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OPTICS

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Consequently, a photon takes the same time to traverse any one path; all the phasors (each assumed to be the same size) have the same phase angle. Thus, they all contribute equally to the likelihood of a photon arriving at P. Putting the phasors tip-to-tail results in a very large net amplitude, which when squared yields a very high probability of light reaching P via the lens. In the language of QED, ***a lens focuses light, by causing all the constituent probability amplitudes to have the same phase angle***.

For other points in the plane containing P that are close to the optical axis, the phase angles will differ proportionately. The phasors placed tip-to-tail will gradually spiral, and the net probability amplitude will initially diminish quickly, but not discontinuously so. Notice that the probability distribution is not a single infinitesimally narrow spike; the light cannot be focused to a point. The phasors for off-axis points cannot all at once add to zero; what happens, happens gradually and continuously. The resulting circularly symmetric probability distribution, $I(r)$, is known as the Airy pattern (p. 469).

5.3 Stops

5.3.1 Aperture and Field Stops

The intrinsically finite nature of all lenses demands that they collect only a fraction of the energy emitted by a point source. The physical limitation presented by the periphery of a simple lens therefore determines which rays shall enter the system to form an image. In that respect, the unobstructed or *clear diameter* of the lens functions as an aperture into which energy flows. Any element, be it the rim of a lens or a separate diaphragm, that determines the amount of light reaching the image is known as the **aperture stop** (abbreviated A.S.). The adjustable leaf diaphragm that is usually located behind the first few elements of a compound camera lens is just such an aperture stop. Evidently, it determines the light-gathering capability of the lens as a whole. As shown in Fig. 5.33, highly oblique rays can still enter a system of this sort. Usually, however, they are deliberately restricted in order to control the quality of the image. The element limiting the size or angular breadth of the object that can be imaged by the system is called the **field stop** or F.S.—it determines the field of view of the instrument. In a camera, the edge of the film itself bounds the image plane and serves as the field stop. Thus, while the aperture stop controls the number of rays from an object point reaching the conjugate image point (Fig. 5.33), it is the field stop that will or will not obstruct those rays *in toto*. Neither the region above the top nor the region below the bottom of the object in Fig. 5.33 passes the field stop. Opening the circular aperture stop would cause the system to accept a larger energy cone and in so doing increase the irradiance at each image point. In contrast, opening the field stop would allow the regions beyond the extremities of the object, which were previously blocked, to be imaged.

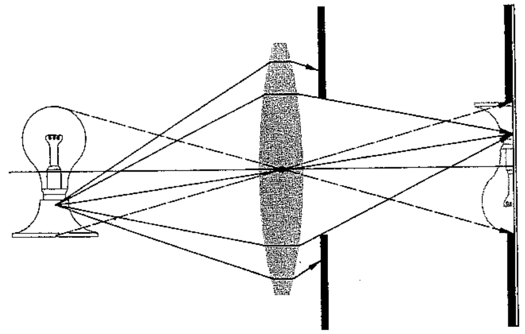

Figure 5.33 Aperture stop and field stop.

5.3.2 Entrance and Exit Pupils

Another concept, useful in determining whether or not a given ray will traverse the entire optical system, is the *pupil*. This is simply an *image of the aperture stop*. The **entrance pupil** of a system is the ***image of the aperture stop as seen from an axial point on the object through those elements preceding the stop***. If there are no lenses between the object and the A.S., the latter itself serves as the entrance pupil. To illustrate the point, examine Fig. 5.34, which is a lens with a *rear aperture stop*. The image of the aperture stop in L is virtual (see Table 5.3) and magnified. It can be located by sending a few rays out from the edges of the A.S. in the usual way. In contrast, the

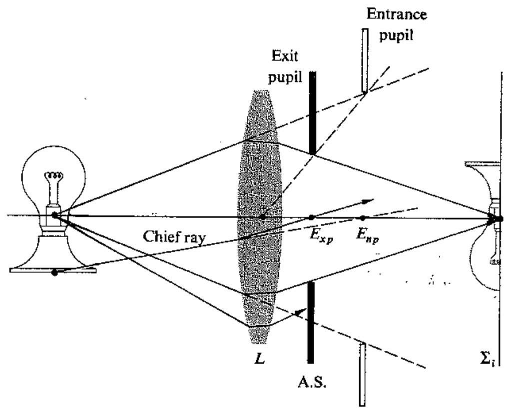

Figure 5.34 Entrance pupil and exit pupil.

exit pupil is the ***image of the A.S. as seen from an axial point on the image plane through the interposed lenses, if there are any***. In Fig. 5.34 there are no such lenses, so the aperture stop itself serves as the exit pupil. Notice that all of this just means that the cone of light actually entering the optical system is determined by the entrance pupil, whereas the cone leaving it is controlled by the exit pupil. No rays from the source point proceeding outside of either cone will make it to the image plane.

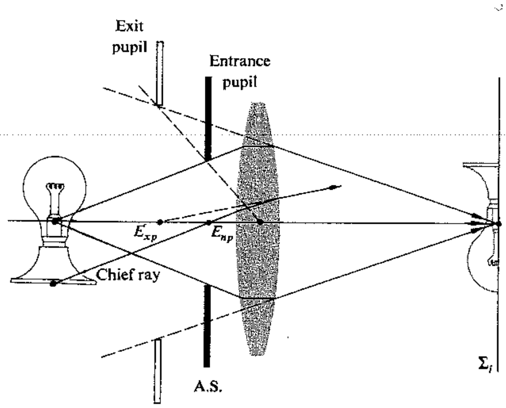

Figure 5.35 A front aperture stop.

To use a telescope or a monocular as a camera lens, you might attach an external *front aperture stop* to control the amount of incoming light for exposure purposes. Figure 5.35 represents a similar arrangement in which the entrance and exit pupil locations should be self-evident. The last two diagrams include a ray labeled the **chief ray**. It is defined to be *any ray from an off-axis object point that passes through the center of the aperture stop. The chief ray enters the optical system along a line directed toward the midpoint of the entrance pupil, E_{np}, and leaves the system along a line passing through the center of the exit pupil, E_{xp}.* The chief ray, associated with a conical bundle of rays from a point on the object, effectively behaves as the central ray of the bundle and is representative of it. Chief rays are of particular importance when the aberrations of a lens design are being corrected.

Figure 5.36 depicts a somewhat more involved arrangement. The two rays shown are those that are usually traced through an optical system. One is the chief ray from a point on the periphery of the object that is to be accommodated by the system. The other is called a **marginal ray**, since it goes from the axial object point to the rim or margin of the entrance pupil (or aperture stop).

In a situation where it is not clear which element is the actual aperture stop, each component of the system must be imaged by the remaining elements to its left. *The image that subtends the smallest angle at the axial object point is the entrance pupil.* The element whose image is the entrance pupil is then the aperture stop of the system for that object point. Problem 5.44 deals with just this kind of calculation.

Notice how the cone of rays, in Fig. 5.37, that can reach the image plane becomes narrower as the object point moves off-axis. The effective aperture stop, which for the axial bundle of rays was the rim of L_1, has been markedly reduced for the off-axis bundle. The result is a gradual fading out of the image at points near its periphery, a process known as **vignetting**.

The locations and sizes of the pupils of an optical system are of considerable practical importance. In visual instruments, the observer's eye is positioned at the center of the exit pupil. The pupil of the eye itself will vary from 2 mm to about 8 mm, depending on the general illumination level. Thus a telescope or binocular designed primarily for evening use might have an exit pupil of at least 8 mm. (You may have

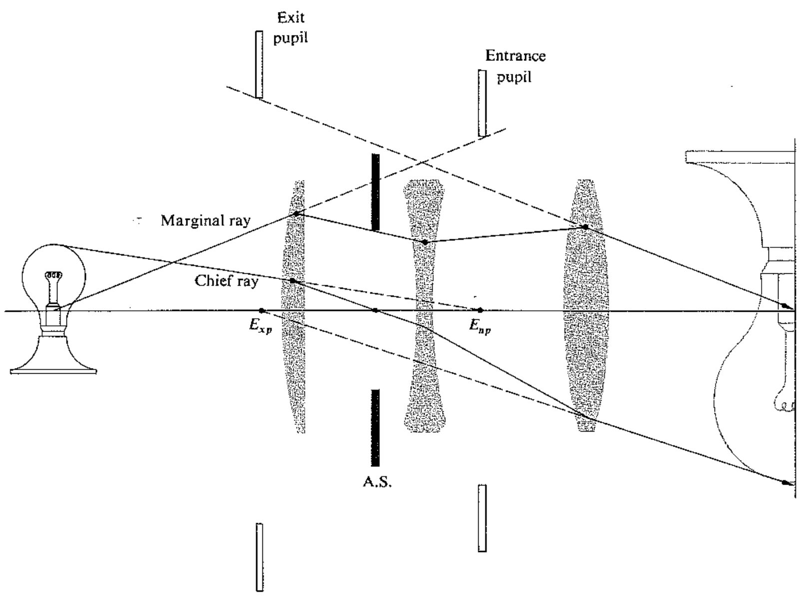

Figure 5.36 Pupils and stops for a three-lens system.

heard the term *night glasses*—they were quite popular on roofs during the Second World War.) In contrast, a daylight version will suffice with an exit pupil of 3 or 4 mm. The larger the exit pupil, the easier it is to align your eye properly with the instrument. Obviously, a telescopic sight for a high-powered rifle should have a large exit pupil located far enough behind the scope so as to avoid injury from recoil.

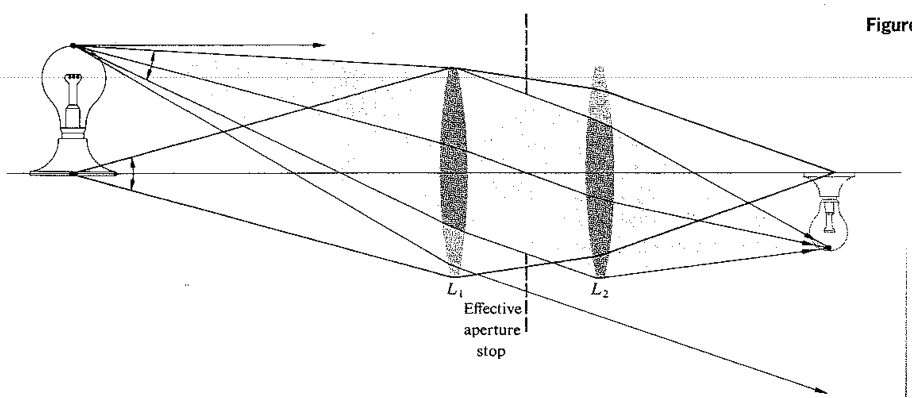

Figure 5.37 Vignetting.

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