theta_2 > \theta_1$) from the normal since $n_2 < n_1$
- For ray 4 we have $\theta_2 = 90^{\circ}$ the corresponding angle of incidence can be found from the condition ( $\sin 90^{\circ} = 1$ )




$$n_2 = n_1 \sin\theta_{1,cr}$$

# Total Internal Reflection: Critical Angle

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

**Snell's Law**

- Critical angle:

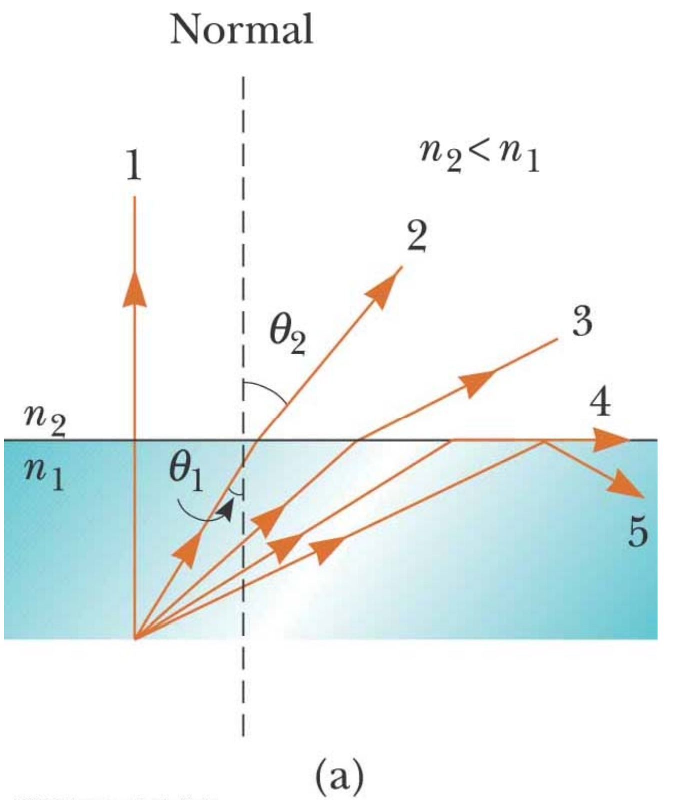
$$n_2 = n_1 \sin\theta_{1,cr}$$

- IMPORTANT:

All the rays with $\theta_1 > \theta_{1,cr}$ are totally reflected, because if $\theta_1 > \theta_{1,cr}$ then from the Snell's law we obtain

$$\sin\theta_2 = \frac{n_1}{n_2}\sin\theta_1 > \frac{n_1}{n_2}\sin\theta_{1,cr} = 1$$

which is impossible





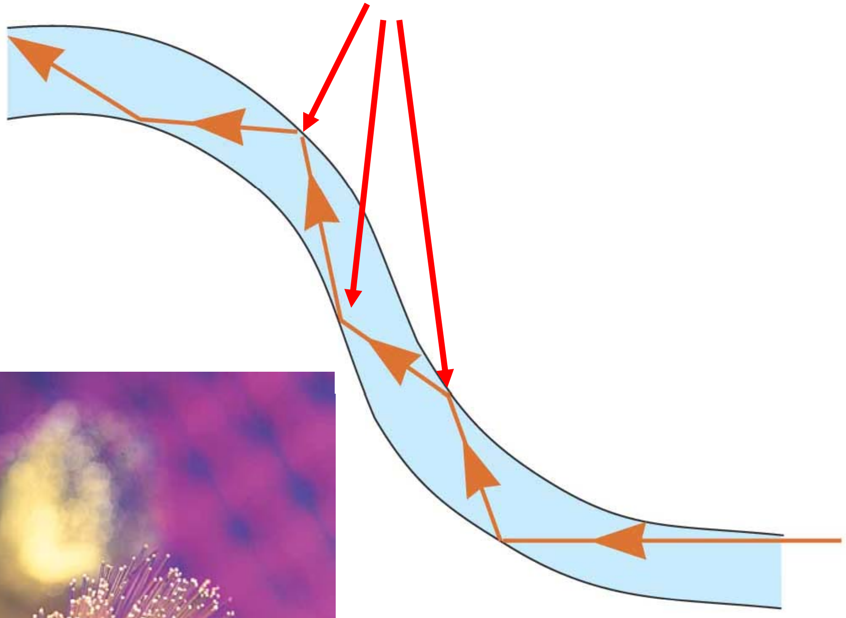

**Example: What is $\theta_{cr}$ for glass-air boundary?**

$n_1 = n_{glass} \approx 1.5$  $n_2 = n_{air} \approx 1$  **then** $\theta_{cr} = \sin^{-1}\frac{n_{air}}{n_{glass}} = \sin^{-1}\frac{1}{1.5} \approx 42^0$

# Fiber Optics

- Plastic or glass rods are used to "pipe" light from one place to another
- Applications include:
  - medical use of fiber optic cables for diagnosis and correction of medical problems
  - Telecommunications

Total Internal Reflection ( $\theta_{\text{incidence}} > \theta_{cr}$ )



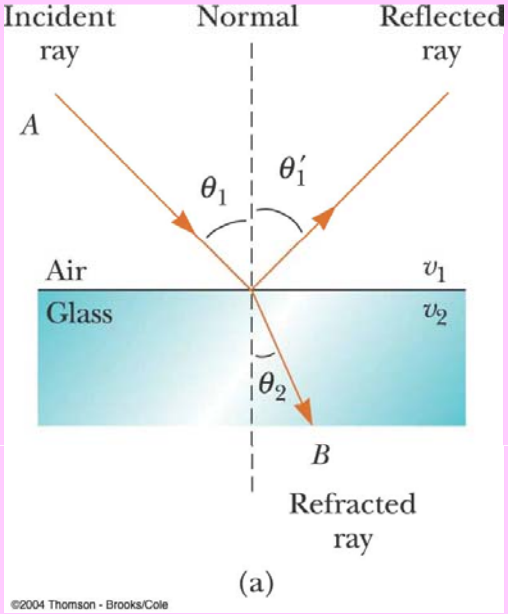
$$v = \frac{c}{n}$$ - The speed of light in the medium

**The law of reflection:**

$$\theta_1 = \theta_1'$$

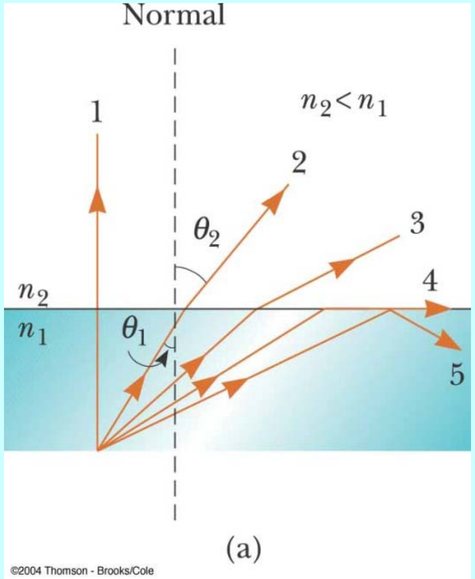
**The law of refraction:**

$$n_2 \sin\theta_2 = n_1 \sin\theta_1$$ **Snell's Law**




**Total Internal Reflection**

$$n_2 = n_1 \sin\theta_{1,cr}$$



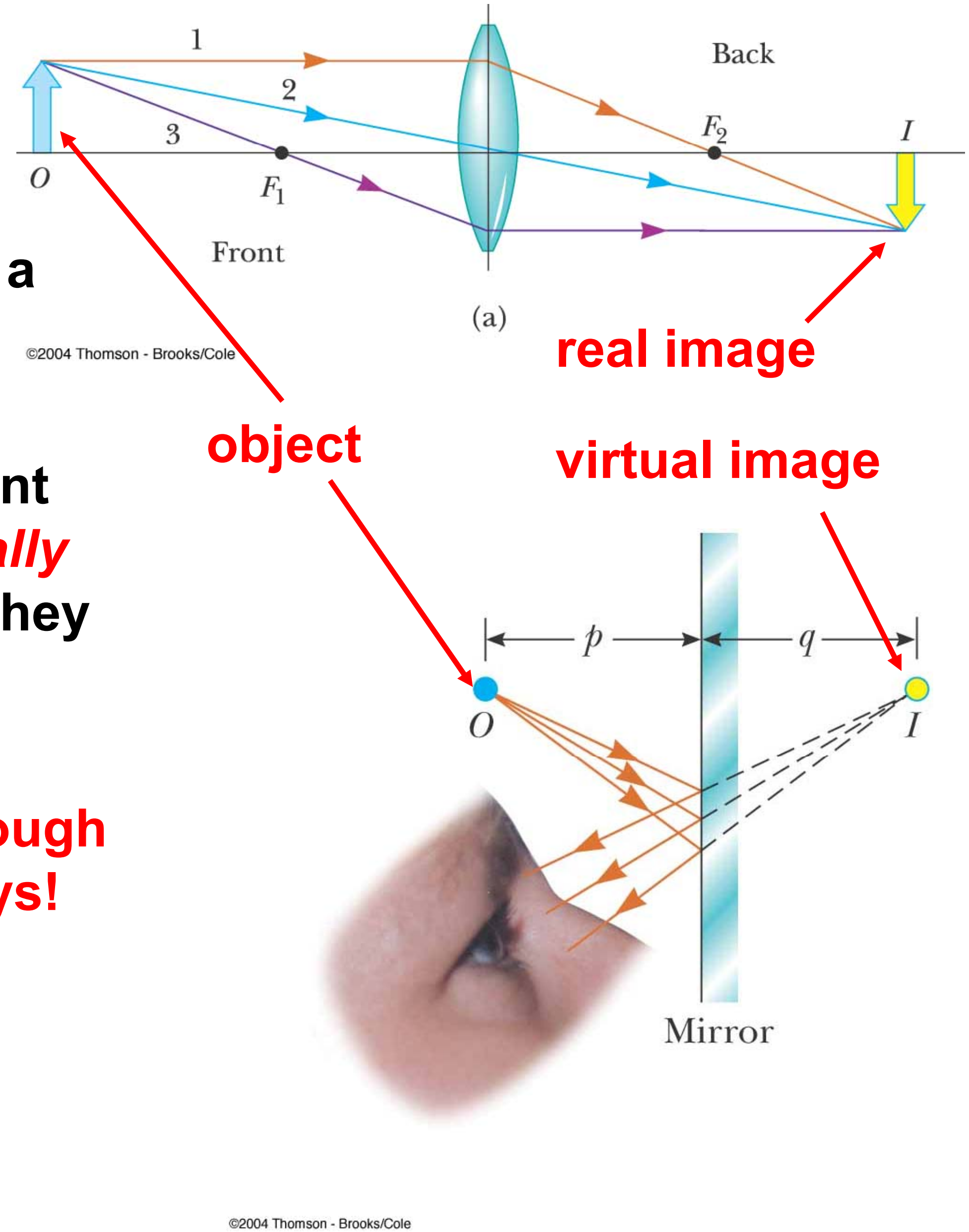
# Ray Optics - Applications: Image Formation

- **Images are always located by extending diverging rays back to a point at which they intersect**

- **Images are located either at a point from which the rays of light *actually* diverge or at a point from which they *appear* to diverge**

- **To find the image it is usually enough to find intersection of just two rays!**

- **Magnification =** $\dfrac{\text{image height}}{\text{object height}}$



# Flat Refracting Surface

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

**Snell's Law**

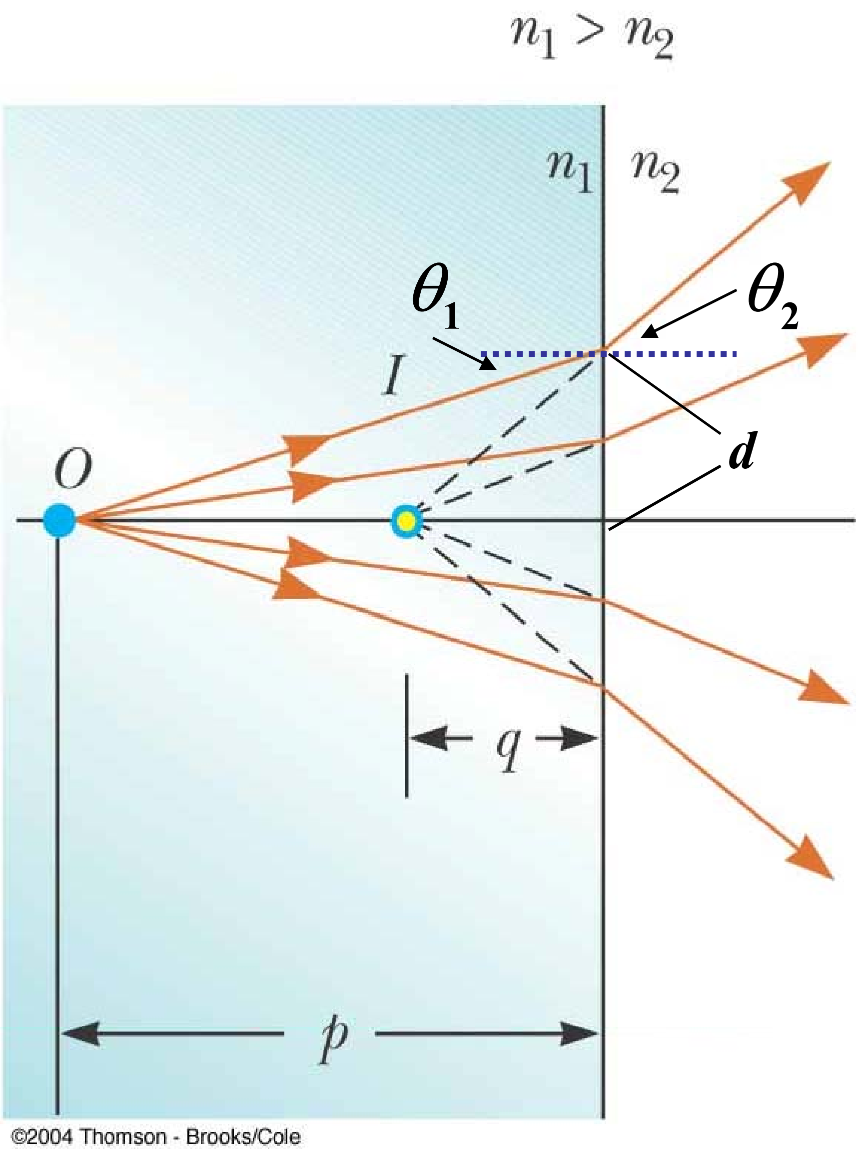
$$\sin\theta_2 \approx \theta_2 \approx \frac{d}{q}$$

$$\sin\theta_1 \approx \theta_1 \approx \frac{d}{p}$$

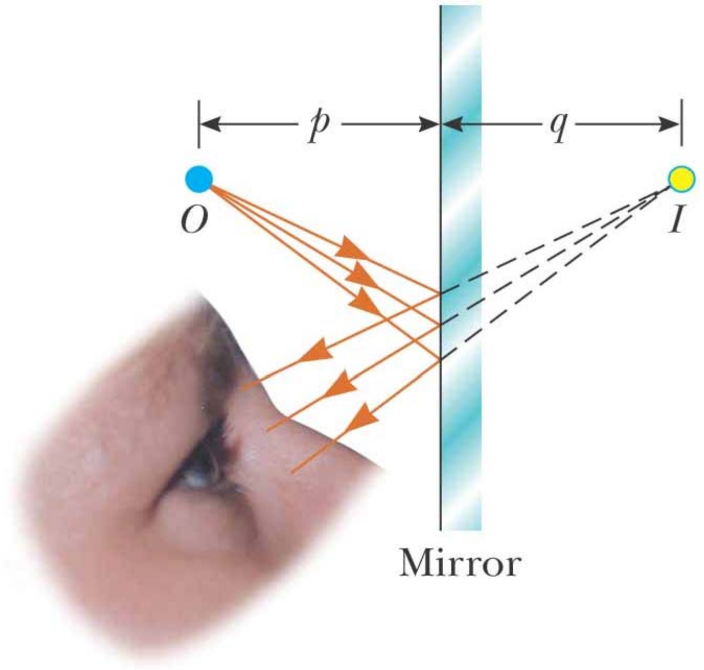
$$n_2 \frac{d}{q} = n_1 \frac{d}{p}$$

$$q = p\frac{n_2}{n_1}$$

**Image is always virtual**

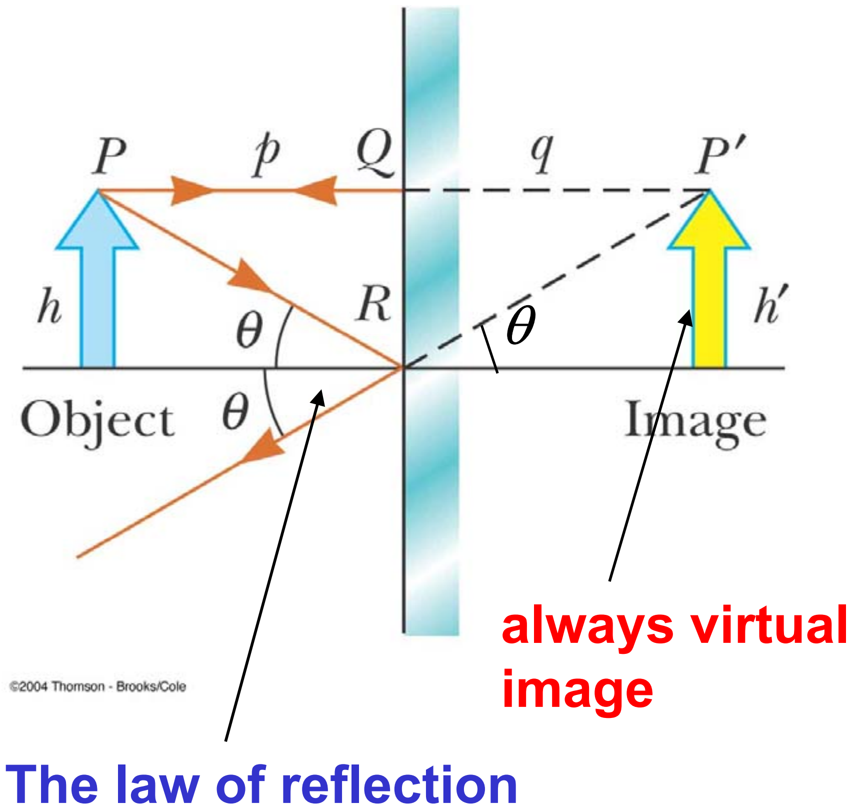


# Flat mirror



# Flat Mirror

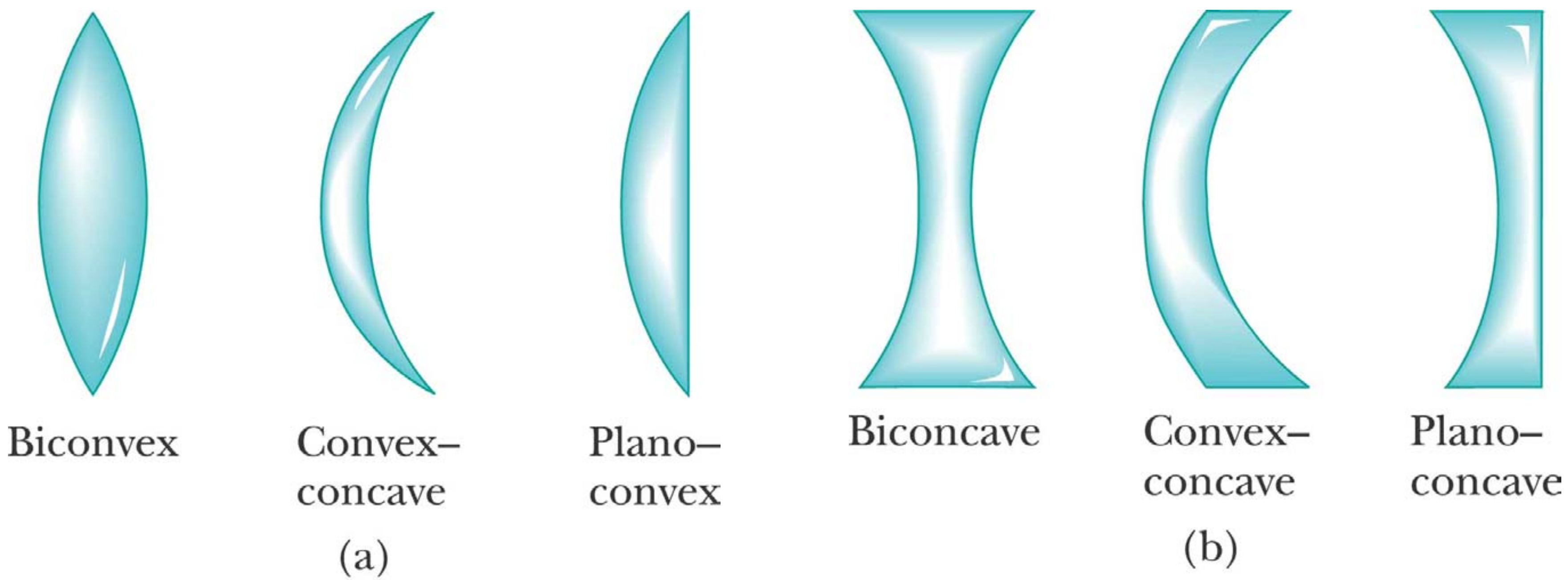
- One ray starts at point *P*, travels to *Q* and reflects back on itself
- Another ray follows the path *PR* and reflects according to the law of reflection
- The triangles *PQR* and *P'QR* are congruent
- $h = h'$ - magnification is 1.



# Geometric Optics - Applications: Thin Lenses

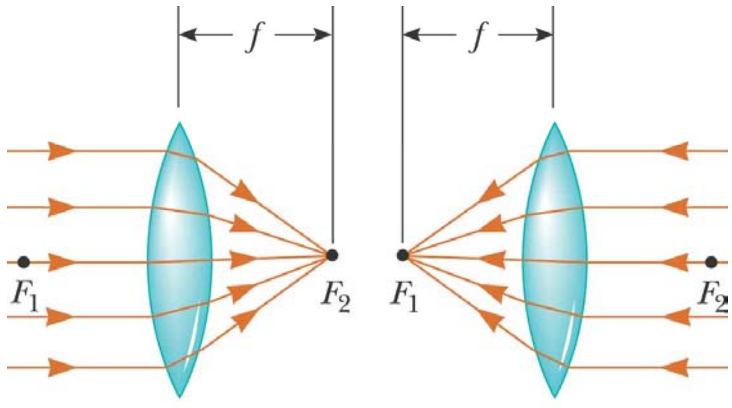
# Thin Lenses

"Thin" means that the width is much smaller than the *radius of curvature*



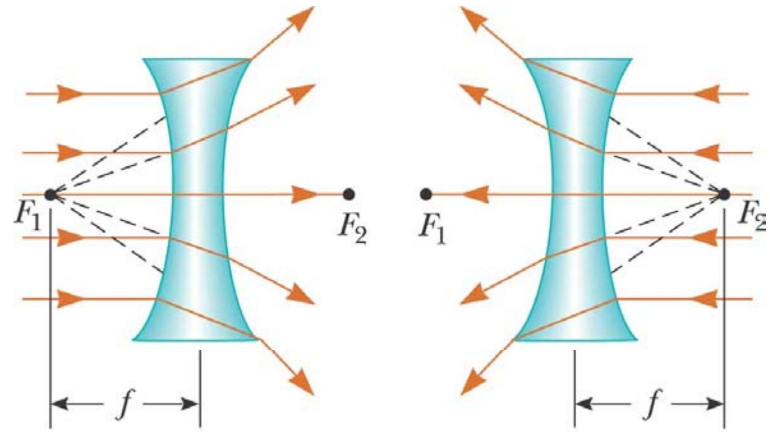
# Thin Lenses: Focal Points

# Thin Lenses: Focal Points: Converging Lenses




Converging Lenses






Diverging Lenses



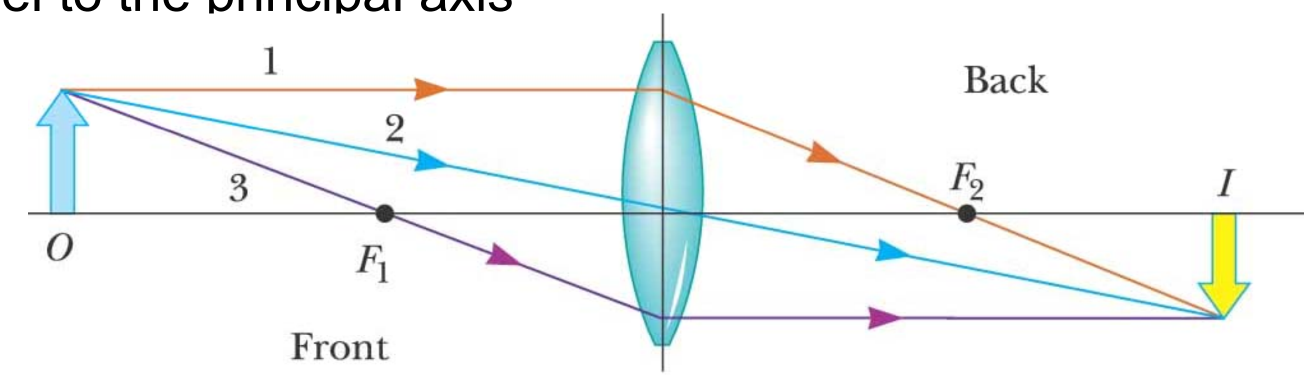
- Because light can travel in either direction through a lens, each lens has two focal points.
- However, there is only one focal length

# Thin Lenses: Ray Diagram

# Converging Lenses

For a converging lens, the following three rays (two is enough) are drawn:

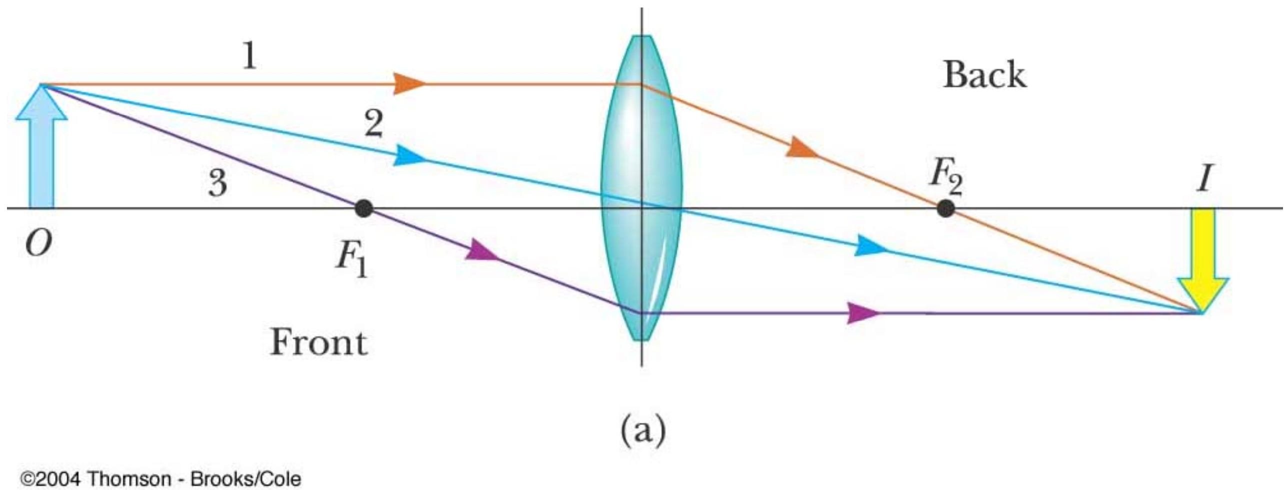
- Ray 1 is drawn parallel to the principal axis and then passes through the focal point on the back side of the lens
- Ray 2 is drawn through the center of the lens and continues in a straight line
- Ray 3 is drawn through the focal point on the front of the lens (or as if coming from the focal point if $s < f$) and emerges from the lens parallel to the principal axis



(a)

# Converging Lenses: Example 1

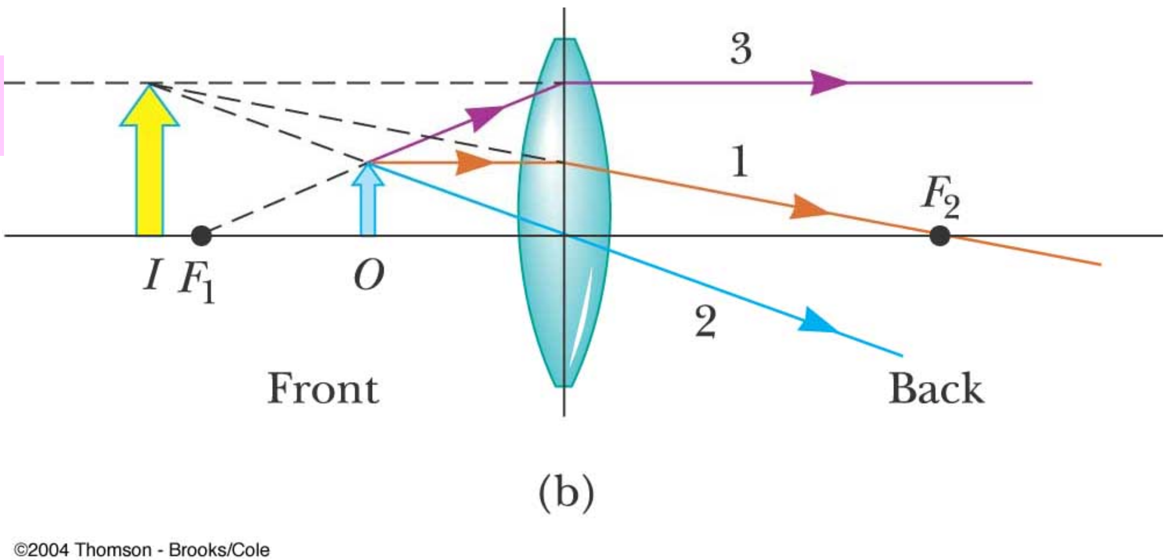
$s > f > 0$




- The image is real
- The image is inverted
- The image is on the back side of the lens

# Converging Lenses: Example 2

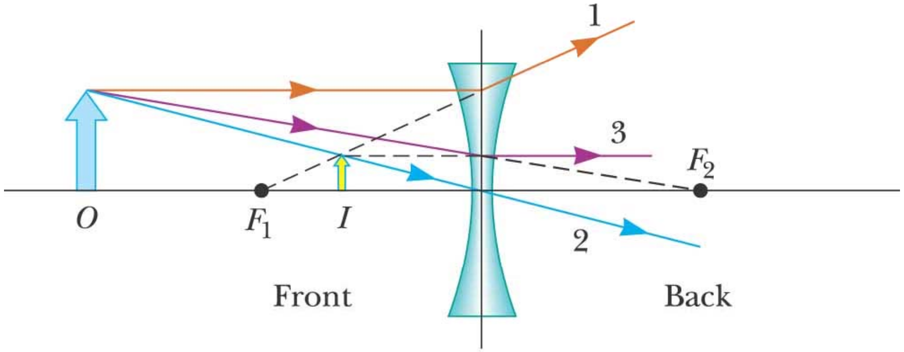
$f > s > 0$




- The image is virtual
- The image is upright
- The image is larger than the object
- The image is on the front side of the lens

# Diverging Lenses

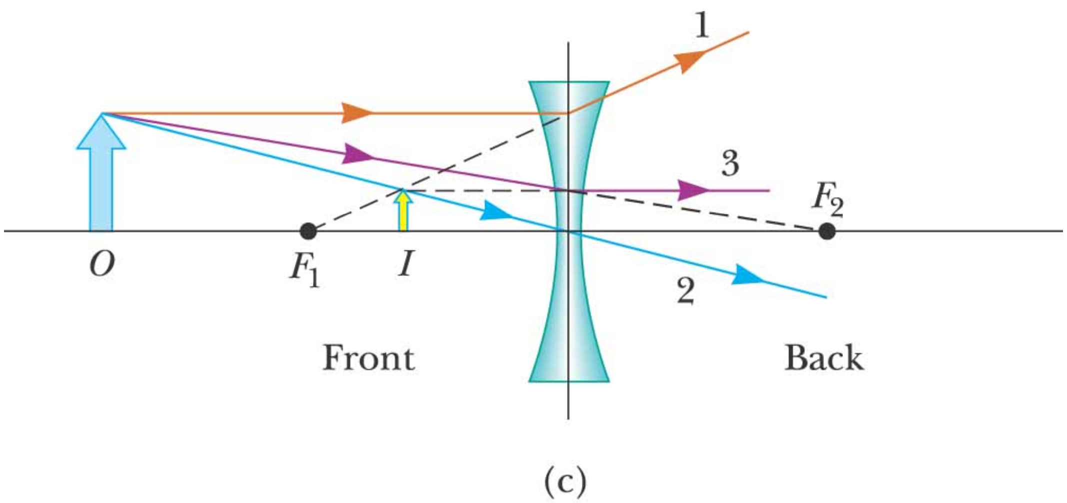
- For a diverging lens, the following three rays (two is enough) are drawn:
  - Ray 1 is drawn parallel to the principal axis and emerges directed away from the focal point on the front side of the lens
  - Ray 2 is drawn through the center of the lens and continues in a straight line
  - Ray 3 is drawn in the direction toward the focal point on the back side of the lens and emerges from the lens parallel to the principal axis



(c)

# Diverging Lenses: Example

$f < 0$

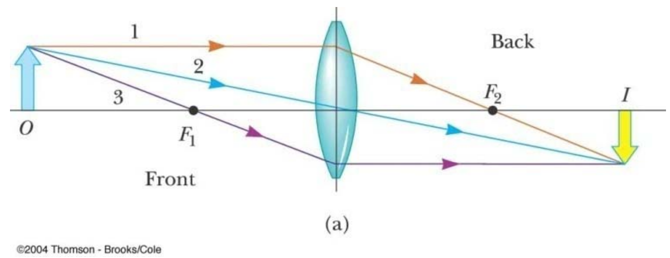





- The image is virtual
- The image is upright
- The image is smaller
- The image is on the front side of the lens

# Image Summary

- For a converging lens, when the object distance is greater than the focal length ($s > f$)
  - The image is real and inverted

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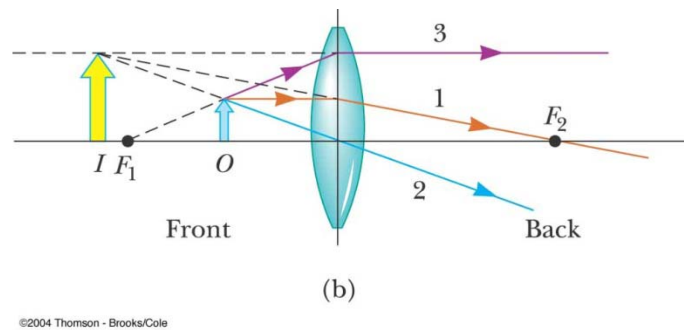
- For a converging lens, when the object is between the focal point and the lens, ($s < f$)
  - The image is virtual and upright

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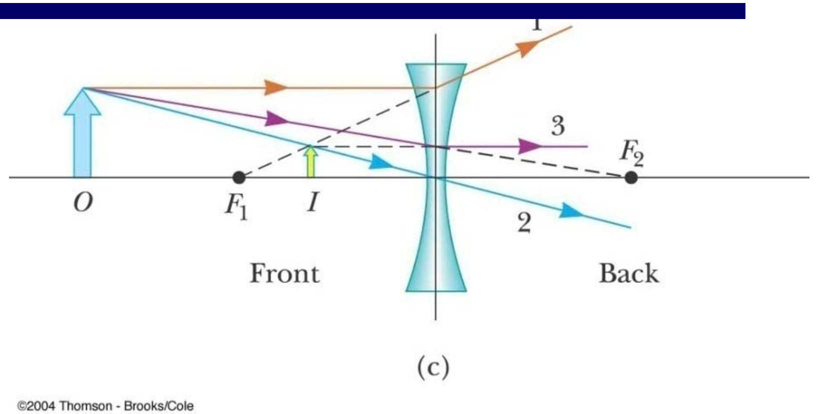
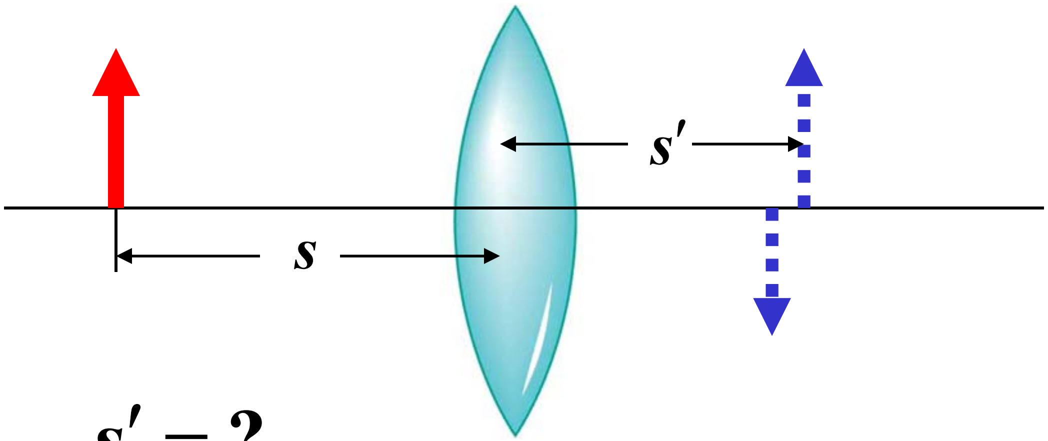
- For a diverging lens, the image is always virtual and upright
  - This is regardless of where the object is placed



# Thin Lenses




$$s' = ?$$

Thin Lens Equation:

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

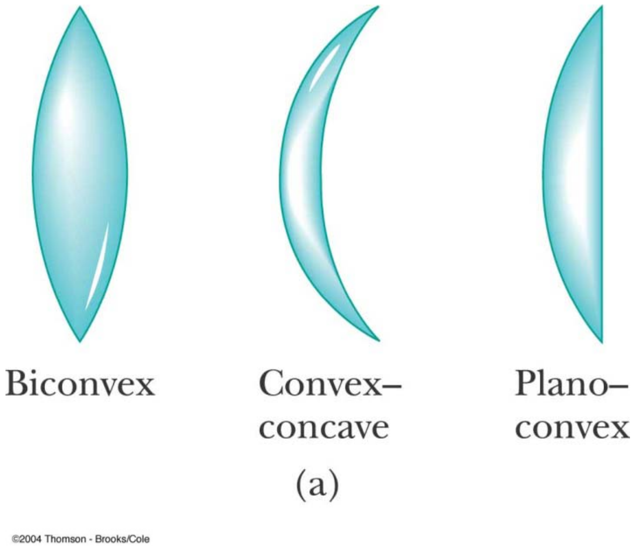
**Object Distance** ($s$) **Image Distance** ($s'$) **Focal Length** ($f$)

The thin lens is characterized by only *one* parameter – FOCAL LENGTH.

# Thin Lenses

$f > 0$

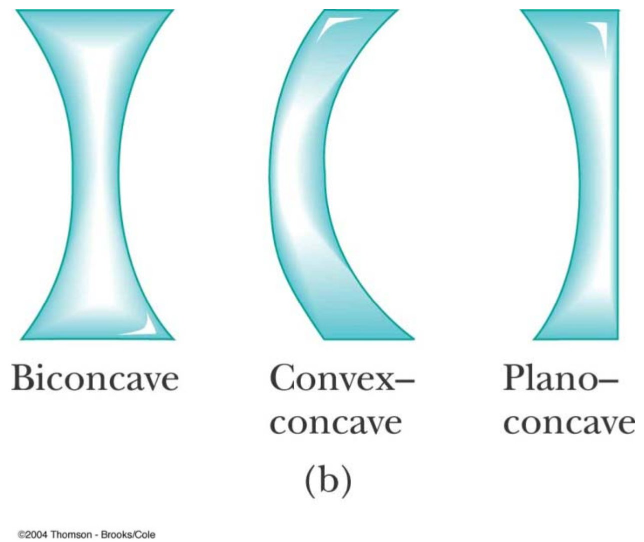
Converging lens




**They are thickest in the middle**

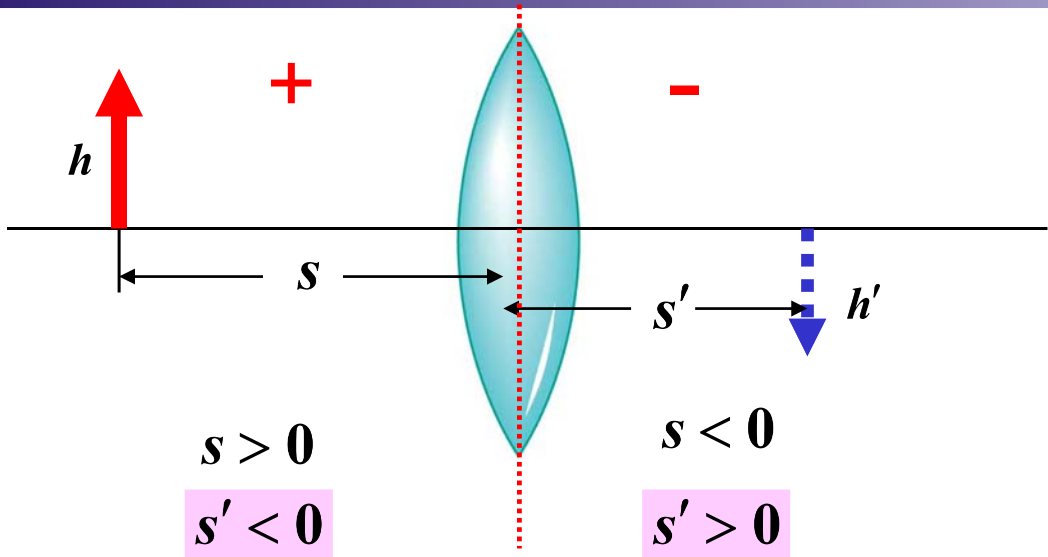
$f < 0$

Diverging lens




**They are thickest at the edges**

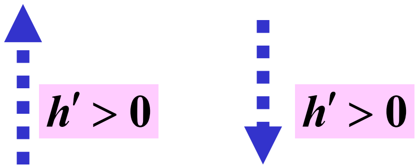
# Thin Lenses: Sign Conventions for $s, s'$




$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

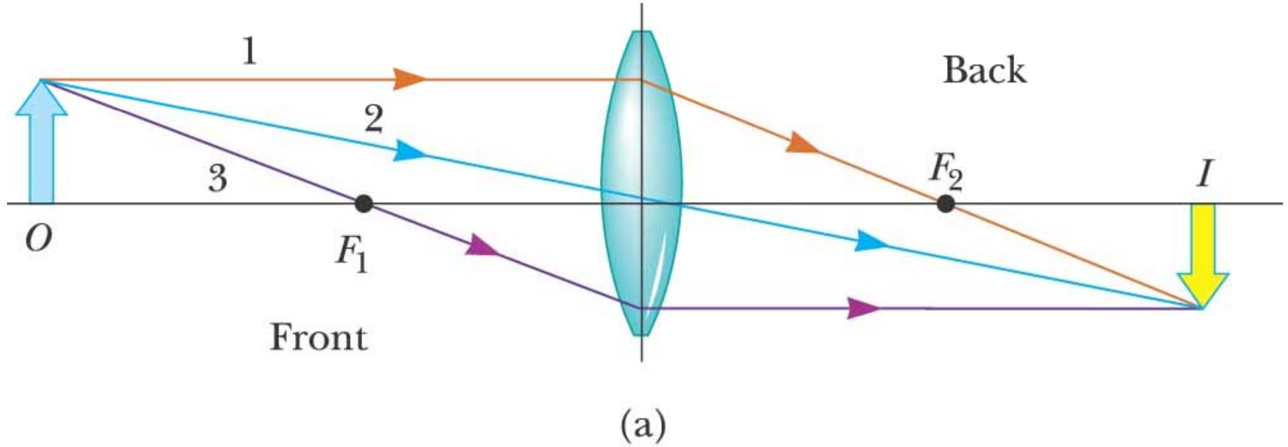
Lateral magnification:

$$M = \frac{h'}{h} = -\frac{s'}{s}$$



# Converging Lenses: Example 1

$$s > f > 0$$





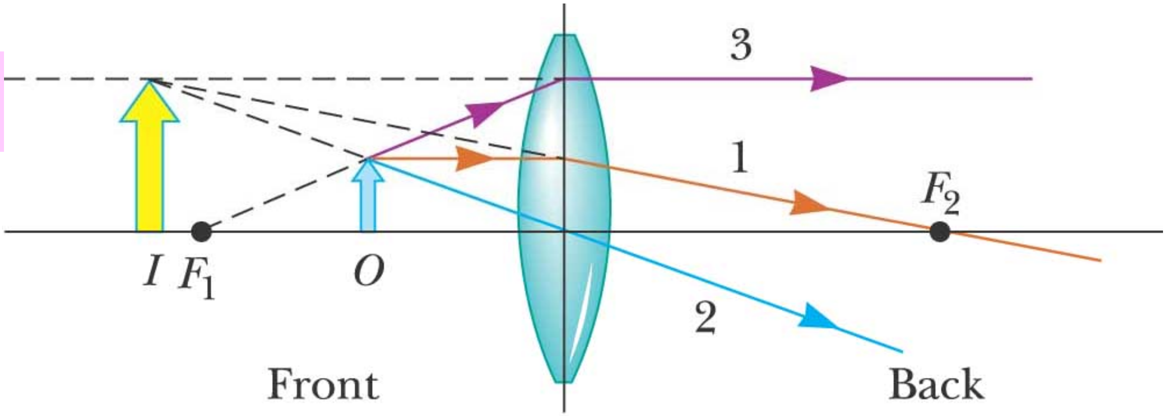

- The image is real
- The image is inverted
- The image is on the back side of the lens

$$s' = \frac{1}{\frac{1}{f} - \frac{1}{s}} = \frac{sf}{s - f} > 0$$

$$M = \frac{h'}{h} = -\frac{s'}{s} < 0$$

# Converging Lenses: Example 2

$$f > s > 0$$




(b)



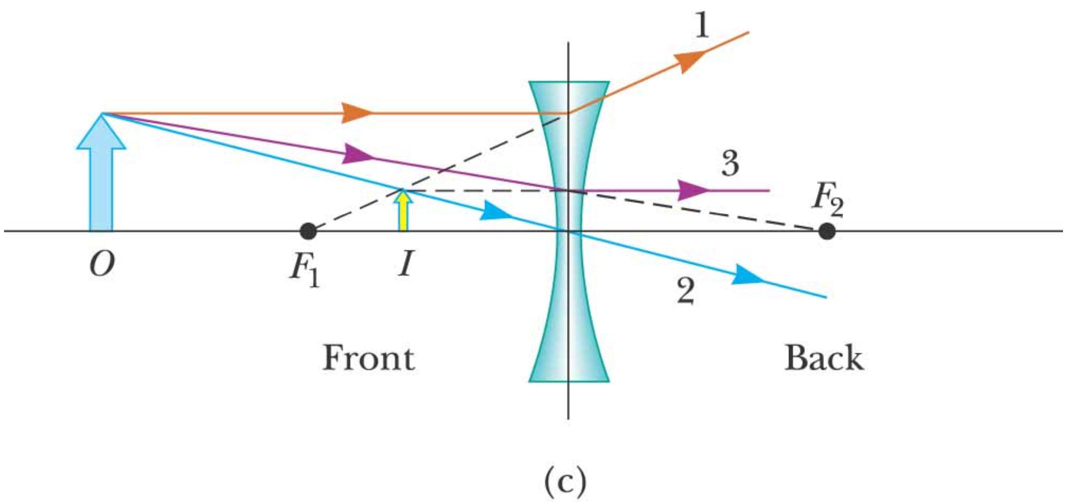
- The image is virtual
- The image is upright
- The image is larger than the object
- The image is on the front side of the lens

$$s' = \frac{1}{\frac{1}{f} - \frac{1}{s}} = \frac{sf}{s - f} < 0$$

$$M = \frac{h'}{h} = -\frac{s'}{s} > 0$$

# Diverging Lenses: Example

$f < 0$





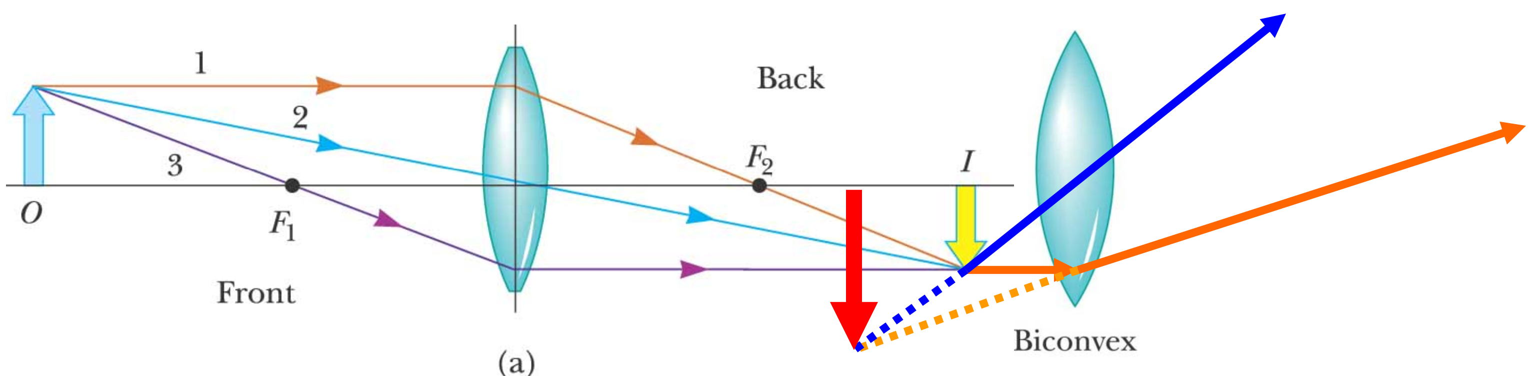

- The image is virtual
- The image is upright
- The image is smaller
- The image is on the front side of the lens

$$s' = \frac{1}{\frac{1}{f} - \frac{1}{s}} = \frac{sf}{s - f} < 0$$

$$M = \frac{h'}{h} = -\frac{s'}{s} > 0$$

# Combination of Two Lenses

- The image formed by the first lens is located as though the second lens were not present
- *The image of the first lens is treated as the object of the second lens*
- Then a ray diagram is drawn for the second lens
- The image formed by the second lens is the final image of the system
- If the image formed by the first lens lies on the back side of the second lens, then the image is treated as a *virtual object* for the second lens
    - *s* will be negative
- The overall *magnification* is the product of the magnification of the separate lenses



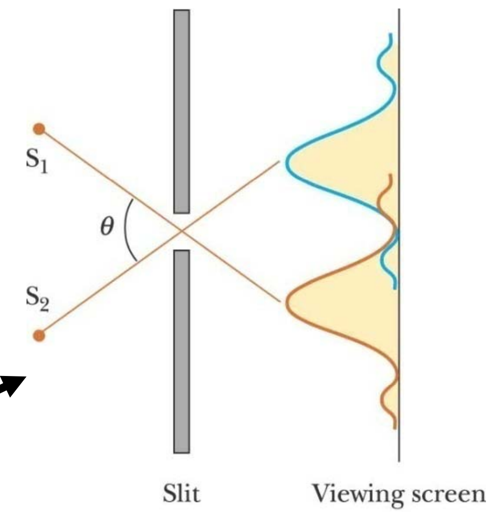
# Resolution

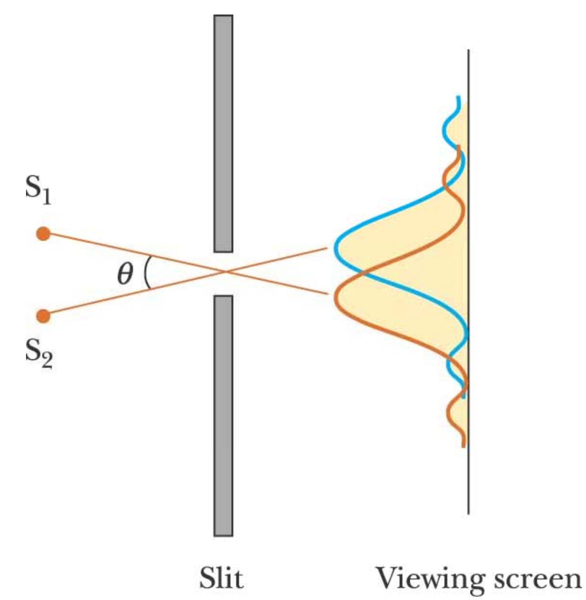
# Resolution

- The ability of optical systems to distinguish between closely spaced objects
- If two sources are far enough apart to keep their central maxima from overlapping, their images can be distinguished

    The images are said to be *resolved*

- If the two sources are close together, the two central maxima overlap and the images are not resolved



# Resolution, Rayleigh's Criterion

**Rayleigh's criterion:**
When the *central maximum* of one image falls on the *first minimum* of another image, the images are said to be just resolved

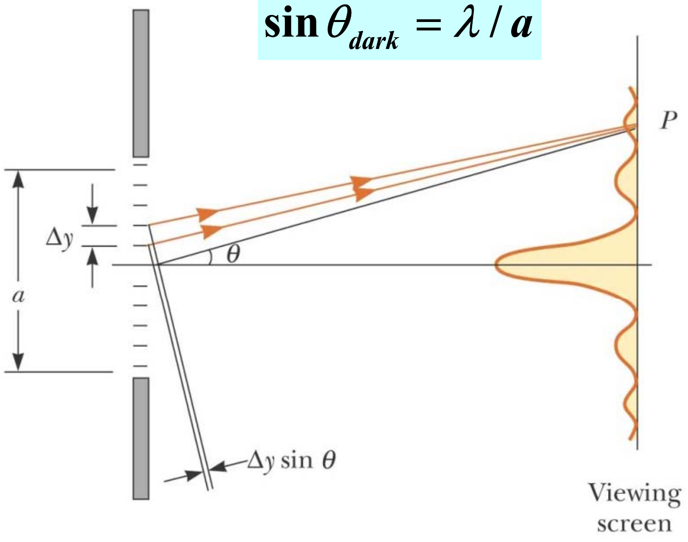
Resolution of a slit:

- Since $\lambda \ll a$ in most situations, $\sin\theta$ is very small and $\sin\theta \sim \theta$
- Therefore, the limiting angle (in rad) of resolution for a slit of width $a$ is

$$\theta_{\min} = \theta_{dark} = \lambda / a$$

- To be resolved, the angle subtended by the two sources must be greater than $u_{\min}$

$\sin\theta_{dark} = \lambda / a$



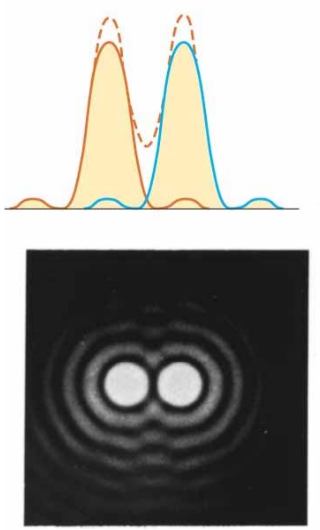
# Resolution: Circular Aperture

- The diffraction pattern of a circular aperture consists of a central bright disk surrounded by progressively fainter bright and dark rings
- The limiting angle of resolution of the circular aperture is

$$\theta_{min} = 1.22\frac{\lambda}{D}$$

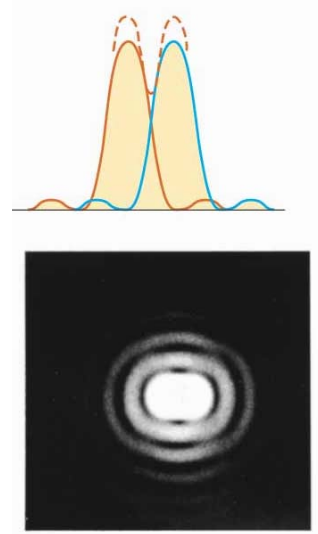
  - *D* is the diameter of the aperture

The images are well resolved



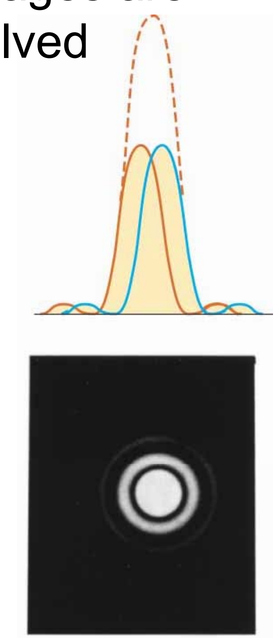
(a)

The images are just resolved



(b)

The images are unresolved



(c)