Moonbows

- Friday somebody asked if rainbows can be seen at night.

Moonbows

- Friday somebody asked if rainbows can be seen at night.
- It's true...

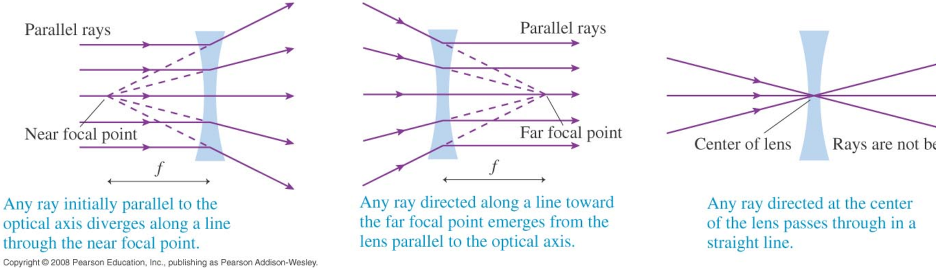
Moonbows

- Friday somebody asked if rainbows can be seen at night.
- It's true...
- ...but they're called Moonbows

Moonbows

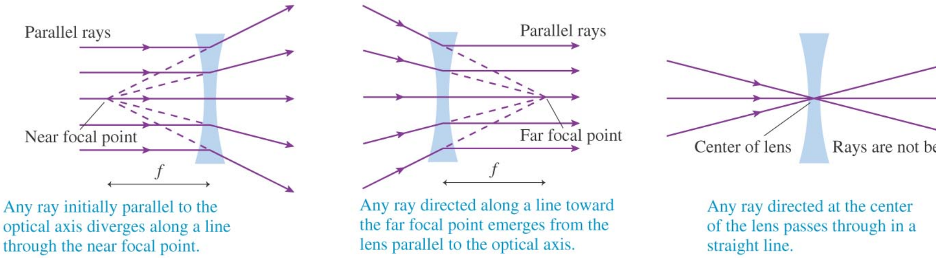
Moonbows

Diverging Lenses



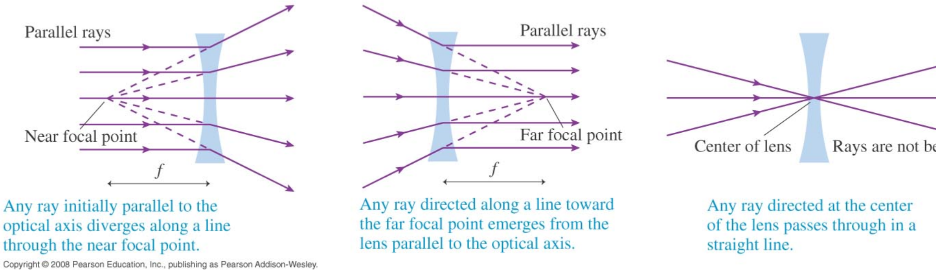
- For diverging lenses we draw the same three sets of rays

Diverging Lenses



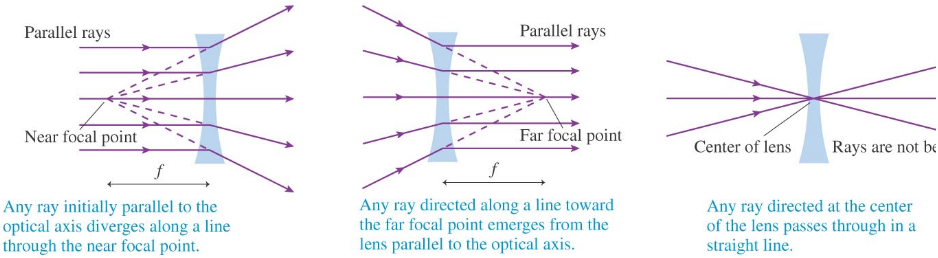
- For diverging lenses we draw the same three sets of rays
- Parallel rays will appear to come from the near focal point

Diverging Lenses



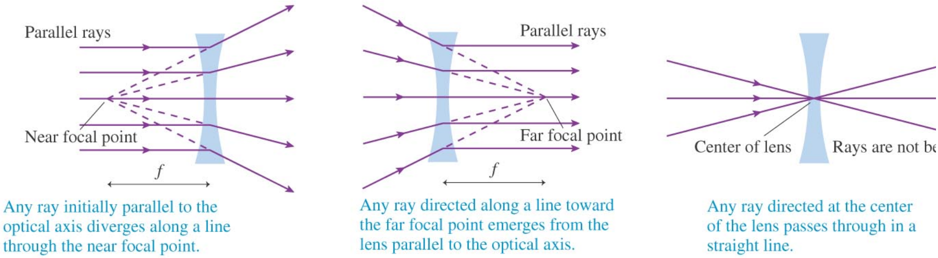
- For diverging lenses we draw the same three sets of rays
- Parallel rays will appear to come from the near focal point
- Rays directed toward the far focal point will come out parallel

Diverging Lenses



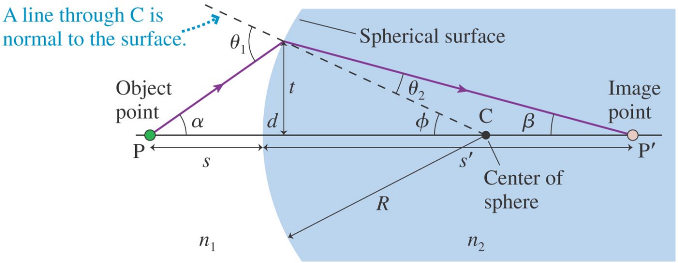
- For diverging lenses we draw the same three sets of rays
- Parallel rays will appear to come from the near focal point
- Rays directed toward the far focal point will come out parallel
- Rays directed at the center of the lens will be unbent

Diverging Lenses



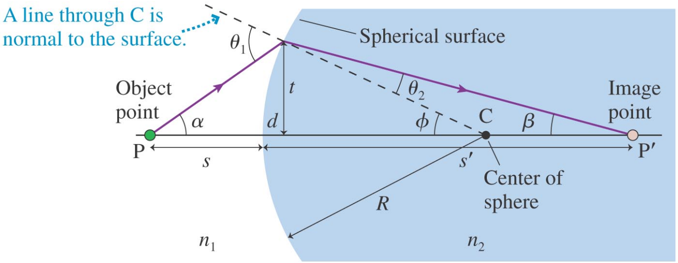
- For diverging lenses we draw the same three sets of rays
- Parallel rays will appear to come from the near focal point
- Rays directed toward the far focal point will come out parallel
- Rays directed at the center of the lens will be unbent
- A virtual image is formed on the object-side of the lens (s' is negative)

Thin Lenses: Refraction Theory (23.7)



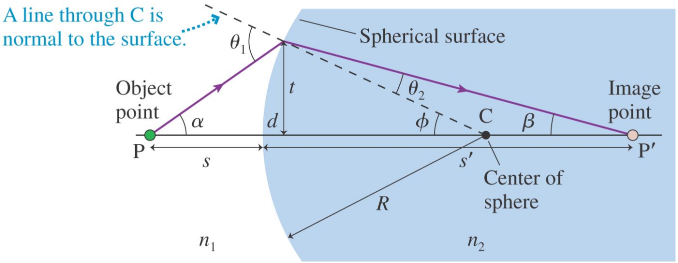
- The figure above shows a spherical boundary between two media with indices of refraction n_1 and n_2.

Thin Lenses: Refraction Theory (23.7)



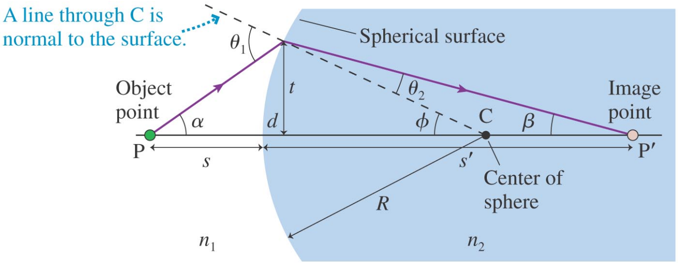
- The figure above shows a spherical boundary between two media with indices of refraction n_1 and n_2.
- The sphere has radius of curvature R, centered at point C.

Thin Lenses: Refraction Theory (23.7)



- The figure above shows a spherical boundary between two media with indices of refraction n_1 and n_2.
- The sphere has radius of curvature R, centered at point C.
- The ray from P is incident on the boundary at angle θ_1 and refracts into the second medium at angle θ_2

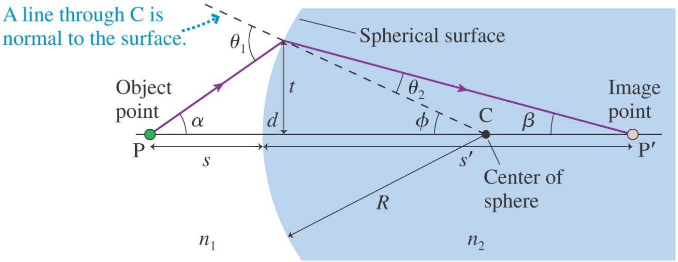
Thin Lenses: Refraction Theory (23.7)



- The figure above shows a spherical boundary between two media with indices of refraction n_1 and n_2.
- The sphere has radius of curvature R, centered at point C.
- The ray from P is incident on the boundary at angle θ_1 and refracts into the second medium at angle θ_2
- Snell's Law plus the small angle approximation gives

$$n_1\theta_1 = n_2\theta_2$$

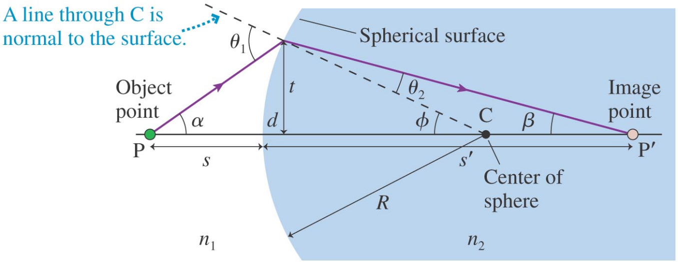
Thin Lenses: Refraction Theory



- As usual, we use triangles to determine:

$$\begin{aligned} \theta_1 &= \alpha + \phi \\ \theta_2 &= \phi - \beta \end{aligned}$$

Thin Lenses: Refraction Theory



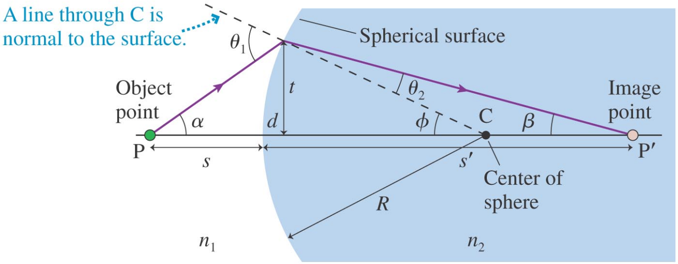
- As usual, we use triangles to determine:

$$\theta_1 = \alpha + \phi$$
$$\theta_2 = \phi - \beta$$

- We can use this in Snell's Law to give

$$n_1(\alpha + \phi) = n_2(\phi - \beta)$$

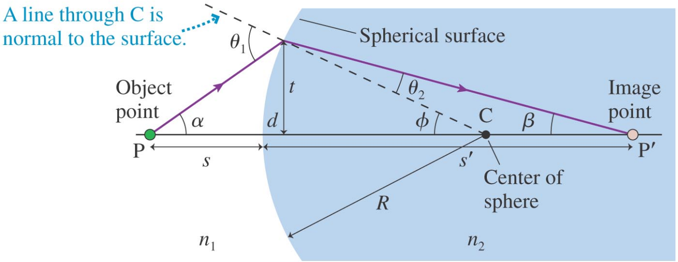
Thin Lenses: Refraction Theory



- Use 3 triangles with common side t (see your text) to show

$$\alpha = \frac{t}{s}, \beta = \frac{t}{s'}, \phi = \frac{t}{R}$$

Thin Lenses: Refraction Theory



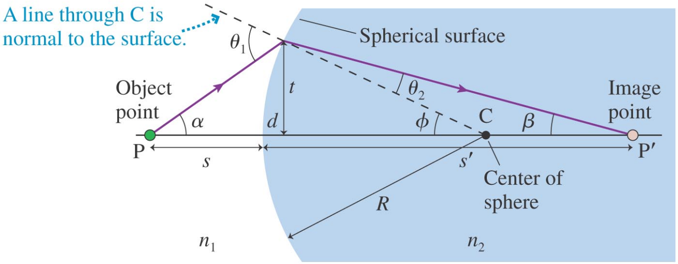
- Use 3 triangles with common side t (see your text) to show

$$\alpha = \frac{t}{s}, \beta = \frac{t}{s'}, \phi = \frac{t}{R}$$

- Plugging these into our new Snell's Law relationship:

$$n_1 \left(\frac{t}{s} + \frac{t}{R} \right) = n_2 \left(\frac{t}{R} - \frac{t}{s'} \right)$$

Thin Lenses: Refraction Theory



- Use 3 triangles with common side t (see your text) to show

$$\alpha = \frac{t}{s}, \beta = \frac{t}{s'}, \phi = \frac{t}{R}$$

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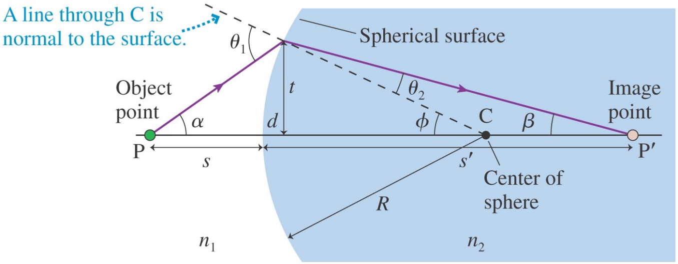
$$n_1\left(\frac{t}{s} + \frac{t}{R}\right) = n_2\left(\frac{t}{R} - \frac{t}{s'}\right)$$

Thin Lenses: Refraction Theory



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$$\alpha = \frac{t}{s}, \beta = \frac{t}{s'}, \phi = \frac{t}{R}$$

- Plugging these into our new Snell's Law relationship:

$$n_1\left(\frac{t}{s} + \frac{t}{R}\right) = n_2\left(\frac{t}{R} - \frac{t}{s'}\right)$$

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

Thin Lenses: Refraction Theory

- Note that this expression is independent of α. All paraxial rays leaving P converge at P'

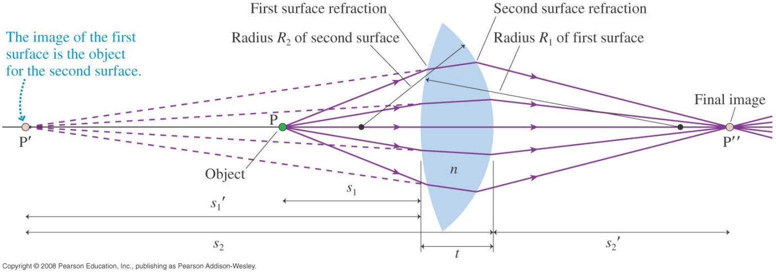
Thin Lenses: Refraction Theory

- Note that this expression is independent of α. All paraxial rays leaving P converge at P'
- Our treatment was developed for a spherical lens which was convex toward the object point but works for other surfaces as long as you are careful about the sign convention:

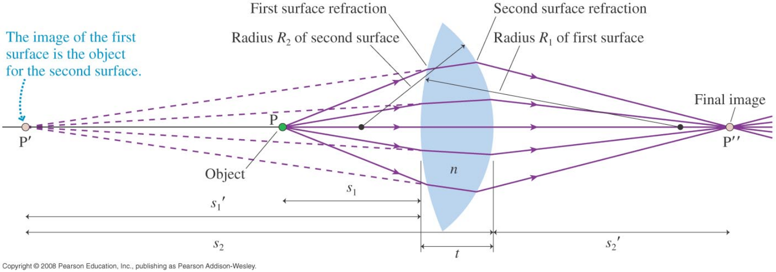
TABLE 23.3 Sign convention for refracting surfaces

	Positive	Negative
R	Convex toward the object	Concave toward the object
s'	Real image, opposite side from object	Virtual image, same side as object

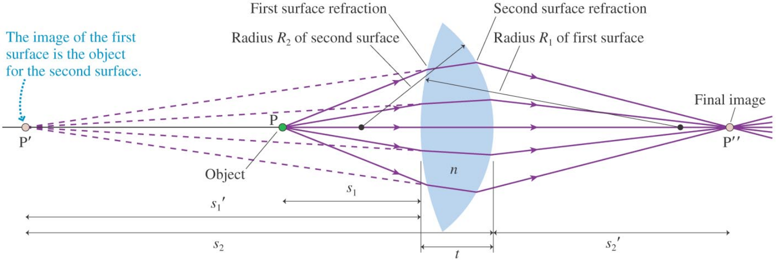
Lenses



- We have so-far assumed that all refraction happens at the mid-point of the lens. Let's look in detail at what is going on in a lens.



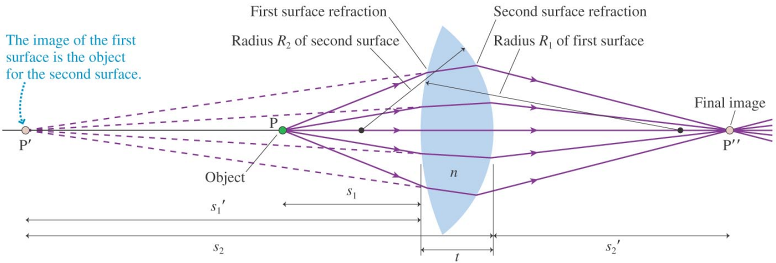
- We have so-far assumed that all refraction happens at the mid-point of the lens. Let's look in detail at what is going on in a lens.
- A lens of thickness t made of material of index n is actually made of two spherical surfaces of radii R_1 and R_2



- We can use our newly derived expressions to write

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

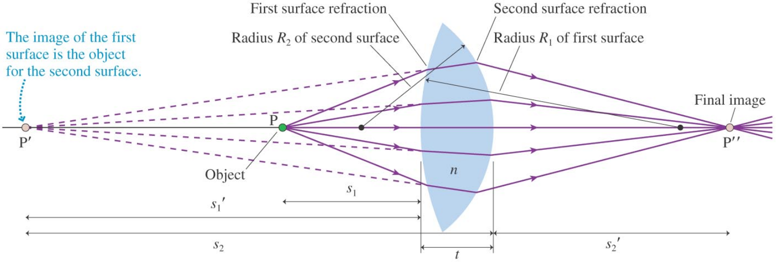
Lenses



- We can use our newly derived expressions to write

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

Lenses

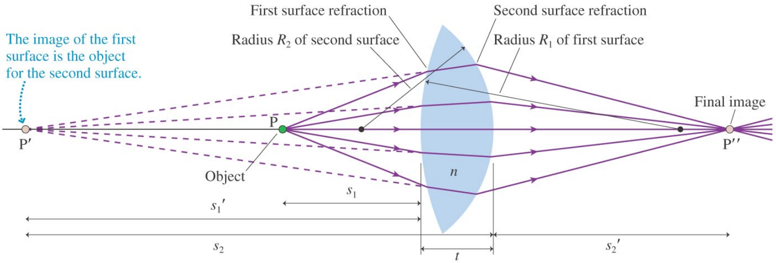


- We can use our newly derived expressions to write

$$\frac{n_1}{s} + \frac{n_2}{s'} = \frac{n_2 - n_1}{R}$$
$$\frac{1}{s_1} + \frac{n}{s_1'} = \frac{n - 1}{R_1}$$

- The image P' from the first surface becomes the object for the second surface!

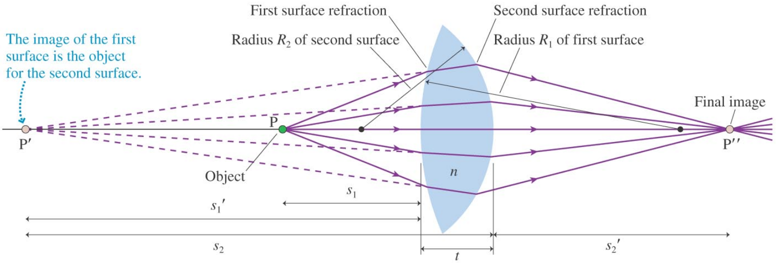
Lenses



- Remember that virtual images give negative image distances. So,

$$s_2 = t + (-s_1')$$

Lenses



- Remember that virtual images give negative image distances. So,

$$s_2 = t + (-s_1')$$

- Also, at the second surface $n_1 = n$ and $n_2 = 1$! So, for the second surface the equation looks like:

$$\frac{n}{t - s_1'} + \frac{1}{s_2'} = \frac{1 - n}{R_2}$$

Lenses

- Letting $t \to 0$

$$\frac{n}{t - s_1'} + \frac{1}{s_2'} = \frac{1 - n}{R_2}$$

Lenses

- Letting $t \to 0$

$$\frac{n}{t - s_1'} + \frac{1}{s_2'} = \frac{1 - n}{R_2}$$

Lenses

- Letting $t \to 0$

$$\frac{n}{t - s_1'} + \frac{1}{s_2'} = \frac{1 - n}{R_2}$$
$$-\frac{n}{s_1'} + \frac{1}{s_2'} = -\frac{n - 1}{R_2}$$

- This looks very similar to the equation we obtained for the first surface. Combining the 2 equations gives

  and

Lenses

- Letting $t \to 0$

$$
\begin{aligned}
\frac{n}{t - s_1'} + \frac{1}{s_2'} &= \frac{1 - n}{R_2} \\
-\frac{n}{s_1'} + \frac{1}{s_2'} &= -\frac{n - 1}{R_2}
\end{aligned}
$$

- This looks very similar to the equation we obtained for the first surface. Combining the 2 equations gives

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

and

Lenses

- Letting $t \to 0$

$$\frac{n}{t - s_1'} + \frac{1}{s_2'} = \frac{1-n}{R_2}$$
$$-\frac{n}{s_1'} + \frac{1}{s_2'} = -\frac{n-1}{R_2}$$

- This looks very similar to the equation we obtained for the first surface. Combining the 2 equations gives

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

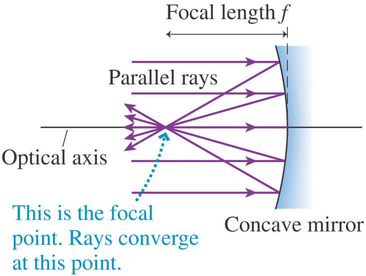
and

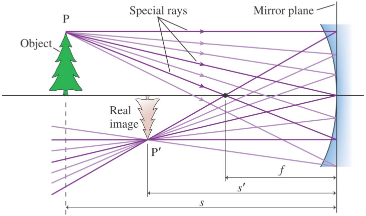
$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) (\text{lens} - \text{maker's equation})$$

Lenses Sign Convention

TABLE 23.4 Sign convention for thin lenses

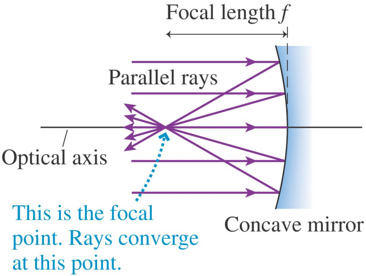
	Positive	Negative
R_1, R_2	Convex toward the object	Concave toward the object
f	Converging lens, thicker in center	Diverging lens, thinner in center
s'	Real image, opposite side from object	Virtual image, same side as object

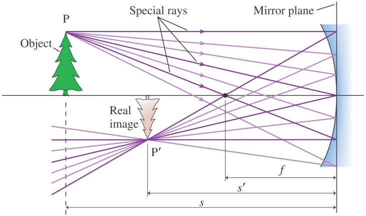




- Curved mirrors can also be used to form images and are commonly used in telescopes, searchlights, rearview mirrors, etc.

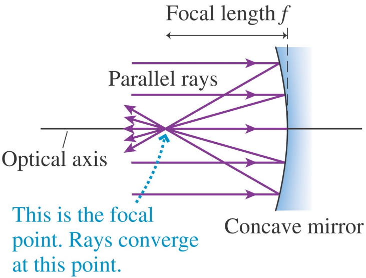
Image Formation with Spherical Mirrors (23.8)

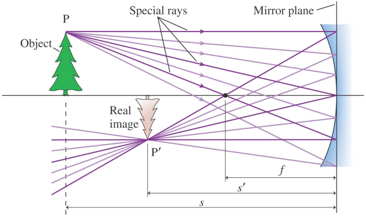




- Curved mirrors can also be used to form images and are commonly used in telescopes, searchlights, rearview mirrors, etc.
- A concave mirror has edges which curve toward the source.

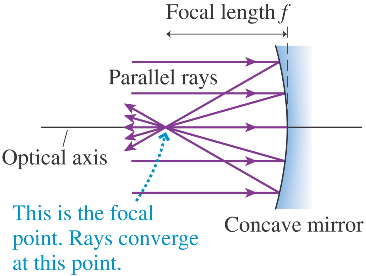
Image Formation with Spherical Mirrors (23.8)

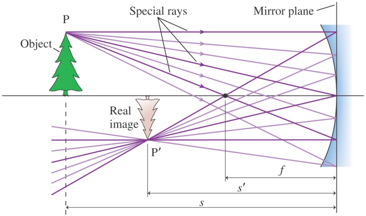




- Curved mirrors can also be used to form images and are commonly used in telescopes, searchlights, rearview mirrors, etc.
- A concave mirror has edges which curve toward the source.
- These mirrors also have a focal point and can form real images.

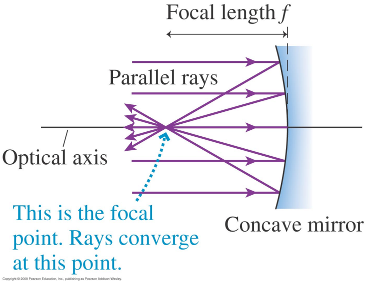
Image Formation with Spherical Mirrors (23.8)

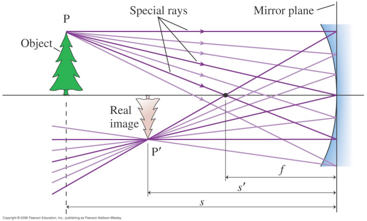




- Curved mirrors can also be used to form images and are commonly used in telescopes, searchlights, rearview mirrors, etc.
- A concave mirror has edges which curve toward the source.
- These mirrors also have a focal point and can form real images.
- The lower figure shows how to find the inverted real image on the same side of the mirror as the object. Use the same three pricipal rays we are used to!

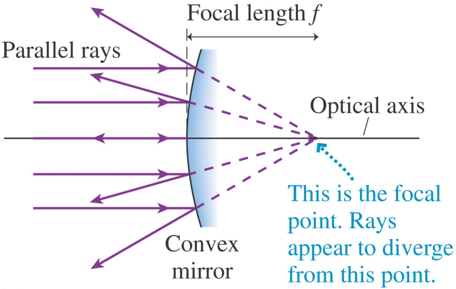
Image Formation with Spherical Mirrors (23.8)

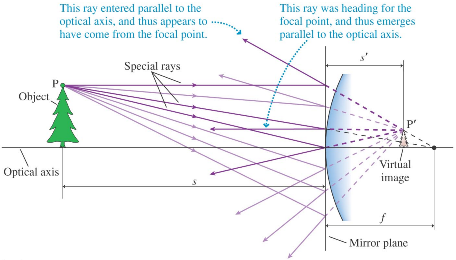




- Curved mirrors can also be used to form images and are commonly used in telescopes, searchlights, rearview mirrors, etc.
- A concave mirror has edges which curve toward the source.
- These mirrors also have a focal point and can form real images.
- The lower figure shows how to find the inverted real image on the same side of the mirror as the object. Use the same three pricipal rays we are used to!
- If $s > f$ the image is real and inverted. Otherwise, a virtual image is formed behind the mirror.

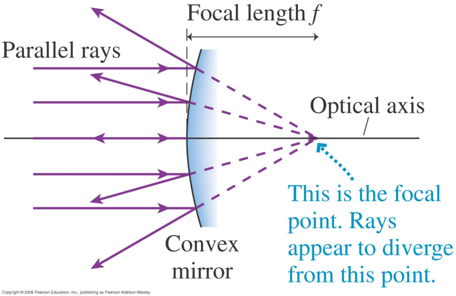
Image Formation with Spherical Mirrors (23.8)

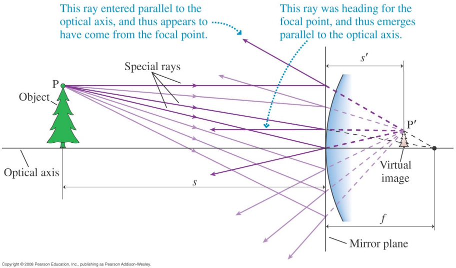




- A convex mirror has edges which curve away from the object.

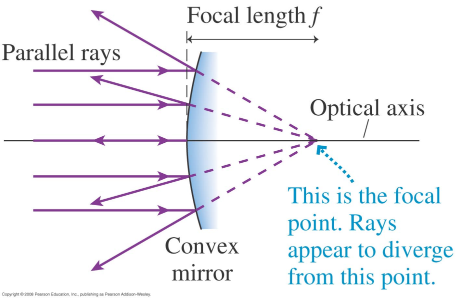
Image Formation with Spherical Mirrors (23.8)

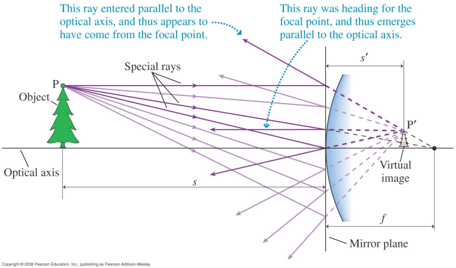




- A convex mirror has edges which curve away from the object.
- The reflected rays appear to come from inside the mirror and a virtual image is formed.

Image Formation with Spherical Mirrors (23.8)





- A convex mirror has edges which curve away from the object.
- The reflected rays appear to come from inside the mirror and a virtual image is formed.
- The image is upright and smaller than the real object. This allows you to have a wider field of view than you would have with a flat mirror.

Image Formation with Spherical Mirrors

The Mirror Equation

- We have developed a thin-lens equation to calculate the image location in that system. We can do the same for spherical mirrors

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}, \text{(thin mirror equation)}$$

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

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- Lateral magnification has the same definition as for a lens

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

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- The focal length of the mirror is related to its radius of curvature:

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

- Lateral magnification has the same definition as for a lens

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

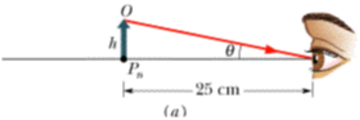
- A similar sign convention exists

TABLE 23.5 Sign convention for spherical mirrors

	Positive	Negative
R and f	Concave toward the object	Convex toward the object
s'	Real image, same side as object	Virtual image, opposite side from object

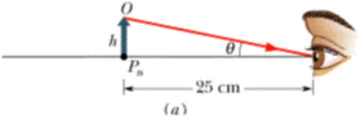
The Simple Magnifier

- If you want to see something small, you bring it close to your eye.



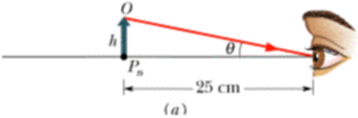
The Simple Magnifier

- If you want to see something small, you bring it close to your eye.
- The closest your eye can focus is called the near point of the eye.



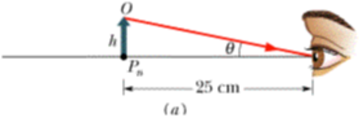
The Simple Magnifier

- If you want to see something small, you bring it close to your eye.
- The closest your eye can focus is called the near point of the eye.
- Everybody has a different near point, it gets less near as you get older.



The Simple Magnifier

- If you want to see something small, you bring it close to your eye.
- The closest your eye can focus is called the near point of the eye.
- Everybody has a different near point, it gets less near as you get older.
- By convention we specify a standard near point to be 25 cm.



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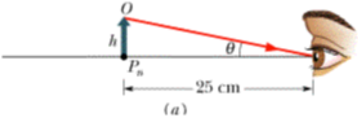
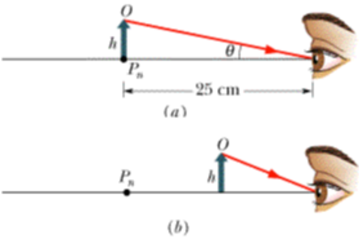
- The closest your eye can focus is called the near point of the eye.
- Everybody has a different near point, it gets less near as you get older.
- By convention we specify a standard near point to be 25 cm.
- If you observe something whose height is h cm at the standard near point then it subtends an angle $\theta_{NP} = h/25$ cm

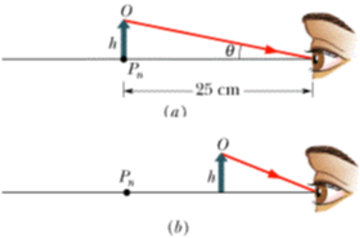


The Simple Magnifier

- If you want to see more detail you might bring it closer.



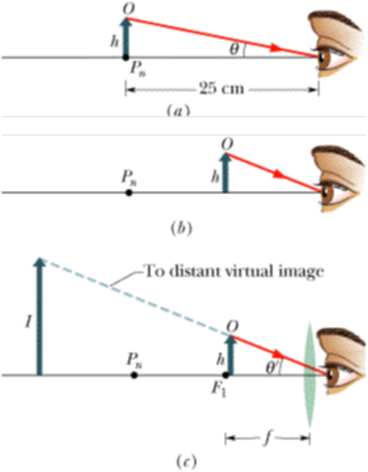
The Simple Magnifier



- If you want to see more detail you might bring it closer.
- but your eye might not be able to focus it clearly.

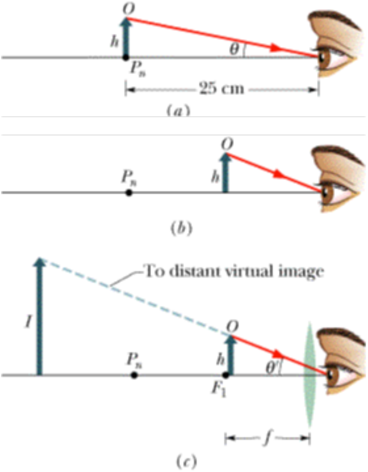
The Simple Magnifier

- If you put a convex lens between your eye and the object



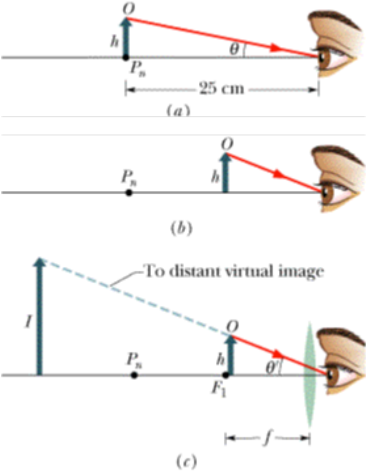
The Simple Magnifier

- If you put a convex lens between your eye and the object
- with the object at or near its focal point, a distance *f* from the lens.



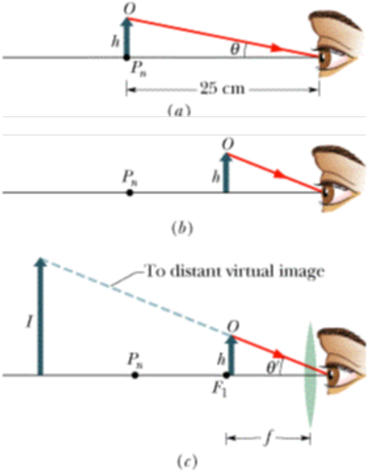
The Simple Magnifier

- If you put a convex lens between your eye and the object
- with the object at or near its focal point, a distance *f* from the lens.
- you get an image far away or at infinity.



The Simple Magnifier

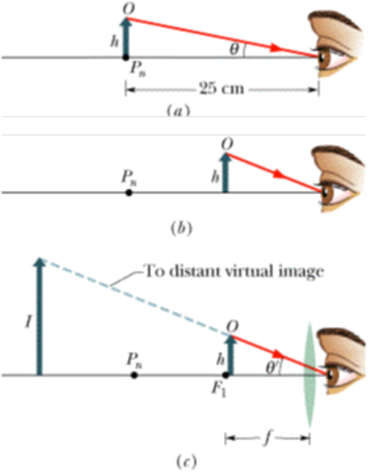
- If you put a convex lens between your eye and the object
- with the object at or near its focal point, a distance *f* from the lens.
- you get an image far away or at infinity.
- The image of the object subtends a greater angle: $\theta' = h/f$



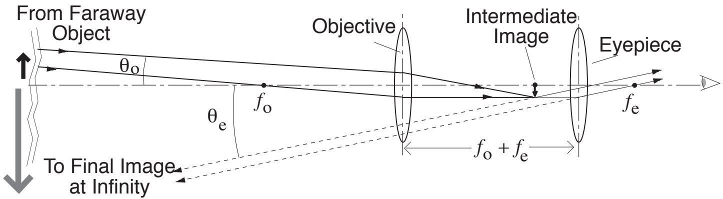
The Simple Magnifier

- If you put a convex lens between your eye and the object
- with the object at or near its focal point, a distance *f* from the lens.
- you get an image far away or at infinity.
- The image of the object subtends a greater angle: $\theta' = h/f$
- the angular magnification is

$$\frac{\theta'}{\theta_{NP}} = \frac{25\text{ cm}}{f}$$

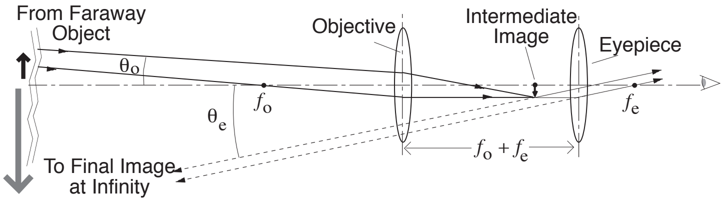


The Telescope



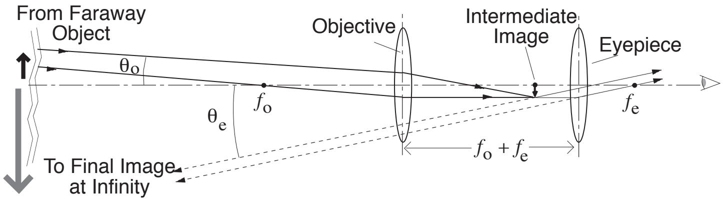
- The telescope consists of two pieces: the eyepiece and the objective. You look through the eyepiece, and you point the objective towards what you're looking at.

The Telescope



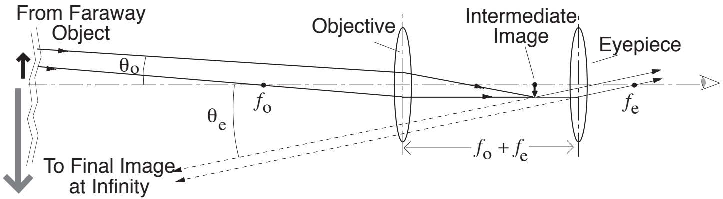
- The telescope consists of two pieces: the eyepiece and the objective. You look through the eyepiece, and you point the objective towards what you're looking at.
- The objective makes a real image and you look at it with the eyepiece.

The Telescope



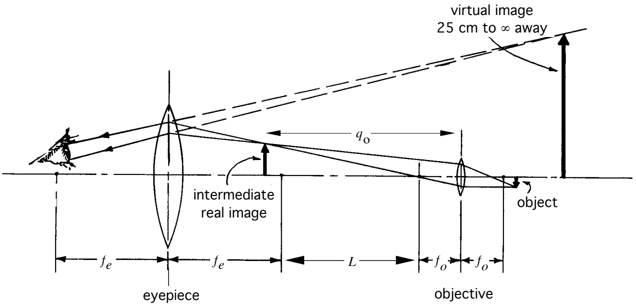
- The telescope consists of two pieces: the eyepiece and the objective. You look through the eyepiece, and you point the objective towards what you're looking at.
- The objective makes a real image and you look at it with the eyepiece.
- Because we assume the object we're looking at is at infinity and the image of it is at, or near, the focal point of the eyepiece, the image is far away, or at infinity.

The Telescope



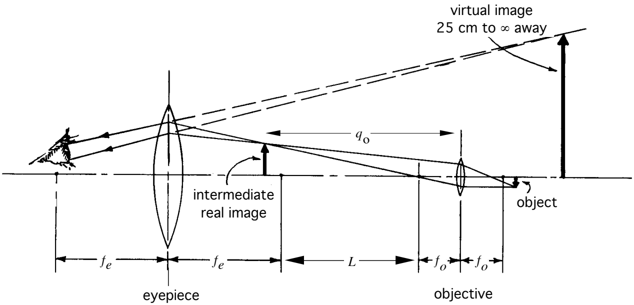
- The telescope consists of two pieces: the eyepiece and the objective. You look through the eyepiece, and you point the objective towards what you're looking at.
- The objective makes a real image and you look at it with the eyepiece.
- Because we assume the object we're looking at is at infinity and the image of it is at, or near, the focal point of the eyepiece, the image is far away, or at infinity.
- The angular magnification is $M = -f_o/f_e$.

The Microscope

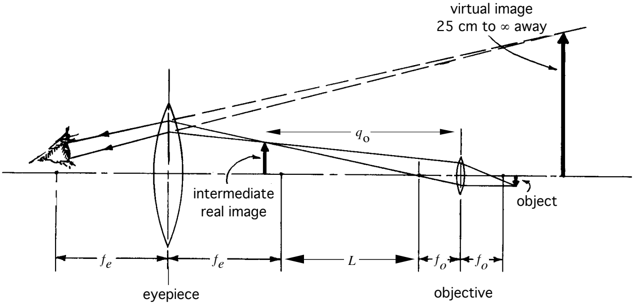


- The microscope also consists an objective and eyepiece

The Microscope

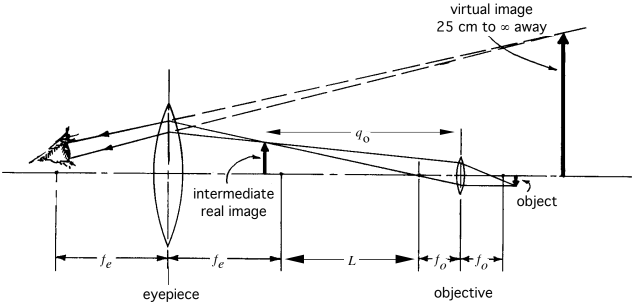


- The microscope also consists an objective and eyepiece
- The difference from the telescope is that the object is very close to the focal point of the objective.



- The microscope also consists an objective and eyepiece
- The difference from the telescope is that the object is very close to the focal point of the objective.
- But, like the telescope, the image it forms is near the focal point of the eyepiece.

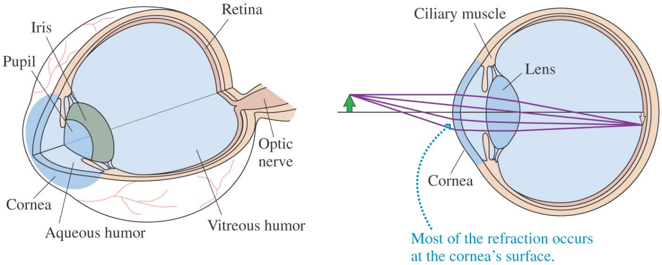
The Microscope



From analysing the geometry we find that the angular magnification is

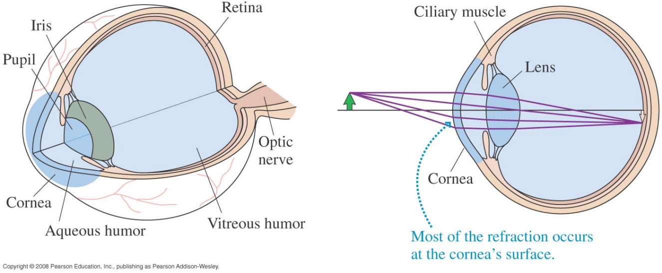
$$M \approx -\frac{L \, 25 \text{ cm}}{f_o f_e}.$$

Vision (24.3)



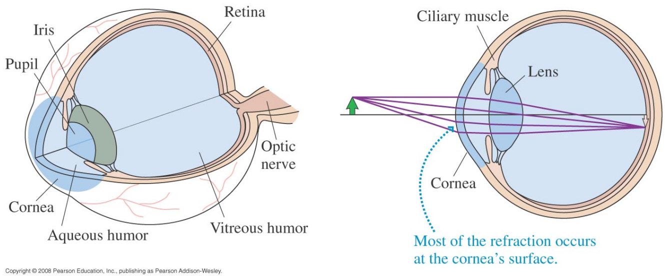
- A Poet: the eyes are the window to the soul

Vision (24.3)



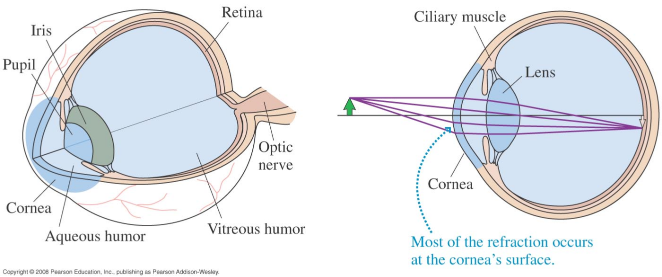
- A Poet: the eyes are the window to the soul
- A Physicist: an eye is a fluid-filled ball about 2.3cm in diameter

Vision (24.3)



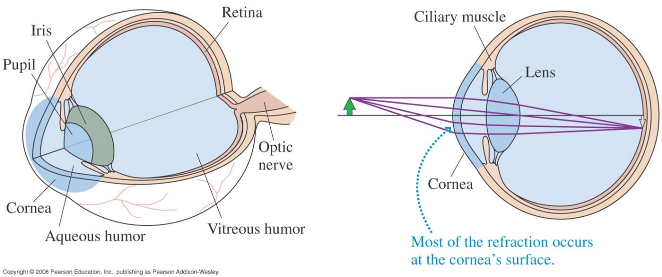
- A Poet: the eyes are the window to the soul
- A Physicist: an eye is a fluid-filled ball about 2.3cm in diameter
- Let's talk about the optical properties of that ball.

Vision



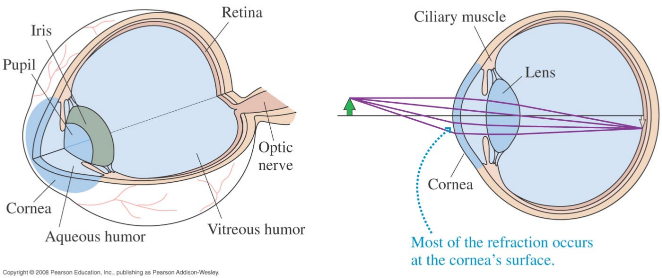
- The cornea is transparent and sharply curved. It works with the lens to provide the refractive power of the eye.

Vision



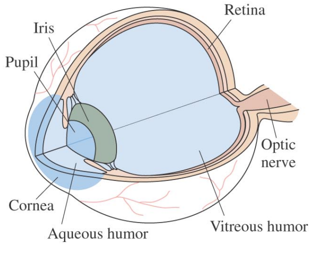
- The cornea is transparent and sharply curved. It works with the lens to provide the refractive power of the eye.
- The fluid has $n = 1.34$ (like water). The lens has $n = 1.44$

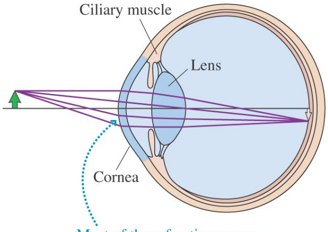
Vision



- The cornea is transparent and sharply curved. It works with the lens to provide the refractive power of the eye.
- The fluid has $n = 1.34$ (like water). The lens has $n = 1.44$
- The pupil is a variable-diameter aperture in the iris. It can adjust from $\approx 1.5mm$ to $\approx 8mm$

Vision





- The cornea is transparent and sharply curved. It works with the lens to provide the refractive power of the eye.
- The fluid has $n = 1.34$ (like water). The lens has $n = 1.44$
- The pupil is a variable-diameter aperture in the iris. It can adjust from $\approx 1.5mm$ to $\approx 8mm$
- The light detector is the retina, which has rods for light and dark and cones for colour.