PHYSICAL SCIENCE and the OBJECTIVES of the SCIENTIST

Science and philosophy, the author suggests, have a mutual need for mutual understanding which poses an important and perhaps vital problem in education.

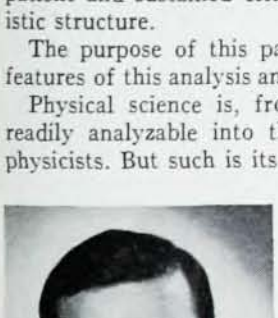
By John J. FitzGerald

THE HISTORY OF WESTERN THOUGHT since the seventeenth century leaves little doubt as to the practical validity of the method of controlled quantitative analysis discovered by Galileo, interpreted by Descartes, and variously generalized by Newton and Einstein. The impact of its success on every level of human activity—religious, political, industrial, and educational (to mention only the more obvious ones)—has awakened the most diverse and even contradictory speculations as to the specific character of the science it yields and the precise intentions of those who engage in it. Often enough, one gathers the impression that these speculations are founded on an arbitrary and quite uncritical conception of the nature of modern science; a conception formulated in terms of what one thinks or wishes to think science is from its effects upon the extrascientific domain (which, in the present context, includes philosophy) rather than in terms of a patient and sustained critical analysis of its characteristic structure.

The purpose of this paper is to suggest the typical features of this analysis and the critical insights it yields.

Physical science is, from this point of view, most readily analyzable into the specific operations of the physicists. But such is its complexity and high specialization that there are few, if any, physicists equally competent in all its operations. Accordingly, it is convenient to classify them as experimentalists, theorists, and criticists to investigate the characteristic functions of each. One may, of course, be any one of these without being the others, but from the viewpoint of physics all are required. As a first approximation, therefore, we may describe physical science as the integrated product of the collective operations of the three types of physicists. If we correlate these types according to the decreasing density of their population, we find the experimentalists most numerous, then the theorists, and finally the criticists. This superficial feature is undoubtedly connected with the ascending order of generality and synthesis which characterizes the specific operations of the three types. In this connection, we may say that the experimentalist is closer to tangible, concrete nature; the theorist, depending as he does upon the data provided by the experimentalist, is one step removed from the experimentalist, and the criticist, depending in his turn upon the conclusions reached and the procedures employed by the theorist, is a step removed from the latter. In practice, of course, these relations between the three types are not so nicely unidirectional, as will become clear when we consider their typical functions in operation. To know the basic character of physical science, therefore, it will be necessary to consider in greater detail the essential notes of each of these fundamental types of physical operations, namely, the experimental, the theoretical, and the critical.

Consider first the experimentalist: his primary function is to expose and verify new data or to describe more precisely data which have already been exposed. He seeks not only to extend our objective knowledge of the universe of common sense experience but also to probe beneath its apparent surface. The results of his systematic and experimentally controlled investigations are averaged and expressed in conventional symbols which are readily communicated and understood



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because of their objectivity. In the most general terms, this objectivity consists in the complex knowledge and skill to construct, apply, read, and interpret instruments of measure. How else is it possible to produce data which can be duplicated and verified in approximately identical terms? This characteristic experimental procedure has been appropriately designated the method of controlled quantitative analysis, and consists substantially in substituting for the content of the immediate incommunicable sensations of the individual observer the significant readings of instruments which are not only more sensitive to certain changes in the space-time continuum of events but also less subjective than our immediate and unaided sense perception.

It is noteworthy that such instrumental procedures are, like the senses for which they substitute, instruments of identification or observation, but unlike the unaided senses they are artificial rather than natural instruments. By exploiting certain regularities originally observed by the unaided senses, such procedures enable the experimentalist to focus and reduce the bewildering qualitative richness presented in spontaneous sensation to relatively simple space-time differences registered on instruments. Thus, the ordinary mercury thermometer exploits the more primitive and direct observation that heat expands solids and substitutes for our tactual perception of heat differences the visual perception of the coincidence of the surface of the mercury column with one of the graduated markings of the tube.

In this way, the experimentalist, by a process of substitution, translates the qualitative richness of direct perceptual data into more or less quantitative terms. The qualification "more or less" is especially relevant here as it conveys the fact that the numbers furnished by experimental procedures are concrete or physical rather than abstract or arithmetical and consequently possess the curious advantage of conveying a physical meaning in a mathematical form. As concrete or physical numbers they embody a twofold reference not involved in arithmetical quantities as such. In the first place, their physical meaning and content are inseparable from instruments which can never achieve an absolute precision. Second, the personal errors of the observer who records them are inescapable however refined the statistical procedures which permit some substantial practical control over such personal factors. A reliably complete exposition of the more typical features of the experimentalists' operations should not ignore the fact that, at least in classical physics, the most irreducible measures of distance and time involved the unverified assumptions of the existence of rigid bodies and simultaneous events.

We might remark here that the substitution of indirect or mediate observations through artificial instruments for the direct observations of the senses does not necessarily imply, as some philosophers and scientists would have it, that the special senses are purely subjective, but only too subjective to be physically useful and reliable. By the use of instrumental procedures the experimentalist simply passes from the psychophysiological relativity of uncontrolled qualitative sense experience to the instrumental relativity of controlled quantitative scientific experience.

Finally, most physical instruments are themselves complicated mechanisms, the use and significance of which are determined quite as much by theoretical considerations as by experimental requirements. As a result, not even a good technician may establish himself on the fictive unshakeable solidity of the so-called brute fact. Anyone of normal sensibility may detect the rate of ticks of a Geiger counter, but to interpret its physical significance a considerable theoretical and experimental knowledge is required. Experimental data today is so loaded with theoretical references that, though the experimentalist need not be a theorist, he must understand the results of relevant theories.

By way of summary, we may recall that the experimentalist appears to be concerned chiefly with the accumulation and specification of objective data; that these data are expressed in the concrete numbers furnished by instruments of measure or mathematical operations upon such numbers; that a physical object, as distinguished from a prescientific experienced thing or event, is described by enumerating the significant readings of the instruments through which it is observed or observable. In varying degrees such a method inescapably isolates from the prescientific experiential context factors which in the context of the original experience are not isolated. Prior to this instrumental isolation or scientific selection, the experimentalist stakes out that part of the indispensable original section of experience which he wishes to investigate. In this respect he controls space-time reality quite as much as it controls him. Even on the experimental level these selective operations of the scientist are always operative. Between the laboratory and nature-in-the-raw, there exists a gap which the unavoidably selective operations of experimental science can never fully close.

Parenthetically, it is of some interest to note that the conditions which limit the selective operations of the individual experimentalist are usually specified by others, even though in the first instance they may be specified by some one individual. To be physically significant, such selected data must be susceptible of repeated verification. Thus, there appears a characteristically cumulative quality in the control and interpretation of experimental data. Within the limits of brute matter, on the one hand, and the method of controlled quantitative analysis on the other, the possibilities of progress on the experimental level appear to be unlimited. Instruments and the conditions of their application appear to be susceptible of unlimited improvement or variation. Yet the condition of this progress remains just that historical traditional cooperation and communication which have given rise to the international community of scientists—a community which is sometimes misconstrued as a voluntary association of world citizens. Though one may, perhaps, voluntarily enter into the association, once admitted, one may not voluntarily alter the inner necessities of the community itself. Such inner necessities arise in the first instance out of the operational procedures of physical sciences as such. Even in its external social features, such science appears to be essentially relative.

TO RETURN to the narrower limits of strictly experimental operations, and at the same time to anticipate a possible misconstruction of the role of the experimentalist, let us consider another and even more significant part of his work, namely, the discovery and formulation of the constant relations which appear between the isolated measures with which he describes nature. The expression of these experimentally observed relations in appropriate conventional signs constitutes an empirical law. Obviously such laws are no more necessary and absolute than the terms or data between which the relations they express are observed to occur. If historically one may point out instances of apparently pure empirical laws, actually physical science has developed to such a stage of formulation and construction that it seems doubtful whether any such purely empirical law exists. For in addition to being data, and as such discoverable by the experimentalist, these empirical relations provide the point of departure for the construction of physical explanations or theories. As a result of this involvement, they acquire a theoretical reference which gradually becomes all but inseparable from their experimental meaning. Hence, physical laws are apt to be considerably more complex in meaning than they appear in their initial experimental formulation.

At least three different but related concepts of law appear in contemporary physical science. At the experimental or empirical level, as noted, a law may appear to be no more than the conventional formulation of a constant relation observed between the distinct properties of a system. In this sense, Ohm's law or the laws of chemical reactions appear to be no more than the statements of observable relations between the number measures provided by appropriate instrumentation applied, under suitable conditions, to a selected area of events. As strictly experimental, such laws simply summarize the evidences of experimental investigations to date. As experimental, they simply state a fact without assigning any reason for the fact. They state that there does in fact exist such a relation between a given set of number measures that any variation in any one member of the set is found to involve a proportionate variation in the other members. In this strictly experimental sense, one may formulate the meaning of a physical law as follows: if a cause, with which the law is completely unconcerned, modifies one of the magnitudes in the observed relation expressed in the law, then the quantitative value of the other terms is found to be modified; if one of the terms of the relation is the measure of time, the law will simply state that the other measures vary in function of the time measure and nothing more. In this sense, the law may very well state that an antecedent precedes a consequent but not because it is the antecedent in the causal sense. In short, on the strictly experimental level, physical laws do not appear to express causal relations and hence do not constitute adequate grounds by themselves for firm prediction.

A more complex and usual sense of the concept of law is apparent when we consider that the theoretical accounts of such experimental regularities introduce into their meaning an extrinsic formal or structural relation which makes possible the unification or synthesis of the laws themselves. In this respect, an experimental law acquires a meta-empirical and more universal reference so that it refers not only to all observed past instances but also to all observable future instances. In this sense an experimental law is additionally the logical consequence of certain theoretical postulates.

Sometimes the postulates themselves from which the experimentally observed laws may be deduced are called laws. The law of universal gravitation is a case in point. From the physical point of view this appears arbitrary and probably arises from the fact that the postulates are suggested by the laws which they are constructed to explain. Since the observed laws are more-or-less constant relations between experimental quantities, it is not surprising that the postulates proposed to explain them should take the form of more general relations between the most fundamental ideal magnitudes. Nor is it surprising that such postulates should be quite as relative as the empirical data which they explain. At this point, however, our concern is rather with the consequences of the theoretical postulates than with the postulates themselves. For these consequences are, at least in part, susceptible of experimental verification and correspond with the laws which the postulates are proposed to explain. In this context, physical laws are impregnated with theoretical references in virtue of which they may be said to be causal. This, perhaps, is the concept of law which provides the firm and habitual basis of scientific prediction shown most strikingly in Newton's law of universal gravitation or Einstein's law of the conservation of mass-energy. The causes, however, implied in these laws are constructed rather than found by the physicist. On the basis of the experimental evidences of which he disposes, these possible causes are the most *convenient* substitutes conceivable by the theorist for the unknown, or even physically unknowable, real causes in nature.

In a yet wider context, on the strength of the repeated verifications of the laws both in the experimental and hypothetico-experimental sense, the spontaneous prescientific conviction in the constancy and harmony of nature is strengthened and there emerges the most general concept of law as "the essential connectivity" of natural events, to use the suggestive terminology of Bridgman. In this sense, the concept of law seems to have a reference to much more than the postulated or possible causes of physical theory. Its reference extends to the real cause or causes operating in nature as given brutally in experience, causes which transcend and are presupposed by the characteristic operations of physics at every level. Such a concept is not susceptible of strictly scientific formulation in the physical sense and lies at the roots of the intelligibility of nature and man alike. It was undoubtedly this concept which Leibnitz had in mind in his formulation of the principle of sufficient reason.

INEVITABLY THE ANALYSIS of the experimental meaning of physical law involves us in a reference to physical theory, the domain of the theorist, in which alone its complete meaning may be grasped. We may therefore turn to a general analysis of the characteristic operations of the theorists. As already suggested, the materials with which the theorist works are largely provided by the experimentalist, but the forms are in part provided by the mathematician.

There is a grave danger of misrepresenting the nature of physical theory today as a result of misinterpreting the sense of its mathematical structure. By emphasizing the experimental origins which inspire as well as confirm the theory, it is possible to avoid misinterpreting its mathematical formalism. In physical science, a theory appears to be related to experimental laws in a way closely analagous to the way in which the laws are related to the isolated number measures which they correlate. In other words, just as a law in physical science expresses in the form of a general algebraic relation a relational property of separate scientific facts, so a theory expresses a general relational property of separate laws. The theory synthesizes or unifies the apparently unrelated laws by implying them in a postulated relation or equation from which they may be mathematically derived. The terms of such a postulate must, at least in the principal part, be physical rather than purely mathematical; they must be susceptible of physical specification and indirect experimental verification. This possibility of physical specification is equivalent to what Bridgman, if I interpret him correctly, has called "the indispensable text of every physical theory".[1]

In general, physical theories appear to be of two types which we may designate the mechanical model and the physico-mathematical theory. These types are not mutually exclusive, however, since the mechanical model may be represented as a special case of the more general mathematical type. The mechanical type consists substantially in imagining and constructing a mechanism, the behavior of whose parts produces effects similar to phenomena observed in nature. It was this type which Einstein and Infeld apparently had in mind when they wrote: "In our endeavor to understand reality we are somewhat like a man trying to understand the mechanism of a closed watch. He sees the face and the moving hands, even hears its ticking, but he has no way of opening the case. If he is ingenious he may form some picture of a mechanism which *could* be responsible for all the things he observes, but he may never be quite sure his picture is the only one which could explain his observations."[2]

Not only is it possible to find a mechanistic explanation for any ordinary physical phenomenon but, as Poincaré has pointed out, the number of such explanations for a given phenomenon is infinite. The value and importance of the mechanical model type are not that it gives or even could give an exact representation of the real nature of the natural phenomena which it proposes to explain, but rather that it offers a convenient and coherent unification of the quantitative relations observed in nature as well as an appropriate analogy in which to describe them.

In modern physics, the mechanical model has been largely succeeded by the physico-mathematical type as a result of new experiences which are so far removed from ordinary experience that the investigator is unable to find in them the counterpart of any of the objects of ordinary experience. At least one requirement must be met in a physico-mathematical theory which need not be met in a purely mathematical theory: ". . . it should provide the tools for calculating the behavior of the physical system which it is constructed to explain, and it is capable of doing this if there is correspondence between those aspects of the physical system which it engages to reproduce and *some* of the results of the mathematical manipulations."[3]

Unlike the mechanical type, the physico-mathematical theory may and does involve symbols which have no physical counterparts. Accordingly, in this type, the explicit and independent operations of the theoretical intelligence become discernible and the physicist may become more clearly aware of the intrusion of the discursive intellect into his account of the universe. We say "may" here by way of acknowledging the tenacity with which some critics of physical theory even at the level of modern theory still cling to the belief that these operations are reiterative of the space-time reality itself. Bridgman describes the belief that all the steps in a mathematical theory must have their counterpart in the physical system as "the outgrowth of a certain mystical feeling about the mathematical construction of the physical world. Some sort of idea like this," he continues, "has been flitting about in the background of the paraphernalia of the thinking of civilization at least since the days of Pythagoras, and every now and then, perhaps after some particularly striking mathematical success, it bursts forth again like a crop of mushrooms after a rain, as in the recent fervid exclamation of Jeans that 'God is a mathematician'. This mystical feeling involves a feeling for the 'real existence' of principles according to which this universe is run. We have seen how meaningless is the contention that principles exist independent of the mind in which they are formulated. What Jeans might have said is that man is a mathematician, and reflected that it is no accident that he forms nature in his own image."[4] I am not so sure that Bridgman's account would be any more acceptable to many than was Jeans' to him. Be that as it may, it remains that on the level of physico-mathematical theory, correct interpretation involves something considerably more than would have been admissable in physical science not so many years ago. As physics has become more conscious of its own most successful procedures it has become more modest as to the absolute significance of its results.

In themselves, physico-mathematical theories may make no serious claim to expressing the universe of nature as it really is. They prescind entirely from the problem of "real existence" which transcends their specific competence. Their unique role is to synthesize *experimental* data in such wise that from their principles may be deduced verifiable quantitative relations as logically necessary consequences. At most, they present a possible picture of nature as shown mediately by actual or possible experimental observations. On these grounds, Eddington's designation of the "physical universe" as the theme of physical science has much to recommend it. On the strictly theoretical level of physical science, we may concur that the 'observed universe' with which physical theories are concerned is really the universe of scientific items provided by experimental procedures as distinguished from the real universe of obscurely distinguishable things and events apprehended through our unaided senses. The wider universe which is the stage of all human and natural activities, though unintelligible from the strictly physical point of view, is more intelligible in itself, providing as it does the initial and final point of reference without which physical science itself collapses. If a growing and sobering awareness of the limitations of his specific operations has convinced the physicist that the problem of existence or reality does not concern him as physicist, it has not convinced him that he must face it on other grounds. If man were just a mathematician or physicist the problem would be less intrusive; but, as he is, the problem intrudes into all areas of human thought to the extent that we might with confidence describe the intelligence generally as the faculty which seeks naturally the meaning of existence.

RELATIVITY THEORY AND QUANTUM MECHANICS made explicit a factor which was always implicit but hitherto unrecognized in every physical theory—namely, the inner necessities of the intelligence which constructs theories on the basis of data provided by controlled experience. At this point, the critical or evaluative phase of scientific activity became a part of physical science itself rather than a luxurious and superfluous speculative exercise, as the epistemological inquiries of a Mach or a Poincaré had appeared to some of their more down-to-earth colleagues.

But at this point, physical science transcended its classical limits into the realm of critical philosophy where, understandably enough, it has not felt entirely at home. Eddington has described the sentiments of the scientist beholding himself in the mirror of philosophy. "Theoretical physicists," he wrote, "through the inescapable demands of their own subject have been forced to become epistemologists, just as pure mathematicians have been forced to become logicians. The invasion of the epistemological branch of philosophy by physics is exactly parellel to the invasion of the logical branch of philosophy by mathematics."[5]

Whatever our estimate of the form in which he expresses it, the authentically philosophical character of Eddington's insight is inescapable. Science, in the restricted sense in which we have considered it, reaches beyond itself in order to know itself. In the process it is confronted with values of another order to which its successful procedures are no longer applicable. In this order scientific isolationism has become quite as impractical as political isolationism. In this order, the scientist is confronted not only with the objectives of science but with his own objectives as scientist.

At least in the practical order, the question of the aims of science has become inseparable from the question of the aims of the scientist, a question which somehow involves the wider issue of the aims of man. The answer to the first question may involve a tedious analysis, of which the broadest features I have tried to suggest in this paper, but eventually it finds its resolution in that self-knowledge of the criticist out of which emerges the broadest issue of the objectives of the scientist in society. The critical operations of modern science in themselves are not science according to any of its traditionally recognizable features, but rather philosophy, and accordingly must be studied in a new light with methods appropriate to the inner necessities of the philosophical discipline. Materially, scientific epistemology belongs to physical science in the sense that the data and operations analyzed are those of physical science. But formally it belongs to philosophy since what is sought are the character and limits of those data and procedures. The object of such a critical investigation therefore is not merely the structure of science but also the instrument with which man erects the structure. The structure is always relative and never complete but the architect, the human intellect, remains identical to itself throughout its interminable quest into the problems of the measurability and control of nature.

If classical physics in its origins abandoned the search into the real natures of things for practical and historical reasons, in its development it often forgot this prudent restriction enunciated by Newton, and mistook its own creations for these forbidden natures. In so doing, the individual scientist was responding to an impulse or instinct which is prior to and greater than the scientific impulse as such. At length the inner necessities of his own creation have forced him to transcend the artificial limits established by the originators of modern science. He has become, for better or worse, in part a philosopher; and shockingly enough he has and must become a philosopher in order to understand his own science.

This circumstance has not failed to elicit undiscerning and complacent invitations to the scientist to enter upon the more enduring grounds and brighter horizons of philosophy. But it would seem that he need not be lured from without where he might more surely enter from within. If the effort to substitute science for philosophy has failed, so also, it must be admitted, has the effort of some philosophers to ignore science. It is difficult to see how a living philosophy may stand aloof —reconciled apparently to an appalling ignorance of the vastly detailed, rigorously coherent structure of modern science whose demonstrable success has conferred upon its architects the irksome glory and heavy responsibility of keeper of the arms in this bewildered and divided world. The scientist, fully as conscious of his role as the prodigal son of old, is returning in spite of himself to his father's house. In short, at the critical level, scientist and philosopher alike have much to offer one another. For if the physicist can no longer ignore philosophy, except perhaps as a highly skilled technologist, neither can the philosopher ignore science, except perhaps as a historian of some specific doctrine or system. To understand not only their own sciences but, more importantly, to understand the one universe of which those sciences are the intelligible account to date, each needs the other.

It is this mutual need, as yet only vaguely understood and not widely grasped, which seems in part to underlie the crisis in our contemporary education. For, granting the desirability of meeting the need, the question naturally arises how it can be met. The average individual does not live long enough, given the organization and ill-defined aims of contemporary education, to become "informed", to say nothing of "formed", in both science and philosophy. At present, specific training in either field employs techniques and methods which beget specifically different dispositions of thought and hardly transferable insights. In consequence some scientists, in response to the needs of their own advancing science, have tended to philosophize without benefit of a sufficient formation in philosophy, and some philosophers have attempted to interpret science without sufficient understanding of its inner character. Instead of integration this situation has produced disintegration, with the dismal result that those who have achieved the greatest control over nature appear to understand the least of nature in itself. History appears to have summoned the scientist from the splendid isolation and genteel association of the laboratory and the scientific community into the seething forum of human events of which physical science in operation is but a small, though brilliant, facet. If matter yields its secrets in part through atomization and quantization, man does not. The comfortable illusion that nature can be explained in uniquely scientific terms has been exploded by science itself.

I think we may conclude then with the suggestion that the nature of science and the objectives of the scientist may not be grasped outside of a philosophical perspective to which science itself leads. To elaborate these objectives requires something more than a knowledge of physical science—a something more which our educational program as presently constituted does not provide.

References

[1] P. W. Bridgman, *The Nature of Physical Theory*, p. 59. Princeton University Press, 1936.
[2] A. Einstein and L. Infeld, *The Evolution of Physics*, p. 33. Simon & Schuster, 1938.
[3] P. W. Bridgman, Op. Cit., p. 65.
[4] Ibid., p. 67.
[5] Sir Arthur Eddington, *The Philosophy of Physical Science*, pp. 6–7. Cambridge University Press, 1939.

Books

Tensor Analysis for Physicists. By J. A. Schouten. 276 pp. Oxford University Press, New York, 1951. $6.00.

Rarely does a reviewer have the privilege of finding himself at complete loss for adequate words of praise; such is indeed the case with Professor Schouten's work. It is the conception of the master craftsman, the incisive execution of a massive form yet fluid and graceful in the sure coherence of its underlying structure and detail: a work of art!

In the brief space allowed, one can only hope to suggest the principal theme: the invariant (qua group) theoretic development of the theory of geometric objects, "affinors". To this extent, therefore, the title, presumably dictated by customary usage, does not give a true impression of either the book's fundamental scope or its intrinsic difficulty for those whose acquaintance with tensor analysis is usually conditioned by the study of relativity.

Part I of this volume follows in full and exhaustive manner the logical development of (parentheses are mine): 1. Spaces Defined by Linear Groups (the affine group G_a and its subgroups); 2. Geometric Objects in E_n (an affine space, the manifold of all linear transformations); 3. Illustrations of Quantities in E_n After Introducing a Subgroup of G_a; 4. Geometric Objects in X_n (the manifold of all invertible analytic transformations); 5. Geometry of Manifolds Which Have a Given Displacement. This is followed by a concise summary of these five chapters, and special mention should be made of Professor Schouten's positive gift for visualization and diagrammatic presentation of geometric entities which are elsewhere usually left in abstracto.

Part II develops applications according to: 6. Physical Objects and Their Dimensions; 7. Applications to the Theory of Elasticity; 8. Classical Dynamics; 9. Relativity; 10. Dirac's Matrix Calculus. In each chapter, though necessarily brief, the reader cannot fail but be impressed by the sureness of treatment and the repeated selection and illumination of the "essentials". Finally, it is for many reasons interesting to see Dirac's methods so fully appreciated and evaluated within a broader framework by one of the finest mathematical minds of our times.

It is a privilege to unqualifiedly recommend this distinguished work, nor can I omit mention of the elegant reproduction which again marks an Oxford volume.

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