LENSES

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A lens is a transmissive optical element or cluster of elements that redirects rays through an angle that varies continuously with position in at least one direction across the element. The rays can be light rays or particle trajectories. A lens can form an image of an illuminated object, or can be used in the coupling or collection of rays. Lenses are often combined into more sophisticated optical devices for a variety of applications.

Lenses occur in a number of forms in nature. Indeed, some evolutionary biologists suggest that the lens may have independently evolved as many as seven separate times in the animal kingdom. The first man-made lenses could conceivably date as far back as 3500 BC when the Phoenicians began manufacturing glass. Perhaps the earliest historical reference to lenses is provided by Aristophanes who, in the fourth century BC, wrote of "burning glasses" used to focus the rays of the sun into spots sufficiently hot to ignite paper. In the eleventh century, Ibn-al-Haitham provided the first description of the operation of a lens, and in 1267 Roger Bacon described experiments with lenses. Particle lenses were developed in the first decades of the twentieth century and were first incorporated into an imaging device - the ELECTRON MICROSCOPE - by Knoll and Ruska in 1931.

The *spherical lens* is a common optical lens made of a dielectric - usually glass - bounded by portions of two spherical surfaces. The line passing though the centers of both spheres defines the axis of the lens. The spherical lens is a *refractive lens*, since REFRACTION redirects the rays of light. In the paraxial approximation that no rays are anywhere far from the lens axis, the laws of GEOMETRICAL OPTICS apply, and one can define a focal length f as the distance for which a parallel beam of light is focused to a spot:

$$\frac{1}{f} = (n' - 1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n' - 1)\,t}{n'R_1R_2}\right] ,$$

where the R_j refer to the radii of curvature of the two spherical surfaces. A radius is negative if the center of the sphere is on the same side of the lens as the incident light. The thickness of the lens along its axis is t, and $n' = n_{lens}/n_{medium}$ is defined in terms of the INDICES OF REFRACTION of the material the lens is made of, n_{lens}, and the medium it is immersed in, n_{medium}. A negative f means that the light becomes more divergent as is passes the lens. The distance f is measured from the principal point located a distance $z = (1-n')\, t\, f \,/\, R_1$ beyond the intersection of the final sphere with the lens axis, as shown in the figure.

Spherical lenses are classified in terms of the curvature of their faces. A convex/convex lens is thus formed by two convex faces. Such a lens will cause a beam of parallel rays to come to a focus. A simple magnifying glass is an example. A concave/concave lens will cause an incident parallel beam to diverge. Such a lens might be used in eyeglasses to correct for near-sightedness. One of the radii of curvature of a spherical lens may be infinite. A plano/convex lens is an example.

If the paraxial approximation is violated, a parallel beam of light is not focused to a point and the lens possesses an ABERRATION. These departures from ideal operation are approximated in terms of rays by the Seidel aberrations: SPHERICAL ABERRATION, coma, astigmatism, distortion, and field curvature. The departures can be quantified in terms of DIFFRACTION by the Strehl ratio, the ratio of light within the central diffraction maximum compared to that of a perfect lens with the same diameter. CHROMATIC ABERRATION results from differing focal lengths for light of different colors and can be present within the paraxial approximation. Lenses have been developed to reduce aberrations. The *aspherical lens* has two non-spherical surfaces which correct some aberrations. A COMPOUND LENS that combines several simple lenses and internal light stops can be designed to reduce aberrations.

The natural tendency of a wave to diffract can also be controlled to create a lensing effect. The simplest such diffractive *lens* is the FRESNEL lens. Many Fresnel lenses resemble DIFFRACTION GRATINGS in that they are comprised of a series of closely-spaced grooves, although the grooves are concentric circles in the Fresnel lens. For parallel incident light, portions of the incident wavefront at a Fresnel lens that will add constructively at the focal point are passed by the lens unaffected. Those which would interfere destructively are either blocked or phase shifted to add constructively. Diffractive lenses have several focal points, one for each order of diffraction. One order can be enhanced relative to others by properly placed stops or by blazing the grating that forms the lens. In a blazed lens, the shape of the individual rulings comprising the lens are altered. Diffractive lenses have severe chromatic aberration. Fresnel-like lenses can be used to focus microwaves for wireless communications.

A *graded index*, or *GRIN lens*, exploits a continuously graded index within one solid unit. In a *GRIN lens* light tends to bend towards the material with the higher index of refraction. *GRIN* lenses are usually made from radially symmetric layers, although a variation along the lens axis can be used. The lens surface may be flat or curved. *GRIN* lenses are widely used for coupling light into optical fibers.

Lenses for charged particles can utilize either an ELECTRIC FIELD or a MAGNETIC FIELD. In either case the deflection results from ELECTROMAGNETIC FORCES from the position-dependent fields. Lenses based on electric fields can either involve apertures, such as the Pierce geometry for a charged particle source, or conducting cylinders, such as the three spaced cylinder einzel lens in which a voltage ratio controls the lens strength. Magnetic lenses are classified by the number of poles used in their construction, such as the quadrupole lens with the ends of four magnets facing the beam. ELECTROMAGNETS are normally used to provide a variable lens.

Some lenses have a special names and purposes. An *objective lens* is the lens of an imaging system that is closest to the object being viewed. A *field lens* is used to reduce the loss of light from off-axis points in an imaging system. It lies at or near an image plane so does not contribute significantly to the focal properties. An *eyepiece* is usually contains both a field lens and a compound lens. A *zoom lens* is a compound lens which changes overall MAGNIFICATION without changing its effective focal length. A *cylindrical lens* focuses light in only one dimension, so is useful for coupling light through a slit. A *solid immersion lens* may be used to improve spatial resolution in a microscope. Such a microscope utilizes photon tunneling by resting the lens directly on the specimen to be imaged. A GRAVITATIONAL LENS results from a GENERAL-RELATIVITY effect, and bends light near massive objects such as stars.

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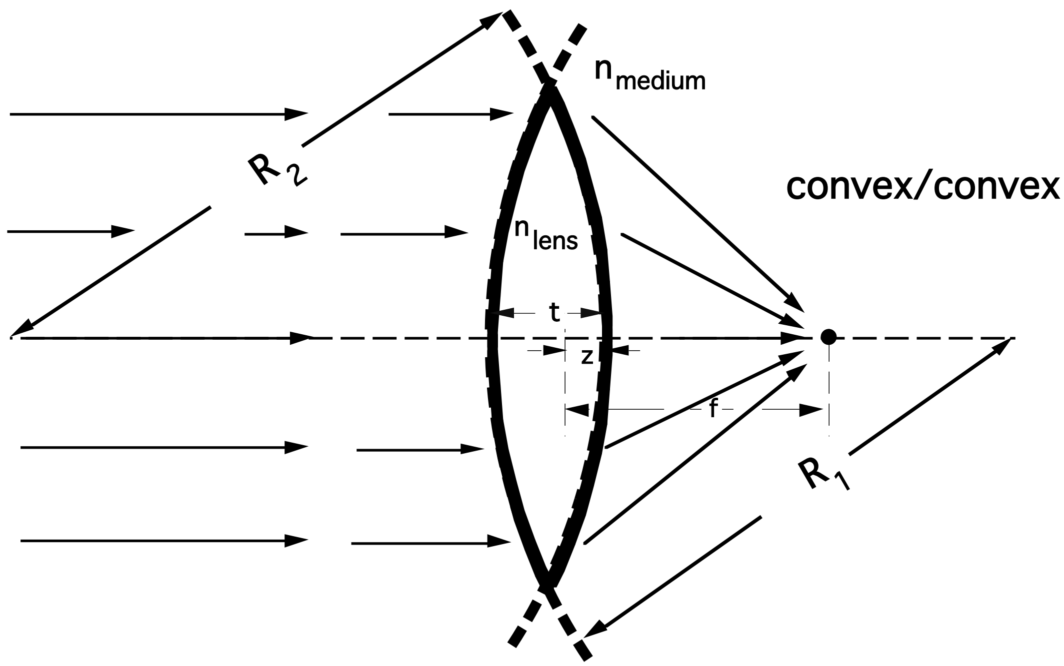
FIGURE CAPTION

Two spherical lenses are shown, indicating the distances f, t, z, and the R_j in two cases. Note the effect of the signs of z and f; we have assumed n' > 1. The dashed rays shown for the concave/concave lens are extrapolations of emergent rays. They show the significance of its negative focal length f.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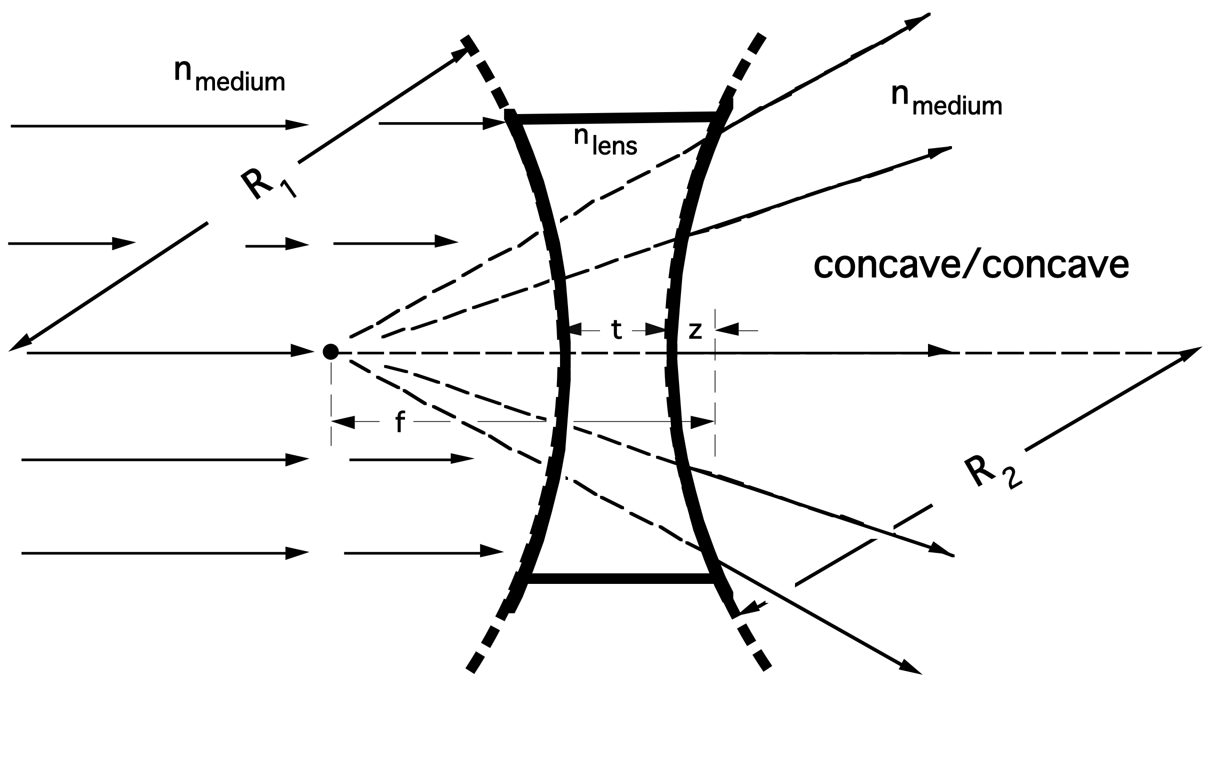
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