Mirror Imaging

Images our eyes pick up, or other optical systems capture, come from light rays emitted from or reflecting off of an object, traveling out in a straight line and into optics that manipulate the ray to form a usable image. Light rays always travel in a straight line until optics or particles manipulate them. The rays could reflect, refract, scatter, absorb, or transmit. We see objects by light reflecting off of them and our eyes pick up a tiny amount of that light and focus an image on our retina.

Many photons traveling out together in bundles of rays have wavefronts associated with their travel. Like water or sound waves, light waves oscillate out from a source, point, or extended. When the rays are bent by reflection or refraction, the wavefronts also change. Light from a point source like an arc lamp, travels out in all directions like a bobber does to the water's surface, only in all dimensions. The big difference is the wavelengths are much, much smaller, so small we cannot see them.

First, there are two basic types of reflections, specular and diffuse. Specular reflections come from surfaces that appear smooth to the incident wavelength and the wavefront is not changed, and the rays remain together as they travel. Light is bouncing off of a shiny surface, like a mirror, glass, a watch or ring, and anything else that is shiny. Specular reflections are the most dangerous because most, if not all, of the beam is continuing. A diffuse reflection is light bouncing off of a rough surface like a laser pointer on a screen or a wall. The rays and waves are totally disturbed and going in many directions. Diffuse reflections are a less hazard because the beam is being separated and split into pieces. In optics, we have two parts to image relay. There is object space and image space. Millions of rays reflecting off of every part of an object will be recombined to the same place in the image space.

Since light travels in a straight line, we can use simple geometric laws to predict what will happen with any optical element. The first is the Law of Reflection. This law has two parts. First, the reflected angle equals the incident angle. These two angles are measured from an imaginary line that is perpendicular to the reflecting surface, or in spherical optics, the line comes from the center of curvature. This line is called the "Normal." Whenever we say something is "Normal" to the surface or optic we mean it is on axis or aligned with the Normal. Second, "the incident ray, reflected ray, and surface normal all lie in the plane of incidence." Later, when we look at other optical characteristics, we will refer to this plane.

In Figure 4-5A, the mirror is lying flat and the plane of incidence is drawn in solid. You do not actually see the plane of incidence, just know that the two beams and their normal create a plane no matter what angle you come into the mirror. In Figure 4-5B, a virtual image is formed by light reflecting off of the person then off of the mirror and into her eye. It is easy to see here that if you placed a screen between the image and the mirror, you wouldn't block any light. The rays do not cross behind the mirror, they reflect off and only appear to come from the image plane. In plane mirrors, only images of the same size and distance can be created.

In imaging, we are concerned with two types of images. Real images and Virtual images. Real images are those you can project onto a screen or camera. Rays from an optical system actually meet at the image plane. If you placed a screen between the optical system and the image plane, the image will go away.

On the other hand, virtual images are not generated by crossing rays. In a virtual image plane, the rays from an optical system spread out and only appear to come from the image plane. If you place a screen between the virtual image plane and the optical system, the image remains unchanged in mirrors.

Light reflecting off of spherical surfaces still follows the Law of Reflection. The normal, again, comes from the center of the sphere or the 'center of curvature.' Now images of different sizes can be created. Example one shows different angles of incidence and how the reflected rays still follow the law of reflection. Ray "d" is coming in "normal" to the surface, so the angle of incidence is zero and the angle of reflection is zero, the light reflects right back on itself, or it reverses. Another way to manipulate the light is to refract it, or the bending as light goes into an optical element. When light makes a transition into a material that has a different 'index of refraction,' it bends. The greater the index of refraction the greater the bending. Your textbook contains a selection of optical materials and their respective indices of refraction at 589nm. Notice the index of refraction of air is close to 1. Water and ice are not the same, and germanium is extremely high. Also, remember that index of refraction is a ratio of the speed of light in a vacuum and the speed of light in the optical element. The plane of incidence includes the refracted ray along with the incident ray, reflected ray, and surface normal.

A second geometric law we can apply is the 'Law of Refraction.' The Law of Refraction also has two parts. The first part is similar to the Law of Reflection. The incident ray, refracted ray, and surface normal all lie in the plane of incidence. The second part is a little different. We can use an equation to explain Snell's Law. Here the ratio of the (sine) of both angles is a constant and is also equal to the ratio of the indices of refraction. In using Snell's Law we can predict what direction the light will bend in the second medium. Light that enters a more dense medium is bent toward the normal, or the angle of refraction is less than the angle of incidence. If light makes a transition from a more dense to a less dense medium, the ray bends away from the normal or the angle of refraction is greater than the angle of incidence.

When light is traveling from a more dense to a less dense medium, like glass to air or water to air, it is possible for the light to refract right along the surface, or the angle of refraction is 90 degrees as in figure 4-10, ray #3. This angle of incidence is call the Critical Angle. Any angle of incidence greater than the critical angle will reflect all of the light back into the more dense medium. This optical magic is called Total Internal Reflection or TIR. This example tells us that any incident angle greater than 41.8 degrees will totally reflect back into the glass. TIR comes in handy in prisms used as mirrors, fiber optics, and diamonds. Diamonds are cut at a specific apex angle to enhance the light reflecting back out of the top due to TIR. Since diamond has such a high index of refraction and low critical angle, much of the light entering the gemstone comes back out. Also, white light going into a diamond gets dispersed because the index of refraction is different for each color, and that's why we see the colors in the diamond if it is cut correctly. The two most important parts to a fiber cable are the core and the cladding. The core has a high index of refraction and the cladding has a lower index of refraction. TIR takes the light down the fiber via reflections.

When light enters and exits a prism, it will bend twice in the same direction. The ray is following the law of refraction both times. If you reference the incoming ray to the outgoing ray, and the prism is rotated

in one direction changing the angle of incidence, there will be a point where the final refracting beam stops and goes the other direction. In other words, the angle of the final refraction will approach the initial ray until it reaches its smallest angle. This angle is called the 'minimum angle of deviation,' and it happens at only one angle of incidence. Color dispersion or frequency dispersion happens when white light enters and exits a prism. Equilateral prisms generate the best color dispersion or rainbows. Prisms use TIR for different image effects. The flat edge works as a 100% reflector without any coating. Binoculars use the Porro-Prism configuration to turn the image so we don't see the image upside down, and it keeps the binoculars from being too long.

Image relay in plane mirrors is just "plain" simple. The image is virtual, so no rays cross in the image plane, and the image is always the same distance away from the mirror as the object. If two mirrors are used, multiple reflections cause more images. The smaller the angle between the mirrors, the greater the number of images. Images in plane mirrors are, well just plain. Curved or spherical mirrors can make images of different sizes and orientations. Spherical mirrors reflect rays that are parallel to the optical axis through the focal point of the mirror. This is true only to rays that are close the optical axis. Rays that are marginal or far away from the optical axis cross closer to the mirror.

The symbol 'r' or the radius is the distance from the center of the mirror to the center of curvature. Half of that distance is the focal point. So, if you have a 20 cm radius, the focal length of the mirror is 10 cm. The middle of all of the optics in an optical train is an imaginary line called the optical axis or principal axis. This is a reference line we will use in tracing out how an image is relayed through optics.

Where the optical axis intersects the mirror is a point called the vertex. We'll use the vertex of a lens to find images. The mirror on the left is a concave, positive, converging mirror. The center of curvature is on the left. The mirror on the right is a convex, negative, diverging mirror. The focal center of curvature is on the right. Parallel rays, like those that come from a distant object, converge onto the focal point of a concave mirror, and they diverge as if they are coming from the focal point of a convex mirror. A concave or positive mirror generally creates a real image in front of the mirror. However, as in a make-up mirror, if the object is closer than the focal length, the image will be magnified and virtual. Concave or negative mirrors always generate an image that is smaller, closer, upright, and virtual.

To find the image graphically, follow this procedure. This assumes you already have the mirror, optical axis, object, focal point, and center of curvature already drawn.

1. Draw a ray (R1) from the bottom of the object to the reflecting surface.
2. Draw a hidden line (HL1) parallel to R1 through the center of curvature.
    a. Ensure HL1 crosses the focal plane.
3. Draw a hidden line (HL2) from the intersection of HL1 and the focal plane.
    a. Extend it toward the point where the incident ray (R1) intersects the reflecting plane.
4. Continue this line as a solid line beyond the reflecting plane. This is the reflected ray (R1a).
5. Where the reflected ray, or hidden line 2 (HL2) appears to cross the optical axis is the image point.
6. Draw Image Plane (IP) as a hidden line perpendicular to the optical axis through the image point.

7. Draw a ray (R2) from the top of the object through the center of curvature. Insure it crosses the image plane.
    a. This ray is right on normal and retro-reflects.
8. Where this ray crosses the image plane, it represents the top of the image.
9. Draw in the image in the correct orientation.
10. Label all planes, points, and rays on your drawing.

To prove our optical system using math, it is just a matter of ratios for mirrors and lenses. Make sure you understand the labels for all object, image, and mirror or lens parameters. The ratio of object height to object distance is the same as image height to image distance. The mirror equation can be used to find image distance if the object distance and focal length or mirror radius are known.

Here is an example with a 20 cm radius concave mirror with an object that is located 50 cm away from the mirror. The real image is close to the mirror, smaller, and inverted. To find the lateral magnification of the system is the ratio of the image height to the object height. The longitudinal magnification is the ratio of the image distance to the object distance times a negative one. The sine represents the orientation of the image with respect to the object. In other words, a negative image height tells us that the image is inverted or on the other side of the optical axis as the object. Using the longitudinal magnification formula, we see the magnification is -0.25. This means the image is one quarter the size of the object and is inverted.

In a convex mirror the image characteristics are always the same, no matter where the object is located, or what the focal length of the mirror is. The virtual image in a convex or negative mirror will come out to have a negative image distance. This means that the image is located on the other side of the mirror, and the negative is also a trigger that the image is virtual.

Reflecting telescopes use mirrors to capture light from distant stars and galaxies. Some use combinations of mirrors and lenses. Using mirrors as primary optics eliminates some aberrations that distort images. Here, a Cassegrain reflector telescope uses a concave primary and a convex secondary. The convex mirror turns the image and pushes the image plane outside of the primary mirror. Telescopes have very powerful magnifications. However, the lateral and longitudinal magnifications of telescopes are tiny. The magnification listed on telescopes and binoculars is the angular magnification. Angular magnification will be discussed in a later unit.