

# APERTURES

## Aperture Stop, Entrance Pupil, and Exit Pupil

Remember, there are four things apertures do in an optical system:



Apertures control the amount of light that gets into an optical system and hence the intensity of the image formed by the system.



Apertures determine the field of view of an optical system.



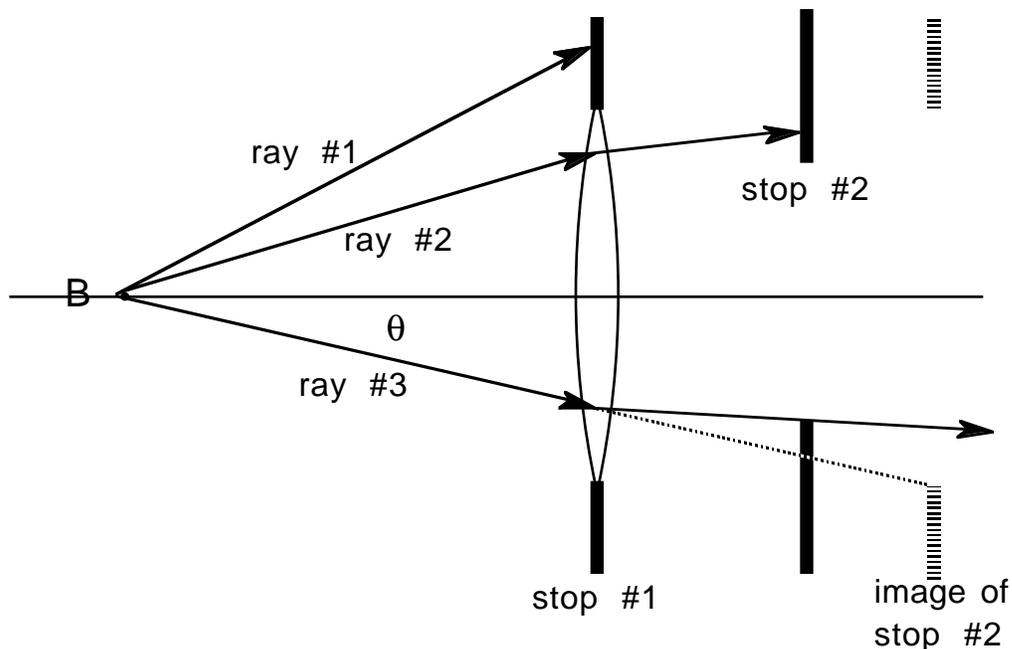
Apertures determine the amount of blur of an out-of-focus image and hence the depth of field and focus of an optical system.



Apertures determine the diffraction limit on resolution of the optical system.

The first three of these are geometric optics effects which we discussed in the context of a simple camera, i.e. a thin lens surrounded by an aperture forming pictures on film. Now we're going to extend the discussion to lens systems which have multiple refractive surfaces and multiple apertures. For example, a photographic objective.

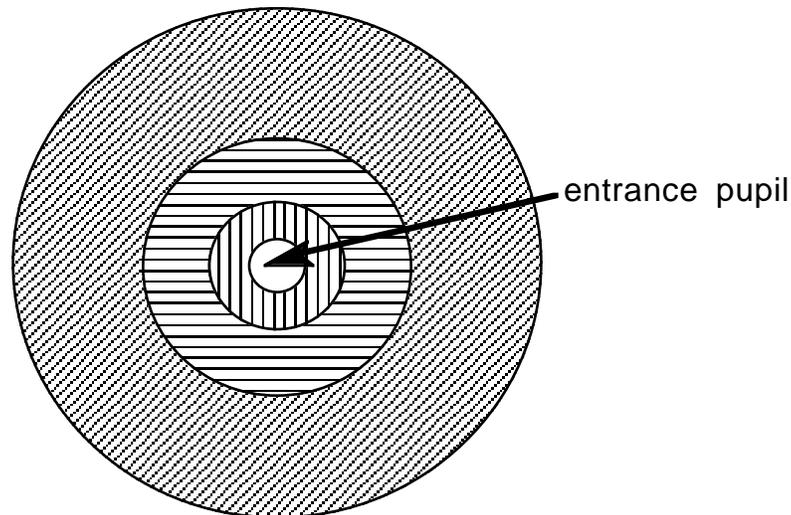
Let's consider a simple example, a converging lens with its aperture in front of another aperture, as shown below.



What rays from axial object B can get through this optical system? Clearly rays that make too big an angle with the optical axis won't get through. Ray #1, for example, runs into stop #1. Ray #2 gets through stop #1, but hits stop #2 after being refracted by the lens. Ray #3 just barely gets through, grazing the edge of stop #2 after being refracted by the lens. Clearly any ray making a smaller angle with the axis than ray #3 will get through. Stop #2 is the limiting aperture in the system. It is called the aperture stop of the system. Stop #1 plays no role in determining how much light gets into the system and can be ignored in that context. From the diagram, the limiting angle on rays entering the system is  $\theta$ . But from the figure,  $\theta$  is the subtense of the image of stop #2, the aperture stop, formed by the lens. That image is called the entrance pupil of the system. Note that the entrance pupil subtends a smaller angle at B than stop #1, the only other stop in the system.

The simple example above may readily be generalized. In any real optical system there are multiple apertures, but only one, the aperture stop, determines which rays traverse the system and, as result, the intensity of images. It is the stop whose image subtends the smallest angle at the object. That image is called the entrance pupil.

To determine the entrance pupil experimentally, put an observer at the object. Have the observer look into the optical system. The stop or stop image that subtends the smallest image is the entrance pupil.



The diagram above shows an observer's eye view of the stop images in an optical system. Clearly the vertically striped stop is the aperture stop and the circle indicated is the entrance pupil.

Mathematically, the entrance pupil may be determined by finding all stop images and determining which subtends the smallest angle at the object. This is a time consuming process if there are many apertures and lenses in the system.

Remember, the entrance pupil is the image of the aperture stop through **all** the lenses, if any, that stand between the aperture stop and object space.

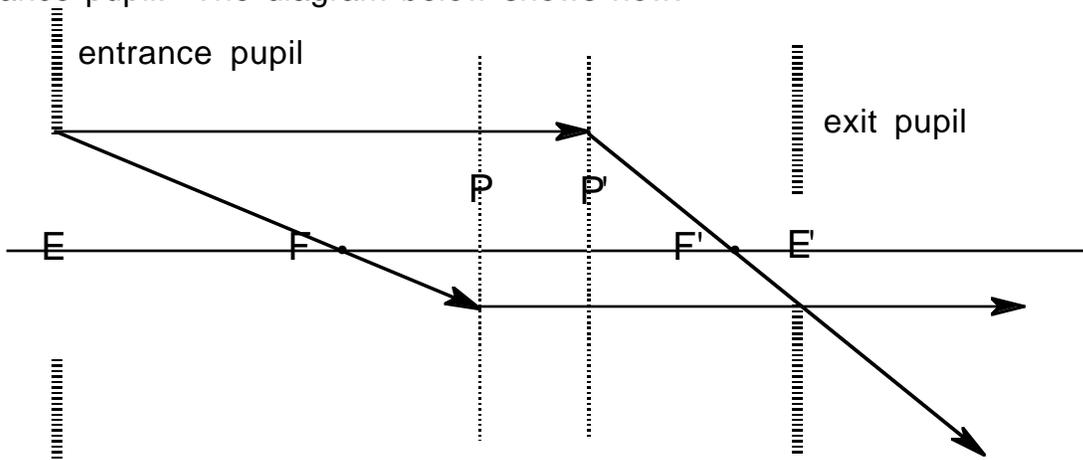
The entrance pupil takes over the role of the lens rim in the simple camera we discussed earlier. The f/number, for example, is defined for a thick lens as

$$f/\text{number} = \text{equivalent focal length} \div \text{entrance pupil diameter}.$$

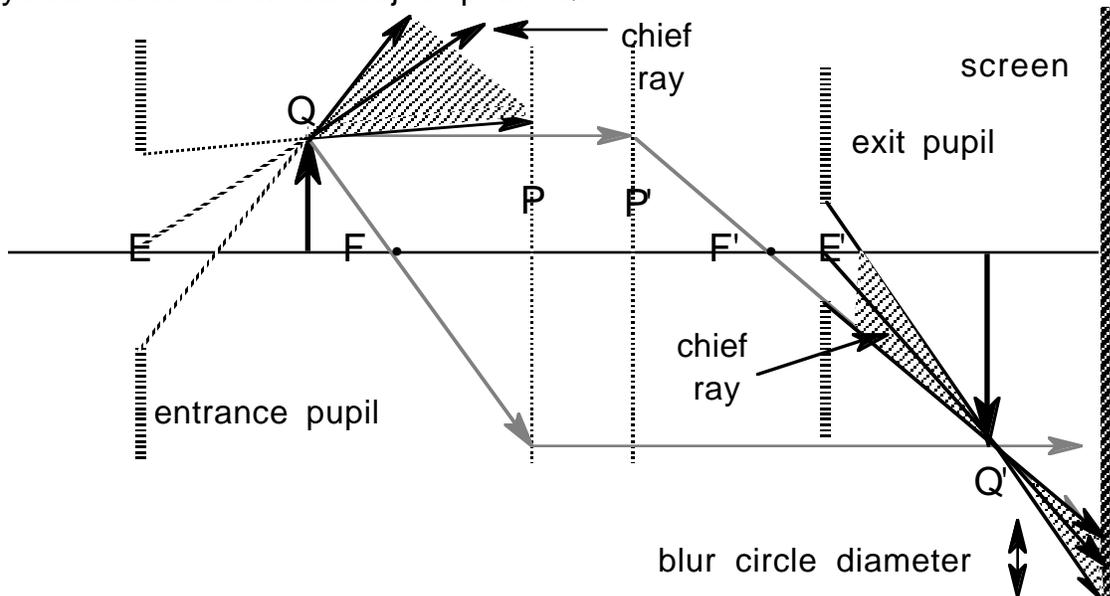
The equivalent focal length,  $f'$ , is the reciprocal of the equivalent power.

So if the image of the aperture stop in object space is the entrance pupil, what would we call the image of the aperture stop in image space? The exit pupil of course! Since they are both conjugate to the aperture stop,

the entrance and exit pupils are conjugate to one another. That means we can use geometric ray tracing to find the exit pupil if we know the entrance pupil. The diagram below shows how:



The exit pupil determines the amount of image blur. In the following diagram we construct the beams of light entering and leaving the optical system above from an object point Q.

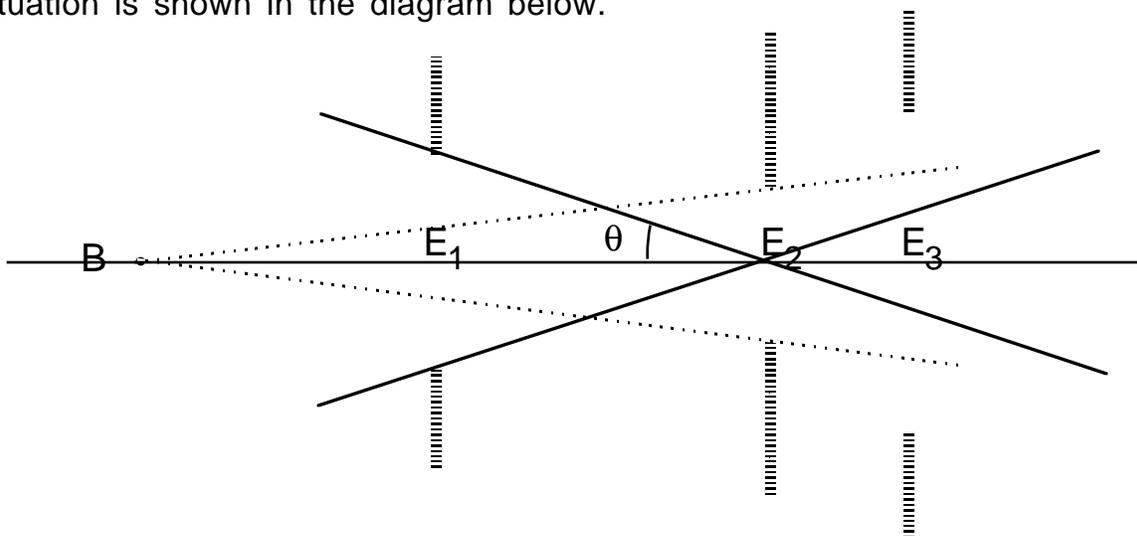


In the rather complicated diagram above, the gray rays are construction rays. These rays would not actually get through the system, but can be used to construct the image. The areas with diagonal shading are part of the beam that actually gets through the system. Note that the entrance pupil determines the entering beam even though it sits behind the object. The portion of the exiting beam that reaches the screen at the right determines the degree of blur. The chief ray is the ray through the center of the entrance pupil. It exits through the center of the exit pupil and then goes to the center of the blur circle. Its direction characterizes the beam.

## Entrance and Exit Ports

The simple camera we discussed earlier had two apertures; the rim of the lens which limited the amount of light admitted to the camera and determined image illuminance and blur, and the border of the film which determined the field of view of the camera. In a general optical system, the entrance pupil assumes the role of the lens rim in the simple camera, but what determines field of view?

Consider an optical system with several stops. Experimentally or theoretically, the images of all the stops through the optics in front of them is found. The resulting pupils are called  $E_1$ ,  $E_2$ ,  $E_3$ , etc. This situation is shown in the diagram below.



Clearly  $E_2$  is the entrance pupil since it subtends the smallest angle at  $B$ . Now look for the pupil that subtends the smallest angle at  $E_2$ . Clearly that is  $E_1$ .  $E_1$  is called the entrance port and the half angle  $\theta$  it subtends at  $E_2$  is the half angle field of half illumination. This is because less than half the light from a point source outside this field of view will traverse the optical system. The rest will be blocked by the entrance port on the way to or from the entrance pupil. Note that the field of view defined this way depends only on the entrance pupil location, not on the entrance pupil size. The stop for which  $E_1$  is the image is called the field stop, which figures since it determines the field of view. The image of the field stop in image space is called the exit port.

Incidentally, when two apertures like the aperture stop and field stop combine to limit field of view it's called vignetting.