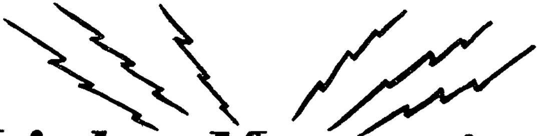

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ABOUT THE AUTHOR: ISAAC ASIMOV is generally regarded as one of this country's leading writers of science and science fiction. He obtained his Ph.D. in chemistry from Columbia University and was Associate Professor of Biochemistry at Boston University School of Medicine. He is the author of over 200 books, including *The Chemicals of Life, The Genetic Code, The Human Body, The Human Brain,* and *The Wellsprings of Life,* all available in Mentor editions.

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UNDERSTANDING PHYSICS

Volume II

Light, Magnetism, and Electricity

ISAAC ASIMOV

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CHAPTER 1

Mechanism

The Newtonian View

In the first volume of this book, I dealt with energy in three forms: motion (kinetic energy), sound, and heat. As it turned out, sound and heat are forms of kinetic energy after all. In the case of sound, the atoms and molecules making up the air, or any other medium through which sound travels, move back and forth in an orderly manner. In this way, waves of compression and rarefaction spread out at a fixed velocity (see page I–156).* Heat, on the other hand, is associated with the random movement of the atoms and molecules making up any substance. The greater the average velocity of such movement, the greater the intensity of heat (see page I–234).

By the mid-nineteenth century the Scottish physicist James Clerk Maxwell (1831–1879) and the Austrian physicist Ludwig Boltzmann (1844–1906) had worked out, in strict detail, the interpretation of heat as random molecular movement (the "kinetic theory of heat"). It then became more tempting than ever to suspect that all phenomena in the universe could be analyzed as being based on matter in motion.

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* When it is necessary to refer to a passage in the first volume, I will precede the page reference by "I." When the reference is to a page in this volume, it will be given without qualification. In other words, I will say "see page I–123" for a reference to the first volume but "see page 123" for a reference to this one.

According to this view, one might picture the universe as consisting of a vast number of parts; each part, if moving, affecting those neighboring parts with which it makes contact. This is exactly what we see, for instance, in a machine like an ordinary clock. One part of the clock affects another by the force of an expanding spring; by moving, interlocking gears; by levers; in short, by physical interconnections of all kinds. In other machines, such interconnections might consist of endless belts, pulleys, jets of water, and so on. On the submicroscopic scale it is atoms and molecules that are in motion, and these interact by pushing each other when they collide. On the cosmic scale, it is the planets and stars that are in motion, and these interact with each other through gravitational influence.

From the vast universe down to the tiniest components thereof, all might be looked on as obeying the same laws of mechanics by physical interaction as do the familiar machines of everyday life. This is the philosophy of mechanism, or the mechanistic interpretation of the universe. (Gravitational influence does not quite fit this view, as I shall point out shortly.)

The interactions of matter in motion obey, first of all, the three laws of motion (see page I–23ff.) propounded by Isaac Newton (1642–1727) in 1687, and the law of universal gravitation that he also propounded. The mechanistic view of the universe may therefore be spoken of, fairly enough, as the "Newtonian view of the universe."

The entire first volume of this book is devoted to the Newtonian view. It carries matters to the mid-nineteenth century, when this view had overcome all obstacles and had gained strength until it seemed, indeed, triumphant and unshakable.

In the first half of the nineteenth century, for instance, it had been found that Uranus traveled in its orbit in a way that could not be quite accounted for by Newton's law of universal gravitation. The discrepancy between Uranus's actual position in the 1840's and the one it was expected to have was tiny; nevertheless the mere existence of that discrepancy threatened to destroy the Newtonian fabric.

Two young astronomers, the Englishman John Couch Adams (1819–1892) and the Frenchman Urbain Jean Joseph Leverrier (1811–1877), felt that the Newtonian view could not be wrong. The discrepancy had to be due to the existence of an unknown planet whose gravitational influence on Uranus was not being allowed for. Independently they calculated where such a planet had to be located to account for the observed discrepancy in

Uranus's motions, and reached about the same conclusion. In 1846 the postulated planet was searched for and found.

After such a victory, who could doubt the usefulness of the Newtonian view of the universe?

And yet, by the end of the century, the Newtonian view had been found to be merely an approximation. The universe was more complicated than it seemed. Broader and subtler explanations for its workings had to be found.

Action at a Distance

The beginnings of the collapse were already clearly in view during the very mid-nineteenth-century peak of Newtonianism. At least, the beginnings are clearly to be seen by us, a century later, with the advantage of hindsight. The serpent in the Newtonian Eden was something called "action at a distance."

If we consider matter in motion in the ordinary world about us, trying to penetrate neither up into the cosmically vast nor down into the submicroscopically small, it would seem that bodies interact by making contact. If you want to lift a boulder you must touch it with your arms or use a lever, one end of which touches the boulder while the other end touches your arms.

To be sure, if you set a ball to rolling along the ground, it continues moving even after your arm no longer touches it; and this presented difficulties to the philosophers of ancient and medieval times. The Newtonian first law of motion removed the difficulty by assuming that only *changes* in velocity required the presence of a force (see page I–24). If the rolling ball is to increase its velocity, it must be struck by a mallet, a foot, some object; it must make contact with something material. (Even rocket exhaust, driving backward and pushing the ball forward by Newton's third law of motion, makes material contact with the ball.) Again, the rolling ball can be slowed by the friction of the ground it rolls on and touches, by the resistance of the air it rolls through and touches, or by the interposition of a blocking piece of matter that it must touch.

Material contact can be carried from one place to another by matter in motion. I can stand at one end of the room and knock over a milk bottle at the other end by throwing a ball at it. I exert a force on the ball while making contact with it; then the ball exerts a force on the bottle while making contact with it. We have two contacts connected by motion. If the milk bottle is balanced precariously enough, I can knock it over by blowing at it. In that case, I throw air molecules at it, rather than a ball, but the principle is the same.

Is it possible, then, for two bodies to interact without physical contact at all? In other words, can two bodies interact across a vacuum without any material bodies crossing that vacuum? Such action at a distance is very difficult to imagine; it is easy to feel it to be a manifest impossibility.

The ancient Greek philosopher Aristotle (384–322 B.C.), for instance, divined the nature of sound partly through a refusal to accept the possibility of action at a distance. Aristotle felt that one heard sounds across a gap of air because the vibrating object struck the neighboring portion of air, and that this portion of the air passed on the strike to the next portion, the process continuing until finally the ear was struck by the portion of the air next to itself. This is, roughly speaking, what does happen when sound waves travel through air or any other conducting medium. On the basis of such an interpretation, Aristotle maintained that sound could not travel through a vacuum. In his day mankind had no means of forming a vacuum, but two thousand years later, when it became possible to produce fairly good vacuums, Aristotle was found to be correct.

It might follow, by similar arguments, that all interactions that seem to be at a distance really consist of a series of subtle contacts, and that no interaction of any kind can take place across a vacuum. Until the seventeenth century it was strongly believed that a vacuum did not exist in nature but was merely a philosophical abstraction, so there seemed no way of testing this argument.

In the 1640's, however, it became clear that the atmosphere could not be infinitely high (see page I–146). Indeed, it was possibly no more than a few dozen miles high, whereas the moon was a quarter of a million miles away, and other astronomical bodies were much farther still. Any interactions between the various astronomical bodies must therefore take place across vast stretches of vacuum.

One such interaction was at once obvious, for light reaches us from the sun, which we now know is 93,000,000 miles away.* This light can affect the retina of the eye. It can affect the chemical reactions proceeding in plant tissue; converted to heat, it can evaporate water and produce rain, warm air, and winds. Indeed, sunlight is the source of virtually all energy used by man. There is

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* Our best telescopes can detect light that has traversed some 35,000,000,000,000,000,000,000 miles of vacuum.

thus a great deal of interaction, by light, between the sun and the earth across the vast vacuum.

Then, once Newton announced the law of universal gravitation in 1687, a second type of interaction was added, for each heavenly body was now understood to exert a gravitational force on all other bodies in the universe across endless stretches of vacuum. Where two bodies are relatively close, as are the earth and the moon or the earth and the sun, the gravitational force is large indeed, and the two bodies are forced into a curved path about their common center of gravity. If one body is much larger than the other, this common center of gravity is virtually at the center of the larger body, which the smaller then circles.

On the earth itself, two additional ways of transmitting force across a vacuum were known. A magnet could draw iron to itself, and an electrically charged body could draw almost any light material to itself. One magnet could either attract or repel another; one electric charge could either attract or repel another. These attractions and repulsions could all be exerted freely across the best vacuum that could be produced.

In the mid-nineteenth century, then, four ways of transmitting force across a vacuum, and hence four possible varieties of action at a distance, were known: light, gravity, electricity, and magnetism. And yet the notion of action at a distance was as unacceptable to nineteenth-century physicists as it had been to the philosophers of ancient Greece.

There were two possible ways out of the dilemma; two ways of avoiding action at a distance.

First, perhaps a vacuum was not really a vacuum. Quite clearly a good vacuum contained so little ordinary matter that this matter could be ignored. But perhaps ordinary matter was not the only form of substance that could exist.

Aristotle had suggested that the substance of the universe, outside the earth itself, was made up of something he called *ether*. The ether was retained in modern science even when virtually all other portions of Aristotelian physics had been found wanting and had been discarded. It was retained, however, in more sophisticated fashion. It made up the fabric of space, filling all that was considered vacuum and, moreover, permeating into the innermost recesses of all ordinary matter.

Newton had refused to commit himself as to how gravitation was transmitted from body to body across the void. "I make no hypotheses," he had said austerely. His followers, however, pictured gravitation as making its way through the ether much as sound makes its way through air. The gravitational effect of a body would be expressed as a distortion of that part of the ether with which it made contact; this distortion would right itself and; in the process, distort a neighboring portion of the ether. The traveling distortion would eventually reach another body and affect it. We can think of that traveling distortion as an "ether wave."

The second way out of the dilemma of action at a distance was to assume that forces that made themselves felt across a vacuum were actually crossing in the form of tiny projectiles. The projectiles might well be far too small to see, but they were there. Light, for instance, might consist of speeding particles that crossed the vacuum. In passing from the sun to the earth, they would make contact first with the sun and then with the earth, and there would be no true action at a distance at all, any more than in the case of a ball being thrown at a bottle.

For two centuries after Newton, physicists vacillated between these two points of view: waves and particles. The former required an ether, the latter did not. This volume will be devoted, in good part, to the details of this vacillation between the two views. In the eighteenth century, the particle view was dominant; in the nineteenth, the wave view. Then, as the twentieth century opened, a curious thing happened—the two views melted into each other and became one!

To explain how this happened, let's begin with the first entity known to be capable of crossing a vacuum—light.

CHAPTER 2

Light

Transmission

Surely light broke in on man's consciousness as soon as he had any consciousness at all. The origins of the word itself are buried deep in the mists of the beginnings of the Indo-European languages. The importance of light was recognized by the earliest thinkers. In the Bible itself, God's first command in constructing an ordered universe was "Let there be light!"

Light travels in straight lines. This, indeed, is the assumption each of us makes from babyhood. We are serenely sure that if we are looking at an object that object exists in the direction in which we are looking. (This is strictly true only if we are not looking at a mirror or through a glass prism, but it is not difficult to learn to make the necessary exceptions to the general rule.)

This straight-line motion of light, its *rectilinear propagation,* is the basic assumption of *optics* (from a Greek word meaning "sight"), the study of the physics of light. Where the behavior of light is analyzed by allowing straight lines to represent the path of light and where these lines are studied by the methods of geometry, we have *geometric optics.* It is with geometric optics that this chapter and the next are concerned.

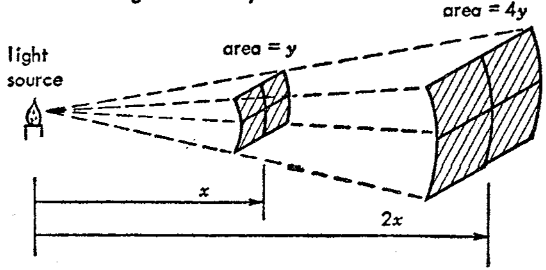
Consider a source of light such as a candle flame. Assuming that no material object blocks your vision at any point, the flame can be seen with equal ease from any direction. Light, therefore, can be visualized as streaming out from its source in all directions. The sun, for instance, can be drawn (in two dimensions) as a circle with lines, representing light, extending outward from all parts of the circumference.

Such lines about the drawing of the sun resemble spokes of a wheel emerging from the hub. The Latin word for the spoke of a wheel is *radius* (which gives us the word for the straight line extending from the center of a circle·to its circumference). For this reason, the sun (or any light source) is said to *radiate* light, and light is spoken of as a *radiation.* A very thin portion of such a light radiation, one that resembles a line in its straightness and ultimate thinness, is a *light ray,* again from *radius.*

Sunlight shining through a hole in a curtain will form a pillar of light extending from the hole to the opposite wall where the intersection of the pillar with the wall will form a circle of bright illumination. If the air of the room is normally dusty, the pillar of light will be outlined in glittering dust motes. The straight lines bounding the pillar of light will be visible evidence of the rectilinear propagation of light. Such a pillar of light is a *light beam* (from the resemblance of its shape to the trunk of a tree; the German word for tree is "Baum," and a similar word, of course, is found in Anglo-Saxon). A light beam may be viewed as a collection of an infinite number of infinitesimally thin light rays.

Light sources vary in brightness. More light is given off by a hundred-watt light bulb than by a candle, and incomparably more light still is given off by the sun. To measure the quantity of light given off by a light source, physicists can agree to use some particular light source as standard. The obvious early choice for the standard was a candle made of a specified material (sperm wax was best) prepared in a particular way and molded to set specifica-

Variation of light intensity with distance



tions. The light emitted by this candle horizontally could then be said to equal 1 *candlepower.* Electric light bulbs of set form have now replaced the candle, especially in the United States, but we still speak of the *international candle,* a measure of light quantity about equal to the older candlepower.

The brightness of a light source varies in some fashion with the distance from which it is viewed: the greater the distance, the dimmer it seems. A book held near a candle may be read easily; held farther away it becomes first difficult and then impossible to read.

This is not surprising. Suppose a fixed amount of light is emerging from the candle flame. As it spreads out in all directions, that fixed amount must be stretched over a larger and larger area. We can imagine the edge of the illumination to be forming a sphere with the light source as center. The sphere's surface grows larger and larger as the light radiates outward.

From plane geometry we know that the surface of a sphere has an area proportional to the square of the length of its radius. If the distance from the light source (the radius of the imaginary sphere we are considering) is doubled, the surface over which the light is spread is increased two times two, or 4 times. If the distance is tripled, the surface is increased 9 times. The total quantity of light over the entire surface may remain the same, but the intensity of light—that is, the amount of light falling on a particular area of surface—must decrease. More, it must decrease as the square of the distance from the light source. Doubling the distance from the light source decreases the light intensity to 1/4 the original; tripling the distance decreases it to 1/9.

Suppose we use the square foot as the unit of surface area and imagine that square foot bent into the shape of a segment of a spherical surface so that all parts of it are equidistant from the centrally located light source. If such a square foot is just one foot distant from a light source delivering 1 candle of light, then the intensity of illumination received by the surface is 1 *foot-candle.* If the surface is removed to a distance of two feet, the intensity of its illumination is 1/4 foot-candle, and so on.

Since light intensity is defined as the quantity of light per unit area, we can also express it as so many candles per square foot. For this purpose, however, a unit of light quantity smaller than the candle is commonly used. This is the *lumen* (from a Latin word for "light"). Thus if one square foot at a certain distance from a light source receives 1 lumen of light, two square feet at that same distance will receive 2 lumens of light, and half a square foot will receive 1/2 lumen. In each case, though, the light intensity will be 1 lumen/foot.^{2} The lumen is so defined that an intensity of 1 lumen/foot^2 equals 1 foot-candle.

Imagine a light source of 1 candle at the center of a hollow sphere with a radius of one foot. The light intensity on each portion of the interior surface of the sphere is 1 foot-candle, or 1 lumen/foot.^{2} Each square foot of the interior surface is therefore receiving 1 lumen of illumination. The area of the surface of the sphere is equal to $4\pi r^2$ square feet. Since the value of r, the radius of the sphere, is set at 1 foot, the number of square feet of surface equals 4π. The quantity π (the Greek letter *pi*) is equal to about 3.14, so we can say that there are about 12.56 square feet on that spherical surface. The light (which we have set at 1 candle) is therefore delivering a total of 12.56 lumens, so we can say that 1 candle equals 12.56 lumens.

Light is transmitted, completely and without impediment, only through a vacuum. All forms of matter will, to some extent at least, absorb light. Most forms do so to such an extent that in ordinary thicknesses they absorb all the light that falls on them and are *opaque* (from a Latin word meaning "dark").

If an opaque object is brought between a light source and an illuminated surface, light will pass by the edges of the object but not through it. On the side of the object opposite the light source there will therefore be a volume of darkness called a *shadow*. Where this volume intersects the illuminated surface there will be a non-illuminated patch; it is this two-dimensional intersection of the shadow that we usually refer to by the word.

The moon casts a shadow. Half its surface is exposed to the direct illumination of the sun; the other half is so situated that the opaque substance of the moon itself blocks the sunlight. We see only the illuminated side of the moon, and because this illuminated side is presented to us at an angle that varies from 0° to 360° during a month, we watch the moon go through a cycle of phases in that month.

Furthermore, the moon's shadow not only affects its own surface, but stretches out into space for over two hundred thousand miles. If the sun were a "point source"—that is, if all the light came from a single glowing point—the shadow would stretch out indefinitely. However, the sun is seen as an area of light, and as one recedes from the moon its apparent size decreases until it can no longer cover all the area of the much larger sun. At that point, it no longer casts a complete shadow, and the complete shadow (or *umbra,* from a Latin word for "shadow") narrows to a point. The umbra is just long enough to reach the earth's surface, however, and on occasion, when the moon interposes itself exactly between earth and sun, a *solar eclipse* takes place over a small area of the earth's surface.

The earth casts a shadow, too, and half its surface is in that shadow. Since the earth rotates in twenty-four hours, each of us experiences this shadow ("night") during each 24-hour passage. (This is not always true for polar areas, for reasons better discussed in a book on astronomy.) The moon can pass through the earth's shadow, which is much longer and wider than that of the moon, and we can then observe a *lunar eclipse.*

Opaque materials are not absolutely opaque. If made thin enough, some light will pass through. Fine gold leaf, for instance, will be traversed by light even though gold itself is certainly opaque.

Some forms of matter absorb so little light (per unit thickness) that the thicknesses we ordinarily encounter do not seriously interfere with the transmission of light. Such forms of matter are *transparent* (from Latin words meaning "to be seen across"). Air itself is the best example of transparent matter. It is so transparent that we are scarcely aware of its existence, since we see objects through it as if there were no obstacle at all. Almost all gases are transparent. Numerous liquids, notably water, are also transparent.

It is among solids that transparency is very much the exception. Quartz is one of the few naturally occurring solids that display the property, and the astonished Greeks considered it a form of warm ice. The word "crystal," first applied to quartz, is from their word for "ice," and the word "crystalline" has as one of its meanings "transparent."

Transparency becomes less pronounced when thicker and thicker sections of ordinarily transparent substances are considered. A small quantity of water is certainly transparent, and the pebbles at the bottom of a clear pool can be seen distinctly. However, as a diver sinks beneath the surface of the sea, the light that can reach him grows feebler and feebler, and below about 450 feet almost no light can penetrate. Thicknesses of water greater than that are as opaque as if they represented the same thickness of rock, and the depths of the sea cannot be seen through the "transparent" water that overlays it.

Air absorbs light to a lesser extent than water does and is therefore more transparent. Even though we are at the bottom of an ocean of air many miles high, sunlight has no trouble penetrating to us, and we in turn have no trouble seeing the much feebler light of the stars.* Nevertheless some absorption exists: it is estimated, for instance, that 30 percent of the light reaching us from space is absorbed by that atmosphere. (Some forms of radiation other than visible light are absorbed with much greater efficiency by the atmosphere, and the thickness of air that blankets us suffices to make the air opaque to these radiations.)

Light is a form of energy, and while it can easily be changed into other forms of energy, it cannot be destroyed. While absorption by an opaque material (or a sufficient thickness of a transparent material) seems to destroy it, actually it is converted into heat.

Reflection

The statement that light always travels in a straight line is completely true only under certain circumstances, as when light travels through a uniform medium—through a vacuum, for instance, or through air that is at equal temperature and density throughout. If the medium changes—as when light traveling through air strikes an opaque body—the straight-line rule no longer holds strictly. Such light as is not absorbed by the body changes direction abruptly, as a billiard ball will when it strikes the edge of a pool table.

This bouncing back of light from an opaque body is called *reflection* (from Latin words meaning "to bend back").

The reflection of light seems to follow closely the rules that govern the bouncing of a billiard ball. Imagine a flat surface capable of reflecting light. A line perpendicular to that surface is called the *normal*, from the Latin name for a carpenter's square used to draw perpendiculars.† A ray of light moving along the normal strikes the reflecting surface head-on and doubles back in its tracks. A speeding billiard ball would do the same.

If the ray of light were traveling obliquely with respect to the reflecting surface, it would strike at an angle to the normal. The

---

* To be sure, if the atmosphere were compressed to the density of water, it would be only some 33 feet thick; and that thickness of water would retain considerable transparency, too.

† Straightforward behavior that is "square" and "on the beam," like a perpendicular, accurately drawn by a carpenter's square, is also "normal." Other types of behavior are "abnormal" or represent "enormities." In fact, the word "normal" has become so familiar in its sense of natural, commonplace, conforming behavior that its original meaning of "a line perpendicular to a plane, or to another line" has almost been forgotten.

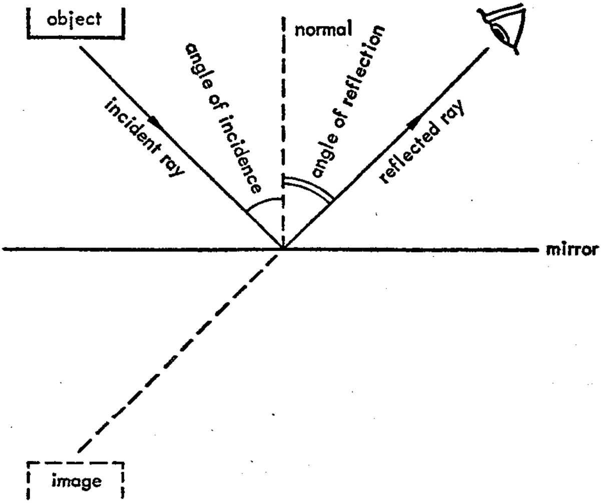
light ray moving toward the surface is the *incident ray*, and its angle to the normal is the *angle of incidence*. The *reflected ray* would return on the other side of the normal, making a new angle, the *angle of reflection*. The incident ray, reflected ray, and normal are all in the same plane—that is, a flat sheet could be made to pass through all three simultaneously without its flatness being distorted.

Experiments with rays of light and reflecting surfaces in dusty air, which illuminates the light rays and makes them visible, will show that the angle of incidence (i) always equals the angle or reflection (r). This can be expressed, simply:

$$i = r \qquad \text{(Equation 2–1)}$$

Actually, it is rare to find a truly flat surface. Most surfaces have small unevennesses even when they appear flat. A beam of light, made up of parallel rays, would not display the same angle of incidence throughout. One ray might strike the surface at a spot where the angle of incidence is 0°; another might strike very close by where the surface has nevertheless curved until it is at an angle of 10° to the light; elsewhere it is 10° in the other direction, or 20°, and so on. The result is that an incident beam of light with rays parallel will be broken up on reflection, with the reflected rays

Reflection of light



traveling in all directions over a wide arc. This is *diffuse reflection.*

Almost all reflection we come across is of this type. A surface that reflects light diffusely can be seen equally well from different angles, since at each of the various angles numerous rays of light are traveling from the object to the eye.

If a surface is quite flat, a good portion of the parallel rays of incident light will be reflected at the same angle. In such a case, although you can see the reflecting object from various angles, you will see far more light if you orient yourself at the proper angle to receive the main reflection. At that point you will see a "highlight."

If a surface is extremely flat, virtually all the parallel rays of an incident beam of light will be reflected still parallel. As a result, your eyes will interpret the reflected beam as they would the original.

For instance, the rays of light reflected diffusely from a person's face make a pattern that the eyes transmit and the brain interprets as that person's face. If those rays strike an extremely flat surface, are reflected without mutual distortion, and then strike your eyes, you will still interpret the light as representing that person's face.

Your eyes cannot, however, tell the history of the light that reaches them. They cannot, without independent information, tell whether the light has been reflected or not. Since you are used from earliest life to interpreting light as traveling in straight, uninterrupted lines, you do so now, too. The person's face as seen by reflected light is seen as if it were behind the surface of reflection, where it would be if the light had come straight at you without interruption, instead of striking the mirror and being reflected to you.

The face that you see in a mirror is an *image.* Because it does not really exist in the place you seem to see it (look behind the mirror and it is not there) it is a *virtual image.* (It possesses the "virtues" or properties of an object without that object actually being there.) It is, however, at the same distance behind the mirror that the reflected object is before it, and therefore seems to be the same size as the reflected object.

In primitive times virtually the only surface flat enough to reflect an image was a sheet of water. Such images are imperfect because the water is rarely quite undisturbed, and even when it is, so much light is transmitted by the water and so little reflected that the image is dim and obscure. Under such circumstances a primitive man might not realize that it was his own face staring back at him.