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PERMANENT ELEMENTS IN THE FLUX OF PRESENT-DAY PHYSICS[1]

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MANY of us could, I believe, confess to a feeling of breathlessness at the rapid changes of our present physical progress, and some of us might even, in a moment of candor, admit a little resentment at our shortness of breath. Let us discuss together what we may perhaps best do to recover our poise.

The changing situation which is responsible for our discomfort is complex. First and foremost there is our changing experimental knowledge, reaching over the entire range from the infinitely small to the infinitely large. The upsetting feature here is not so much that we have discovered an enormous array of new facts, which in themselves are difficult enough to keep pace with, as that these facts have proved in many cases to be irreconcilable with our previous expectations of what was possible, so that we have been forced to change our entire conceptual attitude. These conceptual changes have in many cases been associated with mathematical theories, which are being continually formulated at an ever-accelerating tempo and in a complexity and abstractness increasingly formidable. Some of the more important landmarks in this progression are: The electromagnetic theory of light, the special theory of relativity, the general theory of relativity, the quantum theory of Bohr, the matrix calculus of Heisenberg, the wave mechanics of Schrödinger, the transformation theory of Dirac and Jordan, the group theory of Weyl and now the double quantization theory of Jordan and others.

[1] Address of the retiring vice-president and chairman of Section B—Physics, American Association for the Advancement of Science, Des Moines, Iowa, December, 1929.

These have come crowding on each other's heels with ever-increasing unmannerliness, until the average physicist, for whom I venture to speak, flounders in bewilderment.

Are there not some general principles disclosed in all this welter of mathematical reconstruction in which the average physicist may find a sense of comparative peace, of some security that his endeavors to reconstruct his conceptual attitude will not have to begin over again next week and of some assurance that his program of future activity lies along lines of real significance?

One very broad generalization from past experience is that whenever we extend the domain of experiment we must be prepared for unexpected new facts. If we whole-heartedly accept this generalization as of real significance, important conclusions follow which apply to both our experimental activity and our conceptual outlook. On the experimental side it follows that every real extension of our present experimental range is worth while and necessary. An increase of accuracy of measurement constitutes an increase of range, so that any one who can increase the precision of any sort of measurement makes an important contribution. Not every one may be interested to increase by a factor of ten the precision of weighing, for example, but there are persons to whom this sort of refinement is congenial, and who can now pursue the line in which they are most skilful, while the others of us can enthusiastically applaud their skill.

Further, in formulating to ourselves what the present situation actually is, we should cultivate a more deliberate self-consciousness of the accuracy of our present experimental knowledge. This should get into our courses of instruction, certainly into those for our graduate students if not into the elementary courses. We should all know the limits of accuracy obtainable, for example, in measuring a length or a weight or an interval of time or a temperature; we should know how accurately the inverse square law of gravitation has been established, or how accurately the gravitation constant or the velocity of light or the gas constant has been determined.

Our point of view gives added importance not only to every increase of precision but also to other sorts of increase of the experimental range, and those who take a constitutional satisfaction in pushing our experiments to higher temperatures or to higher electric or magnetic fields or to higher pressures or to higher light intensity or to higher gravitational or accelerational fields may feel a renewed sense of the importance of their contribution. But although experiments over greater ranges or with increased precision acquire an increased importance, it does not follow that all results here are equally interesting or significant, or that the prospective experimenter can expect to make his choice with his eyes shut and be awakened by the knocking of the postman bearing the Nobel prize. The postman is more likely to knock at the door of the man who in extending our range reaches qualitatively new effects, such as the wave-like structure of matter.

On the conceptual side, perhaps the most important principle disclosed by our continual discovery of strange new facts whenever we extend the domain of experiment is that the actual experimental world transcends all our efforts to get into perfect mental contact with it. We must by now feel that it is a little naïve continually to hope that our last theoretical formulation will prove to have arrived at the long-sought goal, when in the past our hopes have been continually shattered by each new discovery. Acceptance of this situation carries with it the conviction that in the last analysis any adequate scheme of getting into touch with experiment can be only descriptive, for no theoretical scheme of explaining nature can be regarded as secure until verified by every possible experiment, and when every such possible experimental check has been applied, the theory degenerates into a description. The fact that every acceptable description of nature is rational might at first be thought to have some deeper significance, but I believe that analysis will show that this means simply that we refuse to accept any description which is not framed in such terms as to be adapted to our mentality, a requirement so inevitable as to be almost without significance.

Another suggestion which may be of value in our search for elements of stability in our attitude is afforded by our ever-increasing appreciation of the importance of the unavoidable subjective element in any account which we can give of our experience. We used to demand that the ultimate goal of physical theories should be nothing less than the discovery of the underlying realities. To-day our demand for reality is much less insistent, in large part because we are much less confident that the ultimate reality, which we thought to be our goal, has any meaning. The meaning to be attached to reality is to a large extent a personal matter and changes with time, but I believe it is fair to say that the sense in which every one used reality a few years ago and the sense in which the majority use it to-day has "uniqueness" as a minimum connotation. It would not have been admitted that two entirely different explanations of the universe could each be equally real, but to-day we see that uniqueness in an explanation is an impossible ideal, and the quest for reality, in so far as reality connotes uniqueness, must be abandoned as a meaningless quest. A sufficient basis for this change of attitude could be found in the proof of Poincaré that any aggregation of phenomena, no matter how complicated, is always susceptible of an infinite number of purely mechanical explanations. The reason that we are not interested in giving an explanation of quantum phenomena on a purely mechanical basis is that any such explanation would involve the assumption of a prohibitively complicated amount of detail concealed beyond the reach of any contact with experiment. It is natural, therefore, to find that the demand that our theories reproduce reality is becoming replaced by the demand of convenience and simplicity. Another requirement in a satisfactory theory has recently been much emphasized by Heisenberg and his school, namely, that our theories should contain only observable quantities. This involves so modifying the concept of reality as to make it closely associated with the possibility of direct observation. But although this alternative formulation of the reality concept has at first a most satisfying aspect, I believe that in the actual working out it is less satisfactory than in anticipation. In fact, I am inclined to think that Heisenberg's demand that only observable quantities enter the theory played only a suggestive rôle in leading to one of the many possible solutions and was as sterile in actually compelling the adoption of his form of theory as was the corresponding demand of Einstein that the law of gravitation be written in an invariant form. For if one examines how the principle works in practice, it will be seen that all that is demanded is that the raw material which is fed into the calculating machine and the final results which are taken out shall connect with direct observations. All the intermediate processes and operations, the internal pistons and gears of the theory, have as much the character of pure inventions as anything which Poincaré might have proposed. However much one might have been inclined fifty years ago to see some warrant for ascribing physical reality to the internal processes of a theory because of its success in meeting the observed situation, certainly no one of the present generation will be capable of so naïve an attitude after our illuminating experience of the physical equivalence of the matrix calculus and the wave mechanics.

As a consequence of all this, the attitude of the physicist to-day is changing toward mathematical theory. As a whole, he takes it far less seriously, recognizes that it contains less of reality and more of a purely suggestive character than he had realized, and lays more emphasis on the demands of simplicity and convenience. There are puzzling questions to be answered and instinctive reactions to be overcome in adopting this point of view. It is hard to resist the conviction that there is some deep underlying significance in the fact that the mathematical operations of the matrix calculus of Heisenberg, for example, make such wonderful contact with experiment. But what the precise significance of this may be eludes formulation, and in the meantime the physicist must fortify himself with somewhat skeptical considerations like the following:

> On the one hand, mathematics is a study of certain aspects of the human thinking process; on the other hand, when we make ourselves master of a physical situation, we so arrange the data as to conform to the demands of our thinking process. It would seem probable, therefore, that merely in arranging the subject in a form suitable for discussion we have already introduced the mathematics—the mathematics is unavoidably introduced by our treatment, and it is inevitable that mathematical principles appear to rule nature.

What do these general considerations have to do with our program of action. In the first place, we are going to be exceedingly cautious in ascribing any finality to the details of the present mathematical theories. There is among the younger and more enthusiastic members of the physical community a tendency to regard the present theories as final which the more sedate members must combat, even in the face of all the successes of the present theories. One of the most certain lessons of the past is that no amount of success in the youth of a theory is any guarantee of a hale and hearty old age; this is to be expected and is a consequence of the transcendence of nature. Against this view, an enthusiastic protagonist of the new theories might with considerable justification, I believe, urge that there are certain elements of genuine novelty in our present outlook which offer a basis for the belief that we may be on the point of breaking away from our often-repeated cycles of revision and reformulation. But although there may be distinctly encouraging signs of a brighter future, I believe that nevertheless there are specific elements of weakness in the present situation which justify the suspicion that our present theories still need thoroughgoing modification. Perhaps one of the most serious weaknesses of the present theory is the way in which it deals with static effects. One important consequence of the Heisenberg principle is that an electron can not stand still, yet a potential energy is substituted into the fundamental equations of the theory which retains the old fiction of an inverse square force emanating from a stationary center, and which palpably has no meaning in terms of direct experiment. Such a thing is entirely opposed to the spirit of our new outlook. We are to expect that presently the apparently static inverse square law of force will be described in statistical terms. Another suggestion that the present theory marks only a half-way stage of progress is to be found in its treatment of the universal constants, such as the gravitation constant, the velocity of light, the charge and the mass of the electron and the quantum h. No one, I suppose, is yet so pessimistic as to give up the hope that eventually we will be able to give an account of these constants, instead of always having to carry them in our equations as elements imposed from without. One may also hope to have sometime a theory of the equality of the charge on proton and electron.

Perhaps these misgivings about the permanence of our present theories seem of too vague and general a character to be of much significance, but I believe that in the past we have been many times too willing to forget any very broad general objections to which our theories may have been subject, in our satisfaction with their success in dealing with fairly wide classes of special phenomena. For example, the fact that the classical principle of equipartition of energy demanded that the atoms be mathematically rigid should in itself have been sufficient to show that any attempt to reduce all action to pure mechanics was certain to fail.

All this must not be allowed in any way to minimize our conviction of the very great importance of carrying through the analysis of all possible consequences of our many new mathematical points of view, but it does suggest that many physicists who are not professionally interested in making new contributions to new mathematical developments, but rather want to understand what there is of permanent significance in present developments, may with a clear conscience omit to work through the details of much of recent mathematics, in the conviction that it is of more or less transient character. But apart from the mathematical details, and perhaps sometimes not intimately connected with them, there are certain broad qualitative points of view characteristic of the new theories which every physicist should grasp and incorporate into his thinking. Perhaps the two most important of these points of view are (1) that the measurable properties of electrons embrace some phenomena which we find convenient to describe in terms of the wave phenomena of ordinary experience, in addition to the older and more familiar phenomena which we have satisfactorily dealt with in terms of a particle picture; and (2) that there is some essential limitation to the sorts of measurement that can be made simultaneously on elementary things, which is formulated in Heisenberg's principle of uncertainty. In speaking of these points of view as two I do not wish to imply that they are not logically connected, for they are very intimately related.

It is possible to direct just criticism at the mathematical deduction of these two principles from the logical premises. The wave mechanics is open to various objections, one of the chief of which to my mind is that it provides no way of dealing with transient phenomena; this fact constitutes to a certain extent a failure of the fundamental principle, for it is only transient phenomena which are directly observed. Further, the deduction of the Heisenberg principle as a necessary consequence of the fundamental assumptions has failed to satisfy many and does indeed seem to contain a certain feature inserted arbitrarily into the theory. But I believe that in spite of these criticisms these two points of view transcend the mathematics by which they were derived, and that, inspired and guided by the mathematics, we have come upon a point of view which is of more permanent value than the mathematics itself.

These two points of view, if I understand correctly the claims made for them, should be sufficient, in conjunction with other physical knowledge which we already have, to determine the nature of the elementary processes and entities which analysis of our physical experience discloses to us. Here we reach the actual frontiers of physical exploration, and doubtless the most fundamental problem confronting us is to acquire understanding of these things. The more complicated things, such as the chemical properties of molecules, involve processes of mathematical synthesis which we need not expect to grasp intuitively and which will not be completely worked out for some time in the future, but of the qualitative nature of the underlying elemental processes and entities all physicists should now attempt to acquire some intuitive command. Since the new theories are formulated so as to be consistent with the cardinal principle that the properties of a thing have no meaning which is not contained in some describable experience, our intuitions should be able to tell us what to expect in various experimental situations involving elementary things. This does not mean that the experience in terms of which our intuition thinks is necessarily an experience so closely connected with actuality that we could go into the laboratory and make the experiments, but the experiments must be such as are allowed in principle by the new theories. For instance, we can conceive ourselves in principle determining the frequency of a single photon by finding the location on a photographic plate of a single developed grain exposed in a spectroscope of infinite resolving power, although we may perfectly well recognize that to make such a measurement is beyond our present experimental skill. Our intuitive grasp of an elementary situation may, then, be tested by our ability to describe what to expect in terms of conceptual experiments. I believe that in the devising and discussing of such conceptual experiments there is an important field which may be cultivated, particularly at the present time, with much profit. It should be possible to build up a formal structure in which the properties of photons and electrons and other elemental things, such as quantum interactions, are described in terms of conceptual experiments, and from simple properties deduce more complicated properties in much the fashion of Euclid. In fact, the resemblance between this ideal and Euclid is a rather close one, for that part of the analysis of Euclid which consists in moving figures about and comparing them by superposition amounts to nothing more than conceptual experiments with geometrical figures. A systematic development of the conceptual experiment would be found by many, I believe, to give a more illuminating insight than a painful acquisition of the details of the present mathematical picture.

As suggestive of what may be done here, I append a list of questions which are to be answered in terms of conceptual experiments allowed by the new point of view.

(1) Are experiments on single "naked" electrons possible? How may one be sure that he has a single electron in his apparatus? Are there any methods of detecting the presence of an electron that do not demand that the electron be traveling with fairly high velocity? Can a stationary electron be detected?

(2) How may the charge of a single electron be measured? Is there any theoretical limit to the accuracy with which a single measurement of charge may be made? Or is an accurate value of e obtainable only from statistical measurement?

(3) What is the evidence that an electron has independent existence in empty space? May one electron stream receive a deflection on impinging on another?

(4) Is the equivalence of the charge on electrons and protons a statistical or an individual effect? How accurately may the charge of an individual electron and proton be proved equal?

(5) How may the magnetic moment of a single electron be found?

(6) What properties may an electron have simultaneously? We know that it can not simultaneously have position and velocity. May the charge, the mass, the momentum and the energy be simultaneously determined?

(7) Is a single electron subject to a gravitational field?

(8) To what extent does an electron have identity? May it be observed continuously, or is there a minimum time between successive observations?

(9) How do the measurable properties of an electron in those places where, according to the wave mechanics, the kinetic energy is negative differ from those of a classical electron?

(10) How may the frequency of a single photon be measured?

(11) May the frequency of a single photon be measured without at the same time compelling it to have some direction, that is, are frequency and direction independent properties?

(12) May the energy of a single photon be measured independently of its frequency?

(13) Does a single photon have a plane of polarization, that is, may the plane of polarization of a single photon be measured? (I have been able to discover no method of doing this.)

(14) Can the velocity of a single photon be measured? All experimental determinations of the velocity of light have been essentially measurements on a steady state.

(15) What experimental method is there of detecting the motion of a single photon?

(16) How many properties does an individual photon have simultaneously? For example, may the velocity, the frequency, the direction, the momentum and the energy be measured simultaneously?

(17) Does a photon have independent existence in empty space? Can two crossed streams of photons be made to disturb each other?

(18) To what extent does a photon have identity?

(19) Is there any method by which the emission of a photon from an atom may be detected which does not involve receiving the emitted photon?

(20) What sort of a constant is h? May it be determined from a single quantum process, or is it essentially statistical? The six methods for determining h listed by Birge are all essentially statistical.

(21) Is there any evidence that two quantum processes ever interfere with each other, or that one begins before the other has ended?

It will very probably be found that the answers to some of these questions can not at present be given without a rather intimate acquaintance with mathematical theory, but I believe that this is merely a temporary phase and that ultimately we shall be able to demand that our theories be so formulated that we can answer these and other questions intuitively without recourse to formal mathematics. In the meantime, I believe that any one who attempts to devise the conceptual experiments by which these questions may be answered is not only increasing his own understanding of fundamentals but is also making an important contribution to physical progress.

THE MUTUAL INFLUENCE OF ORGANIC COMPOUNDS IN THE ANIMAL BODY

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SEVERAL papers read at the Thirteenth International Physiological Congress in Boston impressed the writer as showing that the ideas of the reciprocal influences between organic substances in the sense of