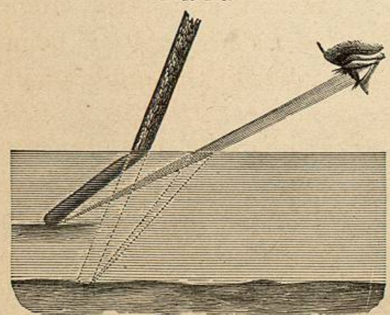
point within the sphere, half-way between its surface and center. The image of $P$ is at the crossing point of the axial ray from $P$ and the backward prolongation of the ray from $P$ which was parallel before reflection. The student can easily trace the rays and determine the position of the image.

## III. REFRACTION OF LIGHT.

**1. Definition.**—When a ray of light passes obliquely from one medium to another of different density, it is *refracted* or bent out of its course.—*Examples:* A spoon in clear tea appears bent.—An oar dipping in still water seems to break at the point where it enters the water.*—Put a cent in a bowl. Standing where you can not see the coin, let another

Fig. 148.



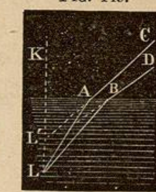
Apparent breaking of a Stick in Water.

* In Fig. 148 is shown a stick sunk till the end is at the bottom of the water. Rays of light from this end are bent as they emerge from the liquid and reach the eye as if they had come from a point considerably higher. The entire bottom, therefore, seems lifted up. Hence, water is always deeper than it appears. Look obliquely into a pail of water, then place your finger on the outside where the bottom seems to be; you will be surprised to find the real bottom is several inches below.—Fill a glass dish with water, and, darkening the windows, let a sunbeam fall upon the surface. The ray will bend as it enters. Dust scattered through the air will make the beam distinct.



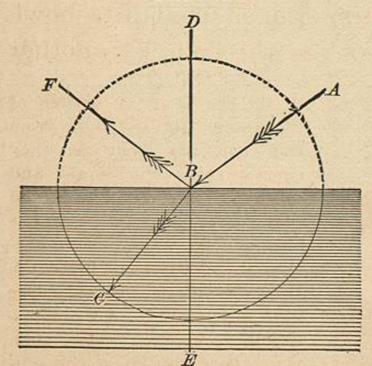
person pour water into the vessel, when the coin will be lifted into view. To understand the apparent change of position, remember that *the object is seen in the direction of the refracted ray as it enters the eye.* Let $L$, Fig. 149, be a body beneath the water. A ray, $LA$, coming to the surface, is bent away from the vertical, $LK$, and strikes the eye as if it came from $L'$. The object will therefore apparently be elevated above its true place.

Fig. 149.




**2. Laws of Refraction.**—From any point, $A$, Fig. 150, let a beam of light, $AB$, pass through air and meet a denser transparent medium at $B$, such as water or glass. At this point let a line, $DE$, be drawn perpendicular to the surface. Then some of the light will be reflected at $B$, the angle of reflection $DBF$ being equal to the angle of incidence, $DBA$. A little of it will be absorbed and changed into heat. The rest will be transmitted, but its direction changed to $BC$. This apparent breaking of the ray is called *refraction*, and the angle $EBC$, which is less than $DBA$, is the *angle of refraction.* If the source of light were at $C$, its direction on emerging at $B$

Fig. 150.




Reflection and Refraction.

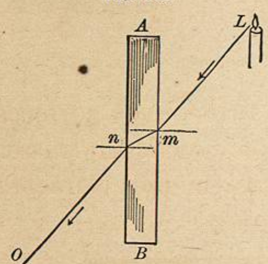
would be $BA$. The angle of refraction now is $DBA$ and the angle of incidence is $EBC$. Hence,

I. In passing into a denser medium, the ray is bent *toward* the perpendicular.

II. In passing into a rarer medium, the ray is bent *from* the perpendicular.*

ILLUSTRATIONS.—*Path of rays through a window-glass.*—When a ray enters a window-glass, it is refracted toward the perpendicular (1st law), and, on leaving, is refracted equally from the perpendicular (2d law). The general direction of objects is therefore unchanged. A poor quality of glass produces distortion by its unequal density and uneven surface.

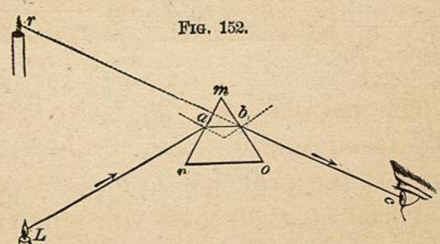
FIG. 151.




Passage of a Ray through Window-glass.

*Path of rays through a prism.*—A ray of light, on entering and on leaving a glass prism, is refracted. The inclination of the sides causes the ray to be *bent twice in the same direction.* The candle, $L$, will therefore appear to be in the direction of $r$.

FIG. 152.



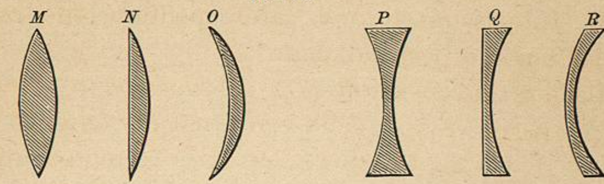

Passage of a Ray through a Prism.

* Both the incident and the refracted ray lie in the same plane as the normal (perpendicular). The ratio between the sines of the angles of incidence and refraction is termed the *index of refraction.* It varies with the media.—*Example:* From air to water it is $\frac{4}{3}$ and from air to glass $\frac{3}{2}$.



**3. Lenses.**—A lens is a transparent body, with at least one curved surface. There are two general classes of lenses, *concave* and *convex.** (See Fig. 153.)

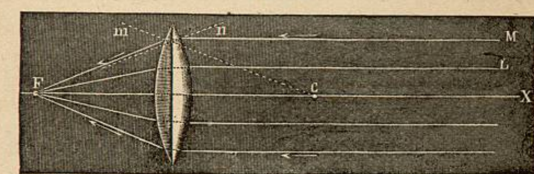
FIG. 153.




Magnifying Lenses. Diminishing Lenses.

(1.) THE BI-CONVEX LENS has two convex surfaces. Its action on light is like that of a concave mirror. A ray, $X$, striking perpendicularly, is not refracted.

FIG. 154.




Bi-convex Lens.

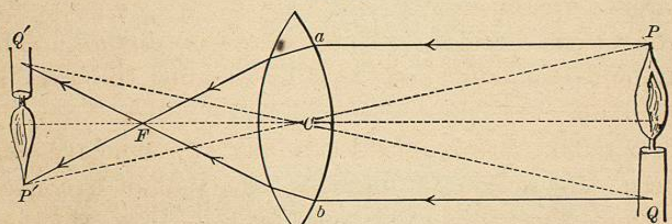
The parallel rays, $M$, $L$, etc., are refracted both on entering and on leaving the lens, and are converged at $F$, the principal *focus.*† If a luminous point be placed at $F$, its rays will emerge parallel.

* Forms of lenses: $M$, double-convex; $N$, plano-convex; $O$, meniscus (crescent); $P$, double-concave; $Q$, plano-concave; $R$, concavo-convex. The first three are styled *magnifiers*, and the second, *diminishers.*

† The convex lens is sometimes termed a *burning-glass*, being used, like the concave mirror, for collecting the sun's rays. Lenses have been manufactured of sufficient power to melt a stone by sun-heat. Even glass globes of water, such as are used for gold-fishes or in the windows of drug stores, may fire adjacent objects

*Construction of Images.*—There is a point, called the *optical center* of the lens, through which the passing ray does not change its general direction after emergence. These are called *axial* rays. The *principal* axis passes not only through the optical center ($C$, Fig. 155), but also through the principal focus, $F$. All rays parallel to it are so refracted as to pass through $F$. Let a candle, $PQ$, be placed in front of a bi-convex lens,* at a distance of ten or

Fig. 155.




Formation of an Image with a Bi-convex Lens.

twelve feet. An axial ray, $PC$, continues its path unchanged. A parallel ray, $Pa$, will after refraction pass through $F$. Where this cuts the axial ray at $P'$, the image of $P$ is found. In like manner $Q'$ is found as the point conjugate to $Q$. The image, $P'Q'$, is *real*, and may be caught on a screen. It is *inverted*, and as much *smaller* than the object as its distance from the optical center is less.

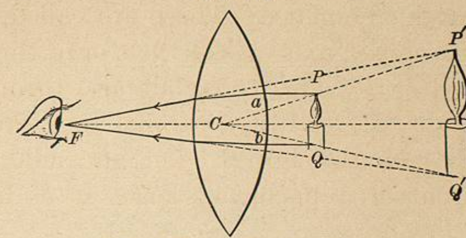
As the candle is made to approach the lens on one side, the image recedes on the other. When

* An ordinary magnifying hand-glass, such as is often used in looking at photographs, or even a spectacle-lens used by an aged person in reading, will be sufficient for these experiments.



brought nearly to $F$, the image on the other side grows very large and distant. When it arrives *within* the focal distance, $FC$, the image suddenly appears on the same side with the object, *erect*, and as much larger as its apparent distance from $C$ is greater. This image is *virtual.* The student can determine this by tracing the rays in Fig. 156.

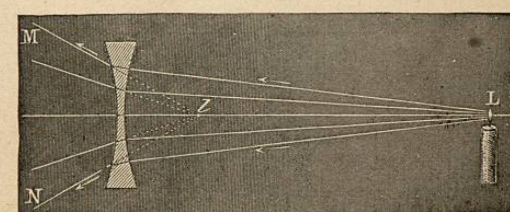
Fig. 156.




Virtual Image with Convex Lens.

(2.) The Bi-concave Lens has two concave surfaces. Its action on light is like that of a convex mirror. Thus, diverging rays from $L$ (Fig. 157) are

Fig. 157.



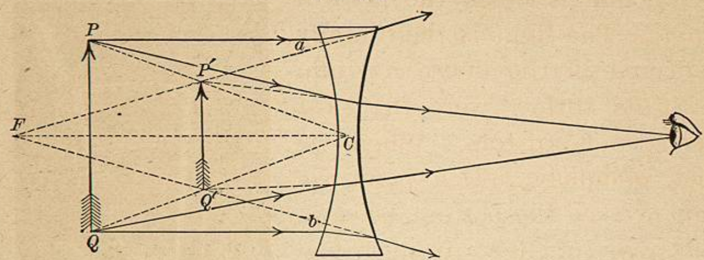

Bi-concave Lens.

rendered more diverging, and, to an eye which receives the rays $MN$, the candle would seem to be at $l$, where the image is seen.*

* Unscrew the eye-piece from an opera-glass; it serves well for experiments with concave lenses. Unscrew the glass at the other end; it serves for those with convex lenses.

*The image formed by a concave lens*, like that of a convex mirror, is *virtual*, *erect*, and *diminished* in

Fig. 158.




Formation of an Image with a Concave Lens.

size (Fig. 158). Let the student determine this by tracing the rays in Fig. 158, in which the arrow *PQ* is the object and *P'Q'* the image.*

**4. Spherical Aberration of Lenses.**—Parallel rays falling on a lens whose surface is like that of a sphere are not all refracted to a single focus. Those which pass through marginal parts of the lens are collected to a focus nearer than that to which the central rays are collected. With a single lens, therefore, it is not easy to secure perfect distinctness of image.

**5. Total Reflection.**—In passing from a dense into a rare medium, the angle of refraction is greater than the angle of incidence. It can not exceed 90°, for then the ray would cease to emerge. The angle

* Remember that parallel rays, *Pa* and *Qb*, become divergent after refraction, as if they had come from a focus, *F*, on the same side of the lens. The images of *P* and *Q* must hence be found on the *backward* prolongations of these emergent rays. Axial rays are drawn from *P* and *Q* to *C*.



of incidence for which the emergent ray would make an angle of 90° with the perpendicular is called the *critical angle*. The light is then totally reflected in the dense medium as if its surface were the most perfect of mirrors. When we look obliquely into a pond, we can not see the bottom, because the rays of light from below are reflected downward at the surface of the water. Hold a glass of water above the level of the eye, and the upper part will gleam like burnished silver.* Thus the internal surface of a transparent body becomes a mirror.

Fig. 159.

Total Internal Reflection.

**6. Mirage.**—Over the heated deserts of Arabia and Africa the traveler sometimes sees a shimmering expanse, as if a quiet lake were in the distance, in which the scattered trees are mirrored upside down. The layer of air close to the uniformly heated sand is less dense than the cooler air above. A ray coming obliquely downward from a tree-top may be so bent from its first direction by passing through

* Place a bright spoon in the glass and notice its image reflected from the surface of the water. Turn the spoon about in the glass and, changing the angle of observation, notice the effect. The real handle may apparently be attached to the image in the water. The spoon will soon be covered with bubbles of air shining, like pearls, from total reflection. This shows also the presence of air in water and the adhesion of gases to solids.

these different media as to be sent obliquely upward to the eye. The low warm layer of air acts like a totally reflecting mirror, and inverted images are dimly seen amid the bright light along the horizon.

FIG. 160.


Mirage.

In Fig. 160, rays of light from a clump of trees are refracted more and more until finally they are bent upward from a layer at *a*, and enter the eye of the Arab as if they came from the surface of a quiet lake.

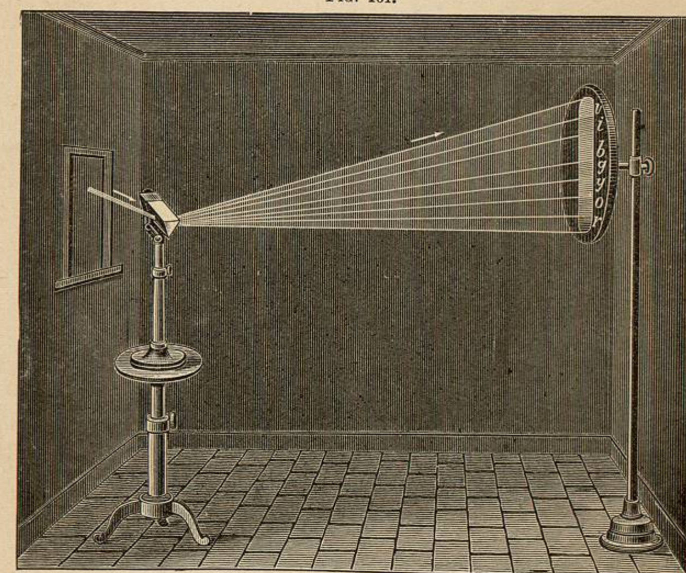
## IV. COMPOSITION OF LIGHT.

**1. The Prismatic Spectrum.**—When a sunbeam is received through a narrow slit and transmitted through a prism, properly placed, the ray is not only bent from its course, but is also spread out into a band of rainbow colors—the solar spectrum. This includes a multitude of tints grading imperceptibly



from one to another. The most prominent are *violet, indigo, blue, green, yellow, orange, red.** If we receive the spectrum on a concave mirror or pass it through a convex lens appropriately adjusted in position, these colors may be recombined so as to form a white band. We therefore conclude that

FIG. 161.



The Prismatic Spectrum.

white light is made up of these many tints. Because each has its own separate index of refraction (see p. 204, foot-note) when passing through the same prism, this refracts them unequally. The deviation of the violet is the greatest, and that of the red is the least, for the visible rays of the spectrum.

* Notice that the initial letters spell the mnemonic word, *Vib-gy-or.*