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III. CHARACTERS DEPENDING UPON LIGHT.

GENERAL PRINCIPLES OF OPTICS.

284. Before considering the optical characters of minerals in general, and more particularly those that belong to the crystals of the different systems, it is desirable to review briefly some of the more important principles of optics upon which the phenomena in question depend.

For a fuller discussion of the optics of crystals, special reference is made to the works of Groth, Liebisch, Mallard, and Rosenbusch (and translation by Iddings) mentioned on pp. 3 and 4; also to the various advanced text-books of Physics. The methods of investigation, with the results of the examination of many species, are given in the admirable memoirs by Des Cloizeaux in Ann. Mines, **11**, 261–342, 1857; **14**, 339–420, 1858; **6**, 557–595, 1864. Also his Nouvelles Recherches, etc., 222 pp., 1867. Early observations were also published by Grailich (Vienna, 1850) and by Grailich and von Lang (Ber. Ak. Wien, **27**, 3, 1857; **32**, 43, 1858; **33**, 369, 1858). References to many important papers in special subjects are given later.

285. Nature of Light.—The propagation of light from a luminous body, as the sun or a candle-flame, is believed to be accomplished by a very rapid wave-motion * in the medium called the *luminiferous ether*, which, it is assumed, pervades all space as well as all material bodies.

286. The Ether.—The assumption of the medium called the ether is necessary, since without this it is impossible to explain the transmission of light through space where no ordinary medium (as the air) is present. Furthermore, as the velocity of light even within solid media, though less than that in a vacuum or in air, is still enormously rapid, it is inconceivable that it should be propagated by the molecules of the body; hence the assumption, otherwise verified, that the ether pervades all material bodies. The properties of the ether,† however, are modified by the molecular structure of the given body, as is proved by the fact that the velocity of light varies with the chemical nature of the substance, and also in certain cases with the direc-

* It is now generally accepted that light is an electro-magnetic phenomenon and that the nature of the periodic motion in the ether by which light is propagated is the same as that involved in the transmission of electric waves produced, for example, by a very rapid oscillatory electric discharge between two spark-knobs. In fact these electric waves have been shown to travel with the same velocity as light-waves, and to exhibit like phenomena of reflection, refraction, polarization, etc.; hence they are believed to differ from light-waves only in their much greater length. For the purposes of the present work, however, light-waves are treated of as if a mechanical phenomenon, but all assumption of variations of the "elasticity of the ether" in crystals as an explanation of the observed variation of light-velocity is avoided.

† Reference is made to an article by Clerk Maxwell in the *Encyclopedia Britannica* for a discussion of the general properties of the luminiferous ether.

tion in the given crystallized medium as corresponding to its particular molecular structure.

287. Wave-motion in General.—A familiar example of wave-motion is given by the series of concentric waves which on a surface of smooth water go out from a center of disturbance, as the point where a pebble has been dropped in. These surface-waves are propagated by a motion of the water-particles which is *transverse* to the direction in which the waves themselves travel; this motion is given from each particle to the next adjoining, and so on. Thus the particles of water at any one spot oscillate up and down,* while the wave moves on as a circular ridge of water of constantly increasing diameter, but of diminishing height. The ridge is followed by a valley, indeed both together properly constitute a wave in the physical sense. This compound wave is followed by another wave and another, until the original impulse has exhausted itself.

Another familiar kind of wave-motion is illustrated by the sound-waves which in the free air travel outward from a sonorous body in the form of concentric spheres. Here the actual motion of the layers of air is forward and back—that is, in the direction of propagation of the sound—and the effect of the transfer of this impulse from one layer to the next is to give rise alternately to a condensed and rarefied shell of air, which together constitute a sound-wave and which expand in spherical waves of constantly decreasing intensity (since the mass of air set in motion continually increases). Sound-waves, as of the voice, may be several feet in length, and they travel at a rate of 1120 feet per second at ordinary temperatures.

288. It is important to understand that in both the cases mentioned, as in every case of free wave-motion, each point on a given wave may be considered as a center of disturbance from which a system of new waves tend to go out. These individual wave-systems ordinarily destroy each other except so far as the onward progression of the wave as a whole is concerned. This is further discussed and illustrated in its application to light-waves (Art. **292** and Figs. 495, 496).

In general, therefore, a given wave is to be considered as the resultant of all these minor wave-systems. If, however, a wave encounters an obstacle in its path, as a narrow opening (*i.e.*, one narrow in comparison with the length of the wave) or a sharp edge, then the fact just mentioned explains how the waves seem to bend about the obstacles, since new waves start from them as centers. This principle has an important application in the case of light-waves, explaining the phenomena of diffraction (Art. **308**).

289. Still another case of wave-motion may be mentioned, since it is particularly helpful in giving a correct apprehension of light-phenomena. If a long rope, attached at one end, be grasped at the other, a quick motion of the hand, up or down, will give rise to a half wave-form—in one case a crest, in the other a trough—which will travel quickly to the other hand and be reflected back with a reversal in its position; that is, if it went forward as a hill-like wave, it will return as a trough. If, just as the wave has reached the end, a second like one be started, the two will meet and pass in the middle, but here for a brief interval the rope is sensibly at rest, since it feels two equal and opposite impulses. This will be seen later to be a case of the simple interference of two like waves opposed in phase.

Again, a double motion of the hand, up and down, will produce a complete wave, with crest and trough, as the result, and this again is reflected back as in the simpler case. Still again, if a series of like motions are continued rhythmically and so timed that each wave is an even part of the whole rope, the two systems of equal and opposite waves passing in the two directions will interfere and a system of so-called stationary waves will

* Strictly speaking, the path of each particle approximates closely to a circle.

be the result, the rope seeming to vibrate in segments to and fro about the position of equilibrium.

Finally, if the end of the rope be made to describe a small circle at a rapid, uniform, rhythmical rate, a system of stationary waves will again result, but now the vibrations of the string will be sensibly in circles about the central line. This last case will be seen to roughly indicate the kind of transverse vibrations by which the waves of circularly polarized light are propagated, while the former case represents the vibrations of waves of what is called plane-polarized light.

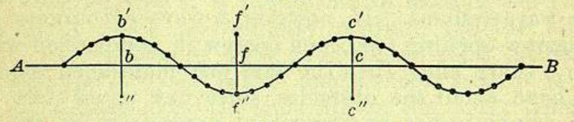
All these cases of waves obtained with a rope deserve to be carefully considered and studied by experiment, for the sake of the assistance they give to an understanding of the complex phenomena of light-waves.

290. Wave-length, Amplitude, etc.—In the cases mentioned, as in all kinds of simple wave-motion, the *length* of a wave is the distance from any one particle of the medium to the next which is moving in the same direction with the same velocity, or, technically expressed, which is in the same *phase*. The *amplitude* of the wave is the excursion to or fro from its position of equilibrium made by each particle in succession. Further, the wave-system travels onward the distance of one wave-length in the time that a given particle makes a complete excursion to and fro.

291. Light-waves.—The propagation of ether-waves involves the same fundamental principles as the familiar forms of wave-motion just considered. Here the motion of the medium is *transverse* to the direction of propagation, and this motion may be regarded as communicated from one set of particles to the next and so on, the ether-waves traveling as concentric spherical waves (in an isotropic medium) outward in all directions from the luminous point.

The nature of the vibrations will be better understood from Fig. 494. If AB represents the direction of propagation of the light, each particle of ether must vibrate at right angles to this as a line of equilibrium. The vibration of the first particle induces a similar movement in the adjacent particle; this is communicated to the next, and so on. The particles vibrate successively from the line AB to a distance corresponding to bb', the *amplitude* of the vibration, then return to b and pass on to b'', and so on. Thus at a given instant there are particles occupying all positions, from that of the

494.



extreme distance b', or c', from the line of equilibrium to that on this line. In this way the wave moves forward, while the motion of the particles is only transverse. The distance between any particle and the next which is in a like position—*i.e.*, of like *phase*, as b' and c'—is the *wave-length;* and the time required for this completed movement is the *time* of vibration, or *vibration-period*. The intensity of the light varies with the amplitude of the vibration, and the color, as explained in a later article, depends upon the length of the waves; the length of the violet waves is about one-half the length of the red waves.

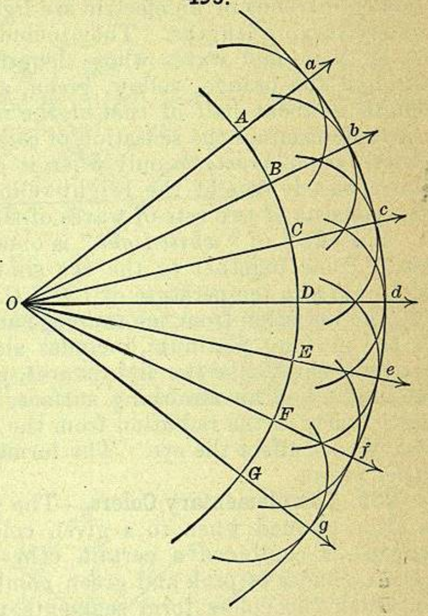
In *ordinary light* the transverse vibrations are to be thought of as taking place in all planes about the line of propagation. In the above figure, vibrations in one plane only are represented; light which is thus one-sided or has only one direction of transverse vibration is said to be *plane-polarized.*

Light-waves have a very minute length, only 0·000023 of an inch for the yellow sodium flame, and they travel with enormous velocity, 186,000 miles

per second in a vacuum; thus light passes from the sun to the earth in about eight minutes. The vibration-period, or time of one oscillation, is consequently extremely brief; it is given by dividing the distance traveled by light in one second by the number of waves included.

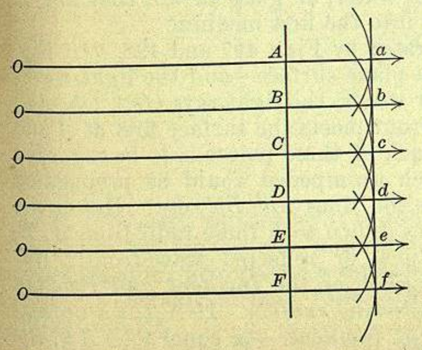
292. Wave-front.—In an isotropic medium, as air, water, or glass—that is, one in which light is propagated in all directions about the luminous point with the same velocity—the waves are spherical in form. The *wave-front* is the continuous surface, in this case spherical, which includes all particles which commence their vibration at the same moment of time. Obviously the curvature of the wave-front diminishes as the distance of the source of light increases, and when the light comes from an indefinitely great distance (as the sun) the wave-front becomes sensibly a plane surface. Such waves are usually called *plane waves.* These cases are illustrated by Figs. 495 and 496. In Fig. 495 the luminous point is supposed to be at O, and the medium being isotropic, it is obvious that the wave-front, as $ABC \ldots G$, is spherical. It is also made clear by this figure how, as briefly stated in Art. **288**, the resultant of all the individual impulses which go out from the successive points, as a, b, c, etc., as centers, form a new wave-front, $abc \ldots g$, concentric with $ABC \ldots G$. In Fig. 496 the luminous body is supposed to be at a great distance, so that the wave-front $AB \ldots F$ is a plane surface. Here also the individual impulses from A, B, etc., unite to form the wave-front $ab \ldots f$ parallel to $AB \ldots F$.

495.



293. Light-ray.—The study of light-phenomena is, in certain cases, facilitated by the conception of a *light-ray,* a line drawn from the luminous point to the wave-front, and whose direction is taken so as to represent that of the wave itself. In Fig. 495 OA, OB, etc., are diverging light-rays, and in Fig. 496 OA, OB, etc., are parallel light-rays. In both these cases, where the medium is assumed to be isotropic, the light-ray is normal to the wave-front. This is equivalent to saying that the light-wave moves onward in a direction normal to the wave-front.

496.



It must be understood that the "light-ray" has no real existence and is to be taken only as a convenient method of representing the direction of motion of the light-waves under varying conditions. Thus when by appropriate means (*e.g.*, the use of lenses) the curvature of the wave-front is altered—for example, if from being a plane surface it is made sharply convex—then the light-rays, at first parallel, are said to be made to diverge. Again, if the convex wave-front is made plane, the diverging light-rays are then said to be made parallel.

294. Wave-length. Color. White Light.—Notwithstanding the very small length of the waves of light, they can be measured with great precision. The visual part of the waves going out from a brilliantly incandescent body, as the glowing carbons of an electric arc-light, may be shown to consist of waves of widely varying lengths. They include red waves whose length is about $\frac{1}{39000}$ of an inch and waves whose length constantly diminishes without break, through the orange, yellow, green, and blue to the violet, whose minimum length is about half of that of the red. The length of each group of these waves determines the sensation of *color* which the eye perceives. This color is strictly *monochromatic* only when it corresponds to one definite wave-length; this is nearly true of the bright-yellow sodium line, though strictly speaking this consists of two sets of waves of slightly different lengths.

The effect of "*white light*" is obtained if all the waves from the red to the violet come together to the eye simultaneously; for this reason a piece of platinum at a temperature of 1500° C. appears "white hot."

The radiation from the sources named, either the sun, the electric carbons, or the glowing platinum, includes also longer waves which do not affect the eye, but which, like the light-waves, produce the effect of sensible heat when received upon an absorbing surface, as one of lampblack. There are also, particularly in the radiation from the sun, waves shorter than the violet which also do not affect the eye. The former are called *infra-red*, the latter *ultra-violet* waves.

295. Complementary Colors.—The sensation of white light mentioned above is also obtained when to a given color—that is, light-waves of given wave-length—is combined a certain other so-called *complementary* color. Thus certain shades of pink and green combined, as by the rapid rotation of a card on which the colors form segments, produce the effect of white. Blue and yellow of certain shades are also complementary. For every shade of color in the spectrum there is another one complementary to it in the sense here defined. The most perfect illustration of complementary colors is given by the examination of sections of crystals in polarized light, as later explained.

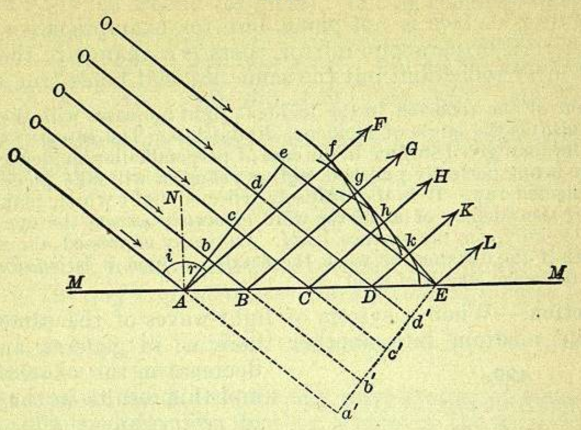
296. Reflection.—When light-waves come to the boundary which separates one medium from another, as a surface of water, or glass in air, they are, in general, in part *reflected* or returned back into the first medium.

The reflection of light-waves is illustrated by Figs. 497 and 498. In Fig. 497, MM is the reflecting surface—here a plane surface—and the light-waves have a plane wave-front ($Abcde$); in other words, the light-rays (OA, Ob, etc.) are parallel. It is obvious that the wave-front meets the surface first at A and successively from point to point to E. Each of these points is to be regarded as the center of a new wave-system which unimpeded would be propagated onward in a given time distances equal to the lines Aa' Bb', etc. Hence the common tangent $fghkE$ to the circular arcs drawn with these radii from A, B, etc., represents the direction of the new or reflected wave-front. But geometrically the angle eAE is equal to fEA, or the *incident and reflected wave-fronts make equal angles with the reflecting surface.* If NA is a normal at A, the angle OAN—called the *angle of incidence*—is equal to NAF, the *angle of reflection.* Hence the familiar law:

The angle of incidence is equal to the angle of reflection.

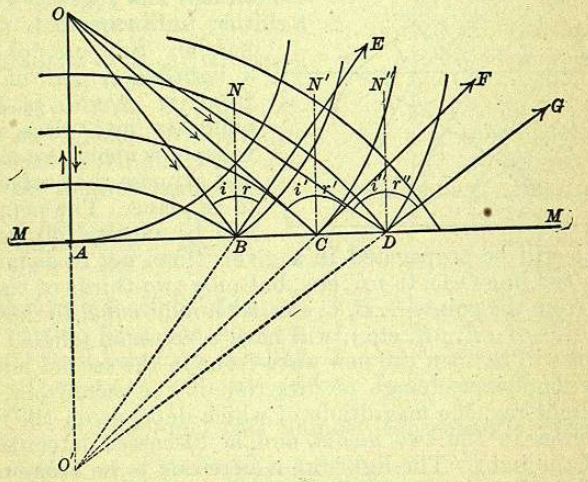
Furthermore, the "incident and reflected rays" both lie in the same plane with the normal to the reflecting surface.

497.



In Fig. 498, where the luminous point is at O, the waves going out from it will meet the plane mirror MM first at the point A and successively at points,

498.



as B, C, D, etc., farther away to the right (and left) of A. Here also it is easy to show that all the new impulses, which have their centers at A, B, C, etc., must together give rise to a series of reflected waves whose center is at O', at a distance equally distant from MM measured on a normal to the surface ($OA = OA'$).

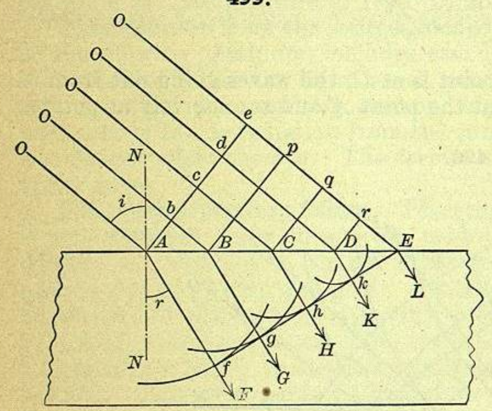
Now the lines OA, OB, etc., which are perpendicular to the wave-front, represent certain incident light-rays, and the eye placed in the direction BE, *CF*, etc., will see the luminous point as if at O'. It follows from the construction of the figure and can be proved by experiment that if *BN*, *CN*, etc., are normals to the mirror the angles of incidence, *OBN*, *OCN'*, etc., are equal to the angles of reflection, *NBE*, *N'BF*, etc., respectively. Hence the above law applies to this case also.

If the reflecting surface is not plane, but, for example, a concave surface, as that of a spherical or parabolic mirror, there is a change in the curvature of the wave-front after reflection, but the same law still holds true.

The proportion of the reflected to the incident light increases with the smoothness of the surface and also as the angle of incidence diminishes. The intensity of the reflected light is a maximum for a given surface in the case of perpendicular incidence (*OA*, Fig. 498). If the surface is not perfectly polished, *diffuse reflection* will take place, and there will be no distinct reflected ray. It is the diffusely reflected light which makes the reflected surface visible; if the surface of a mirror were *absolutely smooth* the eye would see the reflected body in it only, not the surface itself. Optically expressed, the surface is to be considered smooth if the distance between the scratches upon it is considerably less (say one-fourth) than the wave-length of light.

297. Refraction.—When a system of light-waves of the same wave-length passes from one medium into another there is, in general, an increase or decrease in the velocity of the light, and this results in the phenomenon of *refraction*—that is, a change of direction at the bounding surface. The principles applicable here can be most easily shown in the case of light-waves with a plane wave-front, as shown in Fig. 499—that is, where the light-rays *OA*, *OB*, etc., are parallel. Suppose, for example, that a light-wave, part of whose wave-front is *Abcde*, passes from air obliquely into glass, in which its velocity is about two-thirds as great, and suppose the surface of the glass to be plane. The points *A*, *B*, etc., will be successively centers of disturbance which will be propagated in a given time, not to distances equal to *eE* (from *A* in the line *OA*), to *pE*, etc., but only two-thirds of these distances. Circles drawn from the points *A*, *B*, *C*, etc., with radii equal to these diminished values (two-thirds of *eE*, *pE*, etc.), will have a common tangent in the plane *fghkE*, and this will be then the new wave-front in the second medium. Here it is seen that there is a change of direction in the wave-front, or otherwise stated, in the light-ray, the magnitude of which depends on the ratio between the light-velocities in the two media, and, as discussed later, also upon the wave-length of the light. The light-ray is here said to be broken or *refracted*, and for a medium like glass, optically denser than air (*i.e.*, with a lower value of the light-velocity), the refraction is toward the perpendicular. In the opposite case—in an optically rarer medium—the refraction is away from the perpendicular, the angle of refraction is larger than that of incidence (Art. **303**).

499.



298. Refractive Index.—It is obvious from the figure that whatever the direction of the wave-front—that is, of the light-rays—relatively to the given surface, the *ratio* of *eE* to *Af*, which determines the direction of the new

wave-front (*i.e.*, the direction of a refracted ray, *AF*) is constant. This ratio is equal to $\frac{V}{v}$ where V is the value of the light-velocity for the first medium (here air) and v for the second (as glass). If this constant ratio be represented by n, we may write:

$$n = \frac{V}{v} = \frac{eE}{Af} = \frac{AE.\ \text{Sin}\ eAE}{AE.\ \text{Sin}\ AEf} = \frac{\sin eAE}{\sin AEf} = \frac{\sin OAN}{\sin FAN}.$$

Here i (OAN) is the *angle of incidence* and r (FAN) the *angle of refraction;* thus, in its last form,

$$n = \frac{\sin i}{\sin r},$$

we have the familiar relation usually expressed as follows:

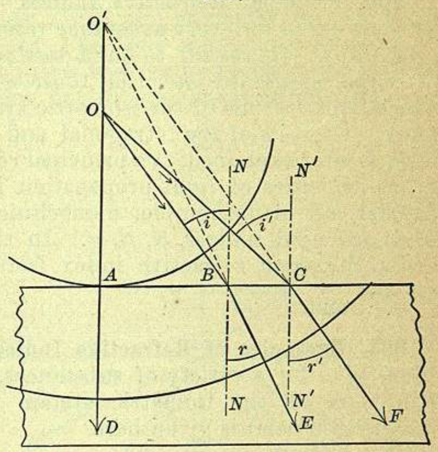
The sine of the angle of incidence bears a constant ratio to the sine of the angle of refraction.

It is also true that the incident and refracted rays lie in a common plane with the normal to the surface.

The above relation holds true for any wave-system of given wave-length in passing from one medium into another, whatever the wave-front or shape of the bounding surface. In Fig. 500* the luminous point is at *O*, and it can be readily shown that the new wave-front propagated in the second medium (of greater optical density) has a flattened curvature and corresponding to this a center at O' $\left(\text{where } \frac{O'A}{OA} = \frac{V}{v}\right)$. Here the incident rays *OB*, *OC*, are refracted at *B* and *C*, the corresponding refracted rays being *BE* and *BF*. For this case also the relation holds good,

$$n = \frac{\sin i}{\sin r} = \frac{\sin i'}{\sin r'}, \text{ etc.}$$

500.



This constant ratio for light of a given wave-length passing from one medium to another, expressed here by n, is called the *index of refraction* or *refractive index*. In the examples given for air and crown glass, $\frac{\sin i}{\sin r} = 1{\cdot}608$, and this number consequently gives the value of the refractive index, or n, for this kind of glass.

The relation between wave-length and refractive index is spoken of in Art. **305**.

If the bounding surface is not plane but curved, as in lenses, there is a change in the curvature of the wave-front in the second medium, but the simple law, $n = \frac{\sin i}{\sin r}$, holds true here also, so long as the medium is isotropic.

* See S. P. Thompson (Light Visible and Invisible, 1897), who develops the formulas for lenses, etc., on the basis of light-waves instead of light-rays.

299. Relation of Refractive Index to Light-velocity.—The discussion of the preceding article shows that if n is the refractive index of a given substance for waves of a certain length, referred to air, V the velocity in air and v the velocity in the given medium, then

$$n = \frac{V}{v}.$$

For two media whose indices are n_1 and n_2 respectively, it consequently follows that

$$\frac{n_1}{n_2} = \frac{v_2}{v_1}.$$

Therefore, *The indices of refraction of two given media for a certain wave-length are inversely proportional to their relative light-velocities.*

Since light-waves are propagated by a transverse motion in the ether which pervades the given body, and is as it were weighted down by its molecules, it is obvious that the velocity of the light-wave itself is measured by the rate of this transverse motion in the ether; hence for waves of the *same length* traveling through media of different refractive power, this latter velocity of transverse vibration is inversely proportional to the refractive indices.

300. Principal Refractive Indices.—The refractive index has, as stated, a constant value for every substance referred, as is usual, to air (or it may be to a vacuum). In regard to solid media, it is evident from Art. **298** and will be further explained later that those which are *isotropic*, viz., amorphous substances and crystals of the isometric system, can have but a single value of this index. Crystals of the tetragonal and hexagonal (and rhombohedral) systems have, as later explained, *two* principal refractive indices, ϵ and ω, corresponding to the velocities of light-propagation in certain definite directions in them. Further, all orthorhombic, monoclinic, and triclinic crystals have similarly *three* principal indices, α, β, γ. In the latter cases of so-called anisotropic media, the mean refractive index is taken, namely, as the arithmetical mean $\frac{\epsilon + 2\omega}{3}$ and $\frac{\alpha + \beta + \gamma}{3}$.

301. Examples of Refractive Indices.—The following table includes the values of n for a variety of substances, for sodium light. For minerals other than those of the isometric system the average value (as defined in the preceding article) is given here.

Ice	1·310	Boracite	1·667
Water	1·335	Flint Glass	1·702
Fluorite	1·434	Garnet (Pyrope)	1·814
Alum	1·456	Zircon	1·952
Rock-salt	1·544	Cerussite	1·986
Quartz	1·547	Sphalerite	2·369
Calcite	1·601	Diamond	2·419
Crown glass	1·608	Rutile	2·712
Aragonite	1·633	Pyrargyrite	3·016
Barite	1·640		

The refractive index for air referred to the ether of a vacuum is 1·000292 for a wave-length equal to that of yellow sodium light ($\lambda = 0·0000589$ cm.).

302. Specific Refractive Power.—The relation between the refractive index and the chemical composition of a given substance is expressed by what has been called the Gladstone law,* namely,

$$\frac{n-1}{d} = \text{constant}.$$

Here n is refractive index (for anisotropic substances, the mean index), and d is the density. The value of the constant is called the *specific refractive power*. The product of the specific refractive power into the molecular weight gives the *refractive equivalent*. Thus for quartz, $n = 1·5$, $d = 2·66$, therefore the value of the specific refractive power is 0·2, and the refractive equivalent is equal to this number multiplied into the molecular weight (60) or 12·6($= 0·2 \times 60$). Similarly the value obtained† for CaO is 13·3, and for MgO 17·1.

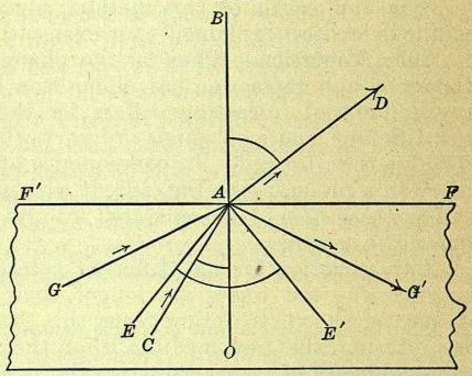
In the case of a complex molecule, it is assumed that the sum of the refractive equivalents of the parts of the molecule divided by the sum of the corresponding molecular weights is equal to the specific refractive power of the given compound. Thus for grossular garnet whose formula may be written $3CaO.Al_2O_3.3SiO_2$, the above relations give

$$\frac{3 \times 13·3 + 19·7 + 3 \times 12·6}{3 \times 56 + 103 + 3 \times 60} = 0·216.$$

Further, $\frac{n-1}{d} = \frac{n-1}{3·5} = 0·216$, and $n = 1·756$; experiment gives $n = 1·747$.

303. Total Reflection. Critical Angle.—In regard to the principle stated in Art. **298** and expressed by the equation $n = \frac{\sin i}{\sin r}$, two points are to be noted. First, if the angle $i = 0°$, then $\sin i = 0$, and obviously also $r = 0$; in other words, when the ray of light (as OA, Fig. 500) coincides with the perpendicular, no change of direction takes place, the ray proceeds onward (AD) into the second medium without deviation, but with a change of velocity.

501.



Again, if the angle $i = 90°$, then $\sin i = 1$, and the equation above becomes $n = \frac{1}{\sin r}$ or $\sin r = \frac{1}{n}$. As n has a fixed value for every substance, it is obvious that there will also be a corresponding value of the angle r for the case mentioned. From the above table it is seen that for water, $\sin r = \frac{1}{1·335}$ and $r = 48°$ 31′; for crown glass, $\sin r = \frac{1}{1·608}$ and $r = 38° 27'$; for diamond, $\sin r = \frac{1}{2·42}$ and $r = 24° 25'$.

In Fig. 501 the ray CA in the glass is refracted on passing into the air in the direction AD, but if the angle $EAO = 38° 27'$, the ray EA will graze the surface or take the direction AF. Any ray, GA, for which the angle GAO is greater than 38° 27′ will not emerge at all, but suffer *total reflection*, being returned in the direction AG'. The surface of glass illuminated from beneath in the direction last named has a brilliant, almost metallic luster. This is the

* See Mallard, Tr. Crist., **2**, 476 *et seq.* 1884; Rosenbusch, Mikr. Phys., **1**, 157 1892.
† A table of these values is given by Mallard and reproduced by Rosenbusch.