# Ch. 13 Light and Reflection

## Electromagnetic Waves

1. White light is a mixture of all the colors of the spectrum: red, orange, yellow, green, blue, indigo and violet (ROY G BIV).
2. There are other forms of radiation that have properties similar to visible light - radio waves and X rays for example - but are not visible to the human eye. All of these radiations are electromagnetic waves.
3. Light does have some particle-like properties. The next few chapters will emphasize the wave-like properties of light.
4. Light consists of electric and magnetic fields that each oscillate in the direction perpendicular to wave motion. The electric and magnetic fields are perpendicular to each other. Because each field oscillates perpendicular to the direction of wave motion, electromagnetic waves are transverse waves.
5. We classify the electromagnetic waves based on their different frequencies (wavelengths). For visible light, different frequencies are perceived as different colors.
6. Like a rainbow in which one color gradually merges into another, there are no sharp dividing lines separating one type of electromagnetic radiation from another.

   (a) Radio waves - longest wavelength (radio and television)

   (b) Microwaves - navigation, cooking

   (c) Infrared - heat waves - trapped by carbon dioxide in the "greenhouse effect" - may be contributing to global warming

   (d) Visible light - red (700 nm) to violet (400 nm)

   (e) Ultraviolet - "black light" - causes sunburn. Absorbed by the ozone layer. But the ozone layer has been damaged by CFCs.

   (f) X-rays

   (g) Gamma rays - produced in high energy events such as the supernova explosion of a star.

7. All electromagnetic waves travel at the same speed in a vacuum, the speed of light. The wave equation $f\lambda = v$ holds for electromagnetic waves. The speed of light in a vacuum is called c. $c = 3.00 \times 10^8$ m/s.

8. Example.
Ultraviolet radiation has wavelength $3\bar{0}\bar{0}$ nm. What is its frequency? $c = 3.00 \times 10^8$ m/s

Given:
$\lambda = 3\bar{0}\bar{0}$ nm $= 3\bar{0}\bar{0} \times 10^{-9}$ m (nano in nm means $10^{-9}$)
$c = 3.00 \times 10^8$ m/s

Unknown
$f$

$f\lambda = c \rightarrow f = \frac{c}{\lambda}$

$f = \frac{3.00 \times 10^8}{300 \times 10^{-9}} = \underline{\underline{1.01 \times 10^{15} \text{ Hz}}}$

9. Wave fronts
(a) Wave fronts connect in phase points, like crests or troughs. They give the shape of the wave. For example, a pebble dropped in a pond produces circular wave fronts.
(b) In the last chapter we saw that rays are drawn perpendicular to wave fronts. Rays indicate the direction of wave motion.

10. The intensity of sound depends on the power of the source and the distance from the source. The same is true of light. Illuminance of a light source is analogous to intensity of a sound source. It measures how bright the light falling on an object is at a given location. It is inversely proportional to the square of the distance from the light source (analogous to $I = \frac{P}{4\pi r^2}$ with sound)

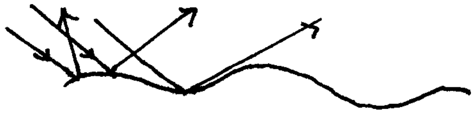
<u>Flat Mirrors</u>

11. Light travels in a straight line through a uniform medium.
12. When light encounters the boundary between two substances, some light can be transmitted into the new medium, some can be absorbed and some deflected. The change in direction of the light is called <u>reflection</u>.

13. Texture of a surface affects how it reflects light.

(a) Diffuse reflection

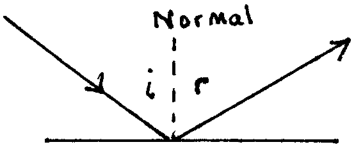
Rough surfaces such as paper and unpolished wood reflect light in many different directions.



Each part of the surface is oriented in a different direction, so the light is reflected in different directions.

(b) Smooth, Shiny surfaces reflect light in a single direction. Smooth surfaces are those that have variations that are small compared to the wavelength of light. Reflection from smooth surfaces is called <u>specular reflection</u>.

14. Law of Reflection




i = angle of incidence, the angle incoming light makes with the normal

r = angle that reflected light makes with normal (angle of reflection)

The law of reflection states that the angle of incidence equals the angle of reflection. $i = r$

Notice that angle i and angle r are measured from the <u>normal</u>, a line drawn perpendicular to the reflecting surface. The angles are not measured from the surface itself.

15. Image Produced by a flat (plane) mirror

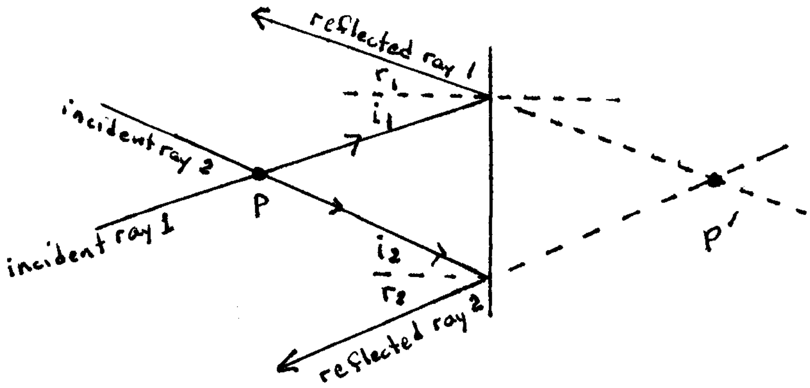
(a) The image appears to be located in back of the mirror (the side of the mirror opposite the object).

(b) The distance from the object to the mirror equals the distance from the mirror to the image

(c) The image is the same size as the object.

16. Image Location can be predicted with ray diagrams.

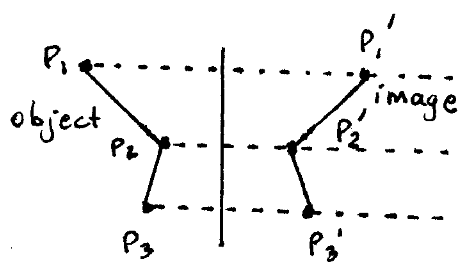
To locate the image of a point, construct the reflections of any two light rays that pass that point. Where the reflections intersect is where the image of the point appears. To construct the reflections, use the law of reflection. You can use a protractor to measure the angle of incidence and then use the protractor to construct a reflected ray with angle of reflection equal to angle of incidence.




Notice that the reflected rays diverge after they leave the mirror. These rays never intersect. The brain processes the light that reaches your eyes. The image forms at the place the reflected rays seem to originate . To find this location, extend the reflected rays on the side of the mirror opposite object P (the right side). Used dashed lines to distinguish the extensions (which are not where light actually travels) from actual light on the object side (left side) of the mirror. Image P' of object P forms where the extensions of the reflected rays intersect.

Notice that distance from object P to mirror = distance from mirror to image P'. Also note that a segment drawn through P and P' would be perpendicular to the mirror.

17. To construct the image of an object, construct the image of a few representative points. Instead of a ray diagram for each point P, use the properties just described : Image lies on a line passing through P that is perpendicular to the mirror. Object to mirror distance equals image to mirror distance

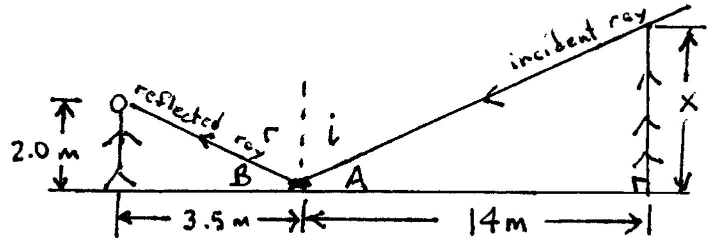



18. Virtual Image
(a) Virtual images are produced by reflected rays that <u>diverge</u>.
(b) Virtual images form due to the way the brain processes the reflected rays. Because the reflected rays that form a virtual image do not actually intersect, virtual images cannot be projected onto a screen.

(c) Flat mirrors always produce virtual images.
(d) Virtual images are erect or right side up (object and image have same orientation)

19. Example
A man's eyes are 2.0 m above the ground. He stands 3.5 m to the left of a small mirror resting on the ground. The man can see the image of the top of a tree that lies 14 m to the right of the mirror when he looks at the mirror. How tall is the tree?

Solution
Draw a sketch and set up a proportion based on similar triangles.




$i = r$
$A = 90 - i$
$B = 90 - r$
So $A = B$
The right triangles are similar (angle - angle) so corresponding sides are in proportion.

| | Triangle on left | | Triangle on right |
|---|---|---|---|
| Vertical side / Horizontal Side | $\frac{2.0}{3.5}$ | = | $\frac{x}{14}$ |

$$(2.0)(14) = 3.5x$$
$$x = \frac{(2.0)(14)}{3.5} = \underline{\underline{8.0\text{ m}}}$$

## Curved Mirrors

20. Spherical mirrors have the shape of part of a sphere's surface.
Concave spherical mirror: reflective coating is on what would be the inside of the sphere

Concave spherical mirror

Convex spherical mirror

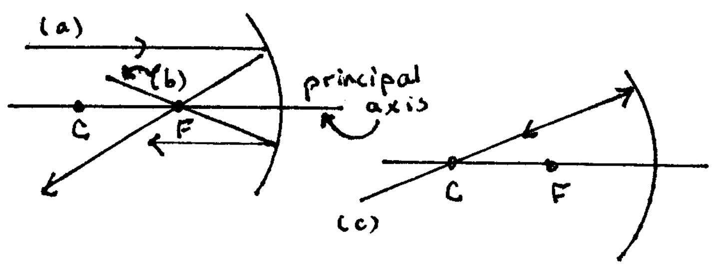
21. Center of Curvature C : center of sphere that mirror is part of
Radius of curvature R : radius of sphere that mirror is part of
Principal axis : a line through center of curvature and the center of the mirror.

22. Real images
Curved mirrors sometimes produce real images.
(a) Real images form by light rays that actually intersect.
(b) The real image forms where the light rays intersect. The image will be visible on a screen placed where the light rays intersect.
(c) Real images are inverted (have orientation opposite that of the object)

23. Spherical Aberration
Rays far from the principal axis are not reflected through exactly the same place as rays close to the axis. Images that are not near the center of the mirror's surface (far from the mirror's axis of symmetry, or principal axis) are distorted.

## Ray Diagrams for Concave Spherical Mirrors

24. Key rays
There are special rays whose reflections can be drawn without using a protractor to insure that the angle of incidence equals the angle of reflection
(a) A ray parallel to the principal axis is reflected through focus F.
(b) A ray passing through focus F is reflected parallel to the principal axis.
(c) A ray passing through center of curvature C is reflected back through the center of curvature




Also note:
f = focal length = distance from focus F to mirror
R = radius of curvature = distance from center of curvature C to mirror
$f = \frac{1}{2} R$

25. Image of a point P
Draw two Key rays through the point P. The image of Point P (P′) forms where the reflections of the Key rays intersect if the image is real. If the image is virtual then it forms where the reflections of the Key rays appear to intersect (where the extensions of the reflected rays intersect).

26. Image of an object

We will use an arrow with tail on the principal axis to illustrate how curved mirrors produce images. You locate the image of the arrow head first. All points on the arrow are the same distance from the mirror. So the image of all points on the arrow form the same distance from the mirror as the image of the arrow head. Drop a perpendicular from the image of the arrow head to the principal axis to fill in the image of the arrow.

27. Six Cases to be considered

The type of image that forms depends on the distance $d_o$ from the object to the mirror. The center of curvature C and focus F divide the principal axis into five regions.

$d_o > C$ (or $C < d_o < \infty$)
$d_o = C$ (or $d_o = 2F$)
$F < d_o < C$ (or $F < d_o < 2F$)
$d_o = F$
$0 < d_o < F$

We also consider rays from a very distant source ($d_o = \infty$) as a special case.

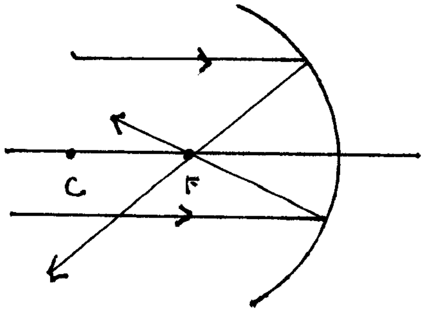
For each case, we use a ray diagram to answer four questions

- where is the image (we give the distance $d_I$ from the image to the mirror)
- size of image (how does image size compare with object size)
- is image real or virtual?
- orientation of image (somewhat redundant since virtual images are always erect and real images are always inverted)

28. Cases for spherical concave mirror

(a) Object very far away ($d_o = \infty$)

The Sun sends out light rays in all directions. But rays reaching the mirror are only a tiny sliver of all of the rays. Light rays reaching the mirror from a distant source all come from the same direction. So the rays are nearly parallel to each other.



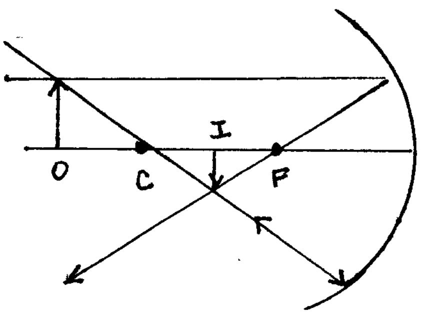

Location of image: $d_I = F$

Size of image: rays intersect on principal axis ∴ image is a point (smaller than object)

Type of image: Real, since reflected rays intersect

Orientation of image: You could say inverted, since real images are inverted. But it makes more sense just to note that the image is a point. A point really cannot be inverted.

(b) Object further from mirror than center of curvature ($2F < d_o < \infty$)




Location of image: $F < d_I < 2F$

Size of image: smaller than object

Type of image: Real (reflected rays intersect)

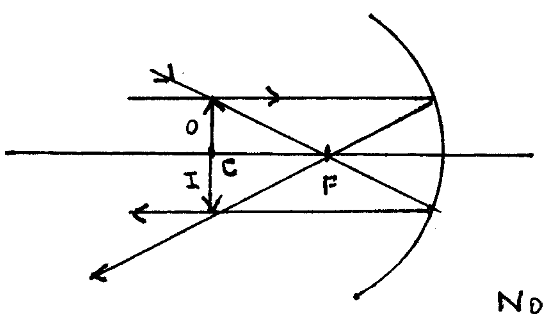
Orientation of image: Inverted

Note: Compare $d_o$ (distance from mirror to object) and $d_I$ (distance from mirror to image)

When $d_I < d_o$ the image will be smaller than the object

$d_I > d_o$ the image will be larger than the object

(c) Object at Center of Curvature ($d_o = C$ or $d_o = 2F$)




Location of Image: $d_I = C$ (or $d_I = 2F$)

Size of Image: Image is the same size as the object

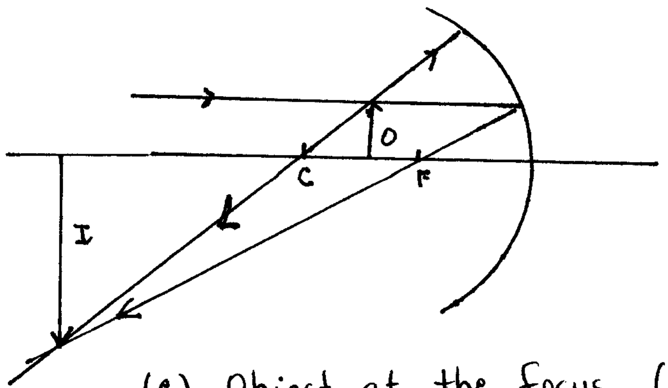
Type of Image: Real (reflected rays intersect)

Orientation of Image: Inverted

Note: Neither the object nor the image is further from the mirror, so neither is larger than the other. So object must be the same size as the image.

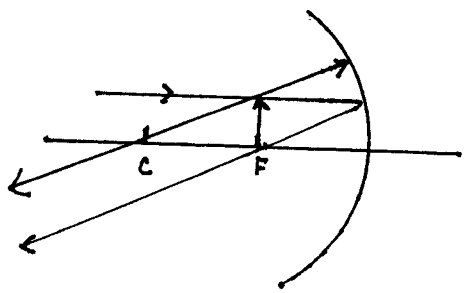
The key ray passing through C is very convenient to use. But it isn't used here because a ray passing through the arrow head and C would not reach the mirror and thus would not be reflected.

(d) Object between focus F and center of curvature C ( $F < d_o < 2F$ )




Location of Image: $2F < d_I < \infty$
Size of Image: Image is larger than object
Type of Image: Real (reflected rays intersect)
Orientation of Image: Inverted

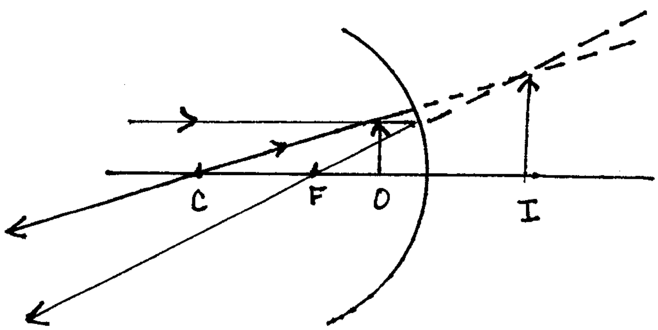
(e) Object at the focus ( $d_o = F$ )




The reflected rays are parallel. The image forms where the reflected rays intersect. Since there is no intersection, there is no image.

Answer to each of the four questions: There is no image

(f) Object between the mirror and the focus ( $d_o < F$ )



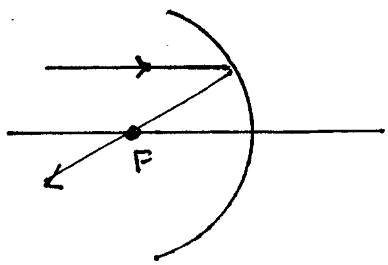

Reflected rays diverge as they move leftward from the mirror. Image forms where the reflected rays appear to originate - at the intersection of the extensions of the reflections.

Location of Image: $d_I < 0$
Size of Image: Larger than the object
Type of Image: Virtual (reflected rays diverge)
Orientation: Erect

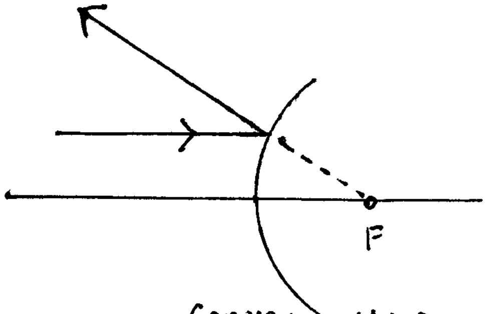
Note: By convention, we take image distance $d_I$ to be negative for virtual images. If $d_I < 0$ then the image is virtual and forms on the right side of the mirror.

## Convex Mirrors, Parabolic Mirrors

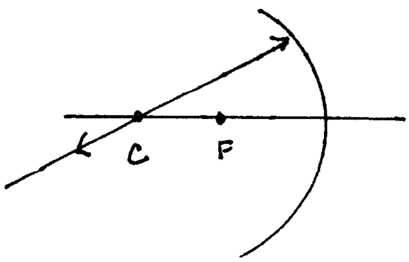
29. Convex Spherical mirrors bulge outward. The mirror is a segment of a sphere that reflects light from the sphere's outer surface. Light reflected by a convex mirror diverges as it leaves the mirror's surface. It appears as if the light originated from a virtual focus behind the mirror. Key rays for the convex mirror are therefore slightly different than those for the concave mirror.



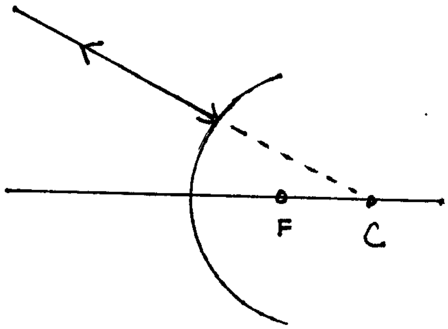

Concave Mirror
A ray parallel to the principal axis is reflected through focus F




Convex Mirror
A ray parallel to the principal axis appears to have passed through virtual focus F

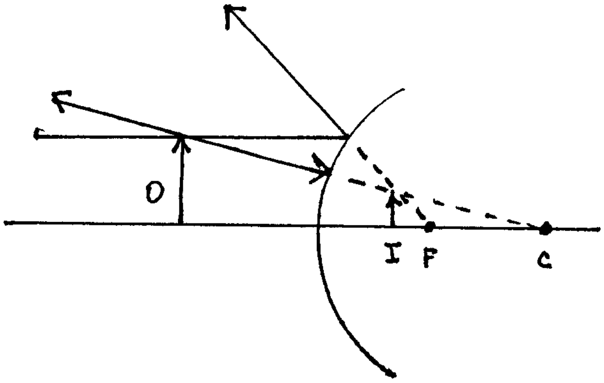



Concave Mirror
A ray passing through center of curvature C is reflected back on itself




Convex Mirror
Any ray whose extension passes through the virtual center of curvature C is reflected back on itself.

30. Ray Diagram for Convex Spherical Mirror
You locate the image of a point as before, but using the Key rays for convex mirrors. There are not multiple cases to consider, however. For any object distance $d_o$, the image produced by a convex spherical mirror has the same qualitative features.




Location of Image: $d_I < 0$
(Virtual image on right side of mirror)

Size of Image: Smaller than object

Type of Image: Virtual (reflected rays do not intersect)

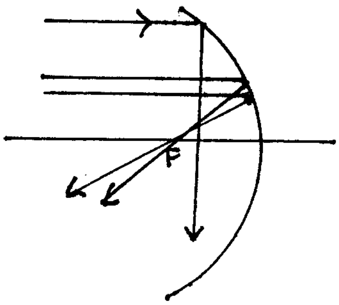
Orientation of Image: erect

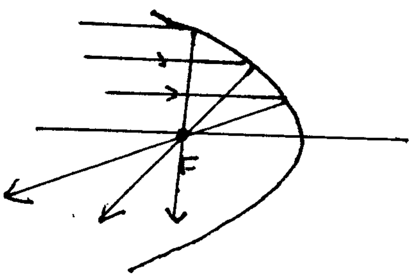
31. Convex Spherical mirrors always produce images that are smaller than the object. These mirrors are well suited for giving an observer a view of a large area. They are used in stores to help security workers. They are also used as rear view mirrors on the outside of cars. The mirrors carry a warning "objects are closer than they appear". The smaller size of the image in the mirror might fool a driver into thinking he has room to move into an adjacent lane when in fact he does not.

32. Parabolic Mirrors

(a) Spherical Aberration
Rays far from the principal axis (and parallel to it) are not reflected exactly through the focus. This leads to the distortion of images produced by large spherical mirrors.

(b) Parabolic mirrors have a shape produced by rotating a parabola about its axis. Rays parallel to the axis of the parabolic mirror are all reflected precisely through the focus of the mirror.




Parabolic Mirror

Spherical Concave Mirror

(c) Telescopes use parabolic mirrors to focus light.

## Mirror Equations

33. Mirror equations can be used to predict the location and size of the images produced by spherical mirrors.

$$\frac{1}{d_o} + \frac{1}{d_I} = \frac{1}{f}$$

$d_o$ = distance from object to mirror
$d_I$ = distance from image to mirror
$f$ = focal length of mirror

$$M = \frac{h_I}{h_o} = \frac{d_I}{d_o}$$

$M$ = magnification of image
$h_I$ = height or size of image
$h_o$ = height or size of object

Note that if an image is smaller than the object then $M < 1$. For example, if $h_I = 6.0$ cm and $h_o = 12$ cm then $M = \frac{h_I}{h_o} = \frac{6.0}{12} = \frac{1}{2}$. $M = \frac{1}{2}$ means that the image is half the size of the object.

34. Sign Conventions.
We examined seven different cases for spherical mirrors (6 for concave mirrors and one for convex). The two mirror equations will work for all cases if the following sign conventions are used.

$d_o$, $h_o$ : always positive

$M$, $d_I$, $h_I$ : positive for real images (image on left side of mirror)
: negative for virtual images (image on right side of mirror)

$f$ : positive for concave mirrors
: negative for convex mirrors

Common Error : The sign of $M, d_I, h_I$ depends on the type of image that is formed (real or virtual).
But the sign of $f$ depends <u>only</u> on the shape of the mirror. A concave mirror has $f > 0$, even when it produces a virtual image.

35. Real Image Example

An object 12 cm tall is placed $6\bar{0}$ cm from a concave spherical mirror whose focal length is $2\bar{0}$ cm.

(a) Where does the image form?

(b) How large is the image?

Given: $h_o = 12$ cm, $d_o = 6\bar{0}$ cm, $f = 2\bar{0}$ cm } be sure you can assign a label ($d_o, d_I, h_I, h_o, f, M$) to each numerical value.

(a) Unknown: $d_I$

$$\frac{1}{d_o} + \frac{1}{d_I} = \frac{1}{f}$$

$$\frac{1}{d_I} = \frac{1}{f} - \frac{1}{d_o}$$

$$\frac{1}{d_I} = \frac{1}{2\bar{0}} - \frac{1}{6\bar{0}} = \frac{3}{6\bar{0}} - \frac{1}{6\bar{0}} = \frac{2}{6\bar{0}} = \frac{1}{3\bar{0}}$$

$$\frac{1}{d_I} = \frac{1}{3\bar{0}} \Rightarrow d_I = 3\bar{0} \text{ cm}$$

The image forms $3\bar{0}$ cm to the left of the mirror.

Notes: $d_I > 0$ means the image is real.

Notice that it is easier to solve $\frac{1}{d_o} + \frac{1}{d_I} = \frac{1}{f}$ for $\frac{1}{d_I}$, not $d_I$ itself. On a calculator, find $\frac{1}{d_I}$ by subtracting: $\frac{1}{20} - \frac{1}{60}$. But remember that this subtraction gives $\frac{1}{d_I}$ rather than $d_I$. So use the reciprocal key after subtracting to find $d_I$

(b) Unknown: $h_I$

$$\frac{h_I}{h_o} = \frac{d_I}{d_o} \Rightarrow h_I d_o = h_o d_I \Rightarrow h_I = \frac{h_o d_I}{d_o}$$

$$h_I = \frac{h_o d_I}{d_o} = \frac{(12)(3\bar{0})}{6\bar{0}} = \underline{\underline{6.0 \text{ cm}}}$$

Note: These problems are made much easier by using your answer from part (a) [ $d_I = 3\bar{0}$ cm ] to help answer part (b), rather than solving part (b) independently

of part (a).

36. Virtual Image Example

An object 3.0 cm tall is placed 4.0 cm from a concave mirror whose focal length is 12 cm.
(a) Where does the image form?
(b) How large is the image?

Given: $h_o = 3.0$ cm
$d_o = 4.0$ cm
$f = 12$ cm

(a) Unknown: $d_I$

$$\frac{1}{d_o} + \frac{1}{d_I} = \frac{1}{f} \rightarrow \frac{1}{d_I} = \frac{1}{f} - \frac{1}{d_o}$$

$$\frac{1}{d_I} = \frac{1}{f} - \frac{1}{d_o} = \frac{1}{12} - \frac{1}{4.0} = \frac{1}{12} - \frac{3}{12} = \frac{-2}{12} = -\frac{1}{6}$$

$$\frac{1}{d_I} = -\frac{1}{6} \rightarrow d_I = -6.0 \text{ cm}$$

So the image is a virtual image that forms 6.0 cm to the right of the mirror.

Note: You may answer $d_I = -6.0$ cm or
6.0 cm to the right of the mirror
NOT -6.0 cm to the right of the mirror

(b) Unknown: $h_I$

$$\frac{h_I}{h_o} = \frac{d_I}{d_o} \rightarrow h_I d_o = h_o d_I \rightarrow h_I = \frac{h_o d_I}{d_o}$$

$$h_I = \frac{h_o d_I}{d_o} = \frac{(3.0)(-6.0)}{4.0} = -4.5 \text{ cm}$$

So the image is a virtual image 4.5 cm tall

Note: Answer $h_I = -4.5$ cm or
a virtual image 4.5 cm tall
NOT a virtual image -4.5 cm tall