1. THIN LENSES

A thin lens may be defined as one whose thickness is considered small in comparison with the distances generally associated with its optical properties. Such distances are, for example, radii of curvature of the two spherical surfaces, primary and secondary focal lengths, and object and image distances. Diagrams of several standard forms of thin lenses were shown in last lecture illustrated the fact that most lenses have surfaces that are spherical in form. Some surfaces are convex, others are concave, and still others are plane. When light passes through any lens, refraction at each of its surfaces contributes to its image-forming properties.

2. FOCAL POINTS AND FOCAL LENGTHS

Diagrams showing the refraction of light by an equiconvex lens and by an equiconcave lens are given in Fig. 1. The axis in each case is a straight line through the geometrical center of the lens and perpendicular to the two faces at the points of intersection. For spherical lenses this line joins the centers of curvature of the two surfaces. *The primary focal point F is an axial point having the property that any ray coming from it or proceeding toward it travels parallel to the axis after refraction.*

The secondary focal point F' is an axial point having the property that any incident ray traveling parallel to the axis will, after refraction, proceed toward, or appear to come from, F'. The two lower diagrams in Fig. 1 are given for the purpose of illustrating this definition. a plane perpendicular to the axis and passing through a focal point is called a *focal plane.*

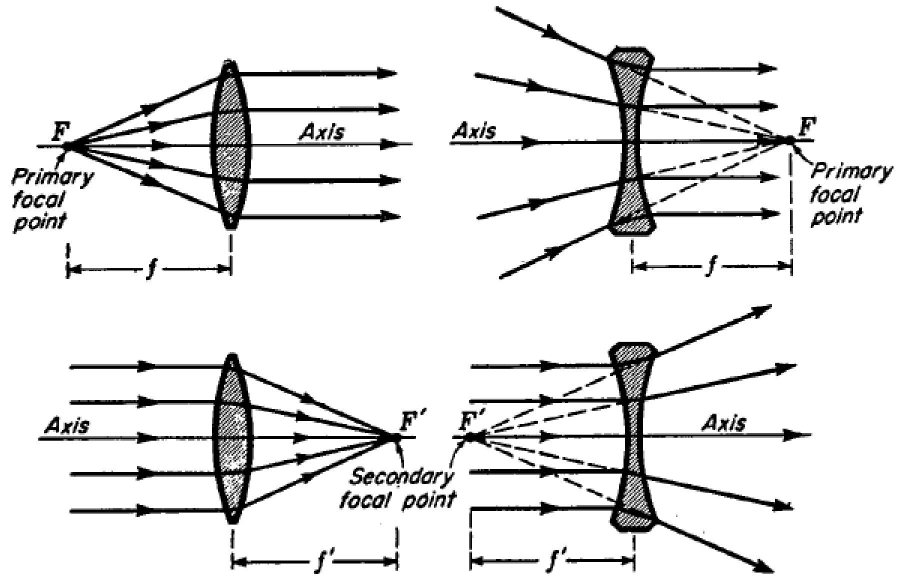

Fig. 1: Ray diagrams illustrating the primary and secondary focal points *F* and *F'* and the corresponding focal lengths *f* and *f'* of thin lenses.

The distance between the center of a lens and either of its focal points is its focal length. These distances, designated *f* and *f'*, usually measured in centimeters or inches, have a positive sign for converging lenses and a negative sign for diverging lenses. that the primary focal point *F* for a converging lens lies to the left of the lens, whereas for a diverging lens it lies to the right. For a lens with the same medium on both sides, we have, by the reversibility of light rays, $f = f'$

Note carefully the difference between a thin lens in air, where the focal lengths are equal, and a single spherical surface, where the two focal lengths have the ratio of the two refractive indices

3. IMAGE FORMATION

When an object is placed on one side or the other of a converging lens and beyond the focal plane, an image is formed on the opposite side (see Fig. 2). If the object is moved closer to the primary focal plane, the image will be formed farther away from the secondary focal plane and will be larger, i.e., magnified. If the object is moved farther away from F, the image will be formed closer to F' and will be smaller. In Fig. 2 all the rays coming from an object point Q are shown as brought to a focus Q', and the rays from another point M are brought to a focus at M'. Such ideal conditions and the formulas given in this chapter hold only for paraxial rays, i.e., rays close to lens axis and making small angles with it.

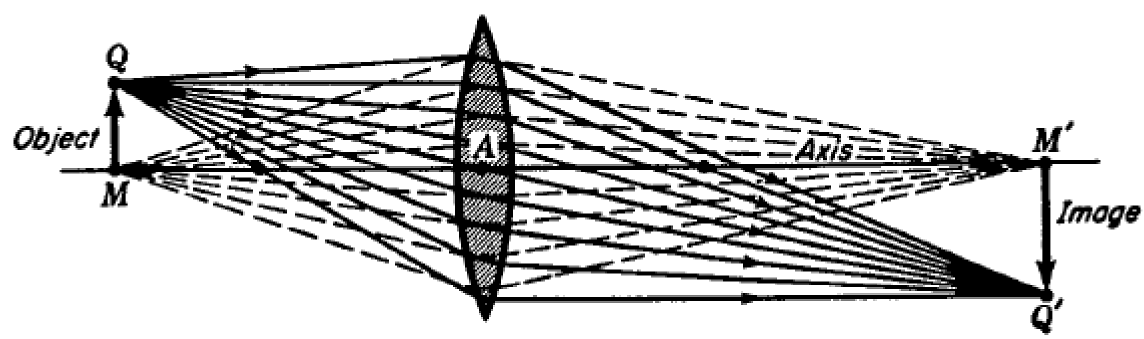

Fig.2: Image formation by an ideal thin lens. All rays from an object point *Q* which pass through the lens are refracted to pass through the image point *Q'*.

4. CONJUGATE POINTS AND PLANES

If the principle of the reversibility of light rays is applied to Fig. 2, we observe that *Q'M'* becomes the object and *QM* becomes its image. The object and image are therefore *conjugate*, just as they are for a single spherical surface. Any pair of object and image points such as M and M' in Fig. 2 are called *conjugate points*, and planes through these points perpendicular to the axis are called *conjugate planes*.

If we know the focal length of a thin lens and the position of an object, there are three. methods of determining the position of the image: (1) graphical construction, (2) experiment, and (3) use of the lens formula

$\frac{1}{s}+\frac{1}{s'}=\frac{1}{f}$	1

Here's is the object distance, s' is the image distance, and f is the focal length, all measured to or from the center of the lens.

5. THE PARALLEL-RAY METHOD

The parallel-ray method is illustrated in Fig. 3. Consider the light emitted from the extreme point Q on the object. Of the rays emanating from this point in different directions the one *(QT)* traveling parallel to the axis will by definition of the focal point be refracted to pass through F'. The ray QA, which goes through the lens center where the faces are parallel, is undeviated and meets the other ray at some point Q'. These two rays are sufficient to locate the tip of the image at Q', and the rest of the image lies in the conjugate plane through this point. All other rays from Q will also be brought to a focus at Q'.

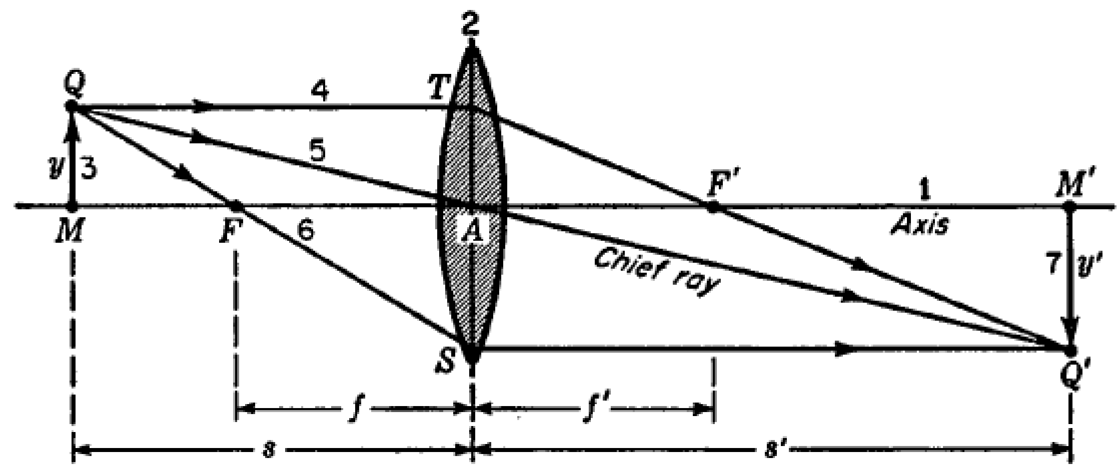

Fig.3: The parallel-ray method for graphically locating the image formed by a thin lens.

6. THE OBLIQUE-RAY METHOD

Let *MT* in Fig. 4 represent any ray incident on the lens from the left. It is refracted in the direction *TX* and crosses the axis at *M'*. The point *X* is located at the intersection between the secondary focal plane *F'* Wand the dashed line *RR'* drawn through the center of the lens parallel to *MT*. The order in which each step of the construction is made is again indicated by the numbers 1,2,3, ... if we actually have rays diverging from *M*, as in Fig. 4, we can find the direction of anyone of them after it passes through the lens by making it intersect the parallel line *RR'* through *A* in the focal plane. This construction locates *X* and the position of the image *M'*. Note that *RR'* is not an actual ray in this case and is treated as such only as a means of locating the point *X*.

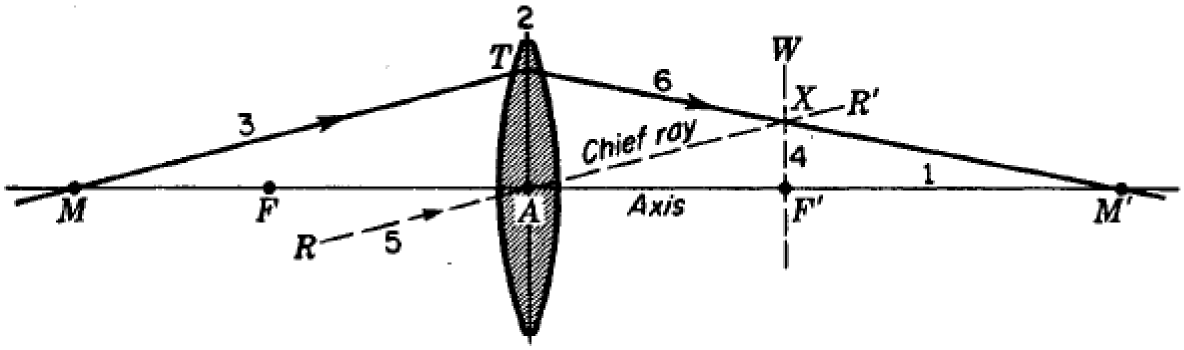

Fig. 4:The oblique-ray method for graphically locating the image formed by a thin lens.

7. USE OF THE LENS FORMULA

Let an object be located 6.0 cm in front of a positive lens of focal length + 4.0 cm. The given quantities are s = +6.0 cm and f = +4.0 cm, and the unknown is s'.?

$$\frac{1}{s}+\frac{1}{s'}=\frac{1}{f} \quad or\ s'=\frac{s\times f}{s-f}$$

$$s'=\frac{(+6)\times(+4)}{(+6)-(+4)}= +12\ cm$$

The image is formed 12.0 cm from the lens and is *real*, as it will always be when s' has a positive sign. In this instance it is inverted. The sign conventions to be used for the thin-lens formulas are identical to those for a single spherical surface