as the cornea; connected with the sclerotic by loose, connective tissue, in which ramify blood-vessels and nerves, and presenting an external, vascular layer and an internal, pigmentary layer, which latter gives its characteristic dark-brown color.

The ciliary processes; peculiar folds of the choroid, which form its anterior border and which embrace the folds of the suspensory ligament of the lens.

The ciliary muscle; situated just outside of the ciliary processes, arising from the circular line of junction of the sclerotic with the cornea, passing over the ciliary processes, and becoming continuous with the fibrous tissue of the choroid. The action of this muscle is to tighten the choroid over the vitreous humor and to relax the ciliary processes and the suspensory ligament of the lens, when the lens, by virtue of its elasticity, becomes more convex. This action is shown by the dotted lines in the figure.

The iris; dividing the space in front of the lens into two chambers occupied by the aqueous humor. The anterior chamber is much the larger. The iris, in its central portion surrounding the pupil, is in contact with the lens. Its circumference is just in front of the line of origin of the ciliary muscle.

The retina; a delicate, transparent membrane, lining the choroid and extending to about $\frac{1}{15}$ of an inch (1·7 mm.) behind the ciliary processes, the anterior margin forming the ora serrata. The optic nerve penetrates the retina a little internal to and below the antero-posterior axis of the globe. The layer of rods and cones is situated next the pigmentary layer, which is external. Internal to the layer of rods and cones, are the four granular layers; next, the layer of nerve-cells; next, the expansion of the fibres of the optic nerve; and next, in apposition with the hyaloid membrane of the vitreous humor, is the limitary membrane.

The crystalline lens; elastic, transparent, enveloped in its capsule and surrounded by the suspensory ligament.

The suspensory ligament; the anterior layer connected with the anterior portion of the capsule of the lens, and the posterior, with the posterior portion of the capsule. The folded portion of this ligament, which is received between the folds of the ciliary processes, is called the zone of Zinn. The triangular canal between the anterior and the posterior layers of the suspensory ligament and surrounding the equator of the lens is called the canal of Petit.

The vitreous humor; enveloped in the hyaloid membrane, which membrane is continuous in front, with the suspensory ligament of the lens.

Refraction in the Eye.

In applying some of the elementary laws of refraction of light to the transparent media of the eye, it is necessary to bear in mind certain general facts with regard to vision, that have as yet been referred to either very briefly or not at all.

The eye is not a perfect optical instrument, looking at it from a purely

physical point of view. This statement, however, should not be understood as implying that the arrangement of the parts is not such as to adapt them perfectly to their uses in connection with the proper appreciation of visual impressions. By physical tests it can be demonstrated that the eye is not entirely achromatic; but in ordinary vision the dispersion of colors is not appreciated. There is but a single point in the retina, the fovea centralis, where vision is absolutely distinct; and it is upon this point that images are made to fall when the eye is directed toward any particular object.

The refracting apparatus is not exactly centred, a condition so essential to the satisfactory performance of perfect optical instruments. For example, in a compound microscope or a telescope, the centres of the different lenses entering into the construction of the instrument are all situated in a straight line. Were the eye a perfect optical instrument, the line of vision would coincide exactly with the axis of the cornea; but this is not the case. The visual line—a line drawn from an object to its image on the fovea centralis—deviates from the axis of the cornea, in normal eyes, to the nasal side. The visual line, therefore, forms an angle with the axis of the cornea. This is known as the angle alpha. This deviation of the visual line from the mathematical centre of the eye is observed both in the horizontal and in the vertical planes. The horizontal deviation varies by two to eight degrees (Schuerman), and the vertical, by one to three degrees (Mandelstamm). Of course this want of exact centring of the optical apparatus, in normal eyes, does not practically affect distinct vision; for when the eyes are directed toward any object, this object is brought in the line of the visual axis; but the angle apha is an important element to be taken into account in various mathematical calculations connected with the physics of the eye.

The area of distinct vision is quite restricted; but were it larger, it is probable that the mind would become confused by the extent and variety of the impressions, and that it would not be so easy to observe minute details and fix the attention upon small objects.

Although certain objects are seen with absolute distinctness only in a restricted field, the angle of vision is very wide, and rays of light are admitted from an area equal to nearly the half of a sphere. Such a provision is eminently adapted to visual requirements. The eyes are directed to a particular point and a certain object is seen distinctly, with the advantage of an image in the two eyes, exactly at the points of distinct vision; the rays coming from without the area of distinct vision are received upon different portions of the surface of the retina and produce an impression more or less indistinct, not interfering with the observation of the particular object to which the attention is for the moment directed; but even while looking intently at any object, the attention may be attracted by another object of an unusual character, which might, for example, convey an idea of danger, and the point of distinct vision can be turned in its direction. Thus, while but few objects are seen distinctly at one time, the area of indistinct vision is very large; and the attention may readily be directed to unexpected or unusual objects that come within any portion of the field of view. The small extent of the area of distinct vision, especially for near objects, may readily be appreciated in watching a person who is attentively reading a book, when the eyes will be seen to follow the lines from one side of the page to the other with perfect regularity. When it is considered that in addition to these qualities, which are not possible in artificial optical instruments, the eye may be accommodated at will to vision at different distances, and that there is correct appreciation of form, etc., by the use of the two eyes, it is evident that the visual organ gains rather than loses in comparison with the most perfect instruments that have been constructed.

Certain Laws of Refraction, Dispersion etc., bearing upon the Physiology of Vision.—Physiologists have little to do with the theory of light, except as regards the modifications of luminous rays in passing through the refracting media of the eye. It will be sufficient to state that nearly all physicists of the present day agree in accepting what is known as the theory of undulation, rejecting the emission-theory proposed by Newton. It is necessary to the theory of undulation to assume that all space and all transparent bodies are permeated with what has been called a luminiferous ether; and that light is propagated by a vibration or an undulation of this hypothetical substance. This theory assimilates light to sound, in the mechanism of its propagation; but in sound the waves are supposed to be longitudinal, or to follow the line of propagation, while in light the particles are supposed to vibrate transversely, or at right angles to the line of propagation. It must be remembered, however, that the undulatory theory of sound is capable of positive demonstration, and that the propagation of sound by waves can take place only through ponderable matter, the vibrations of which can always be observed; but the theory of luminous vibrations involves the existence of an hypothetical ether. It is possible, indeed, that scientific facts may in the future render the existence of such an ether improbable or its supposition unnecessary; but at present the theory of luminous undulation seems to be in accord with the optical phenomena that have thus far been recognized.

The different calculations of physicists with regard to the velocity of light have been remarkably uniform in their results. The lowest calculations put it at about 185,000 miles (297,725 kilometres) in a second, and the highest, at about 195,000 miles (313,818 kilometres). The rate of propagation is usually assumed to be about 192,000 miles (309,000 kilometres).

The intensity of light is in proportion to the amplitude of the vibrations. The intensity diminishes as the distance of the luminous body increases, and is in inverse ratio to the square of the distance.

In the theory of the colors into which pure white light may be decomposed by prisms, it is assumed to be a matter of demonstration that the waves of the different colors of the solar spectrum are not of the same length. The decomposition of light is produced by differences in the refrangibility of the different colored rays as they pass through a medium denser than the air.

The analysis of white light into the different colors of the spectrum shows

that it is compound; and by synthesis, the colored rays may be brought together, producing white light. Colors may be obtained by decomposition of light by transparent bodies, the different colored rays being refracted, or bent, by a prism, at different angles. It is not in this way, however, that the colors of different objects are produced. Certain objects have the property of reflecting the rays of light. A perfectly smooth, polished surface, like a mirror, may reflect all of the rays; and the object then has no color, only the reflected light being appreciated by the eye. Certain other objects do not reflect all of the rays of light, some of them being lost to view, or absorbed. When an object absorbs all of the rays, it has no color and is called black. When an object absorbs the rays equally and reflects a portion of these rays without decomposition, it is gray or white. There are many objects, however, that decompose white light, absorbing certain rays of the spectrum and reflecting others. The rays not absorbed, but returned to the eye by reflection, give color to the object. Thus, if an object absorb all of the rays of the spectrum except the red, the red rays strike the eye, and the color of the object is red. So it is with objects of different shades, the colors of which are given simply by the unabsorbed rays.

A mixture of different colors in certain proportions will result in white. Two colors, which, when mixed, result in white, are called complementary. The following colors of the spectrum bear such a relation to each other: Red and greenish-blue; orange and cyanogen-blue; yellow and indigo-blue; greenish-yellow and violet.

The fact that impressions made upon the retina persist for an appreciable length of time affords an illustration of the law of complementary colors. If a disk, presenting divisions with two complementary colors, be made to revolve so rapidly that the impressions made by the two colors are blended, the resulting color is white.

Refraction by Lenses.—A ray of light is an imaginary pencil, so small as to present but a single line; and the light admitted to the interior of the eye by the pupil is supposed to consist of an infinite number of such rays. In studying the physiology of vision, it is important to recognize the laws of refraction of rays by transparent bodies bounded by curved surfaces, with particular reference to the action of the crystalline lens.

The action of a double-convex lens, like the crystalline, in the refraction of light, may readily be understood by a simple application of the well known laws of refraction by prisms. A ray of light falling upon the side of a prism at an angle is deviated toward a line perpendicular to the surface of the prism. As the ray passes from the prism to the air, it is again refracted, but the deviation is then from the perpendicular of the second surface of the prism. In passing through a prism, therefore, the pencil of light is bent, or refracted, toward the base.

A circle is equivalent to a polygon with an infinite number of sides. A regular, double-convex lens is a transparent body bounded by segments of a sphere. Theoretically a double-convex lens may be assumed to be composed of an infinite number of sections of prisms (Fig. 254, I.), or to make the comparison with prisms more striking, although less accurate, the lens may be assumed to be composed of prisms (Fig. 254, II., Weinhold).

If these prisms or sections of prisms be infinitely small, so that the surface of each receives but a single infinitely small pencil of light, these pencils will be refracted toward the bases of the prisms, and different rays of light from all points of an object may be brought to an infinite number of foci, all these foci, for a plane object, being in the same plane. If the number of sections be equal on every side of the centre of the lens, the bases looking toward the axis of the lens, the rays of light will cross at a certain point, and the image formed by the lens will be inverted. This is illustrated in Fig.

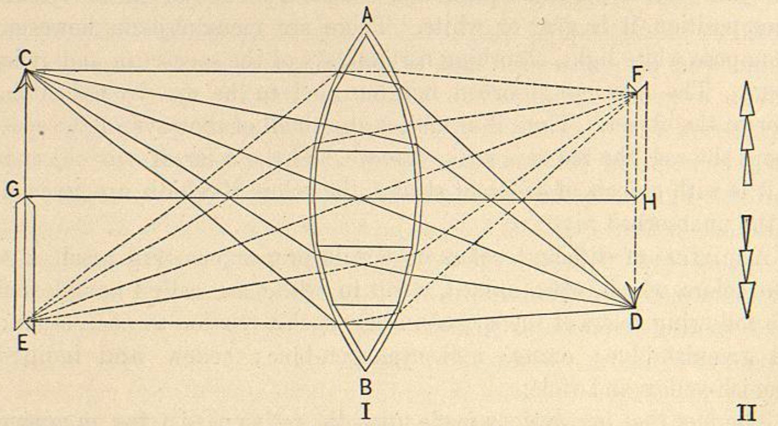

FIG. 254.—*Refraction by convex lenses.*

254, which represents a section of a lens theoretically dissected into six sections of prisms.

If the lens A B (Fig. 254) be assumed to be free from what is known as spherical aberration, the rays from the point C will be refracted, and brought to a focus at the point D. In the same way the rays from E will be brought to a focus at F, the two sets of rays crossing before they reach their focal points. The same is true for all the rays from every point in the image C E, which strike the lens at an angle, but the ray G H, which is perpendicular to the lens, is not deviated. The rays of light are refracted in this way by the cornea and by the crystalline lens. The retina is normally at such a distance from the lens that the rays are brought to a focus exactly at its surface. Inasmuch as the rays cross each other before they reach the retina, the image is always inverted.

Supposing the crystalline lens to be free from spherical and chromatic aberration, the formation of a perfect image depends upon the following conditions:

The object must be at a certain distance from the lens. If the object be too near, the rays, as they strike the lens, are too divergent and are brought to a focus beyond the plane F H D, or behind the retina; and as a consequence the image is confused. In optical instruments the adjustment is made for objects at different distances by moving the lens itself. In the eye,

however, the adjustment is effected by increasing or diminishing the curvatures of the lens, so that the rays are always brought to a focus at the visual surface of the retina. The faculty of thus changing the curvatures of the crystalline lens is called accommodation. This power, however, is restricted within certain well defined limits.

In some individuals the antero-posterior diameter of the eye is too long, and the rays, for most objects, come to a focus before they reach the retina. This defect may be remedied by placing the object very near the eye, so as to increase the divergence of the rays as they strike the crystalline. Such persons are said to be near-sighted (myopic), and objects are seen distinctly, only when very near the eye. This defect may be remedied for distant objects, by placing concave lenses before the eyes, by which the rays falling upon the crystalline are diverged. The opposite condition, in which the antero-posterior diameter is too short (hypermetropia), is such that the rays are brought to a focus behind the retina. This is corrected by converging the rays of incidence, by placing convex lenses before the eyes. In old age the crystalline lens becomes flattened, its elasticity is diminished and the power of accommodation is lessened; conditions which also tend to bring the rays to a focus behind the retina. This condition is called presbyopia. To render near vision—as in reading—distinct, objects are placed farther from the eye than under normal conditions. The defect may be remedied, as in hypermetropia, by placing convex lenses before the eyes, by which the rays are converged before they fall upon the crystalline lens.

The mechanism of accommodation will be fully considered in connection with the physiology of the crystalline lens; and at present it is sufficient to state that in looking at distant objects, the rays as they fall upon the lens are nearly parallel. The lens is then in repose, or "indolent." It is only when an effort is made to see near objects distinctly, that the agents of accommodation are called into action; and then, very slight changes in the curvature of the lens are sufficient to bring the rays to a focus exactly on the visual surface of the retina.

Spherical, Monochromatic Aberration.—In a convex lens in which the surfaces are segments of a sphere, the rays of light from any object are not converged to a uniform focus, and the production of an absolutely distinct image is impossible. For example, if the crystalline lens had regular curvatures, the rays refracted by its peripheral portion would be brought to a focus in front of the retina; the focus of the rays converged by the lens near its centre would be behind the retina; a few, only, of the rays would have their focus at the retina itself; and as a consequence, the image would appear confused. This is illustrated in imperfectly corrected lenses, and is called spherical aberration. It is also called monochromatic aberration, because it is to be distinguished from an aberration which involves decomposition of light into the colors of the spectrum. If an object be examined under the microscope with an imperfectly corrected objective, it is evident that the field of view is not uniform, and that there is a different focal adjustment for the central and the peripheral portions of the lens. In the construction of optical instruments, this difficulty may be in part corrected if the rays of light be cut off from the periphery of the lens, by a diaphragm, which is an opaque screen with a circular perforation allowing the rays to pass to a restricted portion of the lens, near its centre. The iris corresponds to the diaphragm of optical instruments, and it corrects the spherical aberration of the crystalline in part, by eliminating a portion of the rays that would otherwise fall upon its peripheral portion. This correction, however, is not sufficient for high magnifying powers; and it is only by the more or less perfect correction of this kind of aberration by other means, that powerful lenses have been rendered available in optics.

The spherical aberration of lenses which diverge the rays of light is precisely opposite to the aberration of converging lenses. In a compound lens, therefore, it is possible to fulfill the conditions necessary to the convergence of all the incident rays to a focus on a uniform plane, so that the image produced behind the lens is not distorted. Given, for example, a double-convex lens, by which the rays are brought to innumerable focal points situated in different planes. The fact that but a few of these focal points are in the plane of the retina renders the image indistinct. If a concave or a plano-concave lens be placed in front of this convex lens, which will diverge the rays more or less, the inequality of the divergence by different portions of the second lens will have the following effect: As the angle of divergence gradually increases from the centre toward the periphery, the rays near the periphery, which are most powerfully converged by the convex lens, will be most widely diverged by the peripheral portion of the concave lens; so that if the opposite curvatures be accurately adjusted, the aberrant rays may be blended. It is evident that if all the rays were equally converged by the convex lens and equally diverged by the concave lens, the action of the latter would be simply to elongate the focal distance; and it is equally evident that if the aberration of the one be exactly opposite to the aberration of the other, there will be perfect correction. Mechanical art has not effected correction of every portion of very powerful convex lenses in this way; but by a combination of lenses and diaphragms together, highly magnified images, nearly perfect, have been produced. Lenses in which spherical aberration has been corrected are called aplanatic.

It is evident that for distinct vision at different distances, the crystalline lens must be nearly free from spherical aberration. This is not effected by a combination of lenses, as in ordinary optical instruments, but by the curvatures of the lens itself, and by certain differences in the consistence of different portions of the lens, which will be fully considered hereafter.

Chromatic Aberration.—A refracting medium does not act equally upon the different colored rays into which pure white light may be decomposed; in other words, as the pure ray falling upon the inclined surface of a glass prism is bent, it is decomposed into the colors of the spectrum. As a convex lens is practically composed of an infinite number of prisms, the same effect would be expected. Indeed, a simple convex lens, even if the spherical aberration be corrected, always produces more or less decomposition of light.

The image formed by such a lens will consequently be colored; and this defect in simple lenses is called chromatic aberration. At the same time it is evident that the centre of the different rays from an object will be composed of all the colors of the spectrum combined, producing the effect of white light; but at the borders the different colors will be separate and distinct, and an image produced by a simple convex lens will thus be surrounded by a circle of colors, like a rainbow.

In prisms the chromatic dispersion may be corrected by allowing the colored rays from one prism to fall upon a second prism, which is inverted, so that the colors will be brought together and produce white light. Two prisms thus applied to each other constitute, in fact, a flat plate of glass, and the rays of light pass without deviation. If this law be applied to lenses, it is evident that the dispersive power of a convex lens may be exactly opposite to that of a concave lens. By the convex lens the colored rays are separated by convergence and cross each other; and in the concave lens the colored rays are diverged in the opposite direction. If, then, a convex be combined with a concave lens, the white light decomposed by the one will be recomposed by the other, and the chromatic aberration will thus be corrected; but in using a convex and a concave lens composed of the same material, the convergence by the one will be neutralized by the divergence of the other, and there will be no amplification of the object. Newton supposed that dispersion, or decomposition of light, by lenses was always in exact proportion to refraction, so that it would be impossible to correct chromatic aberration and retain magnifying power; but it has been ascertained that there are great differences in the dispersive power of different kinds of glass, without corresponding differences in refraction. This discovery rendered it possible to construct achromatic lenses (Dollond, 1757). According to Ganot, Hall was the first to make achromatic lenses, in 1753, but his discovery was not published.

In the construction of modern optical instruments, the chromatic aberration is corrected, with a certain diminution in the amplification, by cementing together lenses made of different material, as of flint-glass and crown-glass. Flint-glass has a much greater dispersive power than crown-glass. If, therefore, a convex lens of crown-glass be combined with a concave or plano-concave lens of flint-glass, the chromatic aberration of the convex lens may be corrected by a concave lens with a curvature which will reduce the magnifying power about one-half. A compound lens, with the spherical aberration of the convex element corrected by the curvature of a concave lens, and the chromatic aberration corrected in part by the curvature, and in part by the superior refractive power of flint-glass over crown-glass, will produce a perfect image.

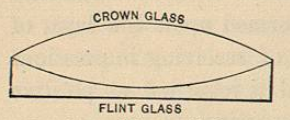

FIG. 255.—*Achromatic lens.*

Although the eye is not absolutely achromatic, the dispersion of light is not sufficient to interfere with distinct vision; but the chromatic aberration is practically corrected in the crystalline lens, probably by differences in the consistence and in the refractive power of its different layers.