



Essays in Science

THE
AUTHORIZED
Albert Einstein
Archives
EDITION

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Preface to the New Edition

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

This volume contains a collection of sixteen essays written before 1935, when Einstein was at the height of his scientific powers but not yet known as the sage of the atomic age. His stature in the 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 thought processes? His theories of relativity and universal gravitation are generally regarded as inaccessible to the ordinary person. Yet we know that he was an original thinker who was able to see beyond the conventional scientific worldview of his age. What is remarkable is that Einstein's greatest discoveries belong to him alone. It is perhaps fitting that this volume is being published one hundred years after Einstein settled the question of why the sky is blue. What we see is a giant intellect 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 first authorized edition of *Mein Weltbild*. These essays had an amazing breadth and made many fundamental points about the nature of the universe. The central theme answered the question of how Einstein came to his theories. He believed that the only source of knowledge was experience, and that in the case of general relativity such experience did not always suggest the scientific truth of a theory. The development of a theory depended on "only intuition resting on a sympathetic understanding of experience." It was the "object of all theory to make the irreducible elements as simple and few in number as possible." He was "convinced that we can discover by purely mathematical construction [...] the key to the understanding of natural phenomena." Experience suggests, the mind constructs (with the help of mathematics), and experience confirms.

Einstein bolstered his argument by tracing the development of various universal theories of science and the advances that these theories brought to our ability to understand the world. Euclid's geometry gave "the human intellect the confidence in itself for subsequent achievements." "Purely logical thinking [such as Euclid] cannot yield us any knowledge of the empirical world." Galileo and Kepler showed that "all knowledge of reality starts from experience and ends in it." And Newton "still 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's "pantheistic" religion revealing itself in the world of experience represented Einstein's conception of God.

Spinoza's metaphysics created a world view which was in conflict with the idea of an ever-expanding universe as predicted by an early version of the generalized relativity theory. By 1917 Einstein had amended his general theory of relativity to include a cosmological term so that the universe would be spatially self-enclosed as outlined in *On the Theory of Relativity*. In 1929, Edwin Hubble verified by astronomical observations that the universe was expanding and consequently there was at some time a "big bang." Had Einstein not added the cosmological term and accepted his early version of the generalized relativity theory the expanding universe would perhaps have been his greatest predication.

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

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

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

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

Einstein’s connection to all things German, and in particular the scientific community in Berlin through his appointment to the Kaiser Wilhelm Institute for Physics, made it very painful for him to give up his German citizenship. Throughout his years in America he sought the friendship and association with German Jews. Through this connection he developed a deep friendship with Dagobert D. Runes, the founder of Philosophical Library, who had written his doctoral dissertation on Spinoza. Many of Einstein’s essays were subsequently published by Philosophical Library, which is now reissuing this volume.

Neil Berg
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University of Illinois at Chicago
August 2013

Preface to Abridged Edition

The World as I See It in its original form includes essays by Einstein on Judaism, Germany, Politics and Pacifism and sundry other topics. These have been omitted in the present abridged edition. The object of this reprint is simply to give the general reader an opportunity to examine some of the 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 he constantly refers to his "accidental" fame and his "unearned popularity." So deep-rooted is this feeling that he has merely tilled his own row, howbeit that row was an inconceivably fertile one, that for many years his friends and intimates were unable to prevail upon him to publish his letters, papers and speeches, although opportunities and requests were showered on him. Even his scientific articles he would release to none save academic journals that do not reach the general public. The imagination of the world is stirred by the name of Albert Einstein, and yet hitherto it has had only the scantiest material to feed upon. Occasional, all-too-brief interviews; a few instances where Einstein suppressed his modesty for the sake of some great humanitarian cause; and the famous four-page pamphlet on the special theory of relativity.

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

These papers were originally published by the Querido Verlag in Amsterdam. In fairness to Professor Einstein, his American publishers would like to make it clear that although they have had full authorization to translate the German text as published in Holland, and although the documents from which the original publication was made have his authentication, there has been no further collaboration by him. Because of this, the publishers have taken extra and unusual care to check every detail of the translation. An expert has gone over the work to make sure that it represents the exact meaning of Professor Einstein. Thus, the responsibility for the accuracy of the translation, though 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 relativity. The difficulties of reaching such an understanding have heretofore been heightened by lack in print of anything but the abstract mathematical formulation of the theory. The papers and speeches published for the first time in this volume will be comprehensible to any well-educated person. They deal only in part with the central core of the theory; but the very fact that they carry its elaborations somewhat afield to particular applications and examples will help the scientific-minded layman to achieve a more complete comprehension of the theory itself. This book presents to the world at large for the first time what Einstein has really accomplished in the field of abstract physics. We cannot help but 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.1

Principles of Research

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

I am quite aware that we have just now light-heartedly expelled in imagination many excellent men who are largely, perhaps chiefly, responsible for the building of the temple of Science; and in many cases our angel would find it a pretty ticklish job to decide. But of one thing I feel sure: if the types we have just expelled were the only types there were, the temple would never have existed, any more than one can have a wood consisting of nothing but creepers. For these people any sphere of human activity will do, if it comes to a point; whether they become officers, tradesmen or scientists depends on circumstances. Now let us have another look at those who have found favor with the angel. Most of them are somewhat odd, uncommunicative, solitary fellows, really less like each other, in spite of these common characteristics, than the hosts of the rejected. What has brought them to the temple? That is a difficult question and no single answer will cover it. To begin with I believe with Schopenhauer that one of the strongest motives that lead men to art and science is escape from everyday life with its painful crudity and hopeless dreariness, from the fetters of one's own ever-shifting desires. A finely tempered nature longs to escape from personal life into the world of objective perception and thought; this desire may be compared with the townsman's irresistible longing to escape from his noisy, cramped surroundings into the silence of high mountains, where the eye ranges freely through the still, pure air and fondly traces out the restful contours apparently built for eternity. With this negative motive there goes a personal one. Man tries to make for himself in the fashion that suits him best a simplified and intelligible picture of the world; he then tries to some extent to substitute this cosmos of his for the world of experience, and thus to overcome it. This is what the painter, the poet, the speculative philosopher and the natural scientist do, each in his own fashion. He makes this cosmos and its construction the pivot of his emotional life, in order to find in 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 possible pictures? It demands the highest possible standard of rigorous precision in the description of relations such as only the use of mathematical language can give. In regard to his subject matter, on the other hand, the physicist has to limit himself very severely: he must content himself with describing the most simple events which can be brought within the domain of our experience; all events of a more complex order are beyond the power of the human intellect to reconstruct with the subtle accuracy and logical perfection which the theoretical physicist demands. Supreme purity, clarity and certainty at the cost of completeness. But what can be the attraction of getting to know such a tiny section of nature thoroughly, while one leaves everything subtler and more complex shyly and timidly alone? Does the 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 physics is based claim to be valid for any natural phenomenon whatsoever. With them, it ought to be possible

to arrive at the description, that is to say, the theory, of every natural process, including life, by means of pure deduction, if that process of deduction were not far beyond the capacity of the human intellect. The physicist's renunciation of completeness for his cosmos is therefore not a matter of fundamental principle.

The supreme task of the physicist is to arrive at those universal elementary laws from which the cosmos can be built up by pure deduction. There is no logical path to these laws; only intuition, resting on sympathetic understanding of experience, can reach them. In this methodological uncertainty, one might suppose that there were any number of possible systems of theoretical physics, all with an equal amount to be said for them; and this opinion is no doubt correct, theoretically. But evolution has shown that at any given moment, out of all conceivable constructions, a single one has always proved itself absolutely superior to all the rest. Nobody who has really gone deeply into the matter will deny that in practice the world of phenomena uniquely determines the theoretical system, in spite of the fact that there is no logical bridge between phenomena and their theoretical principles: this is what Leibnitz described so happily as a "pre-established harmony." Physicists often accuse epistemologists of not paying sufficient attention to this fact. Here, it seems to me, lie the roots of the 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 and endurance with which Planck has devoted himself, as we see, to the most general problems of physics, refusing to let himself be diverted to more grateful and more easily attained ends. I have 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 that of the religious worshiper or the lover; the daily effort comes from no deliberate intention or program, but straight from the heart. There he sits, our beloved Planck, and smiles inside himself at my childish playing-about with the lantern of Diogenes. Our affection for him needs no threadbare explanation. May the love of science continue to illumine his path in the future and lead him to the solution of the most important problem in present-day physics, which he has himself posed and done so much to 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 that anybody can confer on a man like myself. By electing me to your Academy you have freed me from the distractions and cares of a professional life and so made it possible for me to devote myself entirely to scientific studies. I beg that you will continue to believe in my gratitude and my industry 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 my sphere of activity, which is theoretical physics, towards experimental physics. A mathematician friend of mine said to me the other day half in jest: "The mathematician can do a lot of things, but never what you happen to want him to do just at the moment." Much the same often applies to the theoretical physicist when the experimental physicist calls him in. What is the reason for this peculiar lack of adaptability?

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

Once this formulation is successfully accomplished, inference follows on inference, often revealing relations which extend far beyond the province of the reality from which the principles were drawn. But as long as the principles capable of serving as starting points for the deduction remain undiscovered, the individual fact is of no use to the theorist; indeed he cannot even do anything with isolated empirical generalizations of more or less wide application. No, he has to persist in his helpless attitude towards the separate results of empirical research, until principles which he can make 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 heat radiation, and molecular movement at low temperatures. About fifteen years ago nobody had yet doubted that a correct account of the electrical, optical and thermal properties of bodies was possible on the basis of Galileo-Newtonian mechanics applied to the movement of molecules and of Clerk Maxwell's theory of the electro-magnetic field. Then Planck showed that in order to establish a law of heat radiation consonant with experience, it was necessary to employ a method of calculation the incompatibility of which with the principles of classical physics became clearer and clearer. For with this method of calculation Planck introduced the quantum hypothesis into physics, which has since received brilliant confirmation. With this quantum hypothesis he dethroned classical physics as applied to the case where sufficiently small masses are moved at sufficiently low speeds and high rates of acceleration, so that today the laws of motion propounded by Galileo and Newton can only be allowed validity as limiting laws. In spite of assiduous efforts, however, the theorists have not yet succeeded in replacing the principles of mechanics by others which fit in with Planck's law of heat

radiation or the quantum hypothesis. No matter how definitely it has been proved that heat is to be explained by molecular movement, we have nevertheless to admit today that our position in regard to the fundamental laws of this motion resembles that of astronomers before Newton in regard to the motions of the planets.

I have just now referred to a group of facts for the theoretical treatment of which the principles are lacking. But it may equally well happen that clearly formulated principles lead to conclusions which fall entirely, or almost entirely, outside the sphere of reality at present accessible to our experience. In that case it may need many years of empirical research to ascertain whether the theoretical principles 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 the constant velocity of light in empty space, which emerges from the optics of bodies in motion, by no means forces us to accept the theory of a stationary luminiferous ether. On the contrary, there is nothing to prevent our framing a general theory which takes account of the fact that in experiments carried out on the earth we are wholly unconscious of the translatory motion of the earth. This involves using the principle of relativity, which says that the laws of nature do not alter their form when one proceeds from the original (legitimate) system of co-ordinates to a new one which is in uniform translatory motion with respect to it. This theory has received impressive confirmation from experience and has led to a simplification of the theoretical description of groups of facts already connected together.

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

We have ascertained that inductive physics asks questions of deductive, and vice versa, to answer which demands the exertion of all our energies. May we soon succeed in making permanent progress 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 the 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 in terms of cause and effect. Certain it is that a conviction, akin to religious feeling, of the rationality and 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 the world of experience, represents my conception of God. In common parlance this may be described as “pantheistic” (Spinoza).
- (4) Denominational traditions I can only consider historically and psychologically; they have no other 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 advise you to stick closely to one principle: don't listen to their words, fix your attention on their deeds. To him who is a discoverer in this field the products of his imagination appear so necessary and natural that he regards them, and would like to have them regarded by others, not as creations of thought but as given realities.

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

Against such criticism I can defend myself from the personal point of view by assuring you that it is not at my own instance but at the kind invitation of others that I have mounted this rostrum, which serves to commemorate a man who fought hard all his life for the unity of knowledge. Objectively, however, my enterprise can be justified on the ground that it may, after all, be of interest to know how one who has spent a life-time in striving with all his might to clear up and rectify its fundamental concepts looks upon his own branch of science. The way in which he regards its past and present may depend too much on what he hopes for the future and aims at in the present; but that is the inevitable fate of anybody who has occupied himself intensively with a world of ideas. The same thing happens to him as to the historian, who in the same way, even though perhaps unconsciously, groups actual events 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 to the relations between the content of the theory and the totality of empirical fact. We are concerned with the eternal antithesis between the two inseparable components of our knowledge, the empirical and the rational, in our department.

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

But before mankind could be ripe for a science which takes in the whole of reality, a second fundamental truth was needed, which only became common property among philosophers with the advent of Kepler and Galileo. Pure logical thinking cannot yield us any knowledge of the empirical 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 particularly because he drummed it into the scientific world, he is the father of modern physics—indeed, of modern science altogether.

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

A complete system of theoretical physics is made up of concepts, fundamental laws which are 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 are

called axioms and there is no question of the conclusions having to correspond to any sort of experience. If, however, one regard Euclidean geometry as the science of the possible mutual relations of practically rigid bodies in space, that is to say, treats it as a physical science, without abstracting from its original empirical content, the logical homogeneity of geometry and theoretical physics becomes complete.

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

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

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

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

Actually the concepts of time and space appeared at that time to present no difficulties. The concepts of mass, inertia and force, and the laws connecting them seemed to be drawn directly from experience. Once this basis is accepted, the expression for the force of gravitation appears derivable 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, which comprised that of absolute rest, made him feel uncomfortable; he realized that there seemed to be nothing in experience corresponding to this last concept. He was also not quite comfortable about the introduction of forces operating at a distance. But the tremendous practical success of his doctrine may well have prevented him and the physicists of the eighteenth and nineteenth centuries from 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 idea that the fundamental concepts and postulates of physics were not in the logical sense free inventions of the human mind but could be deduced from experience by "abstraction"—that is to say by logical means. A clear recognition of the erroneousness of this notion really only came with the general theory of relativity, which showed that one could take account of a wider range of empirical facts, and that too in a more satisfactory and complete manner, on a foundation quite different from the Newtonian. But quite apart from the question of the superiority of one or the other, the fictitious character of fundamental principles is perfectly evident from the fact that we can point to two essentially different principles, both of which correspond with experience to a large extent; this proves

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

If, then, it is true that this axiomatic basis of theoretical physics cannot be extracted from experience but must be freely invented, can we ever hope to find the right way? Nay more, has the right way any existence outside our illusions? Can we hope to be guided in the right way by experience when there exist theories (such as classical mechanics) which to a large extent do justice to experience, without getting to the root of the matter? I answer without hesitation that there is, in my opinion, a right way, and that we are capable of finding it. Our experience hitherto justifies us in believing that nature is the realization of the simplest conceivable mathematical ideas. I am convinced that we can discover by means of purely mathematical constructions the concepts and the laws connecting them with each other, which furnish the key to the understanding of natural phenomena. Experience may suggest the appropriate mathematical concepts, but they most certainly cannot be deduced from it. Experience remains, of course, the sole criterion of the physical utility of a mathematical construction. But the creative principle resides in mathematics. In a certain sense, 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. The physical world is represented as a four-dimensional continuum. If I assume a Riemannian metric in it and ask what are the simplest laws which such a metric system can satisfy, I arrive at the relativistic 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 can 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 not disappear. De Broglie conjectured the existence of a wave field, which served to explain certain quantum properties of matter. Dirac found in the spinors field-magnitudes of a new sort, whose simplest equations enable one to a large extent to deduce the properties of the electron. Subsequently I discovered, in conjunction with my colleague, that these spinors form a special case of a new sort of 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 understanding of the existence of two sorts of elementary particles, of different ponderable mass and equal but opposite electrical charge. These semivectors are, after ordinary vectors, the simplest mathematical 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 them can be arrived at by the principle of looking for the mathematically simplest concepts and the links between them. In the limited nature of the mathematically existent simple fields and the simplest 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 the atomic structure of matter and energy. For the theory is fundamentally non-atomic in so far as it operates exclusively with continuous functions of space, in contrast to classical mechanics, whose 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, and Dirac, which operates with continuous functions, has overcome these difficulties by a bold piece of interpretation which was first given a clear form by Max Born. According to this, the spatial functions which appear in the equations make no claim to be a mathematical model of the atomic structure. 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. The notion is logically unobjectionable and has important successes to its credit. Unfortunately, however, it compels one to use a continuum the number of whose dimensions is not that ascribed to space by physics hitherto (four) but rises indefinitely with the number of the particles constituting the system under consideration. I cannot but confess that I attach only a transitory importance to this interpretation. I still believe in the possibility of a model of reality—that is to say, of a theory which 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 of the particles in a theoretical model. This seems to me to be the permanent upshot of Heisenberg's principle of uncertainty. But an atomic theory in the true sense of the word (not merely on the basis of an interpretation) without localization of particles in a mathematical model, is perfectly thinkable. For instance, to account for the atomic character of electricity, the field equations need only lead to the following conclusions: A portion of space (three-dimensional) at whose boundaries electrical density disappears everywhere, always contains a total electrical charge whose size is represented by a whole number. In a continuum-theory atomic characteristics would be satisfactorily expressed by integral 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 consider the quantum-riddle solved.

Johannes Kepler

IN ANXIOUS AND UNCERTAIN times like ours, when it is difficult to find pleasure in humanity and the course of human affairs, it is particularly consoling to think of the serene greatness of a Kepler. Kepler lived in an age in which the reign of law in nature was by no means an accepted certainty. How great must his faith in a uniform law have been, to have given him the strength to devote ten years of hard and patient work to the empirical investigation of the movement of the planets and to the discovery of the mathematical laws of that movement, entirely on his own, supported by no one and understood by very few! If we would honor his memory worthily, we must get as clear a picture as we can of his 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 clear grasp of the apparent movements of the planets in the heavens was by regarding them as movements around the sun conceived as stationary. If the planets moved uniformly in a circle around the sun, it would have been comparatively easy to discover how these movements must look from the earth. Since, however, the phenomena to be dealt with were much more complicated than that, the task was a far harder one. The first thing to be done was to determine these movements empirically from the observations of Tycho Brahe. Only then did it become possible to think about discovering the general laws which these movements satisfy.

To grasp how difficult a business it was even to find out about the actual rotating movements, one has to realize the following. One can never see where a planet really is at any given moment, but only in what direction it can be seen just then from the earth, which is itself moving in an unknown manner 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 was necessary first to try and find out about the motion of the earth itself. This would simply have been impossible if there had existed only the sun, the earth and the fixed stars, but no other planets. For in that case one could ascertain nothing empirically except how the direction of the straight sun-earth 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 with reference to the fixed stars, at least according to the accuracy of observation achieved in those days when there were no telescopes. By this means it could also be ascertained in what manner the line sun-earth revolves round the sun. It turned out that the angular velocity of this motion went through a regular change in the course of the year. But this was not of much use, as it was still not known how the distance from the earth to the sun alters in the course of the year. It was only when they found out about these changes that the real shape of the earth's orbit and the manner in which it is described were discovered.

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

This certainty made things easier. But how to ascertain the real shape of the earth's orbit? Imagine a brightly shining lantern M somewhere in the plane of the orbit. We know that this lantern remains permanently in its place and thus forms a kind of fixed triangulation point for determining the earth's orbit, a point which the inhabitants of the earth can take a sight on at any time of year. Let this lantern M be further away from the sun than the earth. With the help of such a lantern it was possible to 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 the sun S and the lantern M. If at this moment we look from the earth E at the lantern M, our line of sight will coincide with the line SM (sun-lantern). Suppose the latter to be marked in the heavens. Now imagine the earth in a different position and at a different time. Since the sun S and the lantern M can both be seen from the Earth, the angle at E in the triangle SEM is known. But we also know the direction of SE in relation to the fixed stars through direct solar observations, while the direction of the line SM in relation to the fixed stars was finally ascertained previously. But in the triangle SEM we also know the angle at S. Therefore, with the base SM arbitrarily laid down on a sheet of paper, we can, in virtue of our knowledge of the angles at E and S, construct the triangle SEM. We might do this at frequent intervals during the year; each time we should get on our piece of paper a position of the earth E with a date attached to it and a certain position in relation to the permanently fixed base SM. 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 this case, gave it to him. There was, for example, the planet Mars; and the length of the Martian year—i.e. one rotation of Mars around the sun—was known. It might happen one fine day that the sun, the earth, and Mars lie absolutely in the same straight line. This position of Mars regularly recurs after one, two, etc., Martian years, as Mars has a self-enclosed orbit. At these known moments, therefore, SM always presents the same base, while the earth is always at a different point in its orbit. The observations of the sun and Mars at these moments thus constitute a means of determining the true orbit of the earth, as Mars then plays the part of our imaginary lantern. Thus it was that Kepler discovered the true shape of the earth's orbit and the way in which the earth describes it, and we who come after—European and 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 line SE at any moment was known, and it was not so terribly difficult for Kepler to calculate the orbits and motions of the rest of the planets too from observations—at least in principle. It was nevertheless a 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 empirically known, but their laws had to be deduced from the empirical data. First he had to make a guess at the mathematical nature of the curve described by the orbit, and then try it out on a vast assemblage of figures. If it did not fit, another hypothesis had to be devised and again tested. After tremendous search, the conjecture that the orbit was an ellipse with the sun at one of its foci was found to fit the facts. Kepler also discovered the law governing the variation in speed during rotation, which is that the line sun-planet sweeps out equal areas in equal periods of time. Finally he also discovered that the 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 and reverence, the object of which is no man but the mysterious harmony of nature into which we are born. As far back as ancient times people devised the lines exhibiting the simplest conceivable form of regularity. Among these, next to the straight line and the circle, the most important were the ellipse and the hyperbola. We see the last two embodied—at least very nearly so—in the orbits of the

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 knowledge cannot spring from experience alone but only from the comparison of the inventions of the intellect with observed fact.

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

IT IS JUST TWO hundred years ago that Newton closed his eyes. It behooves us at such a moment to remember this brilliant genius, who determined the course of western thought, research and practice to an extent that nobody before or since his time can touch. Not only was he brilliant as an inventor of certain key methods, but he also had a unique command of the empirical material available in his day and he was marvelously inventive as regards mathematical and physical methods of proof in individual cases. For all these reasons he deserves our deepest reverence. The figure of Newton has, however, an even greater importance than his genius warrants because of the fact that destiny placed him at a turning point in the history of the human intellect. To see this vividly, we have to remind ourselves that before Newton there existed no self-contained system of physical causality which was 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 be traced back to a strictly regular series of atomic movements, without admitting any living creature or will as an independent cause. And no doubt Descartes had in his own way taken up this quest again. But it remained a bold ambition, the problematical ideal of a school of philosophers. Actual results of a kind to support the belief in the existence of a complete chain of physical causation hardly existed before Newton.

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

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

Galileo had already moved a considerable way towards a knowledge of the law of motion. He discovered the law of inertia and the law of bodies falling freely in the gravitational field of the earth, namely, that a mass (more accurately, a mass-point) which is unaffected by other masses moves

uniformly and in a straight line. The vertical speed of a free body in the gravitational field increases uniformly with the time. It may seem to us today to be but a short step from Galileo's discoveries to Newton's law of motion. But it should be observed that both the above statements refer in their form 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 external force? It was only by considering what takes place during an infinitely short time (the differential law) that Newton reached a formula which applies to all motion whatsoever. He took the conception of force from the science of statics which had already reached a high stage of development. The connection of force and acceleration was only made possible for him by the introduction of the new concept of mass, which was supported, strange to say, by an illusory definition. We are so accustomed today to the creation of concepts corresponding to differential quotients that we can now hardly grasp any longer what a remarkable power of abstraction it needed to reach the general differential law by this double crossing of frontiers, in the course of which the concept of mass had in addition to be invented.

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

On the strength of the foundation here briefly sketched Newton succeeded in explaining the motions of the planets, moons and comets down to the smallest details, as well as the tides and the precession of the movement of the earth—a deductive achievement of unique magnificence. The discovery that the cause of the motions of the heavenly bodies is identical with the gravity with which we are so familiar 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 workable and logically satisfactory basis for the actual science of mechanics; up to the end of the nineteenth century it formed the program of every worker in the field of theoretical physics. All physical events were to be traced back to masses subject to Newton's laws of motion. The law of force simply had to be widened and adapted to the type of event under consideration. Newton himself tried to apply the scheme to optics, assuming light to consist of inert corpuscles. Even the wave theory of light made use of Newton's law of motion, after it had been applied to the mass of a continuum. Newton's equations of motion were the sole basis of the kinetic theory of heat, which not only prepared people's minds for the discovery of the law of the conservation of energy but also led to a theory of gases which has been confirmed down to the last detail, and a more profound view of the nature of the second law of thermodynamics. The development of electricity and magnetism has proceeded right down to our own day along Newtonian lines (electrical and magnetic substance, forces acting at a distance). Even the revolution in electrodynamics and optics brought about by Faraday and Clerk Maxwell, which formed the first great fundamental advance in theoretical physics since Newton, took place entirely under the

egis of Newton's ideas. Clerk Maxwell, Boltzmann, and Lord Kelvin never wearied of tracing the electromagnetic fields and their reciprocal dynamic actions back to the mechanical action of hypothetical continuously diffused masses. As a result, however, of the hopelessness or at any rate the lack of success of those efforts, a gradual revolution in our fundamental notions has taken place since the end of the nineteenth century; theoretical physics have outgrown the Newtonian frame which gave 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 the impetus to overhaul them could only spring from the imperious demands of empirical fact. Before I go into this I must insist that Newton himself was better aware of the weaknesses inherent in his intellectual edifice than the generations of scientists which followed him. This fact has always roused 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 by experience and to introduce the smallest possible number of concepts not directly referable to empirical objects is everywhere evident, he sets up the concept of absolute space and absolute time for which he has often been criticized in recent years. But in this point Newton is particularly consistent. He had realized that observable geometrical magnitudes (distances of material points from one another) and their course in time do not completely characterize motion in its physical aspects. He proved this in the famous experiment with the rotating vessel of water. Therefore, in addition to masses and temporally variable distances, there must be something else that determines motion. This "something" he takes to be relation to "absolute space." He is aware that space must possess a kind of physical reality if his laws of motion are to have any meaning, a reality of the same sort as material points and the intervals between them.

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

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

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

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

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

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