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- B. the distance at which an object must be placed to form an image.
- C. the distance at which parallel light rays are focused.
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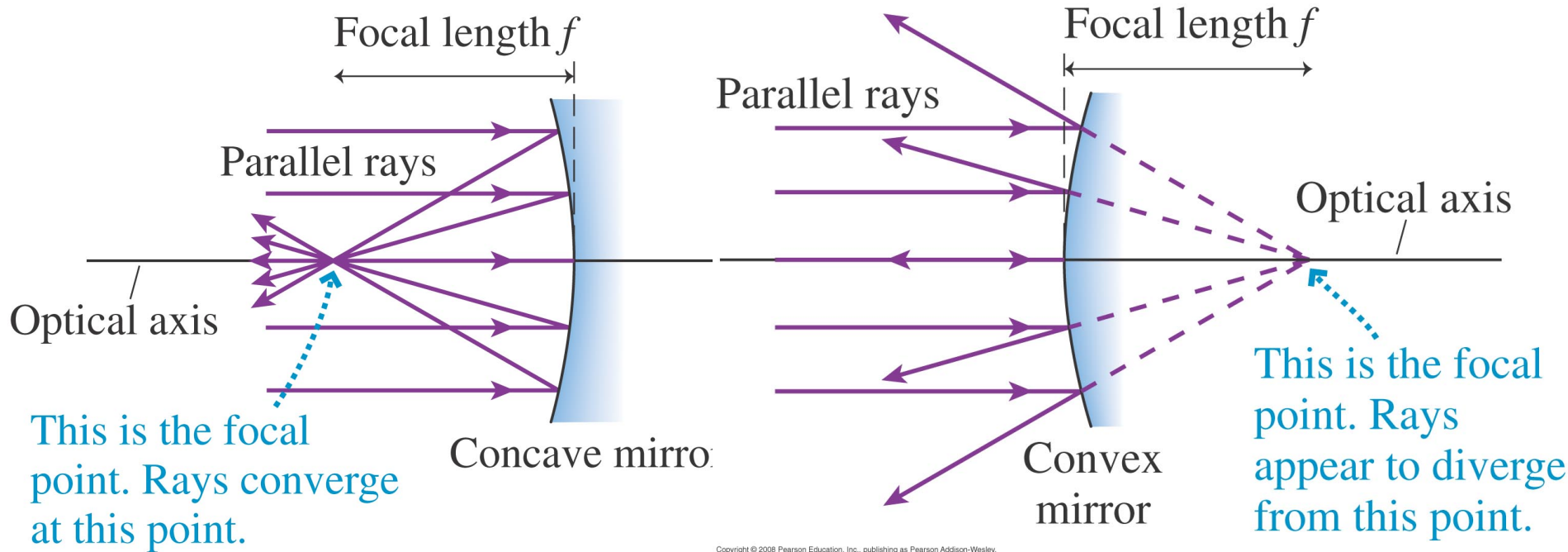
## A paraxial ray

- A. moves in a parabolic path.
- B. is a ray that has been reflected from parabolic mirror.
- C. is a ray that moves nearly parallel to the optical axis.
- D. is a ray that moves exactly parallel to the optical axis.

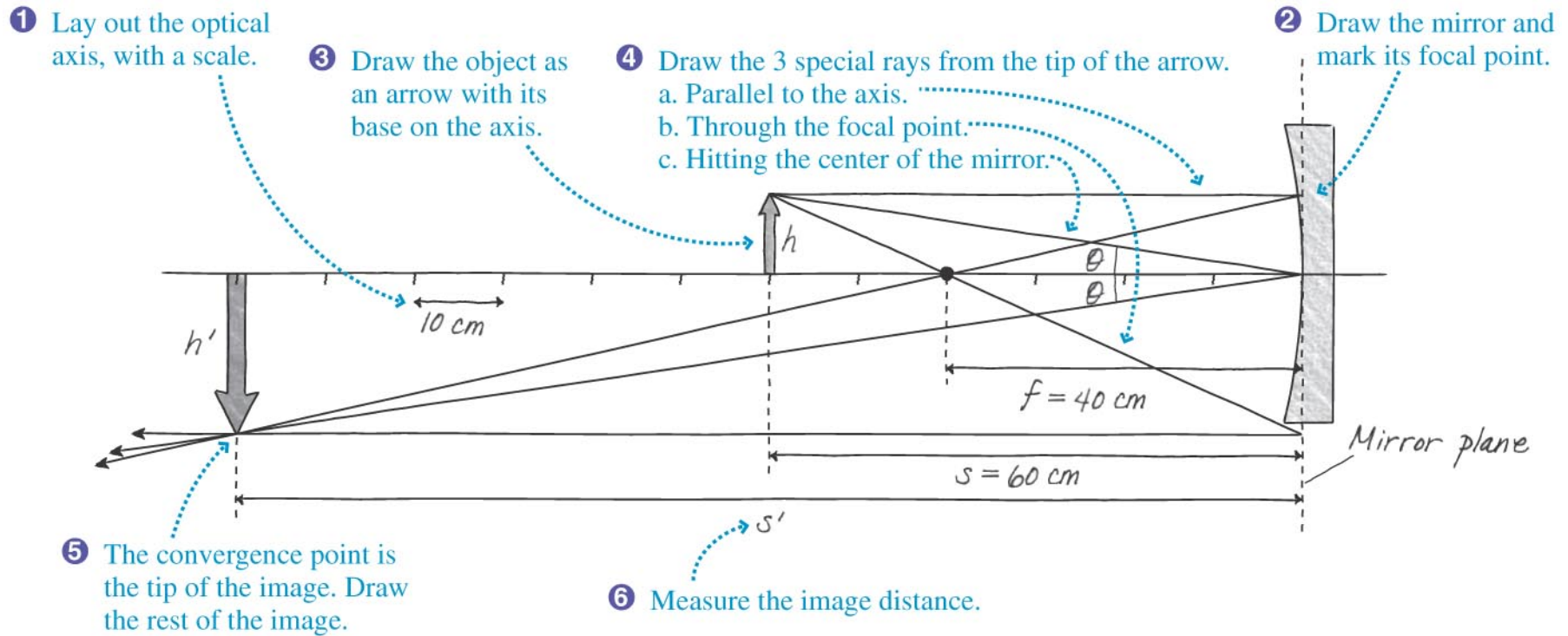
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# Mirrors

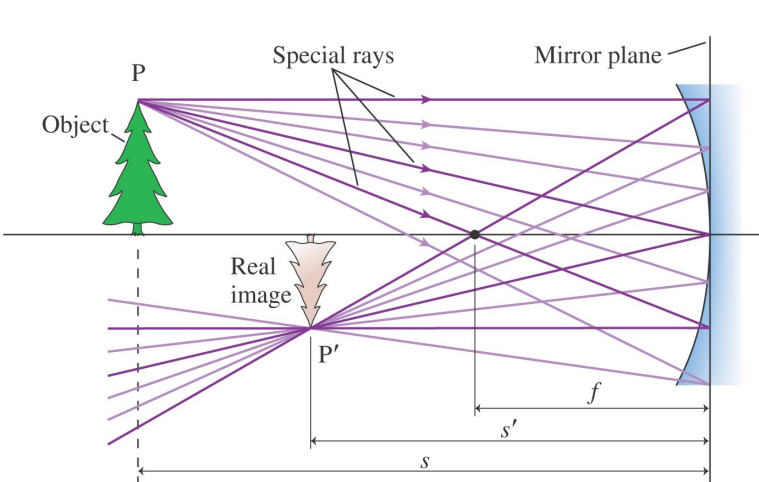


# Ray Diagram: A Mirror

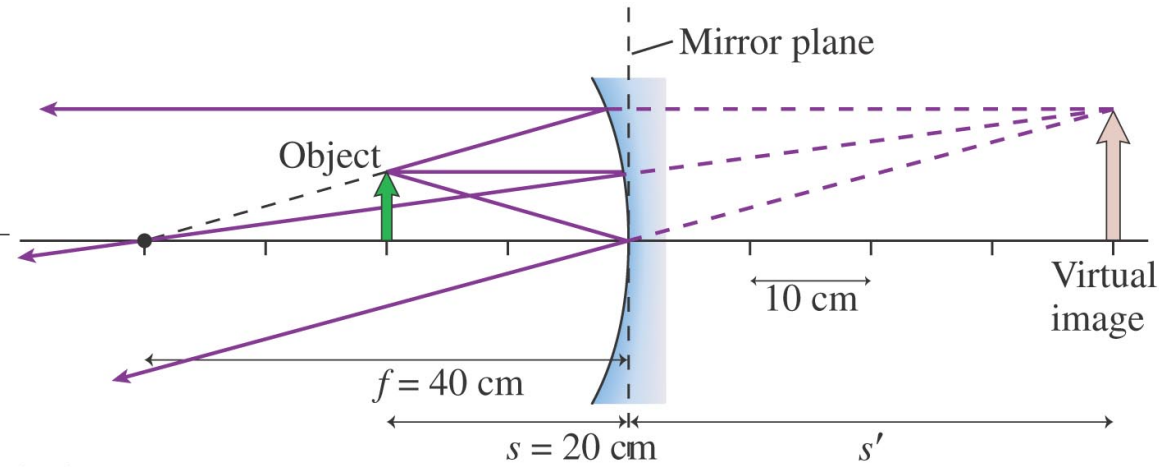




# Imaging Formation by a Mirror



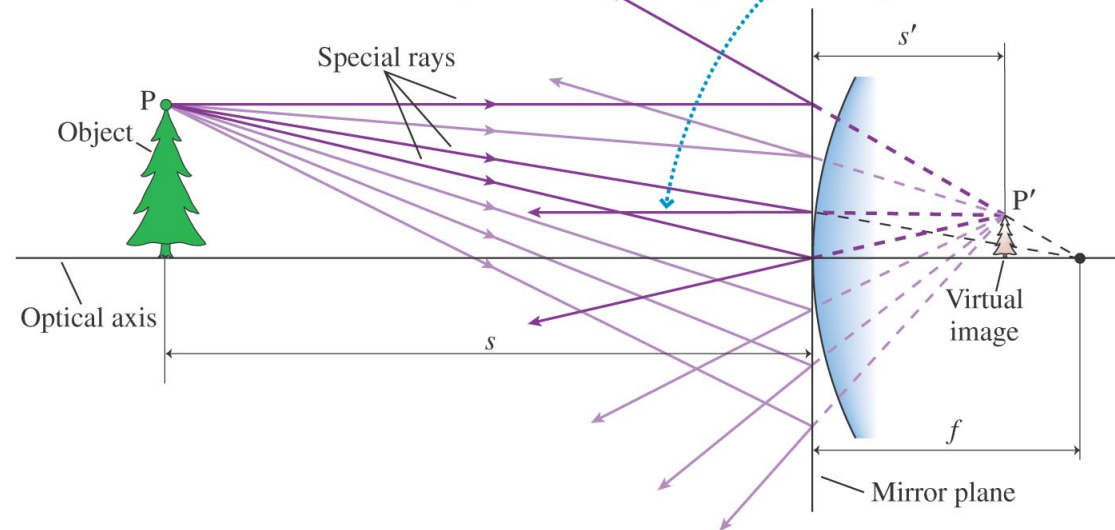
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This ray entered parallel to the optical axis, and thus appears to have come from the focal point.

This ray was heading for the focal point, and thus emerges parallel to the optical axis.

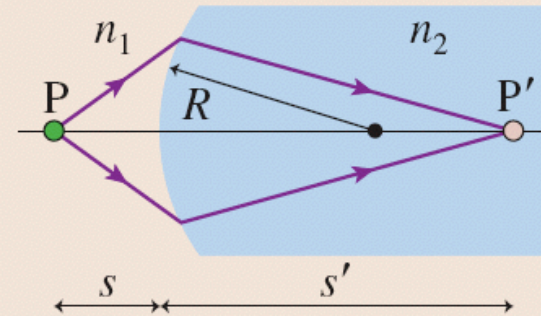


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# Important Concepts

## Image formation

If rays diverge from P and interact with a lens or mirror so that the refracted/reflected rays *diverge* from P' and appear to come from P', then P' is a **virtual image** of P.



If rays diverge from P and interact with a lens or mirror so that the refracted rays *converge* at P', then P' is a **real image** of P.

**Spherical surface:** Object and image distances are related by

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

**Plane surface:**  $R \rightarrow \infty$ , so  $|s'/s| = n_2/n_1$ .

# EXAMPLE A goldfish in a bowl

## QUESTION:

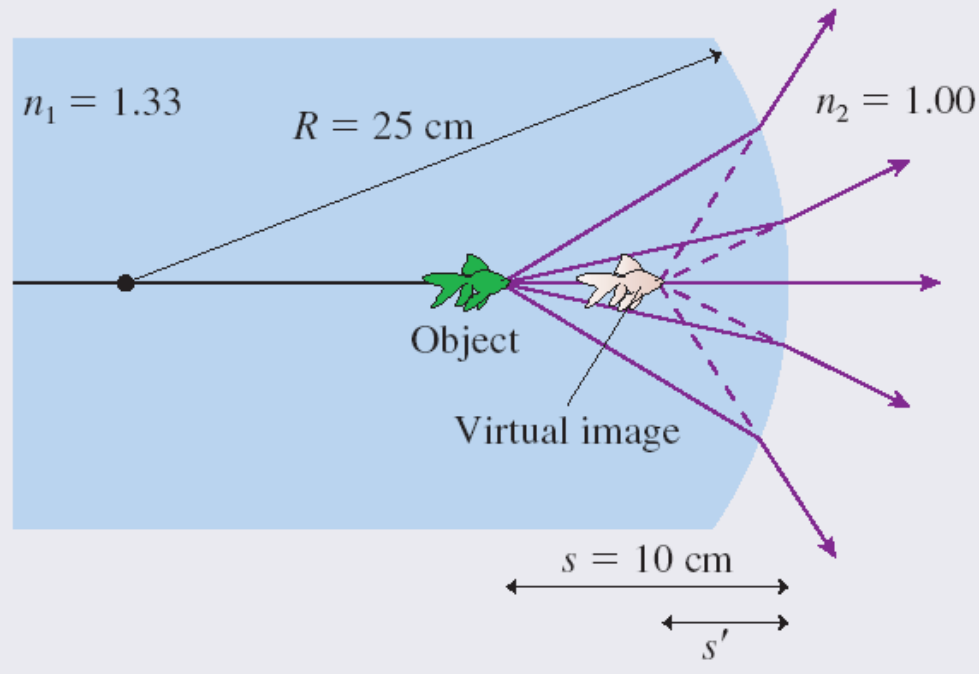
A goldfish lives in a spherical fish bowl 50 cm in diameter. If the fish is 10 cm from the near edge of the bowl, where does the fish appear when viewed from the outside?

**MODEL** Model the fish as a point source and consider the paraxial rays that refract from the water into the air. The thin glass wall has little effect and will be ignored.

# EXAMPLE A goldfish in a bowl

**VISUALIZE** FIGURE 23.46 shows the rays refracting *away* from the normal as they move from the water into the air. We expect to find a virtual image at a distance less than 10 cm.

**FIGURE 23.46** The curved surface of a fish bowl produces a virtual image of the fish.



# EXAMPLE A goldfish in a bowl

**SOLVE** The object is in the water, so  $n_1 = 1.33$  and  $n_2 = 1.00$ . The inner surface is concave (you can remember “concave” because it’s like looking into a cave), so  $R = -25$  cm. The object distance is  $s = 10$  cm. Thus Equation 23.21 is

$$\frac{1.33}{10 \text{ cm}} + \frac{1.00}{s'} = \frac{1.00 - 1.33}{-25 \text{ cm}} = \frac{0.33}{25 \text{ cm}}$$

Solving for the image distance  $s'$  gives

$$\frac{1.00}{s'} = \frac{0.33}{25 \text{ cm}} - \frac{1.33}{10 \text{ cm}} = -0.12 \text{ cm}^{-1}$$

$$s' = \frac{1.00}{-0.12 \text{ cm}^{-1}} = -8.3 \text{ cm}$$

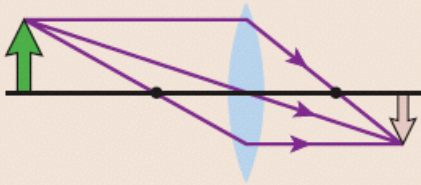
**ASSESS** The image is virtual, located to the left of the boundary. A person looking into the bowl will see a fish that appears to be 8.3 cm from the edge of the bowl.



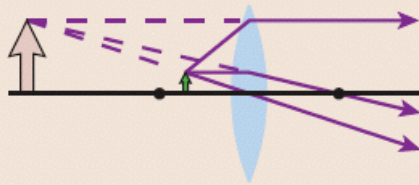
# Applications

## Ray tracing

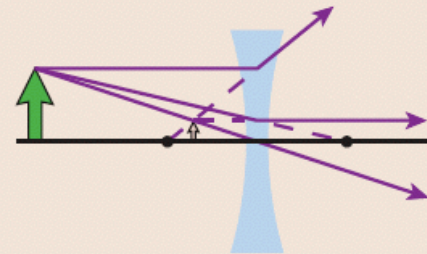
3 special rays in 3 basic situations:



Converging lens  
Real image



Converging lens  
Virtual image



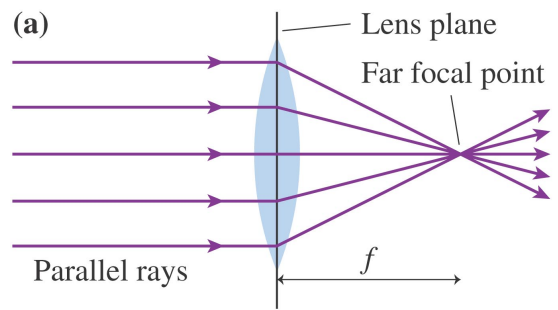
Diverging lens  
Virtual image

**Magnification**  $m = -\frac{s'}{s}$

$m$  is + for an upright image, - for inverted.

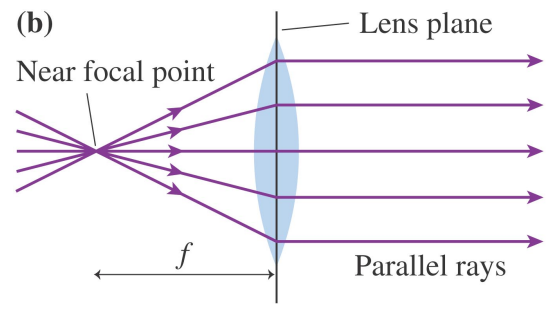
The height ratio is  $h'/h = |m|$ .

# Major Rays



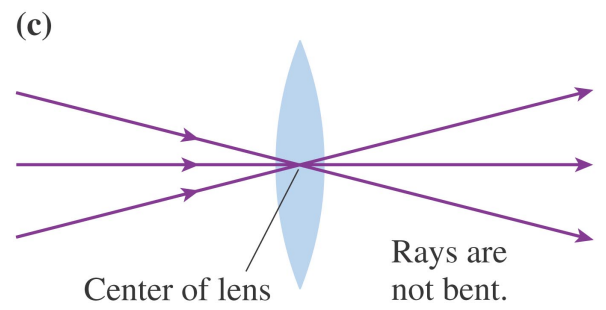
Any ray initially parallel to the optical axis will refract through the focal point on the far side of the lens.

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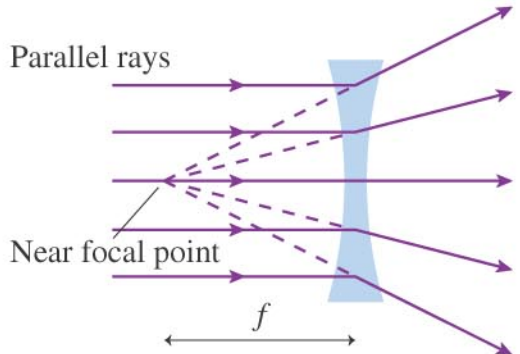
Any ray passing through the near focal point emerges from the lens parallel to the optical axis.

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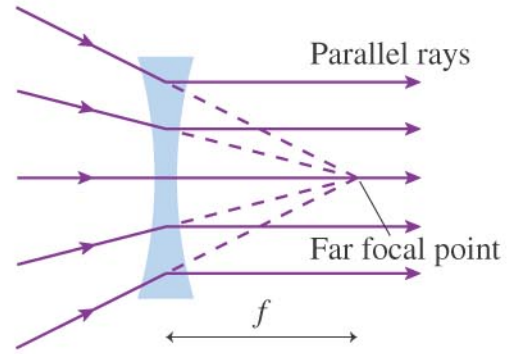
Any ray directed at the center of the lens passes through in a straight line.

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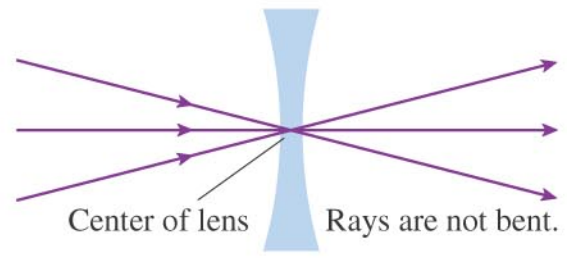


Any ray initially parallel to the optical axis diverges along a line through the near focal point.

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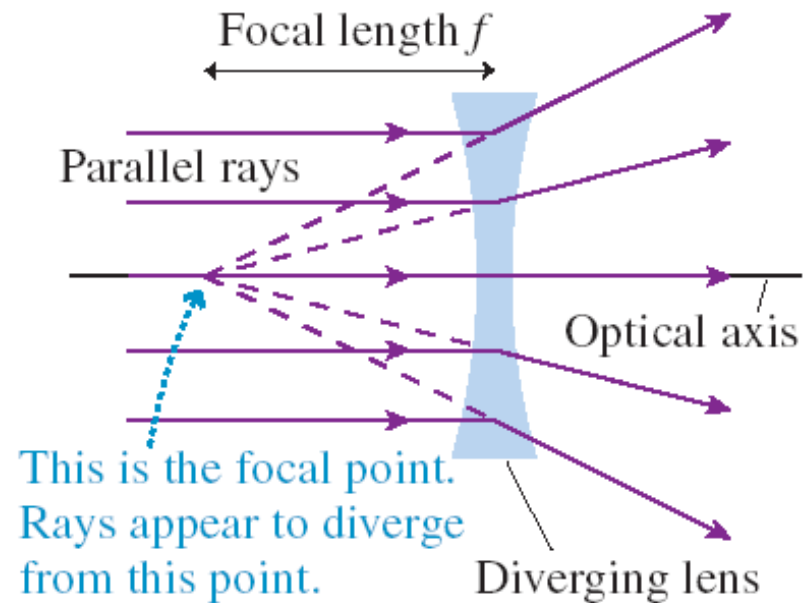
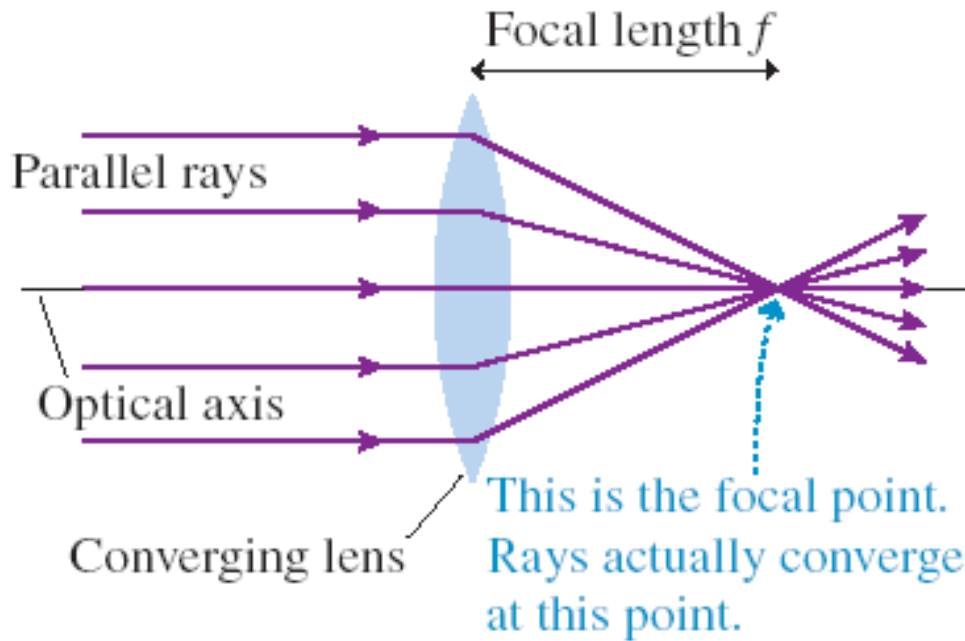


Any ray directed along a line toward the far focal point emerges from the lens parallel to the optical axis.



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

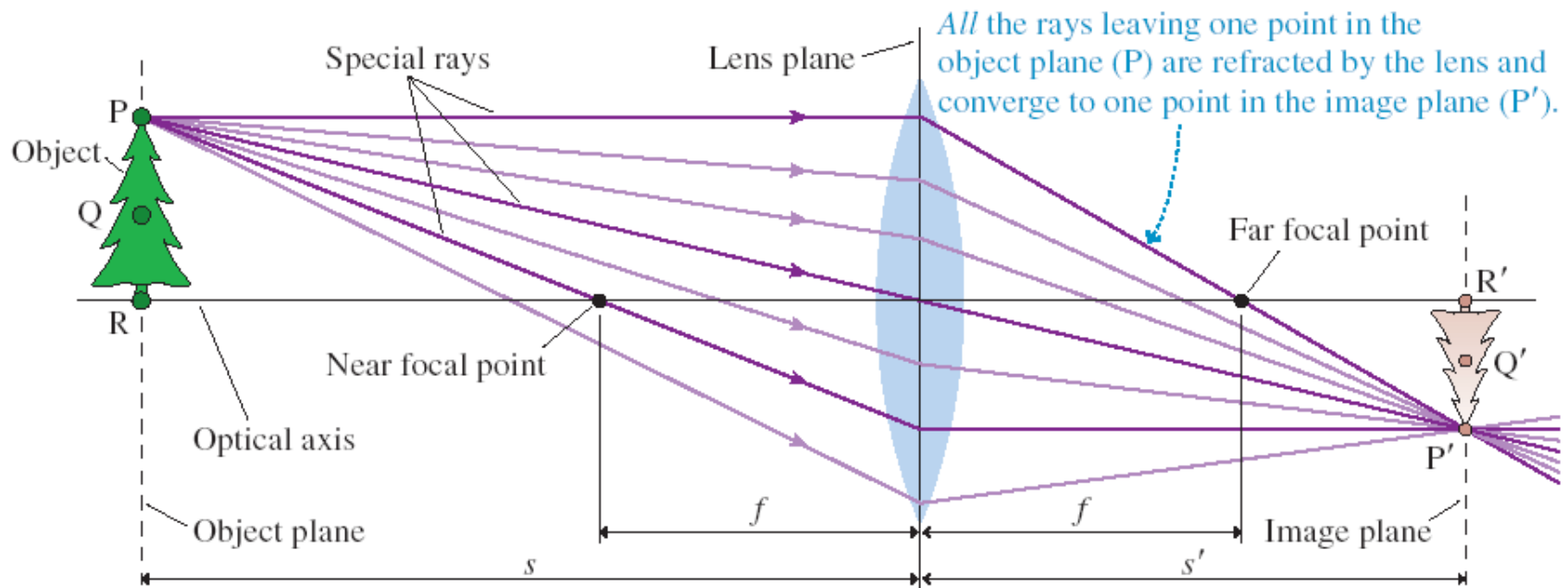
# Thin Lens: Focal Point & Length





# Thin Lenses: Ray Tracing

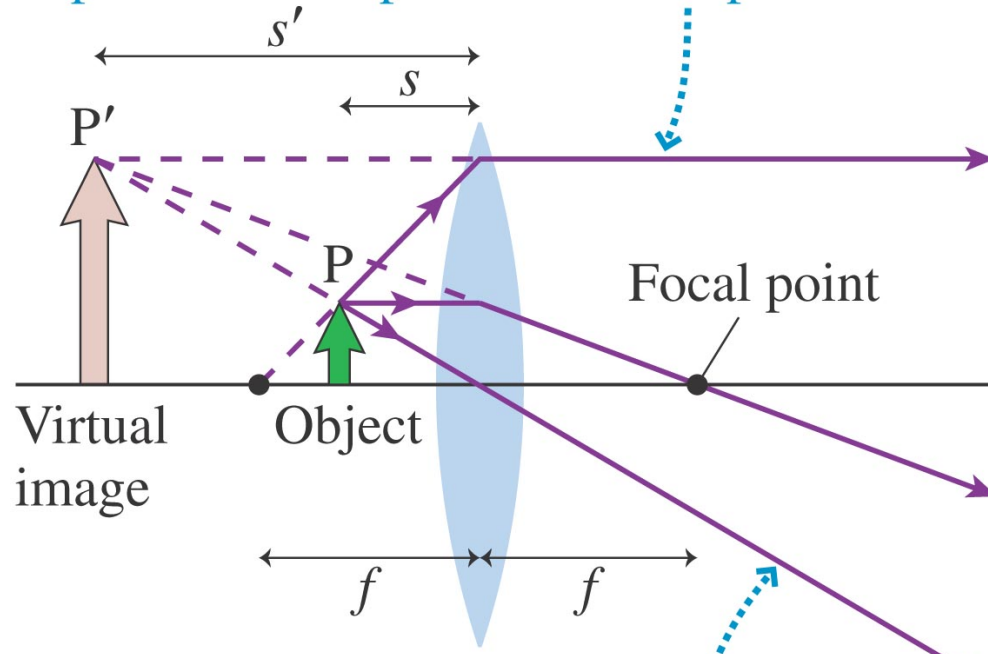
**FIGURE 23.36** Rays from an object point  $P$  are refracted by the lens and converge to a real image at point  $P'$ .



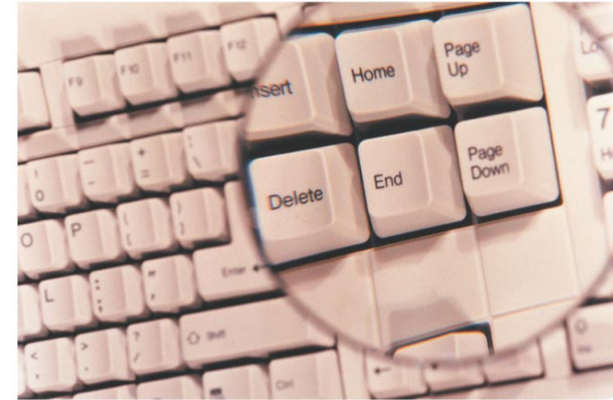
$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f} \quad (\text{thin-lens equation})$$

# Magnifying Glass/Virtual Image

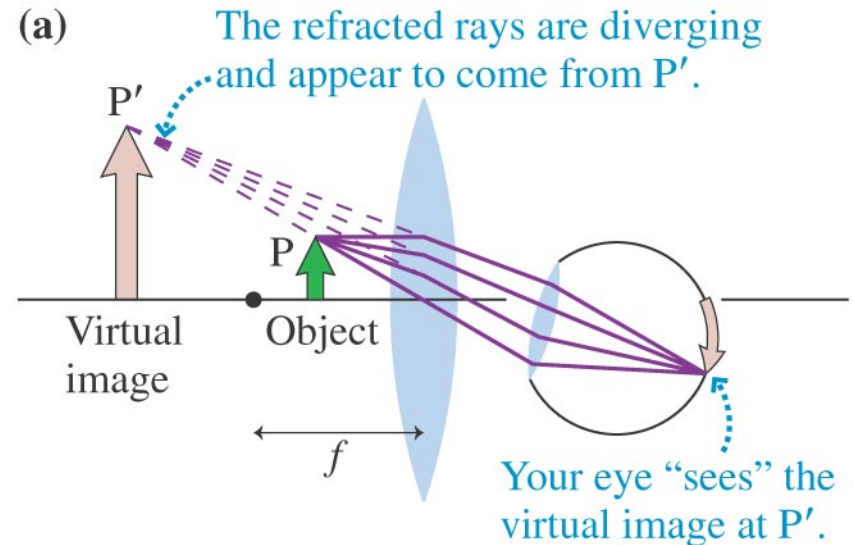
A ray along a line through the near focal point refracts parallel to the optical axis.



The refracted rays are diverging.  
They appear to come from point P'.



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