25.2: Other Optical Instruments

A magnifying glass is a convex lens that lets the observer see a larger image of the object under observation. The lens is usually mounted in a frame with a handle, as shown below.

Magnifying Glass: A magnifying glass is a convex lens that lets the observer see a larger image of the object under observation.

The magnification of a magnifying glass depends upon where the instrument is placed between the user's eye and the object being viewed and upon the total distance between eye and object. The magnifying power is the ratio of the sizes of the images formed on the user's retina with and without the magnifying glass. When not using the lens, the user would typically bring the object as close to the eye as possible without it becoming blurry. (This point, known as the near point, varies with age. In a young child its distance can be as short as five centimeters, while in an elderly person its distance may be as long as one or two meters.) Magnifiers are typically characterized using a "standard" value of 0.25m.

The highest magnifying power is obtained by putting the lens very close to the eye and moving both the eye and the lens together to obtain the best focus. When the lens is used this way, the magnifying power can be found with the following equation:

$$\mathrm{MP}_0=\frac{1}{4}\cdot\Phi+1 \tag{25.2.1}$$

where Φ= optical power. When the magnifying glass is held close to the object and the eye is moved away, the magnifying power is approximated by:

$$\mathrm{MP}_0=\frac{1}{4}\cdot\Phi \tag{25.2.2}$$

Typical magnifying glasses have a focal length of 25cm and an optical power of four diopters. This type of glass would be sold as a 2x magnifier, but a typical observer would see about one to two times magnification depending on the lens position.

The earliest evidence of a magnifying device was Aristophanes's "lens" from 424 BC, a glass globe filled with water. (Seneca wrote that it could be used to read letters "no matter how small or dim.") Roger Bacon described the properties of magnifying glasses in the 13th century, and eyeglasses were also developed in 13th-century Italy.

The Camera

Cameras are optical devices that allow a user to record an image of an object, either on photo paper or digitally.

What is a Camera?

A camera is a device that allows you to record images, either on film or digitally. Cameras can record images as well as movies; movies themselves got their name from moving pictures. The word camera comes from the Latin phrase *camera obscura*, which means "dark chamber. " The camera obscura was an early instrument for projecting images from slides. The camera that you use today is an evolution of the camera obscura.

A camera is usually comprised of an opening, or aperture, that allows light to enter into a hollow area and a surface that records the light at the other end. In the 20th century, these images would be stored on photographic paper that then had to be developed, but now most cameras store images digitally.

How does a Camera Work?

Cameras have a lot of components that allow them to work. Let's look at them one at a time.

The Lens

The camera lens allows the light to enter into the camera and is typically convex. There are many types of lenses that can be used, each for a different type of photography. There are lenses for close-ups, for sports, for architecture, and for portraits.

The two major features of a lens are focal length and aperture. The focal length determines the magnification of the image, and the aperture controls the light intensity. The f-number on a camera controls the shutter speed. This is the speed at which the shutter, which acts as its "eyelid," opens and closes. The larger the aperture, the smaller the f-number must be in order to get the shutter opened and closed fully. The time it takes to open and close the shutter is called the exposure. shows an example of two lenses of the same size but with different apertures.

Focus

Some cameras have a fixed focus, and only objects of a certain size at a certain distance from the camera will be in focus. Other cameras allow you to manually or automatically adjust the focus. shows a picture taken with a camera with manual focus; this allows the user to determine which objects will be in focus and which will not. The range of distance within which objects appear sharp and clear is called the depth of field.

Exposure

The aperture controls the intensity of the light entering the camera, and the shutter controls the exposure — the amount of time that the light is allowed into the camera.

Shutter

The shutter is what opens and closes to allow light through the aperture. The speed at which it opens and closes is called the f-number. For a larger aperture, the f-number is generally small for a quick shutter speed. For a smaller aperture, the f-number is larger, allowing for a slower shutter speed.

The Compound Microscope

A compound microscope is made of two convex lenses; the first, the ocular lens, is close to the eye, and the second is the objective lens.

A compound microscope uses multiple lenses to magnify an image for an observer. It is made of two convex lenses: the first, the ocular lens, is close to the eye; the second is the objective lens.

Compound microscopes are much larger, heavier and more expensive than simple microscopes because of the multiple lenses. The advantages of these microscopes, due to the multiple lenses, are the reduced chromatic aberrations and exchangeable objective lenses to adjust magnification.

shows a diagram of a compound microscope made from two convex lenses. The first lens is called the objective lens and is closest to the object being observed. The distance between the object and the objective lens is slightly longer than the focal length, f_0. The objective lens creates an enlarged image of the object, which then acts as the object for the second lens. The second or ocular lens is the eyepiece. The distance between the objective lens and the ocular lens is slightly shorter than the focal length of the ocular lens, f_e. This causes the ocular lens to act as a magnifying glass to the first image and makes it even larger. Because the final image is inverted, it is farther away from the observer's eye and thus much easier to view.

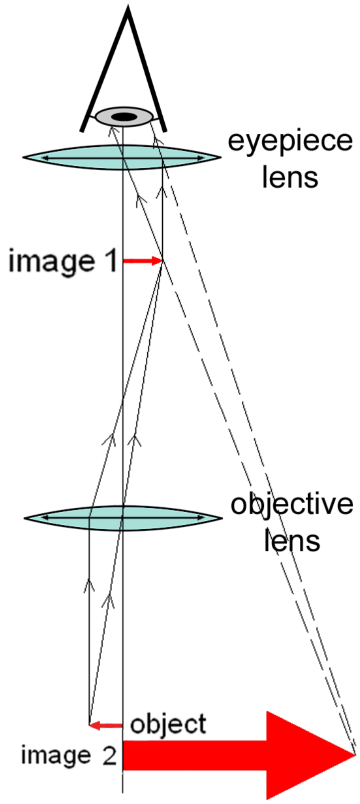


Diagram of a Compound Microscope: This diagram shows the setup of mirrors that allow for the magnification of images.

Since each lens produces a magnification that multiplies the height of the image, the total magnification is a product of the individual magnifications. The equation for calculating this is as follows:

$$\mathrm{m} = \mathrm{m_o m_e} \tag{25.2.3}$$

where m is total magnification, m_o is objective lens magnification, m_e is ocular lens magnification.

The Telescope

The telescope aids in observation of remote objects by collecting electromagnetic radiation, such as visible light.

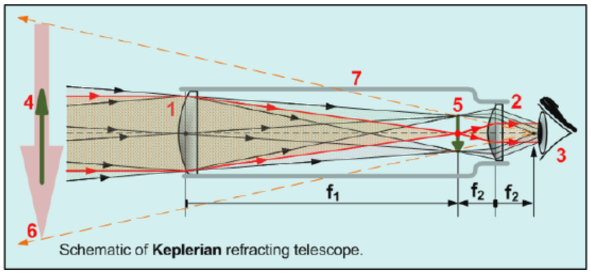
The telescope aids in observation of remote objects by collecting electromagnetic radiation, such as x-rays, visible light, infrared, and submillimeter rays. The first telescopes were invented in the Netherlands in the 1600s and used glass lenses. Shortly after, people began to build them using mirrors and called them reflecting telescopes.

History

The first telescope was a refracting telescope made by spectacle makers in the Netherlands in 1608. In 1610, Galileo made his own improved design. After the refracting telescope was invented, people began to explore the idea of a telescope that used mirrors. The potential advantages of using mirrors instead of lenses were a reduction in spherical aberrations and the elimination of chromatic aberrations. In 1668, Newton built the first practical reflecting telescope. With the invention of achromatic lenses in 1733, color aberrations were partially corrected, and shorter, more functional refracting telescopes could be constructed. Reflecting telescopes were not practical because of the highly corrosive metals used to make mirrors until the introduction of silver-coated glass mirrors in 1857.

Types of Telescopes

Refracting Telescopes



Schematic of Keplerian Refracting Telescope: All refracting telescopes use the same principles. The combination of an objective lens 1 and some type of eyepiece 2 is used to gather more light than the human eye is able to collect on its own, focus it 5, and present the viewer with a brighter, clearer, and magnified virtual image 6.

The figure above is a diagram of a refracting telescope. The objective lens (at point 1) and the eyepiece (point 2) gather more light than a human eye can collect by itself. The image is focused at point 5, and the observer is shown a brighter, magnified virtual image at point 6. The objective lens refracts, or bends, light. This causes the parallel rays to converge at a focal point, and those that are not parallel converge on a focal plane.

Reflecting Telescopes

Reflecting telescopes, such as the one shown in, use either one or a combination of curved mirrors that reflect light to form an image. They allow an observer to view objects that have very large diameters and are the primary type of telescope used in astronomy. The object being observed is reflected by a curved primary mirror onto the focal plane. (The distance from the mirror to the focal plane is called the focal length.) A sensor could be located here to record the image, or a secondary mirror could be added to redirect the light to an eyepiece.

Catadioptric Telescopes

Catadioptric telescopes, such as the one shown in, combine mirrors and lenses to form an image. This system has a greater degree of error correction than other types of telescopes. The combination of reflective and refractive elements allows for each element to correct the errors made by the other.

X-Ray Diffraction

The principle of diffraction is applied to record interference on a subatomic level in the study of x-ray crystallography.

X-ray diffraction was discovered by Max von Laue, who won the Nobel Prize in physics in 1914 for his mathematical evaluation of observed x-ray diffraction patterns.

Diffraction is the irregularities caused when waves encounter an object. You have most likely observed the effects of diffraction when looking at the bottom of a CD or DVD. The rainbow pattern that appears is a result of the light being interfered by the pits and lands on the disc that hold the data. shows this effect. Diffraction can happen to any type of wave, not just visible light waves.

Bragg Diffraction

In x-ray crystallography, the term for diffraction is Bragg diffraction, which is the scattering of waves from a crystalline structure. William Lawrence Bragg formulated the equation for Bragg's law, which relates wavelength to the angle of incidence and lattice spacing. Refer to for a diagram of the following equation: $n\lambda=2d\sin(\theta)$nλ=2dsin(θ)

- n – numeric constant known as the order of the diffracted beam
- λ – wavelength
- d – distance between lattice planes
- θ – angle of diffracted wave

The waves will experience either constructive interference or destructive interference. Similarly, the x-ray beam that is diffracted off a crystal will have some parts that have stronger energy, and others that lose energy. This depends on the wavelength and the lattice spacing.

The X-ray Diffractometer

The XRD machine uses copper metal as the element for the x-ray source. Diffraction patterns are recorded over an extended period of time, so it is very important that the beam intensity remains constant. Film used to be used to record the data, but that was inconvenient because it had to be replaced often. Now the XRD machines are equipped with semiconductor detectors. These XRD machines record images in two ways, either continuous scans or step scanning. In continuous scans, the detector moves in circular motions around the object, while a beam of x-ray is constantly shot at the detector. Pulses of energy are plotted with respect to diffraction angle. The step scan method is the more popular method. It is much more efficient than continuous scans. In this method, the detector collects data at a single fixed angle at a time. To ensure that the incident beam is continuous, XRD machines are equipped with a Soller slit. This acts like polarized sunglasses by organizing random x-ray beams into a stack of neatly arranged waves parallel to the plane of the detector.

X-Ray Imaging and CT Scans

Radiography uses x-rays to view material that cannot be seen by the human eye by identifying areas of different density and composition.

Overview

X-ray imaging, or radiography, used x-rays to view material within the body that cannot be seen by the human eye by identifying areas of different density and composition. CT Scans use the assistance of a computer to take this information, and generate 3 dimensional images.

X-ray Imaging

X-ray radiographs are produced by projecting a beam of X-rays toward an object, in medical cases, a part of the human body. Depending on the physical properties of the object (density and composition), some of the X-rays can be partially absorbed. The portion of the rays that are not absorbed then pass through the object and are recorded by either film or a detector, like in a camera. This provides the observer with a 2 dimensional representation of all the components of that object superimposed on each other. shows an image of a human elbow.

X-Ray Radiography: Radiography of the knee in a modern X-ray machine.

Tomography

Tomography refers to imaging by sections, or sectioning. demonstrates this concept. The three-dimensional image is broken down into sections. (S_1) shows a section from the left and (S_2) shows a section from the right.

CT Scans

CT scans, or computed tomography scans use a combination of X-ray radiography and tomography to produce slices of areas of the human body. Doctors can analyze the area, and based on the ability of the material to block the X-ray beam, understand more about the material. shows a CT Scan of a human brain. Doctors can cross reference the images with known properties of the same material and determine if there are any inconsistencies or problems. Although generally these scans are shown as in, the information recorded can be used to create a 3 dimensional image of the area. shows a three dimensional image of a brain that was made by compiling CT Scans.

Specialty Microscopes and Contrast

Microscopes are instruments that let the human eye see objects that would otherwise be too small.

Microscopes are instruments that let the human eye see objects that would otherwise be too small. There are many types of microscopes: optical microscopes, transmission electron microscopes, scanning electron microscopes and scanning probe microscopes.

Microscope Classes

One way to group microscopes is based on how the image is generated through the microscope. Here are three ways we can classify microscopes:

1.) Light or Photon – optical microscopes

2.) Electrons – electron microscopes

3.) Probe – scanning probe microscopes.

Microscopes can also be classified based on whether they analyze the sample by scanning a point at a time (scanning electron microscopes), or by analyzing the entire sample at once (transmission electron microscopes).

Types of Microscopes

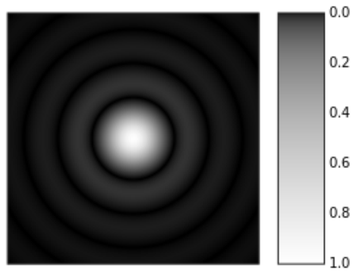
- In optical microscopes, the better the contrast between the image and the surface it is being viewed on, the better the resolution will be to the viewer. There are many illumination techniques to generate improved contrast. These techniques include "dark field" and "bright field." With the dark field technique the light is scattered by the object and the image appears to the observer on a dark background. With the bright field technique the object is illuminated from below to increase the contrast in the image seen by viewers.
- Transmission Electron Microscope: The TEM passes electrons through the sample, and allows people to see objects that are normally not seen by the naked eye. A beam of electrons is transmitted through an ultra thin specimen, interacting with the specimen as it passes through. This interaction forms an image that is magnified and focused onto an imaging device.
- Scanning Electron Microscopes: Referred to as SEM, these microscopes look at the surface of objects by scanning them with a fine electron beam. The electron beam of the microscope interacts with the electrons in the sample and produces signals that can be detected and have information about the topography and composition.
- Atomic Force Microscopy: The AFM is a scanning probe type of microscopy with very high resolution and is one of the foremost tools for imaging at the nanoscale. The mechanical probe feels the surface with a cantilever with a sharp tip. The deflection of the tip is then measured using a laser spot that is reflected from the surface of the cantilever.

Limits of Resolution and Circular Aperatures

In optical imaging, there is a fundamental limit to the resolution of any optical system that is due to diffraction.

The resolution of an optical imaging system (e.g., a microscope, telescope, or camera) can be limited by factors such as imperfections in the lenses or misalignment. However, there is a fundamental maximum to the resolution of any optical system that is due to diffraction (a wave nature of light). An optical system with the ability to produce images with angular resolution as good as the instrument's theoretical limit is said to be diffraction limited.

For telescopes with circular apertures, the size of the smallest feature in an image that is diffraction limited is the size of the Airy disc, as shown in. As one decreases the size of the aperture in a lens, diffraction increases and the ring features from diffraction become more prominent. Similarly, when imaged objects get smaller, features from diffraction begin to blur the boundary of the object. Since effects of diffraction become most prominent for waves whose wavelength is roughly similar to the dimensions of the diffracting objects, the wavelength of the imaging beam sets a fundamental limit on the resolution of any optical system.



Airy Disk: Computer-generated image of an Airy disk. The gray scale intensities have been adjusted to enhance the brightness of the outer rings of the Airy pattern.

The Abbe Diffraction Limit for a Microscope

The observation of sub-wavelength structures with microscopes is difficult because of the Abbe diffraction limit. In 1873, Ernst Abbe found that light, with wavelength λ, traveling in a medium with refractive index n, cannot be converged to a spot with a radius less than:

$$\mathrm{d}=\frac{\lambda}{2(\mathrm{n}\sin\theta)} \tag{25.2.4}$$

The denominator nsinθnsinθ is called the numerical aperture and can reach about 1.4 in modern optics, hence the Abbe limit is roughly d=λ/2. With green light around 500 nm, the Abbe limit is 250 nm which is large compared to most nanostructures, or biological cells with sizes on the order of 1μm and internal organelles which are much smaller. Using a 500 nm beam, you cannot (in principle) resolve any features with size less than around 250 nm.

Improving Resolution

To increase the resolution, shorter wavelengths can be used such as UV and X-ray microscopes. These techniques offer better resolution but are expensive, suffer from lack of contrast in biological samples and may damage the sample. There are techniques for producing images that appear to have higher resolution than allowed by simple use of diffraction-limited optics. Although these techniques improve some aspect of resolution, they generally involve an enormous increase in cost and complexity. Usually the technique is only appropriate for a small subset of imaging problems.

Aberrations

An aberration, or distortion, is a failure of rays to converge at one focus because of limitations or defects in a lens or mirror.

The Basics of Aberrations

An aberration is the failure of rays to converge at one focus because of limitations or defects in a lens or mirror. Basically, an aberration is a distortion of an image due to the fact that lenses will never behave exactly according to the way they were modeled. Types of aberrations vary due to the size, material composition, or thickness of a lens, or the position of an object.

Chromatic Aberration

A chromatic aberration, also called achromatism or chromatic distortion, is a distortion of colors. This aberration happens when the lens fails to focus all the colors on the same convergence point. This happens because lenses have a different index of refraction for different wavelengths of light. The refractive index decreases with increasing wavelength. These aberrations or distortions occur on the edges of color boundaries between bright and dark areas of an image. Since the index of refraction of lenses depends on color or wavelength, images are produced at different places and with different magnifications for different colors. shows chromatic aberration for a single convex lens. Since violet rays have a higher refractive index than red, they are bent more and focused closed to the lens. shows a two-lens system using a diverging lens to partially correct for this, but it is nearly impossible to do so completely.

The law of reflection is independent of wavelength, and therefore mirrors do not have this problem. This is why it is advantageous to use mirrors in telescopes and other optical systems.

Comatic Aberration

A comatic aberration, or coma, occurs when the object is off-center. Different parts of a lens of a mirror do not refract or reflect the image to the same point, as shown in. They can also be result of an imperfection in the lens or other component and result in off-axis point sources. These aberrations can cause objects to appear pear-shaped. They can also cause stars to appear distorted or appear to have tails, as with comets.

Other Aberrations

Spherical aberrations are a form of aberration where rays converging from the outer edges of a lens converge to a focus closer to the lens, and rays closer to the axis focus further. Astigmatisms are also a form of aberration in the lenses of the eyes where rays that propagate in two perpendicular planes have different foci. This can eventually cause a monochromatic image to distort vertically or horizontally. Another aberration or distortion is a barrel distortion where image magnification decreases with the distance from the optical axis. The apparent effect is that of an image which has been mapped around a sphere, like in a fisheye lens.

Key Points

- The magnification of a magnifying glass depends upon where it is placed between the user's eye and the object being viewed and upon the total distance between eye and object.
- The magnifying power is the ratio of the sizes of the images formed on the user's retina with and without the lens.
- The highest magnifying power is obtained by putting the lens very close to the eye and moving both the eye and the lens together to obtain the best focus.
- Cameras work very similarly to how the human eye works. The iris is similar to the lens; the pupil is similar to the aperture; and the eyelid is similar to the shutter.
- Cameras are a modern evolution of the camera obscura. The camera obscura was a device used to project images.
- The most important part of a camera is the lens, which allows the image to be magnified and focused. This can be done manually on some cameras and automatically on newer cameras.
- Movie cameras work by taking many pictures each second and then showing each image in order very quickly to give the effect that the pictures are moving. This is where the name "movie" comes from.
- A compound microscope uses multiple lenses to create an enlarged image that is easier for a human eye to see; this is due to the fact that the final image is farther away from the observer, and therefore the eye is more relaxed when viewing the image.
- The object is placed just beyond to focal length of the objective lens. An enlarged image is then captured by the objective lens, which acts as the object for the ocular lens. The ocular lens is closer to the new image than its focal length, causing it to act as a magnifying glass.
- Since the final image is just a multiple of the size of the first image, the final magnification is a product of both magnifications from each lens.
- Until the invention of silver-backed mirrors, refractive mirrors were the standard for use in telescopes. This was because of the highly corrosive nature of the metals used in older mirrors. Since then, reflective mirrors have replaced refractive mirrors in astronomy.
- There are three main types of optical telescopes: refractive, reflective, and catadioptric.
- Refractive telescopes, such as the one invented by Galileo, use an objective lens and an eyepiece. The image is focused at the focal point and allows the observer to see a brighter, larger image than they would with their own eye.
- Reflective telescopes use curved mirrors that reflect light to form an image. Sometimes a secondary mirror redirects the image to an eyepiece. Other times the image is recorded by a sensor and observed on a computer screen.
- Catadioptric telescopes combine mirrors and lenses to form an image. This system has a greater degree of error correction than other types of telescopes. The combination of reflective and refractive elements allows for each element to correct the errors made by the other.
- Diffraction is what happens when waves encounter irregularities on a surface or object and are caused to interfere with each other, either constructively or destructively.
- The Bragg law pertains to applying the laws of diffraction to crystallography in order to obtain precise images of the lattice structures in atoms.
- The x-ray diffractometer is the machine used to scan the object by shooting a wave at it and recording the interference it encounters.

- Most XRDs are equipped with a Soller slit, which acts like a polarizer for the incident beam. It makes sure that the incident beam being recorded is perfectly parallel to the object being analyzed.
- Radiography uses x-rays to take pictures of materials with in an object that can not be seen. They shoot x-ray beams through the object, and collect the rays on film or a detector on the other side. Some of the rays are absorbed into the denser materials, and this is how the image is produced.
- X-ray radiographs take images of all the materials within an object superimposed on each other.
- The traditional, superimposed images can be helpful for a number of applications, but CT scans enable the observer to see just the desired sections of a material.
- Modern CT scans can even take all the slices, or layers, and arrange them into a three-dimensional representation of the object.
- For better resolution, it is important that there is a lot of contrast between the image and the background.
- Microscopes are classified by what interacts with the object, such as light or electrons. They are also classified by whether they take images by scanning a little at a time or by taking images of the entire object at once.
- Some common types of specialty microscopes are scanning electron micrscopes (SEM), transmission electron microscopes (TEM), both of which are electron microscopes, and atomic force microscopes (ATM) which is a scanning probe microscope.
- Since effects of diffraction become most prominent for waves whose wavelength is roughly similar to the dimensions of the diffracting objects, the wavelength of the imaging beam sets a fundamental limit on the resolution of any optical system.
- The Abbe diffraction limit for a microscope is given as $\mathrm{d}=\frac{\lambda}{2(\mathrm{n}\sin\theta)}$.
- Since the diffraction limit is proportional to wavelength, to increase the resolution, shorter wavelengths can be used such as UV and X-ray microscopes.
- There are many types of aberrations, including chromatic, spherical, comatic, astigmatism, and barrel distortion.
- Chromatic aberrations occur due to the fact that lenses have different refractive indexes for different wavelengths, and therefore colors. These aberrations occur right on the edges of images between light and dark areas of the picture.
- Mirrors do not have chromatic aberrations because they do not rely on the index of refraction, but rather the index of reflection, which is independent of wavelength.
- Comatic aberrations are due to imperfections in lenses and cause the point source to be off-center. This can cause images to appear pear-shaped, or cause images to have tails, as with comets.

Key Terms

- **lens**: an object, usually made of glass, that focuses or defocuses the light that passes through it
- **diopter**: a unit of measure of the power of a lens or mirror, equal to the reciprocal of its focal length in meters. Myopia is diagnosed and measured in diopters
- **convex**: curved or bowed outward like the outside of a bowl or sphere or circle
- **shutter speed**: The duration of time for which the shutter of a camera remains open when exposing photographic film or other photosensitive material to light for the purpose of recording an image
- **chromatic aberration**: an optical aberration, in which an image has colored fringes, caused by differential refraction of light of different wavelengths
- **spherical aberration**: a type of lens aberration that causes blurriness, particularly away from the center of the lens
- **achromatic**: free from color; transmitting light without color-related distortion
- **constructive interference**: Occurs when waves interfere with each other crest to crest and the waves are exactly in phase with each other.
- **crystallography**: The experimental science of determining the arrangement of atoms in solids.
- **destructive interference**: Occurs when waves interfere with each other crest to trough (peak to valley) and are exactly out of phase with each other.
- **radiography**: The use of X-rays to view a non-uniformly composed material such as the human body.
- **tomography**: Imaging by sections or sectioning.
- **superimposed**: Positioned on or above something else, especially in layers
- **contrast**: A difference in lightness, brightness and/or hue between two colors that makes them more or less distinguishable
- **diffraction**: The bending of a wave around the edges of an opening or an obstacle.
- **nanostructure**: Any manufactured structure having a scale between molecular and microscopic.
- **aperture**: The diameter of the aperture that restricts the width of the light path through the whole system. For a telescope, this is the diameter of the objective lens (e.g., a telescope may have a 100 cm aperture).
- **distortion**: (optics) an aberration that causes magnification to change over the field of view.

- **refraction**: Changing of a light ray's direction when it passes through variations in matter.
- **aberration**: The convergence to different foci, by a lens or mirror, of rays of light emanating from one and the same point, or the deviation of such rays from a single focus; a defect in a focusing mechanism that prevents the intended focal point.

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