Lens Imaging

You will now be introduced to how light travels through lenses of different types. Lenses are used in many optical systems to generate a particular size, shape, or type of image for a given application. An ideal lens will transmit 100% of the incident light on them. As rays pass the curved surface of lenses, they are bent, following the Law of Refraction, to redirect toward the image plane. The general idea behind lenses is to take rays from “object land” and relay them to “image land.” Ideally, all rays coming from a point on an object will converge to a single point in the image plane.

In the systems we’ll discuss, there are some terms you should understand before we can dive into ray tracing. The center of each optical surface is called its vertex. An imaginary line down through each vertex and representing the middle of the optical path is the “optical axis.” Objects and images will normally be centered or sitting on the optical axis.

There are six common types of lenses. Three are positive and three are negative. The positive lenses bring light rays closer to the optical axis or “converge” them. Positive lenses are generally thicker in the middle than on the edges. Positive lenses generally bring images closer to the lens system. Negative lenses push light rays further from the optical axis or “diverge” them. If parallel rays are incident on a lens, the wavefronts are planar. The lens bends the rays and the wavefronts as the light passes through. Ideally, the spherical wavefronts appear to have a center near the focal point of the lens, whether it is positive or negative.

Both lens types have two different focal points, a primary and a secondary. The primary focal point on a positive lens is on the left. The secondary is on the right. A negative lens has the focal points reversed, the secondary is on the left and the primary is on the right. Remember this for discussion in the near future. Rays coming from or headed toward the primary focal point of a lens leave the lens parallel. Rays parallel to the optical axis leave the lens toward or coming from the secondary focal point. The objective of lenses is to gather as much light as possible and focus it to create the brightest, clearest image. The brightness and sharpness are most of the time tradeoffs.

F-number and numerical aperture are measures of the acceptance or emittance cone of light for a given lens or optic. F-number is the ratio of the focal length of a lens to its diameter. A low f-number means the light bundle entering the lens is wide, however the image will not be as sharp. Low f-number lenses must be of high quality to generate good images. Image brightness is inversely proportional to the f-number. Low f-numbers mean brighter images. Photographers use f-numbers or f/stops to adjust exposure levels of images. Stopping down from an f/8 to an f/22 reduces the diameter of the aperture, reduces the total amount of light, makes the image sharper, increases the depth of field, and increases the exposure time.

Another term for light gathering ability of a lens is numerical aperture (or N.A.). Numerical Aperture is a measure of the solid angle or cone of light entering a lens or optical element. Mathematically, N.A. is equal to the index of refraction of the surrounding medium times the sine of the acceptance angle. When a lens is in only air, the index of refraction is negligible or 1. In some microscopes, oil immersion objective lenses improve N.A. by eliminating the air to glass transition and increasing the acceptance angle. In fiber optics, the N.A. describes the acceptance cone of light entering or exiting the fiber. The N.A. of the objective lens, that focuses the light into the fiber, must match the N.A. of the fiber for most efficient coupling of light.

Ray tracing is a graphical technique for finding image locations throughout optical systems. There are several methods of ray tracing. The oblique method is universal in that other methods, like 3-ray, follow the oblique method. In later courses you will practice detailed ray tracing to locate images throughout optical systems. When light travels through a lens, it refracts or bends at each surface. However, when lenses are thin enough you can use “thin lens approximation” to locate images. In thin lens approximation, both surfaces are combined to one refracting surface or plane. What else do we need to know about the optical system? The object of a certain height (h_o) is placed a known distance (p) away from the lens. The lens has a primary (f) and secondary (f’) focal point. The lens creates a certain image height (h_i) and a certain distance (q) away from the lens.

The ratio of image height to object height is the lateral magnification. As a rule for positive lenses, ‘the closer the object is to the primary focal point – the larger the image will be.’ Our eye can focus on objects relatively close by. However, if the object is too close it becomes blurry. When this happens, we say that the object is closer than what is called our near point. Everyone’s near point is a little different. If you want to find your near point, close one eye and focus on print on a paper. Move the paper slowly closer to your eye and it will go out of focus. Move it back to where the image is just in focus, and that is your near point. As we age, our lens becomes less flexible and our eye muscles are not as strong so our near point moves out. This is why grandpa holds the paper at the end of his arms reach to read the small print! On average, near points are 25 cm from the eye for young people. If we look through any magnifier like a microscope or telescope, the image we see has to be at our near point or beyond. If an object is placed within the focal point of a positive lens, the lens becomes a magnifying glass. It creates a larger virtual image behind the object. Again, remember the closer the object is to the focal point, the larger the image or the greater the lateral and longitudinal magnification (M).

Angular magnification is more important in optical systems where we are trying to magnify the image. Angular magnification is the ratio of the tangent of the angle the image makes to the optical axis versus the tangent of the angle the object makes on its own without any magnifying optics. If you have a simple magnifying glass or eyepiece, the angular magnification is the near point divided by the focal length of the lens – in centimeters!

There is no direct correlation between lateral magnification and angular magnification. A negative lens will de-magnify the object to make a much smaller image. Sometimes one lens is not adequate enough to create the correct image. Using multiple lenses can improve image characteristics for the application at hand. In general, a positive lens with the image farther than twice the focal length will generate a smaller image closer to the lens than the object. A negative lens in combination with the positive, will take that object and push it away from the positive lens and make it larger. Two positive lenses here form a telephoto lens for a camera. The distance between the lenses adjusts the magnification of the image.

Let’s look at a few common optical devices, starting with the camera. Cameras are generally taking an object that is large and creating a very small image on a screen or piece of film, or more commonly now a CCD (or charged coupling device) array, like in digital cameras. Did you know that in order to create an image on film or a screen, you do not need glass optics? An aperture in an optical system, is one of the most important elements. In a pinhole camera, a light tight enclosure and a small hole, or pinhole, that allows light to enter are the only important pieces. In the dark, place a piece of photographic paper opposite the pinhole. Close up the box and block the pinhole. Aim the pinhole at an object you wish to record, and carefully uncover the pinhole. Let it set for several minutes without disturbing it. Block the pinhole after your exposure is complete and take the paper back to the lab to process it. You should have a nice image of anything in front of the pinhole. In cameras, the aperture size determines how wide of a bundle of rays reaches the film plane. The wider the aperture, or smaller f/stop, the more light reaches the film.

Irradiance is E, A is area, and D & d are diameters of the aperture and film. Again, f/stops are very important in setting up the correct exposure. Too much light and you wash out the image, too little light and the image is dark. On the top of a camera lens, you’ll see a series of numbers, the f/stops. Each consecutive number is different by the square root of 2. For instance, 4 times the square root of 2 is 5.6. Stopping down one setting, like from f/4 to f/5.6 is cutting the irradiance in half. Irradiance or brightness of the image at the film plane is inversely proportional to the square of the f/stop. Film must be exposed with the right amount of light for the right amount of time; this is exposure. So with cameras not only do you set the aperture diameter with the f/stop; but, you also have to set the shutter speed to allow the light to hit the film for the correct time frame. There is a range of settings that will create the same exposure with cameras. This range will give you different effects in the final image. Stopping down will increase the depth of field or the range in which items are in focus. For some instances, the effect of a small depth of field is needed, so you would use the widest aperture possible that will allow the correct exposure. Changing camera lenses will allow for larger or smaller images to reach the film. A short focal length lens will generate a much wider field of view and allow more of an object to be recorded. A long focal length lens will have a narrow field of view.

Telescopes are another common optical device. A telescope consists of an objective lens or mirror, and an eyepiece. The objective lens is larger and there to gather as much light as possible to create a real image. The eyepiece is generally much smaller and has shorter focal length because it is basically magnifying the image generated by the objective. The spacing of the two lenses is the sum of their focal lengths. In telescopes, we are primarily concerned with angular magnification. Angular magnification is the ratio of the focal length of the objective to the focal length of the eyepiece. So a 50cm focal length objective and a 5mm focal length eyepiece will give you a maximum angular magnification of 100x. A B.E.T. or (Beam Expanding Telescope) is very common in the laser field. By expanding the laser beam, you have many advantages like improvement in divergence and image quality. Laser cutting systems may expand the beam in order to focus it down to a smaller spot size on a target material. This shows the relationship between angular magnification and focal lengths beam divergence before and after the B.E.T., diameter in and out of the B.E.T., and focused spot diameter with and without the B.E.T.

Binoculars are just dual terrestrial telescopes. They are labeled with their magnification and objective diameter. Sometimes the field of view is also labeled as distance across at a certain distance out. A 6x 30 pair of binoculars has a 6x angular magnification with an objective lens that is 30mm in diameter. When you place your eye near the eyepiece, you are placing it at the exit pupil of the binoculars, you are placing it in the eye relief. When your entrance pupil of your eye is at the exit pupil of the binoculars you can see the entire field of view. If you pull away, you will see a smaller blurry image of the aperture stop, it looks like a dark ring around the image. Angular field of view, if not labeled, is found by dividing the exit pupil diameter by the sum of the focal lengths of the lenses.