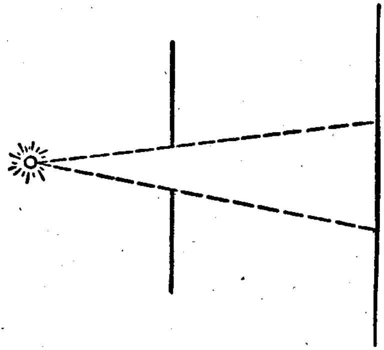
Since the days of these first experiments the very important number representing the velocity of light has been determined many times, with increasing accuracy. In our own century a highly refined technique was devised for this purpose by Michelson. The result of these experiments can be expressed simply: The velocity of light *in vacuo* is approximately 186,000 miles per second, or 300,000 kilometers per second.

LIGHT AS SUBSTANCE

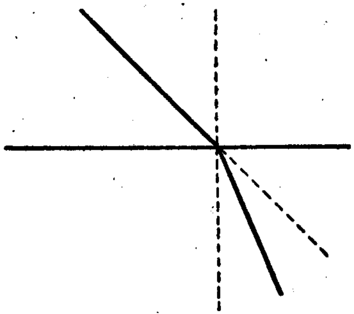
Again we start with a few experimental facts. The number just quoted concerns the velocity of light *in vacuo*. Undisturbed, light travels with this speed through empty space. We can see through an empty glass vessel if we extract the air from it. We see planets, stars, nebulae, although the light travels from them to our eyes through empty space. The simple fact that we can see through a vessel whether or not there is air inside shows us that the presence of air matters very little. For this reason we can perform optical experiments in an ordinary room with the same effect as if there were no air.

One of the simplest optical facts is that the propagation of light is rectilinear. We shall describe a primitive and naïve experiment showing this. In front of a point source is placed a screen with a hole in it. A point source is a very small source of light, say, a small opening in a closed lantern. On a distant wall the hole in the screen will be represented as light on a dark background. The next drawing shows how this phenomenon is connected with the rectilinear propagation of light.

All such phenomena, even the more complicated cases in which light, shadow, and half-shadows appear, can be explained by the assumption that light, *in vacuo* or in air, travels along straight lines.



Let us take another example, a case in which light passes through matter. We have a light beam traveling through a vacuum and falling on a glass plate. What

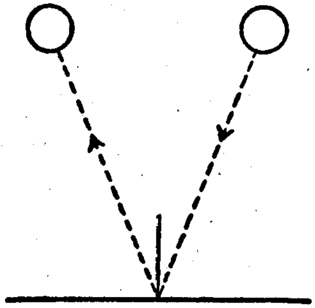


happens? If the law of rectilinear motion were still valid, the path would be that shown by the dotted line. But actually it is not. There is a break in the path, such as is shown in the drawing. What we observe here is the phenomenon known as *refraction*. The familiar appearance of a stick which seems to be bent in the middle if half-immersed in water is one of the many manifestations of refraction.

These facts are sufficient to indicate how a simple mechanical theory of light could be devised. Our aim here is to show how the ideas of substances, particles, and forces penetrated the field of optics, and how finally the old philosophical point of view broke down.

The theory here suggests itself in its simplest and most primitive form. Let us assume that all lighted bodies emit particles of light, or *corpuscles*, which, falling on our eyes, create the sensation of light. We are already so accustomed to introduce new substances, if necessary for a mechanical explanation, that we can do it once more without any great hesitation. These corpuscles must travel along straight lines through empty space with a known speed, bringing to our eyes messages from the bodies emitting light. All phenomena exhibiting the rectilinear propagation of light support the corpuscular theory, for just this kind of motion was prescribed for the corpuscles. The theory also explains very simply the reflection of light by mirrors as the same kind of reflection as that shown in the mechanical experiment of elastic balls thrown against a wall, as the next drawing indicates.

The explanation of refraction is a little more difficult. Without going into details we can see the possibility of a mechanical explanation. If corpuscles fall on the surface of glass, for example, it may be that a force is exerted on them by the particles of the matter, a force which strangely enough acts only in the immediate neighborhood of matter. Any force acting on a moving particle changes the velocity, as we already know. If the net force on the light-corpuscles is an



attraction perpendicular to the surface of the glass, the new motion will lie somewhere between the line of the original path and the perpendicular. This simple explanation seems to promise success for the corpuscular theory of light. To determine the usefulness and range of validity of the theory, however, we must investigate new and more complicated facts.

THE RIDDLE OF COLOR

It was again Newton's genius which explained for the first time the wealth of color in the world. Here is a description of one of Newton's experiments in his own words:

> In the year 1666 (at which time I applied myself to the grinding of optick glasses of other figures than spherical) I procured me a triangular glass prism, to try therewith the celebrated phenomena of colours. And in order thereto, having darkened my chamber, and made a small hole in my window-shuts, to let in a convenient quantity of the sun's light, I placed my prism at its entrance, that it might thereby be refracted to the opposite wall. It was at first a very pleasing divertisement, to view the vivid and intense colours produced thereby.

The light from the sun is "white." After passing through a prism it shows all the colors which exist in the visible world. Nature herself reproduces the same result in the beautiful color scheme of the rainbow. Attempts to explain this phenomenon are very old. The Biblical story that a rainbow is God's signature to a covenant with man is, in a sense, a "theory." But it does not satisfactorily explain why the rainbow is repeated from time to time, and why always in connection with rain. The whole puzzle of color was first scientifically attacked and the solution pointed out in the great work of Newton.

One edge of the rainbow is always red and the other violet. Between them all other colors are arranged. Here is Newton's explanation of this phenomenon: every color is already present in white light. They all traverse interplanetary space and the atmosphere in unison and give the effect of white light. White light is, so to speak, a mixture of corpuscles of different kinds, belonging to different colors. In the case of Newton's experiment the prism separates them in space. According to the mechanical theory, refraction is due to forces acting on the particles of light and originating from the particles of glass. These forces are different for corpuscles belonging to different colors, being strongest for the violet and weakest for the red. Each of the colors will therefore be refracted along a different path and be separated from the others when the light leaves the prism. In the case of a rainbow, drops of water play the role of the prism.

The substance theory of light is now more complicated than before. We have not one light substance but many, each belonging to a different color. If, however, there is some truth in the theory, its consequences must agree with observation.

The series of colors in the white light of the sun, as revealed by Newton's experiment, is called the *spectrum* of the sun, or more precisely, its *visible spectrum.* The decomposition of white light into its components, as described here, is called the *dispersion* of light. The separated colors of the spectrum could be mixed together again by a second prism properly adjusted, unless the explanation given is wrong. The process should be just the reverse of the previous one. We should obtain white light from the previously separated colors. Newton showed by experiment that it is indeed possible to obtain white light from its spectrum and the spectrum from white light in this simple way as many times as one pleases. These experiments formed a strong support for the theory in which corpuscles belonging to each color behave as unchangeable substances. Newton wrote thus:

> . . . which colours are not new generated, but only made apparent by being parted; for if they be again entirely mixt and blended together, they will again compose that colour, which they did before separation. And for the same reason, transmutations made by the convening of divers colours are not real; for when the difform rays are again severed, they will exhibit the very same colours which they did before they entered the composition; as you see blue and yellow powders, when finely mixed, appear to the naked eye, green, and yet the colours of the component corpuscles are not thereby really transmuted, but only blended. For when viewed with a good microscope they still appear blue and yellow interspersedly.

Suppose that we have isolated a very narrow strip of the spectrum. This means that of all the many colors we allow only one to pass through the slit, the others being stopped by a screen. The beam which comes through will consist of *homogeneous* light, that is, light which cannot be split into further components. This is a consequence of the theory and can be easily confirmed by experiment. In no way can such a beam of single color be divided further. There are simple means of obtaining sources of homogeneous light. For example, sodium, when incandescent, emits homogeneous yellow light. It is very often convenient to perform certain optical experiments with homogeneous light, since, as we can well understand, the result will be much simpler.

Let us imagine that suddenly a very strange thing happens: our sun begins to emit only homogeneous light of some definite color, say yellow. The great variety of colors on the earth would immediately vanish. Everything would be either yellow or black! This prediction is a consequence of the substance theory of light, for new colors cannot be created. Its validity can be confirmed by experiment: in a room where the only source of light is incandescent sodium everything is either yellow or black. The wealth of color in the world reflects the variety of color of which white light is composed.

The substance theory of light seems to work splendidly in all these cases, although the necessity for introducing as many substances as colors may make us somewhat uneasy. The assumption that all the corpuscles of light have exactly the same velocity in empty space also seems very artificial.

It is imaginable that another set of suppositions, a theory of entirely different character, would work just as well and give all the required explanations. Indeed, we shall soon witness the rise of another theory, based on entirely different concepts, yet explaining the same domain of optical phenomena. Before formulating the underlying assumptions of this new theory, however, we must answer a question in no way connected with these optical considerations. We must go back to mechanics and ask:

WHAT IS A WAVE?

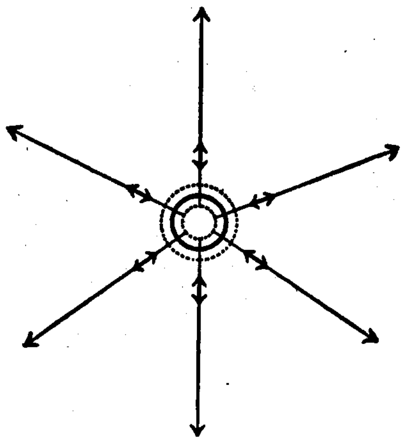
A bit of gossip starting in Washington reaches New York very quickly, even though not a single individual who takes part in spreading it travels between these two cities. There are two quite different motions involved, that of the rumor, Washington to New York, and that of the persons who spread the rumor. The wind, passing over a field of grain, sets up a wave which spreads out across the whole field. Here again we must distinguish between the motion of the wave and the motion of the separate plants, which undergo only small oscillations. We have all seen the waves that spread in wider and wider circles when a stone is thrown into a pool of water. The motion of the wave is very different from that of the particles of water. The particles merely go up and down. The observed motion of the wave is that of a state of matter and not of matter itself. A cork floating on the wave shows this clearly, for it moves up and down in imitation of the actual motion of the water, instead of being carried along by the wave.

In order to understand better the mechanism of the wave let us again consider an idealized experiment.

Suppose that a large space is filled quite uniformly with water, or air, or some other "medium." Somewhere in the center there is a sphere. At the beginning of the experiment there is no motion at all. Suddenly the sphere begins to "breathe" rhythmically, expanding and contracting in volume, although retaining its spherical shape. What will happen in the medium? Let us begin our examination at the moment the sphere begins to expand. The particles of the medium in the immediate vicinity of the sphere are pushed out, so that the density of a spherical shell of water, or air, as the case may be, is increased above its normal value. Similarly, when the sphere contracts, the density of that part of the medium immediately surrounding it will be decreased. These changes of density are propagated throughout the entire medium. The particles constituting the medium perform only small vibrations, but the whole motion is that of a progressive wave. The essentially new thing here is that for the first time we consider the motion of something which is not matter, but energy propagated through matter.

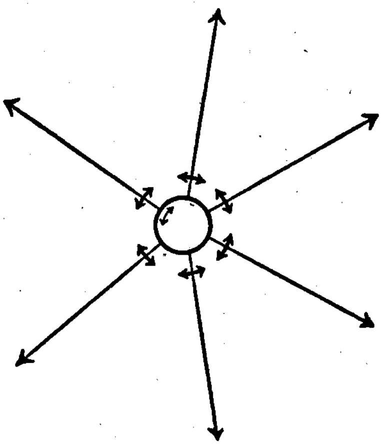
Using the example of the pulsating sphere, we may introduce two general physical concepts, important for the characterization of waves. The first is the velocity with which the wave spreads. This will depend on the medium, being different for water and air, for example. The second concept is that of *wave-length.* In the case of waves on a sea or river it is the distance from the trough of one wave to that of the next, or from the crest of one wave to that of the next. Thus sea waves have greater wave-length than river waves. In the case of our waves set up by a pulsating sphere the wave-length is the distance, at some definite time, between two neighboring spherical shells showing maxima or minima of density. It is evident that this distance will not depend on the medium alone. The rate of pulsation of the sphere will certainly have a great effect, making the wave-length shorter if the pulsation becomes more rapid, longer if the pulsation becomes slower.

This concept of a wave proved very successful in physics. It is definitely a mechanical concept. The phenomenon is reduced to the motion of particles which, according to the kinetic theory, are constituents of matter. Thus every theory which uses the concept of wave can, in general, be regarded as a mechanical theory. For example, the explanation of acoustical phenomena is based essentially on this concept. Vibrating bodies, such as vocal cords and violin strings, are sources of sound waves which are propagated through the air in the manner explained for the pulsating sphere. It is thus possible to reduce all acoustical phenomena to mechanics by means of the wave concept.



It has been emphasized that we must distinguish between the motion of the particles and that of the wave itself, which is a state of the medium. The two are very different but it is apparent that in our example of the pulsating sphere both motions take place in the same straight line. The particles of the medium oscillate along short line segments, and the density increases and decreases periodically in accordance with this motion. The direction in which the wave spreads and the line on which the oscillations lie are the same. This type of wave is called *longitudinal.* But is this the only kind of wave? It is important for our further considerations to realize the possibility of a different kind of wave, called *transverse.*

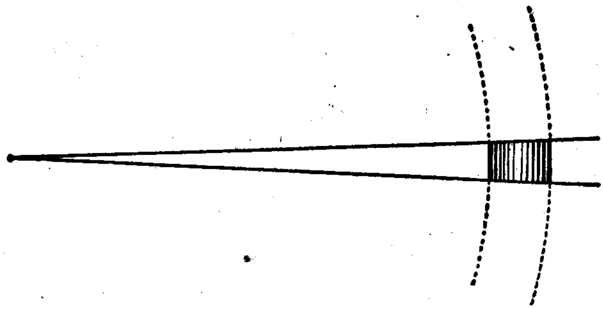
Let us change our previous example. We still have the sphere, but it is immersed in a medium of a different kind, a sort of jelly instead of air or water. Furthermore, the sphere no longer pulsates but rotates in one direction through a small angle and then back again, always in the same rhythmical way and about a definite



axis. The jelly adheres to the sphere and thus the adhering portions are forced to imitate the motion. These portions force those situated a little further away to imitate the same motion, and so on, so that a wave is set up in the medium. If we keep in mind the distinction between the motion of the medium and the motion of the wave we see that here they do not lie on the same line. The wave is propagated in the direction of the radius of the sphere, while the parts of the medium move perpendicularly to this direction. We have thus created a transverse wave.

Waves spreading on the surface of water are transverse. A floating cork only bobs up and down, but the wave spreads along a horizontal plane. Sound waves, on the other hand, furnish the most familiar example of longitudinal waves.

One more remark: the wave produced by a pulsating or oscillating sphere in a homogeneous medium is a *spherical* wave. It is called so because at any given moment all points on any sphere surrounding the source behave in the same way. Let us consider a portion of such a sphere at a great distance from the source. The farther away the portion is, and the smaller we take it, the more it resembles a plane. We



can say, without trying to be too rigorous, that there is no essential difference between a part of a plane and a part of a sphere whose radius is sufficiently large. We very often speak of small portions of a spherical wave far removed from the source as *plane waves*. The farther we place the shaded portion of our drawing from the center of the spheres and the smaller the angle between the two radii, the better our representation of a plane wave. The concept of a plane wave, like many other physical concepts, is no more than a fiction which can be realized with only a certain degree of accuracy. It is, however, a useful concept which we shall need later.

THE WAVE THEORY OF LIGHT

Let us recall why we broke off the description of optical phenomena. Our aim was to introduce another theory of light, different from the corpuscular one, but also attempting to explain the same domain of facts. To do this we had to interrupt our story and introduce the concept of waves. Now we can return to our subject.

It was Huygens, a contemporary of Newton, who put forward a quite new theory. In his treatise on light he wrote:

> If, in addition, light takes time for its passage—which we are now going to examine—it will follow that this movement, impressed on the intervening matter, is successive; and consequently it spreads, as sound does, by spherical surfaces and waves, for I call them waves from their resemblance to those which are seen to be formed in water when a stone is thrown into it, and which present a successive spreading as circles, though these arise from another cause, and are only in a flat surface.

According to Huygens, light is a wave, a transference of energy and not of substance. We have seen that the corpuscular theory explains many of the observed facts. Is the wave theory also able to do this? We must again ask the questions which have already been answered by the corpuscular theory, to see whether the wave theory can do the answering just as well. We shall do this here in the form of a dialogue between N and H, where N is a believer in Newton's corpuscular theory, and H in Huygen's theory. Neither is allowed to use arguments developed after the work of the two great masters was finished.

N: In the corpuscular theory the velocity of light has a very definite meaning. It is the velocity at which the corpuscles travel through empty space. What does it mean in the wave theory?

H: It means the velocity of the light wave, of course. Every known wave spreads with some definite velocity, and so should a wave of light.

N: That is not as simple as it seems. Sound waves spread in air, ocean waves in water. Every wave must have a material medium in which it travels. But light passes through a vacuum, whereas sound does not. To assume a wave in empty space really means not to assume any wave at all.

H: Yes, that is a difficulty, although not a new one to me. My master thought about it very carefully, and decided that the only way out is to assume the existence of a hypothetical substance, the *ether*, a transparent medium permeating the entire universe. The universe is, so to speak, immersed in ether. Once we have the courage to introduce this concept, everything else becomes clear and convincing.

N: But I object to such an assumption. In the first place it introduces a new hypothetical substance, and we already have too many substances in physics. There is also another reason against it. You no doubt believe that we must explain everything in terms of mechanics. But what about the ether? Are you able to answer the simple question as to how the ether is constructed from its elementary particles and how it reveals itself in other phenomena?

H: Your first objection is certainly justified. But by introducing the somewhat artificial weightless ether we at once get rid of the much more artificial light corpuscles. We have only one "mysterious" substance instead of an infinite number of them corresponding to the great number of colors in the spectrum. Do you not think that this is real progress? At least all the difficulties are concentrated on one point. We no longer need the factitious assumption that particles belonging to different colors travel with the same speed through empty space. Your second argument is also true. We cannot give a mechanical explanation of ether. But there is no doubt that the future study of optical and perhaps other phenomena will reveal its structure. At present we must wait for new experiments and conclusions, but finally, I hope, we shall be able to clear up the problem of the mechanical structure of the ether.

N: Let us leave the question for the moment, since it cannot be settled now. I should like to see how your theory, even if we waive the difficulties, explains those phenomena which are so clear and understandable in the light of the corpuscular theory. Take, for example, the fact that light rays travel *in vacuo* or in air along straight lines. A piece of paper placed in front of a candle produces a distinct and sharply outlined shadow on the wall. Sharp shadows would not be possible if the wave theory of light were correct, for waves would bend around the edges of the paper and thus blur the shadow. A small ship is not an obstacle for waves on the sea, you know; they simply bend around it without casting a shadow.

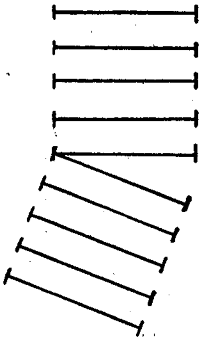
H: That is not a convincing argument. Take short waves on a river impinging on the side of a large ship. Waves originating on one side of the ship will not be seen on the other. If the waves are small enough and the ship large enough a very distinct shadow appears. It is very probable that light seems to travel in straight lines only because its wave-length is very small in comparison with the size of ordinary obstacles and of apertures used in experiments. Possibly, if we could create a sufficiently small obstruction, no shadow would occur. We might meet with great experimental difficulties in constructing apparatus which would show whether light is capable of bending. Nevertheless, if such an experiment could be devised it would be crucial in deciding between the wave theory and the corpuscular theory of light.

N: The wave theory may lead to new facts in the future, but I do not know of any experimental data confirming it convincingly. Until it is definitely proved by experiment that light may be bent I do not see any reason for not believing in the corpuscular theory, which seems to me to be simpler, and therefore better, than the wave theory.

At this point we may interrupt the dialogue, though the subject is by no means exhausted.

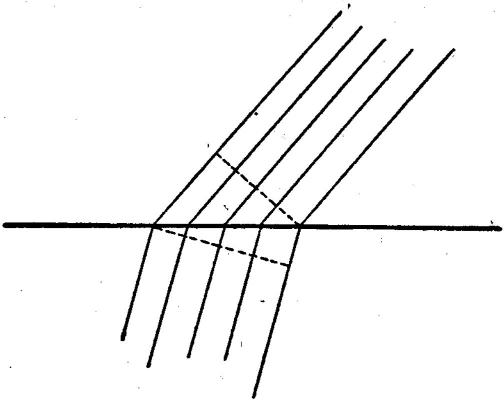
It still remains to be shown how the wave theory explains the refraction of light and the variety of colors. The corpuscular theory is capable of this, as we know. We shall begin with refraction, but it will be useful to consider first an example having nothing to do with optics.

There is a large open space in which there are walking two men holding between them a rigid pole. At the beginning they are walking straight ahead, both with the same velocity. As long as their velocities remain the same, whether great or small, the stick will be undergoing parallel displacement; that is, it does not turn or change its direction. All consecutive positions of the pole are parallel to each other. But now imagine that for a time which may be as short as a fraction of a second the motions of the two men are not the same. What will happen? It is clear that during this moment the stick will turn, so that it will no longer be displaced parallel to its original position. When the equal velocities are resumed it is in a direction different from the previous one. This is shown clearly in the drawing.



The change in direction took place during the time interval in which the velocities of the two walkers were different.

This example will enable us to understand the refraction of a wave. A plane wave traveling through the ether strikes a plate of glass. In the next drawing we see a wave which presents a comparatively wide front as it marches along. The wave front is a plane on which at any given moment all parts of the ether behave in precisely the same way. Since the velocity depends on the medium through which the light is passing it will be different in glass from the velocity in empty space. During the very short time in which the wave front enters the glass, different parts of the wave front will have different velocities. It is clear that the part which has reached the glass will travel with the velocity of light in glass, while the other still moves with the velocity of light in ether. Because of this difference in velocity along the wave front during the time of "immersion" in the glass, the direction of the wave itself will be changed.



Thus we see that not only the corpuscular theory, but also the wave theory, leads to an explanation of refraction. Further consideration, together with a little mathematics, shows that the wave theory explanation is simpler and better, and that the consequences are in perfect agreement with observation. Indeed, quantitative methods of reasoning enable us to deduce the velocity of light in a refractive medium if we know how the beam refracts when passing into it. Direct measurements splendidly confirm these predictions, and thus also the wave theory of light.

There still remains the question of color.

It must be remembered that a wave is characterized by two numbers, its velocity and its wave-length. The essential assumption of the wave theory of light is that *different wave-lengths correspond to different colors.* The wave-length of homogeneous yellow light differs from that of red or violet. Instead of the artificial segregation of corpuscles belonging to various colors we have the natural difference in wave-length.

It follows that Newton's experiments on the dispersion of light can be described in two different languages, that of the corpuscular theory and that of the wave theory. For example:

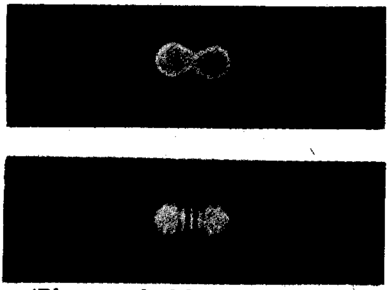
Corpuscular Language	Wave Language
The corpuscles belonging to different colors have the same velocity *in vacuo*, but different velocities in glass.	The rays of different wave-length belonging to different colors have the same velocity in the ether, but different velocities in glass.
White light is a composition of corpuscles belonging to different colors, whereas in the spectrum they are separated.	White light is a composition of waves of all wave-lengths, whereas in the spectrum they are separated.

It would seem wise to avoid the ambiguity resulting from the existence of two distinct theories of the same phenomena, by deciding in favor of one of them after a careful consideration of the faults and merits of each. The dialogue between N and H shows that this is no easy task. The decision at this point would be more a matter of taste than of scientific conviction. In Newton's time, and for more than a hundred years after, most physicists favored the corpuscular theory.

History brought in its verdict, in favor of the wave theory of light and against the corpuscular theory, at a much later date, the middle of the nineteenth century. In his conversation with H, N stated that a decision between the two theories was, in principle, experimentally possible. The corpuscular theory does not allow light to bend, and demands the existence of sharp shadows. According to the wave theory, on the other hand, a sufficiently small obstacle will cast no shadow. In the work of Young and Fresnel this result was experimentally realized and theoretical conclusions were drawn.

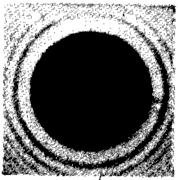
An extremely simple experiment has already been discussed, in which a screen with a hole was placed in front of a point source of light and a shadow appeared on the wall. We shall simplify the experiment further by assuming that the source emits homogeneous light. For the best results the source should be a strong one. Let us imagine that the hole in the screen is made smaller and smaller. If we use a strong source and succeed in making the hole small enough, a new and surprising phenomenon appears, something quite incomprehensible from the point of view of the corpus-

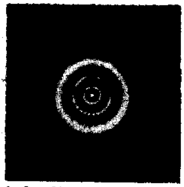
PLATE II



(Photographed by V. Arkadiev)

Above, we see a photograph of light spots after two beams have passed through two pin holes, one after the other. (One pin hole was opened, then covered and the other opened.) Below, we see stripes when light is allowed to pass through both pin holes simultaneously.





(Photographed by V. Arkadiev)

Diffraction of light bending around a small obstacle.

Diffraction of light passing through a small hole.

cular theory. There is no longer a sharp distinction between light and dark. Light gradually fades into the dark background in a series of light and dark rings. The appearance of rings is very characteristic of a wave theory. The explanation for alternating light and dark areas will be clear in the case of a somewhat different experimental arrangement. Suppose we have a sheet of dark paper with two pinholes through which light may pass. If the holes are close together and very small, and if the source of homogeneous light is strong enough, many light and dark bands will appear on the wall, gradually fading off at the sides into the dark background. The explanation is simple. A dark band is where a trough of a wave from one pinhole meets the crest of a wave from the other pinhole, so that the two cancel. A band of light is where two troughs or two crests from waves of the different pinholes meet and reinforce each other. The explanation is more complicated in the case of the dark and light rings of our previous example in which we used a screen with one hole, but the principle is the same. This appearance of dark and light stripes in the case of two holes and of light and dark rings in the case of one hole should be borne in mind, for we shall later return to a discussion of the two different pictures. The experiments described here show the *diffraction* of light, the deviation from the rectilinear propagation when small holes or obstacles are placed in the way of the light wave.

With the aid of a little mathematics we are able to go much further. It is possible to find out how great or, rather, how small the wave-length must be to produce a particular pattern. Thus the experiments described enable us to measure the wave-length of the homogeneous light used as a source. To give an idea of how small the numbers are we shall cite two wave-lengths, those representing the extremes of the solar spectrum, that is, the red and the violet.

The wave-length of red light is 0.00008 cm.
The wave-length of violet light is 0.00004 cm.

We should not be astonished that the numbers are so small. The phenomenon of distinct shadow, that is, the phenomenon of rectilinear propagation of light, is observed in nature only because all apertures and obstacles ordinarily met with are extremely large in comparison with the wave-lengths of light. It is only when very small obstacles and apertures are used that light reveals its wave-like nature.

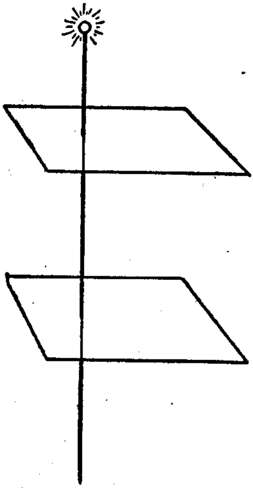
But the story of the search for a theory of light is by no means finished. The verdict of the nineteenth century was not final and ultimate. For the modern physicist the entire problem of deciding between corpuscles and waves again exists, this time in a much more profound and intricate form. Let us accept the defeat of the corpuscular theory of light until we recognize the problematic nature of the victory of the wave theory.

LONGITUDINAL OR TRANSVERSE LIGHT WAVES?

All the optical phenomena we have considered speak for the wave theory. The bending of light around small obstacles and the explanation of refraction are the strongest arguments in its favor. Guided by the mechanical point of view we realize that there is still one question to be answered: the determination of the mechanical properties of the ether. It is essential for the solution of this problem to know whether light waves in the ether are longitudinal or transverse. In other words: is light propagated like sound? Is the wave due to changes in the density of the medium, so that the oscillations of the particles are in the direction of the propagation? Or does the ether resemble an elastic jelly, a medium in which only transverse waves can be set up and whose particles move in a direction perpendicular to that in which the wave itself travels?

Before solving this problem let us try to decide which answer should be preferred. Obviously, we should be fortunate if light waves were longitudinal. The difficulties in designing a mechanical ether would be much simpler in this case. Our picture of ether might very probably be something like the mechanical picture of a gas that explains the propagation of sound waves. It would be much more difficult to form a picture of ether carrying transverse waves. To imagine a jelly as a medium made up of particles in such a way that transverse waves are propagated by means of it is no easy task. Huygens believed that the ether would turn out to be "air-like" rather than "jelly-like." But nature cares very little for our limitations. Was nature, in this case, merciful to the physicists attempting to understand all events from a mechanical point of view? In order to answer this question we must discuss some new experiments.

We shall consider in detail only one of many experiments which are able to supply us with an answer. Suppose we have a very thin plate of tourmaline crystal, cut in a particular way which we need not describe here. The crystal plate must be thin so that we are able to see a source of light through it. But now let us take two such plates and place both of them between our eyes and the light. What do we expect to see? Again a point of light, if the plates are sufficiently thin. The chances are very good that the experiment will confirm our expectation. Without worrying about the statement that it may be chance, let us assume we do see the light point through the two crystals. Now let us gradually change the position of one of the crystals by rotating it. This statement makes sense only if the position of the axis about which the rotation takes place is fixed. We shall take as an axis the line determined by the incoming ray. This means that we displace all the points of the one crystal except those



on the axis. A strange thing happens! The light gets weaker and weaker until it vanishes completely. It reappears as the rotation continues and we regain the initial view when the initial position is reached.

Without going into the details of this and similar experiments we can ask the following question: can these phenomena be explained if the light waves are longitudinal? In the case of longitudinal waves the particles of the ether would move along the axis, as the beam does. If the crystal rotates, nothing along the axis changes. The points on the axis do not move, and only a very small displacement takes place nearby. No such distinct change as the vanishing and appearance of a new picture could possibly occur for a longitudinal wave. This and many other similar phenomena can be explained only by the assumption that light waves are transverse and not longitudinal! Or, in other words, the "jelly-like" character of the ether must be assumed.

This is very sad! We must be prepared to face tremendous difficulties in the attempt to describe the ether mechanically.

ETHER AND THE MECHANICAL VIEW

The discussion of all the various attempts to understand the mechanical nature of the ether as a medium for transmitting light, would make a long story. A mechanical construction means, as we know, that the substance is built up of particles with forces acting along lines connecting them and depending only on the distance. In order to construct the ether as a jelly-like mechanical substance physicists had to make some highly artificial and unnatural assumptions. We shall not quote them here; they belong to the almost forgotten past. But the result was significant and important. The artificial character of all these assumptions, the necessity for introducing so many of them all quite independent of each other, was enough to shatter the belief in the mechanical point of view.

But there are other and simpler objections to ether than the difficulty of constructing it. Ether must be assumed to exist everywhere, if we wish to explain optical phenomena mechanically. There can be no empty space if light travels only in a medium.

Yet we know from mechanics that interstellar space does not resist the motion of material bodies. The planets, for example, travel through the ether-jelly without encountering any resistance such as a material medium would offer to their motion. If ether does not disturb matter in its motion, there can be no interaction between particles of ether and particles of matter. Light passes through ether and also through glass and water, but its velocity is changed in the latter substances. How can this fact be explained mechanically? Apparently only by assuming some interaction between ether particles and matter particles. We have just seen that in the case of freely moving bodies such interactions must be assumed not to exist. In other words, there is interaction between ether and matter in optical phenomena, but none in mechanical phenomena! This is certainly a very paradoxical conclusion!

There seems to be only one way out of all these difficulties. In the attempt to understand the phenomena of nature from the mechanical point of view, throughout the whole development of science up to the twentieth century, it was necessary to introduce artificial substances like electric and magnetic fluids, light corpuscles, or ether. The result was merely the concentration of all the difficulties in a few essential points, such as ether in the case of optical phenomena. Here all the fruitless attempts to construct an ether in some simple way, as well as the other objections, seem to indicate that the fault lies in the fundamental assumption that it is possible to explain all events in nature from a mechanical point of view. Science did not succeed in carrying out the mechanical program convincingly, and today no physicist believes in the possibility of its fulfillment.

In our short review of the principal physical ideas we have met some unsolved problems, have come upon difficulties and obstacles which discouraged the attempts to formulate a uniform and consistent view of all the phenomena of the external world. There was the unnoticed clew in classical mechanics of the equality of gravitational and inertial mass. There was the artificial character of the electric and magnetic fluids. There was, in the interaction between electric current and magnetic needle, an unsolved difficulty. It will be remembered that this force did not act in the line connecting the wire and the magnetic pole, and depended on the velocity of the moving charge. The law expressing its direction and magnitude was extremely complicated. And finally, there was the great difficulty with the ether.

Modern physics has attacked all these problems and solved them. But in the struggle for these solutions new and deeper problems have been created. Our knowledge is now wider and more profound than that of the physicist of the nineteenth century, but so are our doubts and difficulties.

WE SUMMARIZE:

In the old theories of electric fluids, in the corpuscular and wave theories of light, we witness the further attempts to apply the mechanical view. But in the realm of electric and optical phenomena we meet grave difficulties in this application.

A moving charge acts upon a magnetic needle. But the force, instead of depending only upon distance, depends also upon the velocity of the charge. The force neither repels nor attracts but acts perpendicular to the line connecting the needle and the charge.

In optics we have to decide in favor of the wave theory against the corpuscular theory of light. Waves spreading in a medium consisting of particles, with mechanical forces acting between them, are certainly a mechanical concept. But what is the medium through which light spreads and what are its mechanical properties? There is no hope of reducing the optical phenomena to the mechanical ones before this question is answered. But the difficulties in solving this problem are so great that we have to give it up and thus give up the mechanical view as well.