5. Physics in the Arts

Reflections on Light

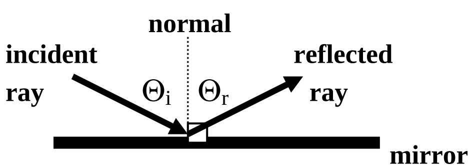
5.1 flat mirrors

Throughout the ages, mirrors have been highly prized for their ability to produce an accurate likeness of a person or scene. Whether used in amusement park activities, artwork, or as dental tools, mirrors are all fundamentally alike. They are all highly polished materials that make use of the law of reflection.

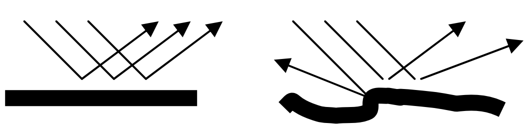
The **law of reflection** states that the angle at which a ray of light strikes a mirror is the same as the angle it reflects at. In physics terms, we say the **incident** (in-coming) **angle** is equal to the **reflected** (out-going) **angle**.

$$\Theta_i = \Theta_r$$

Both angles are measured from a line which is perpendicular to the surface that the light ray strikes. This line is called the **normal.**



Recall the earlier discussion on diffuse and specular reflection. The law of reflection works for all materials, but when the surface's normals change, the reflected rays do not come off parallel to one another; this results in diffuse (matte finish) reflection.

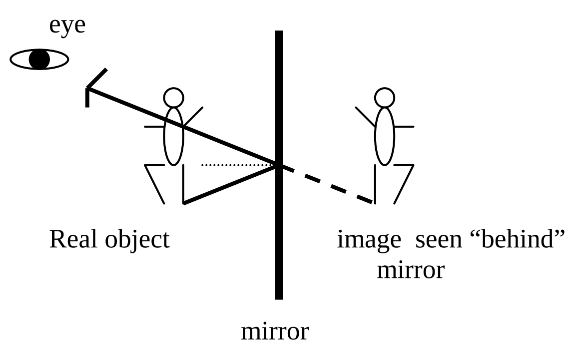


Specular surface (glossy finish) — diffuse surface (matte finish)

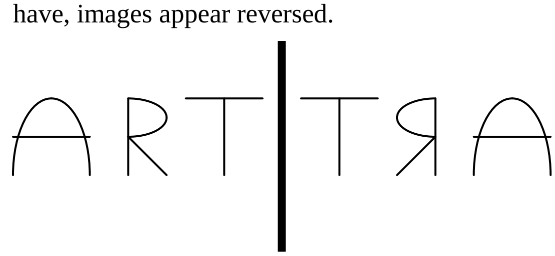
If you've ever tilted a paper to see if the white-out has dried, you have used these ideas. When it is liquid, the white-out shines specularly. When it dries, it is rougher, becoming a diffuse reflector.

The smoother the surface, the stronger the resulting reflection of light. Most materials absorb some light and reflect the rest; this means most objects will only provide a weak reflection. The brain can easily tell the difference between a weak reflection and the real object.

However, mirrors reflect nearly all light incident upon them. The eye, unaware that the light it detects been detoured, sees a strong image *behind* the mirror. That is, when you look at yourself in the bathroom mirror, you see your image as existing behind the mirror, though you know that to be an impossibility. Your *brain* tells you it is an image and not a real object located there.



The image you see in a flat mirror appears to be as far behind the mirror as the object is in front of the mirror. In addition, the image is exactly the same size as the original object. There are differences between the original object and its image, though. Because images have the same distance to the mirror as the original objects have, images appear reversed.



mirror

Because an image formed from a flat mirror can never be focused onto paper, it is called a **virtual image**. A virtual image is one which can be seen only when looking into a mirror or through a lens. Just like virtual reality games in which you see objects which you cannot actually touch, virtual images are ones which you can see but not touch or focus onto a screen.

5.2 Kaleidoscopes and Mirror Houses

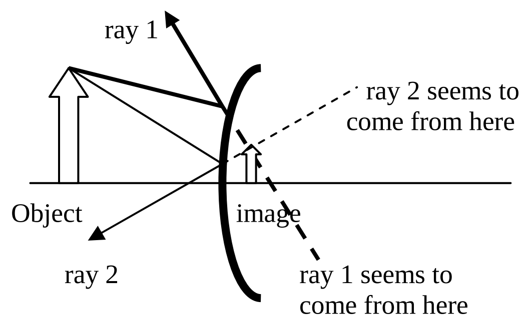
The more perfect the mirror, the harder it is for the eye to detect that the light's path has been altered. A house of mirrors at an amusement park is an excellent example of this. The walls of the house are all mirrors polished so that it is difficult to tell images from original objects. Because you see multiple reflections as you move through the house, you are apt to reach for a doorknob only to find your knuckles bumping into the solid glass of a mirror. Dim lighting can assist this impression, as it makes both objects and images dimmer and thus harder to distinguish from one another.

Kaleidoscopes also make use of multiple flat mirrors. A kaleidoscope is a long, cylindrical device with two plane mirrors running the length of the tube and a hole at one end in which to look. The unusual geometric designs seen in a kaleidoscope are actually multiple reflections of colorful objects placed inside the kaleidoscope. When the angle between the mirrors is an integral factor of 360 degrees (such as 45, 60, or 30 degrees), the viewer will see complete and distinct virtual images in a symmetric pattern. Other angles will show reflections as well, but the images will overlap, and thus the images and original objects will be easily distinguished from one another.

5.3 Curved Mirrors: convex

In the corner of a typical shop you will see a large mirror shaped like the back of a spoon. If you look into it, you will see images of nearly everything in the store. Because such a large scene is shown in such a small amount of space, all of the images are much tinier and they seem farther away from the mirror than the original objects. No matter where you view the mirror from, you will always see small, upright, virtual images. This anti-theft device is a **convex** (outwardly curving) mirror.

A similar mirror is used for the side-view mirror on the passenger's side of a car. Such mirrors can be very useful, as they show a greater range of view than a flat mirror would. However, because the images are not the same size as the original object, and because they do not appear the same distance "behind" the mirror as the original object is in front of it, the driver might mistake the distance of approaching cars. For this reason, the message "objects in mirror are closer than they appear" is etched on the glass.



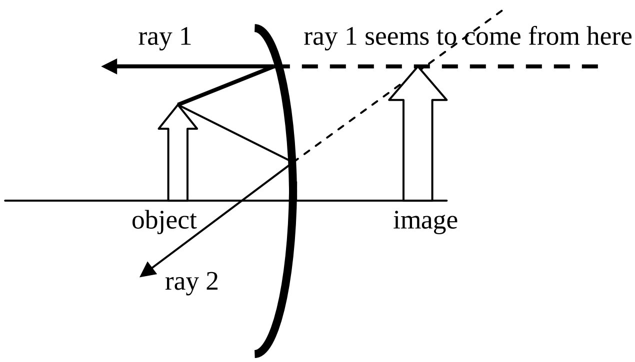
all images produced by a convex mirror are small, upright, and virtual

Notice that the light rays are actually diverging as they leave the mirror. This is what makes the image a virtual one. The viewer thinks the rays originated from a spot behind the mirror because that is the direction the light is coming from. Since the rays never truly crossed, they can never be focused onto a screen. These images exist only in the eyes and minds of the viewers. However, if the viewer happens to be a camera with film, the camera will "see" what the eye sees, and the film will be exposed in the pattern of the virtual image. This is not the same as having the image form directly on a screen.

5.4 Curved Mirrors: concave

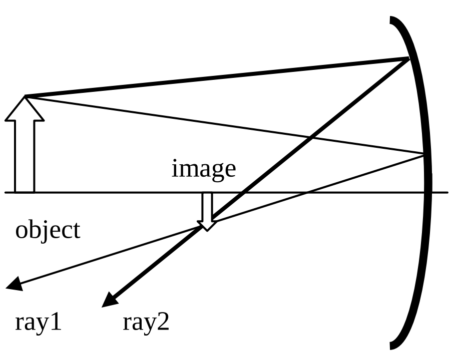
On the top of many a vanity counter is a mirror which is curved inward, like the inside of a spoon. If you look into this shaving or makeup mirror, you will see an enlarged, upright, virtual view of your face. This is a **concave** mirror.

Place a concave mirror on a counter in front of you so that you can see your face reflected back at you. You should see an image larger than life.



objects close to a concave mirror produce large, virtual, upright images

Now back away from the mirror slowly. At a certain point, the image "whites" out; that is, you can no longer see any recognizable image at all. If you continue to back up, the image that appears is suddenly upside down. Even more bizarrely, if you hold a sheet of paper the same distance away from the mirror that you were standing when the image whited out, and aim the mirror out the window, you will see an image of what's outside projected upside down onto the paper. An image which can be focused on a screen is called a **real** image.



Objects far from concave mirrors have small, upside down, real images

In all virtual images, the light rays are diverging; that is, they are moving apart from one another. The eye is fooled into thinking the rays have come from a common location and thus sees a virtual image.

In the case of real images, the light rays truly cross. Where they cross, an image is formed, and this image can be projected onto a screen. A real image can only be viewed via a screen. How, then, could you see the *real*, upside down image in the concave mirror when you viewed your own image from far off? The retina of your eye provides the screen for the light rays to focus on, allowing you to see the image. You can only see real images in this manner when you are standing at the precise location where the rays are converging. If you stand at any other point, it is like having a slide projector but no screen. No image of that object will be seen.

So what is happening at the point where the image is whited out? If a far object's reflected rays converge to form a real image, and a close object's reflected rays diverge forming a virtual image, there must be a point where the rays neither converge nor diverge, but rather are exactly parallel. Here, no image at all forms. This spot is called the **focal point**.

Light rays which come from an object located at the focal point will reflect off the mirror parallel to one another. Interestingly, light coming from an object so far away that the rays are parallel to one another will form an image at the focal point. Thus, by aiming a concave mirror at a far-off object and locating where the image forms, you are determining the focal point of the mirror.

If you could see the entire sphere that a particular mirror was cut from, you could easily find out the focal point. The radius of the sphere is exactly twice the focal point distance; thus if a mirror were made by silvering the inside of a glass globe of radius 30 centimenters, the focal point distance of that mirror would be 15 centimenters from the mirror. A mirror made by silvering the back of the same glass globe would have a focal point distance of –15cm; that is, the focal point is 15 centimenter from the mirror but on the "wrong" side of the mirror. This trick will come in handy when you are predicting where an image will be located.

5.5 The Mirror Equation

The mirror equation can be used to predict where an image will form for a particular mirror and a particular distance that an object is placed before the mirror. For a mirror of focal point distance f with an object placed a distance d_o from the mirror, d_i represents the distance the resulting image is from the mirror.

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

All values on the proper side of the mirror are positive, while values on the "wrong" side of the mirror (where no physical object could truly be) are negative. Thus a concave mirror has a positive focal point distance, since the center of the sphere --and thus the focal point – is in front of the mirror, while a convex mirror has a negative focal point distance, since the center of that sphere is behind the mirror. Object distances are always positive, since you never place an object behind a mirror. Image distances are positive for real images, which form on the proper side of the mirror and can be focused onto paper. Image distances are negative for virtual images, which are seen to exist "inside" the mirror, where no physical object could truly be.

5.6 Magnification

The size of the resulting image can also be determined with knowledge of the type of mirror and the object itself. Magnification can be calculated by using the object distance, which is pre-determined, and the image distance, which can be obtained via the mirror equation. For a given object distance, d_o, and image distance, d_i, the magnification of the image, M, will be as follows:

$$M = -\frac{d_i}{d_o}$$

But magnification is simply how large the image is compared to the original object, so it can also be written:

$$M = \frac{h_i}{h_o}$$

where h_i is the image height and h_o is the height of the original object. A negative height means the object is inverted; since only real images are upside down, this method will also tell you if you have a real image, and thus will confirm whether you have a concave mirror or not. A positive height with a magnification greater than one means an enlarged, virtual image, which indicates a concave mirror. A positive height with a magnification less than one means a reduced, virtual image, which must have come from a convex mirror.

5.7 Pyromania I: Mirrors

Just like coal or oil can be converted into heat energy by burning it, so similarly can light be converted into heat energy with the use of a concave mirror. Recall that a concave mirror forms a real image when the object is farther from the mirror than the focal point distance. This is due to the fact that the light rays being reflected by the mirror really cross, focusing at a particular location in space.

Generally, the amount of light (and energy) coming from a particular object is not much. However, when a concave mirror is aimed at the sun, there is so much energy being focused to such a tiny location, that a piece of paper placed at the right spot receives enough energy to start smoldering and then burning. The sun's rays arrive at the mirror almost parallel to one another, so when they reflect, they all converge at the focal point of the mirror. This is the special location at which the paper must be positioned.

5.8 Funhouses

Funhouses designed for small children often have mirrors which give you a seriously distorted image of yourself. You may have a neck which is two feet long, or no middle at all, or both. A quick examination of such mirrors shows that they are a combination of convex and concave mirrors. The image of the neck which was too long was due to the concave top of the mirror which produced a magnified, upright image from the light coming from your neck. When you looked into the middle part of the mirror, you were looking into a convex mirror, which made images upright but much smaller than the original objects being viewed. By varying the type and curvature of the mirrors, the makers caused different alterations to be given to your image, often to the point where it is hardly recognizable as your own.

5.9 Anamorphic art

Look into a convex mirror and you will see a distorted view of the scene around you. Now imagine designing a piece of art which, when viewed via that same mirror, is seen *undistorted*. This is **anamorphic art**. The subject of the actual artwork appears deformed unless it is viewed with the help of a mirror or from a particular, skewed perspective. Such artwork was popular in Shakespeare's time; in fact, in one of his works he describes such a piece:

"Like perspectives, which rightly gazed upon,
Show nothing but confusion, eyed awry,
Distinguish form."

There are several types of anamorphic art, each dependent upon the method needed to translate them into understandable images. The type which requires a cylindrical mirror—which is not too different from a spherical, convex mirror—is one of the easiest to produce, requiring only a grid somewhat resembling polar coordinate graph paper. Just like a shop anti-theft mirror takes an entire room's worth of images and pushes them into a tiny space, the cylindrical mirror takes the expanded drawing and packs it into a compact image. In the latter case, however, the image begins deformed and ends clear, whereas with the theft mirror, the opposite is true.

Another type of anamorphic art uses a conical decoder mirror. The original art for these works is particularly indecipherable without the accompanying mirror, as the outermost part of the picture becomes the innermost part of the image. These may also be made with a corresponding grid, though a common method is to use photographic equipment.

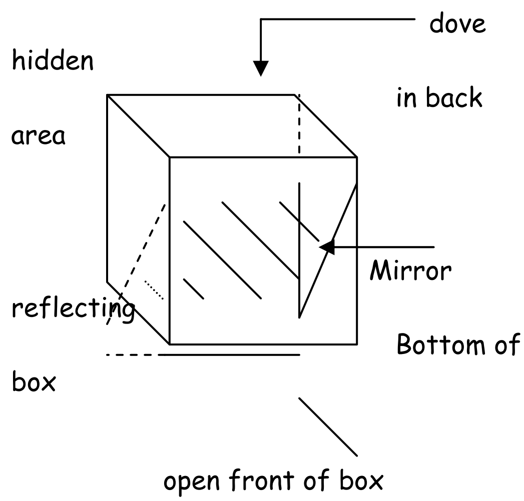
A third type of anamorphic art, particularly popular in the risqué Victorian era, is made to be viewed without a mirror at all. When viewed on edge, a greatly elongated picture can be seen in its undistorted form. This was used in Hans Holbein's painting "The Ambassadors." When seen head-on, the painting merely has an odd set of streaks. The additional image of a skull is only seen in its true form when viewed from a glancing angle.

5.10 Magicians' Tricks

Over the years, magicians have impressed and amazed their audiences by pulling objects from empty boxes, causing people to disappear, and creating talking head illusions. Toys sold in magic shops boasted of being x-ray machines that allow the viewer to see through any object. All of these inventions require only the cunning use of mirrors to make them work.

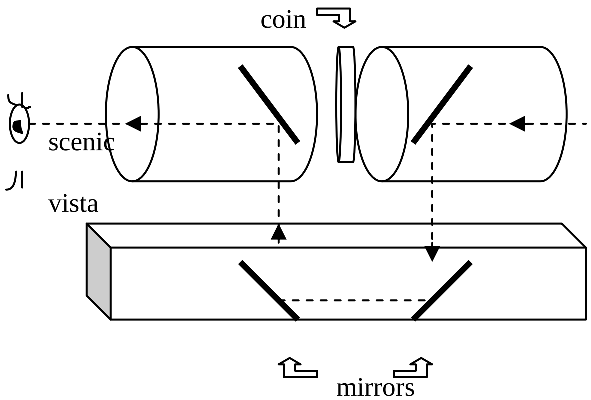
The magician opens the front flap of the box to show the audience that the box is empty. Sure enough, there is nowhere anything larger than an ant could hide; the box is obviously empty. The magician closes the flap again, perhaps covers the box with a silk cloth, intones some impressive gibberish, and, whipping off the silk, opens a top flap of the box and pulls out a white dove, which then flies in dramatic circles about the room. The audience of six-year-olds gasps in surprise and disbelief.

The trick is almost boring once you take a peek into the mechanics of the box. The picture below shows how a mirror is used to fool the audience into thinking that a box containing a dove is empty.



The mirror is positioned to reflect the bottom of the box so that the audience believes it is viewing the entire box when in actuality only half of the box is visible. Turn the box sideways and have a person sitting in the hidden region with their head extending out through a hole in the top of the box, and the talking head illusion has been created.

The x-ray toy is nothing more than two pair of mirrors aimed at 45 degree angles to shunt the light around the object (such as a coin) while making the viewer think the light is traveling a straight path.



The viewer expects to see the tube blocked by the coin, but instead, she sees the scenic vista on the other side of the cylinder.   Basically, this toy is like a pair of periscopes linked together.

5.11 Problems to Do:

1. What is the law of reflection?

2. a) What is the incident angle?

   b) What is the reflected angle?

3. How are angles measured?

4. What determines if a surface will give a specular or a diffuse reflection?

5. How far behind a flat mirror will your image seem to be if you stand 1 meter in front of the mirror?

6. Why do things seem reversed when they are seen in a mirror?

7. What is a virtual image?

8. When you look into a bathroom mirror, are you looking at a virtual image?

9. Name three places you will see virtual images.

10. Describe how to make a kaleidoscope.

11. Why must the mirrors be placed at an angle from one another that is an integral factor of 360?

12. What does a convex mirror look like?

13. Are images seen in a convex mirror:
small or enlarged?
upright or upside down?
real or virtual?

14. Where are two places that commonly use convex mirrors?

15. Do light rays which reflect off a convex mirror converge or diverge after reflection?

16. Can a virtual image be seen by a human eye?

17. Can a virtual image by photographed?

18. Can a virtual image be focused directly onto a screen similarly to how slides are focused onto a screen?

19. What is the name given to a mirror shaped like the inside of a spoon?

20. What type of image will be produced if you stand very close to a concave mirror:
Real or virtual?
Small or enlarged?
Upright or upside down?

21. How do you know if an image is real or virtual?

22. What happens if you stand at the focal point distance and look into a concave mirror?

23. What type of images are seen if you stand farther than the focal point distance from a concave mirror?

24. What happens to the light which comes from the focal point distance after it reflects off a concave mirror?

25. What is the mirror equation?

26. What can the mirror equation be used to find out?

27. When is the focal point distance considered to be negative? When is it positive?

28. When is the image distance considered to be negative? When is it positive?

29. When is the object distance considered to be negative? When is it positive?

30. You stand 10 cm in front of a convex mirror of focal point -5.0 cm. You do not need to convert distances to meters.
a) What is the image distance?
b) Does the image seem to be in front of the mirror or behind it?
c) Which is closer to the mirror: object or image?
d) Is the image real or virtual?

31. A candle is placed 50 cm in front of a mirror. Its image appears to be 75 cm **inside the mirror**.
a) Is the image real or virtual?
b) What is the focal point of the mirror?
c) Is the mirror convex or concave?

32. A picture is held up to a concave mirror. The picture is 1 meter away from the mirror. The focal point distance of the mirror is 2 meters.
a) What is the image distance?
b) Is the image in front of the mirror or behind it?
c) Is the image real or virtual?

33. The same picture is held 4 meters away from the same concave mirror as question #32.
a) What is the new image distance?
b) Is the image in front of the mirror or behind it?
c) Is the image real or virtual?

34. The same picture is held 1 meter away from a convex mirror of focal point –2 meters.
a) What is the image distance?
b) Is the image in front of the mirror or behind it?
c) Is the image real or virtual?

35. The picture is held 4 meters away from the same convex mirror as question #34.
a) What is the new image distance?
b) Is the image in front of the mirror or behind it?
c) Is the image real or virtual?

36. What are the two magnification equations?

37. What does it mean if the height is negative?

38. What does it mean if the magnification is less than one?

39. What does it mean if the magnification is equal to one?

40. What does it mean if the magnification is negative?

41. How can you use magnification to determine which type of mirror you have?

42. How can a mirror be used to start a fire? Be specific regarding mirror type and location of screen!

43. Why does the above procedure work?

44. How do funhouse mirrors create such peculiar images of people?

45. What is anamorphic art?

46. Explain one type of anamorphic art.

47. Explain a second type of anamorphic art.

48. Explain a third type of anamorphic art.

49. How can a magician make a dove suddenly appear in a previously empty box?

50. What changes could be made to the dove trick to make it appear as though a “decapitated” head were able to talk to an audience?

51. How does the “x-ray” toy work?