Class 11

April 18, 2023 9:12 AM

ENGI-1500
Physics -2

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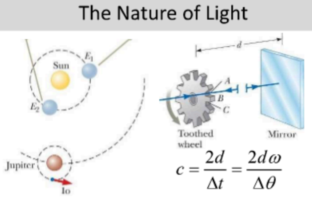
Humber Institute of Technology and Advanced Learning
Winter 2023

HUMBER

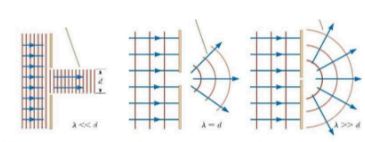
Reminder of the previous week

The Nature of Light



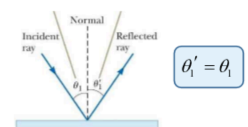
$$c = \frac{2d}{\Delta t} = \frac{2d\omega}{\Delta\theta}$$

The Ray Approximation in Ray Optics



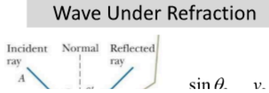
Wave Under Reflection

Law of Reflection

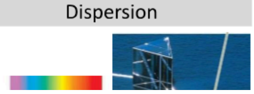


$$\theta_1' = \theta_1$$

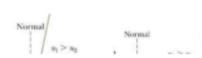
Wave Under Refraction

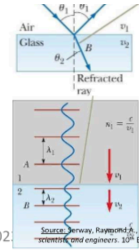


Dispersion



Total Internal Reflection





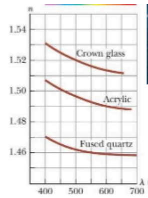
$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$$

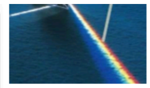
$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$

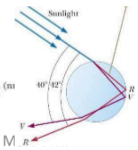
Snell's Law of Refraction

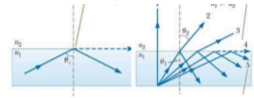
$$\boxed{n_1 \sin\theta_1 = n_2 \sin\theta_2}$$

Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

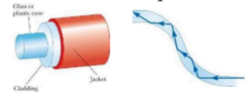








$$\sin\theta_c = \frac{n_2}{n_1}$$



Week 13 / Class 11

Image Formation (Ch. 35)

Outline of Week 13 / Class 11

- Reminder of the previous week
- Image Formation (Ch. 35)
  - Images Formed by Flat Mirrors
  - Images Formed by Spherical Mirrors
  - Images Formed by Refraction [Optional / Reading]
  - Images Formed by Thin Lenses
  - Lens Aberrations
  - Optical Instruments
- Examples
- Next week's topic

Image Formation (Ch. 35)

→ **Images Formed by Flat Mirrors**

Images Formed by Spherical Mirrors

Images Formed by Refraction [Optional/Reading]

Images Formed by Thin Lenses

Lens Aberrations

Optical Instruments

Image Formation (Ch. 35)

Images Formed by Flat Mirrors

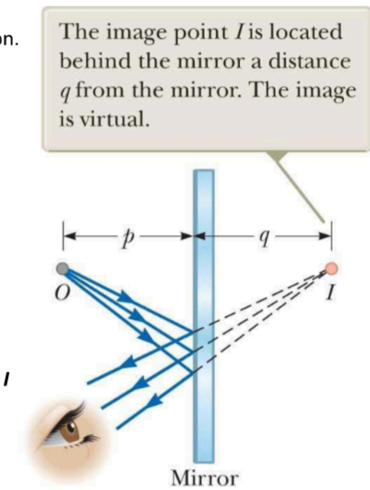
Images Formed by Flat Mirrors

- Image formation by mirrors can be understood through the concept of wave under reflection.

- Consider the simplest possible mirror – a flat mirror.
- Figure: A point light source is placed at ***O***
  - Mirror surface: dark blue edge
  - Mirror is perpendicular to screen
  - Distance ***p* = object distance**

- Diverging light rays leave the source and are reflected from the mirror (obeying the law of reflection)
  - Upon reflection→ rays continue to diverge

- Backward extensions of the diverging rays can be traced back to the point of intersection at ***I***
  - Due to the diverging, the viewer perceives the rays originate at point *I*
- Point ***I*** (at distance ***q*** behind the mirror) = **image** of the object at *O*
  - Distance ***q* = image distance**



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

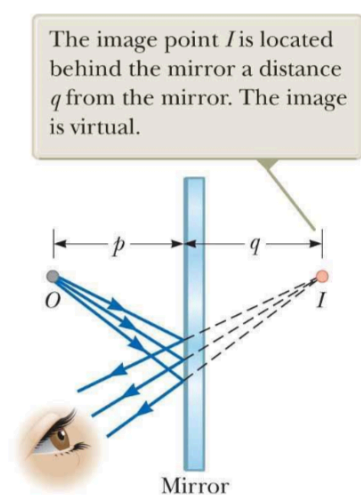
Images Formed by Flat Mirrors

- Images can be located:
  - At a point from which rays of light ***actually*** diverge
  - At a point from which they ***appear*** to diverge

- Images can be classified as **real** or **virtual**.
  - **Real image**: formed when all light rays pass through and diverge from the image point
  - **Virtual image**: formed when most (or all) light rays do *not* pass through the image point but only appear to diverge from that point

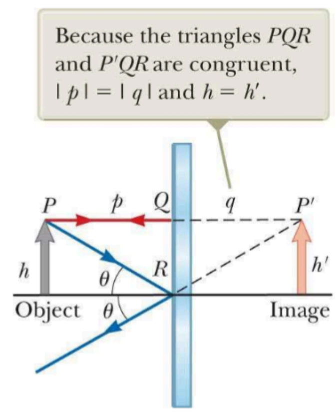
- Image formed by the mirror in the figure is **virtual:** no light rays from the object actually exist behind the mirror.
- The image of an object seen in a ***flat mirror is always virtual***

- Real images can be displayed on a screen (i.e., movie theater)
- Virtual images cannot be displayed on a screen



Images Formed by Flat Mirrors

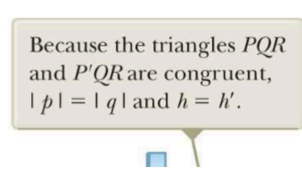
- We can use the simple geometry in the figure to examine the properties of an image formed by a flat mirror.
- Even though there are infinite number of choices of direction in which light rays could leave each point on the object (represented by a gray arrow), we need to choose only two rays to determine where an image is formed.
  - One of those rays starts at ***P***, follows a path ***perpendicular*** to the mirror to ***Q***, and ***reflects*** back on ***itself***.
  - The second ray follows the oblique path ***PR*** and reflects as shown in the figure according to the ***law of reflection***.
- An observer in front of the mirror would ***extend*** the two reflected rays back to the point at which they appear to have originated, which is point ***P'*** behind the mirror.
- We can repeat this process for points other than P and we would obtain a virtual image.
  - Triangles *PQR* and *P'QR* congruent
  - *PQ* = *P'Q*
  - $|p| = |q|$ (q negative for this type of image)
  - object height h = image height h'



Images Formed by Flat Mirrors

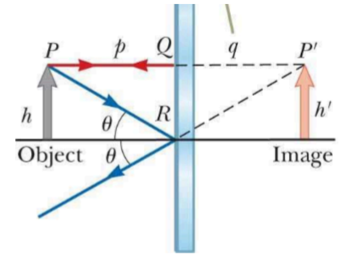
Lateral Magnification

- The object height ***h*** equals the image height ***h'*** in the figure.
- Let us define **lateral magnification** M of an image as follows:



$$M = \frac{\text{image height}}{\text{object height}} = \frac{h'}{h}$$

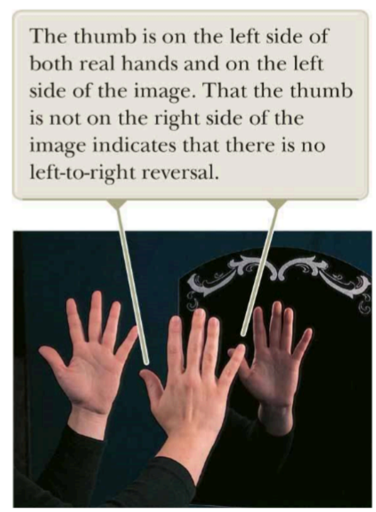
- For a flat mirror: M = +1
- Positive M means the image arrow points same way as the object arrow)



Images Formed by Flat Mirrors

Apparent Left-Right Reversal

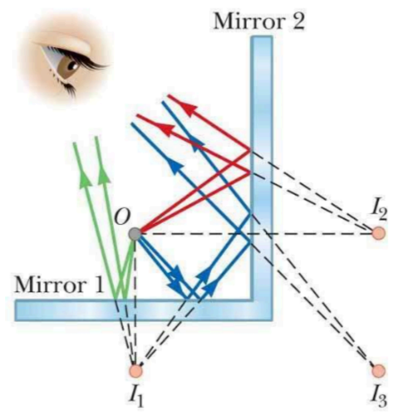
- A flat mirror produces an image that has an apparent ***left–right reversal***.
- You can see this reversal by standing in front of a mirror and raising your right hand as shown in the figure. The image you see raises its left hand. Likewise, your hair appears to be parted on the side opposite your real part.
- This reversal is ***not actually a left–right reversal***
- The reversal is actually a ***front–back reversal***, caused by the light rays going forward toward the mirror and then reflecting back from it. → Optional reading from the textbook.



Multiple Images Formed by Two Mirrors

Example 35.1

Two flat mirrors are perpendicular to each other as in the figure, and an object is placed at point ***O***. In this situation, multiple images are formed. Locate the positions of these images.

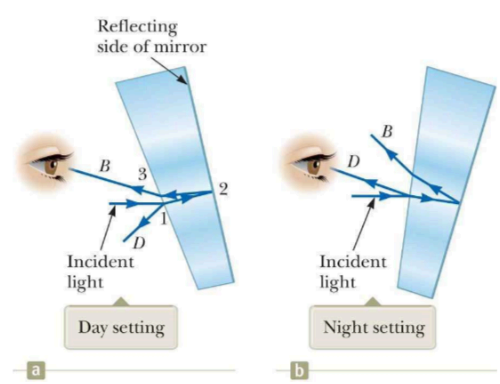


Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

The Tilting Rear View Mirror

Example 35.2

Many rear view mirrors in cars have a ***day setting*** and a ***night setting***. The night setting greatly diminishes the intensity of the image so that lights from trailing vehicles do not temporarily blind the driver. How does such a mirror work?



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

The Tilting Rear View Mirror

Example 35.2

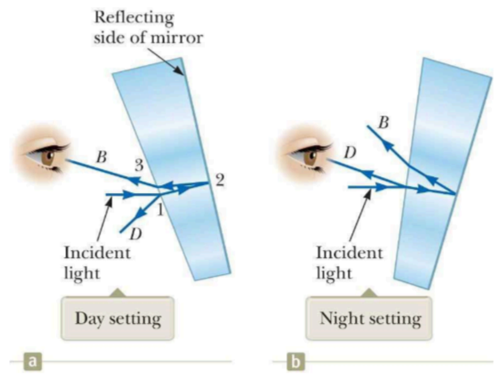
Many rear view mirrors in cars have a ***day setting*** and a ***night setting***. The night setting greatly diminishes the intensity of the image so that lights from trailing vehicles do not temporarily blind the driver. How does such a mirror work?

Solution

The mirror consists of a reflective coating on the back of a wedge of glass (tapered).

In the day setting, the light from an object behind the car strikes the glass wedge at point 1. Most of the light enters the wedge, refracting as it crosses the front surface, and reflects from the back surface at 2 to return to the front surface at 3, where it is refracted again as it re-enters the air as ray ***B (for bright).*** In addition, a small portion of the light is reflected at the front surface of the glass at 1 as indicated by ray ***D (for dim).***

This dim reflected light is responsible for the image observed when the mirror is ***in the night setting***. In that case, the wedge is rotated so that the path followed by the bright light (ray B) does not lead to the eye. Instead, the dim light reflected from the front surface of the wedge travels to the eye, and the brightness of trailing headlights does not become a hazard.



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Image Formation (Ch. 35)

Images Formed by Spherical Mirrors

Images Formed by Spherical Mirrors

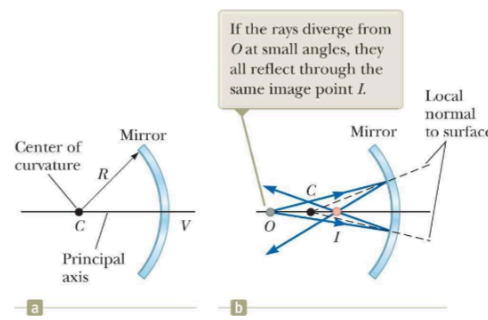
Concave Mirrors

- In this section we will study the images formed by curved mirrors. Many shapes are possible but we will restrict our study to spherical mirrors.

- Let's consider reflection of light from the ***inner, concave surface*** of a spherical mirror as shown in the figure → ***concave mirror***.

- Solid, curved dark blue line is the reflecting surface of the concave mirror
  - Mirror ***radius of curvature***: ***R***
  - ***Center of curvature***: point ***C***
  - Point ***V***: ***center of spherical section***
  - Line through *C* and *V*: **principal axis** of the mirror

- A point source of light is placed at point ***O***
- Obeying law of reflection:
  - Reflected rays from ***O*** converge and cross at point ***I***
  - Then continue to diverge from *I* as if object were there.
- Observer to the left of ***O*** would see light rays diverging from ***I***
  - ***Image at point I: real***

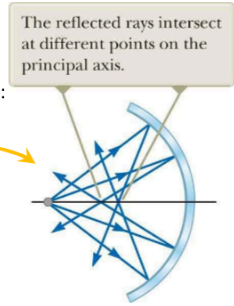


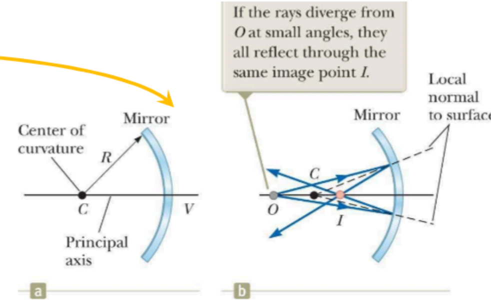
 Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Spherical Mirrors

Concave Mirrors

- In this section, we will consider only rays that diverge from the object and make a ***small angle with the principal axis***. Such rays are called ***paraxial rays***.
  - All paraxial rays reflect through the image point
- Rays that are far from the principal axis converge to other points on the principal axis:
  - Producing blurred images (***spherical aberration***)
  - To some extent, this is present in all spherical mirrors



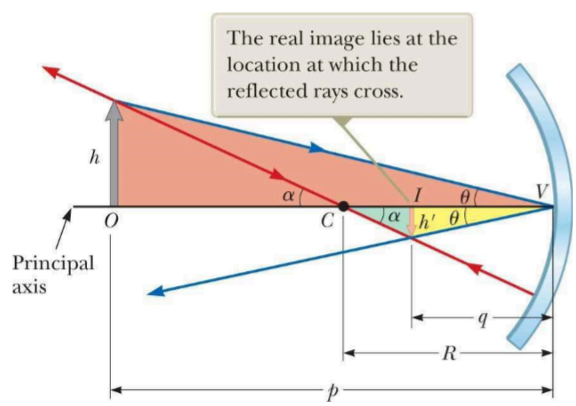


Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Spherical Mirrors

Concave Mirrors

- If the object distance '***p***' and the radius of curvature '***R***' are known, we can use the figure on the right to calculate the image distance '***q***'.
  - By convention, these distances are measured from point ***V***.
- Let's focus on two rays leaving the tip of the object (red and blue rays).
  - The red ray passes through the center of curvature C of the mirror, hitting the mirror perpendicular to the mirror surface and reflecting back on itself.
  - The blue ray strikes the mirror at its center (point V) and reflects as shown, obeying the law of reflection.
- The image of the tip of the arrow is located at the point where these two rays intersect.



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Spherical Mirrors

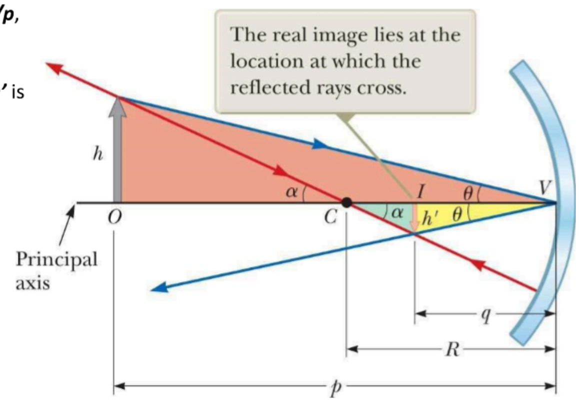
Concave Mirrors

- From the large, red right triangle in the figure, we see that ***tanθ=h/p***,
- and from the yellow right triangle, we see that ***tanθ=-h'/q***.
- The negative sign is introduced because the ***image is inverted***, so ***h'*** is taken to be negative.
- Therefore, the magnification of the image is:

$$M = \frac{h'}{h} = -\frac{q}{p}$$

- From the green right triangle and the small red triangle:

$$\tan\alpha = \frac{-h'}{R-q} \qquad \tan\alpha = \frac{h}{p-R}$$



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Spherical Mirrors

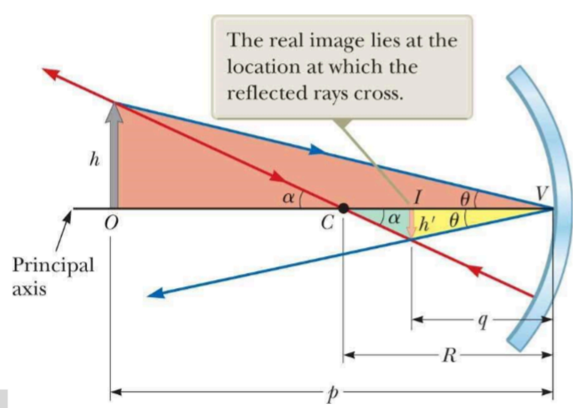
Concave Mirrors

$$M = \frac{h'}{h} = -\frac{q}{p} \qquad \tan\alpha = \frac{-h'}{R-q} \qquad \tan\alpha = \frac{h}{p-R}$$

$$\frac{h'}{h} = -\frac{R-q}{p-R}$$

$$\frac{R-q}{p-R} = \frac{q}{p} \rightarrow \frac{1}{p} + \frac{1}{q} = \frac{2}{R}$$

Mirror Equation



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Spherical Mirrors

Concave Mirrors → Focal Point & Focal Length

$$\frac{1}{p} + \frac{1}{q} = \frac{2}{R}$$ Mirror Equation

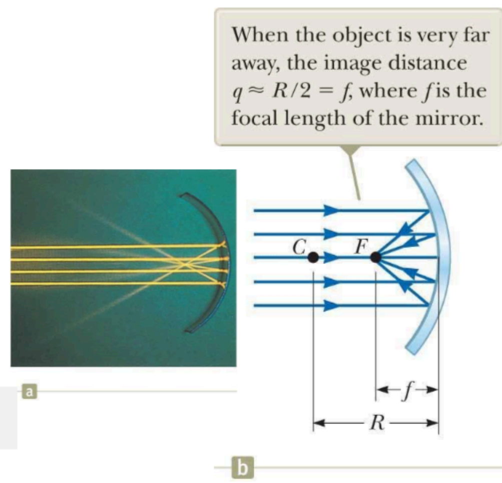
If the object is very far from the mirror (p>>R), if ***p*** can be said to approach infinity; then 1/p approaches 0 (***1/p→0***).

Then the equation reduces to ***q~=R/2***

When the object is very far from the mirror, the image point is halfway between the center of curvature and the center point on the mirror as shown in the figure.

The incoming rays from the object are essentially parallel in this figure because the source is assumed to be very far from the mirror.

$$f = \frac{R}{2}$$ The image point in this special case is called the **focal point *F***, and the image distance is called the **focal length *f***.



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Spherical Mirrors

Concave Mirrors → Focal Point & Focal Length

A satellite-dish antenna is a concave reflector for communication signals from a satellite in orbit around the Earth.

Because the satellite is so far away, the signals are carried by microwaves that are parallel

when they arrive at the dish.

These waves reflect from the dish and are focused on the receiver.

Images Formed by Spherical Mirrors

Concave Mirrors → Focal Point & Focal Length

- Combining the previous equations, we can express the **mirror equation** in terms of the focal length:

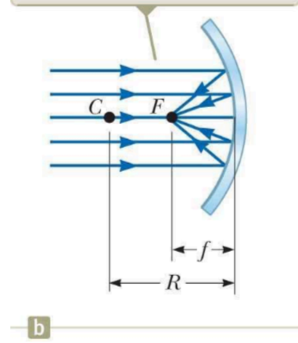
$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

- Note: focal length of the mirror depends only on the curvature of the mirror
  - Not on the material from which the mirror is made
  - Formation of the image results from rays reflected from the surface of the material

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

- The situation is different for lenses →
  - Light actually passes through the material
  - Focal length depends on the type of material from which lens is made

When the object is very far away, the image distance $q \approx R/2 = f$, where f is the focal length of the mirror.

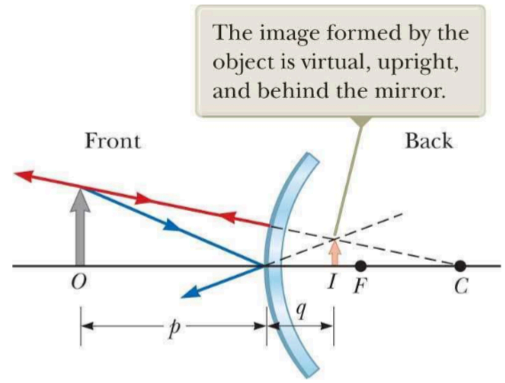


Images Formed by Spherical Mirrors

Images Formed by Spherical Mirrors

Convex Mirrors

- The figure on the right shows formation of an image by a ***convex mirror*** (silvered so that the light is reflected from the outer, convex surface)
  - Sometimes called the ***diverging mirror***:
    - Rays from any point on the object diverge after reflection as though they were coming from some point behind the mirror
- Image:
  - ***Virtual*** because the reflected rays only appear to originate at an image point as indicated by dashed lines
  - Always **upright** and **smaller** than the object
- Previous concave mirror equation can be used for either concave or convex mirrors if we adhere to a strict sign convention.
- The region in which light rays originate and move toward the mirror is the ***front side*** of the mirror.
- The other side is the ***back side***.



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Spherical Mirrors

Convex Mirrors: large field of view

Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Spherical Mirrors

Convex Mirrors

- The region in which light rays originate and move toward the mirror is the ***front side*** of the mirror.
- The other side is the ***back side***.
- Figure shows the ***sign conventions*** for the object and the image distances for any type of mirrors
- The table summarizes the ***sign conventions for all quantities***
- Note: virtual object will be discussed later

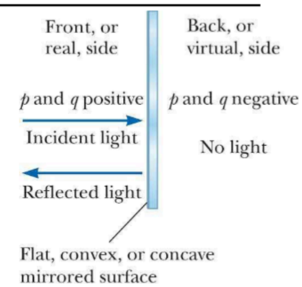


TABLE 35.1 Sign Conventions for Mirrors

Quantity	Positive When . . .	Negative When . . .
Object location (p)	object is in front of mirror (real object).	object is in back of mirror (virtual object).
Image location (q)	image is in front of mirror (real image).	image is in back of mirror (virtual image).
Image height (h')	image is upright.	image is inverted.
Focal length (f) and radius (R)	mirror is concave.	mirror is convex.
Magnification (M)	image is upright.	image is inverted.

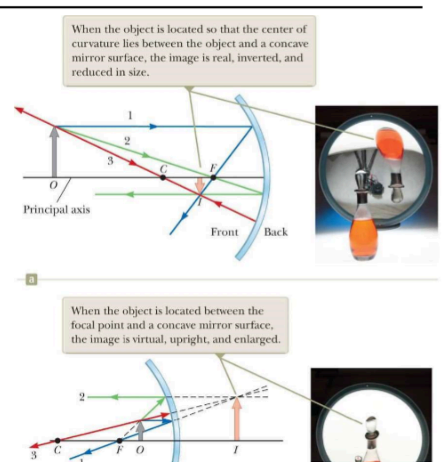
Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Spherical Mirrors

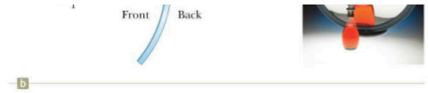
Ray Diagrams for Concave Mirrors

- The positions and sizes of images formed by mirrors can be conveniently determined with ray diagrams.
- ***Ray diagrams***: accurate but do not require a protractor.
  - Pictorial representations that reveal the nature of the image
  - Can be used to check results calculated from the mathematical representation using the mirror and magnification equations
  - To draw a ray diagram, we must know
    - the position of the object and
    - location of the mirror's focal point
    - location of the mirror's center of curvature

- Ray 1 is drawn from the top of the object parallel to the principal axis and is reflected through the focal point F.
- Ray 2 is drawn from the top of the object through the focal point (or as if coming from the focal point if $p < f$) and is reflected parallel to the principal axis.



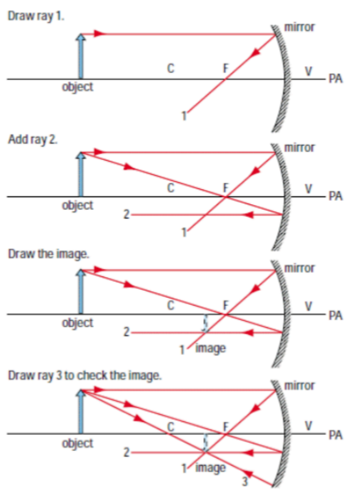
par axis.
- Ray 3 is drawn from the top of the object through the center of curvature C (or as if coming from the center C if $p < 2f$) and is reflected back on itself.



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Spherical Mirrors

Ray Diagrams for Concave Mirrors



a) Converging spherical mirror

http://myphysicswebschool.blogspot.com/2011_07_17_archive.html

Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Spherical Mirrors

Ray Diagrams for Concave Mirrors

- Intersection of any two rays locates the image
  - Third ray serves as check of construction
  - Image point must always agree with the value of ***q*** calculated from the mirror equatior

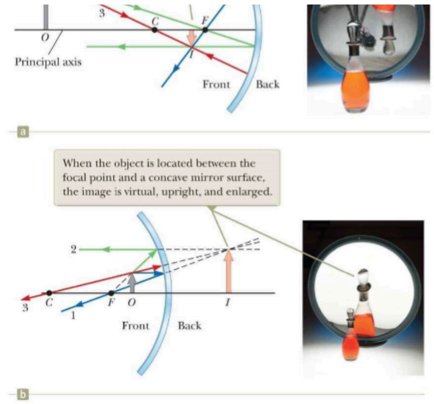
When the object is located so that the center of curvature lies between the object and a concave mirror surface, the image is real, inverted, and reduced in size.

- As the object is moved closer to the mirror → the real, inverted image moves to the left and becomes larger as the object approaches the focal point.
- When object at C (distance p = 2f from mirror)
  - q = 2f:
  - Image located at location of object
  - Magnification = –1
- As object continues to move from center of curvature toward the focal point:
  - Image grows larger (|M| > 1)
  - Moves to the left
- When object at focal point:
  - Image infinitely far to the left
- When object lies between focal point and mirror surface :
  - Image to the right, behind the mirror, virtual, upright, and enlarged

$$M = \frac{h'}{h} = -\frac{q}{p}$$

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

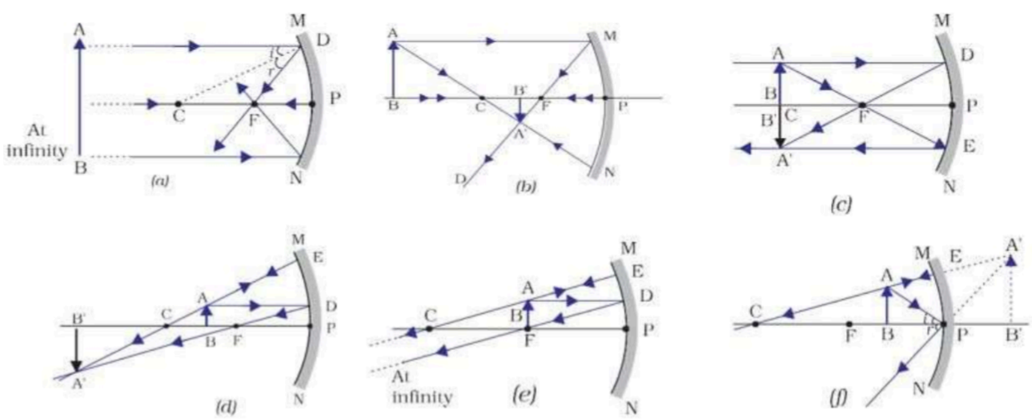
$$f = \frac{R}{2}$$



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Spherical Mirrors

Ray Diagrams for Concave Mirrors



$$M = \frac{h'}{h} = -\frac{q}{p}$$

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

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

https://www.logicalclass.com/contant/view/688

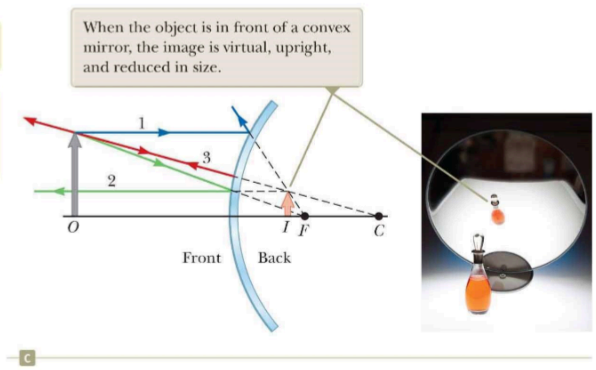
Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Spherical Mirrors

Ray Diagrams for Convex Mirrors

- Ray 1 is drawn from the top of the object parallel to the principal axis and is reflected *away from* the focal point *F*.

- Ray 2 is drawn from the top of the object toward the focal point on the back side of the mirror and is reflected parallel to the principal axis.
- Ray 3 is drawn from the top of the object toward the center of curvature *C* on the back side of the mirror and is reflected back on itself.



- In convex mirrors, image is always:
  - Virtual
  - Upright
  - Reduced in size

- As object distance decreases:
  - Virtual image increases in size
  - Virtual image moves away from the focal point and approaches the mirror

Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Spherical Mirrors

Ray Diagrams for Convex Mirrors

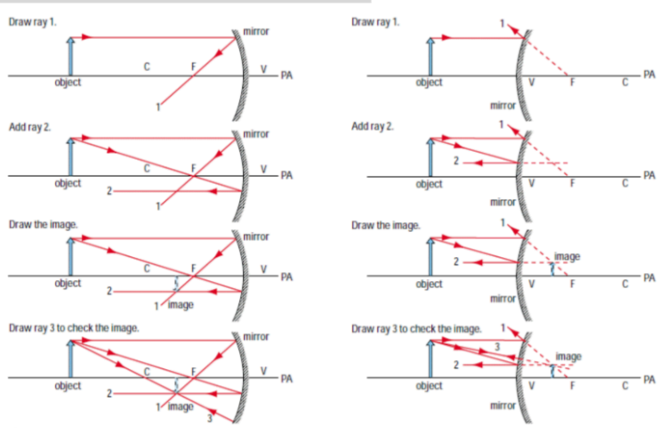


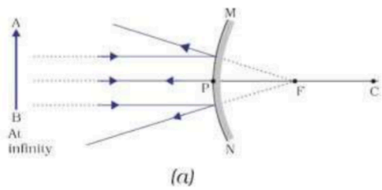
Figure One The steps in drawing ray diagrams to determine the location and characteristics of images formed by spherical mirrors

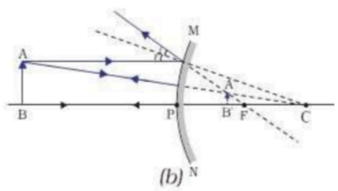
http://myphysicswebschool.blogspot.com/2011_07_17_archive.html

Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Spherical Mirrors

Ray Diagrams for Convex Mirrors





$$M = \frac{h'}{h} = -\frac{q}{p}$$

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

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

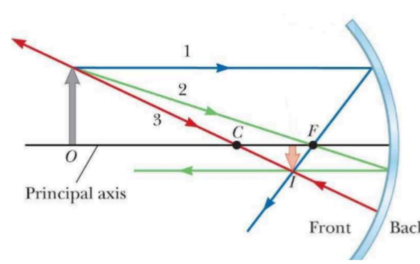
https://www.logicalclass.com/contant/view/688

Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

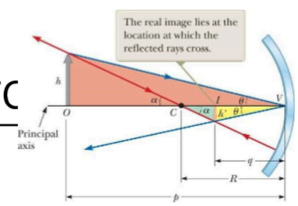
The Image Formed by a Concave Mirror

Example 35.3

A spherical mirror has a focal length of **F=10.0cm**.
(A) Locate and describe the image for an object distance of **O=25.0cm**.
(B) Locate and describe the image for an object distance of **O=5.00cm**.



The Image Formed by a Concave Mirrc



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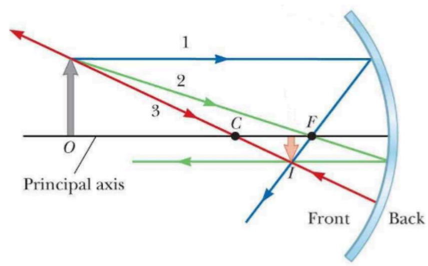
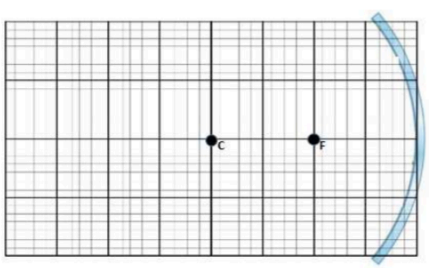
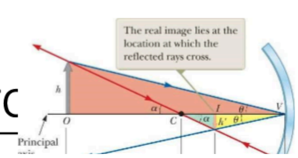


Solution

(A) O=25cm
Let's solve with ray diagrams first:



The Image Formed by a Concave Mirrc



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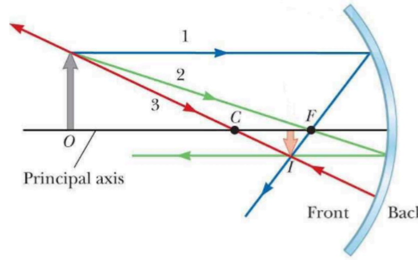
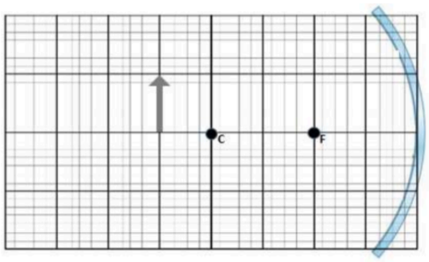


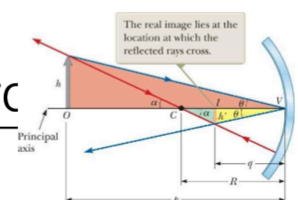
Solution

(A) O=25cm
Let's solve with ray diagrams first:



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

The Image Formed by a Concave Mirrc



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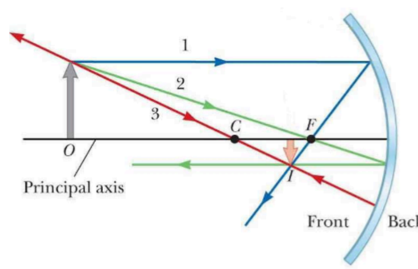
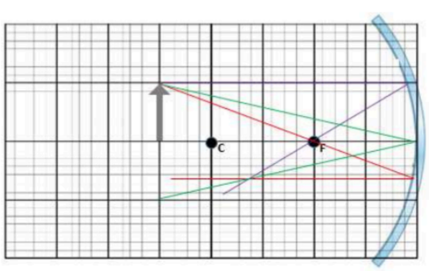


Solution

(A) O=25cm
Let's solve with ray diagrams first:



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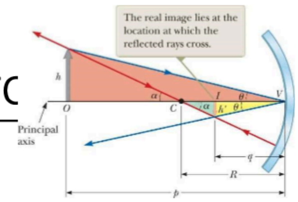
The Image Formed by a Concave Mirrc



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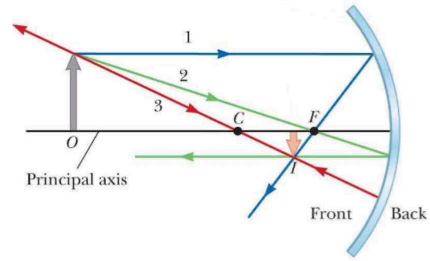

Solution

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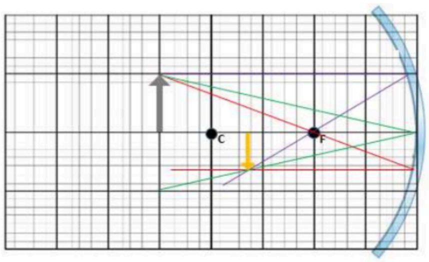
Let's solve with ray diagrams first:



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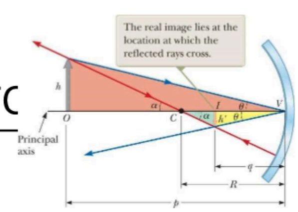

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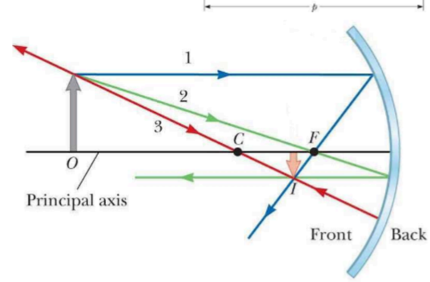
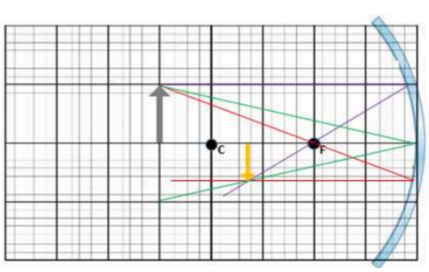


Solution

(A) O=25cm
Now let's solve with equations:



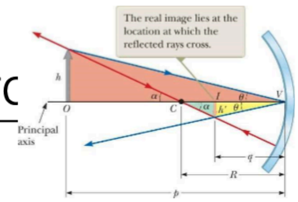
$$\frac{1}{q}=\frac{1}{f}-\frac{1}{p}\Rightarrow q=\frac{fp}{p-f}$$

$$q=\frac{(10.0\text{ cm})(25.0\text{ cm})}{25.0\text{ cm}-10.0\text{ cm}}$$

$$=\boxed{16.7\text{ cm}}$$

$$M=-\frac{q}{p}=-\frac{16.7\text{ cm}}{25.0\text{ cm}}=\boxed{-0.667}$$

The Image Formed by a Concave Mirro



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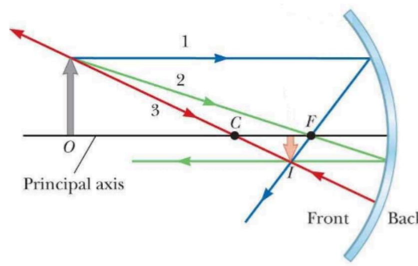
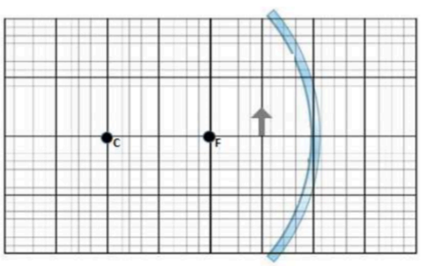


Solution

(B) O=5cm



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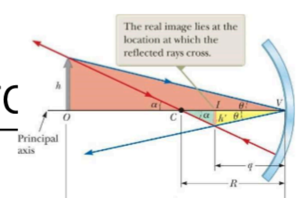

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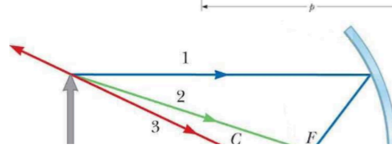

Solution

(B) O=5cm

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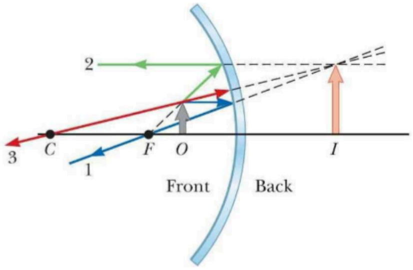
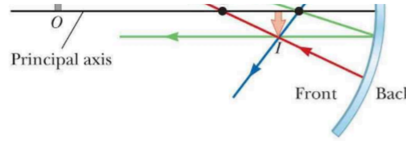


$$q = \frac{fp}{p - f}$$

$$q = \frac{(10.0\text{ cm})(5.0\text{ cm})}{5.0\text{ cm} - 10.0\text{ cm}}$$

$$= \boxed{-10.0\text{ cm}}$$

$$M = -\frac{q}{p} = -\left(\frac{-10.0\text{ cm}}{5.00\text{ cm}}\right) = \boxed{+2.00}$$



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

The Image Formed by a Convex Mirror

Example 35.4

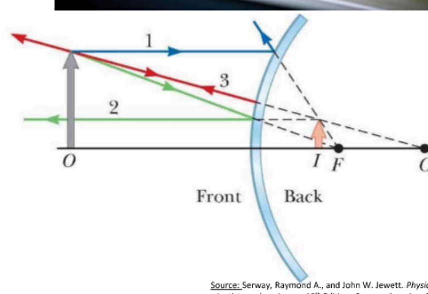
An automobile sideview mirror on the passenger side as shown in the photo shows an image of a truck located **50.0m** from the mirror. The focal length of the mirror is **f=-0.60m**.

(A) Find the position of the image of the truck.

(B) Find the magnification of the image.

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

$$M = \frac{h'}{h} = -\frac{q}{p}$$



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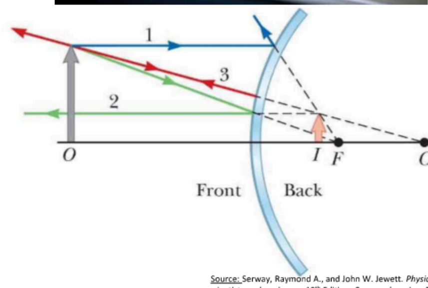
$$\frac{1}{p}+\frac{1}{q}=\frac{1}{f}$$

$$M=\frac{h'}{h}=-\frac{q}{p}$$

Solution

For part A

$$q=\frac{fp}{p-f}=\frac{(-0.60\text{ m})(50.0\text{ m})}{50.0\text{ m}-(-0.60\text{ m})}=\boxed{-0.59\text{ m}}$$



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(B) Find the magnification of the image.

$$\frac{1}{p}+\frac{1}{q}=\frac{1}{f}$$

$$M=\frac{h'}{h}=-\frac{q}{p}$$

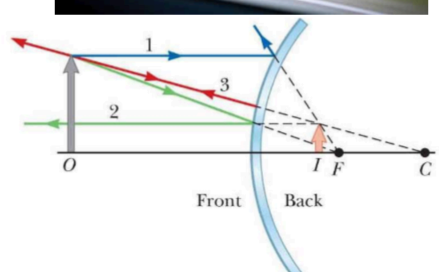
Solution

For part A

$$q=\frac{fp}{p-f}=\frac{(-0.60\text{ m})(50.0\text{ m})}{50.0\text{ m}-(-0.60\text{ m})}=\boxed{-0.59\text{ m}}$$

For part B

$$M=-\frac{q}{p}=-\left(\frac{-0.59\text{ m}}{50.0\text{ m}}\right)=\boxed{+0.012}$$



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Image Formation (Ch. 35)

Images Formed by Refraction [Optional study – reading from textbook]

Image Formation (Ch. 35)

Images Formed by Thin Lenses

- p1 = object distance to surface 1
- q1: = image distance to surface 1 ([-] for virtual; [+] for real)
- p2 = object distance to surface 2
- q2: = image distance to surface 2 ([-] for virtual; [+] for real)

Images Formed by Thin Lenses

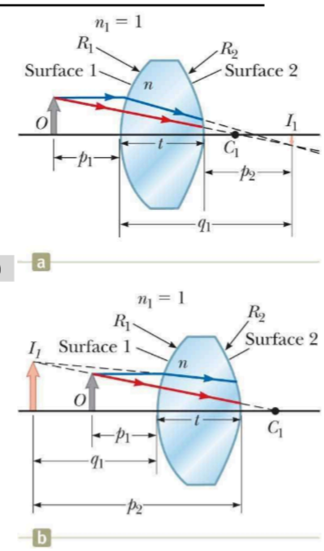
- Lenses are commonly used to form images by refraction in optical instruments (i.e, cameras, telescopes, and microscopes)
- Light passing through a lens experiences refraction at two surfaces:
  - The image formed by one refracting surface serves as the object for the second surface.
- Illustration: **Real** (a) and **virtual** (b) images formed by the first surface
- Object-Image equations for surface 1 and surface 2:

$$\frac{1}{p_1}+\frac{n}{q_1}=\frac{n-1}{R_1} \qquad \frac{n}{p_2}+\frac{1}{q_2}=\frac{1-n}{R_2}$$

Please refer to the textbook for derivation (35.3)

$$\frac{n_1}{p}+\frac{n_2}{q}=\frac{n_2-n_1}{R}$$

- Derivation steps skipped – please refer to the textbook.



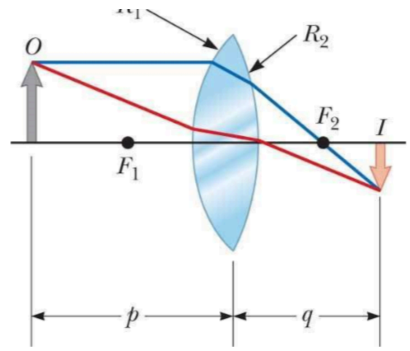
Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Thin Lenses

- [Derivation steps skipped – please refer to the textbook].
- For a thin lens (where thickness is small compared to the radii of curvature), the equations can be re-organized as:

$$\frac{1}{p}+\frac{1}{q}=(n-1)\left(\frac{1}{R_1}-\frac{1}{R_2}\right)$$

- Equation is valid with the following assumptions:
  - p = position of the object
  - q = position of the final image
  - For paraxial rays
  - When lens thickness t << R1 and R2



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Thin Lenses

- The focal length ***f*** of a thin lens is the image distance that corresponds to an infinite object distance, just as with mirrors.

$$\frac{1}{p}+\frac{1}{q}=(n-1)\left(\frac{1}{R_1}-\frac{1}{R_2}\right)$$

Letting ***p*** approach **∞** and **q** approach ***f***, we see that the inverse of the focal length for a thin lens is

$$\frac{1}{f}=(n-1)\left(\frac{1}{R_1}-\frac{1}{R_2}\right)$$

Lens makers' equation

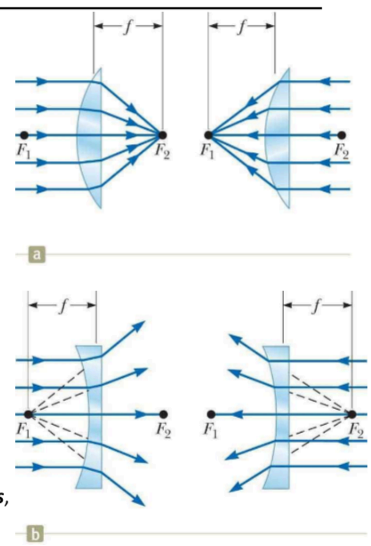
- Can be used to determine values of R1 and R2 needed for a given index of refraction and desired focal length f
- If index of refraction and radii of the curvature of the lens is known → Equation can be used to find focal length

$$\frac{1}{p}+\frac{1}{q}=\frac{1}{f}$$

Thin lens equation

- Used to relate image distance and object distance with the focal length for a thin lens.

- Because light can travel in either direction through a lens, ***each lens has two focal points***, for light rays passing through in either direction.



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Images Formed by Thin Lenses

Sign Conventions for Thin Lenses

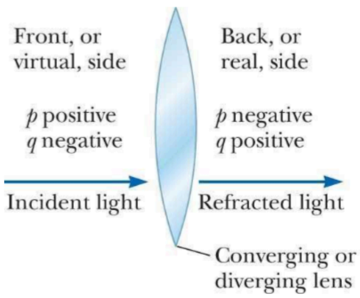


TABLE 35.3 Sign Conventions for Thin Lenses

Quantity	Positive When . . .	Negative When . . .
Object location (p)	object is in front of lens (real object).	object is in back of lens (virtual object).
Image location (q)	image is in back of lens (real image).	image is in front of lens (virtual image).
Image height (h')	image is upright.	image is inverted.
R_1 and R_2	center of curvature is in back of lens.	center of curvature is in front of lens.
Focal length (f)	a converging lens.	a diverging lens.

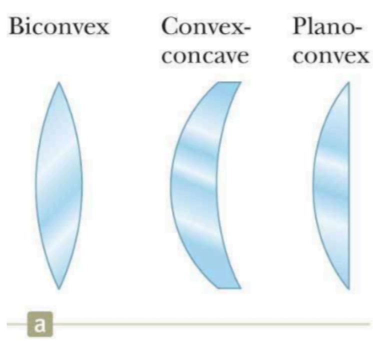
Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

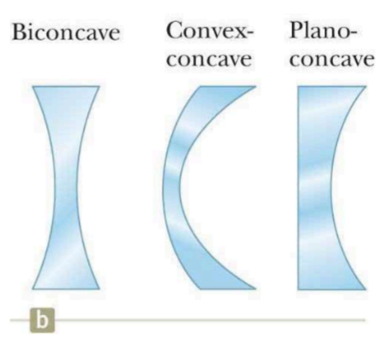
Images Formed by Thin Lenses

Converging and Diverging Lens Shapes

Various lens shapes:

- Converging lens is thicker at the center than at the edge
- Diverging lens is thinner at the center than at the edge





Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Images Formed by Thin Lenses

Magnification of Images

- Consider a thin lens through which light rays from an object pass.
- As with mirrors, a geometric construction shows that the lateral magnification of the image is:

$$M = \frac{h'}{h} = -\frac{q}{p}$$

- From this expression, it follows that when M is positive, the image is upright and on the same side of the lens as the object.
- When M is negative, the image is inverted and on the side of the lens opposite the object.

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Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

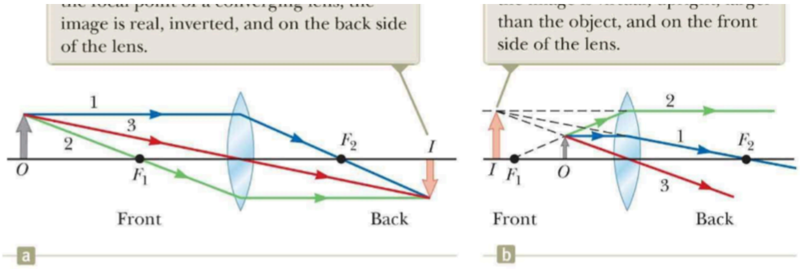
Images Formed by Thin Lenses

Ray Diagrams: Converging Lens

- Ray 1 is drawn parallel to the principal axis. After being refracted by the lens, this ray passes through the focal point on the back side of the lens.
- Ray 2 is drawn through the focal point on the front side of the lens (or as if coming from the focal point if $p < f$) and emerges from the lens parallel to the principal axis.
- Ray 3 is drawn through the center of the lens and continues in a straight line.

When the object is in front of and outside the focal point of a converging lens, the

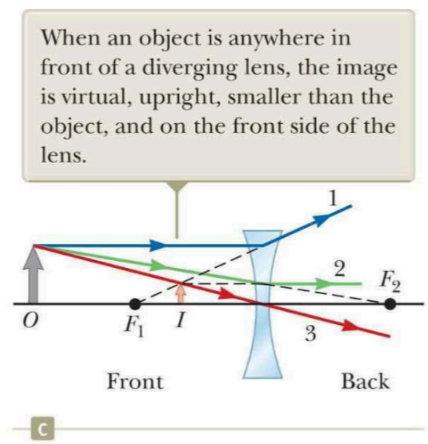
When the object is between the focal point and a converging lens, the image is virtual, upright, larger



Images Formed by Thin Lenses

Ray Diagrams: Diverging Lens

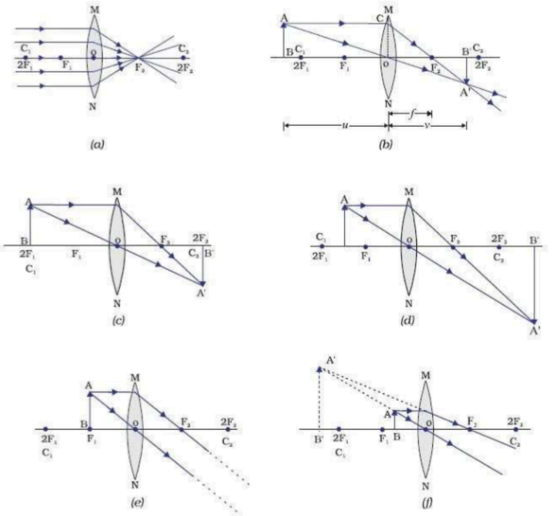
- Ray 1 is drawn parallel to the principal axis. After being refracted by the lens, this ray emerges directed away from the focal point on the front side of the lens.
- Ray 2 is drawn in the direction toward the focal point on the back side of the lens and emerges from the lens parallel to the principal axis.
- Ray 3 is drawn through the center of the lens and continues in a straight line.



Images Formed by Thin Lenses

Images Formed by Thin Lenses

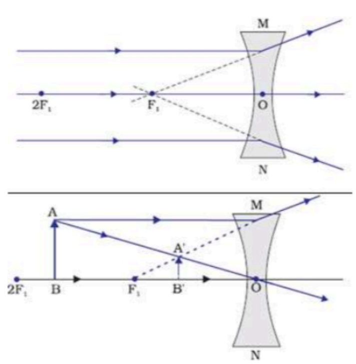
Ray Diagrams for a Converging Lens



- Converging lens: object to the left of the focal point (p > f) →
  - Image real and inverted
  - Lens acts like video projector
- Converging lens: object between the focal point and the lens (p < f) →
  - Image virtual and upright
  - Lens acts as a magnifying glass

Images Formed by Thin Lenses

Ray Diagrams for a Diverging Lens



- Diverging lens:
  - Image always virtual and upright regardless of where the object is placed

Images Formed by a Converging Lens

- q: [-] for virtual; [+] for real
- M: [-] for inverted; [+] upright

Example 35.8

$$M = \frac{h'}{h} = -\frac{q}{p} \qquad \frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

A converging lens has a focal length of 10.0 cm.

(A) An object is placed 30.0 cm from the lens. Construct a ray diagram, find the image distance, and describe the image.

(B) An object is placed 5.00 cm from the lens. Construct a ray diagram, find the image distance, and describe the image.

Images Formed by a Converging Lens

- q: [-] for virtual; [+] for real
- M: [-] for inverted; [+] upright

Example 35.8

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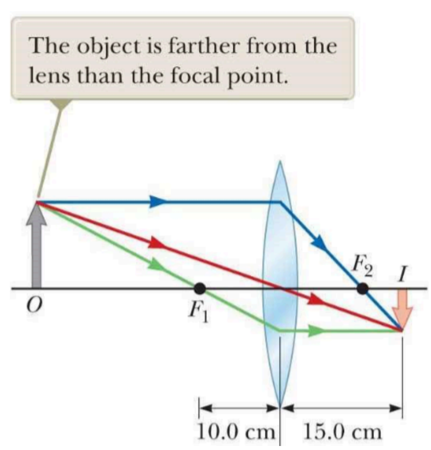


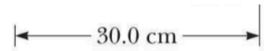
Solution

For part A

$$q = \frac{fp}{p-f} = \frac{(10.0 \text{ cm})(30.0 \text{ cm})}{30.0 \text{ cm} - 10.0 \text{ cm}}$$

$$= \boxed{+15.0 \text{ cm}}$$

$$M = -\frac{q}{p} = -\frac{\quad}{30.0\text{ cm}} = \boxed{-0.500}$$



Images Formed by a Converging Lens

- q: [-] for virtual; [+] for real
- M: [-] for inverted; [+] upright

Example 35.8

$M = \frac{h'}{h} = -\frac{q}{p}$ $\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$

A converging lens has a focal length of 10.0 cm.

(A) An object is placed 30.0 cm from the lens. Construct a ray diagram, find the image distance, and describe the image.

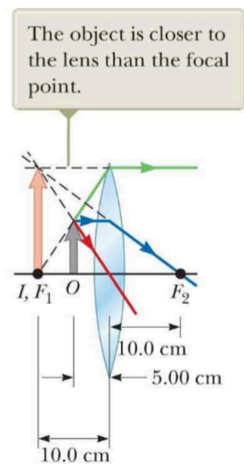
(B) An object is placed 5.00 cm from the lens. Construct a ray diagram, find the image distance, and describe the image.

Solution

For part B

$$q = \frac{fp}{p-f} = \frac{(10.0\text{ cm})(5.00\text{ cm})}{5.00\text{ cm} - 10.0\text{ cm}} = \boxed{-10.0\text{ cm}}$$

$$M = -\frac{q}{p} = -\left(\frac{-10.0\text{ cm}}{5.00\text{ cm}}\right) = \boxed{+2.00}$$



Images Formed by a Converging Lens

- q: [-] for virtual; [+] for real
- M: [-] for inverted; [+] upright

Example 35.9

$M = \frac{h'}{h} = -\frac{q}{p}$ $\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$

A diverging lens has a focal length of 10.0 cm.

(A) An object is placed 15.0 cm from the lens. Construct a ray diagram, find the image distance, and describe the image.

(B) An object is placed 5.00 cm from the lens. Construct a ray diagram, find the image distance, and describe the image.

Images Formed by a Converging Lens

- q: [-] for virtual; [+] for real
- M: [-] for inverted; [+] for upright

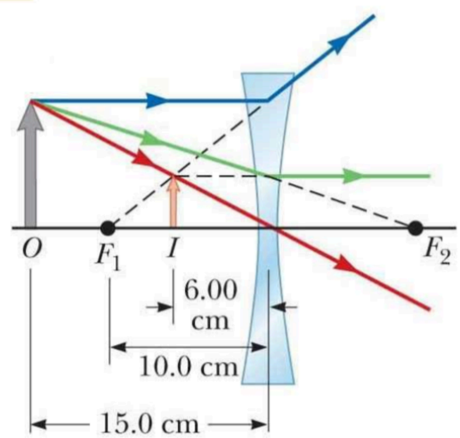
Example 35.9

$M = \frac{h'}{h} = -\frac{q}{p}$ $\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$

A diverging lens has a focal length of 10.0 cm.

(A) An object is placed 15.0 cm from the lens. Construct a ray diagram, find the image distance, and describe the image.

(B) An object is placed 5.00 cm from the lens. Construct a ray diagram, find the image distance, and describe the image.



Solution

For part A

$$q = \frac{fp}{p-f} = \frac{(-10.0\text{ cm})(15.0\text{ cm})}{15.0\text{ cm} - 10.0\text{ cm}} = \boxed{-6.00\text{ cm}}$$

$$M = -\frac{q}{p} = -\left(\frac{-6.00\text{ cm}}{15.0\text{ cm}}\right) = \boxed{+0.400}$$

Images Formed by a Converging Lens

- q: [-] for virtual; [+] for real
- M: [-] for inverted; [+] upright

Example 35.9

$M = \frac{h'}{h} = -\frac{q}{p}$ $\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$

A diverging lens has a focal length of 10.0 cm.

(A) An object is placed 15.0 cm from the lens. Construct a ray diagram, find the image distance, and describe the image.

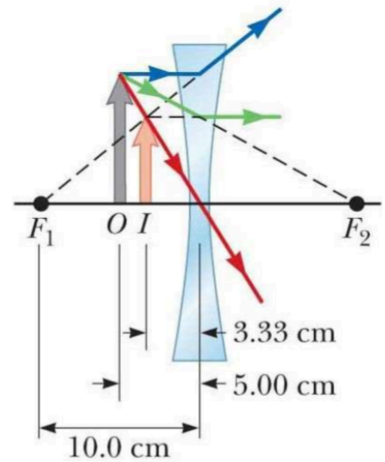
(B) An object is placed 5.00 cm from the lens. Construct a ray diagram, find the image distance, and describe the image.

Solution

For part B

$$q = \frac{fp}{p-f} = \frac{(-10.0\text{ cm})(5.00\text{ cm})}{5.00\text{ cm} - (-10.0\text{ cm})} = \boxed{-3.33\text{ cm}}$$

$$M = -\frac{q}{p} = -\left(\frac{-3.33\text{ cm}}{5.00\text{ cm}}\right) = \boxed{+0.667}$$

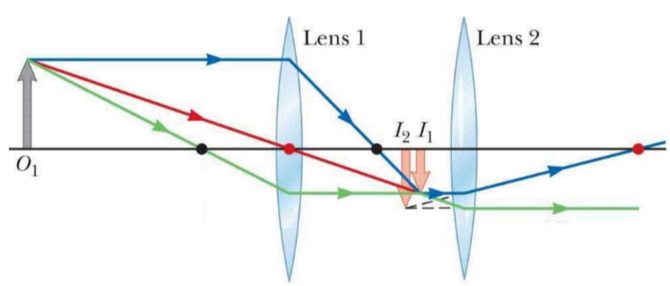


Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Combination of Thin Lenses

- If two thin lenses are used to form an image:
  - First, the image formed by the first lens is located as if the second lens were not present.
  - Then a ray diagram is drawn for the second lens, with the images formed by the first lens now serving as the object for the second lens.
  - The second image formed is the final image of the system.
  - If the image formed by the first lens lies on the back side of the second lens, that image is treated as a virtual object for the second lens (that is, in the thin lens equation, p is negative).

- Same procedure extends to a system of three or more lenses.
- Overall magnification of the image due to combination of lenses = product of individual magnifications:
  - $M = M_1 \times M_2$
- For more than two optical elements:
  - Magnifications due to all elements multiplied together



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Image Formation (Ch. 35)

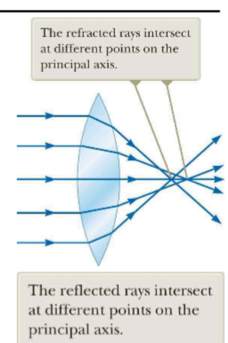
Lens Aberrations

Lens Aberrations (Deviations)

- Our analysis of mirrors and lenses:
  - Assumes rays make small angles with principal axis (paraxial) and
  - Lenses are thin
- In our analysis models: all rays leave a point source and focus at a single point
  - Producing sharp image
- These assumptions are **not always valid**.

- ***Spherical aberration*** occurs because the focal points of rays far from the principal axis of a spherical lens (or mirror) are different from the focal points of rays of the same wavelength passing near the axis.

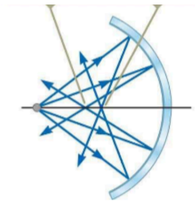
- Figure on the right (top) illustrates spherical aberration for parallel rays passing through a



converging lens.

- Rays passing through points near the center of the lens are imaged farther from the lens than rays passing through points near the edges.

- Figure on the right (bottom) illustrates spherical aberration for light rays leaving the point object and striking a spherical mirror.



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Lens Aberrations (Deviations)

Cameras and Adjustable Apertures

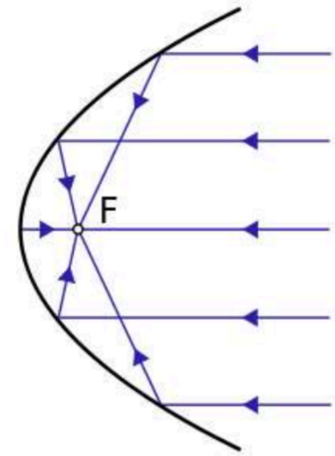
- Many cameras have an adjustable aperture to control light intensity and reduce spherical aberration
  - ***Aperture***: the adjustable opening that controls the amount of light passing through a lens.
- Sharper images are produced as the aperture size is reduced
  - With a smaller aperture, only the central portion
  - Greater percentage of paraxial rays, sharper imag
- However, less light passes through the lens
  - To compensate → longer exposure time is u

Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.
https://photographycourse.net/types-of-camera-lenses/

Lens Aberrations (Deviations)

Parabolic Reflecting Surface

- Mirrors: spherical aberration is minimized by using a parabolic reflecting surface
  - Parabolic mirrors with high-quality optics are very expensive to make
- Parallel light rays incident on a parabolic surface focus at a common point (figure)
  - Regardless of the distance from the principal axis.
- Parabolic reflecting surfaces used in many astronomical telescopes to enhance image quality

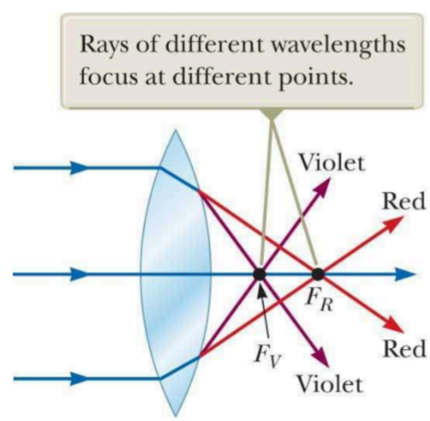


Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Lens Aberrations (Deviations)

Chromatic Aberration

- Recall ***dispersion***: material's index of refraction varies with wavelength
  - Example: violet rays refracted more than red rays when white light passes through a lens
- Figure: the focal length of a lens is greater for red light than for violet light
- Other wavelengths: focal points intermediate between red and violet
  - Causes a blurred image (**chromatic aberration**)
- Chromatic aberration is greatly reduced by:
  - Combining a converging lens made of one type of glass and a diverging lens made of another type of glass



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

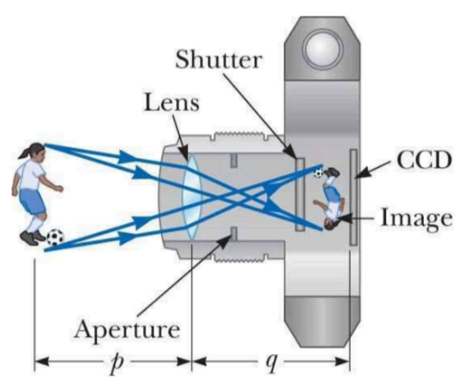
Image Formation (Ch. 35)

Optical Instruments

Optical Instruments

The Camera

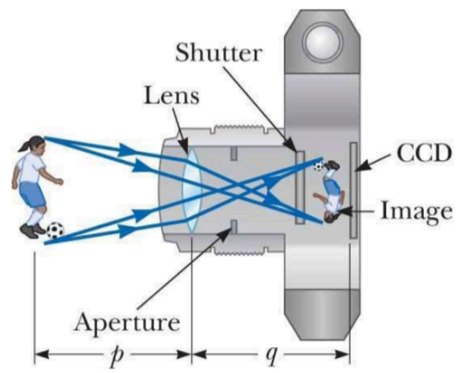
- **Camera** consists of:
  - Light-tight chamber
  - A converging lens that produces real images
  - Light-sensitive component is behind the lens where images are formed
- Images in a digital camera are formed on ***charge-coupled devices*** (CCDs)
  - Digitizes image → Turning it into binary code
- Digital information stored on memory chip for playback on camera's display screen
  - Can be downloaded to a computer
- Film cameras are similar to the digital cameras except that light forms images on a light-sensitive film rather than on a CCD
- Film must then be chemically processed to produce images on the paper



Optical Instruments

The Camera

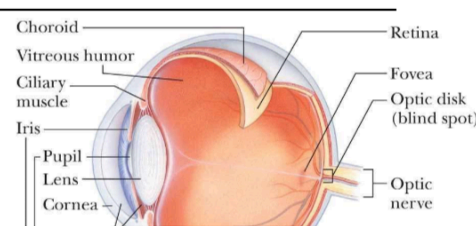
- For digital cameras:
  - Camera focuses by varying the distance between the lens and CCD
  - A proper focusing is necessary to form sharp images
  - Best lens-to-CCD distance depends on:
    - Object distance
    - Focal length of the lens
- Shutter (behind the lens): a mechanical device opened for selected time intervals → ***exposure times***
  - Photograph moving objects by using short exposure times
  - Photograph dark scenes (with low light levels) by using long exposure times
- Typical shutter speeds (exposure times): 1/30 s, 1/60 s, 1/125 s, and 1/250 s
- In practice, stationary objects are normally shot with an intermediate shutter speed of 1/60 s



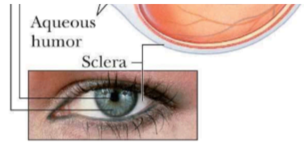
Optical Instruments

The Eye

- The eye focuses light and produces sharp images
  - Far more complex, intricate, and effective than a camera
- Light entering the eye first passes through the transparent ***cornea***
  - Behind cornea:
    - Clear liquid (***aqueous humor***)



- Variable aperture (*pupil* → opening in *iris*)
- ***Crystalline lens***

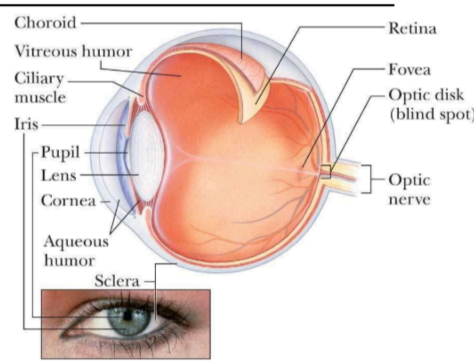


- Most of the refraction occurs at the outer surface of the eye:
  - Where cornea is covered with a ***film of tears***
- Relatively little refraction occurs in the crystalline lens
  - Aqueous humor is in contact with the lens, and has an average index of refraction close to that of the lens
- ***Iris*** (colored portion of the eye) → is a muscular diaphragm that controls the pupil size
- The Iris regulates the amount of light entering the eye by:
  - ***Dilating*** the pupil in low-light conditions
  - ***Contracting*** the pupil in high-light conditions

Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Optical Instruments

The Eye



- Cornea–lens system focuses light onto the back surface of the eye (*retina*)
  - Retina consists of millions of sensitive receptors
- When stimulated by light → receptors send impulses via optic nerves to the brain
  - Where image is perceived
- Distinct image of an object is observed when the image falls on the retina
- **Accommodation**: the eye focuses on an object by varying the shape of the pliable crystalline lens through a process called *accommodation*.
  - Lens adjustments take place swiftly
    - We are not aware of the change
- Accommodation is limited:
  - Objects very close to the eye produce blurred images

Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

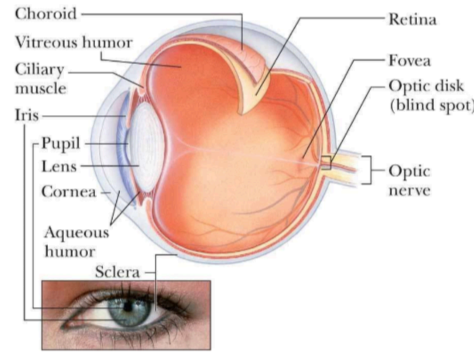
Optical Instruments

The Eye

- **The Near point** → closest distance for which the lens can accommodate to focus light on the retina
  - Distance usually increases with age
  - Average value of 25 cm

- At age 10: near point of eye typically ≈ 18 cm
  - Increases to ≈ 25 cm at age 20
  - 50 cm at age 40
  - 500 cm or greater at age 60

- **The Far point** → greatest distance for which the lens of the relaxed eye can focus light on the retina
  - Person with normal vision can see very distant objects
    - Far point is approximated as infinity



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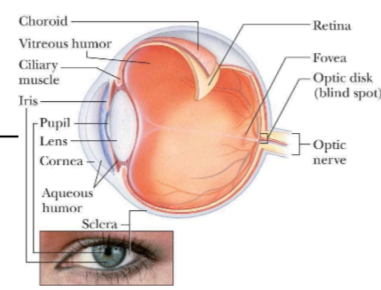
Optical Instruments

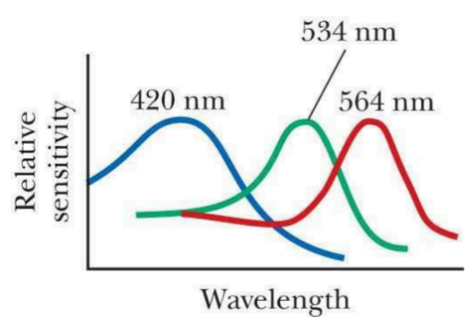
The Eye



- The Retina is covered with two types of light-sensitive cells: **rods** and **cones**

  - ***Rods***: not sensitive to color
    - More light sensitive than the cones
    - Responsible for ***scotopic vision*** (dark-adapted vision)
    - Rods spread throughout the retina
    - Allow good *peripheral vision* for all light levels
    - Allow *motion detection* in dark

  - ***Cones***: concentrated in fovea
    - Sensitive to different wavelengths of light
    - Three categories of these cells: ***red, green, and blue cones*** (figure)
    - If red and green cones are stimulated simultaneously (yellow light shining on them) → Brain interprets the color as yellow
    - If all three types of cones are stimulated by separate colors red, blue, and green → White light is seen
    - If all three types of cones stimulated by light that contains *all* colors (e.g., sunlight) → White light is seen



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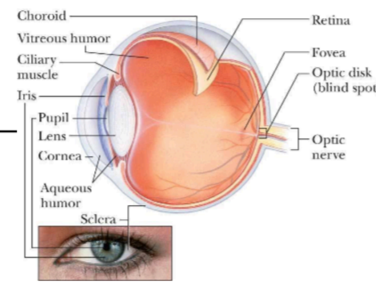
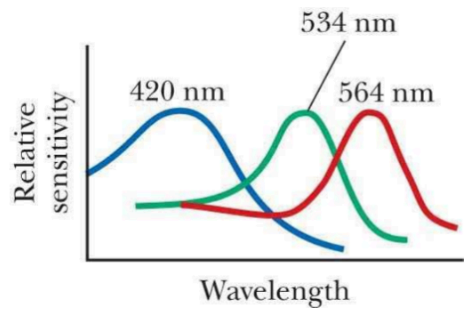
Optical Instruments

The Eye



- Televisions and computer monitors take advantage of the eye's visual illusion:
  - They have only red, green, and blue dots on the screen
  - With specific combinations of brightness in three primary colors → our eyes can be made to see any color
- Page of a multicolored book: made of tiny, matted, translucent fibers that scatter light in all directions
  - Resultant mixture of colors appears white



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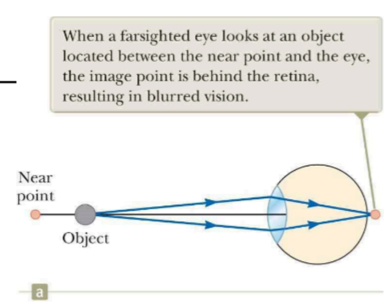
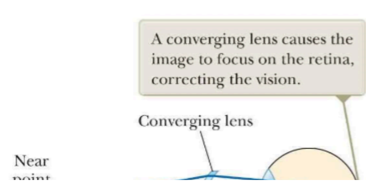
Optical Instruments

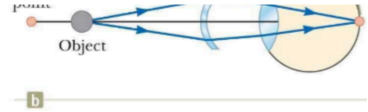
Conditions of The Eye: Farsightedness (Hyperopia)



- Figure (a): **farsightedness** (or *hyperopia*) →
  - The eye suffers a ***mismatch*** between the focusing range of the lens–cornea system and the length of the eye
    - **Result**: light rays from a near object reach the retina **before they converge** to form an image
- A farsighted person can usually see faraway objects clearly but not the nearby objects
  - Near point of a normal eye is ≈ 25 cm
  - Near point of a farsighted person is much farther away
- The ***refracting*** power in the cornea and lens is insufficient to focus light from all but distant objects satisfactorily
  - The condition can be corrected by placing a converging lens in front of the eye (figure (b))



- The lens refracts the incoming rays more toward the principal axis before entering the eye
  - Allowing them to converge and focus on the retina

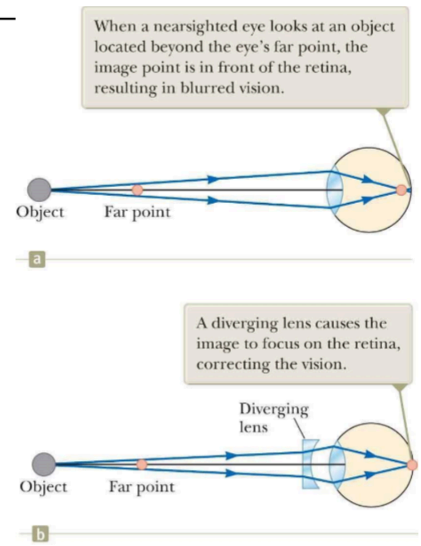


Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Optical Instruments

Conditions of The Eye: Nearsightedness(Myopia)

- **Nearsightedness** (or myopia): another mismatch condition →
  - The eye focuses well on the nearby objects but not on the faraway objects
  - The Far point of a nearsighted eye is not infinity
    - May be as short as < 1 m
- Maximum focal length of a nearsighted eye is insufficient to produce a sharp image on the retina
  - Rays from a distant object converge to focus in front of the retina
  - Continue past that point and diverge by the time they reach the retina
    - → Causing blurred vision (figure (a))
- Nearsightedness can be corrected with a diverging lens (figure (b)) .
- The lens refracts the rays away from the principal axis before they enter the eye, allowing them to focus on the retina.



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Optical Instruments

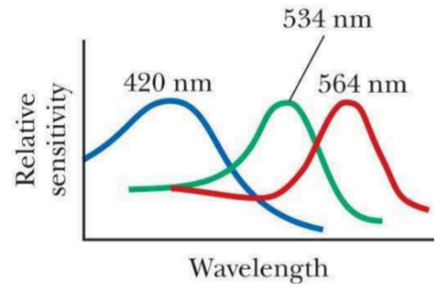
Conditions of The Eye: Color Blindness

- Some people have difficulties with color blindness

- Some people have difficulties with color blindness
  - ***Dichromat***: only have functioning cones for two of the three colors
  - ***Anomalous trichromats***: range of sensitivity of (most often) red- and green-sensitive cones shifted
    - More overlap between red and green curves in the figure
      - Difficult to distinguish red and green

- New type of glasses offers some relief for anomalous trichromats
  - Designed to filter out wavelength regions in which curves in the figure cross
    - Allows individual to see three distinct wavelength regions

- Many people trying these new glasses report remarkable improvement in their perception of colors



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

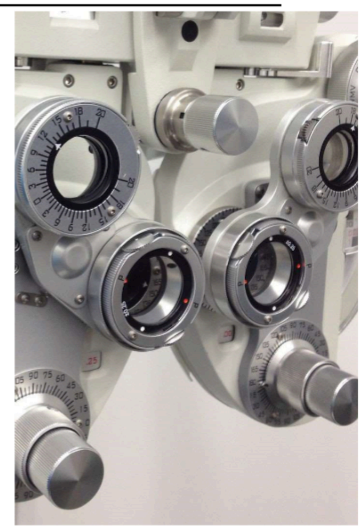
Optical Instruments

Conditions of The Eye: Others

- Presbyopia
- Astigmatism

- Optometrists and ophthalmologists usually prescribe lenses measured in ***diopters***: the power P of a lens in diopters equals the inverse of the focal length in meters: **P=1/f**.

- For example, a converging lens of focal length +20cm (0.2m) has a power of P=+5.0 diopters, and a diverging lens of focal length -40cm (-0.4m) has a power of P=-2.5 diopters.



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018. https://en.wikipedia.org/wiki/File:Deakin_University,_School_of_Medicine,_Optometry,_Phoropter.jpg

Optical Instruments

Quick Quiz 35.7

Two campers wish to start a fire during the day. One camper is ***nearsighted***, and one is ***farsighted***.
Whose glasses should be used to focus the Sun's rays onto some paper to start the fire?

(a) either camper
(b) the nearsighted camper
(c) the farsighted camper

Optical Instruments

Quick Quiz 35.7

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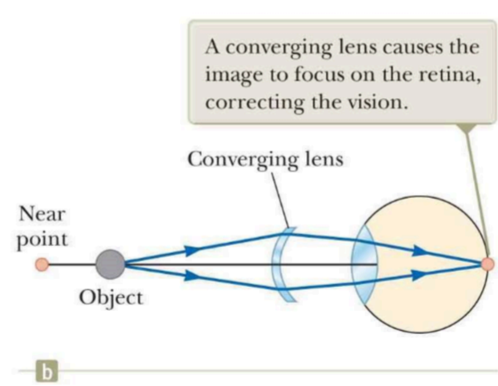
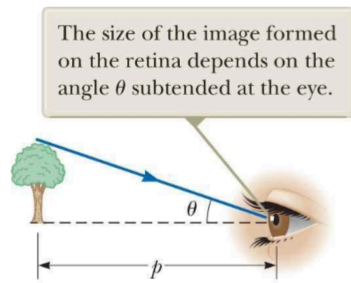
*The Sun's rays must converge onto the paper to burn it.
A farsighted person wears converging lenses.

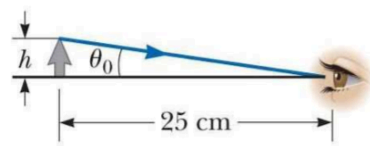


Optical Instruments

The Simple Magnifier

- A simple magnifier (magnifying glass): consists of a single converging lens
  - Increases the apparent size of an object
- Top figure: the object is viewed at some distance ***p*** from the eyes
  - **Size of the image formed at the retina depends on the angle θ** subtended by the object at the eye
- As the object moves closer to the eye:
  - θ increases
  - Larger image is observed
- Average normal human eye cannot focus on object closer than ≈ 25 cm (near point) (bottom figure)
  - θ maximum at near point



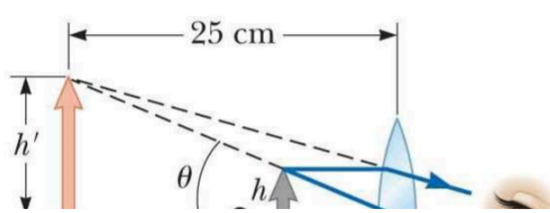


Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

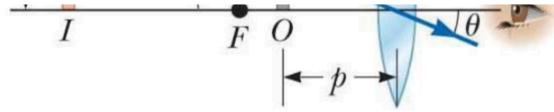
Optical Instruments

The Simple Magnifier

- Figure illustrates a converging lens placed in front of the eyes to increase the apparent angular size of the object
- Object is located at point O → Immediately inside the focal point of the lens



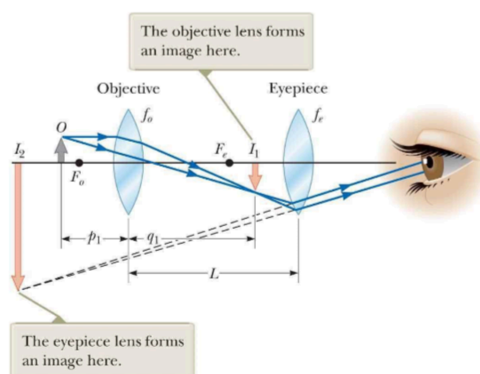
- Lens forms a virtual, upright, enlarged image



Optical Instruments

The Compound Microscope

- **Compound microscope** (figure): consists of
  - One lens (***objective***) → very short focal length f_o **< 1 cm**
  - Second lens (***eyepiece***) → focal length f_e **of few centimeters**
    - Lenses separated by a distance $L >> f_o$ **or** f_e
- Object is placed just outside the focal point of the objective lens
  - Forms a real, inverted image at I_1
  - Image located at or close to the focal point of the eyepiece
- Eyepiece serves as a simple magnifier
  - Produces at I_2 virtual, enlarged image of I_1



Optical Instruments

Optical Instruments

The Compound Microscope

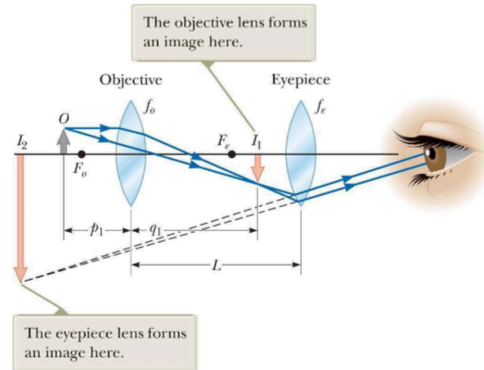
Optional

- Lateral magnification M_1 of first image: $M_1 = -\dfrac{q_1}{p_1}$
- From the figure: $q_1 \approx L$ and $p_1 \approx f_o$
  - Object very close to the focal point of the objective
- Lateral magnification by the objective: $\Rightarrow M_o \approx -\dfrac{L}{f_o}$
- Angular magnification by eyepiece for object (corresponding to image at I_1) placed at focal point of eyepiece:

$$m_e = \frac{25 \text{ cm}}{f_e}$$

- Overall magnification of image formed by compound microscope defined the product of lateral and angular magnifications:

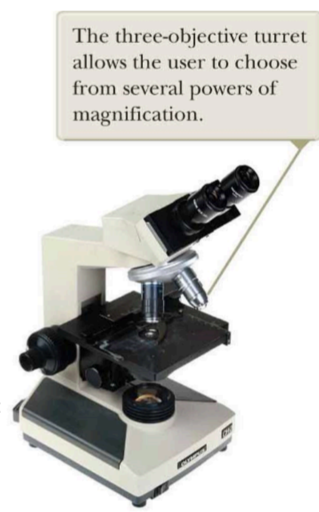
$$M = M_0 m_e = -\frac{L}{f_0}\left(\frac{25 \text{ cm}}{f_e}\right)$$



Optical Instruments

The Compound Microscope

- ***Microscope***: extended human vision to incredibly small objects
  - Capabilities steadily increased with improved techniques for precision grinding of lenses
- "If one were extremely patient and careful, would it be possible to construct a microscope that would enable the human eye to see an atom?"
  - Answer: no, if light is used to illuminate the object
- For an object under the optical microscope (that uses visible light) to be seen:
  - Object must be at least as large as the wavelength of light
- Because the diameter of any atom is many times smaller than the wavelengths of visible light
  - Atom must be observed using other types of "microscopes"

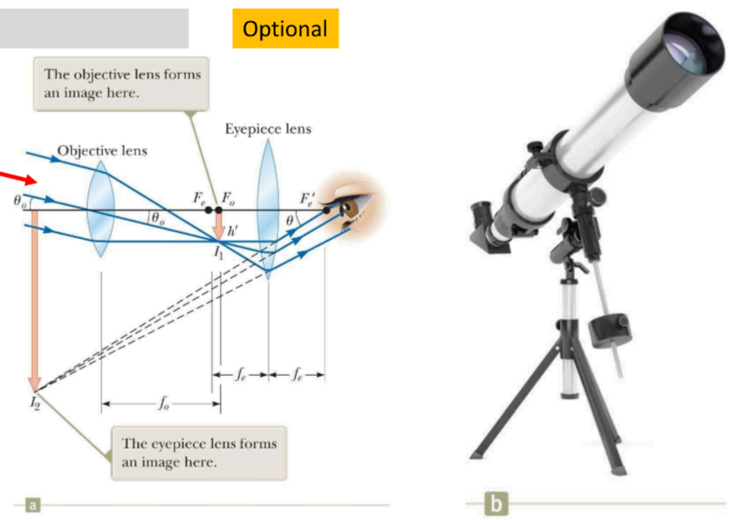


Optical Instruments

The Telescope

Optional

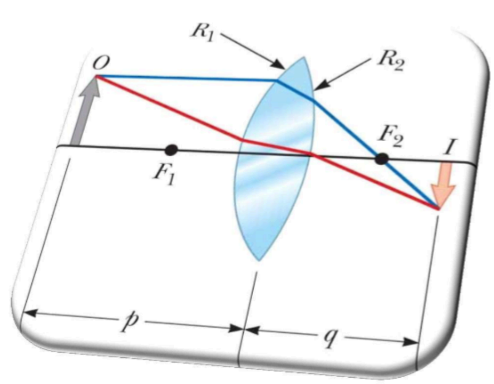
Distant objects (e.g., planets in our solar system)



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Summary of Week 13, Class 11

- Reminder of the previous week
- Image Formation (Ch. 35)
  - Images Formed by Flat Mirrors
  - Images Formed by Spherical Mirrors
  - Images Formed by Refraction [Optional / Reading]
  - Images Formed by Thin Lenses
  - Lens Aberrations
  - Optical Instruments
- Examples
- Next week's topic



Reading / Preparation for Next Week

Topics for next week:

- Wave Optics (Ch. 36)
- Diffraction and Polarization (Ch. 37)