EXPERIMENT & THEORY IN PHYSICS

It is natural that a man should consider the work of his hands or his brain to be useful and important. Therefore nobody will object to an ardent experimentalist boasting of his measurements and rather looking down on the 'paper and ink' physics of his theoretical friend, who on his part is proud of his lofty ideas and despises the dirty fingers of the other. But in recent years this kind of friendly rivalry has changed into something more serious. In Germany a school of extreme experimentalists, led by Lenard and Stark, has gone so far as to reject theory altogether as an invention of the Jews and to declare experiment to be the only genuine 'aryan' method of science. There is also a movement in the opposite direction which—though not racial—is not much less radical, claiming that to the mind well trained in mathematics and epistemology the laws of Nature are manifest without appeal to experiment. Two distinguished astronomers, Milne and Eddington, follow this philosophy, though it seems to lead them in rather different directions.

It is not my purpose here to discuss any of the fascinating theories of these men; but I wish to direct your attention to Eddington's philosophy, which proclaims the triumph of theory over experiment. I am a theoretical physicist (of Jewish origin) and might be expected to rejoice in this philosophy. But I do not rejoice.

On the contrary, I consider these ideas to be a considerable danger to the sound development of science. It is this conviction which has induced me to accept your suggestion of this difficult subject. However, I do not wish to argue with Eddington on deep philosophical principles, nor to compete with him in his unsurpassed mastery of dialectics in controversy. What I wish to show you in a simple way is the mutual relationship between theory and experiment in the actual historical development of science, and to offer a balanced opinion on the present situation and future possibilities.

But even this modest programme is not easy, because of the fact that an active scientist has little time to spend on the history of science. I have read very little, far too little, of the original literature, and the greater part of my knowledge is second-hand, taken from textbooks, handbooks and encyclopaedias. There are, however, two encouraging points. I know a few of the great classical masterpieces of mathematics and physics, enough to be certain about the historical and personal background on which they have grown. And secondly, I am old enough to say that in my own lifetime I have watched the development of modern physics, which means a very considerable part of the whole of physics. It seems to me that this provides sufficient material to form an opinion.

Scanning the history of science we notice a kind of cycle, periods of experimental expansion alternating with periods of theoretical development. Theories have a tendency to become more and more abstract and general. They culminate in principles which are first opposed by the philosophers, but later assimilated. As soon as they have become a part of a philosophical system there begins a process of dogmatisation and petrification. This feature is already noticeable in the oldest quantitative sciences, mathematics and astronomy. There is no doubt that the first geometrical knowledge discovered by the Sumerians, Babylonians and Egyptians was purely empirical. The Greeks discovered the logical interdependence of geometrical facts and founded the first deductive science as formulated in Euclid's work. If you are a modern mathematician you can of course look at geometry as a product of pure thinking, taking the axioms and postulates as definitions and the whole system as an entertaining game. But that is certainly not what the Greek philosophers meant their geometry to be: they believed they were dealing with properties of real things. The fact that the predictions of their theories were confirmed by experience in all cases led to the conviction that the axioms of Euclidean geometry contain final truth.

The Euclidean system has lived 2000 years. It has survived the decline and fall of the Graeco-Roman civilisation, and all the later upheavals of history. It went through all phases of more or less conscious dogmatisation. Even after the dawn of the modern scientific age with its critical revision of traditional opinions the actual validity of Euclid's statements was not doubted, but its possibility was made the object of philosophical speculations. Kant took it for granted that we have some direct and exact knowledge about certain things—space, time, causality, etc.—and explained it by the assumption that actually we have to do not with the things themselves, but with the forms of our intuition of these things. It is plausible that these forms of thinking are given to us *a priori*, that is prior to experience. Kant's main example of *a priori* knowledge were the theorems of geometry, *ipso verbo* understood to mean Euclid's canon.

The idea that we can produce knowledge *a priori* has its roots in the historical fact of the persistence of Greek geometry, which was replaced by a more general theory only in our own time. The real reason for the longevity of Greek geometry is the accuracy with which it describes the behaviour of bodies in our terrestrial surroundings. The first doubts were raised not on account of experimental evidence, but on logical grounds. Some mathematicians found one of Euclid's axioms, that about parallel lines, less evident than the others and began to wonder whether it could not be proved from the rest. All efforts to do this were in vain, and in the end the attempt was made (first by Gauss, but not published; then independently by Bolyai and by Lobachevsky) to prove the independence of the axiom of parallels by constructing a system of geometry in which it did not hold. These constructions of non-Euclidean geometry were successful. Gauss even made measurements in order to find out which geometry is valid in the real world. He and his successor Riemann clearly realised the empirical character of geometry. Riemann created the mathematical foundations on which Einstein, in our own time, succeeded in reducing geometry to a part of physics by his general theory of relativity.

The history of astronomy is parallel to that of geometry with the difference that some of the Greek philosophers already had clear ideas about the spherical

Cambridge University Press
978-1-107-66566-8 - Experiment and Theory in Physics
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Excerpt
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shape of the earth, the central position of the sun in the planetary system and about the real distances between its members, ideas which were lost or suppressed in the dark ages. The Church had accepted Greek philosophy and science in the form given to it by Aristotle and Ptolemy. Looking at this historic phenomenon from our point of view we may say that the stagnation of science in the middle ages is due to an excessive veneration for the mind as opposed to material phenomena, leading to a preference for theoretical speculation rather than experiment.

Indeed, the beginning of modern science in the Renaissance consisted in a new philosophy, which considered systematic experiment to be the main source of knowledge. Francis Bacon was its prophet, Galileo and Newton its real founders. Scholastic philosophy was already assailed by Descartes and other philosophers, who used mainly logical and metaphysical arguments; the theories of the Universe of these rationalists, however, seem to us unconvincing, as they are not based on sufficient evidence of observation or experiment. For the essential distinction between our time and the middle ages consists in the renunciation of tradition and the establishment of experience as the true source of knowledge. The Renaissance meant not only the rediscovery of Greek literature, but a revival of the Greek spirit, of the sceptical and at the same time constructive attitude of Greek philosophy. Then the method of inductive reasoning was established, which leads from single observations to general laws. This method itself can be made an object of philosophical analysis; it is clear that it presupposes not only a fundamental belief in the existence of natural laws, but also criteria for distinguishing genuine regularities from accidental ones, and other principles of this kind. But I cannot dwell on these abstract problems. I only wish to state that the revolution which replaced scholasticism by modern science has dethroned the deductive method from its dominating position and put it in its proper place. Both Galileo and Newton were absolutely clear about the inductive character of the new philosophy; the theories which they formed by synthesis of experimental results were used for suggesting new experiments, and if these tests were favourable the theory was considered as confirmed. That is the legitimate method of science, a blending of deduction and induction, which is described in innumerable textbooks. But it is not the whole story.

Galileo and Newton were both anxious to avoid metaphysical speculation (*hypotheses non fingo*). But a short time later, when the laws of mechanics were fully known, we find attempts to derive them from principles which by their formulation suggest some non-empirical origin. The most successful of these principles is that of least action. Maupertuis was certainly led to it by a teleological idea; Nature was supposed to act like a human being, with a definite purpose which it tries to attain with the smallest amount of 'action' possible. Why the mathematical expression which he gave for this action should be so dear to Nature as to be spent parsimoniously is of course difficult to explain. We know to-day that the actual motions do not correspond to real minima of action except for short time intervals, but to stationary states, and we consider the principle of least action only as a very useful and powerful tool for condensing complicated differential equations in a short expression.

The power of this principle, in the form given to it by Hamilton, is seen by the fact that not only classical mechanics of particles and rigid bodies, but also elasticity and hydrodynamics, electromagnetism and all the modern field theories connected with ultimate particles (electron, proton, meson) can be formulated with its help. To give an example, let us consider electromagnetism.

For this purpose assume the existence of a scalar potential Φ and a vector potential A, and introduce for the sake of abbreviation the vectors

$$E = -\operatorname{grad} \Phi - \frac{1}{c}\frac{\partial A}{\partial t}, \quad H = \operatorname{curl} A. \tag{1}$$

Then the principle of action for electrodynamics in empty space is given by

$$\delta \iint \tfrac{1}{2}(E^2 - H^2)\, dv\, dt = 0, \tag{2}$$

where dv is the element of volume and the integration is extended over the space and time considered, while the symbol δ means a small variation of the potentials.

The results of this variation are conditions in the form of differential equations, and these turn out to be Maxwell's equations

$$\operatorname{curl} H = \frac{1}{c}\frac{\partial E}{\partial t}, \quad \operatorname{curl} E = -\frac{1}{c}\frac{\partial H}{\partial t} \tag{3}$$

for empty space, provided E and H are interpreted as the vectors of the electric and magnetic field.

The variational principle has something convincing in the way it condenses a great domain of phenomena in one short expression, and this perfection is further enhanced if it is considered with the eye of the mathematician, who has learnt the principle of relativity and knows that E and H together form a so-called six-vector having definite transformation properties for changes of the frame of reference, i.e. Lorentz transformations of space and time. For there exist only two invariants, E^2-H^2 and $(E.H)^2$, and as the electrodynamic action must be invariant, it can be only a function of these; add to this the postulate that the resulting equations ought to be linear, then the action must be quadratic, and you are led directly to the expression given above.

This seems to be straightforward reasoning from first principles. Given the knowledge and the penetrating brain of our mathematician, Maxwell's equations are a result of pure thinking and the toil of experimenters antiquated and superfluous.

I need hardly explain to you the fallacy of this standpoint. It lies in the fact that none of the notions used by the mathematicians, such as potential, vector potential, field vectors, Lorentz transformations, quite apart from the principle of action itself, are evident or given *a priori*. Even if an extremely gifted mathematician had constructed them to describe the properties of a possible world, neither he nor anybody else would have had the slightest idea how to apply them to the real world. The problem of physics is how the actual phenomena, as observed with the help of our sense organs aided by instruments, can be reduced to simple notions which are suited for precise measurement and used for the formulation of quantitative laws. It was a long way from the first observation of simple electric phenomena, like the attraction of small particles or the observation of small sparks, to the concept of electric field and potential, a still longer way to the interaction of these with the corresponding magnetic forces, and to the system of Maxwell's equations connecting them.

When I was a student, forty years ago, the idea of the field *in vacuo* was extremely strange to us, assimilable only with difficulty. From this point to the full development of relativity with its formal apparatus of Lorentz transformations, its invariants, covariant vectors and tensors is again a long and tedious journey. The relativisation of time was forced upon us: Einstein's paper was later than the experiments of Michelson and Morley, and even Lorentz himself was reluctant to give up his absolute stationary ether and to accept the equivalence of different times admitted by his transformations.

The order of historical events clearly shows the true position of the variational principle: It stands at the end of a long chain of reasoning as a satisfactory and beautiful condensation of the results. It may even have helped to find these results (though I doubt it in this case of electromagnetism). But it has little to do with the formation of the fundamental new concepts which are the characteristic feature of electrodynamics. The revolutionary conception which distinguishes electrodynamics from classical mechanics is that of the field. One can see in Faraday's work how it sprang from his observations of dielectric, paramagnetic and diamagnetic properties; but it needed Maxwell's powerful mathematics to formulate it. However, that was not mathematics pure and simple, but an amazing act of divination. The facts known at the time would have led (for the vacuum) not to the complete set of equations (3), but instead of the first one to

$$\text{curl } H = 0.$$

Maxwell's decisive step consisted in adding the missing term $\frac{1}{c}\frac{\partial E}{\partial t}$ without proper empirical foundation, first guided by mechanical models of the ether, later by reasons of mathematical perfection or beauty, or however you may describe the act of genius. It is this term which leads to the prediction of waves with the finite velocity c, to the electromagnetic theory of light, to wireless and all that modern radio-engineering stands for.

Indeed this is a brilliant example of the possibilities which exist for the theoretical physicist: he can trace deficiencies in the perfection of a theory and can try to amend them by what you may call 'mathematical guessing'. If he is successful, if the modified theory predicts phenomena confirmed by new experiments, we may call these 'synthetic' predictions. This kind of prophecy is rarer but much more impressive—at least in my opinion—and generally of much greater importance than the normal 'analytical' type of scientific prophecy based on well-established theory. Of the latter kind there are so many examples that it is difficult to pick out a characteristic one. They happen in the everyday life of a physicist or engineer who designs an apparatus and expects it will work 'according to plan'.

If you enter a room and you see the head and body