Chapter 3 : THE SPECIAL THEORY OF RELATIVITY

THE facts and considerations given in the preceding chapter led us to the conclusion that light is an electrical process rather than a mechanical one. It is not related to either water waves or sound waves. It is more akin to radio waves emitted into space from aerials and consisting in rapid changes of an electric and magnetic field. With such a statement, it is true, the problem of the existence of ether, assumed formerly, is not yet answered in the negative. All that is proved is that ether is not a substance, in the mechanical sense of the word, comparable to what we call matter. The question remains: Is it not possible that electrical prenomena may also be grounded in a substance? Can't there possibly exist a particularly fine substance underlying electrical fields and related to them as water is to water waves? Don't electrical phenomena become intelligible only when an ether is assumed?

The question of the existence of such an electrical ether cannot be dismissed without further ado. An ether may exist; yet it should be realized that the supposition has an exceedingly weak foundation. It rests on a belief which is unlikely ever to be verified, namely, on a belief that the phenomena occurring within the fine pores of matter do not appreciably differ from those occurring in the cruder material structures accessible to our senses. This conjecture is not justified by anything we know; for indeed, the progress of natural science has shown in all of its fields that nature is different, in its inner organization, from what it appears to our crude senses. Let us recall, for instance, the discoveries of biology, the science of living beings, which inform us that all living organisms consist of countless cells producing a unified living being only in collaboration. No one can say that this assumption is supported by the evidence of vision; yet it is true. And one should not be surprised that the science of physics, looking far deeper into the nature of things than biology, has come upon even greater discoveries. It seems that the vast changes in our ideas concerning the physical world are an outgrowth of the fact that the requirements of scientific precision have grown quite substantially. As long as men are satisfied with the range of exactness given by sensory perception, they can put up with a rather simple explanation of nature. But as soon as the precise measurements made possible by the modern art of experimentation are introduced, inexactitudes and contradictions are found in current theories; as a result, involved theories have to be devised to make facts agree with interpretations. Thus, the tremendous development in the field of theoretical physics during the last century was an effect of achievements of experimental physics. One should not forget that the physicists were not led to their bold assertions by mere ecstasy of speculation: they were guided by the urgent need to make theories and facts agree and to explain the discoveries revealed by improved physical instruments.

In fact, Einstein's theory of relativity, the most magnificent achievement of modern physics, was suggested by closest adherence to experimental facts; this is its strength. We may admire the grandeur of its structure of thought and the depth of its ideas; but this alone would never have secured for it that firm position in physics which it enjoys today. This position was secured because it is able to explain experimental facts, to foretell events; it was the later confirmation of these events which made this theory great.

Einstein built his theory on an extraordinary confidence in the exactitude of the art of experimentation. A number of physical experiments were under consideration, at that time, which aimed to determine the state of motion of this hypothetical light-ether. To be more exact: as ether was supposed to fill the whole of the world's space, the earth had to move through it. The goal of these experiments was to measure the motion of the earth in regard to ether. The result of all these experiments was, however, negative. The existence of ether could not be determined. It was at this point that confidence in the results of experiments became significant: Einstein was certain that the experiments would have had a positive result did ether exist at all; he concluded, therefore, that there is no such thing as ether. This conclusion as regards the non-existence of ether could be ventured only insofar as it presupposed the unconditional trustworthiness and exactness of experimental findings.

We must here describe more accurately the trend of thought which led to the decisive examination of the existence of ether. If one maintains that there is no ether, one must comprehend that such a statement requires conceptual clarification. It can mean only a definite assertion concerning the properties of light; namely, that light has no properties of the kind characterizing "coarse" waves, exemplified by waves of water or air. Among the properties of substance, in the old sense of the word, we include impenetrability; and we have shown that this property does not apply to light as an electrical field. There is a second property of substance—the determination of a state of motion. We must now clarify this point.

When we observe a water wave, we necessarily ascribe to it a certain rate of velocity. The wave takes a period of time to travel from a ship to the shore. This velocity is determined by the nature of water, by the speed with which each water particle carries along the next one, by the power of the inner cohesion of water. It is clear, moreover, that the time required by the wave to traverse a certain distance depends on one more factor. Suppose it is low tide, and water recedes away from the land; then, obviously, the period of traveling will be lengthened, for the wave will be retarded. The velocity of the wave is normally considered with regard to the water's surface. If, however, this water surface is as a whole in motion,

then this motion must be added to or substracted from, the velocity of the wave, according to its direction. The speed required by the wave to reach the shore is composed, therefore, of two velocities, that of the wave and that of the water surface. Consequently, the combined velocity will vary with the direction. In the case of a low tide, the velocity of the wave in the direction of the shore will be retarded, while the velocity of the wave moving from the ship to an island situated farther in the sea will be increased. Only with regard to the water surface is the speed of the wave equal in all directions. That is what is understood by the determination of a state of motion. If we apply measurements to water as our reference system, then there prevails an equal velocity in all directions; and the state of motion of water is, consequently, the distinctive state of motion, in terms of which the calculated velocity of the wave receives its natural value.

Such reflections were entertained with regard to ether and in connection with astronomical relations. As light traverses the world's space, ether must fill it like a great mass of water in which planets float like isles. Insofar as planets move around the sun, they must be characterized by a different state of motion from that of ether. Thus one comes to the assumption that the velocity of light, as measured on a planet like the earth, must vary with direction, simply because ether is understood as a substratum of light waves and only with regard to it can the velocity of light receive its natural value. In the eighties of the last century, an American physicist, Michelson, devised his famous experiment (since repeated many times) designed to test this line of reasoning.

The arrangement of Michelson's experiment is graphically presented in Fig. 5. The apparatus consisted of two horizontal metal bars AB and AC. In A there is a source of light from which rays are sent to B and C where they are reflected in a mirror and meet again at A. The dotted arrows of the figure are supposed to indicate this path; for a better view of the whole process they have been drawn partly below and partly above the bars, whereas the real path in both directions lay of course exactly in the axis of the bar. The question is: if the rays leave A simultaneously, will they return to it also simultaneously? This would be the case were the apparatus and its metal bars to rest motionless in ether, for then the speed of light is equally great in both directions AB and AC. But the apparatus rests on the earth and hence participates in the motion of the earth through ether. It follows that the velocity of light must be different in the two directions. A simple calculation shows that, when the earth moves through ether in the direction AB, the ray A-B-A must return to the starting point a little later than the ray A-C-A.

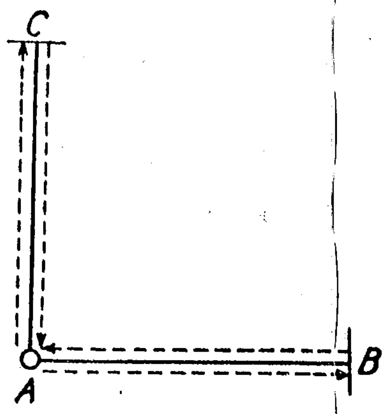

Fig. 5. The diagram of Michelson's experiment.

Michelson felt sure at the time that it was possible to prove the tardy return of that ray; after all, his methods were exact enough, and he used the finest optical instruments. The belated arrival of the ray could be proved by means of interference, by the appearance of shadow-bands created by the coincidence of hills and dales of the two currents of waves (see Ch. 2). Yet the surprising result was that no shadow-bands appeared at all: there was no retardation of the ray.

This unexpected result kept the scientific world long in perplexity. The first man to attempt an explanation of the phenomenon was the Dutchman H. A. Lorentz. He assumed that the bar AB became shorter in consequence of its motion through ether; as a result the path A-B-A became shortened, and the ray came back just as quickly as the other ray. There is no objection to this explanation, except that it overlooks the fact that the problem of ether acquires a very peculiar turn. In brief, it signifies that ether exerts shortening forces upon the moving bodies in such a manner that the differences in the velocity of light connected with motion cannot be demonstrated. In other words, we are expected to believe in the existence of ether and also to assume that the proof of the existence of ether is impossible. In view of such findings, it would seem to be more plausible to stop believing in ether: for whatever defies every attempt of proof has no existence for the physicist.

Einstein accepted the latter alternative, and the convincing power of his doctrine lies precisely in its openly logical deductions. We may now formulate his view, as following from the preceding. There is no ether, in the sense of a carrying medium of light; and there is no special frame of reference in which the velocity of light is equally great in all directions. Rather, this is the case in every uniformly moving frame of reference. When measured on the moving planet of the earth, the velocity of light is identical in all directions; when measured on a differently moving planet or on a body "resting" in the solar system (such bodies, for all we know, do not exist), the velocity of light is still the same in all directions.

Einstein's doctrine signifies a definite turn in the history of the problem of ether and transforms hitherto negative findings into a positive principle. It cannot be said, to be sure, that it explains the negative findings; it proceeds the other way around and, assuming them as established, asserts that no special explanation can be here expected at all. This procedure can be compared to that of introducing the principle of the conservation of energy. Insofar as the efforts of innumerable inventors to create a perpetuum mobile have proved fruitless, this principle of energy stands for a circumscription of the fact rather

than for its explanation: the feat is impossible.

Einstein's doctrine required, and was given by him, a considerable supplementation in connection with the theory of knowledge. For the contention that for every uniformly moving frame of reference the velocity of light is equal in all directions takes us in one important respect beyond the experiment of Michelson. In that experiment the velocity of light was not measured in one single direction, but as the totality of time necessary for a light-beam to travel there and back. However, how do we know that the velocity is not greater or smaller in the direction AB than it is in the direction BA, with the result that, in measuring the total time at A, the difference drops out? Is it not possible that Einstein's contention that the velocity of light is identical in both directions is a faulty hypothesis?

The answer to these questions leads to the famous doctrine of the relativity of simultaneity. This most profound of Einstein's thoughts must here be explained in greater detail.

Einstein distinguishes between simultaneity at the same spot and simultaneity of events separated by distance. This distinction becomes particularly clear when we take astronomic dimensions into consideration. An astronomical observer is attached to his spatial place; yet he receives messages or signals from distant points. He is able to record immediately only the simultaneity of their arrival to his place. Although this place is by no means a mathematical point, nevertheless it may be considered as virtually dimensionless as compared to distances traversed by light in a few seconds and referred to by the theory of relativity. The arrival of a signal may be designated as a coincidence, as a "point-event"; that is to say, as a phenomenon spatially and temporally dimensionless. Such a simultaneity at an identical point may be taken without change from the older physics. The logical problem arising beyond the realm of sensory perception is this: How does an observer arrive at the temporal order of events separated by space?

"By means of physical measurements," is the first prompt answer. The observer measures the spatial distance and divides it by the speed of the signal; thus he gets the time in which the distance was traversed. If a beam of light from Sirius reaches the earth simultaneously with a beam from the sun, then it is possible to estimate at what time each of the beams was emitted by taking into consideration the respective distances of the stars and the velocity of light.

That is, of course, correct. But first one must know the velocity of light. How can it be measured?

There is fundamentally but one method for the measurement of a signal velocity, which we shall represent schematically in the following way. Let us imagine two clocks located at two different points (Fig. 6). A signal is given at the first point, say, at 12 o'clock. It reaches the second point at 5 minutes after 12. Hence it took five minutes to cover the distance which we proceed to measure; when this is determined, the velocity in question is found

by division. This is th only possible method of measuring the velocity.

But is it true? Wasn't the velocity of light measured by Michelson in an entirely different manner? Michelson sent a beam of light to a distant point and arranged for its reflection and return. He had to measure only the time at the starting point without considering the moment at which the beam reaches the mirror. However, he thus found merely the sum-total of periods necessary to traverse the path to and fro. He could not determine what interests us most, the velocity in a single direction. Our contention is therefore correct.

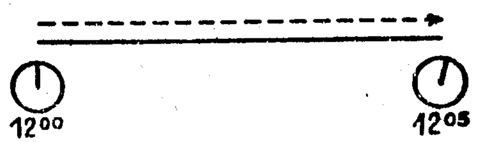

Fig. 6. A Diagram of the Measurement of the Speed of Light.

We notice that our measurement of the velocity of light has resulted in a difficulty. In order to estimate that velocity we need two clocks at different points. In order to make the differences in time read from the clocks meaningful, the latter must be adjusted; that is to say, it is necessary to ascertain whether or not the clocks show the same figures at the same time. But we have arranged for the measurement of velocity solely for the purpose of finding a means of ascertaining the simultaneity at points located remotely from each other. We find ourselves in a vicious circle: in order to determine ~~the simultaneity of~~

distant events, we must know a velocity; and in order to measure the velocity, we must be capable of judging the simultaneity of events separated by distance.

Einstein has shown a way out of this logical circle: the simultaneity of distant events cannot be *verified*, it can only be *defined*. It is arbitrary; we can determine it in any manner without committing a mistake. When accordingly we make measurements, the results will contain the same simultaneity which has been introduced by definition; this process can never lead to a contradiction.

This is Einstein's famous theorem of the relativity of simultaneity. It requires a decisive change in our views, but it is unlikely that it will remain, for all times to come, as strange or bewildering as it appears to be at a first glance. As a matter of fact, anybody who grasps the idea completely will find it as intelligible and natural as the old idea of time; he will discover, moreover, that the new doctrine readily answers certain questions suppressed or neglected by the old theory. In the end he will find it difficult to think along the lines of the older view. The experience is similar to one frequently occurring when somebody goes to another country: he finds at first that he is unable to get adjusted to the new language; then forgets about it, till one day, on returning to his native land, he discovers that the new language is really more familiar to him than his native tongue.

The significance of this solution of the problem of simultaneity consists in that it makes intelligible Einstein's contention concerning the non-existence of any special

frame of reference with regard to the propagation of light (and hence the non-existence of ether). Apart from this new thought, Einstein's principle would contain a logical contradiction.

This principle must now be formulated in a more exact manner. The velocity of light is identical in all directions in a uniformly moving frame of reference, provided simultaneity is correspondingly defined. This additional statement makes Einstein's contentions clear. We notice that the abandonment of the concept of macroscopic substance (together with that of a special state of motion) is bound up with the relativity of simultaneity in a peculiar manner. The profound significance for physics of investigations in the theory of knowledge thus becomes obvious.

But Einstein's theory of simultaneity has a presupposition without which it could not be maintained: it is nothing other than the assumption that no velocity greater than that of light can occur in nature. We must think it over very carefully why this assumption is so important.

For this purpose we shall explain Einstein's theory in the following manner. A light signal is sent out from A at 12 o'clock (fig. 7); it is then reflected and returns to A at 10 minutes after 12 o'clock. At what time did it reach B? According to Einstein, this cannot be determined by experiments; we can only establish it by definition. We may, for instance, record it as having occurred at 12:05; but we can think of it also as occuring at 12:02 or 12:08. But we may not declare that the arrival at B takes place at 11:59; for then the light would have arrived at B earlier than it has started from A. We know that no physical occurrences can run backward as to time. This is the only limitation; any number within the stretch of time between 12:00 and 12:10 can be chosen.

Let us therefore set the time for the arrival of the lightbeam at 12:02. Can this lead to no contradiction? There would always be a possibility of contradiction were there signals faster than light in existence. Let us suppose that there is a signal requiring three minutes less than light to traverse the distance AB. Let this signal be sent from the point A simultaneously with the light-beam. As the light-beam arrives at B at 12:02, the other signal will arrive, according to our assumption, at 12:02 minus 3 minutes, that is, at 11:59. Now, both signals were sent out from A at 12 o'clock. It follows, absurdly enough, that the new signal arrives at B sooner than it starts from A. The determination of simultaneity has led us to a contradiction; but only because we have accepted the possibility of the existence of signals traveling faster than light.

A contradiction in Einstein's theory of simultaneity is impossible only if there are no signals traveling faster than light. That is another contention of Einstein. Indeed, it is the most important contention of his special theory of relativity. The statement must be made still clearer, if we are to accept it fully.

We must admit, of course, that no physicist has up to now found signals traveling faster than light; but are we certain that such signals do not exist? There are many things, no doubt, of which we have no knowledge today,

but which we may come across perhaps tomorrow. Who would have thought 150 years ago that one could travel from New York to Boston in 5 hours, a distance requiring at that time at least several days? Who would have believed then that it might become possible to converse orally across that distance, as it is now done every day over the telephone? May not similar surprises await us in the science of physics? May not some day a spreading process be discovered in comparison to which the velocity of light will appear like Stephenson's first train as compared with a modern express train?

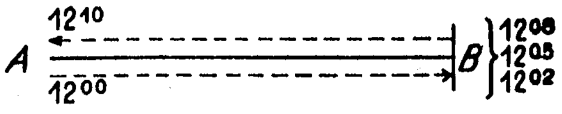

Fig. 7. *A Diagram of the Course of a Light-Signal.*

Ready as the physicist may be to admit the possibility of any technical dream of the future, he cannot accept this dream. If a utopian poet should portray the day when a regular traffic to Mars began or when the highly progressed humanity rescued the earth from the chains of the sun grown cold and steered the planet toward other stars, the physicist would have no objection, for physical reasons, to such conjectures. But to every fancy in which even the smallest action spreads quicker than light, in which waves of some kind "run ahead of light" as it were, he must respond with a blunt "impossible." Cautious as he may be in denying possibilities, he realizes that there are denials which must be uttered with assurance, unless his entire science is to lose its meaning. There are denials expressing a law of nature; and this is one of them.

Such denials are, after all, common in physics. One can easily show that every law of nature carries within itself a statement of denial. The law of the conservation of energy, for instance, can be expressed in this form: there will never be found a process, even in one hundred thousand years, in which the amount of energy increases apart from an outside influence. Thus, the positive law of the conservation of energy contains within itself a negative consequence. And vice versa, the negative law of the limitation of the velocity of light can be formulated to show its positive kernel. We now want to bring out this kernel.

In the first place, Einstein brings into the picture a peculiar contention concerning the energy of moving bodies. Every body in motion carries within itself an amount of energy which increases with the velocity of the body. This energy is required to start the motion; we recognize it, on the other hand, in the impact provided by a moving body to one standing still. According to Einstein, the content of energy in a moving body grows with an increasing speed faster than assumed by the old theory. In order to bring a body up to the velocity of light, an infinite amount of energy would be required. It is therefore impossible for a body to move quicker than light; in fact, no material object can reach that velocity.

In the second place, the law of the limitation of light-velocity rests upon the knowledge that light does not constitute a physical phenomenon of its own but rather represents a special case of the transfer of electrical activity in general. In the preceding chapter we had an opportunity to see that light is an electrical phenomenon and that light waves represent only a section of the great realm of electrical waves. What is maintained by Einstein with regard to light goes, therefore, for all electrical waves of which light is but a representative. But according to our knowledge of the internal structure of all substances, there are basically only two ways of transfering power from body to body: gravitation and the electrical wave. Every other manifestation of force is composed of them. If they both move with the velocity of light, as Einstein contends, then a slowing up may occur within the atoms of the body, when the power runs in a zig-zag course; but it can never be accelerated. Einstein's law of the limit character of the light-velocity means thus nothing other than a formulation of the fact that light represents one original form of the transfer of action, the other representing an equal speed limit.

Only with the addition of this idea does Einstein's theory of the relativity of simultaneity become intelligible. It even leads to a clarification of the concept of simultaneity itself. What do we mean when we speak of simultaneity? Let us take an example. Let us say that I wish to visit a friend of mine in Southampton. I depart in a steamer from New York at 12 o'clock. Now it happens that my friend leaves Southampton for New York precisely at the same time. Neither of us knows about the other's departure. Only at the last moment do we send telegrams to each other. We shall now consider a small delay of the telegram due to its being written out and carried out, and we shall assume that the telegram arrives within a few minutes. Such a telegram is then the quickest practical signal, although the delay makes it a little slower than the velocity of light. If both telegrams start out simultaneously, each will reach its destination slightly late, that is, after the ship's departure. Had my friend left but a few minutes later, my telegram would have reached him and kept him in Southampton. And vice versa, had I left a little later, I would have received the telegram and could have avoided a superfluous trip. The fact that we both left simultaneously simply means that it was impossible either for my telegram to reach him or for his telegram to reach me. We find that simultaneity means an exclusion of causal connection. When two events P and Q take place simultaneously, there is no possible effect of P on Q or of Q on P.

If this is the definition of the concept of simultaneity, then the indeterminacy of simultaneity is at once apparent. As my telegram takes several minutes to reach Southampton, my friend could have left at 12:01 without receiving the telegram. On the basis of this "telegraphic" speed, the two events could have been called simultaneous. Now it is true that the velocity of light is considerably greater; the light-signal—or what is the same: the radio waves apart from the delay by writing and delivering the telegram—require only a fraction of a second to

traverse the distance over the ocean. But light does not travel infinitely fast. Because of the great velocity of light the interval of time within which simultaneity is arbitrary is short; but it is not a nought. We understand now how the relativity of simultaneity is connected with the limit character of the velocity of light: as there is a finite limit to all velocities transferring action, a possible causal connection of two distant events is necessarily excluded for a short duration: the arbitrariness of simultaneity lies precisely within this duration.

The unique position which light occupies in the theory of relativity may be expressed also in a different manner. Whereas in Einstein's original theory of relativity light served merely to determine simultaneity, it became clear in the later revision of the theory that light may be used for all measurements of time, for the designation of the measure of time, and even for the measurement of space. One may construct a geometry of light* in which light determines the comparison of spatial distances. Thus light comes to serve as the ordering net of physics, which gathers within the meshes of its rays all the events of the world and puts them in a numerical order.

With this idea in mind, one may further represent the content of Einstein's theory of space-time in the following way. Clocks and yardsticks, the material instruments for measuring space and time, have only a subordinate function. They adjust themselves to the geometry of light and obey all the laws which light furnishes for the com-

---

*See H. Reichenbach, *The Philosophy of Space and Time*, English translation, Maria Reichenbach and John Freund, Dover Publications, Inc., New York, 1957.

parison of magnitudes. One is reminded of a magnetic needle adjusting itself to the field of magnetic forces, but not choosing its direction independently. Clocks and yardsticks, too, have no independent magnitude; rather, they adjust themselves to the metric field of space, the structure of which manifests itself most clearly in the rays of light.

In view of the preceding argument, this seems to be a fairly plausible statement; yet it leads to a noteworthy conclusion concerning the behavior of clocks. According to it, it is possible to show that moving clocks behave differently from those in repose. Movement exerts a retarding influence upon clocks. If a clock is moved from place to place and finally returned to its original place, it is slower than a clock which remained motionless at one and the same spot. The contention would be totally inconsequential, to be sure, were it applicable merely to clocks: the physicist then would calculate the influence of the motion and accordingly set the clock properly. But the theory of relativity maintains much more; it maintains, namely, that any running mechanism, regardless of kind, would manifest a similar retardation. Were an observer to make a journey with the clock and try to check the retardation of the clock by means of measuring devices taken along, he would be unable to notice any difference, insofar as the clock would go without any change with regard to his devices. Even if he investigates the processes of his own organism, estimates the period between two meals on the basis of hunger pangs, or measures the dura-

tion of normal sleep by the clock brought along, he still would be unable to discern any difference from previous experiences.

If this is to be fully understood, we must realize that all the processes of the human body are rooted in physicochemical changes and ultimately rest on the motion of atoms and electrons. But the processes of these elementary particles will be slowed down in the same proportion as the clock; man's feelings and perceptions will be, consequently, in complete accord with the clock.

These reflections lead the theory of relativity to assert that nobody can be forced to acknowledge the retardation of a moving clock as long as it is compared with other objects participating in its motion. One may simply declare that nothing has changed during the motion. Only regarding objects of another state of motion can we speak of a delay of our clock.

In application to astronomical relations, that is, to great distances and great velocities, these considerations lead to remarkable conclusions. Let us suppose that the above mentioned ship of space to Mars has been actually invented and that one of twin brothers undertakes the long voyage while the other remains on the earth. Years pass, and the twin at home has grown old. Then one day the ship of space returns with his brother who looks only a few years older than on the day of his departure. The brother has not noticed during his trip, of course, the fact of his preserved youth, as all of his fellow-travelers have remained in the same age relationship as himself, and all the clocks on board have made as many double turns as there have been days of the travelers' aging. Subjectively, the traveler lived but a few years, while the persons remaining on the earth lived through a great many years. If the traveler remains on the earth, the period of his whole life, from his own standpoint, will appear to him no longer than that of other people; but now he will be able to reach a much later age than his brother and his generation of men will ever be able to attain.

This example has caused much surprise and even controversy in the discussion of the theory of relativity; but it is impossible to deny that it follows necessarily from the theory of relativity and that all physical facts speak for the correctness of the contention. The theory of relativity will not declare, to be sure, anything concerning the possibility of ever traveling across the space of the universe, for the simple reason that prophesies with regard to technical progress are outside its domain. But it may assert that, if such a trip is ever undertaken, the travelers are bound to age slower, as explained in the above example. The hypothetical form of the assertion is right, even compulsory, insofar as all available facts are in favor of the doctrine of relativity. We cannot accept the objection that the case is inconceivable. Quite the contrary, everything described in it is quite conceivable; and fiction has more than once resorted to such imagery, for instance, in the form of the monk of Heisterbach. The novelty of the case consists only in that it is now the imagery which represents the truth.

Since we have undertaken to illustrate the contentions of the theory of relativity by cases of astronomical utopias, let us add one more remark concerning celestial telephoning. Our statement to the effect that no signal can travel faster than light leads to rather sad conclusions, in this connection. A beam of light requires about 8 minutes to cover the distance separating the earth from the sun, and 16 minutes to cover it both ways. The distance of Mars is sometimes greater, sometimes smaller than that of the sun, and therefore the corresponding figures will vary. Let us take an average position of Mars, the distance of which corresponds approximately to that of the sun; in that case, the electrical waves conveying a telephone conversation will take 16 minutes for the round trip. This would mean that, in making a call to an inhabitant of Mars, we must wait a quarter of an hour to get an answer to a question. Such slowness of communication would be quite unpleasant, and the cozy chats characteristic of everyday telephone calls would hardly occur in communication with Mars. The situation is considerably worse with regard to fixed stars and their planets. In fact, the nearest fixed star is about 8 light years away from us. We would have to wait at the telephone receiver for sixteen years to get an answer, not to mention the case of more distant stars an answer from which could be received only by our great-grand-children.

The prospects for celestial intercourse compare unfavorably to those of traveling. There is no limit to possibilities of reaching remote planets. One might surmise that the traveling to a distant star would take so long that the traveler's span of life will not suffice to complete the journey. This argument, however, is inconclusive because of the fact that the speed of traveling holds back old age. The closer is the speed of traveling to that of light, the less would the traveler age and the slower would seem to him the flight of time. A trip over a distance of one hundred light years might mean to him, subjectively, a two-year aging.

These inferences from the theory of relativity are indeed quite fantastic. It is a strange matter of fact that the strictest scientific manner of thinking leads to ideas such as are found in the fairy tales of the Orient. Truth seems to be richer in diversity even than poets' imagination. Attractive as the theory of relativity may appear to those who turn pages of natural science as if they were pages of a picture book, entrancing speculations were not responsible for the scientific acceptance and influence of the theory. Its success resides rather in the persuasive power of the soberest and sharpest thinking as well as in its overwhelming capacity of explaining experimental facts within the frame of one unified theory. In the following chapters we shall attempt to show the fruitfulness of this method of thinking with regard to other fundamental problems.

Chapter 4 : THE RELATIVITY OF MOTION

THE idea of the relativity of motion, which gave Einstein's theory its name, leads us back to the older root of this theory, referred to in the first chapter. The Copernican view of the world and its consolidation through the mechanics of Newton have become the starting point of reflections which began to bear fruit only after Einstein combined them with his criticism of the problem of ether. To be able to understand this, we must examine somewhat closer the problem of the relativity of motion.

The idea of the relativity of motion has a strangely compelling force, once it is well understood. Who is not familiar with the phenomenon commonly experienced in a railroad car: one's own train stands still, while a train on the next track starts moving—but the impression is opposite, that one's own train has started. Only after a while does one notice the illusion. But a thought may occur in connection with this experience: what right have I to call what I distinctly saw an illusion. Was it an illusion? Was it untrue? May I not contend with an equal right that the other train stood still while my train was moving? To be sure, I had not noticed at the time that the surroundings, e.g., the depot, remained standing still and that I, therefore, was motionless with regard to this environment. But what of it if I include this environment into my conception? May I not then declare that the other train stood still and that my train together with the depot, even the whole earth, was moving past it? May I not declare this with an equal right?

Once this idea is understood, it is impossible to get rid of it. It is easy to see that the large size of the depot, as opposed to that of the moving train, cannot serve as a disproof: the difference in size is quite irrelevant. If two bodies located in empty space, a large one and a small one, were to move toward each other, should one say that the large body is standing still while the small one is moving? This would make no sense. That motion cannot depend on size is clear from a situation in which the bodies are of equal size; here size certainly cannot determine which body is at rest.

The following consideration holds true. Suppose that body A is at rest and body B is moving toward it; the movement would be recognized by the diminution of the mutual distance. Let us then suppose that B is at rest while A is moving; again we notice only the diminution of the mutual distance. There is, therefore, no way of concluding from the observed phenomena as to which of the bodies is moving, insofar as the observed phenomena are the same in both instances. Hence it is nonsensical to speak of a "true" movement. One can only say that the bodies move toward each other; their movement is relative. This is consequently the answer toward which such a process of reasoning leads: there is no true movement,

no absolute movement, but only relative movement.

This idea has been repeatedly uttered. And it is interesting that it precipitated once before a quarrel over the relativity of movement, a quarrel which received then no less publicity than Einstein's theory in our days. It happened at the time of Newton and Leibniz; Newton's theory of absolute motion was combatted by Leibniz. The famous correspondence, in which these questions are discussed, has been preserved since those days. Leibniz defended in it the relativity of motion against the theologian Clarke, a friend of Newton, and offered for his views arguments which even today play a part in the discussion of relativity. He emphatically stated that all appearances are the same, regardless of whether one ascribes motion to one or the other of the two bodies. The problem, he added, is not different even in the case of one thousand bodies, and "the angels themselves" could not decide, on the basis of the observed phenomena, which body is really in motion. From Leibniz comes also the demonstration of the concept of relativity by means of the famous principle of the identity of indiscernibles; what is indiscernible is not different, and it is therefore meaningless to talk of absolute motion.

Nevertheless, the grounds cited by Newton in favor of absolute motion could not be weakened by Leibniz. Newton realized that all familiar proofs of the relativity of motion can be justified only kinematically, that is to say, insofar as motion is regarded as a change of place, as a visible phenomenon requiring no reasons. But the moment one starts looking for the active forces of motion the picture changes completely; and therefore, points out Newton, the relativity of motion is untenable dynamically, that is, from the standpoint of the theory of forces. To understand this we must give an outline of Newton's theory.

First of all, Newton differentiates between uniform and accelerated motion. A body left by itself in an empty space will not change its motion; it will move at an even speed and in a straight path. To the law of inertia, already established by Galileo, Newton added this thought: there is a force responsible for every change of motion: and conversely, the presence of forces indicates that the body is not in a uniform, but an accelerated motion.

The same reasoning applies, correspondingly, to a retarded motion. It has become therefore customary in science to regard the retarded motion as "negatively accelerated." This is merely a convenient method of expression, which no one need abhor. The circular or "rotary" motion is also considered as an accelerated motion; though its velocity may remain the same as to magnitude, it continuously changes its direction and consequently cannot be classified as a uniform motion.

The rotary motion offers an excellent illustration of Newton's idea of the absolute motion. Let us take an example. Imagine a merry-go-round surrounded by a round building similar to what we see at fairs. When we sit in it, we get fairly soon the impression that we stand still, together with the merry-go-round, while the building moves around us. If we forget for a moment what we saw before getting in, namely, that the building stands firmly on the ground and that the merry-go-round is equipped with wheels, have we any way of determining, while sitting in the merry-go-round, whether it is the building or the merry-go-round that moves?

Indeed, we have. For we feel, while sitting in the merry-go-round, an outward pull caused by the so-called centrifugal power. This power forces us against the railing. Were the merry-go-round to stand still and the building to move, then the sight for the eyes would be the same, but the push toward the railing, the centrifugal power, would not be there. A true state of rest can be recognized by the absence of the centrifugal power. Its appearance or disappearance plays a decisive role in the question of absolute motion.

This was Newton's idea explained by him in a similar example (that of a revolving pail). We can, he declared, determine even the direction of the rotation. Suppose there is another, smaller merry-go-round attached to the larger one approximately at its center, but revolving in the opposite direction. We climb now into the smaller merry-go-round and investigate: is the outward push (that is, the centrifugal power) stronger or weaker than in the larger one? If it is stronger, then the rotation of the smaller merry-go-round is faster than that of the larger one; and the direction of the rotation is the same. But if it is weaker, then the smaller merry-go-round rotates backward, in the opposite direction to that of the larger one.

We must admire the logical accuracy with which the great physicist constructed his doctrine of the absolute motion and of the absolute space. In the following lines we cite from his principal work the passages recapitulating his theory. He writes in *The Mathematical Principles of Natural Philosophy*:

"II. Absolute space, in its own nature, without regard to any thing external, remains always similar and immovable.

"Relative space is a measure of this space or a certain movable part of it, which is defined by our senses by its position with regard to bodies, and is usually taken for motionless space. . . .

"IV. Absolute motion is the translation of a body from one absolute place into another; and relative motion, the translation from one relative place into another. . . .

"And so, instead of absolute place and motion, we use relative ones . . . in philosophical discussion, we ought to abstract from our senses. . . For it may be that there is no body really at rest, to which the places and motions of others may be referred. . . .

"The effects which distinguish absolute from relative motion purely relative, but in a true and absolute motion lar motions. For there are no such forces in a circular motion purely relative, but in a true and absolute motion

they are greater or less according to the quantity of the motion."

The words with which he closes the introduction to his main work show how sure Newton felt of his affirmation of absolute motion, namely:

"How we are to obtain the true motions from their causes, effects, and apparent differences, and the converse, namely, to derive the causes and effects from the true or apparent motions, shall be explained more at large in the following treatise. For to this end it was that I composed it."

These words of Newton demonstrate sharply the contrast which may exist between the objective importance of a discovery and the subjective significance attributed to it by its author. Whereas the physical work of Newtonian dynamics has become a firmly established part of science—merely raised by its later development to a higher form of knowledge, but otherwise remaining, as an approximation, permanently valid—Newton's philosophical interpretation of his work has been of a restricted duration. Nevertheless, a consistent development of the theory of absoluteness has contributed to the deeper insights of today; for only the compulsion to refute Newton's arguments could lead to the final clarification of the idea of general relativity, which was to be extended from relativistic kinematics to relativistic dynamics.

Almost 200 years had to pass before a real refutation of Newton's thought was found. In the eighties of the last century, Ernst Mach, in criticizing Newton's work, found the counter-argument. If we return to our example of a merry-go-round, this was Mach's idea: Newton has overlooked that the case of the merry-go-round at rest and of the building in rotation does not represent the opposite of the original case. He has forgotten to take into consideration the surroundings of the building, the earth, the whole universe. For, in revolving, the merry-go-round does not revolve with regard to the building alone but also with regard to the earth. In the contrary case we must let not only the building revolve round the resting merry-go-round, but also the earth and the universe—only then shall we present an equivalent but reverse picture.

But in that case, continued Mach, the centrifugal force will appear again in the merry-go-round; for this case is no other than the original one, though presenting a kinematically different description. In this description, the centrifugal force should be understood as an effect of the revolving earth-mass or even of the star-mass. These moving masses produce a pulling field experienced by me within the merry-go-round. In a quite surprising way, the concept of force becomes thus involved in the reversion leading to the two equivalent interpretations. The same observable effect, namely, the pressure against the railing, appears in one conception as a consequence of the merry-go-round's movement, in the other, as a consequence of the rotation of the surrounding masses. That rotating masses should form such a field of radially divergent forces, is for the science of physics a new but not an

unusual thought. According to this conception, the Newtonian attraction of masses would be supplemented by the new forces arising out of rotary movement. One could imagine (according to Mach) that the walls of the building are several miles thick; then, in rotating around the merry-go-round, the mass of the walls would produce in the middle of the merry-go-round a field of radially divergent forces, corresponding to the centrifugal field. This field, of course, would be by far inferior in strength to that produced by the rotating universe.

Could this be demonstrated experimentally? But, remarks Mach, the proof is already available. For we do observe the centrifugal force; if we interpret it as an effect of the revolving masses of stars, then this is all that can be asked for from observation. The new conception differs from the old one only in the interpretation, not in what can be observed by the senses. Nevertheless, it may be possible to devise experiments in which the idea of Mach would lead to new observations. Imagine a rotating fly-wheel of a huge machine; it represents a rotating mass and should exercise in its interior a propelling action creating near its axis an area of "centrifugal force." Mach did not, of course, mean here the action of the wheel's own centrifugal force, from whose explosive effect the wheel is protected only by its solidity; rather, he wanted to say that a small body at rest, if placed near the axis, would be subjected to a pull toward the edge of the wheel. This action is, to be sure, so minute that it cannot be demonstrated; the mass of the largest fly-wheel is, indeed, exceedingly small in comparison to that of the universe or of the fixed stars the rotation of which produces the ordinary centrifugal force.

But even more important than this physical consequence is the relativization of the concept of force, as expressed by Mach. For, what Mach says is that in accordance with varying descriptions of the state of motion, the field of forces, too, must be presented in a different fashion. No sooner does the concept of force partake of relativity than the dynamic distinction of one state of motion disappears; and then there is no absolute motion in any sense.

Here lies the weight of the argument. The relativity of motion is tenable not only kinematically but also dynamically, if the relativization of the concept of force is introduced. Even forces are not absolute quantities; they depend upon the system of reference. When one passes to a differently moving system, the forces have to be measured differently. What appears as action of inertia when the merry-go-round is conceived as moving, appears as action of gravitation, when it is imagined as standing still and the earth as rotating. Even the Copernican world-view appears to be shaken by this consideration. It makes no sense, accordingly, to speak of a difference in truth between Copernicus and Ptolemy: both conceptions are equally permissible descriptions. What has been considered as the greatest discovery of occidental wisdom, as opposed to that of antiquity, is questioned as to its truth-value. Though this fact clearly warns us to be wary

in the formulation and evaluation of scientific results, nevertheless it by no means signifies a step backward in the progress of history. The doctrine of relativity does not assert that Ptolemy's view is correct; it rather contests the absolute meaning of either view. This new insight could be gained only because the historical development went through both conceptions, because the replacement of the Ptolemaic world-view by the Copernican world-view established the new mechanics which finally provided the physicist with a means of recognizing the one-sidedness of the Copernican world-view itself. The road to truth followed here the three dialectical steps which Hegel regarded as necessary for all historical development, the steps leading from a thesis over an antithesis to a higher synthesis.

It would be saying too much to regard the fulfillment of the third stage as given in Mach's idea. When Mach replied to Newton that the centrifugal force must be accounted for in terms of the relative motion alone, he offered merely a program, not a physical theory; in fact, it was merely a beginning of a program for the physical theory elaborating the idea. Indeed, not only the centrifugal force but all mechanical phenomena must be accounted for in terms of the relative motion; the question is, above all, how to explain relativistically the phenomena of motion in the field of gravitation, i.e., the planets' movements.

It was the great achievement of Newtonian mechanics that it provided the Copernican world-view with a dynamic foundation. Whereas there existed no difference from the kinematic standpoint, between the Copernican and the Ptolemaic systems Newton, taking the standpoint of dynamics decided in favor of Copernicus. For his theory of gravitational force offered to the latter view a mechanical explanation; whereas the complicated planetary orbits of Ptolemy did not fit into any explanation. If the question is how to provide both conceptions of the universe with an equal justification in terms of dynamics, then a general theory of gravitation has to be found, which explains the Ptolemaic as well as the Copernican planetary motion as a phenomenon of gravitation. Here lies the great mathematico-physical achievement of Einstein, in comparison to which Mach's thought appears merely as a first suggestion. Einstein has indeed found a comprehensive theory of gravitation, and only because of this discovery, which places his name in the same category with Copernicus and Newton, can we say that the problem of the relativity of motion has been brought, physically, to its conclusion.