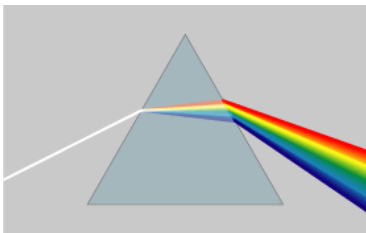


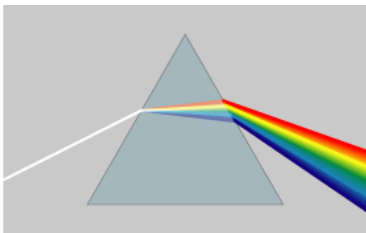


Dispersion (23.5)

- The speed of light in a material depends on its wavelength

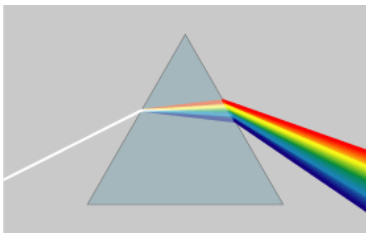


Dispersion (23.5)



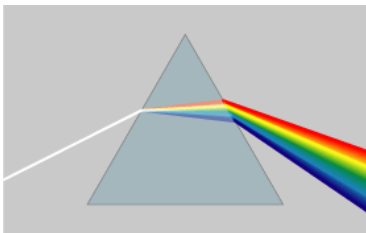
- The speed of light in a material depends on its wavelength
- White light is a mixture of wavelengths and colours.

Dispersion (23.5)



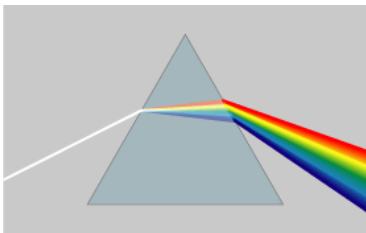
- The speed of light in a material depends on its wavelength
- White light is a mixture of wavelengths and colours.
- Different colours refract at different angles when a ray of white light crosses a boundary between two transparent media.

Dispersion (23.5)



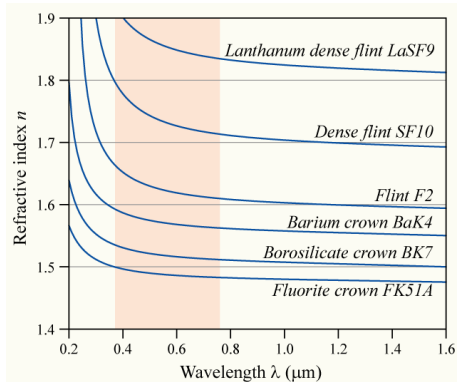
- The speed of light in a material depends on its wavelength
- White light is a mixture of wavelengths and colours.
- Different colours refract at different angles when a ray of white light crosses a boundary between two transparent media.
- Thus the colours are separated.

Dispersion (23.5)



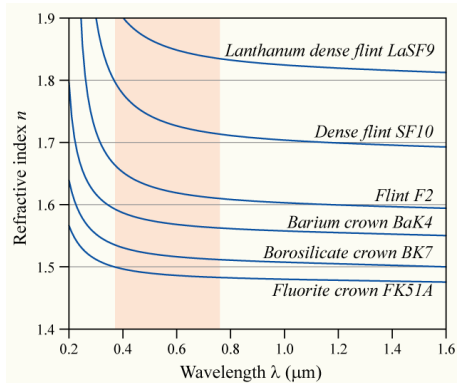
- The speed of light in a material depends on its wavelength
- White light is a mixture of wavelengths and colours.
- Different colours refract at different angles when a ray of white light crosses a boundary between two transparent media.
- Thus the colours are separated.
- Notice that blue light is bent more than red.

Dispersion



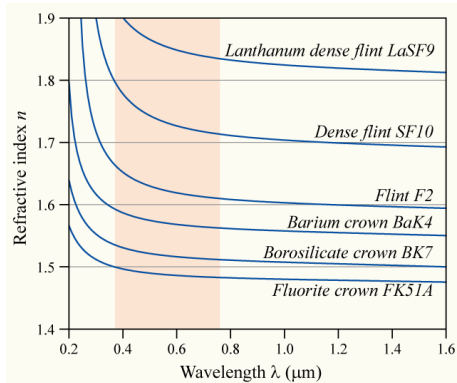
- The index of refraction in most materials is larger at lower wavelengths. The shaded region is visible light.

Dispersion



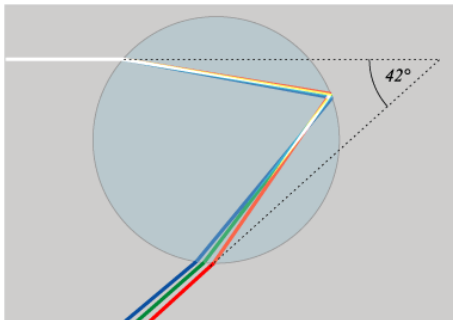
- The index of refraction in most materials is larger at lower wavelengths. The shaded region is visible light.
- Short wavelength light travels more slowly in glass, water, etc.

Dispersion



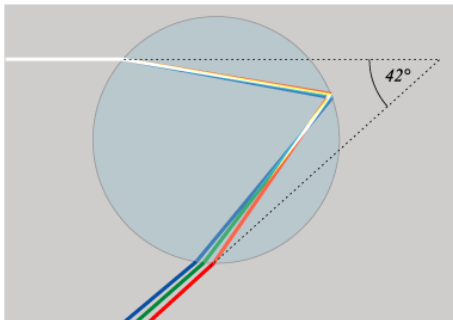
- The index of refraction in most materials is larger at lower wavelengths. The shaded region is visible light.
- Short wavelength light travels more slowly in glass, water, etc.
- This effect is called **dispersion** and depends on the chemical composition of the material.

Rainbows



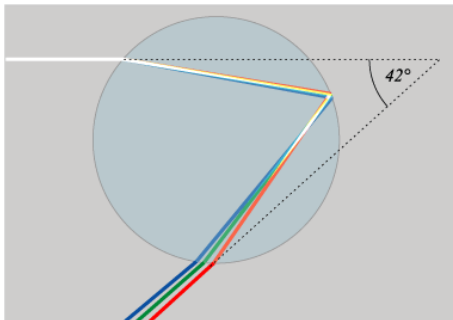
- Rainbows are caused by light refracting in water droplets in the air.

Rainbows



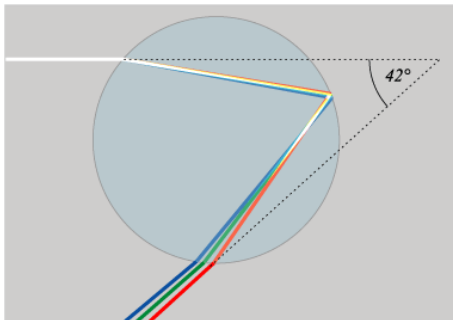
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- White light from the sun enters a droplet and reflects off the back.

Rainbows



- Rainbows are caused by light refracting in water droplets in the air.
- White light from the sun enters a droplet and reflects off the back.
- When entering and leaving a droplet, the beam refracts and different colours leave the droplet going in different directions.

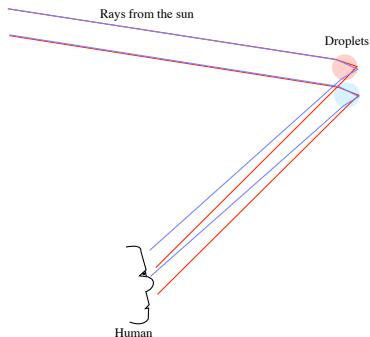
Rainbows



- Rainbows are caused by light refracting in water droplets in the air.
- White light from the sun enters a droplet and reflects off the back.
- When entering and leaving a droplet, the beam refracts and different colours leave the droplet going in different directions.
- Red light is bent less and leaves at a shallower downward angle than blue.

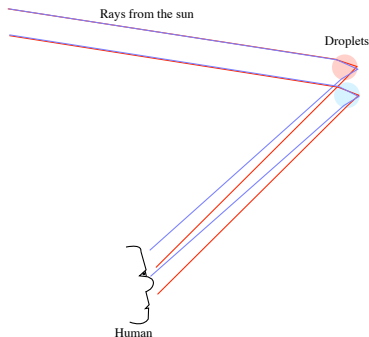
Rainbows

- When you look up in the sky with your back to the sun.



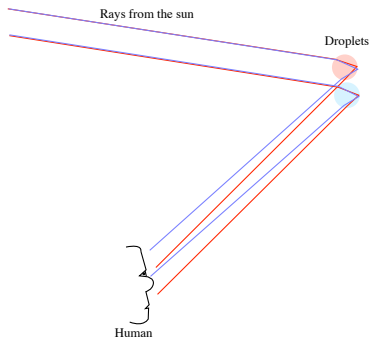
Rainbows

- When you look up in the sky with your back to the sun.
- Rays from the sun are reflected by all the droplets in the sky



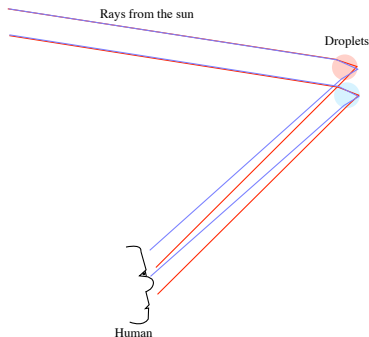
Rainbows

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Rainbows

- When you look up in the sky with your back to the sun.
- Rays from the sun are reflected by all the droplets in the sky
- Some of the droplets reflect visible light to your eye.
- The droplets that reflect red light are higher than the ones that reflect blue because red light goes down at a steeper angle.



Rainbows

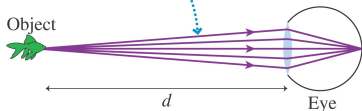


Image Formation by Refraction (23.4)

- Your brain determines how far away something is by how much the images in both eyes differ: **parallax**.

(a) A fish out of water

The eye sees the object at distance d .



(b) A fish in the aquarium

The eye sees the image at distance d' .

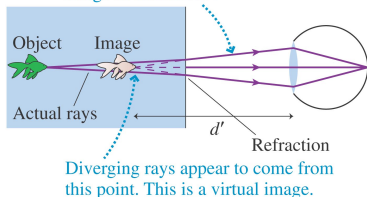
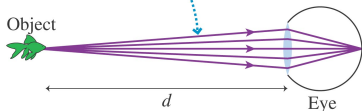


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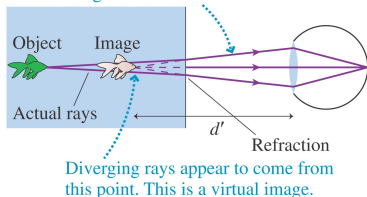
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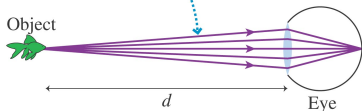


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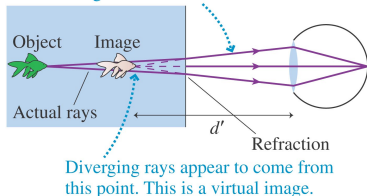
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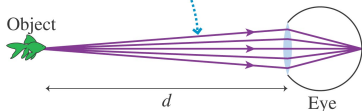


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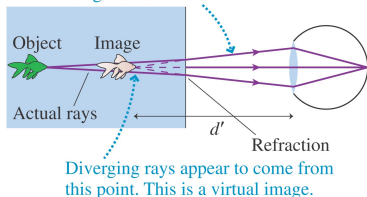
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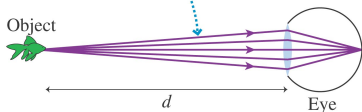


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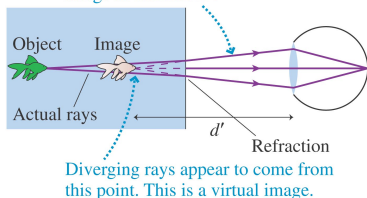
(a) A fish out of water

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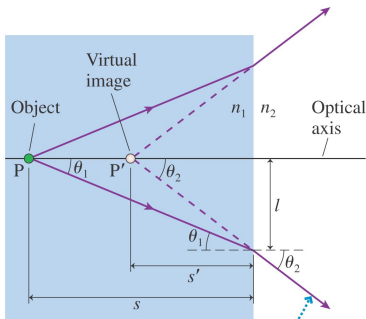
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- However, your brain can be fooled! The fish on the left looks different when it is in water compared to when it is in air.
- In water the rays reflected from the fish refract at the air/water boundary.
- Water has a higher n than air, so the rays refract away from the normal and the projected rays converge in front of the actual position of the fish.
- We actually see a **virtual image** of the fish.

Image Formation by Refraction

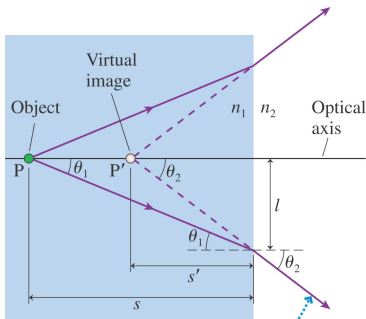
- Analyzing the effect, for object P we see a virtual object P' .



Rays diverge from the virtual image at P' .

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Image Formation by Refraction

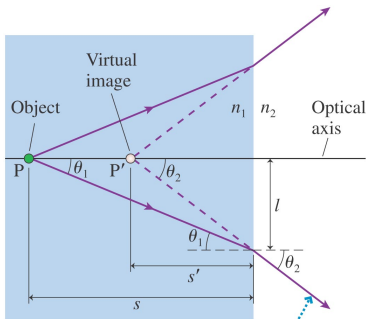


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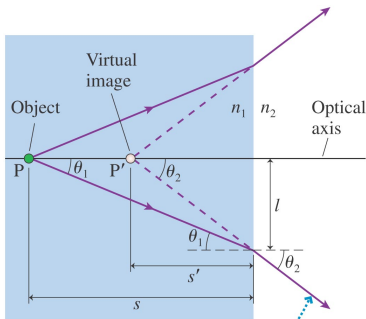


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- A line perpendicular to the boundary is the **optical axis**

Image Formation by Refraction



Rays diverge from the virtual image at P' .

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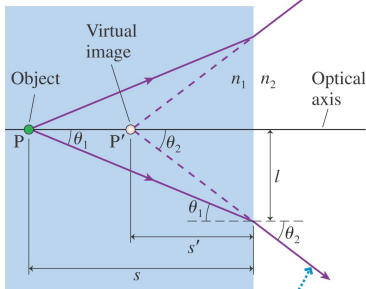
- Analyzing the effect, for object P we see a virtual object P' .
- Distance s is called the **object distance**, s' is known as the **image distance**.
- A line perpendicular to the boundary is the **optical axis**
- Using two triangles with common side l we have $l = s \tan \theta_1 = s' \tan \theta_2$ and

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

Image Formation by Refraction

- Remembering

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



Rays diverge from the virtual image at P'.

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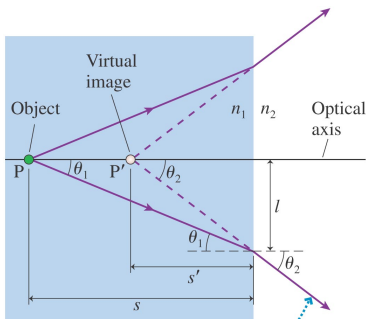
Image Formation by Refraction

- Remembering

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

- We can use Snell's Law

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



Rays diverge from the virtual image at P'.

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Image Formation by Refraction

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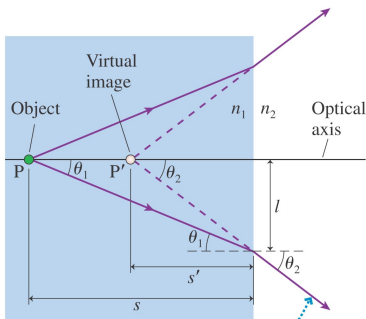
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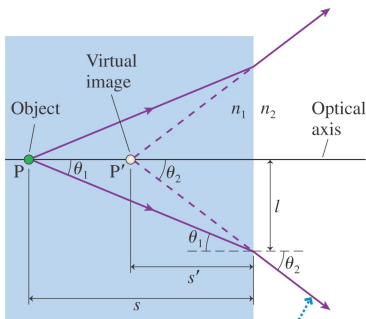
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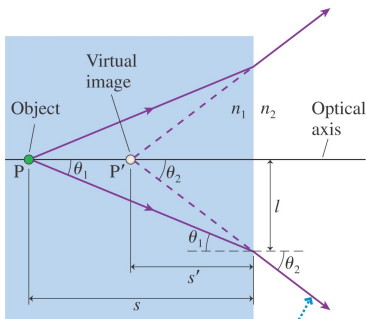
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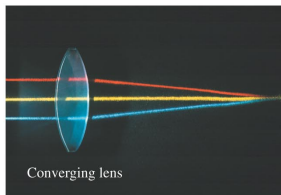
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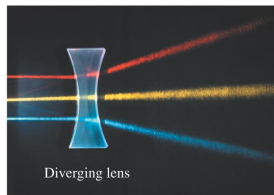
Rays diverge from the virtual image at P'.

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Thin Lenses: Ray Tracing (23.6)

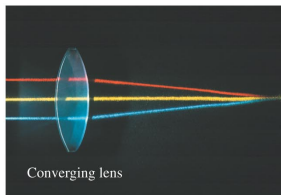


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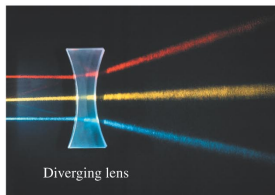


- A **lens** is a transparent material that uses refraction to form an image from diverging light rays.

Thin Lenses: Ray Tracing (23.6)

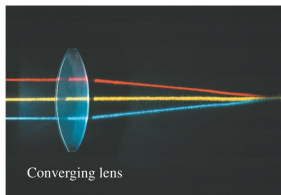


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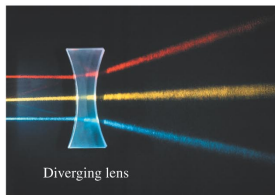


- A **lens** is a transparent material that uses refraction to form an image from diverging light rays.
- The geometrical method for understanding the effect of a given lens is known as **ray tracing**

Thin Lenses: Ray Tracing (23.6)

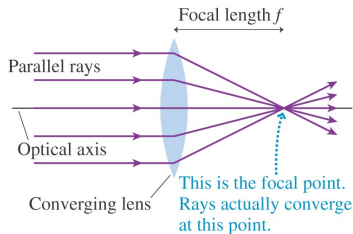


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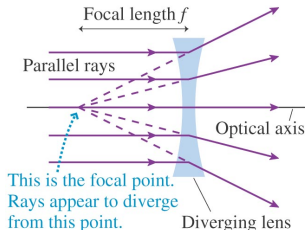


- A **lens** is a transparent material that uses refraction to form an image from diverging light rays.
- The geometrical method for understanding the effect of a given lens is known as **ray tracing**
- A **converging lens** causes parallel rays to refract toward the optical axis. A **diverging lens** causes parallel rays to refract away from the optical axis.

Thin Lenses: Ray Tracing

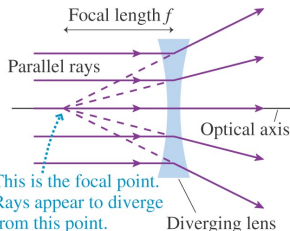
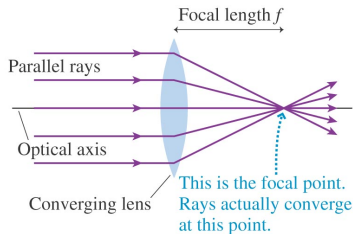


- For a converging lens the **focal point** of the lens is where all initially parallel rays meet. The **focal length** is the distance from the lens to this point.



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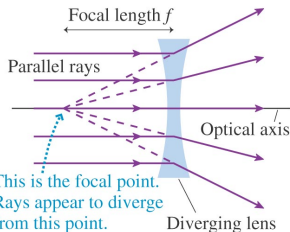
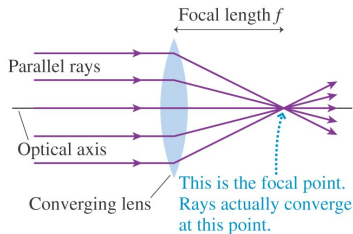
Thin Lenses: Ray Tracing



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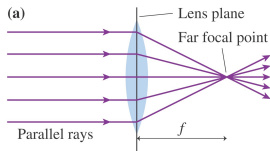
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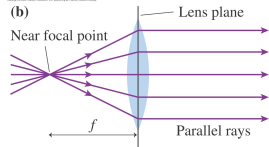
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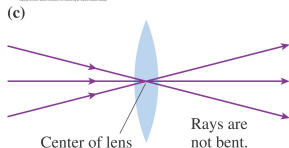
Converging Lenses



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



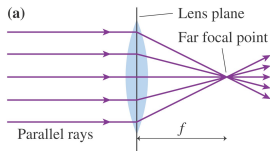
Any ray passing through the near focal point emerges from the lens parallel to the optical axis.



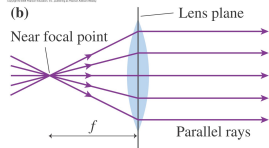
Any ray directed at the center of the lens

- We model our lenses as **thin lenses** - ignore their thickness. All refraction occurs as the rays pass the lens plane.

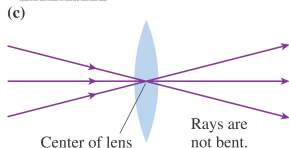
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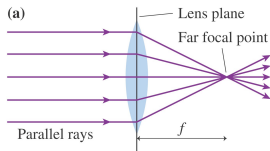
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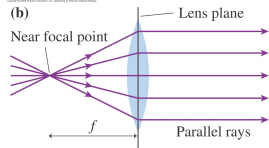
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- The picture on the left shows three important types of rays to trace:

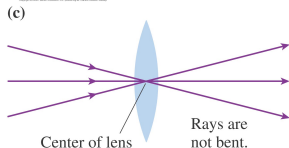
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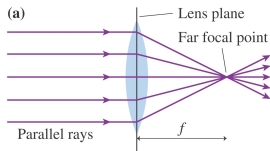
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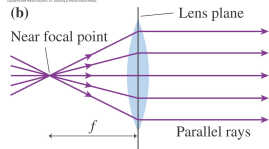
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- The picture on the left shows three important types of rays to trace:
 - 1 Parallel rays converging at the focal point

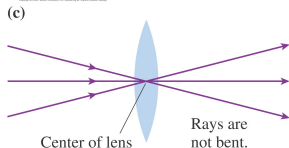
Converging Lenses



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



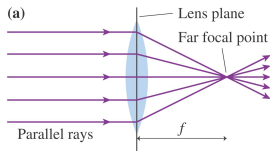
Any ray passing through the near focal point emerges from the lens parallel to the optical axis.



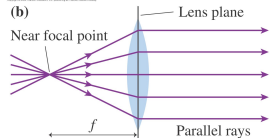
Any ray directed at the center of the lens

- We model our lenses as **thin lenses** - ignore their thickness. All refraction occurs as the rays pass the lens plane.
- The picture on the left shows three important types of rays to trace:
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 - 2 Rays from the focal point becoming parallel

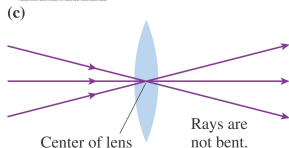
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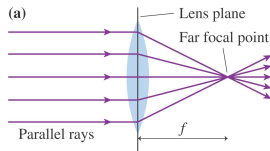
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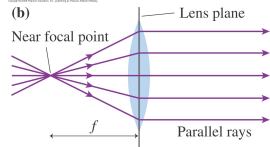
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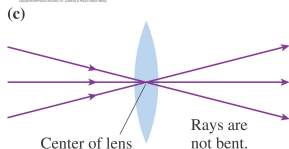
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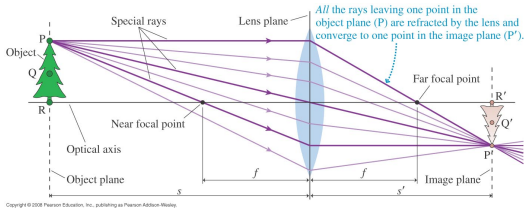
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Any ray directed at the center of the lens

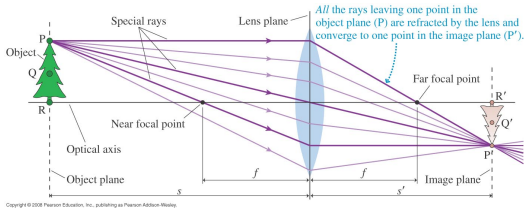
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- The picture on the left shows three important types of rays to trace:
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 - 3 Rays passing through the center of the lens following a straight line
- You will become used to making use of these three special cases.

Real Images



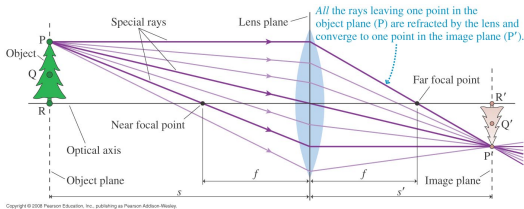
- If you place an object at a distance greater than the focal length away from a converging lens you will get a **real image** of the object on the other side of the lens.

Real Images



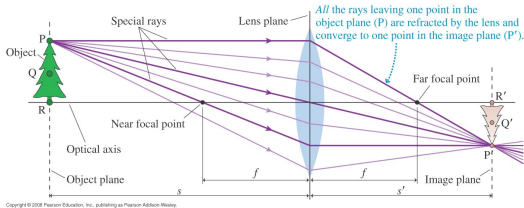
- If you place an object at a distance greater than the focal length away from a converging lens you will get a **real image** of the object on the other side of the lens.
- The real image is inverted and can be projected onto a screen.

Real Images



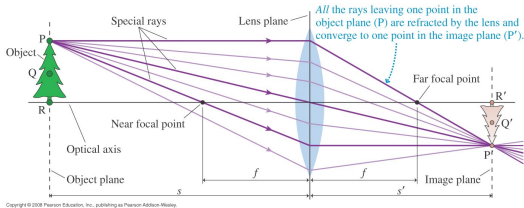
- If you place an object at a distance greater than the focal length away from a converging lens you will get a **real image** of the object on the other side of the lens.
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Real Images



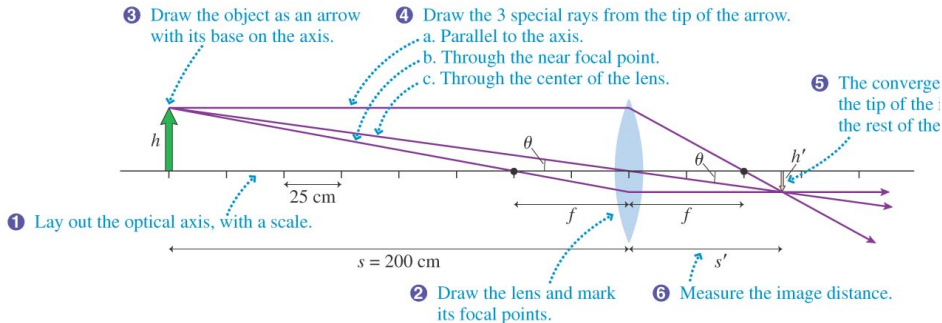
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Real Images



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- Rays strike the full lens surface. A bigger lens collects more light.
- The real image exists whether or not you put a screen there.

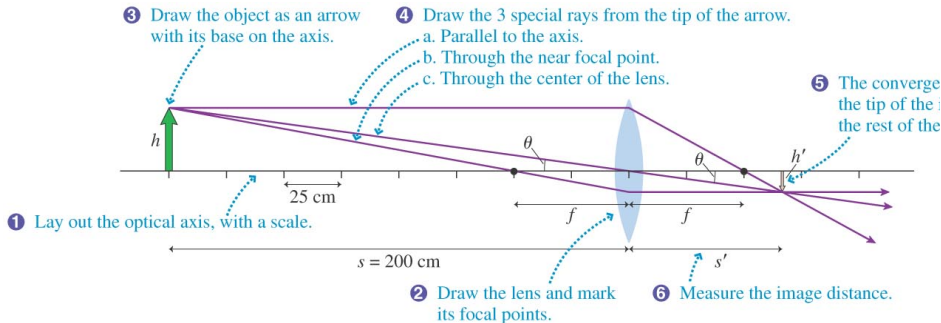
Ray Tracing Example



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1 Draw and optical axis and center the lens on the axis

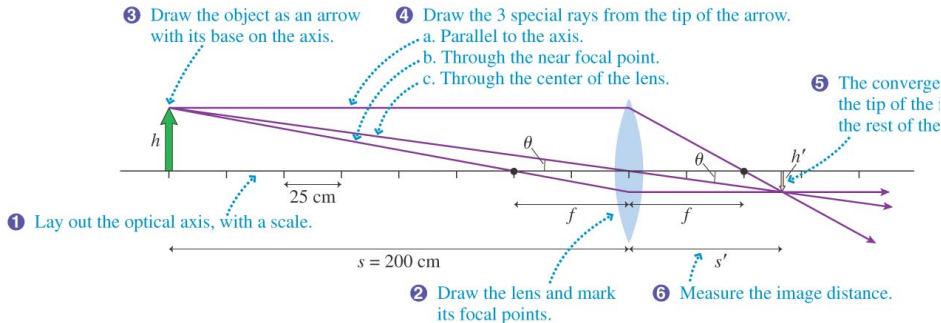
Ray Tracing Example



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- 1 Draw and optical axis and center the lens on the axis
- 2 Represent the object with an arrow at distance s

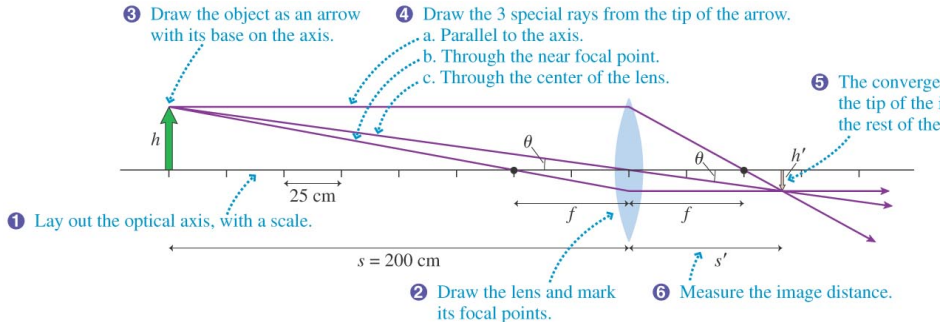
Ray Tracing Example



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- 1 Draw and optical axis and center the lens on the axis
- 2 Represent the object with an arrow at distance s
- 3 Draw three “special” rays from the tip of the arrow: one parallel to the axis, one through the near focal point and one through the center of the lens.

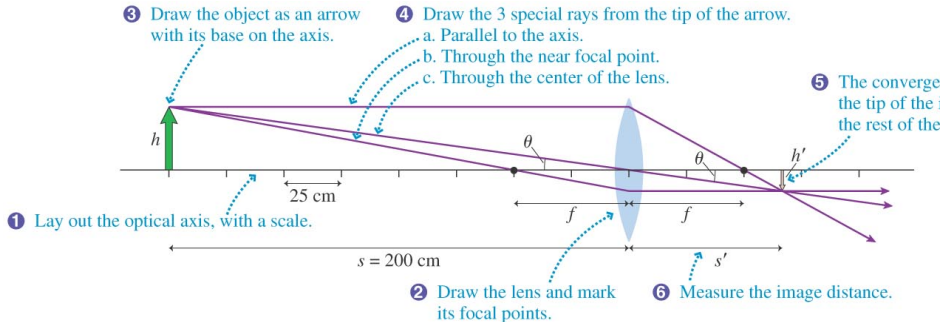
Ray Tracing Example



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4 Extend the rays until they converge

Ray Tracing Example



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- 4 Extend the rays until they converge
- 5 Measure the image distance s'

Lateral Magnification

- Your textbook shows how the height of the image depends on the object and image distances:

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

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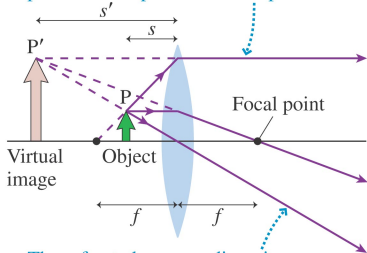
- We can then define the **lateral magnification** as

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- The absolute value of m gives the ratio of the image height to the object height (hence the word “magnification”).

Virtual Images

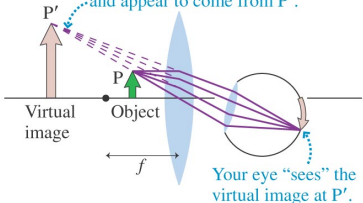
A ray *along a line* through the near focal point refracts parallel to the optical axis.



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

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(a) The refracted rays are diverging
and appear to come from P' .

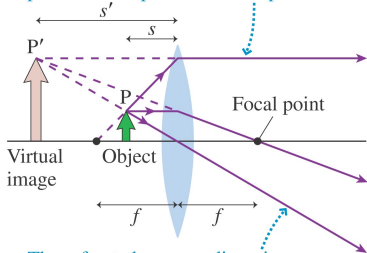


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- What happens if you put an object inside the focal length of the lens??

Virtual Images

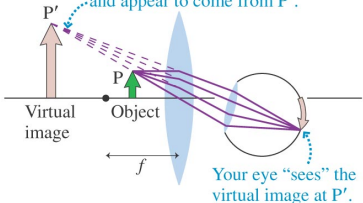
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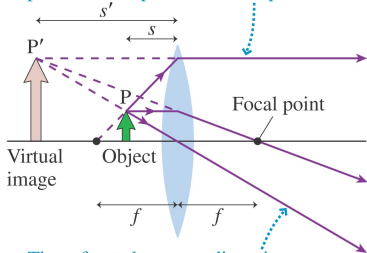
Your eye "sees" the
virtual image at P' .

- What happens if you put an object inside the focal length of the lens??
- You still get an image of the object but it is a **virtual image**

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Virtual Images

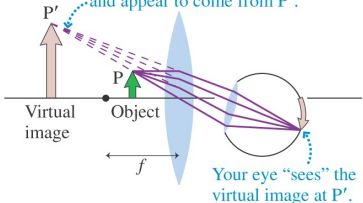
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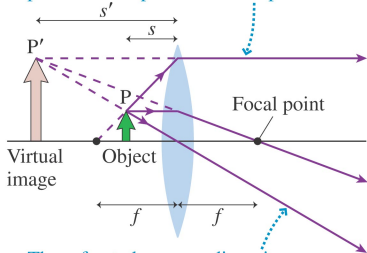


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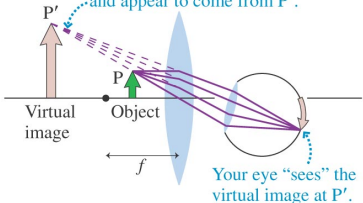
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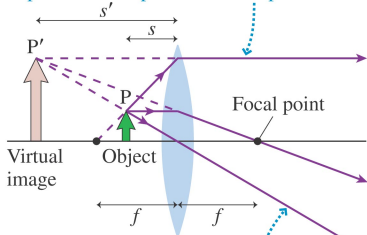
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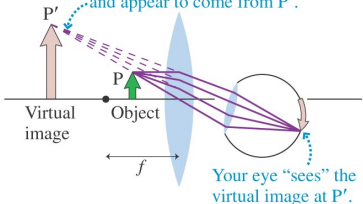
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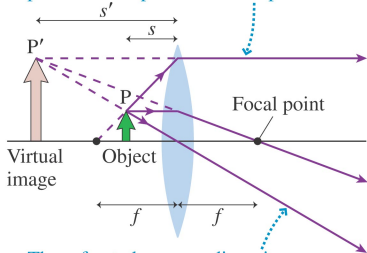


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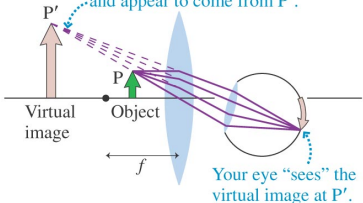
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- You have built a magnifying glass!!
- The image distance (s') for a virtual image is negative, making $m = s'/s$ positive (upright image).