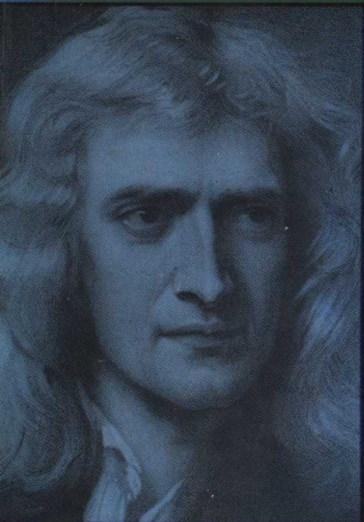

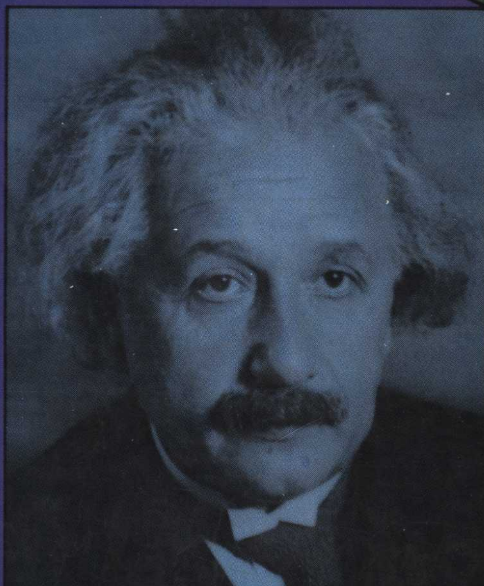

A. d'ABRO

THE EVOLUTION OF SCIENTIFIC THOUGHT

FROM NEWTON TO EINSTEIN

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This history first sketches the essential features of Newton's great discoveries, and the apparent inevitableness of absolute space and time in classical science; then Riemann's non-euclidean geometry is discussed, and finally the way in which Einstein transported his ideas into the realm of physics, giving us thereby that supreme achievement of modern thought, the theory of relativity. Although non-technical language is used throughout, great care is given to an accurate presentation of facts.

Part I is devoted to pre-relativity physics and the reasons for its breakdown. The remainder of the book discusses Einstein's special and general theories of relativity, which rescued physics from the contradictions of classical Newtonian theory. Throughout, d'Abro touches on the contributions of Riemann, Weyl, Lorentz, Planck, Eddington, Maxwell, Hertz, and many others to modern relativity physics. He closes with a philosophical discussion of the methodology of science and of the general significance of the theory of relativity.

Revised, corrected 2nd (1950) edition. Author's prefaces and foreword. Appendix: The Space and Time Graphs. 15 portraits of celebrated physicists. 21 diagrams. 481pp. 5⅜ x 8. 20002-7 Paperbound

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PREFACE

TO THE FIRST EDITION

ALTHOUGH in the course of the last three centuries scientific theories have been subject to all manner of vicissitude and change, the governing motive that has inspired scientists has been ever the same—a search for unity in diversity, a desire to bring harmony and order into what might at first sight appear to be a hopeless chaos of experimental facts.

In this book the essential features of Newton's great discoveries, the apparent inevitableness of absolute space and time in classical science, are passed in review. Then we come to Riemann, that great mathematician who wrested the problem of space from the dogmatic slumber where it had rested so long. Finally we see how Einstein succeeded in transporting to the realm of physics the ideas that Riemann had propounded, giving us thereby that supreme achievement of modern thought, the theory of relativity.

Although I have used non-technical language, great care has been given to an accurate presentation of facts. In certain parts, however, notably in those devoted to non-Euclidean geometry and to the principle of Action, a looseness of presentation has appeared unavoidable owing to the extreme technicality of the subjects discussed. But as it was a question of presenting these subjects loosely or leaving them out of the picture entirely, it appeared preferable to sacrifice accuracy to general comprehensiveness.

Here, however, the reader may be reminded that even for those who are interested solely in trends of thought or in the evolution of ideas, no popular or semi-popular book can ever aspire to take the place of the highly technical mathematical works. The superiority of the latter lies not in the bare mathematical formulæ which they contain. Rather does it reside in the power the mathematical instrument has of giving us a deeper insight into the problems of nature, revealing unsuspected harmonies and extending our survey into regions of thought whence the human intelligence would otherwise be excluded. Thus the sole rôle a semi-popular book can hope to perform is to serve as a general introduction, to whet the appetite for further knowledge, if a craving for knowledge is within us. To presume, as the philosophers do, that a vague understanding of a highly technical subject, gleaned from semi-popular writings, or from the snatching at a sentence here and there in a technical book, should enable them to expound a theory, criticise it, and, worse still, ornament it with their own ideas, is an opinion which has done much to create a spirit of distrust towards their writings. The answer Euclid gave to King Ptolemy, "There is no royal road, no short cut to knowledge," remains true to-day, still truer than in the days of ancient Alexandria, when science had not yet grown to the proportions of a mighty tree.

I wish to take this opportunity to express my gratitude to Prof. Leigh Page of Yale University for his kindness in looking over the manuscript and offering many valuable suggestions.

A. D' ABRO

NEW YORK, 1927.

TO THE SECOND EDITION

SLIPS and errors that were present in the first edition have been corrected in the present edition, and some unnecessary repetitions have been eliminated. The chapter on the finiteness of the Universe has been re-written entirely, and has been supplemented by a brief discussion of the Expanding Universe of the Abbé Lemaitre.

A. D' ABRO

New York, 1949.

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FOREWORD

"And now, in our time, there has been unloosed a cataclysm which has swept away space, time and matter, hitherto regarded as the firmest pillars of natural science, but only to make place for a view of things of wider scope, and entailing a deeper vision."

H. WEYL ("Space, Time and Matter").

THE theory of relativity represents the greatest advance in our understanding of nature that philosophy has yet witnessed.

If our interest is purely philosophical, we may wish to be informed briefly of the nature of Einstein's conclusions so as to examine their bearing on the prevalent philosophical ideas of our time. Unfortunately for this simplified method of approach, it is scarcely feasible. The conclusions themselves involve highly technical notions and, if explained in a loose, unscientific way, are likely to convey a totally wrong impression. But even assuming that this first difficulty could be overcome, we should find that Einstein's conclusions were of so revolutionary a nature, entailing the abandonment of our ideas on space, time and matter, that their acceptance might constitute too great a strain on our credulity. Either we would reject the theory altogether as a gigantic hoax, or else we should have to accept it on authority, and in this case conceive it in a very vague and obscure way.

From a perusal of the numerous books that have been written on the subject by a number of contemporary philosophers, the writer is firmly convinced that the only way to approach the theory, even if our interest be purely philosophical, is to study the scientific problem from the beginning. And by the beginning we refer not to Einstein's initial paper published in 1905; we must go back much farther, to the days of Maxwell and even of Newton. Here we may mention that however revolutionary the theory of relativity may appear in its philosophical implications, it is a direct product of the scientific method, conducted in the same spirit as that which inspired Newton and Maxwell; no new metaphysics is involved. Indeed Einstein's theory constitutes but a refinement of classical science; it could never have arisen in the absence of that vast accumulation of mathematical and physical knowledge which had been gathered more especially since the days of Galileo. Under the circumstances it is quite impossible to gain a correct impression of the disclosures of relativity unless we first acquaint ourselves with the discoveries of classical science prior to Einstein's time. It will therefore be the aim of this book, before discussing Einstein's theory proper, to set forth as simply as possible this necessary preliminary information.

Modern science, exclusive of geometry, is a comparatively recent creation and can be said to have originated with Galileo and Newton. Galileo was the first scientist to recognise clearly that the only way to further our understanding of the physical world was to resort to experiment. However obvious Galileo's contention may appear in the light of our present knowledge, it remains a fact that the Greeks, in spite of their proficiency in geometry, never seem to have realised the importance of experiment (Democritus and Archimedes excepted).

To a certain extent this may be attributed to the crudeness of their instruments of measurement. Still, an excuse of this sort can scarcely be put forward when the elementary nature of Galileo's experiments and observations is recalled. Watching a lamp oscillate in the cathedral of Pisa, dropping bodies from the leaning tower of Pisa, rolling balls down inclined planes, noticing the magnifying effect of water in a spherical glass vase, such was the nature of Galileo's experiments and observations. As can be seen, they might just as well have been performed by the Greeks. At any rate, it was thanks to such experiments that Galileo discovered the fundamental law of dynamics, according to which the acceleration imparted to a body is proportional to the force acting upon it.

The next advance was due to Newton, the greatest scientist of all time if account be taken of his joint contributions to mathematics and physics. As a physicist, he was of course an ardent adherent of the empirical method, but his greatest title to fame lies in another direction. Prior to Newton, mathematics, chiefly in the form of geometry, had been studied as a fine art without any view to its physical applications other than in very trivial cases.* But with Newton all the resources of mathematics were turned to advantage in the solution of physical problems. Thenceforth mathematics appeared as an instrument of discovery, the most powerful one known to man, multiplying the power of thought just as in the mechanical domain the lever multiplied our physical action. It is this application of mathematics to the solution of physical problems, this combination of two separate fields of investigation, which constitutes the essential characteristic of the Newtonian method. Thus problems of physics were metamorphosed into problems of mathematics.

But in Newton's day the mathematical instrument was still in a very backward state of development. In this field again Newton showed the mark of genius, by inventing the integral calculus. As a result of this remarkable discovery, problems which would have baffled Archimedes were solved with ease. We know that in Newton's hands this new departure in scientific method led to the discovery of the law of gravitation. But here again the real significance of Newton's achievement lay not so much in the exact quantitative formulation of the law of attraction, as in his having established the presence of law and order at least in one important realm of nature, namely, in the motions of heavenly bodies. Nature

* As exemplified in the Pythagorean discovery of the relationship between the length of a vibrating string and the pitch of its note, a discovery utilised in musical instruments. Another example is represented by Archimedes' solution of the problem of Hieron's gold tiara.

thus exhibited rationality and was not mere blind chaos and uncertainty. To be sure, Newton's investigations had been concerned with but a small group of natural phenomena (planetary motions and falling bodies), but it appeared unlikely that this mathematical law and order should turn out to be restricted to certain special phenomena; and the feeling was general that all the physical processes of nature would prove to be unfolding themselves according to rigorous mathematical laws.

It would be impossible to exaggerate the importance of Newton's discoveries and the influence they exerted on the thinkers of the eighteenth century. The proud boast of Archimedes was heard again—"Give me a lever and a resting place, and I will lift the earth."—But the boast of Newton's successors was far greater—"Give us a knowledge of the laws of nature, and both future and past will reveal their secrets."

To-day these hopes appear somewhat childish, but this is because we have learnt more of nature than was ever dreamt of by Newton's contemporaries. Nevertheless, although we recognise that we can never be demigods, the mathematical instrument in conjunction with the experimental method, still constitutes our most fruitful means of progress.

Now Newton, in his application of mathematics to the problems of physics, had been concerned only with the very simplest of physical problems—planetary motions, mechanics, propagation of sound, etc. But when it came to applying the mathematical method to the more intricate physical problems, a considerable advance was necessary in our scientific knowledge, both mathematical and empirical. Thanks to the gradual accumulation of physical data, and thanks to the efforts of Newton's great successors in the field of pure mathematics (Euler, Lagrange, Laplace), conditions were ripe in the first half of the nineteenth century for a systematic mathematical attack on many of nature's secrets.

The mathematical theories constructed were known under the general name of *theories of mathematical physics*. In so far as they represented a mere application of mathematics to natural phenomena, they had their prototype in Newton's celestial mechanics. The only difference was that they dealt with a wide variety of physical phenomena (electric, hydrostatic, etc.), no longer with those of a purely mechanical nature. The most celebrated of these theories (such as those of Maxwell, Boltzmann, Lorentz and Planck) were concerned with very special classes of phenomena. But with Einstein's theory of relativity, itself a development of mathematical physics, the scope of our investigations is so widened that we are appreciably nearer than ever before to the ideal of a single mathematical theory embracing all physical knowledge. This fact in itself shows us the tremendous philosophical interest of the theory of relativity.

Now in all these theories of mathematical physics, the same type of procedure is invariably followed. Experimenters establish certain definite facts and detect precise numerical relationships between magnitudes, for example, between the intensity of an electric current flowing along a wire and the intensity and orientation of the magnetic field surrounding the wire. The mathematical physicist then enters upon the scene, assigns certain letters of the alphabet to the physical entities involved (in the present case electric current designated by i and magnetic intensity designated by H) and by this means translates the numerical relationships discovered by the experimenter into mathematical form. He thus obtains a mathematical relationship or equation α which is assumed to constitute the mathematical image of the concrete physical phenomenon A. His task will now be to extract from his mathematical equation or equations α all their necessary mathematical consequences. In this way, provided his technique does not fail him, he may be led to new equations β. These new equations β, when translated back from the mathematical to the physical, will express new physical relationships B.

The mathematician assumes that just as his equations β were the necessary mathematical consequences of his original equations α, so also must the physical translation of β constitute a physical phenomenon B, which follows as a necessary consequence of the existence of the physical phenomenon A. If A occurs, B must ensue.

We thus understand the significance of a theory of mathematical physics. Its utility is to allow us to foresee and to foretell physical phenomena. In this way it suggests definite experiments which might never have been thought of, and permits us to anticipate new relationships and new laws and to discover new facts. From a philosophical point of view, by establishing a rational connection between seemingly unconnected phenomena, it enables us to detect the harmony and unity of nature which lie concealed under an outward appearance of chaos.

Of course the experimenter in the first place must be very careful to give accurate information to the mathematician; for if by any chance his information should be only approximately correct, the mathematical translation α would likewise be lacking in accuracy, and the mathematical consequences of α might be still further at variance with the world of physical reality. It is as though, when firing at a distant target, we were to point the rifle a wee bit too far to one side; the greater the range, the wider would be the divergence. Dangers of this sort are of course inevitable, for human observations are necessarily imperfect. In any case, therefore, the mathematician's physical anticipations will always require careful checking up by subsequent experiment. Obviously, however, something much deeper is at stake than mere accuracy of observation.

Mathematical deductions are mind-born; they pertain to reason and are not dependent on experience. When, therefore, we assume that our mathematical deductions and operations will be successful in portraying the workings of nature, we are assuming that nature also is rational, and that therefore a definite parallelism or correspondence exists between the two worlds, the mathematical and the physical. *A priori*, there appears to be no logical necessity why any such parallelism should exist. Here, however, we are faced with a situation over which it is useless to philosophise. Success has attended the efforts of mathematical physicists in so large a number of cases that, however marvellous it may appear, we can scarcely escape the conclusion that nature must be rational and susceptible to mathematical law. In fact, were this not the case, prevision would be impossible and science non-existent.

It may be that nature is only approximately rational; it may be that her appearance of rationality is due to the very crudeness of our observations and that more refined experiments would yield a very different picture. Heisenberg and Bohr have suggested that the difficulties which confront us in the study of quantum phenomena may indeed be due to the fact that nature is found to be irrational when we seek to examine her processes in a microscopic way. This is a possibility which we cannot afford to reject. But at any rate, as long as our theories appear to be verified by experiment, we must proceed as though nature were rational, and hope for the best.

Now it must not be thought that the introduction of the mathematical instrument into our study of nature creates any essential departure from the commonplace method of ordinary deductive and inductive reasoning. There is no particular mystery about mathematical analysis; its only distinguishing feature is that it is more trustworthy, more precise, and permits us to proceed farther and along safer lines.

Consider, for example, the well-known change of colour from red to white displayed by the light radiated through an aperture made in a heated enclosure, as the temperature increases. From this elementary fact of observation Planck, thanks to mathematical analysis, was able to deduce the existence of light quanta and thence the possibility that all processes of change were discontinuous, and that a body could only rotate with definite speeds. Obviously, commonplace reasoning unaided by mathematics would never have led us even to suspect these extraordinary results.

Now when we say that a theory of mathematical physics is correct, all we mean is that the various mathematical consequences we can extract from its equations call for the existence of physical phenomena which experiment has succeeded in verifying. On the other hand, if our mathematical anticipations do not tally with experimental verification, we must recognise that our theory is incorrect. This does not mean that it is incorrect from a purely mathematical point of view, for in any case it exemplifies a possible rational world; but it is incorrect in that it does not exemplify our real world. We must then assume that our initial equations were in all probability bad translations of the physical phenomena they were supposed to represent.

In a number of cases, however, it has been found unnecessary to abandon a theory merely because one of its anticipations happened to be refuted by experiment. Instead, it is often possible to assume that the discrepancy between the mathematical anticipation and the physical result may be due to some contingent physical influence, which, owing to the incompleteness of the physical data furnished us by the experimenters, our equations have failed to take into consideration. A case in point is afforded by the discovery of Neptune.

The Newtonian mathematical treatment of planetary motions assigned a definite motion to the planet Uranus. Astronomical observation then proved that the actual motion of Uranus did not tally with these mathematical anticipations. Yet it was not deemed necessary to abandon Newton's law; Adams and Leverrier suggested the possibility that an unknown planet lying beyond the orbit of Uranus might be responsible for the deviations in Uranus' motion. Taking the existence of this unknown planet into consideration in his mathematical calculations, Leverrier succeeded in determining the exact position which it would have to occupy in the heavens at an assigned date. As is well known, at the precise spot calculated, the elusive planet (presently named Neptune) was discovered with a powerful telescope.

This procedure of ascribing discrepancies in our mathematical anticipations to the presence of contingent influences rather than to the falsity of our theory is only human. There is no inclination, merely because the hundredth case turns out to be an exception, to abandon a theory which has led to accurate anticipations in 99 cases out of 100. But we must realise that this procedure of appealing to foreign influences, while perfectly legitimate in a tentative way, must be applied with a certain amount of caution; in every particular case it must be justified by *a posteriori* determination of fact. Thus Leverrier was also the first to discover certain irregularities in the motion of the planet Mercury. As in the case of Uranus, he attempted to ascribe these discrepancies to the presence of an interior planet which he called Vulcan and which he assumed to be moving between the orbit of Mercury and the sun. Astronomers have, however, failed to find the slightest trace of Vulcan, and a belief in its existence has been abandoned. If contingent influences are to be invoked for Mercury's anomalies, we must search for them in some other direction.

In this particular case all other suggestions were equally unsatisfactory. Hence even before the advent of Einstein's theory, doubts had been raised as to the accuracy of Newton's law of gravitation. The procedure of patching up a mistaken theoretical anticipation with hypotheses *ad hoc* has not much to commend it. Yet when, as was the case with Vulcan and Neptune, the influence we appeal to is of a category susceptible of being observed directly, the method is legitimate. But when our hypothesis *ad hoc* transcends observation by its very nature, and when, added to this, its utility is merely local, accounting for one definite fact and for no other, it becomes worse than useless.

This abhorrence of science for the unverifiable type of hypothesis *ad hoc* so frequently encountered in the speculations of the metaphysicians is not due to a mere phenomenalistic desire to eliminate all that cannot be seen or sensed. It arises from a deeper motive entailing the entire *raison d'être* of a scientific theory. Suppose, for instance, that our theory had led us to anticipate a certain result, and that experiment or observation should prove that in reality a different result was realised. We could always adjust matters by arbitrarily postulating some local invisible and unverifiable influence, which we might ascribe to the presence of a mysterious medium—say, the ether *A*. We should thus have added a new influence to our scheme of nature.

If we should now take this new influence into consideration, the first numerical result would, of course, be explained automatically, since our ether *A* was devised with this express purpose in view. But we should now be led to anticipate a different numerical result for some other phenomenon. If this second anticipation were to be disproved by experiment we could invoke some second unverifiable disturbing influence to account for the discrepancy, while leaving the first result unchanged. Let us call this new influence the ether *B*. We might go on in this way indefinitely.

But it is obvious that our theory of mathematical physics whose object it was to allow us to foresee and to foretell would now be useless. No new phenomenon could be anticipated, since past experience would have shown us that unforeseen influences must constantly be called into play if theory were to be verified by experiment. Under these circumstances we might just as well abandon all attempts to construct a mathematical model of the universe.

Suppose now that by modifying once and for all our initial premises we are led to a theory which allows us to foresee and foretell numerical results that are invariably verified with the utmost precision by experiment, without our having to call to our assistance a number of foreign hypotheses. In this case we may assume that the new theory is correct, since it is fruitful; and that our former theory was incorrect, because it led us nowhere.

The considerations we have outlined have an important bearing on the understanding of the outside world as shared by the vast majority of scientists. If we hold that the simplest of all the mathematical theories which finds itself in accord with experiment constitutes the correct theory, giving us the correct representation of the real world, we shall recognise that it would be a dangerous procedure to saddle ourselves with a number of hypothetical presuppositions at too early a stage of our investigations. To be sure, we may have to make a certain number of fundamental assumptions, but we must regard these as mere working hypotheses which may have to be abandoned at a later stage if peradventure they lead to too complicated a synthesis of the facts of experiment. We shall see, for instance, that relativity compels us to abandon our traditional understanding of space and time. It is this fact more than any other which has been responsible for the cool reception accorded to the theory by many thinkers. When, however, we become convinced that Einstein's synthesis is the simplest that can be constructed if due account be taken of the results of ultra-refined experiment, and when we realise that a synthesis based on the classical understanding of separate space and time would be possible only provided we were willing to introduce a host of entirely disconnected hypotheses *ad hoc* which would offer no means of direct verification, we cannot easily contest the soundness of Einstein's conclusions.

There are some, however, who argue that we have an *a priori* intuitional understanding of space and time which is fundamental, and that we should sacrifice simplicity of mathematical co-ordination if it conflicts with these fundamental intuitional notions. Needless to say, no scientist could subscribe to such views. Quite independently of Einstein's discoveries, mathematicians had exploded these Kantian opinions on space and time many years ago. As Einstein very aptly remarks in his Princeton lectures:

"The only justification for our concepts and system of concepts is that they serve to represent the complex of our experiences; beyond this they have no legitimacy. I am convinced that the philosophers have had a harmful effect upon the progress of scientific thinking in removing certain fundamental concepts from the domain of empiricism where they are under our control to the intangible heights of the *a priori*. For even if it should appear that the universe of ideas cannot be deduced from experience by logical means but is in a sense a creation of the human mind without which no science is possible, nevertheless this universe of ideas is just as little independent of the nature of our experiences as clothes are of the form of the human body. This is particularly true of our concepts of time and space which physicists have been obliged by the facts to bring down from the Olympus of the *a priori* in order to adjust them and put them in a serviceable condition."

In the passage just quoted, Einstein argues from the standpoint of the physicist, but the opinions he expresses will certainly be endorsed by pure mathematicians. They, more than all others, have been led to realise how cautious we must be of the dictates of intuition and so-called common sense. They know that the fact that we can conceive or imagine a certain thing only in a certain way is no criterion of the correctness of our judgment. Examples in mathematics abound. For example, before the discoveries of Weierstrass, Riemann and Darboux the idea that a continuous curve might fail to have a definite slant at every point was considered absurd; and yet we know to-day that the vast majority of curves are of this type. In the same way our intuition would tell us that a line, whether curved or straight, being without width, would be quite unable to cover an area completely; yet once again, as Peano and others have shown, our intuition would have misled us. Many other examples might be given, but they are of too technical a nature and need not detain us. At all events, mathematicians, as a whole, refused to question the soundness of Einstein's theory on the sole plea that it conflicted with our traditional intuitional concepts of space and time, and we need not be surprised to find Poincaré, one of the greatest mathematicians of the nineteenth century, lending full support to Einstein when the theory was so bitterly assailed in its earlier days.

We have now to consider in a very brief way certain of the philosophical problems which antedate Einstein's discoveries, but with which his theory is intimately connected. Long before the advent of Einstein, problems pertaining to the relativity of motion through empty space had occupied the attention of students of nature. There were some who held that empty space, and with it all motion, must be relative; that states of absolute motion or absolute rest through empty space were meaningless concepts. According to these thinkers, in order to give significance to motion and rest, it was necessary to refer the successive positions of the body to some other arbitrarily selected body taken as a system of reference. We should thus obtain relative rest or motion of matter, with respect to matter. All these views were in full accord with our visual perceptions and they were expressed by what is known as the **visual or kinematic principle of the relativity of motion.** Other thinkers preferred to uphold the opposing philosophy. They assumed that space was absolute; that all motion must be absolute; that there was meaning to the statement that a body was in motion or at rest in space, regardless of the presence of other bodies to be used as terms of comparison. The controversy might have continued indefinitely, had it not been for the appearance of the scientist with his empirical methods of investigation.

Galileo and Newton were the first to recognise in a clear way that, provided certain very plausible assumptions were made, the dynamical evidence adduced from mechanical experiments proved the relativistic philosophy to be untenable. Classical science was therefore compelled to recognise the absoluteness of space and motion. It is true that many philosophers still defended the relativity of all motion. But their failure to take into consideration the real obstacles that seemed to bar the way to a relativistic conception of motion, coupled with the looseness of their scientific arguments, precluded their opinions from exercising any influence on scientific thought. Now it is to be noted that notwithstanding the absolute nature which Newton attributed to all states of motion and of rest in empty space, a certain type of absolute motion called Galilean * or again uniform translationary motion (defined by an absolute velocity but no absolute acceleration), was recognised by him as being incapable of detection, so far as experiments of a mechanical nature were concerned. This complete irrelevancy of absolute velocity or absolute Galilean motion to mechanical experiments was expressed in what is known as the **Galilean or Newtonian or classical or dynamical principle of the relativity of Galilean motion** through empty space. The existence of such a principle of relativity created a duality in the physical significance of motion, hence of space, but the philosophical importance of the principle, as referring to the problem of space, was lessened by the fact that this relativity applied solely to experiments of a mechanical nature. It was confidently assumed that electromagnetic and optical experiments would be successful in revealing the absolute Galilean motions which had eluded mechanical tests.

Such was the state of affairs when Einstein, in 1905, published his celebrated paper on the electrodynamics of moving bodies. In this he remarked that the numerous difficulties which surrounded the equations

* The appellation *Galilean motion* does not appear to have been adopted generally. However, as it is shorter to designate "uniform translationary motion" under this name, we shall adhere to the appellation.