

# Definition of Terms

## FOCAL LENGTH ( $f$ )

Two distinct terms describe the focal lengths associated with every lens or lens system. The effective focal length (EFL) or equivalent focal length (denoted  $f$  in figure 1.33) determines magnification and hence the image size. The term  $f$  appears frequently in lens formulas and in the tables of standard lenses. Unfortunately, because  $f$  is measured with reference to principal points which are usually inside the lens, the meaning of  $f$  is not immediately apparent when a lens is visually inspected.

The second type of focal length relates the focal plane positions directly to landmarks on the lens surfaces (namely the vertices) which are immediately recognizable. It is not simply related to image size but is especially convenient for use when one is concerned about correct lens positioning or mechanical clearances. Examples of this second type of focal length are the front focal length (FFL, denoted  $f_f$  in figure 1.33) and the back focal length (BFL, denoted  $f_b$ ).

The convention in all of the figures (with the exception of a single deliberately reversed ray) is that light travels from left to right.

## FOCAL POINT (F OR F'')

Rays that pass through or originate at either focal point must be, on the opposite side of the lens, parallel to the optical axis. This fact is the basis for locating both focal points.

## PRIMARY PRINCIPAL SURFACE

Let us imagine that rays originating at the front focal point F (and therefore parallel to the optical axis after emergence from the opposite side of the lens) are singly refracted at some imaginary surface, instead of twice refracted (once at each lens surface) as actually happens. There is a unique imaginary surface, called the principal surface, at which this can happen.

To locate this unique surface, consider a single ray traced from the air on one side of the lens, through the lens and into the air on the other side. The ray is broken into three segments by the lens. Two of these are external (in the air), and the third is internal (in the glass). The external segments can be extended to a common point of intersection (certainly near, and usually within, the lens). The principal surface is the locus of all such

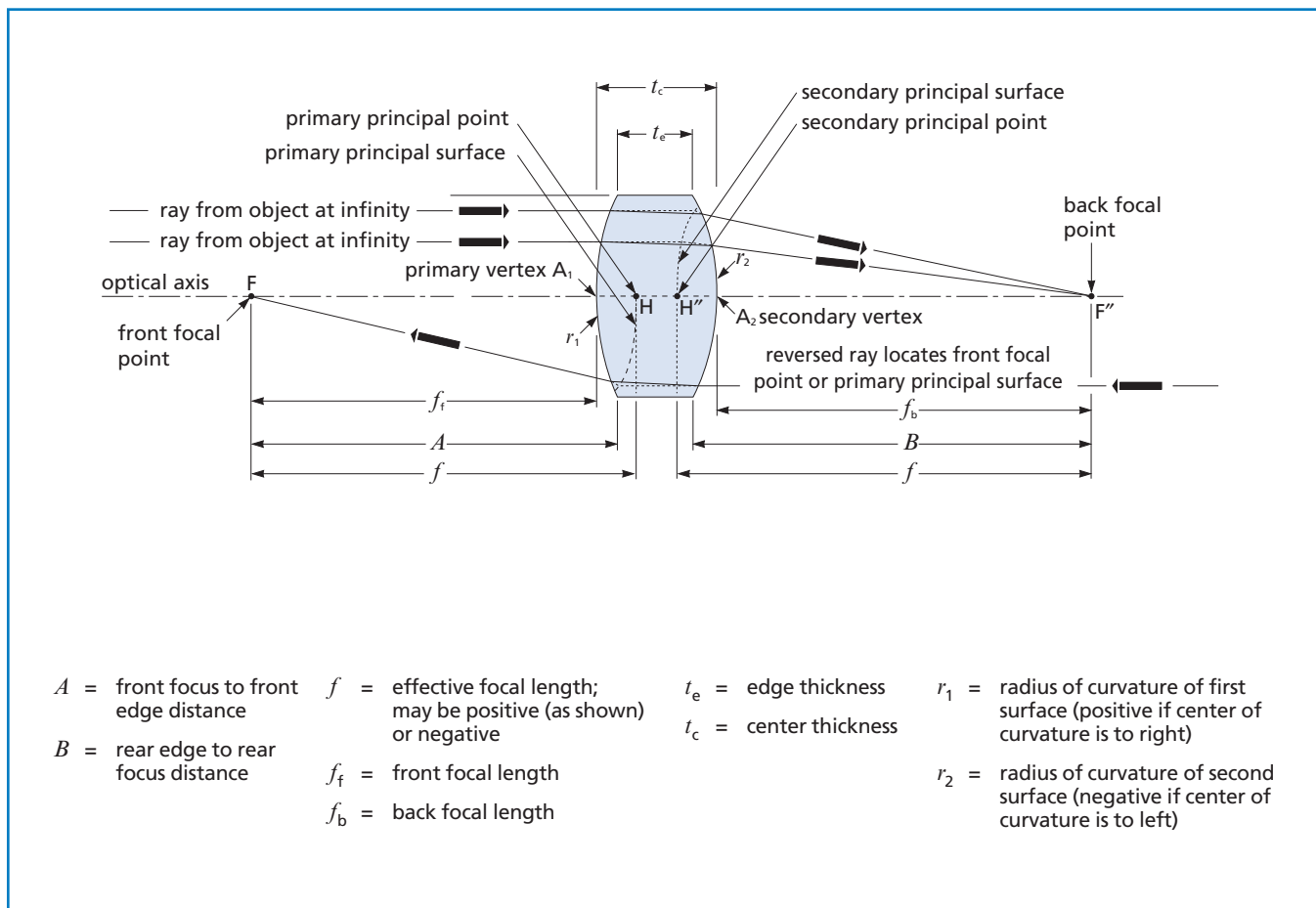


Figure 1.33 Focal length and focal points

points of intersection of extended external ray segments. The principal surface of a perfectly corrected optical system is a sphere centered on the focal point.

Near the optical axis, the principal surface is nearly flat, and for this reason, it is sometimes referred to as the principal plane.

### **SECONDARY PRINCIPAL SURFACE**

This term is defined analogously to the primary principal surface, but it is used for a collimated beam incident from the left and focused to the back focal point  $F''$  on the right. Rays in that part of the beam nearest the axis can be thought of as once refracted at the secondary principal surface, instead of being refracted by both lens surfaces.

### **PRIMARY PRINCIPAL POINT (H) OR FIRST NODAL POINT**

This point is the intersection of the primary principal surface with the optical axis.

### **SECONDARY PRINCIPAL POINT (H'') OR SECONDARY NODAL POINT**

This point is the intersection of the secondary principal surface with the optical axis.

### **CONJUGATE DISTANCES ( $s$ AND $s''$ )**

The conjugate distances are the object distance,  $s$ , and image distance,  $s''$ . Specifically,  $s$  is the distance from the object to H, and  $s''$  is the distance from H'' to the image location. The term infinite conjugate ratio refers to the situation in which a lens is either focusing incoming collimated light or is being used to collimate a source (therefore, either  $s$  or  $s''$  is infinity).

### **PRIMARY VERTEX ( $A_1$ )**

The primary vertex is the intersection of the primary lens surface with the optical axis.

### **SECONDARY VERTEX ( $A_2$ )**

The secondary vertex is the intersection of the secondary lens surface with the optical axis.

### **EFFECTIVE FOCAL LENGTH (EFL, $f$ )**

Assuming that the lens is surrounded by air or vacuum (refractive index 1.0), this is both the distance from the front focal point (F) to the primary principal point (H) and the distance from the secondary principal point (H'') to the rear focal point (F''). Later we use  $f$  to designate the paraxial EFL for the design wavelength ( $\lambda_0$ ).

### **FRONT FOCAL LENGTH ( $f_f$ )**

This length is the distance from the front focal point (F) to the primary vertex ( $A_1$ ).

### **BACK FOCAL LENGTH ( $f_b$ )**

This length is the distance from the secondary vertex ( $A_2$ ) to the rear focal point (F'').

### **EDGE-TO-FOCUS DISTANCES ( $A$ AND $B$ )**

$A$  is the distance from the front focal point to the primary vertex of the lens.  $B$  is the distance from the secondary vertex of the lens to the rear focal point. Both distances are presumed always to be positive.

### **REAL IMAGE**

A real image is one in which the light rays actually converge; if a screen were placed at the point of focus, an image would be formed on it.

### **VIRTUAL IMAGE**

A virtual image does not represent an actual convergence of light rays. A virtual image can be viewed only by looking back through the optical system, such as in the case of a magnifying glass.

### **F-NUMBER ( $f/\#$ )**

The f-number (also known as the focal ratio, relative aperture, or speed) of a lens system is defined to be the effective focal length divided by system clear aperture. Ray f-number is the conjugate distance for that ray divided by the height at which it intercepts the principal surface.

$$f/\# = \frac{f}{CA}. \quad (\text{see eq. 1.7})$$

### **NUMERICAL APERTURE (NA)**

The NA of a lens system is defined to be the sine of the angle,  $\theta_1$ , that the marginal ray (the ray that exits the lens system at its outer edge) makes with the optical axis multiplied by the index of refraction ( $n$ ) of the medium. The NA can be defined for any ray as the sine of the angle made by that ray with the optical axis multiplied by the index of refraction:

$$NA = n \sin \theta. \quad (1.30)$$

### **MAGNIFICATION POWER**

Often, positive lenses intended for use as simple magnifiers are rated with a single magnification, such as  $4\times$ . To create a virtual image for viewing with the human eye, in principle, any positive lens can be used at an infinite number of possible magnifications. However, there is usually a narrow range of magnifications that will be comfortable for the viewer. Typically, when the viewer adjusts the object distance so that the image appears to be essentially at infinity (which is a comfortable viewing distance for most individuals), magnification is given by the relationship

$$\text{magnification} = \frac{254 \text{ mm}}{f} \quad (f \text{ in mm}). \quad (1.31)$$

Thus, a 25.4-mm focal length positive lens would be a  $10\times$  magnifier.

### **DIOPTERS**

The term diopter is used to define the reciprocal of the focal length, which is commonly used for ophthalmic lenses. The inverse focal length of a lens expressed in diopters is

$$\text{diopters} = \frac{1000}{f} \quad (f \text{ in mm}). \quad (1.32)$$

Thus, the smaller the focal length is, the larger the power in diopters will be.

### **DEPTH OF FIELD AND DEPTH OF FOCUS**

In an imaging system, depth of field refers to the distance in object space over which the system delivers an acceptably sharp image. The criteria for what is acceptably sharp is arbitrarily chosen by the user; depth of field increases with increasing f-number.

For an imaging system, depth of focus is the range in image space over which the system delivers an acceptably sharp image. In other words, this is the amount that the image surface (such as a screen or piece of photographic film) could be moved while maintaining acceptable focus. Again, criteria for acceptability are defined arbitrarily.

In nonimaging applications, such as laser focusing, depth of focus refers to the range in image space over which the focused spot diameter remains below an arbitrary limit.

### **APPLICATION NOTE**

#### **Technical Reference**

For further reading about the definitions and formulas presented here, refer to the following publications:

Rudolph Kingslake, *Lens Design Fundamentals* (Academic Press)

Rudolph Kingslake, *System Design* (Academic Press)

Warren Smith, *Modern Optical Engineering* (McGraw Hill).

Donald C. O'Shea, *Elements of Modern Optical Design* (John Wiley & Sons)

Eugene Hecht, *Optics* (Addison Wesley)

Max Born, Emil Wolf, *Principles of Optics* (Cambridge University Press)

If you need help with the use of definitions and formulas presented in this guide, our applications engineers will be pleased to assist you.