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Some Problems of Our Natural Sciences

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Two categories of limitations of present-day physical science are discussed. The first relates to the inadequacy of physics to deal with the phenomena of life and consciousness. The second relates to weaknesses within physical theory itself, with regard to the definition of space-time points in general relativity and quantum mechanics as well as with regard to problems of quantum mechanical measurement theory.

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1. A LIMITATION OF THE AREA OF PRESENT-DAY PHYSICS

The reductionistic materialism reintroduced into Western thought during the Enlightenment was taken up by several scientists and philosophers in the middle of the 19th century, including Comte and Marx. They all had, of course, strong political interests and convictions. According to their theories, man is simply a machine, and his life and behavior are governed by the laws of physics, which are deterministic. Their ideas, which also had political implications, were largely abandoned in our century. Early in the century it was recognized that the area of physics is very restricted—the first physics book I read said "atoms and molecules may exist but this is irrelevant from the point of view of physics." Chemistry was, at that time, entirely separate from physics. As a result of the achievements of quantum mechanics, this has changed completely and it is fair to say that, fundamentally, chemistry is now part of physics, but of course, only fundamentally. However, the phenomena of life, the existence of emotions, pain, pleasure, desires, are still entirely outside the area of physics. We do not know whether the description of these phenomena of life will ever become truly united with physics. We can hope that this will happen even if we admit that this is not now the case, and that the basic idea of materialism is not now valid, and was much less valid when that idea was proposed. The hope that it becomes valid is very much supported by the past success

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of the fundamental unification of chemistry and physics. It is weakened by the recognition of Darwin that man is fundamentally an animal; we all believe that an animal's knowledge is very limited and will remain so. And we all realize that the phenomena of our life, of our emotions, desires, and cognitions, are outside the area of our physics. Their existence and their interaction with the phenomena of physics constitute a limitation of the area and also of the validity of the present laws of physics. Let me discuss now earlier limitations, particularly of quantum mechanics, and then the inner weaknesses of our theory.

2. EARLIER BOUNDARIES OF QUANTUM MECHANICS

One of the most important, perhaps the most important, observation which led to the founding of quantum mechanics is that of Heisenberg, who proposed that quantum theory not consider the motion of the electrons in atoms, but be restricted to the consideration of energy levels and of transition probabilities. This proposal of a very positivistic nature led to the early development of quantum mechanics by M. Born and P. Jordan—it surely had very narrow boundaries, since not even collisions or the motions of particles were recognized by it. It was confined to the description of the interaction of atoms with electromagnetic radiation.

The next marvelous progress was embodied in Schrödinger's "second equation," which implicitly introduced the wave function in configuration space (a function depending on all the position coordinates of all the particles under consideration) as the description of the state of the system. The "second equation" (the content of the "first equation" turned out to be identical with that of the Born-Heisenberg-Jordan theory) gave the time dependence of the wave function in configuration space. I will call it the Schrödinger equation.

Our present quantum mechanics differs in its philosophical aspects little from that of Schrödinger. The spin's description was introduced (mostly by Pauli) soon after Schrödinger's equation became known. Somewhat later, an attempt was made to make the quantum equations relativistically invariant. The function depending on the variables of configuration space was replaced by a much more complicated function in order to assure real relativistic invariance. This is called "field theory." Unless some of the velocities are close to light velocity, however, the Schrödinger equation (with the introduction of the spin variables) is still valid and is used extensively. Its principal limitation, that of excluding a description of the phenomenon of life, has not been overcome by the field theories.

It is important to notice in this connection that the verifiability of Schrödinger's theory is very different from that of classical theory. In classical theory, it is in principle possible to determine the initial state of the system considered, and also that of a later stage. This renders the verification of the equation giving the later stages of the system on the basis of the knowledge of its initial state clearly possible. In quantum mechanics this is entirely impossible—there is no way to ascertain what the wave function at any given time was. In addition, it is recognized that any "measurement" carried out on the system will change its state. This is, of course, true in general, but is disregarded in classical theory—disregarded because the systems considered are macroscopic—and if the measuring apparatus, carefully designed, is very small, it will have little, and perhaps negligible, effect on the system.

In addition, the description of classical systems, such as a set of planets, is simpler than that of quantum mechanical ones; it can be given by a finite set of numbers, the positions and velocities of the objects. This is not true for the quantum mechanical description—it involves a function, the wave function. The classical description of a deformable object, such as a vibrating elastic body, is also given by functions, and the theory is difficult to verify, but in such cases very simple equations of motion are usually valid and assumed to be correct. In quantum mechanics the description of the interaction of the system considered with the measuring apparatus is not so simple. To describe it, let us start with the situation in which the system is in a state in which the outcome of the measurement is definite. Let us denote its wave function by $\psi_k(X)$, the X standing for all its variables. Let us further denote the wave function of the measuring apparatus by $m(\mu)$, μ being the variables of the apparatus. Then the interaction of the two will change the initial state of the two, $\psi_k(X)m(\mu)$, into

$$\mu_k(X)m(\mu) \to \psi_k(X)m_k(\mu) \tag{1}$$

where $m_k(\mu)$ is a state of the apparatus which shows the proper value k of the measured quantity. The postulation of (1) is both natural and necessary.

But if we consider a general state of the system, which is a linear combination $\sum a_k\psi_k$ of the states ψ_k, because of the linear nature of the time development equation the state of the two will become, as a result of the measurement interaction,

$$\sum a_k\psi_k(X)m(\mu) \to \sum a_k\psi_k(X)m_k(\mu) \tag{2}$$

This means that the outcome of the apparatus–system interaction does not lead with a definite probability $|a_k|^2$ to the state m_k of the apparatus, but to a rather complicated wave function of apparatus and system. It can be—and is—claimed, of course, that if we look at the apparatus, we see its pointer with a probability $|a_k|^2$ pointing to the value k of the observable, but if we claim this, we implicitly admit that our interaction with the apparatus is not described by quantum mechanics. If it were, our final state after interacting with the apparatus would also involve a linear combination of states each describing us as having acquired a particular impression of the state of the apparatus, i.e., the state vector of the system, apparatus plus observer, would be something like

$$\sum a_k \psi_k(X) m_k(\mu) \sigma_k \tag{2a}$$

where σ_k is a state of the observer. But this is not so. After the observation, the observer is in one of the states σ_k, not in a linear combination. If we admit that the observer actually sees the apparatus' pointer in one of the directions k, we admit that this state is not described by quantum mechanics which leads to (2a).

It is good to admit at this point that, originally, both the apparatus and also the observer may not be in a definite state, but have various probabilities in different states. However, each of the original states of apparatus plus observer transforms, as a result of the interaction with the object, into a superposition of the type (2a) and this is in contradiction with the fact that after the interaction with the object their state is only one of the $m_k(\mu)\sigma_k$, not a superposition of them.

The preceding is a generally accepted argument against the possibility of describing life by the laws of present-day quantum mechanics. Surely, our mind is never in a superposition state; we either see a flash or do not see it—our mind is never a superposition of the two states. Our impressions and our emotions are not described by quantum mechanics—in fact the latter even less than the former.

Inspired by an observation of Bell (1965), I proposed an equation for macroscopic bodies which admits that they cannot be isolated from the environment, and hence that a probabilistic equation will better describe their behavior than a deterministic one. Such an equation can also account for the fact that our mind is not in a superposition of different impressions—that its state breaks up into several states, each describing only one impression. Of course, the proposed equation does not alter the fact that our mental states, our impressions and emotions, are not described by quantum mechanics; hence even if the proposed changes of the present equations should prove useful—which is not at all sure—the area of our present physics would not at all extend to the phenomena of life and emotions. There would still be no wave function for pain, pleasure, knowledge, or desire, and this remains a significant limitation of its area of applicability.

As to the possibility of having a macroscopic isolated system, I considered a 1 cm^3 of tungsten and put it into intergalactic space. But even tungsten, which does not evaporate at the temperature of intergalactic space

(3 K), is influenced by the cosmic radiation of the apparently empty space. The number of light quanta per cm^3 is

$$\int \frac{8\pi h\nu^3}{c^3}(e^{-h\nu/kT}\cdots)\frac{1}{h\nu}\,d\nu \approx 16\pi\left(\frac{kT}{hc}\right)^3 \qquad (3)$$

which is a few hundred at $T = 3$ K. This means that per second some 10^{13} light quanta strike the tungsten cube. Most of these are ineffective, but, according to my estimate, its quantum state changes after about 1 msec. This change is induced by the cosmic radiation and it would be impossible to introduce the state of this into the initial conditions, since it is influenced itself by many other parts of the world. Hence, the time development of the tungsten cube, and similarly that of all macroscopic objects particularly if they are not in intergalactic space, cannot be fully described by deterministic equations and I have proposed a probabilistic one (Wigner, 1970) which admits the fact that "the future is uncertain," and that the time development of macroscopic objects also depends on the state of the distant environment. This equation is, of course, not useful, since its character and constants depend also on the character and density of the environment, but it does show that our present physics is far from final, that it will undergo fundamental modifications, perhaps also by philosophers. Perhaps I should reiterate that the equation I proposed, and the problem I considered, has nothing to do with the truly basic problem of life and consciousness; it shows only that the basic deterministic idea of our present-day physics has to be modified if applied to macroscopic systems. Such a modification, even if it could be effectively carried out, may not yet touch the problem of life—the truly fundamental problem.

The modification of the quantum mechanical equations just described has no practical effect as long as we stay in the present area of physics. In practice, it deals almost exclusively with time intervals shorter than 10^{-3} sec and with no macroscopic objects in the microscopic sense, i.e., not with the total wave function of objects, which would demand 10^{23} variables—not even with objects that demand a good deal fewer variables.

Having discussed the limitations of the area of present-day physics at some length, I now turn to its inner problems—to problems within the area over which it does claim validity.

3. GENERAL RELATIVITY VS. QUANTUM MECHANICS

3.1. The Definition of Space–Time Points

Quantum mechanics told us that we should describe situations or events only in terms of quantities that can be observed. This is also the reason that the wave function's variables are only position coordinates—the momentum coordinates cannot be measured together with these. The question then arises whether the basic quantities of the general relativity theory, the metrics g_{ik} can be measured. These are functions of space-time coordinates and give, in the form of the expression $\sum g_{ik}\, dx_i\, dx_k$, the space-time distance between the point defined by the variables of the g_{ik} and the point with coordinates increased by dx_i. Can the g_{ik} be measured? How can space-time points be defined? This is a difficult question and, as we will see, it also plays an important role outside the general theory of relativity. But in general relativity, it is a basic question.

In classical theories, space-time points are best defined as crossing points of the paths of two objects—naturally infinitely small ones. And in general relativity, it is implicitly assumed that there are infinitely many such very light objects, so that the intersections of their world-lines define a sufficiently dense set of space-time points. This is, evidently, a very wild assumption and one must admit that the general relativity theory is not really positivistic.

The situation is worse in quantum mechanics. The objects have no paths and the coincidence of two is not defined—there is no "point of collision." The collision matrix, which can be determined by many repeated experiments, does not define the point of collision. It is implicitly assumed, both in general relativity and in quantum mechanics, that there are macroscopic measuring systems which enable the determination of the coordinates of space-time points, but the influence of these systems on the systems under observation can be neglected. Altogether, as will be discussed further, the real existence of space-time points and the possibility of determining their coordinates is an assumption both in general relativity theory and in quantum mechanics—particularly in the field theories of the latter—but is very questionable in both. I believe that even the probability of the system's particles to have given positions at definite times is not determinable—the magnitude of the field strengths at a space like surface even less. The point will be further supported below. Its realization will, I believe, fundamentally change our quantum mechanics and probably all fundamental concepts of our physics.

3.2. Another Problem of the Specification of Space–Time Points

Can a wave function be defined which specifies the position of a particle at a definite point of space at a definite time? As was mentioned before, in classical physics space-time points can be specified as crossing points of two world-lines—perhaps also by the pointer of a clock proceeding on one world-line—but this surely would not be the specification of a microscopic point. The situation is much worse in quantum theory. We will consider the assertion that a particle of spin 0 is, at time 0, at the origin of the coordinate system. What is its state vector then? This and related questions have been thoroughly investigated by M. H. L. Pryce as well as others, including E. Schrödinger. The following discussion is based on an article by T. D. Newton and myself (Newton and Wigner, 1949). This article shows, implicitly, that no state vector gives a truly localized state in true agreement with the special theory of relativity. For the sake of simplicity, I will consider a particle of spin 0.

It is simplest to describe the states of such a particle by a wave function with coordinates in momentum space—it is then easy to make sure that the wave function has no negative energy components. It depends on the three spatial momentum coordinates—the components of p. The energy p_0 is determined by these and the mass m of the particle

$$p_0 = c(p^2 + m^2c^2)^{1/2} \tag{4}$$

where the positive sign of the square root is to be taken. The scalar product of two wave functions ψ and φ is then given by

$$(\psi, \varphi) = \int \psi(p)^*\varphi(p)\, dp_x\, dp_y\, dp_z/p_0 \tag{4a}$$

This is invariant under the transformations of the group of the special relativity theory. The wave function of the state at the origin of the coordinate system is clearly invariant under rotations, hence the corresponding ψ depends only on the length of the momentum p. It should be orthogonal to the wave functions of states displaced within the light cone. This includes, of course, purely spacelike displacements. Displacement by the vector x is represented by multiplication of the wave function by $e^{ix\cdot p/\hbar}$ in which $x \cdot p$ is the scalar product of x and the spatial part of the momentum vector. This leads to

$$\psi(p) = \sqrt{p_0} \tag{5}$$

which is indeed the wave function proposed by Newton and myself and discussed also by others. The position-dependent form of (5), that is, its proper Fourier transform, is

$$\psi(r) = (h/r)^{5/4} H_{5/4}(imcr/h) \tag{5a}$$

which is a rather complicated expression. But the $\psi(p)$ should be orthogonal not only to the wave functions that arise from it by purely spatial displacement, i.e., to

$$\psi_x(p) = \sqrt{p_0}\, e^{ip\cdot x/h} \tag{6}$$

[which is correct according to (4a)], but also to those that result from it by an additional time displacement by t,

$$\psi_{x,t}(p) = \sqrt{p_0}\, e^{i(p\cdot x - p_0 t)/h} \tag{6a}$$

as long as the space-time vector is within the light cone, i.e., as long as $ct < x$. This is not the case and this shows that at least particles of spin 0 cannot be truly localized. And the situation is pretty much the same for higher spins. This is the other reason I believe our present idealized space-time concept will undergo modification.

It may be good to admit, though, that the preceding argument applies only to elementary systems. If we have a system consisting of many particles—perhaps a macroscopic system—some of its parts may be at rest having the state vector of (5); but it is possible to assume that others may be "at rest" if viewed from a moving coordinate system. The total state vector then contains a product of (5) and the state vectors of these other particles, which are really in motion. The resulting product state vector will then be orthogonal to the state vectors of a similar character over practically the whole light cone. Clearly, if we want the composite system to be truly localized with a good approximation, its state vector must be a product of many factors of the character (5), but moving—it must be the state vector of a macroscopic body. And the position of a macroscopic body is not so easily defined.

The preceding remark applies also to other fundamental difficulties of quantum mechanics. If it is applied to macroscopic systems, it becomes equivalent with the classical theory and its problems diminish in significance, but only diminish.

4. TWO OTHER PROBLEMS OF QUANTUM MECHANICAL MEASUREMENT THEORY

The preceding argument shows that the determination of the presence of an object at a space-time point is possible, at best, if the object consists of many particles, that is, if it is essentially macroscopic. This already suggests that all measuring instruments must be macroscopic and since it is virtually impossible to determine the total state vector of a macroscopic object, it raises the suspicion that there may be a fundamental distinction between microscopic and macroscopic systems, between the objects within quantum mechanics' validity and the measuring objects that verify the statements of that theory. This was indicated already in Section 1.

There is other evidence for this limitation and the desirability of introducing changes in the laws of quantum mechanics if applied to macroscopic objects, such as measuring instruments. It was demonstrated some time ago (Wigner, 1952), by considering the interaction between object and measuring instrument, that only those quantities can be precisely measured that commute with all additive conserved quantities, such as the three components of the momentum and of the angular momentum. This includes, naturally, the difficulty of the measurement of the position and even the components of the angular momentum. If one is satisfied with a measurement of limited accuracy, that can be achieved, but requires a measuring apparatus in a state of superposition of many values of momentum and angular momentum—it has to be a macroscopic system. Since the measurement of position momentum and angular momentum coordinates is a natural objective of measurements, and since all these demand a macroscopic measuring system, this again indicates that there is not only a separation of the description of living systems from the present area of physics but also a separation of the physics for macroscopic from that of microscopic systems—natural but disappointing.

The last remark in this connection is another criticism of our "measurement theory." This refers to the wave function at a definite time, which is virtually impossible, since signals from the distant parts of the object under measurement cannot be obtained instantaneously. The measurement takes time and it would be desirable to take this into account when describing it. This is not easy and may create a new problem—the time extension of the measurement process will depend on the space extension of the wave function of the object of measurement.

The discussion of the present section is rather pessimistic as to the philosophical value of our present-day physics. One may be inclined to agree with Heisenberg, who said, originally, that quantum mechanics describes only the energy values of the possible states of atoms (and molecules) and transition probabilities between these. Later he said that the principal subject—I would say, principal other subject—is the collision matrix, which is, as Goldrich and I have shown (Goldrich and Wigner, 19), observable to a very large extent. And these make, one can claim, the most important contributions of quantum mechanics.

5. FINAL, AND MORE OPTIMISTIC, REMARKS

The titles of the preceding sections indicate that these are principally concerned with the limitations of the validity of our present science and with its weaknesses. It may be good therefore to recall how much the development of our science has done for mankind, how much it has changed our life, and how much it has made it more interesting.

The first observation in this connection refers to a change that has taken place in the present century—in the last third of the development of our science and of physics, as I define it. The change I am referring to is in the life expectancy of a newborn baby. As it is usually, though not quite perfectly, calculated, this was 47 years in 1900; it is 74 years now. The change has been even greater in less advanced countries.

This change is largely due to the greater availability of physicians, but, I believe, even more to the development of the medical sciences, which were, and are, greatly supported by physics. X rays are one example.

Another great change is that individuals can choose their occupation much more freely. A few hundred years ago this was prescribed by the situation into which people were born. And the production of food required a much larger fraction of the working force than it does now. This has had, I must admit, one quite unfavorable consequence: a fraction of young people are not attracted to any truly useful occupation but are striving mainly for power and influence. But the favorable effect is much greater: many more of us can be devoted to learning and to the development of knowledge. This country has about 2500 universities and more than half of them were founded in this century. The 2500 universities have, on the average, about 100 teachers each—there are about a quarter million teachers at universities. Most of them are devoted not only to teaching, but also to expanding our knowledge, that is, to research. And from this point of view it is very good that our science is, as we saw, very, very incomplete; there are many problems awaiting solution and this will probably also be so in the distant future. It may be true that most of the solutions of problems that will be presented by the large majority of scientists will be of a very special nature and restricted to narrow areas, but even such contributions will give pleasure and satisfaction to the contributor. To illustrate the enormous expansion of interest in science, in particular, I may mention that the American Physical Society had 96 members in 1900—it has more than 33,000 members now. We hope that all find pleasure in their work.

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