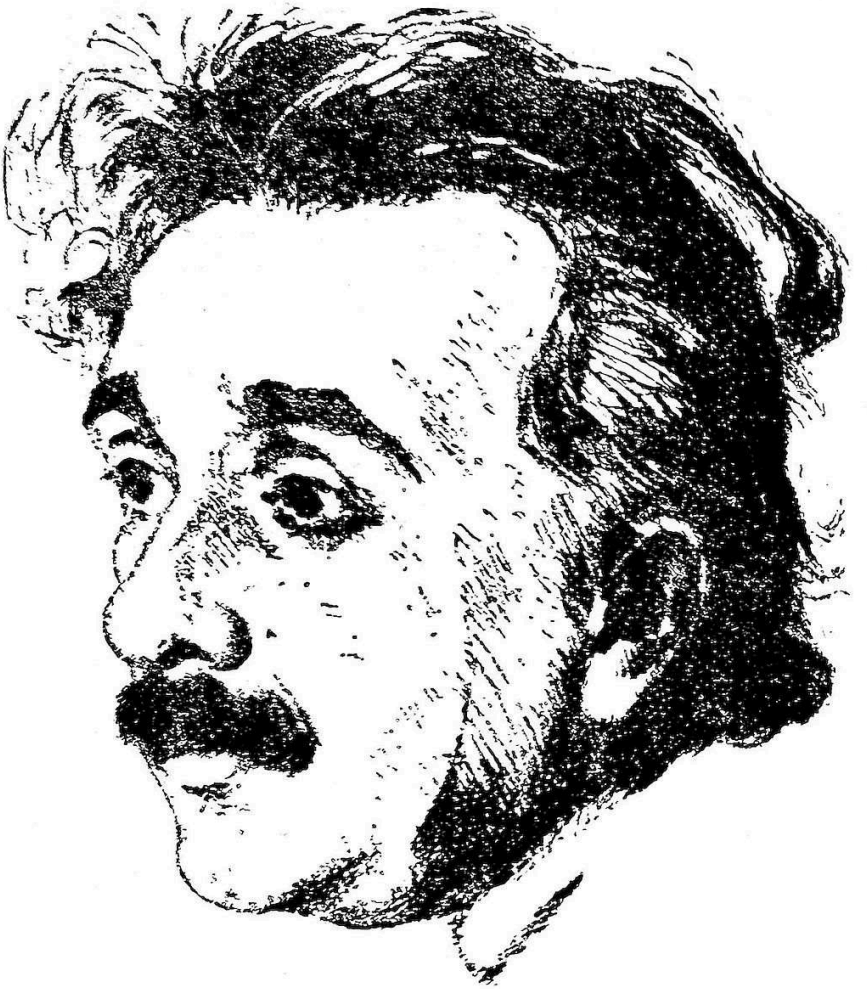
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Introduction to Einstein

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DR. ALBERT EINSTEIN

A Popular Explanation of the Einstein Theory That Approaches an Actual Visualization of the Subject.

The preparation of this essay on the Principle of Relativity has been undertaken after a careful study of practically all the literature hitherto published on the subject purporting to be of a popular or semi-popular nature. With due appreciation of the merit of many of these works, a perusal of them has made it increasingly apparent that the writers have not succeeded in eliminating technical phraseology sufficiently to bring the subject down to the level of the untrained reader, and that a *really* popular exposition of both the Special and the General Theory is needed.

Notwithstanding the laudable efforts of some to meet this need it is manifest that the public continues to be in the dark and many erroneously suppose that "only twelve men in the world" can really comprehend this new theory of the universe. Even book reviews ofttimes betray a surprising lack of appreciation of the fundamentals of Einstein's noble contribution to science.

It is the purpose of this booklet therefore, to bring within the scope of visualization, as nearly as possible, the very essence of relativity, and to state its principles in terms devoid of unfamiliar phrases and illustrations. The popular mind is not satisfied with vague statements, mathematical equations and formulæ. It calls for an explanation in words of every day usage, and where a technical term *must* be employed then a definition of that term in language simple and lucid. To meet these requirements without sacrificing scientific accuracy has been the earnest endeavor of the author.

Acknowledgment is hereby made to Dr. S. I. Bailey and Dr. G. D. Birkhoff of Harvard, Dr. Edward Kasner of Columbia, Prof. Victor Schmidt of Cincinnati, and Dean J. A. Robison of the Oakland Technical High School (Calif.), all of whom have kindly criticized the manuscript and made valuable suggestions for improvement of the text.—W. F. H.

New York, Dec., 1922.

Introduction to Einstein and Universal Relativity

What Is Einstein's Contribution?

Albert Einstein, orthodox Jew of German birth and ardent Zionist, is the most discussed figure in intellectual circles in the world today. It is not as a Jew nor as a Zionist, however, that we find him so much in the limelight of public opinion, although as such he is a distinguished figure and has only recently toured Europe and America in the interest of the Zionist movement. What has lately made the name of Einstein a byword upon the lips of scientists, philosophers and the multitudes of more common mortals is his revolutionary treatment of time, space and gravitation which materially affects various branches of accepted science and thereby threatens to throw certain portions of our school books and other scholarly works into the discard.

The ideas which led to the development of Einstein's theory are not new. Newton appreciated the principle of mechanical relativity and presented it in much detail. But to Einstein belongs the credit of completely disentangling the idea of relativity of motion from the ancient conception of absoluteness of velocity and carrying out the relativistic viewpoint to its logical conclusion. In so doing, however, he found it necessary to discard or revamp many popular theories and "laws of nature." But consistency is a jewel wherever found, and Einstein seems to have placed the gem into its proper setting.

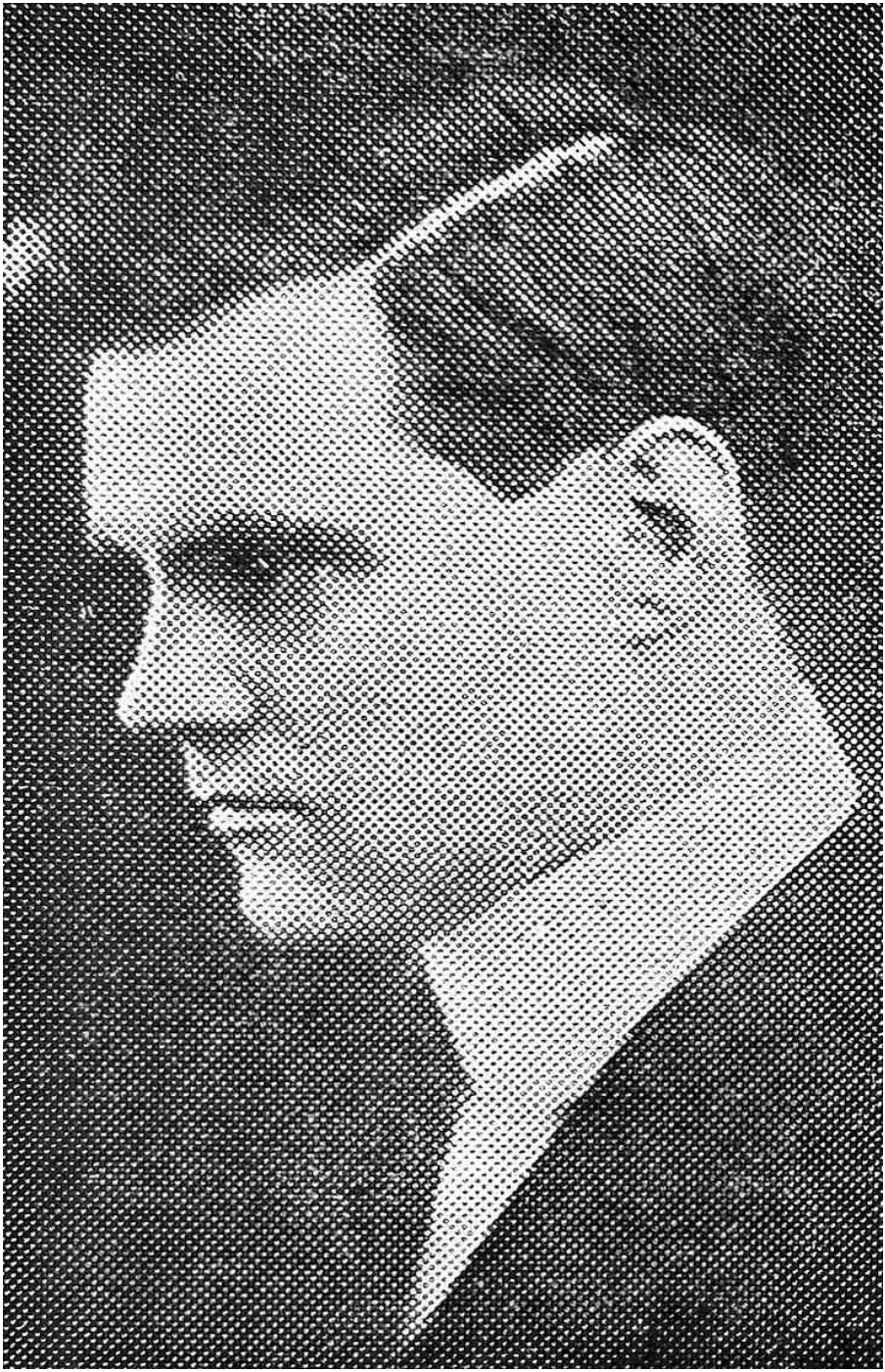
This Jewish scientist, born in 1878 of humble parentage, began delving into the mysteries of the universe at an early age. When only sixteen, it is said, he contributed a paper, modest in its brevity, which was read before an assemblage of German scientists with marked appreciation of its merit, and soon thereafter his active mind began to traverse new and unbeaten paths of scientific thought. During the years that followed his ideas took more definite form, and in 1905, while occupying a chair in a Swiss university, Einstein published his first "Principle of Relativity," now called the "Special Theory of Relativity," which treats the physical laws relating to uniform, rectilinear motion, i. e., motion in its simplest form.

Einstein's hypothesis, unlike most theories advanced, did not originate with any physical "discovery" or observation. In a sense it grew out of the philosophic notion of the relativity of all knowledge. He laid hold of the idea that everything is measured by or considered *relative* to something else; that our concepts of absolute position, absolute motion and absolute time are groundless for the reason that we have no immovable and unchangeable standard anywhere in the universe as a starting point. While there is nothing new or revolutionary in this fact, yet it actually produced certain scientific "revolutions" when carried out to a consistent end.

Prior to Einstein, the principle of relativity had been recognized and philosophized upon to a certain point and then dropped when it ran counter to hitherto unquestioned

conceptions. Einstein, on the contrary, contended that if the principle is admitted at all it must be admitted at every point irrespective of what it contradicts. After, therefore, his theory was fully developed it was then subjected to certain physical tests, with the result that it has been quite fully confirmed. This mode of theoretical development is called *a priori* as against the more usual *a posteriori* method, wherein the theory *follows* rather than precedes certain particular phenomena.

It was in 1915, during the stress of the great war, that Professor Einstein, working unconcernedly in his laboratory in Berlin, completed and published what is now called his "General Principle of Relativity." Due to hostilities, the details of his developed theory did not reach the outside world until after the armistice in 1918; but such meagre accounts of it as did cross the German border were sufficient to awaken Eddington and other British scientists to the extent that they hastily equipped two research expeditions, dispatching one to the Island of Principe off the coast of Africa and the other to Sobral, Brazil, to test Einstein's hypothesis about the deflection of light rays in a gravitational field, by taking photographs of stars near the sun during the solar eclipse of May 29, 1919, which was total in the regions mentioned.



It was the announced results of these expeditions, confirming as they did this new theory of gravitation, that has made Albert Einstein famous.

There are, of course, opponents of the Einstein theory in the circle of scientists in both Europe and America, though they are comparatively few in proportion to the number who see merit in his postulates if not, indeed, a complete solution of gravitational and other phenomena which have baffled the sages of every century. Sir Oliver Lodge is a leading opponent of the Einstein theory among a certain few British scientists, but his opposition is easily accounted for when it is remembered that Einstein, by ignoring the ether and denying other unproven hypotheses, has materially upset Sir Oliver's spiritistic playground.

Einstein, to say the least, has stimulated the scientific thought of the world to an extent unprecedented by anyone since the days of Newton. If the Principle of Relativity is not universal, then any theory concerning it cannot long stand; it would predict results which actual experiment would disprove. It must be admitted, however, that experiments to date tend to confirm the Theory of Relativity as propounded by Einstein.

Concepts Versus Reality

Relativity is a term appropriately applicable to that school of thought standing midway between mathematics, physics and astronomy, which concerns itself with determining the relationship between observers and their objects. Two or more observers may view a certain phenomenon or set of phenomena and reach divergent conclusions as to distance, position, size or other physical quantities commonly involved. It is not for anyone to arbitrarily conclude that one particular observation is correct and that all the others are consequently in error.

It is the task of the relativist to consider the findings of the various observers, note the conditions attending each, eliminate the peculiarities of the varying viewpoints and the qualities which have been unmindfully superimposed by each observer upon the external object. He must then set down a general rule or law which will embody the inter-relations of the data before him and which will also hold good for all other observers regardless of distance, position or motion of their frames of reference.

A frame of reference is simply an arbitrary set of mutually perpendicular lines or planes from which measurements may be made for purposes of describing the location of points within a given area or region. If a *two*-dimensional area (i. e., a *plane* surface) is being dealt with, then our frame of reference would consist merely of two *lines* drawn perpendicular to each other. Thence, any point within the right-angle formed by these two lines may be described by specifying its distance from each line.

If we are to locate a given point in a *three*-dimensional region (i.e., where length, breadth and also *height* are involved), then our frame of reference must consist of *planes* instead of lines, three in number, each perpendicular to the other two, like the

floor and two adjacent walls of a room. If any point within a room is to be located we would first select as a frame of reference, let us say, the east and south walls together with the floor. The location of the point may then be described with accuracy by simply specifying its distance from each of the two walls together with its height above the floor.

The perpendiculars of a frame of reference are called its *axes*, and the distances from a given point to the axes are called its *co-ordinates*. A little reflection will suffice to show that it is quite impossible to record the exact location of anything, either in space or in a plane, without making use of a reference frame and two or more co-ordinates.

Unlimited Choice of Reference Frames

We are not limited in our selection or choice of reference frames. They may be close by or relatively remote from the point or object whose location we wish to describe. The axes may be physical or purely imaginary. They may be in any direction or position whatsoever, so long as they are mutually perpendicular and embrace the area in which the point or object is located. They may be at rest relative to the object and in motion relative to the observer, or vice versa, or either at rest or in motion relative to both. If the relative velocity is known, the co-ordinates may be determined as certainly as though both the object and the observer, together with his reference frame, were relatively at rest.

An observer usually prefers to select a frame of reference which partakes of his own motion, for the sake of convenience and simplicity. Hence for purposes of either local or astronomical observation we may choose an imaginary axis perpendicular to the surface of the earth. But we must admit that as the earth rotates our perpendicular rotates with it. Consequently it is really changing its direction from moment to moment. Such rotation, however, is not detected so long as we confine our observations to terrestrial things, because our frame of reference is at rest relative to the earth and to all things fixed upon the earth; but for astronomical observations the matter becomes somewhat complicated due to the various relative motions involved.

Astronomers often choose as a reference frame an imaginary line reaching from the earth's center to the center of the sun, together with another line perpendicular thereto extending from the earth to some other planet or point in space. But neither the earth or the sun, or in fact any other body of matter, is at rest; nor do they move in a perfectly straight line or plane. The axes of such a frame of reference continuously undergo a change of direction. Indeed, a reference frame attached to any physical body in the universe must of necessity move, because all matter of which we have any knowledge is in motion; and a frame of reference attached to nothing would be meaningless.

By reason of the motion of all objects and of frames of reference it is necessary that the latter be supplemented by clocks for determining the times of occurrences of physical events encountered in our measurements. We may therefore say that no frame of reference, when used for physical purposes, is complete without a set of

accurately synchronized timepieces. The element of time is an essential factor in any calculation of physical quantities because motion is forever involved.

Velocity (rate of motion) means distance traveled within a given time. Only when distance and time are combined can we determine our co-ordinates with universal accuracy. This will be more fully understood when we come to consider the four-dimensional aspect of the universe. But for all practical purposes the time element cannot be divorced from the distance measurement of moving bodies even when viewed in the ordinary three-dimensional sense.

Suppose, for sake of illustration, we are assigned the task of charting or recording the precise course of a ball shot from a cannon. In order to specifically state the history of its flight it will be necessary to indicate the position of the cannon ball during each moment of its journey. We will say this is a possibility without attempting an explanation of the method of measurement used. When our task is completed we will have a set of four figures for each successive second, as follows:

(1) distance from cannon.

(2) distance from ground.

(3) distance to right or left.

(4) duration of time.

When these four sets of figures are carefully set down they may be transmitted on paper or by telegraph and the recipient will be able to determine therefrom the history of the fired ball with as much accuracy as though he had been personally present and made the observations himself. This, however, would be impossible were the time factor omitted.

The foregoing illustration is given merely to show that time is fully as important as distance measurement in specifying the location of any moving body (and everything in the universe is moving). It is in no sense intended to show how time is really a fourth dimension. This fact will be brought out in subsequent pages; but thus far we have followed, rather, our ordinary concepts of time as an independent element, detached from any unit of space measurement whatsoever. Such a conception, however, comes from a lifelong training which is based upon a limited scope of vision.

Knowledge Broadens Many Concepts

Concepts do not necessarily represent the reality merely because they are easy to believe. They may be simply following in a groove caused by centuries of "thoughtless reasoning." Prior to Galileo, human concept taught that "up" and "down" were absolute directions which never vary. It was easy to so believe, and nobody even thought to call such concept in question. But eventually it became known that two plumb lines which point "down" to earth do not hang parallel to each other. They each point to a common center like the spokes of a wheel.

Now if two plumb lines happen to be about six thousand miles (one-fourth the circumference of the earth) apart, they then hang practically perpendicular to each other. When this erstwhile paradox was established as a certain fact mankind were obliged to change their former concepts of the absoluteness of the "up" and "down" directions. Einstein now asks us to revise our concepts of the absoluteness and independence of time and space and gives us his reasons therefor.

In the light of Einstein's treatment of the principle of relativity it is seen that no particular reference frame possesses any advantage over any other for mathematical accuracy irrespective of the physical laws involved. It would not be difficult, of course, to grasp this fact in a mechanical sense provided units of length and of time were absolute quantities which are unaffected by the motion of the reference frame. But as will be subsequently seen, such units when viewed independently, do vary constantly, and rigidity becomes in reality a meaningless term.

In the face of this apparently insurmountable difficulty, however, Einstein shows in his Special Theory that any unaccelerated (i.e., uniformly moving) frame of reference is as suitable as any other for the mathematical expression of physical laws. This is accomplished by regarding the universe and all objects therein as existing in four dimensions, viz., length, breadth, thickness and *time*—the latter altering the length unit according to the relative velocities of the reference frames.

It is naturally impossible to mentally visualize or graphically portray more than three dimensions, but they can be mathematically conceived. We shall endeavor presently to show how time takes its place alongside the ordinary three dimensions in the true geometry of the universe, possessing the value of a fourth co-ordinate or dimension. In reality it supersedes in importance the other three in the sense that it possesses the illusive quality of automatically correcting or adjusting physical values which otherwise would be inconsistently altered by the velocities of our frames of reference.

Irrespective of whether we can visualize the matter or not, it will be necessary for the reader to divest himself of all previous conceptions of time and of space as universally absolute, separate and unvarying in their unit length if he would comprehend the Einstein Theory of Relativity. He must guard against the notion that time and space are independent elements that should be measured separately. He must adjust himself to the relativistic viewpoint that time and space are so interlinked that either, when taken alone, becomes meaningless except by analogy. When, therefore, we measure the distance between bodies or the dimensions of the bodies themselves, we are not calculating the miles or units of *space* merely, but of *space-time*.

We will not attempt but will purposely avoid, in a work of this scope, the setting out of algebraic equations, believing they would not tend to make the essay *popularly* readable however much they may appeal to the mathematical student. Therefore it must suffice here to state that the numerical value of time required for a light ray to traverse a given distance, together with the relative velocity between the frame of reference and the object, become considerable physical factors in calculation where great distances and enormous velocities are being dealt with. These items, however, are infinitesimal when merely earthly distances and ordinary velocities are involved.

Einstein's equations, therefore, may be said to have no practical bearing upon the ordinary things with which we have to do in daily experience—we may continue to use our yardstick and our pocket timepiece exactly as before. But this in no wise diminishes the fundamental importance of the matter. Scientific interest rests not in the *amount* of variance from accustomed laws, but rather in the fact that a variance exists and why.

Universe a Four-Dimensional Continuum

We shall at this point merely touch upon the space-time character of the universe as Einstein sees it, leaving the subject for treatment in appropriate order later on. Einstein did not originate the geometry which he uses; he has simply made a masterful application of the work of Riemann, Minkowski and others in the outworking of his theory. Various geometers, notably Minkowski, departing from the beaten path of Euclid, had come to view the universe as a four-dimensional continuum in which space and time are inseparably interlinked, and Einstein saw in this a solution of several phenomenal problems which had arisen in recent years to which the laws of Newton appeared inapplicable.

The term *continuum* denotes a continuity of units. The geometer speaks of a straight line as a one-dimensional continuum, because it consists of a continuity of *points* extending in one direction. A plane, likewise, is termed a two-dimensional continuum for the reason that it is a continuity of *lines* laid side by side producing an area of length and also breadth. Accordingly the whole spatial universe has been long regarded as a three-dimensional continuum, i. e., a continuity of *planes* piled one on top of another, extending from infinity to infinity.

As for *time*, it has been commonly looked upon as something entirely separate and apart from space. Humanity has habitually regarded it as an independent one-dimensional continuum, i. e., a continuity of *instants*, each being of universally definite duration, beginning where its predecessor ended and ending where its successor begins, and thus flowing on forever regardless of motion, location or any physical condition.

Time and Space Inseparable

But what ground have we for regarding space and time as independent and unrelated continua? Does not *time* thrust itself upon us at every turn, wherever we undertake a measurement in space? This might not be so if we could regard space as motionless and then really measure it from point to point. But absolute space cannot be measured. The best that can be done is to measure from one body of matter to another body of matter—and all matter is in motion and continuously changing position, hence the entrance of time into all physical calculation.

Everything in the universe is somewhere at some time and somewhere else at some other time. Thus it is seen that time must intersect space at every point wherever moving matter is involved. And if for any reason whatsoever the time units are

shortened or lengthened then the points which they intersect are in reality distorted irrespective of what our conception of such a state of affairs might be.

Instead, therefore, of regarding the universe as a continuity of immovable points it is in reality a continuity of *events* in each one of which *time* is an essentially governing factor. Consequently the term *event* in a four-dimensional continuum is analogous to the term *point* in a three-dimensional continuum. Something does not necessarily need to *happen* at each *event* in the continuum in order to constitute them "events." On the contrary, the continuum of events exists as a background for phenomena, and when happenings occur in any region whatsoever, the events (time and space points combined) are there, ready to give forth their testimony to the mathematician when he calls for his location data.

The fact that we cannot diagram such a continuum in no sense detracts from its reality. A combined space and time is no less real than the conceptual independent space and time which it supplants. There are various other continua in the world about us which cannot be represented by lines and angles or physical models. There is, for instance, the continuum of color, reaching from ultra violet to ultra red with its infinite number of graduating hues in between. Then there is the continuum of sound which cannot be visualized in any degree. The scale of musical notes is a perfect continuity, extending from the lowest to the highest audible sound and beyond, yet we cannot *see* a continuum of this character any more than we can visualize the four-dimensional continuum of space-time.

From the foregoing it will be seen that the difficulty of making clear in few words the substance of the Einstein theory is due to its radical departure from our ordinary concepts of things. Many pages might be utilized to fully define such apparently simple terms as time, space, distance, straight line, etc., and after these are seen from the viewpoint of the relativist, then the reader is equipped to proceed with his study of relativity, but not before.

The aforementioned handicap has been apparent to every writer who has attempted to make the theory of relativity popularly readable. The following pages will discuss these terms in an applied fashion and will attempt to give the necessary foundation knowledge without which it would be impossible to appreciate the theory as expounded later in this essay and in other works on the same subject. The reader will undoubtedly find it profitable to review the foregoing paragraphs after he has perused the arguments which follow.

Relativity and Its Effects

Relativity, as applied to motion of all matter and systems of matter in the universe, stands opposed to the idea of *absolute velocity*. If nothing is stationary in the entire universe from which we may determine the *actual* rate of motion of bodies, then the best we can do to describe the velocity of anything is to say that it moves at such and such a speed *relative* to something else which is also moving at some unknown rate except as it is related to some other moving body.

We may say that the earth is traveling at the rate of over eighteen miles per second in its annual trip around the sun. But this does not represent the actual velocity of our earth. It describes merely our motion relative to the sun; but who shall say how rapidly our sun is moving through space[1] and carrying us with it, just as we carry the moon with us as we revolve around the sun. We know the sun is apparently approaching a distant star cluster, but we cannot determine whether our system is moving toward it or whether the cluster is moving toward us, or both. We may be, in fact, chasing it through the heavens as a dog chases a rabbit, and gaining on it a trifle each century; or it may be really chasing us. All we know about it is that the distance between the two systems is growing gradually less.

Then, again, who knows but that the entire stellar universe, including not only our solar system but all other systems as well, may be revolving about one common center located in the remote regions of space? And if so, in what general direction does it revolve? These reflections immediately convince us that all motion is purely relative; that no velocity can be looked upon as being absolute. Hence our eighteen-mile-per-second velocity around the sun is probably infinitesimal in comparison to our *actual* speed through space, if such could really be determined by some stationary standard.

Einstein did not originate the doctrine of relativity; it has been a much discussed philosophic subject for centuries and particularly of the nineteenth century. What he did, however, was to formulate a particular theory concerning it which co-ordinates and satisfies the observed laws of nature and accounts for discrepancies which have long troubled mathematicians and scientists who have based their calculations on the theories of the past, notably Newton's laws.

Mercury's Perihelion

A striking example of such a discrepancy which Einstein has accounted for, is the unusual yearly advancement of the perihelion of Mercury's orbit. Due to gravity, all planets revolve about the sun in ellipses rather than in perfect circles, with the sun a trifle to one side of the center of such ellipse. This brings the planet nearer to the sun at one end of the ellipse than at the other. The near end of the orbit is called the *perihelion*, while the distant end is called the *aphelion*. See Fig. 1.

Newton's law would indicate that if our spherical sun had but one planet revolving around it, the orbit of that planet would never change its position unless disturbed by some outside cause, its perihelion and aphelion being fixed. But where there are more than one planet in a system, a slow annual advance of the perihelion would be produced. The amount of such advance is easily calculated; hence it has been an astonishment to astronomers to find that the perihelion of Mercury actually advances 42 minutes (that is, seven-tenths of a degree) per century more than Newton's law allows for. Einstein, however simply points out that at perihelion a planet is moving with greater velocity than at aphelion because of its relative nearness to the sun, and that its velocity (the *time* element) must be reckoned with in addition to the Newtonian gravitational advance. He computed that this should increase the advance

of Mercury's perihelion by 43 minutes per century, which most fully accounts for the observed discrepancy.

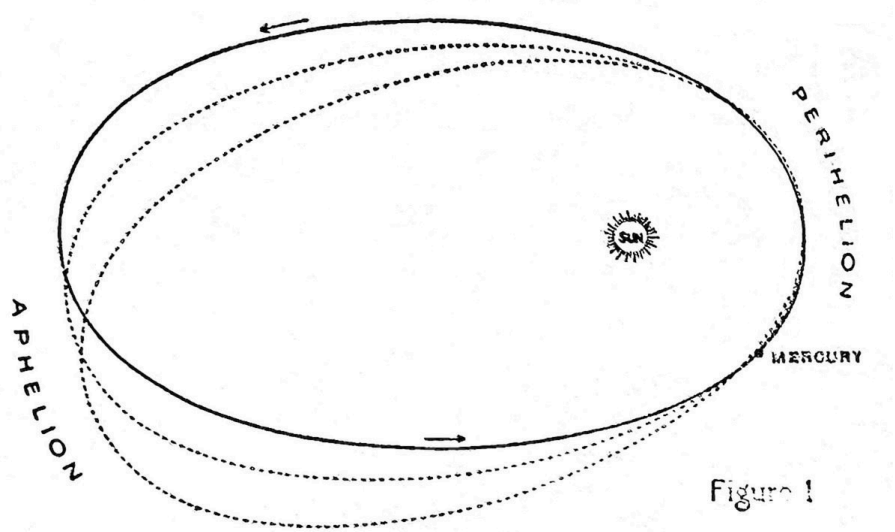


FIG. 1.

Opponents of Einstein have attempted to account for the aforementioned discrepancy on the ground that the sun is not a perfect sphere, and that its equatorial diameter exceeds its polar diameter sufficiently to add the required amount to the attraction at perihelion. But this involves other difficulties, as for instance, a change of 3 minutes per century in the inclination of the orbit, which manifestly does not exist. The orbits of the other planets in our solar system are not sufficiently eccentric to reveal any marked difference between Newton's and Einstein's calculated results. But Einstein's success in connection with Mercury has placed his theory upon a very satisfactory foundation.

We have seen that all motion is relative. The same is true of *time* because motion and time are inseparable. But even if this were not so, where would we find an absolute standard or universal unit of time any more than an absolute rate of motion of matter? We on earth count time according to the rotation of the earth on its axis, and we call the period of rotation a day, but the other planets in our solar system have days of very different length from ours, some shorter and some longer.

All heavenly bodies possess their respective time standards, all different from ours and different from each other. Which shall be taken as the *absolute* standard? There is no universal standard. Time is not an absolute quantity; it is relative even as motion is relative. A "perfect timekeeper" if suddenly transferred from earth to Jupiter would immediately be seen to keep a different time due to the differences in velocity of the two planets.

The Universal Unit

We have already emphasized that conceptual time, as an independent one-dimensional continuum, is fictitious. It does not really exist as such, but is a component part of space-time. The question naturally arises in our minds: if time does not exist in and of itself, and if there is no universal time unit, then how is it possible for Einstein or anybody else to make a calculation in which time is involved and arrive at any definite conclusion? The answer is that there is a universal unit, but not a universal *time* unit. This true unit is the *separation-interval* between events in the space-time continuum. It is a combination of distance and time.

Such a combination unit may be partially illustrated by a crude analogy. Suppose we are calculating the distance between two points in a plane. We would first describe a triangle and let the hypotenuse of the triangle connect the two points in question. But somebody else might erect a different triangle from ours which would describe the distance between the two points equally well. The triangles would have the same hypotenuse, but their respective bases and altitudes would be dissimilar, as shown in Figure 2.

Let us think of the bases as representing time and the altitudes as representing space, while the hypotenuse stands for our separation-interval. Even as we may have many base-altitude combinations for our common hypotenuse, so we may have numerous combinations of space and time for the same separation-interval. In certain combinations the space element is greater than in others, while the time element is correspondingly smaller, and vice versa, although the separation-interval, like our hypotenuse, remains a constant.

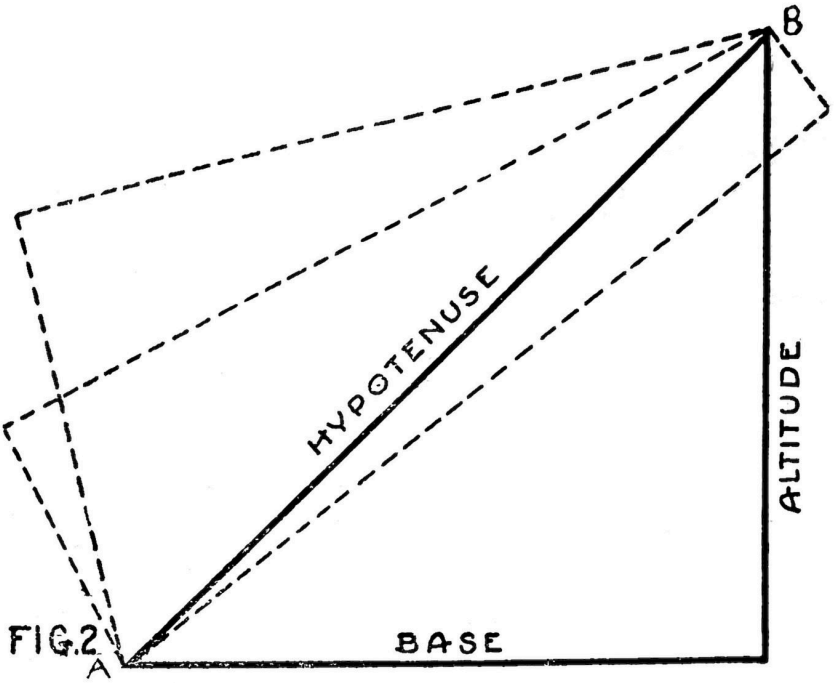


FIG. 2.

It may be somewhat easier for the reader to appreciate the non-existence of a universal unit of length than it is for him to comprehend the unreality of independent time. No unit of length can be taken as a universal standard of measure, because measurements are relative and dependent upon the motion of the observer and his reference frame, or upon the velocity of the object relative thereto. This has been scientifically established by experiments made with particles emitted by radioactive substances whose velocities range from 20,000 to 170,000 miles per second.

Lorentz and Fitzgerald, previous to Einstein, had suggested that all moving matter suffers a physical contraction in the direction of its motion, but their theory is not particularly convincing. To Einstein belongs the credit of postulating upon this subject in a manner that agrees with experiment and satisfactorily answers several phenomenal questions. He points out that there is an *apparent* contraction which is proportional to the relative velocity between object and observer, but that this "contraction" does not exist if the observer happens to be moving along with the object which he is measuring.

To illustrate: If an ocean liner measures 1,000 feet in length while lying at the pier, theoretically it would be a trifle less than 1,000 feet while under way if viewed by an observer on shore. If, however, the measurement were taken by an observer aboard

the moving ship, using the same yardstick that was used at the pier, the result would still be 1,000 feet. Einstein's contention is that the ship undergoes no physical shortening such as Lorentz and Fitzgerald supposed, but it is simply the victim of a phenomenon of observation. The apparent contraction, however, holds good for all object or bodies of matter in exact ratio to their velocity relative to the observer as specified in Einstein's mathematical formula, and is just as real in practical calculation as though it were a physical factor.

Motion and Contraction

It is within the realm of possibility, of course, that some degree of physical contraction does result from motion, on the theory that the electro-magnetic forces operating between the atoms and molecules of matter undergo a change due to velocity. If, therefore, the yardstick and everything else aboard the moving ship suffered a physical contraction exactly proportional to the length of the ship itself, then there would be no way of detecting it by any measurement taken aboard the vessel.

It hardly appears reasonable, however, that materials of different density would undergo the same proportional contraction, as for instance a wooden yardstick and the steel sides of a ship, inasmuch as they are of entirely different molecular composition. The Einstein theory therefore proposes an observational variation rather than a physical contraction of the object, and shows that it equally exists whether we regard ourselves as at rest and the object as moving away from us, or whether we consider the object as stationary and ourselves as speeding past it.

Let us suppose our observational instruments are lifted from their fixed position on shore and placed aboard a railway train and carried in the same direction and at the same velocity as the coastwise vessel. In this event the ship would measure full 1,000 feet in length just as it did when we measured it at the pier, because the observer under the conditions stated would be at rest relative to the moving ship. But if our train carried us faster than the ship, then the ship would again begin to measure short because our *relative* motion would be the same as though we were stationary and the ship were moving away from us in the opposite direction.

The foregoing illustration is merely theoretical, however, because the variation is too small for observation in cases of small distances and low velocities. Nevertheless, when the velocity approximates that of light rays the apparent contraction becomes plainly visible. Some of the particles emitted by radioactive substances possess a velocity of about nine-tenths that of light and in such cases the amount of apparent shortening which they undergo can be computed because it is very great. And should the velocity become equal to that of light rays (i. e., 186,300 miles a second), then, says Einstein, the observed length of the particle would be reduced to zero.

Einstein does not claim that relative velocities greater than 186,300 miles a second cannot be attained, but he does contend that velocities greater than that relative to an observer cannot be observed. Thus if a body of matter were moving away from an observer at only half the velocity of light, and the observer himself should suddenly

become accelerated in the opposite direction until the relative velocity between the two became equal to or greater than that of light, then the observed *length* of the body in the direction of motion would be zero, although its width would be unaffected.

"Absolute Length" Fictitious

All this leads us ultimately to the conclusion that there is no such thing as determining the *absolute* dimensions of anything, because relativity of motion and the time element are undeniable factors in all measurements. The assertion that these are infinitesimal so far as the quantities we ordinarily have to deal with are concerned does not alter the fact that "*absolute* length" is a fictitious phrase. For this reason we cannot reckon the *absolute distance* between any two conceptual points in the universe; we must calculate in units of *space and time* combined or else accept the fact that our conclusions are simply of local and not of universal significance.

We may, for instance, make a measurement of the distance between Neptune and the sun according to Euclidean geometry, obtaining a certain result. But if we were on another planet and there chose a reference frame which has a wholly different relative velocity to the frame of reference which we used here on earth, and with this new reference frame we measured the identically same space between Neptune and the sun we would obtain a very different result. Which measurement would be correct? Neither would be correct if by that term we mean the *absolute* distance if the universe were motionless and unwarped by matter.

Hence in measuring great distances involving enormous velocities we cannot ignore the principle of relativity and hope to obtain universally accurate results. It is because of this oversight that Euclid's geometry is found to be inadequate in such cases. But as already suggested, there is a geometry that is universal in its application, in which *time* enters as a fourth dimension. The measurements taken according to such a geometry do not, therefore, represent distance merely, but a blending of distance and time. This is the geometry which Einstein employs. It will be discussed in greater detail further on.

The Special Theory of Relativity

We will now consider Einstein's original theory of 1905, which has subsequently been called the "Special" or "Restricted" Theory of Relativity, before attempting an examination of his "General Principle" which he announced ten years later. By so doing we will find it a stepping stone of much worth, leading us naturally to the General Theory which will be discussed later.

The Special Theory is summarized in two postulates (propositions), one relating to uniform, straight-ahead motion, and the other to the velocity of light rays. It is the combination of these two propositions that necessitates the interrelation of time and space. If both are true, and the weight of evidence seems to be on Einstein's side, then the space-time geometry already alluded to must be correct. In any event our new conception of space and time as heretofore mentioned has doubtless prepared our

minds to appreciate the postulates which we will now paraphrase in non-technical terms as follows:

(1) EVERY LAW OF NATURE MAY BE STATED IN A FORM WHICH WILL HOLD GOOD BETWEEN ALL OBSERVERS AND OBJECTS PROVIDED THE OBSERVERS AND OBJECTS ARE EACH MOVING IN A STRAIGHT LINE AND WITH UNIFORM VELOCITY; AND UNDER THESE CONDITIONS NO OBSERVER COULD POSSIBLY DETECT HIS OWN MOTION BY ANY LOCAL EXPERIMENT WHATSOEVER, UNLESS HE MAKES REFERENCE TO OBJECTS OUTSIDE HIS OWN MOVING SYSTEM.

(2) LIGHT RAYS IF UNOBSTRUCTED HAVE AN OBSERVED CONSTANT VELOCITY IRRESPECTIVE OF THE RELATIVE VELOCITY BETWEEN THE OBSERVER AND THE SOURCE OF LIGHT.

On the surface there is nothing unusual about the first postulate; it appears to be simply another way of setting forth the mechanical principle of relativity announced by Newton. But it really involves more than that, because so long as we regard all bodies and measured lengths and times as rigid and unchanged by the motion of our reference frames, then it is not true that every law of nature holds good between observer and objects as set forth in the postulate. Electro-magnetic laws, for instance, are an exception, for they really do change their form in proportion to the relative motion of our reference frames.

This first postulate simply demands a restatement of the laws of nature to make them harmonize with the principle of relativity *in toto*. As already observed, many inconsistencies arise in regard to time, distances and dimensions if we hold to our old conceptions that units of time and of lengths are absolute quantities which cannot vary under any circumstance or condition. We know by experiment that they do vary, hence the need of a restatement of nature's laws to account for the facts resulting from motion. This postulate, however, concerns only one kind of motion, viz., uniform and rectilinear motion. Rotating and accelerated and generally irregular motions are dealt with under the General Theory which will be considered later.

Laws of Nature Not Unalterable

In this connection it is well to bear in mind that a "law of nature," as the term is commonly used, is not some God-given formula that cannot be altered. It is but a human description of the operation of nature, based on observed facts. As our powers of observation and knowledge increase it sometimes occurs that our "laws of nature" are found to be inadequate and need revision. That is precisely what Einstein calls for. In mathematics we may stipulate that "things equal to the same thing are equal to each other," but physically speaking the phrase is wholly ambiguous. Things observed to be equal while in uniform relative motion lose their equality when their velocities vary.

It will be noted that Einstein in his first postulate also specifies that when an observer is moving straight ahead at uniform velocity he will be unable to detect his own motion and will believe himself to be at rest unless he performs an experiment on some outside object that is not moving along with him. The truth of this is apparent to

anyone who has been aboard a smoothly running train while entering or leaving a station, and has been unable to determine whether it is his train or the train on the next track that is in motion, or both, until finally his train ceases to move uniformly and he experiences a jolt as it suddenly comes to a halt, or is thrown against the back of his seat as it begins to speed up. Or perhaps while the train was moving uniformly he performed an observational experiment on some outside object, such as a house or a telegraph pole, and thereby arrived at the conclusion that his train is moving rather than the one alongside it.

Similarly we on earth are prone to consider ourselves as at rest and the heavenly bodies as moving around us, and for untold centuries mankind never stopped to question that conception. Even since we have come to know that we are merely one of the millions of rotating heavenly spheres which go to make up a universe, we are disinclined to admit that ours is not in some sense a favored position, or that an earthly reference frame is not somehow intrinsically better. But reflection convinces us that this is not so; and since it is not so, we would do well to put our science on a universal rather than upon a purely local basis by altering whatever age-old conception is necessary to make it agree with the principle of relativity.

Paradoxical Behavior of Light

It is the second postulate rather than the first that is astounding, because it substantially states that light rays from a given source will reach an observer who is running away from the rays just as quickly, i. e., at the same velocity, as they would reach another observer who is moving toward the rays. If an explosion should take place on the sun at this moment it would, of course, take the light about eight minutes to reach the earth, traveling at a constant velocity of 186,300 miles a second. Einstein's declaration is that if two observers are on opposite sides of the rotating earth, one revolving away from the sun and the other revolving toward it, the instruments of each observer will indicate that the rays from the flash are traveling past him at exactly 186,300 miles a second regardless of whether he is traveling toward or away from the sun.

Ordinary concept would assume that in the one case the observer's own velocity toward the sun should shorten the time it takes the light to reach him and thereby make it appear to him that the light is traveling faster than 186,300 miles a second, while in the other case we would suppose that the observer's instruments would indicate that the light is traveling slower than 186,300 miles a second due to his own velocity away from the sun which should lengthen the period of transit of the rays in overtaking him. But actual experiment appears to contradict this and to corroborate Einstein's postulate, paradoxical though it seems to our accustomed concepts. Only by viewing the universe as a four dimensional (not as a three dimensional) continuum can the matter be understood.

It is not, of course, any more strange that when *light* waves once start on their journey, the velocity of those waves would thereafter be unaffected by the movement of the source from which they originated, than that waves of *water* would not be increased or retarded by any forward or backward movement of the ship after the

waves have been started on their course across the lake. Newton knew that the velocity of light past an observer is not increased by reason of the source of light moving toward the observer. But what he did not see was that *neither is the velocity of light increased by reason of the observer moving toward the light*.

In other words, after admitting the principle of relativity in a mechanical sense, practically as stated in Einstein's first postulate, Newton then denied or at least overlooked that principle when it touched the subject of the propagation of light. Take, for instance, the case of light rays reaching us from certain distant stars. We cannot surely know whether the source of light is traveling toward us, or whether we are moving toward the source of light. Newton would say that the velocity of light would be unaffected in the first instance, but increased in the second. Einstein says it makes no real difference which way it is, because the principle of relativity is universal, all motion is relative, and the universe is so constructed that the velocity of light always appears constant to all observers irrespective of their motion or of the motion of the source of light relative to them.

If, however, we were traveling away from a given source of light at a greater velocity than light itself can travel it would certainly not be true that light, under such a condition, would register a constant velocity. But such a rate of motion is manifestly impossible of physical attainment, light being considered to possess the maximum velocity greater than which no material body can travel. In other words, 186,300 miles a second is the limiting velocity beyond which physical phenomena does not reach, because all matter would evidently suffer complete dissolution, being reduced to the state of free electrons, by the time such a velocity would be attained. Light is matter in the free electronic state, and the velocity of such a form of matter is known to be 186,300 miles a second, as has been stated.

Light, being a form of matter, is acted upon by gravitation. This was first demonstrated during the solar eclipse of May 29, 1919, when photographs were taken of various stars whose light at that season had to pass very near the sun in order to reach us. Three months later photographs were taken of these same stars after they had moved from their former positions. Their normal relative motion being known, it was easy to determine from the two sets of photographs whether their displacement was entirely due to that motion. It was found that their displacement was considerably less than it would have been under normal conditions, thereby indicating that the light from these stars had been deflected as it passed near the sun's rim, making it appear to the observer that these stars then occupied positions which they did not occupy. See Fig. 3.

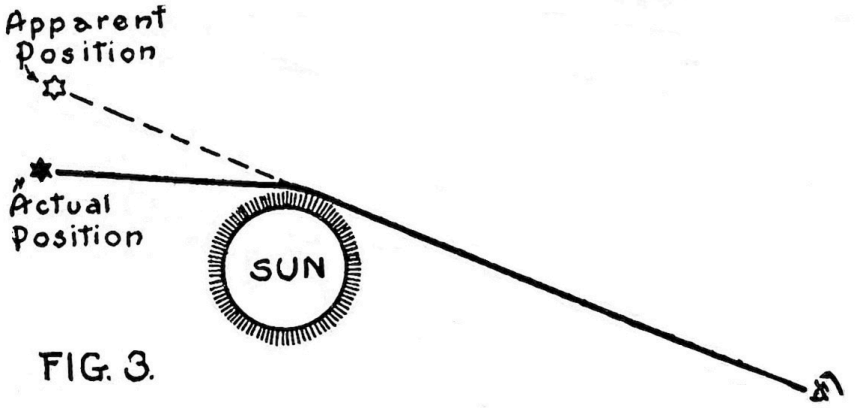


FIG. 3.

Electronic Structure of Matter

Light and electricity both travel at the same velocity, and in the final analysis they are the same form of matter. All ponderable matter is made up of molecules, and molecules consist of atoms of varying elements, except where the substance is elementary throughout, in which case the molecules are made up of a certain number of atoms of the same element. An atom is an aggregation of negatively charged particles of electricity, called electrons, which revolve and vibrate at enormous rates around a central nucleus of "protons" carrying a positive charge. If we conceive of a handful of sand as whirling around and around at such an enormous velocity as to appear as a globe several feet in diameter we have a visualization of the ultra microscopic atom and its comparative dimension to that of the individual electrons and protons which compose it.

Electrons and protons are manifestly identical in all form of matter, but all atoms do not contain the same number of them. An atom of hydrogen contains only one electron and one proton, while atoms of heavier matter contain a vast number. It is the *number of electrons and protons per atom*, together with their respective vibratory rates, that constitute the difference between elements. Hence every known form of matter, if reduced to the electronic state, would be found to consist of the same original stuff. Light, therefore, may be termed *free electrons*, i. e., electrons which are not bound into atoms, and consequently glide off in every direction at the highest possible velocity of which matter is capable, viz., 186,300 miles per second.

Thus it may be seen that all other forms of matter, since they consist of electrons in the atomic or "bound" state, could not possess a velocity equal to that of *free* electrons. But electrons do not become "free" simply by reason of matter undergoing a change of form. Water, for instance, may be changed into a solid (ice) or into gas

(steam), but the electrons continue to revolve around their nucleus in true atomic order, and the atoms continue to hold together in the molecular state, the only change being in their rate of vibration which affects the degree of elasticity between the molecules and between the atoms. Hence whether water be in the solid, liquid or gaseous state, the molecules thereof will be found intact, each consisting of two atoms of hydrogen and one atom of oxygen (H_2O).

When matter is being burned up, producing a flame or a glow of light, this phenomenon indicates that some of the electrons have been freed from their atomic condition and have started off on their journey in the form of light rays, while another portion of them remain bound as atoms but undergo a change of form, becoming either gas or ashes.

Michelson-Morley Experiment

Returning now to Einstein's second postulate, that the velocity of unobstructed light rays appears to be constant to all observers irrespective of the relative velocity between the observer and the source of light. The evidence on which this theory is based was first produced by Michelson and Morley in 1887 who at that time undertook an experiment to ascertain if possible the velocity of the earth relative to the ether. The experiment revealed that light registers a constant velocity, whether it travels in the direction of the earth's rotation, or against the rotation, or at right angles thereto. The experiment was repeated many times with different apparatus and under various conditions, but always with the same result.

It is interesting to note the details of this experiment. Light is known to travel in waves, because rays coming against each other from opposite directions can be made to "interfere" in precisely the same manner as waves in water. If waves in the ocean come together from different directions, one of two things will happen; they will either unite and produce a larger wave, or else they will strike in a manner to measurably kill off both waves. If the crests of the two waves coincide they reinforce each other, but if they strike at right angles, the destruction of the wave motion results. This is called "interference."

Light rays conduct themselves in the same manner, thereby revealing their wave-like nature. This is not contradictory to the idea that light rays really consist of individual electrons, freed from atomic attraction. Possibly each separate electron which goes to make up a ray of light vibrates in a wave-like manner, possessing a wave motion within itself. Waves of light are exceedingly minute and we do not ordinarily witness any reinforcement or interference of light rays about us, because there is no occasion for them to "pile up." However, in laboratory experiments, interference of light waves has been produced, and to whatever extent the interference kills off the wave motion, to that extent darkness ensues irrespective of the brightness of the light at its source.

Michelson and Morley worked on the theory that if they sent rays of light from west to east (the direction of the earth's rotation) and then reflected them back over their course it should take longer to make the eastward trip than the westward,

because in the first instance the earth is carrying the objective point away from the light while in the latter instance it would be rushing to meet the oncoming reflected rays. Under this condition there should be a noticeable *interference* of the light waves due to the difference in distance and time involved in making the two halves of the round trip. But to the amazement of all there was no interference whatever, notwithstanding the fact that the apparatus was ten times larger than it needed to be to reveal such interference of the waves had it really occurred.

The conclusion reached by Einstein as a result of this experiment is that since light rays consist of matter in its basic or electronic state, freed from atomic attraction, they therefore possess the limiting velocity of which matter is capable. Hence they could not travel more rapidly than 186,300 miles a second even if given a quick send-off, nor would our traveling toward the light affect its apparent velocity to us—unless it were possible for us to be traveling forward more rapidly than light itself can travel. This would undoubtedly be impossible, inasmuch as any physical body would necessarily consist of electrons in the atomic or "bound" state and therefore could not possess the mobility that free electrons would enjoy. The universe, then, being a four-dimensional continuum, is so constructed that the velocity of light always appears constant to all observers within it.

This is what Einstein means when he postulates that light *in vacuuo* (i. e., unobstructed) possesses a constant velocity irrespective of the relative velocity of observer and source of light. That is, it is constant so far as the observer is concerned. Thus if a flash should occur on any heavenly body and we were moving toward the flash at say 40,000 miles a second and another observer were moving away from it at say 60,000 miles a second, the experiment of each observer would indicate that the light has reached him at exactly 186,300 miles a second, although according to Euclid's conception of space the light has been obliged to travel 100,000 miles a second faster to reach the one observer than the other. But Euclid's conception is faulty, as will be seen shortly.

How, then, would it be possible for the light rays to possess the same apparent velocity per second for the two observers? It would not be possible if "time" and "distance" are absolute quantities having the same meaning for all observers. But if "seconds" and "miles" mean one thing to observer "A" and a totally different thing to observer "B," then the apparent contradiction of facts becomes harmonious. This is the essence of the doctrine of relativity. Observer "A" himself does not use the terms "seconds" and "miles" consistently, i. e., as unvarying quantities, nor does anyone. They mean one thing today and something else tomorrow, depending upon what we are measuring and the relative velocity between the observer and the object. The observer is not aware of this inconsistency. To him there is no inconsistency whatever. Nevertheless, only by acknowledging the varying quantities of time and of space, and admitting the geometry which combines the two into one unit, can the Michelson-Morley experiment and other similar observations be understood and explained.

Simultaneity a Meaningless Term

We have been taught that the true length of a moving body is "the distance between *simultaneous* positions of its end points"—a very good definition, but impossible of application for the reason that we cannot determine the *simultaneous* positions of any two points in the universe. Simultaneity is a meaningless term so long as the absolute velocity of the observer and the absolute velocity of the object being measured are unknown. We may know the *relative* velocity between them, but that is not sufficient. The two may be relatively at rest—but for all we know the entire universe may be speeding through space at thousands of miles a second in either one direction or another.

We may *see* two events occur at the same instant, but that does not prove that they actually *occurred* simultaneously. Before we could compute the exact time of the occurrence of either of the events we must know the direction in which, and the velocity at which the universe as a whole is moving, together with any and all velocities of the observer at the moment. This knowledge we do not possess. Until the *absolute* velocity of bodies can be determined the question of simultaneity must remain unsolved.

The General Principle of Relativity

When in 1905 Einstein published the foregoing postulates which are limited to uniform, rectilinear motion he may have considered that it would be expecting too much to look for a general principle of relativity such as would hold good for all kinds of rotating and irregular motions and by which observers of different and variable velocities might agree as to the reality of things under their observation. Concluding, however, that the universe must surely be constructed in a consistent manner he finally set out to find some rule or principle by means of which an observer in one region would be seen to possess no advantage over an observer in any other region of the great expanse in arriving at accurate conclusions.

Of course Einstein hardly expects to go to the Pleiades or to Betelguese and from there take measurements and make calculations; he is doubtless content to make all his observations from this earth. But how may he be sure that observations made from a reference frame located in this particular region of the universe will be true to the reality since it is manifest that observers located elsewhere and using different reference frames must necessarily reach conclusions different from ours if they employed our accustomed laws? Maybe they would be much nearer the reality than we! What right have *we* to assume a monopoly on truth! None whatever until we can formulate nature's laws in a manner that will hold good for every part of the universe alike.

Until we are able to do this our science must be like the vain efforts of the unskilled fisherman who harpoons for fish. Ignorant of the trick that water plays on the line of sight he strikes directly at the spot where he "sees" the fish and always misses his prey. The skilled harpooner, on the contrary, understands the law of refraction of light rays in water, and knows how to allow for this refraction; hence he strikes a little this side of where the fish appears to be and is rewarded with success. He is guided by a proven law and thereby ascertains the true location of the fish,

whereas the other man follows "blind" observation which is quite frequently deceptive.

Einstein's "General Principle of Relativity" is not, in fact, a mere generalization of the Special Theory in the sense that it simply enlarges upon the two postulates which we have already considered. On the contrary it handles the subject of Relativity from quite a new standpoint, and therefore might be said to belong to an entirely different school of thought. It does not lend itself to visualization as readily as does the Special Theory, and is consequently more difficult of explanation and comprehension. However, what we have already learned concerning Relativity will materially aid us in understanding what follows, for the two theories are, after all, dealing with the same general subject matter. We shall therefore endeavor to link the two phases of the subject in a logical and consistent manner.

We know, as a matter of fact, that "uniform, straight-ahead motion" which Einstein in his original theory assumed to exist, is an ideality that does not appear in nature, because all motion with which we are familiar is to some extent irregular, nor does any material object move in a perfectly straight line. But realizing the necessity for a standard from which to proceed, Einstein properly enough assumed a standard of absolute perfection and absolute simplicity of motion, even though it does not actually exist anywhere around us. In exactly the same manner Euclidean geometry assumes and deals with theoretical points, lines and planes which have no material existence in fact.

As set forth in Einstein's first postulate of the Special Theory, an observer on a uniformly moving system could not possibly detect the motion of his system without making reference to some outside object. In the case of bodies or systems moving irregularly (i. e., with acceleration) however, an observer thereon would detect "forces" acting upon himself and upon all other objects on his system, due, of course, to the acceleration. Recalling the illustration of the moving train: so long as it is moving with perfect uniformity an observer thereon would not know he is in motion at all until he made a comparison with some outside object. But if the train suddenly slows down he is thrown forward in his seat; if it speeds up he is thrown backward. This force is called *inertia*. Now if we had never experienced it before and were put aboard a noiseless and uniformly moving car from which we could not see out we would be unable to interpret these strange "forces" that we would feel as the motion of the car became accelerated. We would probably attempt to explain them as some sort of magnetic attraction, exactly as we are accustomed to explain the "force" of gravity.

Gravitation and Inertia

In the General Principle of Relativity Einstein deals with these forces (inertial and gravitational) and attributes them to a common cause, viz., acceleration of motion, and has put the matter upon a consistent mathematical basis which at once accounts for certain discrepancies long observed in Euclidean geometry and in Newton's laws. It is obvious enough that where there is no acceleration of motion there could be no centrifugal or inertial force exhibited: but we have been accustomed to looking upon

gravitation as something entirely different—as a mysterious drawing power or attractive force that is somehow inherent in matter. But gravitation is non-existent if we fall with the proper acceleration. To use Einstein's own illustration: if we were in a closed room poised somewhere in gravitational space, and began to fall with the acceleration common to that field, there would be no gravitational effects to be observed. Objects released by our hand would not fall but would remain where they are, and we could raise ourselves from the floor and stand midway between the floor and the ceiling as easily as upon the floor itself.

Again assume we are in a closed room poised in space, in a region remote from any gravitational field whatsoever. Then suppose we began to rise with a constant acceleration. Forthwith we would feel our feet pressing against the floor. Objects released from our hand would strike the floor by reason of the floor rising up to meet them, and in all respects the effects would be identical with that of gravitation. In other words we would have created an artificial gravitational field, and it would be due to our accelerated motion.

The characteristics of gravitation and inertia are identical. No amount of insulation or screening will diminish the "pull" of gravity on anything. Furthermore, gravity acts on every kind and quantity of matter alike, so that if a feather weighing less than an ounce and a pig of lead weighing a ton were held side by side at the top of a great vacuum tube and allowed to drop at the same instant, the feather would reach bottom within the same time as the lead, each falling at an acceleration of approximately 32 feet per second. It is the resistance of the air that retards the fall of light materials, such as a feather, but in a vacuum there is no resistance and gravity is found to act on all matter to the same degree under such conditions. The same is true of inertia *in vacuuo*.

When this relationship between the two forces is recognized we are prepared to believe Einstein when he states that inertial force and gravitational force are due to a common cause, viz., acceleration. This does not mean that our earth, for instance, is being accelerated in all directions at once, expanding out to meet "falling" objects such as in the case of the artificial gravitational field mentioned in the above paragraph. It does mean, however, that the falling objects themselves are accelerated, but as will be presently seen this acceleration is not due to any attractive force exerted by a "center of gravity" but rather to a warped condition of space which surrounds all bodies of matter.

Neither Newton nor Einstein have attempted to analyze the structure of matter and on this basis explain the phenomenon of gravitation. Newton evidently believed, however, that every particle of matter exerts a drawing force upon every other particle of matter, hence he formulated his law which specifies this attraction between bodies as being directly proportional to the product of their mass and inversely proportional to the square of the distance between them. But he did not attempt to make clear what that "drawing force" is, or *why* it is inherent in all matter, nor did he explain how or through what medium or mechanism it operates.

Newton contented himself with merely dealing with the phenomenon of gravitation in the abstract. So does Einstein, but with this difference: the latter denies

the existence of any mechanism whatever in connection with gravitational force so far as any attractive power from within is concerned, and accounts for it on purely geometrical grounds. This is the most difficult phase of the Einstein theory for the layman to grasp, for the reason that it involves the whole structure of non-Euclidean geometry with which the public is generally unfamiliar.

Non-Euclidean Geometry

Euclid, the famous Greek mathematician, in the third century B. C. published the first systematic treatise on geometry (the science of space and its measurement), and his axioms and theorems are generally taught in our high schools and colleges today. Euclid proceeded upon the simple theory that all space consists of points, lines and planes. He defined a *point* as that which has position but not size; a *line* (continuity of points) as possessing length but no breadth or thickness; and a *plane* (continuity of lines) as having length and breadth, but no thickness. They are simply abstract terms having no physical existence in nature, except as they exist in our minds. Nevertheless they have proved themselves convenient in measurement and calculation.

But when mathematicians, after centuries of earnest effort, were unable to prove Euclid's postulate concerning parallel lines, it occurred to some of them that possibly the whole Euclidean system rests upon a faulty foundation. Then it was that Saccheri in Italy, Legendre in France, Gauss in Germany, Bolyai in Hungary and Lobatschewsky in Russia, all masters of Euclidean geometry, conceived of other methods of decomposing space than that proposed in Euclid's *Elements*.

Thus it was that early in the nineteenth century, almost simultaneously in many countries, did many non-Euclidean geometric works come to be published. These were of the same general character or form, commonly called Hyperbolic geometry. Each of them is as consistent in itself as is the geometry of Euclid. But to Riemann belongs the credit of formulating a geometry which in the light of Einstein is seen to approach much nearer to the reality of nature than does the Euclidean or any other system.

Riemann produced his general work along this line in 1854 which was far ahead of his time. He actually prophesied the connection of geometry with matter, and had he possessed a little more vision he would doubtless have worked out the details as well as the principles underlying gravitation in much the same manner as Einstein has done. Riemann's efforts in the field of non-Euclidean geometry has materially aided Einstein in the development of the present theory. Minkowski's work was utilized by Einstein to much profit in the outworking of the Special Theory, particularly his clarification of *time* as a fourth dimension.

Time as a Fourth Dimension

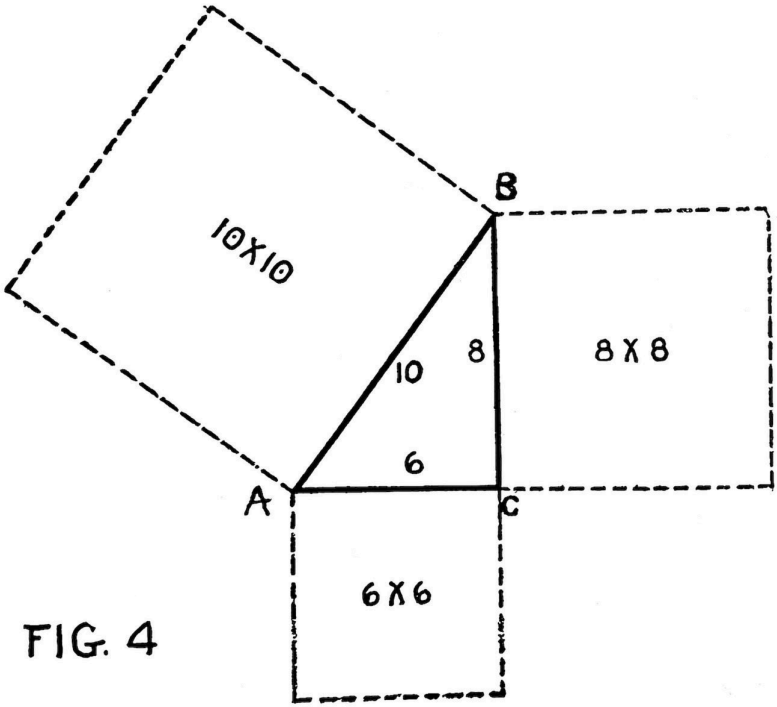


FIG. 4.

It is natural for us to think of all matter as possessing but three dimensions—length, breadth and thickness—and we have been accustomed to making our measurements of matter and of space on that basis. Using the formula of Pythagoras we have ascertained the distance between any two points in a *plane* (a two-dimensional area) by extracting the square root of the sum of the squares of the co-ordinate axes, i. e., the base and the altitude as in the accompanying diagram. See Figure 4.

If point A is 8 miles south and 6 miles west of point B then A and B are 10 miles apart, thus:

The square of 8 is 64

The square of 6 is 36

The square root of 100 is 10

Likewise, the distance between any two points in a three-dimensional region (as from an upper to the remotest lower corner of a room) is generally considered to be "the square root of the sum of the squares of the three sides" (Fig. 5).

Thus if the distance O to X is 12 feet and X to Y is also 12 feet, while Y to Z is 14 feet, then the straight diagonal distance from O directly through the room to point Z is

22 feet, because the sum of the squares of the three sides (144 + 144 + 196) yields a total of 484, and the square root of that number is 22. This simple formula will hold good for all ordinary measurements, but for great distances in space a slight correction is found necessary because of the little trick that light rays are prone to factor, i. e., the numerical value of the interval of time required for a light ray to traverse play upon us. We must subtract the *time* from the distance. Hence if our cube were large enough to fill a goodly portion of the universe we would no longer say that the diagonal distance from O to Z is $\sqrt{(x^2 + y^2 + z^2)}$ but rather $\sqrt{(x^2 + y^2 + z^2 - t^2)}$, ——t, of course, representing *time*.

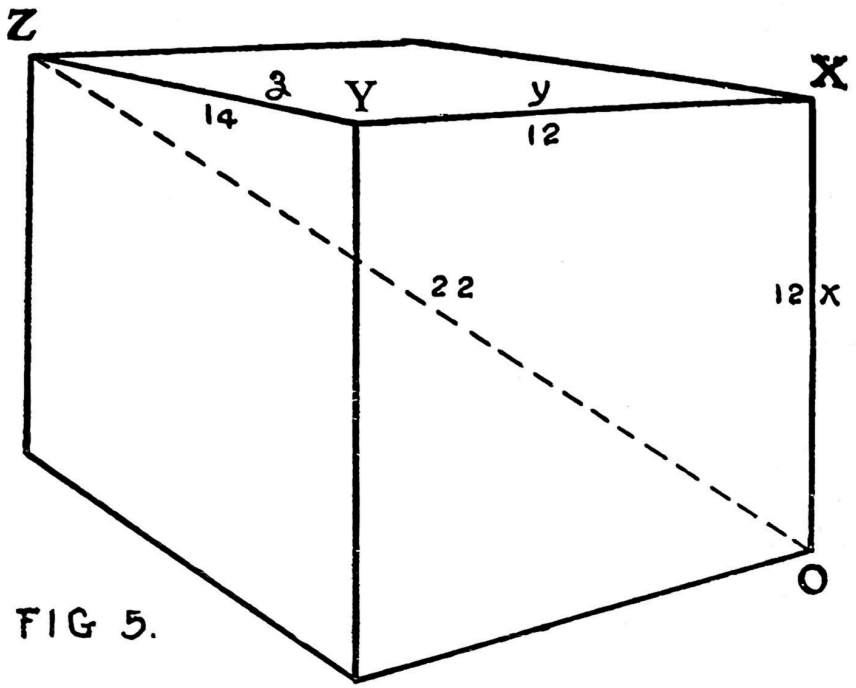


FIG. 5.

Now recall what we learned in the preceding pages, that the velocity of light always appears to be the same to all observers irrespective of the relative velocity between the observer and the source of light. It is manifest, therefore, that in making measurements the time factor (t) *really* represents one quantity for one observer and a totally different quantity for another observer notwithstanding the fact that it appears to be a constant to all observers. Inasmuch as the velocity of light does appear to be constant to all observers its actual stretching or contracting of units is not manifest. Therefore the corrected equation as given above (the subtraction of the *time* element) holds good for all observers irrespective of their motion.

The point of interest to the non-Euclidean geometer in connection with any measurement, be it remembered, is not the abstract *distance* between points, because distance is not a constant and is not determinable unless we know the *absolute* velocity of the observer and of the points being measured, which knowledge we do not possess. What we should look for, then, is the *distance and time combined*, or the *separation-interval* as it is aptly called. The time factor automatically corrects the units for each observer, no matter what his motion may be, and thus the separation-interval appears a constant.

The foregoing illustrates how time takes its place alongside the ordinary three dimensions of space, and is in reality a fourth dimension, although it is not a thing that can be visualized as we can visualize the length or breadth or thickness of any object. In the following paragraphs we shall examine further into the geometry of the universe, particularly as it relates to the phenomenon of gravitation.

Geometry with a Physical Meaning

Certain news dispatches and book reviews have erroneously reported Professor Einstein as having said "only twelve men in the world can understand the Principle of Relativity." The statement becomes absurd in view of the scores of volumes now in print, all of which set forth more or less clearly the details of the Einstein theory. What he alluded to in the remark so generally misquoted and misconstrued is his mathematical equations (calculus of tensors). He questioned if there are more than a dozen mathematicians in the world who are familiar with this abstruse differential calculus because it is not generally taught in the university text books.

This calculus is a veritable maze of formulæ, really invented by Riemann and Cristoffel, but systematized by the celebrated Italian mathematicians, Ricci and Levi-Cevita, and is impractical for any ordinary use. This is why so few mathematicians have familiarized themselves with it. Einstein, however, found it invaluable in dealing with such complex geometrical problems as his theory produced.

Briefly, the non-Euclidean geometer deals with *surfaces* rather than planes, and his fundamental postulates are sufficiently broad to apply to all regular surfaces whether they be planes, spheres, cylinders, conicoids or even spheroids or ellipsoids. He considers a "straight" line as being the shortest distance between two points *on a surface*, hence if the surface is curved the "straight" line connecting any two points thereon will also be curved. This *shortest* distance between points is called a *geodesic*. If the surface happens to be a *plane* then the geodesics connecting points thereon are really straight lines in the Euclidean sense, but this would not be true for any other kind of a surface. Thus it is seen that Euclidean geometry is simply a limiting case of this more general geometry.

Geometers of the elliptic or spherical school, including Einstein, declare that in nature there is no such thing as a purely Euclidean straight line such as may be prolonged in opposite directions to infinity. On the contrary they hold that any "straight" line if prolonged sufficiently would return upon itself, because the universe is so constructed. In other words, what we ordinarily call a straight line is but an arc

of a near infinite circle which possesses the *least possible curvature*. Magazine writers in an endeavor to make clear this portion of the theory of Relativity have strikingly declared that "according to Einstein a man might look through a telescope in any direction whatsoever and behold the back of his neck." This jest, though omitting essential facts, is not without geometrical foundation. If we possessed a near infinite telescope and should live for a near infinite period of time to enable the rays of light to traverse this near infinite circle, then, if there were no obstructions along our line of sight, we might be rewarded with a round trip view of the rear portion of our body—though the simpler method would be to use two ordinary mirrors.

All this, however, has an important bearing upon Einstein's interpretation of gravitation. Not only does he contend for Lobatschewsky's "curvature of space" but he also holds that surrounding every body of matter there is a *special* space-curvature (four dimensional), the degree of which depends upon the body's observed mass. This special curvature or "warp" of space constitutes the "gravitational field" surrounding all large bodies of matter and causes the acceleration of falling particles in that field. This distortion of space increases in proportion to the mass of the body causing it, and decreases with the distance from that body until ultimately it becomes *nil* or practically so in a region remote from all matter.

Perhaps the nearest approach to a visualization of this space-curvature (which constitutes a gravitational field) is to consider the lines of force in a magnetic field. The reader is doubtless familiar with the age-old experiment of placing file dust on a thin sheet of cardboard or plate of glass and then holding a horseshoe magnet underneath with the two poles touching the sheet or plate. Immediately the filings arrange themselves into curved lines between the poles as shown in Fig. 6.

This experiment indicates that between the poles of a magnet are constant lines of force, invisible to sight but manifesting themselves when attractable particles are in or near their path. The earth, likewise, is a great magnet, having one magnetic pole in upper Canada above Hudson Bay, about 70° north latitude, and another pole in the Antarctic Ocean south of Australia. Between these two magnetic poles continually flow these invisible curved lines of force, just as with our horseshoe magnet in Figure 6. These lines of force are the cause of compasses pointing in a northerly and southerly direction. Other planets undoubtedly possess magnetic poles similar to those of the earth.

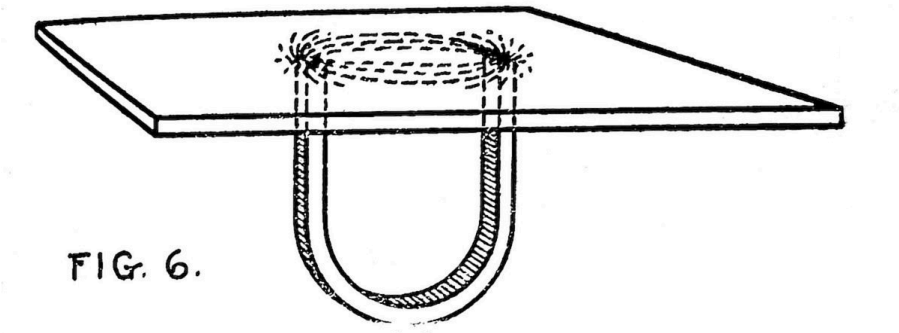


FIG. 6.

The Background of Gravitation

Now let us conceive of invisible geometric lines pervading the entire spatial universe somewhat analogous to these lines of force in a local magnetic field. To each point in these lines let us ascribe an electric and gravitational potential (remembering, of course, that we are dealing with *four*-dimensional space), and we have before us, in a nearly visualized, sense, the background of the new theory of gravitation.

Einstein was the first to present the subject of gravitation from this viewpoint. For centuries up to this time geometry and physics were considered as belonging to entirely different schools of thought, but under the master hand of Einstein the two sciences have been welded together into one. As Freundlich puts it, "quantities which hitherto had only a purely geometrical import, for the first time became animated with physical meaning." Thus "empty space" is no longer empty, even though the existence of the ether be denied. When the study of free electrons has sufficiently advanced, it may be seen that these elementary particles of electricity, or energy-particles, freed from atomic or mass attraction, play an important role in gravitational phenomena.

Figure 7 represents in a crude fashion the special curvature of space in the region of a large body of matter, for instance our earth, with the points (events) situated at finite instead of infinite nearness to each other for sake of illustration. It will be readily seen that the distortion of the geometric lines would necessarily alter the relative positions of the point-potentials.

Any falling body moves in a geodesic, i. e., from one point to the *next nearest* point in space-time.[2] In an undisturbed region, remote from matter, the points (events) may be considered as so arranging themselves that any four neighboring ones would constitute practically a square. It may then be seen that the easiest path for falling bodies would be to follow the *sides* of the squares because by so doing they would be following the *geodesic* or shortest distance between points. (See Fig. 7.) But in the region of a large body of matter the lines of points become so distorted that the *diagonal* of any four neighbor points becomes the geodesic. Then the path of the

falling particle will accordingly deviate. It will always follow the geodesic, or easiest path.

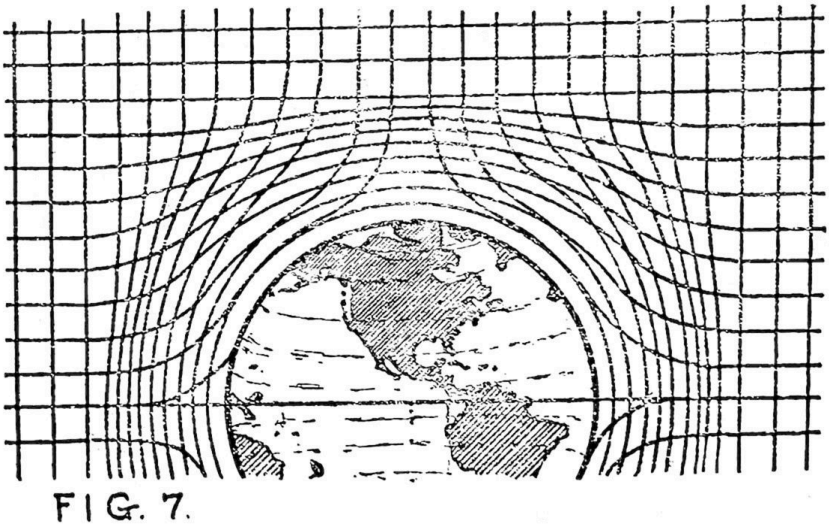


FIG. 7.

This causes the falling particle to take a direction which points toward the center of the gravitational field—but the center of gravity is exerting no drawing or attractive force as Newton supposed. Gravity is thus seen to be not an external *drawing* power operating between bodies of matter, but an inherent order of nature in space. The acceleration as well as the direction of the falling particle is accounted for by this theory. As the separation-interval between points becomes shorter—due to the constantly accentuated distortion as the large body is approached—the falling particle would be correspondingly accelerated. The distortion being constantly increased the acceleration would likewise be constant.

Newton, in his law of inertia, postulated that any particle of matter at rest will forever remain at rest if not disturbed, but when once set in motion it will continue to move at uniform velocity in a straight line unless interfered with by outside force. Einstein, on the contrary, holds that any particle of matter if left to itself will *move* (let us say *fall*, if you please) in the easiest direction (i. e., in a geodesic) at constant velocity unless it encounters a gravitational field (a distorted region), in which event it will become accelerated, and will also, if necessary, change its direction, in obedience to the principle of least action. In other words, it is natural for matter to possess energy, therefore natural for it to be in motion and unnatural for it to be at rest. And the contention has this much in its favor: every particle of matter in the universe, from the infinitesimal electron to the more gigantic sun and super-system of outer space, *is moving*, so far as our most modern observations extend. Nothing has yet been discovered to be at rest.

FOOTNOTES:

[1] When either “space” or “time” is mentioned independently of the other in this treatise it may be understood that the terms are used in the ordinary conceptual sense for purposes of simplicity.

[2] The reader must bear in mind that four-dimensional, not the ordinary three-dimensional, space is here discussed. The author has endeavored, however, to treat the matter in such a manner as to approach a visualization of this otherwise quite complex subject.

TRANSCRIBER'S NOTES

Simple typographical errors have been silently corrected; unbalanced quotation marks were remedied when the change was obvious, and otherwise left unbalanced.

Punctuation, hyphenation, and spelling were made consistent when a predominant preference was found in the original book; otherwise they were not changed.

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