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Optical Lens

1.1. INTRODUCTION

Light carries information from the world to our eyes and brains. Therefore, we can see colors and shapes of the objects. It has been verified that light is a kind of electromagnetic radiation. The electromagnetic radiation is generated by the oscillation or acceleration of electrons or other electrically charged particles. The energy produced by this vibration travels in the form of electromagnetic waves. Like a water wave or the wave formed by swinging a rope, a light wave has the properties of wavelength, amplitude, period, frequency, and speed. Figure 1.1a shows light as a wave with those properties. In Figure 1.1a, wavelength is the distance between adjacent crests or troughs, measured in meters, while amplitude is the height of the wave, measured in meters. The period is the time it takes for one complete wave to pass a given point, measured in seconds. The frequency is the number of complete waves that pass a point in one second, measured in inverse seconds, or hertz (Hz). The speed is the horizontal speed of a point on a wave as it propagates, measured in meter/second. For light traveling in vacuum, the speed of light is commonly given the symbol c. It is a universal constant that has the value $c = 3 \times 10^8$ m/sec. The speed of light in a medium is generally expressed as $v = c/n$, where n is the refractive index of the medium. Since the propagation direction and the vibration direction of a light wave are perpendicular, light is a transverse wave.

To human eyes, the visible wavelength of a light wave is distributed in a range from ~380 to ~780 nm. Each color has a different wavelength. Red has the longest wavelength and violet has the shortest wavelength. When all the waves are seen together, they make white light.

Besides the wave property, light can also be considered as particles, as shown in Figure 1.1b. These particles are called photons, which carry a specific amount of energy. Light exhibits wave and particle duality, depending on what we do with it and what we try to observe. For example, light manifests wave properties through interference and diffraction, while it can be treated as particles (photons)

Introduction to Adaptive Lenses, First Edition. Hongwen Ren and Shin-Tson Wu.

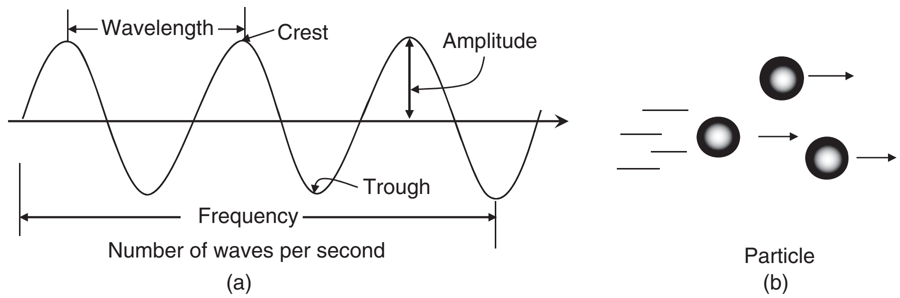

Figure 1.1. Property of light as (**a**) a wave and (**b**) particles.

through photoelectric effect [1]. The wave and particle duality nature can be linked nicely by the de Broglie relation: $p = h/\lambda$, where p is the momentum of the particle, λ is the wavelength, and h is Planck's constant.

When light interacts with matter, several phenomena could take place, such as reflection, refraction, absorption, diffraction, interference, and polarization [2]. In order to control or modulate light to achieve these optical properties, various optical devices have been developed. For example, we have mirrors to reflect light, eyeglasses to see better, telescopes to see farther, and microscopes to see objects hundreds or thousands of times larger than they actually are. Light can also be used for medicine and communication. The light from a laser can be used to perform tissue surgery. Many internet and telephone cables are now being replaced by optical fibers, which carry an enormous amount of information in a small space [3].

Many different optical devices have been developed. There is no doubt that the lens is the most widely used optical device. The lens has been studied and developed for a long history. The oldest man-made lens can be dated back to 3000 years ago. It may have been used as a magnifying glass, or as a burning glass to start fires by concentrating sunlight. Lenses have become indispensible devices in many areas. Owing to the development of optical materials, fabrication techniques, and new operation mechanisms, the performances of lenses have been improved significantly. A typical lens is made of glass, plastic, polymer, or polycarbonate. From the aspect of geometrical structure, a lens has two refraction surfaces with a perfect or approximate axial symmetry; at least one surface is a segment of a sphere. Conventional lenses are used to form images by converging or diverging the incident beam. They are used in building various optical devices and instruments, such as cameras, telescopes, microscope, projectors, optical readers, laser scanners, laser printers, fiber optical switches, and many more. Optical lenses are now the key elements in image processing, information storage, optical communication, vision correction, three-dimensional (3D) displays, and other scientific applications. The market of optical lenses is huge, and the demand of optical lenses has been growing continually. On the other hand, the development of novel optical and electronic products has evoked new concept lens. Thus, conventional solid lenses are insufficient due to their inherent shortcomings.

In this chapter, we will introduce the operation mechanism of a solid lens based on the law of light refraction. Through a lens or a lens system, the relationship between image and object are given. The merits and demerits of the lens or lens system are discussed. Inspired from the structure of human eye and human eye's operation mechanism, two possible ways of realizing an eye-like lens are anticipated.

1.2. CONVENTIONAL LENS

1.2.1. Refraction of Light

When light from a vacuum enters a medium, such as glass, water, or clear oil, it travels at a different speed. The speed of light in a given medium is related to a quantity called the index of refraction (n), which is defined as the ratio of the speed of light in vacuum (c) to the speed of light in the medium (v): $n = c/v$. When light propagates from one medium with $n = n_1$ to another with $n = n_2$, its speed changes. The change in speed is responsible for the bending of light, that is, refraction. The refraction occurs at the boundary of two media having different refractive indices. Figure 1.2 depicts the refraction of light propagating from medium 1 to medium 2.

The angles of incidence and refraction are measured relative to a line perpendicular to the boundary between the media called the normal. The media that the light passes from and to are transparent. The light will bend based on the following relationship, called Snell's law:

$$n_1 \sin\theta_i = n_2 \sin\theta_r, \tag{1.1}$$

where n_1 is the refractive index of medium 1, θ_i is the angle of incidence between the incident ray and the normal, n_2 is the refractive index of medium 2, and θ_r is the angle of refraction between the refracted ray and the normal.

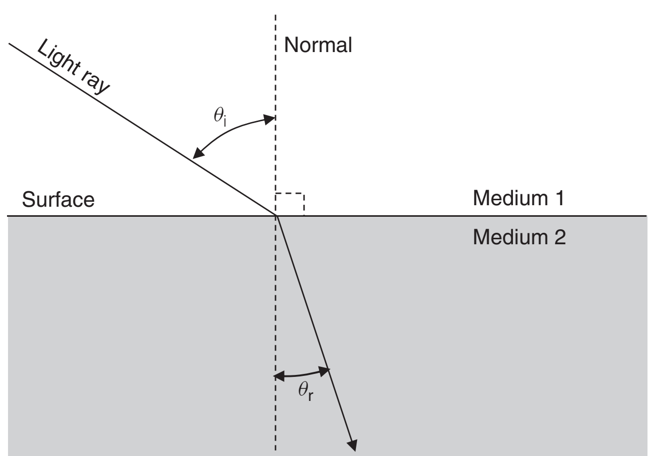

Figure 1.2. The refraction of light at the interface of two different mediums.

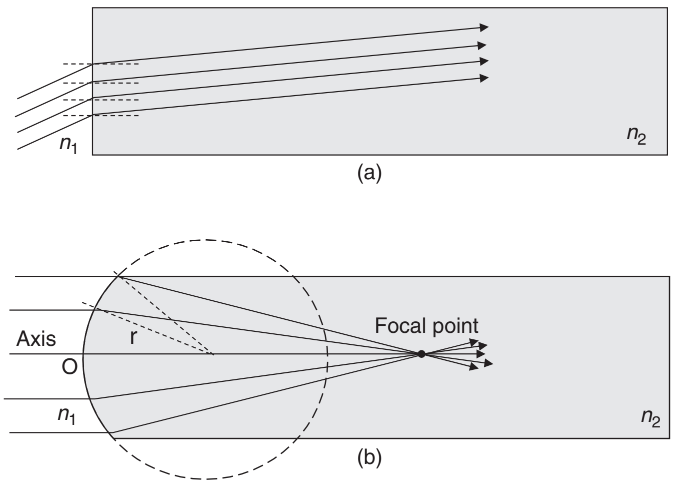

Figure 1.3. A beam of light passing through a medium with (**a**) a flat surface and (**b**) a spherical surface.

When a beam of light with parallel rays enters medium 2 at a tilted angle, the rays are bent with the same refraction angle without crossing, as shown in Figure 1.3a. As a comparison, if the surface is polished with a spherical shape, then the parallel rays of the beam are refracted with different refraction angles. Let us suppose $n_1 < n_2$, the rays come together at a point in the medium on the axis, as shown in Figure 1.3b. The point where the rays focus together is called the *focal point*. The distance from the focal point to the apex O of the curved surface is called the *focal length*. The medium has the ability to focus light because of its curved surface. Similarly, an optical lens has the ability to focus light because it employs at least one curved surface.

1.2.2. A Simple Lens

A simple lens or singlet lens is a lens consisting of a single element. A simple lens has two refraction surfaces with a perfect or approximate axial symmetry. Several types of lenses, such as spherical lens, gradient index of refraction (GRIN) lens, ball lens, and Fresnel lens, have been used in building optical instruments [2, 4]. Among them, the spherical lenses are the most commonly used ones. For a spherical lens, at least one of its surfaces exhibits a spherical shape. According to the curvature of the surfaces, they can be classified into five basic types: plano-convex, bi-convex, plano-concave, bi-concave, and convex–concave (meniscus), as shown in Figure 1.4. Plano-convex and bi-convex lenses have positive optical power. They will converge a parallel input beam into a real focal point at some distance behind the lens. Plano-concave and bi-concave elements have negative power. They will diverge a parallel input beam from a virtual point in front of the lens element. Convex–concave lenses can be either positive or negative, depending on the two

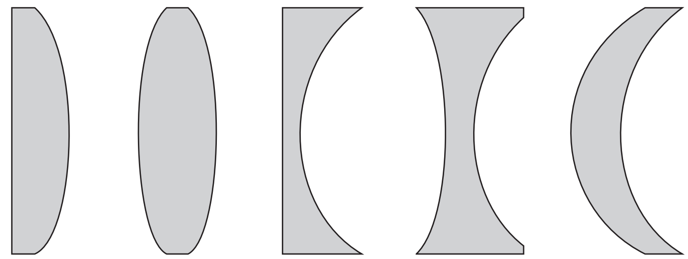

Figure 1.4. Five basic shapes of simple lenses.

surface curvatures and the thickness of the element. The operation principle of a lens (either by converging or diverging a beam of light) can be explained by Snell's law. Here, we choose a bi-convex lens, as an example, for locating an image and giving the lens focus equation. To get a perfect geometrical image, the bi-convex lens is considered as a thin lens and the rays satisfy the paraxial condition. Figure 1.5 illustrates the method of locating the image of an object placed in front of the lens. The distance between the object and the lens is S_O. One can locate the image by just tracing ray 1 and ray 2 from the top of the object. Ray 1 from the top of the object is parallel to the principal axis. After the ray is refracted through the lens, this ray passes through the focal point of the lens. Ray 2 is the undeviated ray through the center of the lens. This ray intersects with ray 1 at a point at the top of the image. This intersection point of ray 1 and ray 2 shows the location of the image on the principal axis at I. The distance from the image to the lens center is S_I. In Figure 1.5, the focal length f is a function of the object distance S_O and the image distance S_I from the lens center. Their relationship is expressed by

$$\frac{1}{S_O} + \frac{1}{S_I} = \frac{1}{f}. \tag{1.2}$$

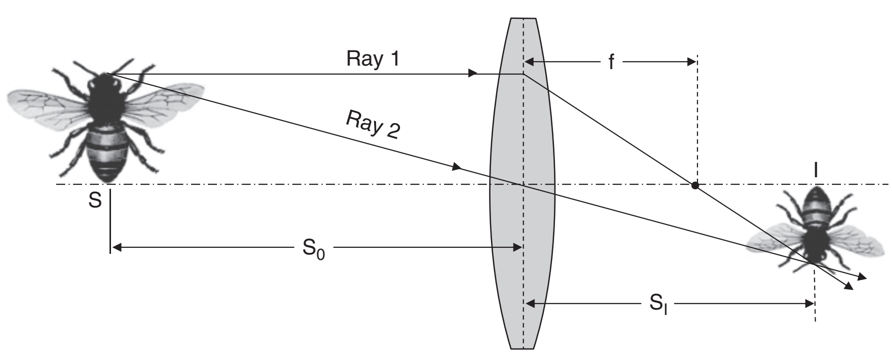

Figure 1.5. Object and image location for a thin lens.

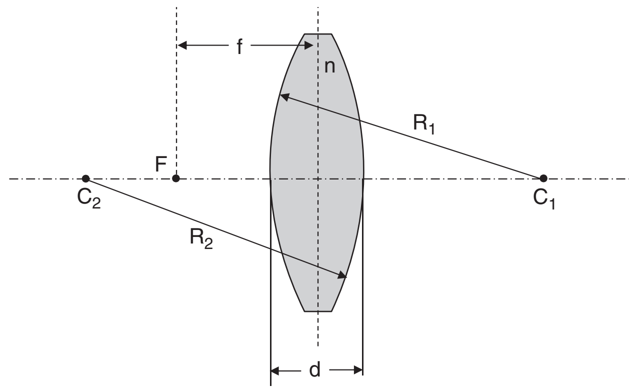

Figure 1.6. A bi-convex lens with marked parameters.

Equation (1.2) is the basic equation for thin lenses. It applies to other single lenses shown in Figure 1.4. Considering that the lens is a thin lens, the focal length of the lens is dependent on the lens geometrical structure and the refraction index of the lens material.

Figure 1.6 shows a bi-convex lens with the defined geometrical surface. The index of refraction of the lens material is n, the radius of the left surface curvature is R_1, and the radius of the right surface curvature is R_2. If the lens is thin enough ($d \to 0$), then using Gaussian's approximation, we have the very useful thin lens equation (f), often referred to as the Lensmaker's formula:

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right). \tag{1.3}$$

Equation (1.3) is also applicable to other lenses shown in Figure 1.4. If $R_1 = \infty$ and $R_2 < 0$, then the lens is the plano-convex; if $R_1 = \infty$ and $R_2 > 0$, then the lens is the plano-concave; if $R_1 < 0$ and $R_2 > 0$, then the lens is bi-concave; If $R_1 > 0$ and $R_2 > 0$, then the lens is meniscus convex or meniscus concave. Because the lenses are made of some kind of solid material such as glass, plastic, or polycarbonate, once the surfaces of the lens are formed, the radius of each surface curvature is fixed. As a result, from equation (1.3) it is impossible to change the focal length of the lens.

1.2.3. A Compound Lens

From equation (1.3), both surface curvature and refraction index of the lens cannot be changed arbitrarily. To get a variable focal length, a compound lens is required. A *compound lens* is a collection of at least two simple lenses which are arranged one after another with a common axis. The compound lenses are commonly found in cameras and other optical instruments. Figure 1.7 shows a compound lens with two convex lenses separated by a distance d, where F_1 is the focal point of lens

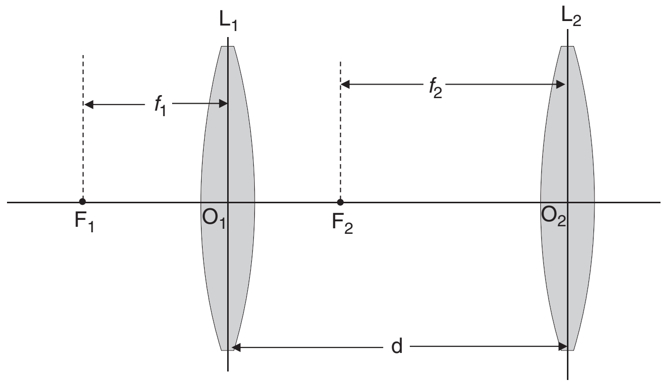

Figure 1.7. A compound lens system.

L_1 and F_2 is the focal point of lens L_2. Such a compound lens still obeys the law of refraction. If the two lenses are separated in the air by a distance d which is not too much greater than the sum of the two focal lengths, then this combination behaves as a single lens. One can use an effective focal length f to express the focal length of the two lenses. The effective focal length for the combined system is given by

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}, \tag{1.4}$$

where f_1 and f_2 are the focal lengths of lens (L_1) and lens (L_2), respectively. From equation (1.4), when the distance d is varied, the effective focal length $\boldsymbol{f}$ will be changed correspondingly. Considering the optical performance of the compound system, the distance d cannot be changed in a wide range. As a result, the associated change in focal length is rather limited. For practical applications, three or more lenses are necessary to get a wide range of focal length change by adjusting the distances among them.

1.3. ABERRATION AND RESOLUTION

1.3.1. Paraxial Optics

When an object is placed in front of a medium that has a spherically curved surface, an image is formed because the light rays are focused by the curved surface. To get a clear image, some conditions should be satisfied. To study what these conditions are, let us analyze the medium with the simplest structure as Figure 1.3b shows. To define the parameters clearly, we redraw the figure as Figure 1.8. In Figure 1.8,

- C is the center of the spherical surface.
- S is the position of the point source.

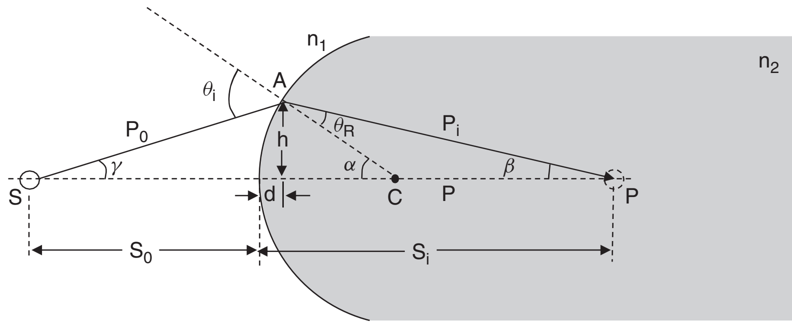

Figure 1.8. Refraction at a spherical surface.

- P is the position of the image.
- S_o is the distance of the object from the surface along the optical axis.
- S_i is the distance from the surface to the image.

A ray from the point source S strikes the curved surface at A. If $n_1 < n_2$, the light enters the medium and is bent toward the normal. If θ_i and θ_R are small and satisfy $\sin\theta \approx \theta$ (paraxial approximation), then equation (1.1) can be simplified as

$$n_1\theta_i = n_2\theta_R. \tag{1.5}$$

From Figure 1.8, $\theta_i = \gamma + \alpha$ and $\alpha = \theta_R + \beta$, we then have

$$\gamma n_1 + \beta n_2 = (n_2 - n_1)\alpha. \tag{1.6}$$

If angles γ, β, and α are small (paraxial rays), and the distance $d \ll S_o, d \ll S_i$, and $d \ll R$, then $\gamma \sim \tan\gamma = h/S_o, \beta \sim \tan\beta = h/S_i$, and $\alpha \sim \tan\alpha = h/R$. Thus, we have

$$\frac{n_1}{S_o} + \frac{n_2}{S_i} = \frac{n_2 - n_1}{R}. \tag{1.7}$$

where R is the radius of the curvature. Equation (1.7) is called Gauss's equation. If $S_i \to \infty$, then S_o is at the focal point, and the focal length f can be written as

$$\frac{n_1}{f} = \frac{n_1}{S_o} = \frac{n_2 - n_1}{R}. \tag{1.8}$$

If medium 2 has two spherical surfaces with radius R_1 and R_2, and medium 1 is air ($n_1 = 1$), then using equation (1.8), the focal length can be expressed as

$$\frac{1}{f_1} = \frac{n_2 - 1}{R_1}, \tag{1.9}$$

$$\frac{1}{f_2} = \frac{n_2 - 1}{-R_2}. \tag{1.10}$$

From equations (1.3), (1.9), and (1.10), the sum of equation (1.9) and equation (1.10) is the same as equation (1.3). From the above deduction, paraxial optics applies when rays are close to the optical axis, that is, the paraxial rays. Based on paraxial approximation, one can determine their points of convergence. In principle, these points coincide with the points of convergence of an aberration-free system. Gaussian approximation does not provide direct information about image aberrations, so it is easy for us to find the location of the paraxial focus of an optical surface, or element. While deriving equation (1.5), we only keep the first-order terms during Taylor's expansion. Thus, paraxial optics is also called first-order optics.

1.3.2. Aberration

Based on Gauss's approximation, one can construct images by using graphical methods. From Figure 1.8, point S forms a "perfect" image without any aberration. But in reality it is not exactly true, because the paraxial approximation, $\sin\theta \approx \theta$, is somewhat unsatisfactory if rays from the periphery of a lens are considered. Images formed by real lenses are never exactly identical to the predictions of the simple paraxial ray methods mentioned above. According to Snell's law, equation (1.1) can be expanded by the following form [5]:

$$n_1\left(\theta_i - \frac{\theta_i^3}{3!} + \frac{\theta_i^5}{5!} + \cdots\right) = n_2\left(\theta_R - \frac{\theta_R^3}{3!} + \frac{\theta_R^5}{5!} + \cdots\right). \tag{1.11}$$

From equation (1.11), the paraxial approximation only keeps the θ terms (first-order optics). If the θ^3 terms are included, then equation (1.7) will have a more complicated form:

$$\frac{n_1}{S_o} + \frac{n_2}{S_i} = \frac{n_2 - n_1}{R} + h^2\left[\frac{n_1}{2S_o}\left(\frac{1}{S_o} + \frac{1}{R}\right)^2 + \frac{n_2}{2S_i}\left(\frac{1}{R} - \frac{1}{S_i}\right)^2\right]. \tag{1.12}$$

The additional terms in the brackets of equation (1.12) represent the deviation from the first-order theory, and quantify the aberration of the lens. By using a monochromatic light, the aberrations are usually divided into following five broad groups [2, 6].

A. Spherical Aberration (SA). Spherical aberration (SA) is an image imperfection that is due to the spherical lens shape. For a lens made with spherical surfaces, rays that are parallel to the optic axis but at different distances from the optic axis fail to converge to the same point. The peripheral light rays are bent more than the central ones as shown in Figure 1.9. For a single, convex lens, light that strikes the lens close to the optical axis is focused at position **a**. The light that traverses the margins of the lens comes to a focus at a position **b** closer to the lens. The difference between the focal points for rays that are close to the axis and for rays that strike the lens near its edge is called *spherical aberration*. Positive

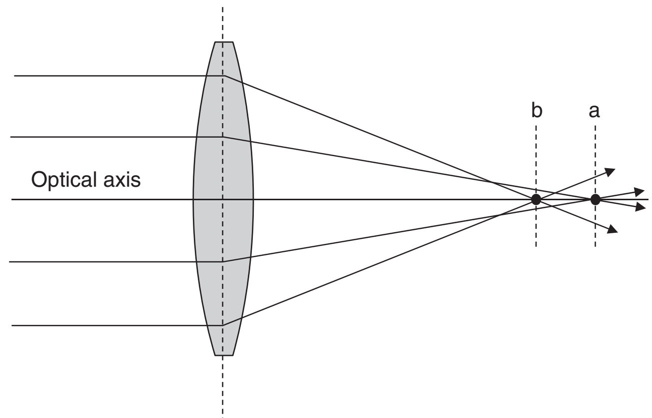

Figure 1.9. Schematic representation of spherical aberration.

spherical aberration means that rays near the edge of the lens have an effective focal point that is closer to the lens than rays that strike the lens near the axis. Negative spherical aberration means that rays near the edge of the lens have an effective focal point that is at a greater distance from the lens than rays that strike the lens near the axis.

Since the effective focal point determines the position of the image for any object, if the rays are separated into concentric zones, rays in different zones will have different focal points on its principal axis; thus several images can be formed by the lens. When these images are received in one screen, the images are overlapped and the observed image is blurred. Spherical aberration obviously increases with the diameter of the lens, and it can be minimized by limiting the opening of the lens so that only rays in the paraxial region can pass through it.

B. Coma. Coma aberration is similar to spherical aberration. It is an image degrading aberration associated with a point even a short distance from the axis. When parallel rays pass through a lens at an oblique angle (θ), as shown in Figure 1.10, the rays cannot be focused as a point, but as a comet-shaped image. Coma can be improved by stopping down the lens.

C. Astigmatism. Astigmatism is an aberration of off-axis rays that causes radial and tangential lines in the object plane to focus sharply at different distances in the image space. This effect is explained in Figure 1.11. Let us consider P as the object point. Four rays from the P point strike on the lens border. The top ray is labeled PA and the bottom ray is labeled PB. The APB plane containing both the chief ray and the optical axis is called tangential (or meridianal) plane. Rays in the tangential plane converge to a sharp image P_T if spherical aberration is corrected. The right ray is labeled PC and the left ray is labeled PD. The CPD plane containing the chief ray is called the *sagittal plane*. This plane is perpendicular to the tangential

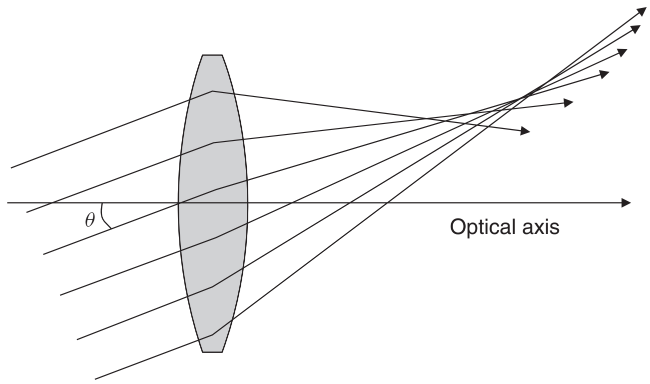

Figure 1.10. Schematic representation of coma.

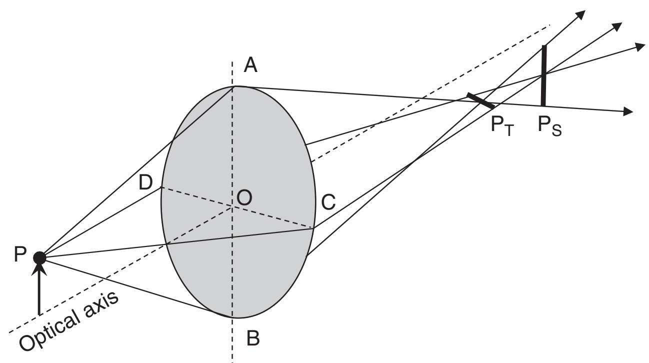

Figure 1.11. Schematic description of astigmatism aberration.

plane. For the rays in the CPD plane, they produce a sharp image P_S if coma is not considered. Light rays lying in the tangential and sagittal planes are refracted differently and both sets of rays intersect the chief ray at different image points, termed the tangential line segment P_T (tangential focal plane) and the sagittal line segment P_S (sagittal focal plane). These rays fail to produce a sharp focused point.

D. Field Curvature. Even if all of the aforementioned aberrations could be eliminated, this effect would remain. It arises because the image plane is not really a plane but a spherical surface. Figure 1.12 illustrates this effect. When a straight object PQ is placed in front of a lens, the formed image P′Q′ is curved. This is because the outer ray has a closer focus than the inner ray, causing the rays through the center of the lens to intersect the rays through the foci as shown. Constructing intermediate points between P and Q and their images subsequently shows curvature. When field curvature is present, close objects seem to have an inward curve, and far away objects seem to have an outward curve. It is possible to correct this

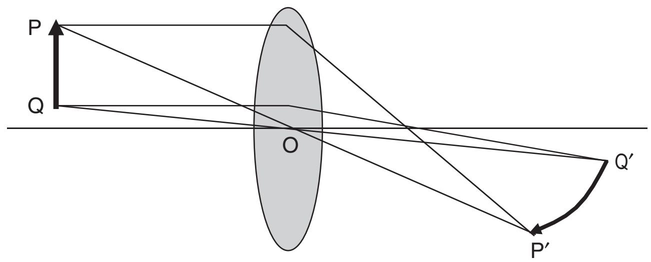

Figure 1.12. Schematic representation of field curvature.

effect using a combination of a positive lens and a negative lens that are positioned closely, and this is usually done in camera lenses.

E. Distortion. This effect is caused by variation in magnification of the image across the field of view. When the magnification of a lens differs at the edge of the lens and at the center, the image of a square object will be abnormally curved. Figure 1.13 illustrates two kinds of distortion.

In Figure 1.13a, the lens has too much magnification at its edges, causing a surfeit of magnification of the square at the corners. This is commonly called *pincushion distortion*, or *positive distortion*. In Figure 1.13b, the lens has too little power at its edges, causing a barrel, or negative distortion.

Except for the aforementioned five aberrations using a monochromatic light, when a light contains multiple wavelengths, the lens will produce chromatic aberration. When this kind of light propagates in a medium, the refractive index is wavelength-dependent; that is, the shorter wavelengths will bend more than the longer one. Therefore, a lens will not focus different colors in exactly the same place. It is possible to minimize this aberration by using two lenses made of

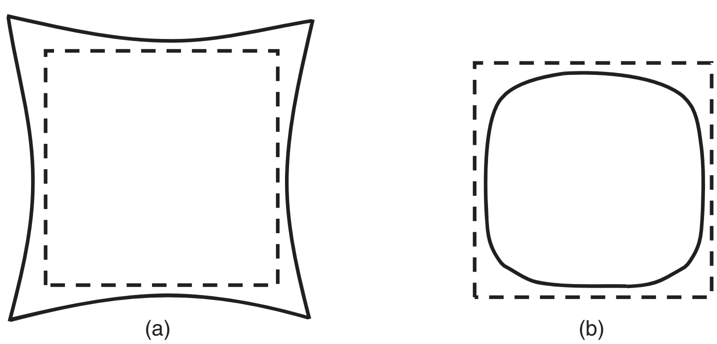

Figure 1.13. Two types of distortion. (**a**) Pincushion and (**b**) barrel.

different materials so that variation in the refractive index of one lens is canceled by the opposite variation of the other one.

1.3.3. Resolution

The observed image as shown in Figure 1.5 is not perfect due to the lens aberration. In a normal case, aberrations always exist in a simple lens or a compound lens system. The lens aberration will degrade the quality of the image. As mentioned above, spherical aberration, coma, astigmatism, field curvature, and distortion are the main aberrations for a monochromatic light. If the light contains multiple wavelengths, then the lens will produce chromatic aberration. In most cases, it does not make much sense by just evaluating only one kind of aberration. On the other hand, it will be complicated and sometimes it is impossible to evaluate all the aberrations for a lens or a compound lens at the same time, especially when the lens aperture is very small or micro-sized.

Nowadays, the quality of most optical systems is judged by the physical measures of diffraction pointed spread function (PSF), phase transfer function (PTF), or modulation transfer function (MTF). Since MTF is a direct measure of how well the various details in the object are produced in the image, MTF has become the most widely accepted criterion for specifying and judging an image quality. MTF is a quantity representing a relationship between the sample and the resultant image. To define MTF, rectangular black and white bars with specified frequency is chosen, as shown in Figure 1.14.

The frequency content is measured in line pairs/mm. One cycle contains one black line and one white line. We can measure the amount of light coming from each. The maximum amount of light will come from the white bars, and the minimum amount will from the black bars. If the light is measured in terms of radiances, the modulation (or contrast) M of a spatial frequency (ν) is given by

$$M(\nu) = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \tag{1.13}$$

where $I_{\max}$ and $I_{\min}$ stand for the maximum and minimum radiance. When modulation is defined in terms of light, it is frequently referred to as *Michelson contrast*.

Figure 1.14. Black and white gratings with low (**left**) and high frequencies (**right**).

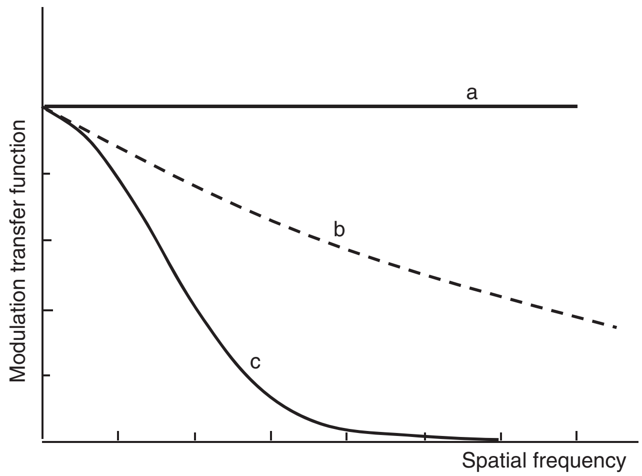

Figure 1.15. MTF plot as a function of spatial frequency for three different cases.

Now, let us assume that we have a square-wave grating of a specific frequency (υ) and modulation, and this stimulus is passed through a lens. The modulation of the image can now be measured. The MTF is defined as the ratio of image modulation to object modulation, or

$$\mathrm{MTF}(\nu) = \frac{\mathrm{M}_{\mathrm{image}}(\nu)}{\mathrm{M}_{\mathrm{object}}(\nu)}. \tag{1.14}$$

For the object with pure black and white bars, the denominator $\mathrm{M}_{\mathrm{object}}(\nu) = 1$. When describing the performance of a lens, we typically use a plot of MTF against spatial frequency. Figure 1.15 shows MTF as a function of spatial frequency at three different cases. In an ideal case, the MTF of the lens does not change even though the spatial frequency increases, as straight line a shows; in the case without any aberration, diffraction limit is the only reason to cause the MTF to decrease, as shown by line b; and in a normal case, MTF decreases quickly because of lens aberrations and diffraction limit, as line c depicts. In comparison with the diffraction-limited case, the MTF of the normal case drops much faster. The point at which we can no longer see any variation in the image is the point at which the MTF is zero, and that is the definition of the "resolution" of the lens. A lens or lens system with less aberration always gives a higher resolution.

To measure MTF, a resolution test target (such as the US Air Force three-bar test target) is widely used as the object. The pattern of one resolution test target is shown in Figure 1.16 as an example. The left-hand chart with a white background is called *positive version*. The right-hand chart with a black background is called the *negative version*. The target consists of "six" groups in three layers of patterns. The largest groups, forming the first layer, are located on outer sides. The smaller layers repeat the same pattern but are progressively smaller toward the

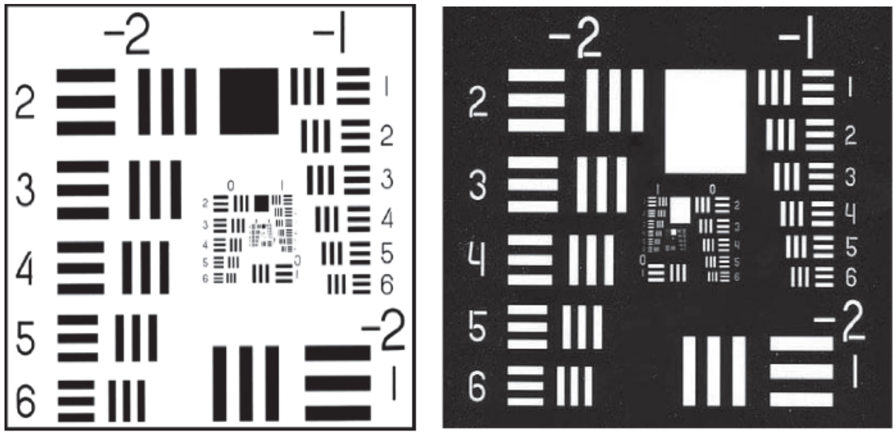

Figure 1.16. US Air Force 1951 three-bar resolution test target.

center. Each group consists of six elements. An element consists of two patterns at right angles for testing both tangential and sagittal resolution. Each pattern consists of three black lines and two white lines of equal width, with line length five times the width. Element size decreases geometrically as the sixth root of two, causing the spatial frequency to double for six element size reductions. The resolution is defined by the group and element just before the black and white bars start blending together. The resolution is expressed as

$$\text{Resolution(lp/mm)} = 2^{Group+(element-1)/6}. \qquad (1.15)$$

At the scale of the original target, the spatial frequencies range from 0.25 line pairs/mm to 228 line pairs/mm. In the following chapters, MTF (or resolution) will be the frequently used parameter to evaluate the performance of various adaptive lenses.

1.4. MERITS AND DEMERITS OF SOLID LENS

Optical lenses made of solid materials usually exhibit very good optical performances. Some key features are highlighted as follows:

A. *Controllable Geometric Shape.* Using polishing or magneto-rheological finishing (MRF) technique, the surface of an optical lens can be fabricated with spherical or parabolic shape, depending on the requirements. Using polishing technique, the lens surface can yield an extremely high degree of precision. For example, spherical lenses can achieve $\lambda/4$ or better surface accuracy at $\lambda = 632.8$ nm (He–Ne laser), but it is hard to approach the precision near $\lambda/20$ due to the limitation of the fabrication method. To decrease the spherical aberration, the lens surface can be grinded with aspherical shape. Using

MRF technique, the lens can yield surface precision to $\lambda/40$ with aspherical shape [3]. Other lenses such as Ball lens and Fresnel lens are also feasible to be fabricated using solid materials.

B. *Selection of Materials.* Optical glass, plastic, and polycarbonate are the most commonly used materials for fabricating lenses. Other materials, such as optical crystals and polymers, can also be used to fabricate some special lenses. Among them, the optical glass is the biggest family in which contains many different glasses. The selection of materials for fabricating lenses is very wide. Therefore, the performance of lens or a lens system, such as chromatic aberration, can be optimized and controlled by choosing suitable materials.

C. *Scalable Aperture Size.* For a solid, theoretically speaking, the lens aperture can be fabricated at any size. Depending on the practical applications, the apertures of solid lenses are usually distributed from micron-sized lens to meter-scaled lens. For example, for CD and CD-ROM uses, the aperture of the lens (convex) is about several hundred micrometers; for the camera lens, the aperture can reach tens of centimeters. Lenses with large aperture are often used in telescopes.

Solid lenses have several other advantages, such as broadband, high transmittance by coating a transmissive film on the lens surfaces, and high stability without the concerns of temperature change and mechanical vibration. However, solid lens has some inherit issues. For instance, the surface profile of a singlet lens is fixed once the lens is produced. To change the focal length, two or more lenses are required, thus the system is bulky and heavy. It is inefficient to adjust the focal length of the compound lens system. The dynamic response is not fast. The driving mechanism of the camera lens system is mainly mechanical.

1.5. ADAPTIVE OPTICAL LENSES

For humans, the eye is the window to the world. When light rays travel inside the eyes, we can see objects both far and near. The eye is the most important sense organ to us. Approximately 90% of information received is through the eyes. The human eye is enormously complicated—a perfect and interrelated system of about 40 individual subsystems. To know how it works and what the performances it has, we need to know the human eye structure first.

1.5.1. Eye Structure

Figure 1.17 shows a simplified diagram of the human eye. The human eye is about 2.5 cm in diameter, and the pressure of the fluid within it maintains its near-spherical shape. The eye as a whole behaves like a thick lens. We consider here only the physics of various parts of the eye.

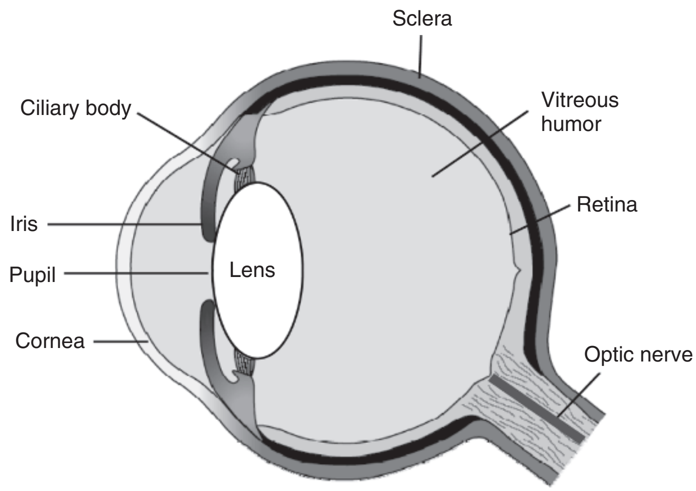

Figure 1.17. Side-view structure of the human eye.

The major parts of the human eye are cornea, pupil, iris, lens, ciliary body, vitreous humor, retina, and optic nerve [7, 8]. When the eye focuses on an object, light passes through the cornea and is regulated by the pupil opening. Light then passes through the pupil, to the lens, and further to the vitreous humor. Subsequently, the light reaches the retina. The iris is used to control the size of the pupil, so that the amount of light enters to the lens can be tuned. The retina is the light-sensitive part of the eye. Its surface is coated with millions of rods and cones [9]. The rods are sensitive to very low levels of light, but are monochromatic and cannot detect color. The cones contain three types of cones that can detect red, green, and blue lights, respectively. When these rods and cones are struck by light, they undergo a chemical reaction.

A person can view a wide range of colors because these cones work collectively to combine their respective colors to produce new colors. As these cones work together, colored signals are sent to the optic nerve and the eye's duty is finished. As the information is passed on to the optic nerve, it produces sensations of color in the visual centers of the brain.

1.5.2. Lens Character

From Figure 1.17, the lens has a bio-convex shape. It is located just behind the iris. It is held in position by zonules extending from an encircling ring of muscle. When the ciliary muscle is relaxed, the diameter of the lens curvature increases. As a result, the zonules are under tension, and the lens is flattened. When the ciliary muscle contracts, the diameter of the lens curvature decreases, the zonules relax, and the lens becomes more convex. The changes of the lens shape enable the eye to adjust its focus between far objects and near objects. The lens with changed shape

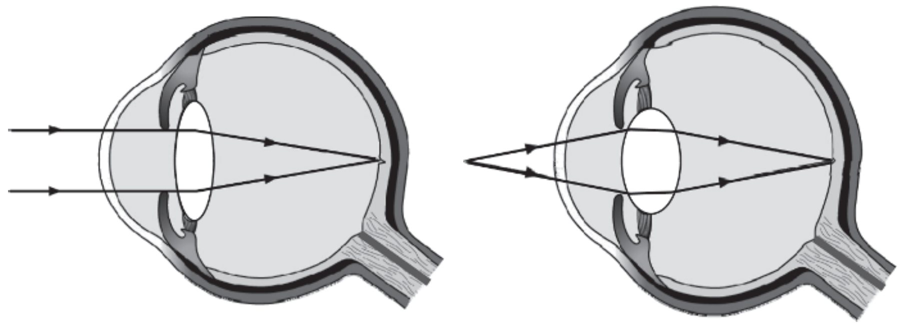

Figure 1.18. Lens for far object (**left**) and near object (**right**) vision by changing the lens shape.

for distance vision and close vision is briefly illustrated in Figure 1.18. We can see that a singlet lens can change its focal length adaptively. Such a lens functions as a compound lens or a lens system.

1.5.3. Performances

A healthy human eye perform the following functions:

A. *Broadband.* A typical human eye responds to wavelengths from about 390 to 750 nm. In terms of frequency, this corresponds to a band in the vicinity of 400–790 THz. A light-adapted eye generally has a relatively high light transmittance in the 500- to 700-nm range [9].

B. *Accommodation.* The ability of the eye to adjust its focal length is known as accommodation [10]. In the eyeball, light rays passing through the cornea are bent by its curvature toward the pupil. The lens flexes to change its curvature and finish the focusing process. When an object is located at infinity, the focal length, or the distance from the lens to the retina, is about $\sim$24 mm. When the distance between the object and the eye is shorter than 25 cm, the focal length cannot be adjusted so as to form a clear image on the retina. This distance is known as the least distance of clear vision. In this case, the focal length of the lens is $\sim$22 mm.

C. *Resolution.* Visual acuity is often measured in cycles per degree (CPD), which measures an angular resolution, or how much an eye can differentiate one object from another in terms of visual angles. Resolution in CPD can be measured by bar charts of different numbers of white/black stripe cycles. For a human eye with excellent acuity, the maximum theoretical resolution would be 1.2 arc-minute per line pair, or a 0.35 mm/line pair, at 1 m.

D. *Response Time.* The response time means the reaction time of accommodation responding to sudden changes in focus. Research results show that the average values obtained for movement time are 0.64 sec for far-to-near accommodation and 0.56 sec for near-to-far accommodation.

E. *Efficiency.* When a human eye moves its focus from one object to another, the adjusted focal length is very accurate without obvious defocus. In comparison with a conventional lens system which is operated mechanically, such as a camera lens system, the focal length adjustment exhibits high efficiency. The operation of the human eye belongs to adaptive focus rather than mechanical focus.

In addition to the above mentioned properties, the human eye has some other unique properties, such as multiple axes, rotatable movement, and wide field of vision angle (greater than 90° in the temporal field) [7].

1.5.4. The Eye-Inspired Lens

A healthy human eye exhibits high optical performances. It is a wonderful optical device. Such an optical device has inspired many scientists to develop eye-like adaptive lenses. One example is modern cameras that operate on the same basic principle as our eyes. In the past decades, various adaptive lenses have been developed. They can be roughly classified into two categories: surface profile change and refractive index change.

A. Surface Profile Change. Like a human eye, most diverging or converging light of adaptive lenses is due to the shape deformation. Usually the material used for the lens is elastic solid or fluidic liquid. Figure 1.19 shows the side-view structures of two different approaches for deforming the shape of a lens. Suppose the lens is placed in horizontal direction and its center locates on x axis. In Figure 1.19a, the volume of the lens keeps constant. In the original state, the aperture (diameter) of the lens is ab (the dashed line). After deformation, the aperture of the lens becomes $a'b'$ (the solid line). For this kind of lens, both surface curvature and the lens aperture change. For example, an aperture stretchable elastomeric solid lens [11, 12], an electrowetting lens [13], and a dielectric liquid lens [14, 15] are this kind of lens. In Figure 1.19b, the aperture of the lens (ab) does not change, but the volume of the lens increases (the solid curve) or decreases (the dashed curve). Therefore, the shape of the lens surface will change accordingly. Conventional elastic membrane lens belongs to this kind of lens. In Chapters 2, 3, and 4, we will describe some important lenses that work based on these two principles.

B. Refractive Index Change. Unlike the lens with a shape change, a lens can also exhibit a variable focal length due to the change of refractive index. Figure 1.20 depicts the variable refractive index of the lens material across the lens aperture. Let us assume that the refractive index of the material can be varied by an external voltage. In the original state, the material gives a uniform refractive index distribution across the lens aperture, the flat line as Figure 1.20 shows. When an external voltage is applied to the material, it gives a refractive index with gradient distribution across the lens aperture, as shown in the curved line in Figure 1.20.

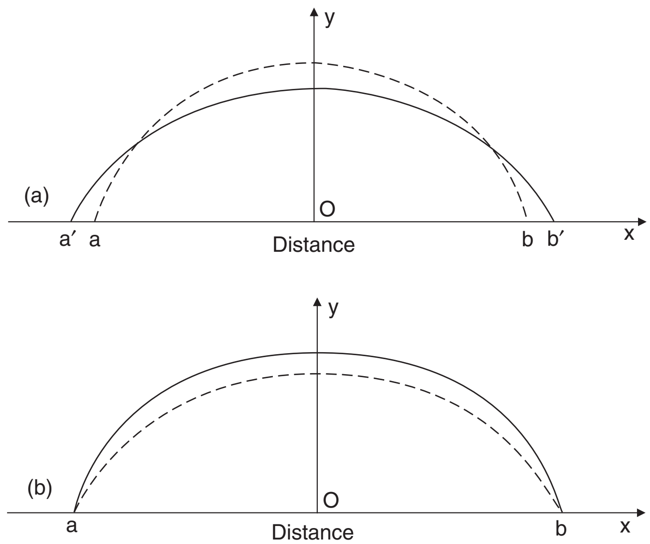

Figure 1.19. Two basic approaches for deforming a lens shape.

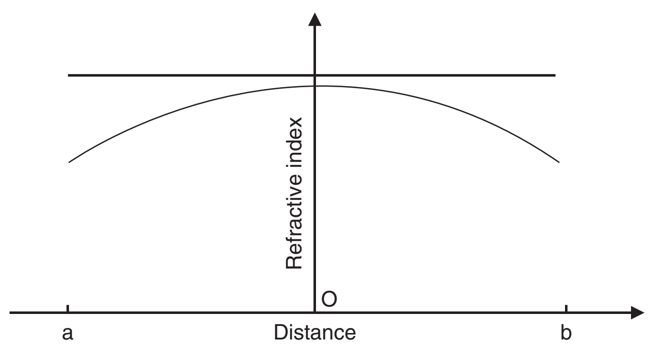

Figure 1.20. Distribution of refraction index across the lens aperture.

Devices with such a refractive index change will behave as a lens. Liquid crystal (LC) is the material that can realize such a refractive index distribution [16, 17]. In Chapter 6, we will describe the performances of tunable focus LC lenses based on the principle of refractive index redistribution.

In summary, light has wave and particle dual natures. Light manifests in many forms, such as reflection, refraction, diffraction, interference, or polarization when it enters a new medium. According to Snell's law, when the surface of a new medium is curved, light will converge or diverge depending on whether its refractive index is larger or smaller than that of the previous medium. A lens can converge or diverge light because it has at least one curved surface.

Solid lenses made of glass, plastic, polymer, or polycarbonate have a fixed focal length. To change the focal length, a compound lens with two or more lenses is required. The focal length of the lens system can be adjusted by varying the distance between the lenses. Such a lens system offers high image quality, but it is bulky, heavy, inefficient, and costly.

Aberrations are commonly present with a lens or a lens system. To evaluate the lens performance, a convenient method is to use the resolution target to test the image quality.

The human eye is a naturally formed adaptive optic lens. A healthy human eye can arbitrarily vary its focal length and also exhibits many advantages over a conventional solid lens. Inspired by the human eye, various adaptive lenses based on the shape change of a surface profile and refractive index change of the lens material have been demonstrated. Some examples will be given in detail in the following chapters.

1.6. HOMEWORK PROBLEMS

1. When your eye is relaxed, does the lens have its largest or shortest focal length?
2. From the human eye structure, as shown in Figure 1.18, the index of refraction of vitreous humor is $n_i = 1.33$, and the distance from lens to retina is $s_i =$ 24 mm. Estimate the "accommodation" of the eye when observing object located from infinity to 25 cm.
3. In a human eye, the distance between the lens and the retina (called image distance) always keeps constant when the focal length of the lens and the distance from the object to the lens change. If a compound lens is used to mimic the human eye's: variable focal length without changing the image distance, at least how many lenses are required in the lens system?

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