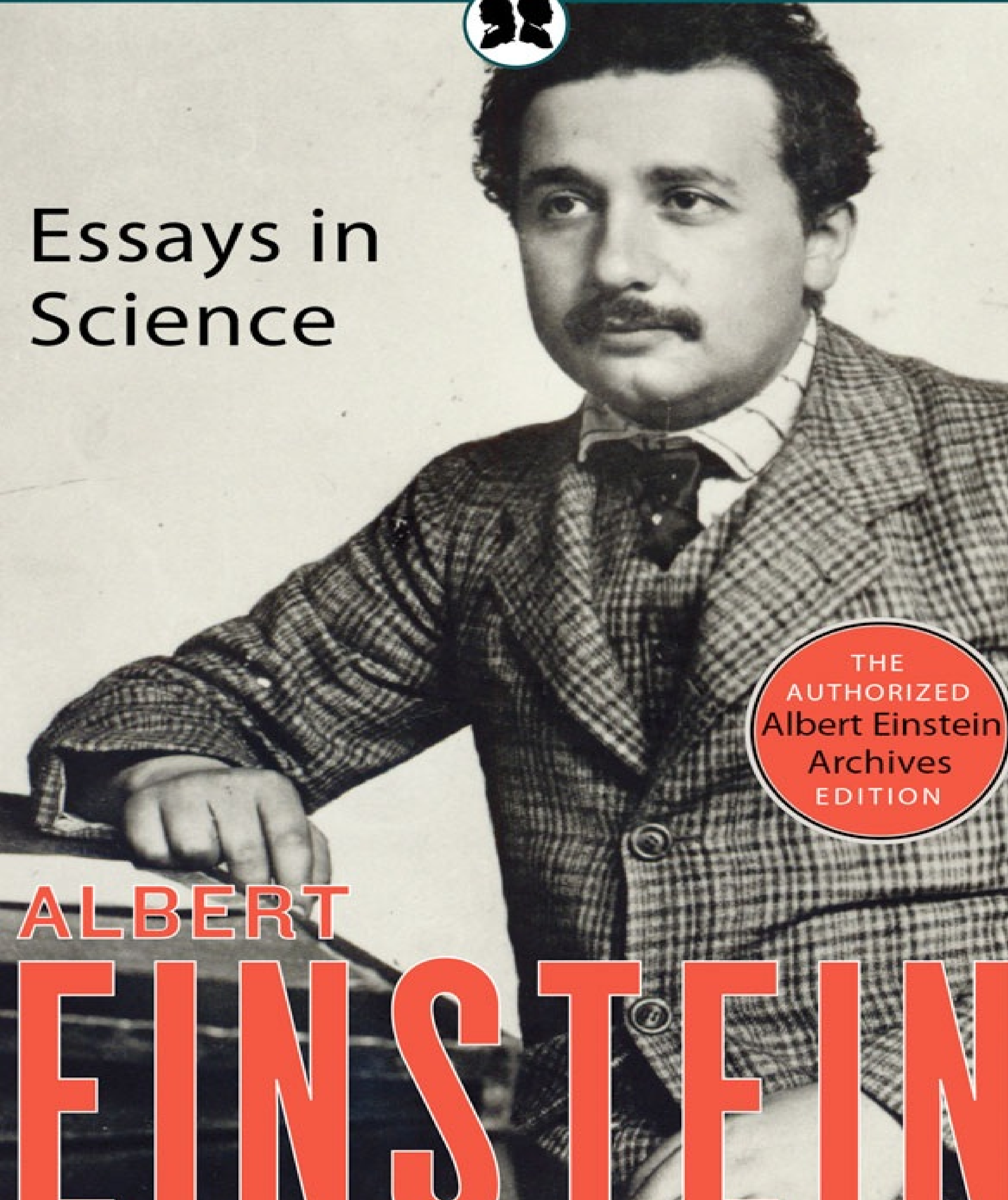
Essays in
Science
THE
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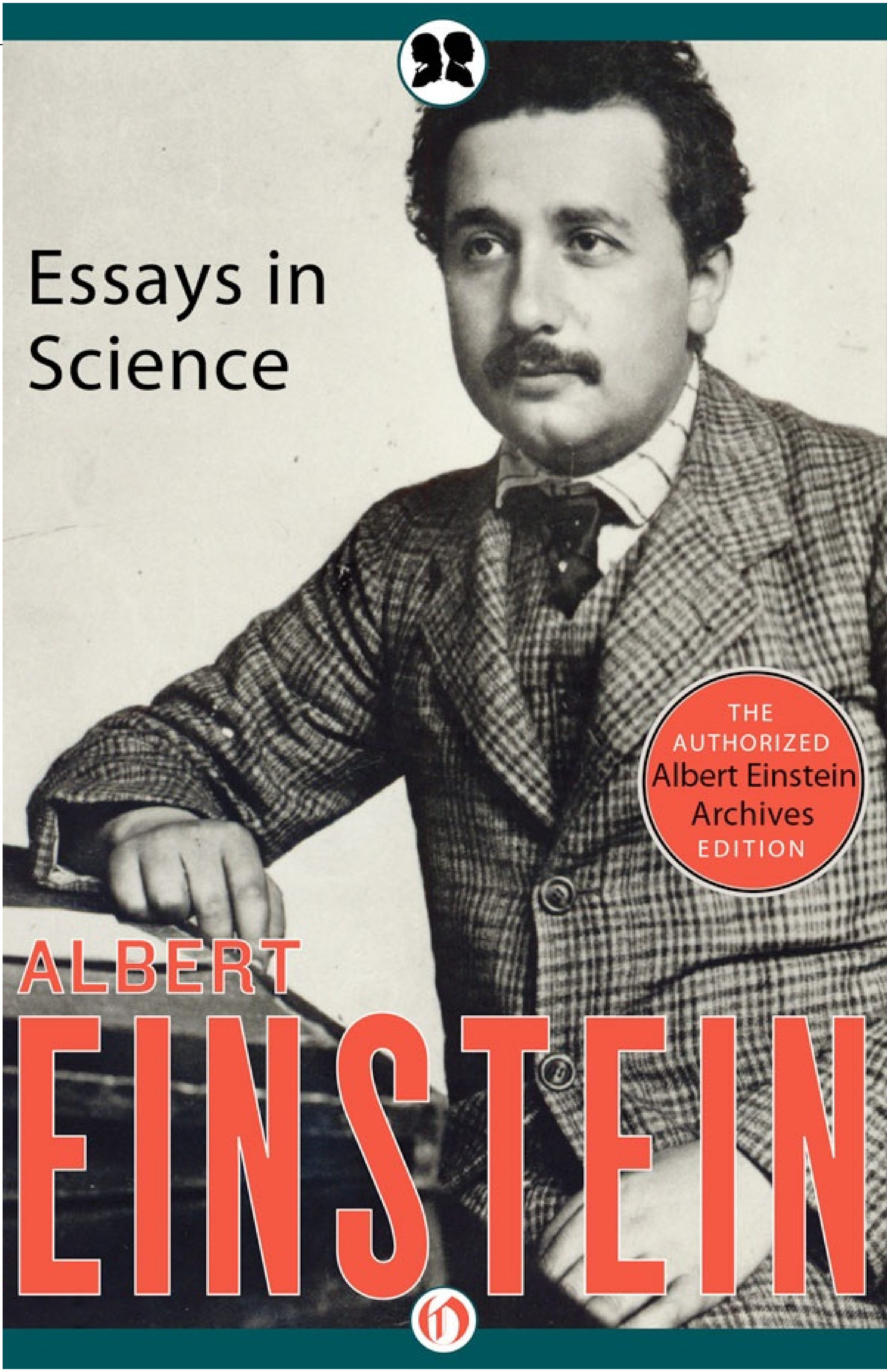
Albert Einstein
Archives
EDITION
ALBERT
EINSTEIN


Essays in Science
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Essays in Science

Albert Einstein

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Preface to the New Edition

ALBERT EINSTEIN WAS THE greatest physicist of the twentieth century. His image and name a recognizable to almost everyone, along with his equation $E=mc^2$, which describes the relationsh between energy and mass. His impact on science and intellectual thought during his lifetime w profound.

This volume contains a collection of sixteen essays written before 1935, when Einstein was at th height of his scientific powers but not yet known as the sage of the atomic age. His stature in th world allowed him to express his views on philosophical issues relating to the field of physics. The essays established his early foray into this area.

Why are we so interested in all aspects of Einstein’s philosophical positions and his thoug processes? His theories of relativity and universal gravitation are generally regarded as inaccessible the ordinary person. Yet we know that he was an original thinker who was able to see beyond th conventional scientific worldview of his age. What is remarkable is that Einstein’s greate discoveries belong to him alone. It is perhaps fitting that this volume is being published one hundre years after Einstein settled the question of why the sky is blue. What we see is a giant intelle struggling as an ordinary person to make sense of the realities of life in the twentieth century.

This volume concentrates on the essays on science that Albert Einstein included in the fir authorized edition of *Mein Weltbild*. These essays had an amazing breadth and made man fundamental points about the nature of the universe. The central theme answered the question of ho Einstein came to his theories. He believed that the only source of knowledge was experience, and th in the case of general relativity such experience did not always suggest the scientific truth of a theor The development of a theory depended on “only intuition resting on a sympathetic understanding experience.” It was the “object of all theory to make the irreducible elements as simple and few number as possible.” He was “convinced that we can discover by purely mathematical constructio […] the key to the understanding of natural phenomena.” Experience suggests, the mind construc (with the help of mathematics), and experience confirms.

Einstein bolstered his argument by tracing the development of various universal theories of scien and the advances that these theories brought to our ability to understand the world. Euclid’s geomet gave “the human intellect the confidence in itself for subsequent achievements.” “Purely logic thinking [such as Euclid] cannot yield us any knowledge of the empirical world.” Galileo and Kepl showed that “all knowledge of reality starts from experience and ends in it.” And Newton “sti believed that the basic laws of his system could be derived from experience.”

Further, in his essay *On Scientific Truth*, the idea of a superior mind as conceived in Spinoza “pantheistic” religion revealing itself in the world of experience represented Einstein’s conception God.

Spinoza’s metaphysics created a world view which was in conflict with the idea of an eve expanding universe as predicted by an early version of the generalized relativity theory. By 191 Einstein had amended his general theory of relativity to include a cosmological term so that th universe would be spatially self-enclosed as outlined in *On the Theory of Relativity*. In 1929, Edw Hubble verified by astronomical observations that the universe was expanding and consequently the was at some time a “big bang.” Had Einstein not added the cosmological term and accepted his ear version of the generalized relativity theory the expanding universe would perhaps have been h greatest predication.

With the advent of Maxwell, Faraday, Hertz, and Lorentz there was a shift from description o ~~material points to electro-magnetic fields, which became the ultimate entity. According to Einste~~ the development of field theory led directly to the special theory of relativity once he realized th field theory creates “reciprocal actions between bodies […] by processes which are propagate through space at a finite speed.” Such fields “ruled out the existence of forces acting at a distanc with the resulting destruction of the notion of absolute simultaneity.” Einstein felt that a final leap ha to be made to develop the general theory of relativity. Such a theory can no longer be based o observation and reality. The theory must first be conceived through intuition by making the theory a simple as possible and then checked to see if it fits reality. It happens that generalized relativi depends heavily on mathematical constructions due to Riemann, Ricci, and Levi-Civita, which we already known. It is clear that Einstein felt that he would not have been able to complete his theo without their mathematical constructions.

Where does quantum mechanics fit into all this? Can field theory find a way to include quantu mechanics? Can there be a “unified” field theory? In 1934, Einstein had hope of finding a solution b spent the remainder of his life looking unsuccessfully for it.

Another interesting thread throughout *Essays in Science* involved the use of mathematics developing a theory of reality. Starting with Euclid, the mathematics was whole unto itself. This wa followed by Kepler, who developed the motion of the planets using circles and ellipses, which exhib “the simplest conceivable form of regularity.” According to Einstein, Kepler’s “achievement is particularly fine example of the truth that knowledge cannot spring from experience alone but on from the comparison of inventions of the intellect with observed facts.” Kepler’s laws represente integrals of the motion. Newton’s mechanics required the development of the calculus, ordinar derivatives, and differential equations. Field theory required partial derivatives. And finally, gener relativity required the Rici calculus and the concept of invariant derivatives, which were independe of the geometry of space.

In the essay *The Cause of the Formation of Meanders* . . . Einstein used simple arguments to giv the “elementary principles involved [and a] short qualitative exposition of them.” In the next pages h used thought experiments to prove his thesis. Together with the following essay, *The Flettner Shi* they provide outstanding examples of Einstein’s mind at work.

Einstein’s connection to all things German, and in particular the scientific community in Berli through his appointment to the Kaiser Wilhelm Institute for Physics, made it very painful for him t give up his German citizenship. Throughout his years in America he sought the friendship an association with German Jews. Through this connection he developed a deep friendship with D Dagobert D. Runes, the founder of Philosophical Library, who had written his doctoral dissertation o Spinoza. Many of Einstein’s essays were subsequently published by Philosophical Library, which now reissuing this volume.

Neil Berg
Associate Professor Emeritus of Mathemati
University of Illinois at Chicag
August 20

Preface to Abridged Edition

The World as I See It in its original form includes essays by Einstein on Judaism, Germany, Politic and Pacifism and sundry other topics. These have been omitted in the present abridged edition. Th object of this reprint is simply to give the general reader an opportunity to examine some of th distinguished scholar's papers dealing with science.

Publisher’s Note

to the original edition, entitled “The World as I See It”

ALBERT EINSTEIN IS ONE of the most modest people in the world. In the letters and papers in this book h constantly refers to his “accidental” fame and his “unearned popularity.” So deep-rooted is this feelin that he has merely tilled his own row, howbeit that row was an inconceivably fertile one, that for man years his friends and intimates were unable to prevail upon him to publish his letters, papers an speeches, although opportunities and requests were showered on him. Even his scientific articles h would release to none save academic journals that do not reach the general public. The imagination the world is stirred by the name of Albert Einstein, and yet hitherto it has had only the scantie material to feed upon. Occasional, all-too-brief interviews; a few instances where Einstein suppresse his modesty for the sake of some great humanitarian cause; and the famous four-page pamphlet on th special theory of relativity.

The publishers do not know what good fortune at last prompted Albert Einstein to relax his attitud a little. Perhaps he felt that in times like these each man must sacrifice himself if he can help but little to alleviate the horrible conditions which have fallen upon the world. If anything could brea Einstein’s silence, it was the threat of war in Europe. Perhaps, too, it was the persecution of h people, the Jews. Perhaps it was, in some small degree, a further extension of his modesty in a desi to show how much his scientific work has been prepared for, supported, and amplified by le heralded collaborators, as he explains in his articles and speeches on Kepler, Newton, Maxwel Planck, Niels Bohr and others. Whatever the cause, he at last gave permission to one of his intimate who prefers to conceal his identity beneath the initials J.H., because his was a labor of love, to colle and publish certain of his writings.

These papers were originally published by the Querido Verlag in Amsterdam. In fairness t Professor Einstein, his American publishers would like to make it clear that although they have h full authorization to translate the German text as published in Holland, and although the documen from which the original publication was made have his authentication, there has been no furth collaboration by him. Because of this, the publishers have taken extra and unusual care to check eve detail of the translation. An expert has gone over the work to make sure that it represents the exa meaning of Professor Einstein. Thus, the responsibility for the accuracy of the translation, thoug every attempt has been made to insure it, must not be placed with Professor Einstein.

There is a saying that only twelve people in the world can understand Einstein’s theory of relativit The difficulties of reaching such an understanding have heretofore been heightened by lack in print anything but the abstract mathematical formulation of the theory. The papers and speeches publishe for the first time in this volume will be comprehensible to any well-educated person. They deal on in part with the central core of the theory; but the very fact that they carry its elaborations somewh afield to particular applications and examples will help the scientific-minded layman to achieve more complete comprehension of the theory itself. This book presents to the world at large for th first time what Einstein has really accomplished in the field of abstract physics. We cannot help bu feel that its publication is an event of historical importance.

Translators’ Note

I have had the benefit of the expert supervision of Dr. H. Stafford Hatfield, to whom my thanks are due.

A.

Principles of Research

IN THE TEMPLE OF Science are many mansions, and various indeed are they that dwell therein and th motives that have led them thither. Many take to science out of a joyful sense of superior intellectu power; science is their own special sport to which they look for vivid experience and the satisfactio of ambition; many others are to be found in the temple who have offered the products of their brai on this altar for purely utilitarian purposes. Were an angel of the Lord to come and drive all the peop belonging to these two categories out of the temple, it would be noticeably emptier, but there wou still be some men, of both present and past times, left inside. Our Planck is one of them, and that why we love him.

I am quite aware that we have just now light-heartedly expelled in imagination many excellent m who are largely, perhaps chiefly, responsible for the building of the temple of Science; and in ma cases our angel would find it a pretty ticklish job to decide. But of one thing I feel sure: if the types have just expelled were the only types there were, the temple would never have existed, any more th one can have a wood consisting of nothing but creepers. For these people any sphere of human activi will do, if it comes to a point; whether they become officers, tradesmen or scientists depends circumstances. Now let us have another look at those who have found favor with the angel. Most them are somewhat odd, uncommunicative, solitary fellows, really less like each other, in spite these common characteristics, than the hosts of the rejected. What has brought them to the templ That is a difficult question and no single answer will cover it. To begin with I believe wi Schopenhauer that one of the strongest motives that lead men to art and science is escape fro everyday life with its painful crudity and hopeless dreariness, from the fetters of one’s own ev shifting desires. A finely tempered nature longs to escape from personal life into the world objective perception and thought; this desire may be compared with the townsman’s irresistib longing to escape from his noisy, cramped surroundings into the silence of high mountains, where th eye ranges freely through the still, pure air and fondly traces out the restful contours apparently bu for eternity. With this negative motive there goes a personal one. Man tries to make for himself in th fashion that suits him best a simplified and intelligible picture of the world; he then tries to so extent to substitute this cosmos of his for the world of experience, and thus to overcome it. This what the painter, the poet, the speculative philosopher and the natural scientist do, each in his ow fashion. He makes this cosmos and its construction the pivot of his emotional life, in order to find this way the peace and security which he cannot find in the narrow whirlpool of personal experience.

What place does the theoretical physicist’s picture of the world occupy among all these possib pictures? It demands the highest possible standard of rigorous precision in the description of relation such as only the use of mathematical language can give. In regard to his subject matter, on the oth hand, the physicist has to limit himself very severely: he must content himself with describing th most simple events which can be brought within the domain of our experience; all events of a mo complex order are beyond the power of the human intellect to reconstruct with the subtle accuracy a logical perfection which the theoretical physicist demands. Supreme purity, clarity and certainty at th cost of completeness. But what can be the attraction of getting to know such a tiny section of natu thoroughly, while one leaves everything subtler and more complex shyly and timidly alone? Does th product of such a modest effort deserve to be called by the proud name of a theory of the Universe?

In my belief the name is justified; for the general laws on which the structure of theoretical physi is based claim to be valid for any natural phenomenon whatsoever. With them, it ought to be possib to arrive at the description, that is to say, the theory, of every natural process, including life, by mean of ~~pure deduction, if that process of deduction were not far beyond the capacity of the human intellec~~ The physicist’s renunciation of completeness for his cosmos is therefore not a matter of fundament principle.

The supreme task of the physicist is to arrive at those universal elementary laws from which th cosmos can be built up by pure deduction. There is no logical path to these laws; only intuitio resting on sympathetic understanding of experience, can reach them. In this methodologic uncertainty, one might suppose that there were any number of possible systems of theoretical physic all with an equal amount to be said for them; and this opinion is no doubt correct, theoretically. B evolution has shown that at any given moment, out of all conceivable constructions, a single one h always proved itself absolutely superior to all the rest. Nobody who has really gone deeply into th matter will deny that in practice the world of phenomena uniquely determines the theoretical syster in spite of the fact that there is no logical bridge between phenomena and their theoretical principle this is what Leibnitz described so happily as a “pre-established harmony.” Physicists often accus epistemologists of not paying sufficient attention to this fact. Here, it seems to me, lie the roots of th controversy carried on some years ago between Mach and Planck.

The longing to behold this pre-established harmony is the source of the inexhaustible patience an endurance with which Planck has devoted himself, as we see, to the most general problems of o science, refusing to let himself be diverted to more grateful and more easily attained ends. I hav often heard colleagues try to attribute this attitude of his to extraordinary will-power and discipline- wrongly, in my opinion. The state of mind which enables a man to do work of this kind is akin to th of the religious worshiper or the lover; the daily effort comes from no deliberate intention or progran but straight from the heart. There he sits, our beloved Planck, and smiles inside himself at my childis playing-about with the lantern of Diogenes. Our affection for him needs no threadbare explanatio May the love of science continue to illumine his path in the future and lead him to the solution of th most important problem in present-day physics, which he has himself posed and done so much solve. May he succeed in uniting the quantum theory and electrodynamics in a single logical system.

(*Address on the occasion of Max Planck’s sixtieth birthday delivered at the Physical Society in Berlin*)

Inaugural Address to the Prussian Academy of Sciences (1914)

GENTLEMEN,

FIRST OF ALL, I have to thank you most heartily for conferring the greatest benefit on me th anybody can confer on a man like myself. By electing me to your Academy you have freed me fro the distractions and cares of a professional life and so made it possible for me to devote myse entirely to scientific studies. I beg that you will continue to believe in my gratitude and my indust even when my efforts seem to you to yield but a poor result.

Perhaps I may be allowed a propos of this to make a few general remarks on the relation of m sphere of activity, which is theoretical physics, towards experimental physics. A mathematician frier of mine said to me the other day half in jest: “The mathematician can do a lot of things, but nev what you happen to want him to do just at the moment.” Much the same often applies to th theoretical physicist when the experimental physicist calls him in. What is the reason for this peculi lack of adaptability?

The theorist’s method involves his using as his foundation general postulates or “principles” fro which he can deduce conclusions. His work thus falls into two parts. He must first discover h principles and then draw the conclusions which follow from them. For the second of these tasks h receives an admirable equipment at school. Once, therefore, he has performed the first task in son department, or for some complex of related phenomena, he is certain of success, provided his indust and intelligence are adequate. The first of these tasks, namely, that of establishing the principl which are to serve as the starting point of his deduction, is of an entirely different nature. Here there no method capable of being learned and systematically applied so that it leads to the goal. Th scientist has to worm these general principles out of nature by perceiving certain general featur which permit of precise formulation, amidst large complexes of empirical facts.

Once this formulation is successfully accomplished, inference follows on inference, often revealir relations which extend far beyond the province of the reality from which the principles were draw But as long as the principles capable of serving as starting points for the deduction rema undiscovered, the individual fact is of no use to the theorist; indeed he cannot even do anything wi isolated empirical generalizations of more or less wide application. No, he has to persist in h helpless attitude towards the separate results of empirical research, until principles which he can mal the basis of deductive reasoning have revealed themselves to him.

This is the kind of position in which theory finds itself at present in regard to the laws of hea radiation, and molecular movement at low temperatures. About fifteen years ago nobody had y doubted that a correct account of the electrical, optical and thermal properties of bodies was possib on the basis of Galileo-Newtonian mechanics applied to the movement of molecules and of Cle Maxwell’s theory of the electro-magnetic field. Then Planck showed that in order to establish a law heat radiation consonant with experience, it was necessary to employ a method of calculation th incompatibility of which with the principles of classical physics became clearer and clearer. For wi this method of calculation Planck introduced the quantum hypothesis into physics, which has sin received brilliant confirmation. With this quantum hypothesis he dethroned classical physics applied to the case where sufficiently small masses are moved at sufficiently low speeds and hig rates of acceleration, so that today the laws of motion propounded by Galileo and Newton can only allowed validity as limiting laws. In spite of assiduous efforts, however, the theorists have not y succeeded in replacing the principles of mechanics by others which fit in with Planck’s law of he radiation or the quantum hypothesis. No matter how definitely it has been proved that heat is to b ~~explained by molecular movement, we have nevertheless to admit today that our position in regard~~ the fundamental laws of this motion resembles that of astronomers before Newton in regard to th motions of the planets.

I have just now referred to a group of facts for the theoretical treatment of which the principles a lacking. But it may equally well happen that clearly formulated principles lead to conclusions whic fall entirely, or almost entirely, outside the sphere of reality at present accessible to our experience. I that case it may need many years of empirical research to ascertain whether the theoretical principl correspond with reality. We have an instance of this in the theory of relativity.

An analysis of the fundamental concepts of space and time has shown us that the principle of th constant velocity of light in empty space, which emerges from the optics of bodies in motion, by n means forces us to accept the theory of a stationary luminiferous ether. On the contrary, there nothing to prevent our framing a general theory which takes account of the fact that in experimen carried out on the earth we are wholly unconscious of the translatory motion of the earth. Th involves using the principle of relativity, which says that the laws of nature do not alter their for when one proceeds from the original (legitimate) system of co-ordinates to a new one which is uniform translatory motion with respect to it. This theory has received impressive confirmation fro experience and has led to a simplification of the theoretical description of groups of facts alread connected together.

On the other hand, from the theoretical point of view this theory is not wholly satisfactory, becaus the principle of relativity just formulated prefers *uniform* motion. If it is true that no absolu significance can be attached to *uniform* motion from the physical point of view, the question arise whether this statement must not also be extended to non-uniform motions. It became clear that on arrives at a quite definite enlargement of the relativity theory if one postulates a principle of relativi in this extended sense. One is led thereby to a general theory of gravitation which includes dynamic For the present, however, we have not the necessary array of facts to test the legitimacy of ou introduction of the postulated principle.

We have ascertained that inductive physics asks questions of deductive, and vice versa, to answe which demands the exertion of all our energies. May we soon succeed in making permanent progre by our united efforts!

On Scientific Truth

(1) IT IS DIFFICULT even to attach a precise meaning to the term “scientific truth.” So different is th meaning of the word “truth” according to whether we are dealing with a fact of experience, mathematical proposition or a scientific theory. “Religious truth” conveys nothing clear to me at all.

(2) Scientific research can reduce superstition by encouraging people to think and survey things terms of cause and effect. Certain it is that a conviction, akin to religious feeling, of the rationality intelligibility of the world lies behind all scientific work of a higher order.

(3) This firm belief, a belief bound up with deep feeling, in a superior mind that reveals itself in th world of experience, represents my conception of God. In common parlance this may be described “pantheistic” (Spinoza).

(4) Denominational traditions I can only consider historically and psychologically; they have no oth significance for me.

On the Method of Theoretical Physics

IF YOU WANT TO find out anything from the theoretical physicists about the methods they use, I advi you to stick closely to one principle: don't listen to their words, fix your attention on their deeds. T him who is a discoverer in this field the products of his imagination appear so necessary and natur that he regards them, and would like to have them regarded by others, not as creations of thought b as given realities.

These words sound like an invitation to you to walk out of this lecture. You will say to yourselve the fellow's a working physicist himself and ought therefore to leave all questions of the structure theoretical science to the epistemologists.

Against such criticism I can defend myself from the personal point of view by assuring you that it not at my own instance but at the kind invitation of others that I have mounted this rostrum, whic serves to commemorate a man who fought hard all his life for the unity of knowledge. Objectivel however, my enterprise can be justified on the ground that it may, after all, be of interest to know ho one who has spent a life-time in striving with all his might to clear up and rectify its fundamenta looks upon his own branch of science. The way in which he regards its past and present may depe too much on what he hopes for the future and aims at in the present; but that is the inevitable fate anybody who has occupied himself intensively with a world of ideas. The same thing happens to hi as to the historian, who in the same way, even though perhaps unconsciously, groups actual even around ideals which he has formed for himself on the subject of human society.

Let us now cast an eye over the development of the theoretical system, paying special attention the relations between the content of the theory and the totality of empirical fact. We are concerne with the eternal antithesis between the two inseparable components of our knowledge, the empiric and the rational, in our department.

We reverence ancient Greece as the cradle of western science. Here for the first time the worl witnessed the miracle of a logical system which proceeded from step to step with such precision th every single one of its propositions was absolutely indubitable—I refer to Euclid's geometry. Th admirable triumph of reasoning gave the human intellect the necessary confidence in itself for i subsequent achievements. If Euclid failed to kindle your youthful enthusiasm, then you were not bo to be a scientific thinker.

But before mankind could be ripe for a science which takes in the whole of reality, a secon fundamental truth was needed, which only became common property among philosophers with th advent of Kepler and Galileo. Pure logical thinking cannot yield us any knowledge of the empiric world; all knowledge of reality starts from experience and ends in it. Propositions arrived at by pure logical means are completely empty as regards reality. Because Galileo saw this, and particular because he drummed it into the scientific world, he is the father of modern physics—indeed, modern science altogether.

If, then, experience is the alpha and the omega of all our knowledge of reality, what is the functio of pure reason in science?

A complete system of theoretical physics is made up of concepts, fundamental laws which a supposed to be valid for those concepts and conclusions to be reached by logical deduction. It is the conclusions which must correspond with our separate experiences; in any theoretical treatise the logical deduction occupies almost the whole book.

This is exactly what happens in Euclid's geometry, except that there the fundamental laws a called axioms and there is no question of the conclusions having to correspond to any sort experience. ~~If, however, one regard Euclidean geometry as the science of the possible mutual relatio~~ of practically rigid bodies in space, that is to say, treats it as a physical science, without abstractin from its original empirical content, the logical homogeneity of geometry and theoretical physi becomes complete.

We have thus assigned to pure reason and experience their places in a theoretical system of physic The structure of the system is the work of reason; the empirical contents and their mutual relatio must find their representation in the conclusions of the theory. In the possibility of such representation lie the sole value and justification of the whole system, and especially of the concep and fundamental principles which underlie it. These latter, by the way, are free inventions of th human intellect, which cannot be justified either by the nature of that intellect or in any other fashi a *priori*.

These fundamental concepts and postulates, which cannot be further reduced logically, form th essential part of a theory, which reason cannot touch. It is the grand object of all theory to make the irreducible elements as simple and as few in number as possible, without having to renounce th adequate representation of any empirical content whatever.

The view I have just outlined of the purely fictitious character of the fundamentals of scientif theory was by no means the prevailing one in the eighteenth or even the nineteenth century. But it steadily gaining ground from the fact that the distance in thought between the fundamental concep and laws on one side and, on the other, the conclusions which have to be brought into relation with o experience grows larger and larger, the simpler the logical structure becomes—that is to say, th smaller the number of logically independent conceptual elements which are found necessary support the structure.

Newton, the first creator of a comprehensive, workable system of theoretical physics, still believe that the basic concepts and laws of his system could be derived from experience. This is no doubt th meaning of his saying, *hypotheses non fingo*.

Actually the concepts of time and space appeared at that time to present no difficulties. Th concepts of mass, inertia and force, and the laws connecting them seemed to be drawn directly fro experience. Once this basis is accepted, the expression for the force of gravitation appears derivab from experience, and it was reasonable to hope for the same in regard to other forces.

We can indeed see from Newton's formulation of it that the concept of absolute space, whic comprised that of absolute rest, made him feel uncomfortable; he realized that there seemed to nothing in experience corresponding to this last concept. He was also not quite comfortable about th introduction of forces operating at a distance. But the tremendous practical success of his doctrin may well have prevented him and the physicists of the eighteenth and nineteenth centuries fro recognizing the fictitious character of the foundations of his system.

The natural philosophers of those days were, on the contrary, most of them possessed with the id that the fundamental concepts and postulates of physics were not in the logical sense free inventio of the human mind but could be deduced from experience by "abstraction"—that is to say by logic means. A clear recognition of the erroneousness of this notion really only came with the gener theory of relativity, which showed that one could take account of a wider range of empirical facts, a that too in a more satisfactory and complete manner, on a foundation quite different from th Newtonian. But quite apart from the question of the superiority of one or the other, the fictitio character of fundamental principles is perfectly evident from the fact that we can point to tw essentially different principles, both of which correspond with experience to a large extent; this prov

at the same time that every attempt at a logical deduction of the basic concepts and postulates
mechanics from elementary experiences is doomed to failure.

If, then, it is true that this axiomatic basis of theoretical physics cannot be extracted fro experience but must be freely invented, can we ever hope to find the right way? Nay more, has th right way any existence outside our illusions? Can we hope to be guided in the right way b experience when there exist theories (such as classical mechanics) which to a large extent do justice experience, without getting to the root of the matter? I answer without hesitation that there is, in m opinion, a right way, and that we are capable of finding it. Our experience hitherto justifies us believing that nature is the realization of the simplest conceivable mathematical ideas. I am convince that we can discover by means of purely mathematical constructions the concepts and the lav connecting them with each other, which furnish the key to the understanding of natural phenomen Experience may suggest the appropriate mathematical concepts, but they most certainly cannot b deduced from it. Experience remains, of course, the sole criterion of the physical utility of mathematical construction. But the creative principle resides in mathematics. In a certain sens therefore, I hold it true that pure thought can grasp reality, as the ancients dreamed.

In order to justify this confidence, I am compelled to make use of a mathematical conception. Th physical world is represented as a four-dimensional continuum. If I assume a Riemannian metric in and ask what are the simplest laws which such a metric system can satisfy, I arrive at the relativi theory of gravitation in empty space. If in that space I assume a vector-field or an anti-symmetric tensorfield which can be inferred from it, and ask what are the simplest laws which such a field ca satisfy, I arrive at Clerk Maxwell's equations for empty space.

At this point we still lack a theory for those parts of space in which electrical density does n disappear. De Broglie conjectured the existence of a wave field, which served to explain certa quantum properties of matter. Dirac found in the spinors field-magnitudes of a new sort, whos simplest equations enable one to a large extent to deduce the properties of the electron. Subsequently discovered, in conjunction with my colleague, that these spinors form a special case of a new sort field, mathematically connected with the four-dimensional system, which we called "semivectors The simplest equations to which such semivectors can be reduced furnish a key to the understandi of the existence of two sorts of elementary particles, of different ponderable mass and equal b opposite electrical charge. These semivectors are, after ordinary vectors, the simplest mathemati fields that are possible in a metrical continuum of four dimensions, and it looks as if they describe in an easy manner, certain essential properties of electrical particles.

The important point for us to observe is that all these constructions and the laws connecting the can be arrived at by the principle of looking for the mathematically simplest concepts and the li between them. In the limited nature of the mathematically existent simple fields and the simp equations possible between them, lies the theorist's hope of grasping the real in all its depth.

Meanwhile the great stumbling-block for a field-theory of this kind lies in the conception of t atomic structure of matter and energy. For the theory is fundamentally non-atomic in so far as operates exclusively with continuous functions of space, in contrast to classical mechanics, who most important element, the material point, in itself does justice to the atomic structure of matter.

The modern quantum theory in the form associated with the names of de Broglie, Schrödinger, a Dirac, which operates with continuous functions, has overcome these difficulties by a bold piece interpretation which was first given a clear form by Max Born. According to this, the spatial functio which appear in the equations make no claim to be a mathematical model of the atomic structu Those functions are only supposed to determine the mathematical probabilities of the occurrence such structures if measurements were taken at a particular spot or in a certain state of motion. Th ~~notion is logically unobjectionable and has important successes to its credit. Unfortunately, howeve~~ it compels one to use a continuum the number of whose dimensions is not that ascribed to space b physics hitherto (four) but rises indefinitely with the number of the particles constituting the syste under consideration. I cannot but confess that I attach only a transitory importance to th interpretation. I still believe in the possibility of a model of reality—that is to say, of a theory whic represents things themselves and not merely the probability of their occurrence.

On the other hand it seems to me certain that we must give up the idea of a complete localization the particles in a theoretical model. This seems to me to be the permanent upshot of Heisenberg principle of uncertainty. But an atomic theory in the true sense of the word (not merely on the basis o an interpretation) without localization of particles in a mathematical model, is perfectly thinkable. F instance, to account for the atomic character of electricity, the field equations need only lead to th following conclusions: A portion of space (three-dimensional) at whose boundaries electrical densi disappears everywhere, always contains a total electrical charge whose size is represented by a who number. In a continuum-theory atomic characteristics would be satisfactorily expressed by integr laws without localization of the formation entity which constitutes the atomic structure.

Not until the atomic structure has been successfully represented in such a manner would I consid the quantum-riddle solved.

Johannes Kepler

IN ANXIOUS AND UNCERTAIN times like ours, when it is difficult to find pleasure in humanity and th course of human affairs, it is particularly consoling to think of the serene greatness of a Keple Kepler lived in an age in which the reign of law in nature was by no means an accepted certainty. Ho great must his faith in a uniform law have been, to have given him the strength to devote ten years hard and patient work to the empirical investigation of the movement of the planets and th mathematical laws of that movement, entirely on his own, supported by no one and understood b very few! If we would honor his memory worthily, we must get as clear a picture as we can of h problem and the stages of its solution.

Copernicus had opened the eyes of the most intelligent to the fact that the best way to get a cle grasp of the apparent movements of the planets in the heavens was by regarding them as movemen around the sun conceived as stationary. If the planets moved uniformly in a circle around the sun, would have been comparatively easy to discover how these movements must look from the eart Since, however, the phenomena to be dealt with were much more complicated than that, the task was far harder one. The first thing to be done was to determine these movements empirically from th observations of Tycho Brahe. Only then did it become possible to think about discovering the gener laws which these movements satisfy.

To grasp how difficult a business it was even to find out about the actual rotating movements, or has to realize the following. One can never see where a planet really is at any given moment, but on in what direction it can be seen just then from the earth, which is itself moving in an unknown mann around the sun. The difficulties thus seemed practically unsurmountable.

Kepler had to discover a way of bringing order into this chaos. To start with, he saw that it wa necessary first to try and find out about the motion of the earth itself. This would simply have bee impossible if there had existed only the sun, the earth and the fixed stars, but no other planets. For that case one could ascertain nothing empirically except how the direction of the straight sun-ear line changes in the course of the year (apparent movement of the sun with reference to the fixed stars In this way it was possible to discover that these sun-earth directions all lay in a plane stationary wi reference to the fixed stars, at least according to the accuracy of observation achieved in those day when there were no telescopes. By this means it could also be ascertained in what manner the line su earth revolves round the sun. It turned out that the angular velocity of this motion went through regular change in the course of the year. But this was not of much use, as it was still not known ho the distance from the earth to the sun alters in the course of the year. It was only when they found o about these changes that the real shape of the earth's orbit and the manner in which it is describe were discovered.

Kepler found a marvelous way out of this dilemma. To begin with it was apparent fro observations of the sun that the apparent path of the sun against the background of the fixed sta differed in speed at different times of the year, but that the angular velocity of this movement wa always the same at the same point in the astronomical year, and therefore that the speed of rotation the straight line earth-sun was always the same when it pointed to the same region of the fixed stars. was thus legitimate to suppose that the earth's orbit was a self-enclosed one, described by the earth the same way every year—which was by no means obvious a *priori*. For the adherent of th Copernican system it was thus as good as certain that this must also apply to the orbits of the rest the planets.

This certainty made things easier. But how to ascertain the real shape of the earth's orbit? Imagine ~~brightly shining lantern M somewhere in the plane of the orbit. We know that this lantern remain~~ permanently in its place and thus forms a kind of fixed triangulation point for determining the earth orbit, a point which the inhabitants of the earth can take a sight on at any time of year. Let this lanter M be further away from the sun than the earth. With the help of such a lantern it was possible determine the earth's orbit, in the following way:—

First of all, in every year there comes a moment when the earth E lies exactly on the line joining th sun S and the lantern M. If at this moment we look from the earth E at the lantern M, our line of sig will coincide with the line SM (sun-lantern). Suppose the latter to be marked in the heavens. No imagine the earth in a different position and at a different time. Since the sun S and the lantern M ca both be seen from the Earth, the angle at E in the triangle SEM is known. But we also know th direction of SE in relation to the fixed stars through direct solar observations, while the direction the line SM in relation to the fixed stars was finally ascertained previously. But in the triangle SE we also know the angle at S. Therefore, with the base SM arbitrarily laid down on a sheet of paper, v can, in virtue of our knowledge of the angles at E and S, construct the triangle SEM. We might do th at frequent intervals during the year; each time we should get on our piece of paper a position of th earth E with a date attached to it and a certain position in relation to the permanently fixed base SN The earth's orbit would thereby be empirically determined, apart from its absolute size, of course.

But, you will say, where did Kepler get his lantern M? His genius and Nature, benevolent in th case, gave it to him. There was, for example, the planet Mars; and the length of the Martian year—i. one rotation of Mars around the sun—was known. It might happen one fine day that the sun, the ear and Mars lie absolutely in the same straight line. This position of Mars regularly recurs after one, tw etc., Martian years, as Mars has a self-enclosed orbit. At these known moments, therefore, SM alway presents the same base, while the earth is always at a different point in its orbit. The observations the sun and Mars at these moments thus constitute a means of determining the true orbit of the eart as Mars then plays the part of our imaginary lantern. Thus it was that Kepler discovered the true sha of the earth's orbit and the way in which the earth describes it, and we who come after—European Germans, or even Swabians, may well admire and honor him for it.

Now that the earth's orbit had been empirically determined, the true position and length of the li SE at any moment was known, and it was not so terribly difficult for Kepler to calculate the orbits a motions of the rest of the planets too from observations—at least in principle. It was nevertheless immense work, especially considering the state of mathematics at the time.

Now came the second and no less arduous part of Kepler's life work. The orbits were empirical known, but their laws had to be deduced from the empirical data. First he had to make a guess at th mathematical nature of the curve described by the orbit, and then try it out on a vast assemblage figures. If it did not fit, another hypothesis had to be devised and again tested. After tremendo search, the conjecture that the orbit was an ellipse with the sun at one of its foci was found to fit th facts. Kepler also discovered the law governing the variation in speed during rotation, which is th the line sun-planet sweeps out equal areas in equal periods of time. Finally he also discovered that th square of the period of circulation around the sun varies as the cube of the major axes of the ellipse.

Our admiration for this splendid man is accompanied by another feeling of admiration a reverence, the object of which is no man but the mysterious harmony of nature into which we are bor As far back as ancient times people devised the lines exhibiting the simplest conceivable form regularity. Among these, next to the straight line and the circle, the most important were the ellip and the hyperbola. We see the last two embodied—at least very nearly so—in the orbits of th heavenly bodies.

It ~~seems that the human mind has first to construct forms independently before we can find~~ them things. Kepler’s marvelous achievement is a particularly fine example of the truth that knowledg cannot spring from experience alone but only from the comparison of the inventions of the intelle with observed fact.

The Mechanics of Newton and Their Influence on the Development o Theoretical Physics

IT IS JUST TWO hundred years ago that Newton closed his eyes. It behooves us at such a moment remember this brilliant genius, who determined the course of western thought, research and practice an extent that nobody before or since his time can touch. Not only was he brilliant as an inventor certain key methods, but he also had a unique command of the empirical material available in his da and he was marvelously inventive as regards mathematical and physical methods of proof individual cases. For all these reasons he deserves our deepest reverence. The figure of Newton ha however, an even greater importance than his genius warrants because of the fact that destiny place him at a turning point in the history of the human intellect. To see this vividly, we have to remir ourselves that before Newton there existed no self-contained system of physical causality which w capable of representing any of the deeper features of the empirical world.

No doubt the great materialists of ancient Greece had insisted that all material events should l traced back to a strictly regular series of atomic movements, without admitting any living creature will as an independent cause. And no doubt Descartes had in his own way taken up this quest agai But it remained a bold ambition, the problematical ideal of a school of philosophers. Actual results a kind to support the belief in the existence of a complete chain of physical causation hardly existe before Newton.

Newton's object was to answer the question: Is there such a thing as a simple rule by which one ca calculate the movements of the heavenly bodies in our planetary system completely, when the state motion of all these bodies at one moment is known? Kepler's empirical laws of planetary movemer deduced from Tycho Brahe's observations, confronted him, and demanded explanation.[1] These lav gave, it is true, a complete answer to the question of *how* the planets move around the sun (tl elliptical shape of the orbit, the sweeping of equal areas by the radii in equal times, the relatic between the major axes and the period of circulation around the sun); but they did not satisfy tl demand for causal explanation. They are three logically independent rules, revealing no inn connection with each other. The third law cannot simply be transferred quantitatively to other centr bodies than the sun (there is, e.g., no relation between the rotatory period of a planet around the su and that of a moon around its planet). The most important point, however, is this: these laws a concerned with the movement as a whole, and not with the question *how the state of motion of system gives rise to that which immediately follows it in time*; they are, as we should say now, integr and not differential laws.

The differential law is the only form which completely satisfies the modern physicist's demand fo causality. The clear conception of the differential law is one of Newton's greatest intellectu achievements. It was not merely this conception that was needed but also a mathematical formalisr which existed in a rudimentary form but needed to acquire a systematic form. Newton found this als in the differential and the integral calculus. We need not consider the question here whether Newto hit upon the same mathematical methods independently of Leibnitz or not. In any case it w absolutely necessary for Newton to perfect them, since they alone could provide him with the mear of expressing his ideas.

Galileo had already moved a considerable way towards a knowledge of the law of motion. F discovered the law of inertia and the law of bodies falling freely in the gravitational field of the eart namely, that a mass (more accurately, a mass-point) which is unaffected by other masses move uniformly and in a straight line. The vertical speed of a free body in the gravitational field increas ~~uniformly with the time. It may seem to us today to be but a short step from Galileo's discoveries t~~ Newton's law of motion. But it should be observed that both the above statements refer in their for to the motion as a whole, while Newton's law of motion provides an answer to the question: how do the state of motion of a mass-point behave in an *infinitely short time* under the influence of an extern force? It was only by considering what takes place during an infinitely short time (the differential lav that Newton reached a formula which applies to all motion whatsoever. He took the conception o force from the science of statics which had already reached a high stage of development. Th connection of force and acceleration was only made possible for him by the introduction of the ne concept of mass, which was supported, strange to say, by an illusory definition. We are so accustome today to the creation of concepts corresponding to differential quotients that we can now hardly gras any longer what a remarkable power of abstraction it needed to reach the general differential law by double crossing of frontiers, in the course of which the concept of mass had in addition to be invente

But a causal conception of motion was still far from being achieved. For the motion was on determined by the equation of motion in cases where the force was given. Inspired no doubt by th uniformity of planetary motions, Newton conceived the idea that the force operating on a mass w determined by the position of all masses situated at a sufficiently small distance from the mass question. It was not till this connection was established that a completely causal conception of motio was achieved. How Newton, starting from Kepler's laws of planetary motion, performed this task f gravitation and so discovered that the kinetic forces acting on the stars and gravity were of the san nature, is well known. It is the combination of the Law of Motion with the Law of Attraction whic constitutes that marvelous edifice of thought which makes it possible to calculate the past and futu states of a system from the state obtaining at one particular moment, in so far as the events take plac under the influence of the forces of gravity alone. The logical completeness of Newton's conceptu system lay in this, that the only things that figure as causes of the acceleration of the masses of system are *these masses themselves*.

On the strength of the foundation here briefly sketched Newton succeeded in explaining the motion of the planets, moons and comets down to the smallest details, as well as the tides and the precession movement of the earth—a deductive achievement of unique magnificence. The discovery that th cause of the motions of the heavenly bodies is identical with the gravity with which we are so famili from everyday life must have been particularly impressive.

But the importance of Newton's achievement was not confined to the fact that it created a workab and logically satisfactory basis for the actual science of mechanics; up to the end of the nineteen century it formed the program of every worker in the field of theoretical physics. All physical even were to be traced back to masses subject to Newton's laws of motion. The law of force simply had be widened and adapted to the type of event under consideration. Newton himself tried to apply th scheme to optics, assuming light to consist of inert corpuscles. Even the wave theory of light made u of Newton's law of motion, after it had been applied to the mass of a continuum. Newton's equation of motion were the sole basis of the kinetic theory of heat, which not only prepared people's minds fo the discovery of the law of the conservation of energy but also led to a theory of gases which has bee confirmed down to the last detail, and a more profound view of the nature of the second law thermodynamics. The development of electricity and magnetism has proceeded right down to our ow day along Newtonian lines (electrical and magnetic substance, forces acting at a distance). Even th revolution in electrodynamics and optics brought about by Faraday and Clerk Maxwell, which forme the first great fundamental advance in theoretical physics since Newton, took place entirely under th aegis of Newton's ideas. Clerk Maxwell, Boltzmann, and Lord Kelvin never wearied of tracing th ~~electromagnetic fields and their reciprocal dynamic actions back to the mechanical action~~ hypothetical continuously diffused masses. As a result, however, of the hopelessness or at any rate th lack of success of those efforts, a gradual revolution in our fundamental notions has taken place sinc the end of the nineteenth century; theoretical physics have outgrown the Newtonian frame which gav stability and intellectual guidance to science for nearly two hundred years.

Newton's fundamental principles were so satisfactory from the logical point of view that th impetus to overhaul them could only spring from the imperious demands of empirical fact. Before go into this I must insist that Newton himself was better aware of the weaknesses inherent in h intellectual edifice than the generations of scientists which followed him. This fact has always rouse my respectful admiration, and I should like therefore to dwell on it for a moment.

I. In spite of the fact that Newton's ambition to represent his system as necessarily conditioned b experience and to introduce the smallest possible number of concepts not directly referable empirical objects is everywhere evident, he sets up the concept of absolute space and absolute tim for which he has often been criticized in recent years. But in this point Newton is particular consistent. He had realized that observable geometrical magnitudes (distances of material points fro one another) and their course in time do not completely characterize motion in its physical aspects. H proved this in the famous experiment with the rotating vessel of water. Therefore, in addition masses and temporally variable distances, there must be something else that determines motion. Th "something" he takes to be relation to "absolute space." He is aware that space must possess a kind physical reality if his laws of motion are to have any meaning, a reality of the same sort as materi points and the intervals between them.

The clear realization of this reveals both Newton's wisdom and also a weak side to his theory. Fo the logical structure of the latter would undoubtedly be more satisfactory without this shadow concept; in that case only things whose relations to perception are perfectly clear (mass-point distances) would enter into the laws.

II. The introduction of forces acting directly and instantaneously at a distance into th representation of the effects of gravity is not in keeping with the character of most of the process familiar to us from everyday life. Newton meets this objection by pointing to the fact that his law reciprocal gravitation is not supposed to be a final explanation but a rule derived by induction fro experience.

III. Newton's teaching provided no explanation for the highly remarkable fact that the weight an the inertia of a body are determined by the same quantity (its mass). The remarkableness of this fa struck Newton himself.

None of these three points can rank as a logical objection to the theory. In a sense they mere represent unsatisfied desires of the scientific spirit in its struggle for a complete and unita penetration of natural events by thought.

Newton's doctrine of motion, considered as the key idea of the whole of theoretical physic received its first shock from Clerk Maxwell's theory of electricity. It became clear that the reciproc actions between bodies due to electric and magnetic forces were affected, not by forces operatin instantaneously at a distance, but by processes which are propagated through space at a finite spee Faraday conceived a new sort of real physical entity, namely the "field," in addition to the mass-poi and its motion. At first people tried, clinging to the mechanical mode of thought, to look upon it as mechanical condition (motion or force) of a hypothetical medium by which space was filled up (th ether). But when this interpretation refused to work in spite of the most obstinate efforts, peop sample content of Essays in Science

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