Space, Field, and Ether in Contemporary Physics

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THE RELATIONSHIP BETWEEN MATTER AND SPACE may be expressed by saying that matter occupies space and shapes its geometry. This statement, however obvious and comprehensive it may seem, does not embrace all the properties of space. It holds only for matter in bulk occupying large volumes of space—in short, on the macroscopic plane.

One of the most important results of quantum field theory, the implications of which have only recently been realized, is that empty space exhibits dynamic properties in the presence of matter and field. This interaction between matter, field, and empty space is of a radically different nature from the static, geometrized effect that matter has on space in accordance with relativity theory.

The Compton wavelength of the electron, $\frac{h}{mc}$, one of the elementary lengths of physics, signifies the emergence of the dynamic properties of empty space—or the vacuum, as it is called—as well as its creation properties, which exhibit empty space more in a quasi-passive character. Vacuous space is something much more complex than can be described by simple mathematics. Its properties arise because the universe contains matter. Were there no electromagnetic fields or electrons, for instance, there would be no electromagnetic field, electric charge, or current fluctuations in the vacuum.

With reference to its creation properties, empty space behaves as if it were a sea of negative energy electrons—of latent electrons. This connotation is well known and needs no detailed discussion here (*1*). It is evoked to explain the well-known phenomenon of electron-pair creation.

The dynamic properties of the empty, or vacuous, regions of space in this region of magnitude arise out of the zero-point oscillations of the electromagnetic field and the zero-point fluctuations of electric charge and current (*1*). Because of the zero-point oscillations of the electromagnetic field, the average value of the electric and magnetic field strengths, when measured over a space-time extension of the order of the electron Compton wavelength, will not be zero, as one would expect for empty space, but will fluctuate upon repeated measurements. These fluctuations will become greater as the space-time region becomes smaller. Because of the possibility of the creation of electron pairs by these electromagnetic field oscillations (the electromagnetic field here is, of course, a quantized system of virtual photons), there will ensue electric charge and current fluctuations that will also become of greater value as the space-time region of measurement becomes smaller.

These vacuum-fluctuation phenomena, unobservable in principle as well as in practice, were not taken seriously until their physical consequences received experimental confirmation in the now famous Lamb shift. There is also an interaction of a charge, electron or proton (the principal contribution is from the electron), with the latent electrons of empty space, causing a displacement of these electrons and giving rise to what is called the polarization of the vacuum. As to the reality of this phenomenon, there may still remain a few dissenters. However, this effect will cause another hydrogen S level displacement, about 1/40 of the Lamb shift, and it may be within the range of present-day experimental technique. Recent calculations involving terms of higher order in the interactions would seem to indicate the existence of such an effect (*2*).

The dynamical properties of the vacuous regions of space should be viewed not as belonging to empty space, but as arising out of its interaction with matter and radiation fields. Without interaction this dynamism of empty space is but a formal abstraction lacking physical reality. It is interaction that bestows upon it its substancelike properties. The concept of isolated particle and isolated field existing as absolutes without interaction with other matter and fields is also but a formal abstraction lacking physical reality (as will be discussed later). This fundamental and unique role of interaction in physical phenomena, however, is nowhere else so clearly brought out as in these vacuum interactions.

It is probably not correct to consider the interaction between empty space and matter even formally as a perturbation, because the various types of interaction between the two give rise to infinite energies. Dyson (*3*) has shown that these infinities are of a basic nature and cannot be eliminated by any formal mathematical procedures, such as the renormalization method. A more serious objection against perturbation theory, although of a different nature, was recently brought forward by Van Hove (*4*). These infinities are not an indication that quantum electromagnetic theory is wrong (5), but rather that the theory is in a sense an open one. That is to say, as we consider smaller and smaller regions of space, we shall find that electromagnetic phenomena do not exist by themselves but are connected with the occurrences of other types of phenomena. This will involve other matter and radiation fields and the creation of different particles other than electrons and photons. The elementary particles are not absolute; they are all related, and their number may well be legion. It is this large number of elementary particles and their relatedness that introduce a new and undreamt-of complexity into physics.

It is not unlikely that there are several elementary lengths in physics, each one signifying the emergence of some new phenomenon or the limit of the unambiguous application of some particular physical concepts and laws.

For distances of the order of the Compton wavelength of the π meson, $\frac{h}{\mu c}$, the region of nuclear interaction, the concept of a static potential does not seem to have an unlimited validity. All attempts so far to account for the saturation property of nuclear forces by a static potential have not been successful, and it appears possible that many-body forces may have to be evoked (6). Moreover, the experimental results on proton-proton scattering from 120 to 345 mev have defied theoretical interpretation in terms of conventional interactions and models.

For distances of the order of, and less than, the Compton wavelength of the proton, $\frac{h}{Mc}$, it is probable that the very concept of measurement loses some of its concise and clear-cut classical meaning. In this region the elementary particles must be recognized as complex interacting systems consisting of the "bare" particle and the virtual quanta of their associated fields, which they are continuously emitting and absorbing (5). The elementary particles themselves all have about the same size, about 10^{-13} cm, which is larger than the region in which such measurement takes place. Consequently, any position measurement, say, of a particle in this region will involve an interaction so vigorous as to cause the structure of the elementary particle that is used for the measurement to come into play. Because the various elementary particles have different structures, a position measurement will not have the unambiguity necessary for the concept to have a concise meaning. Instead, the result of the measurement will depend on the type of particle employed for the measurement. Each type of particle—electron, proton, or photon—will yield a different set of measurements and, consequently, there will be no objective probability distribution essential for a measurement.

It is of interest to note that the elementary particles, which are more than a billion times smaller than living cells, have this in common with them. They are both complex, interacting systems that must be considered as wholes. No observation is possible on these elusive fundamental units, living and nonliving, that would reveal the nature of the interaction between their component systems. The difference between the two is that we have succeeded in forming some theoretical conceptions of the interacting systems that constitute the fundamental particle, and we can verify them by their experimental consequences. No such theoretical knowledge of the "self-interactions" of the living cell (those interactions that produce the unity and organization of the cell) is available. It may well be that fundamental advances in this field will not be forthcoming until we gain a better theoretical knowledge that would suggest the decisive experiments necessary for an understanding of the living cell, and that would go hand-in-hand with experiment and observation.

Pertaining to the importance and function of theory, where direct observation is not possible, it is the author's opinion that one of the most important achievements resulting from the recent relativistic covariant formulation of the quantum electrodynamics is the explanation of the Lamb shift and the anomalous magnetic moment of the electron as the *measurable consequences of the unobservable field and charge fluctuations of empty space interacting with the electron. The real in physics encompasses more than the directly observable and measurable.* Interaction and charge are fundamental in nature, and there are interactions besides those that are directly involved in measurement and observation. The self-interactions are an example, and they may have important physical consequences.

It has been stated that the elementary particle is an open, even complex, system in constant interaction with the vacuum fluctuations of its associated fields. For example, the structure of the electron includes its virtual photon field, and the structure of the nucleon its virtual meson cloud. But elementary physical systems themselves may be related to other elementary physical systems, as suggested above. The divergence of the higher order terms in the electron self-energy interaction may indicate the necessity of simultaneously taking into consideration the existence of other kinds of particles. Thus there may be a theoretical indication of the relatedness of the elementary particles. There is also experimental evidence suggesting this. Transitions involving decay and collision processes between V-particles, nucleons, and π-mesons; π-mesons, μ-mesons, electrons, and neutrinos; neutral π-mesons, γ-rays, and electrons; K-mesons, μ-mesons, electrons; protons, electrons, and photons, show, as was pointed out by Heisenberg, that one elementary particle may be related to another by a series of real and/or intermediate steps.

All this suggests that in the atomic and nuclear domain the assumption that elementary particles are closed systems may not have an unlimited validity. The great revolutionary finding that contemporary physical theory points to is that the simplicity which has so uniquely characterized physics since its birth needs essential qualifications. The simplicity that will remain as characteristic of physics will be of an aesthetic, symbolic nature, expressed only in the formalism of its mathematics.

It is in the extremely high-energy region, where interaction can take place within a radius of the nucleonic Compton wavelength $\frac{h}{Mc}$, that one may meet with this new complex aspect of physics. Here it may no longer be valid to assume that clear, unambiguous distinctions can be made between and among the various component systems in interaction. It may not be possible to isolate the interacting systems and to treat them as being separate but for their mutual perturbations.

It was Dirac's idea that some of these difficulties, at least in certain aspects, should be recognized on the classical level—for instance, that interaction should not be considered simply as a perturbation. Dirac's recent work (*7–9*) recognizes the coexistence of particle, field, and interaction, all on an equal dynamical footing. The electrons, in his new theory, are not considered apart from their interaction with the electromagnetic field, because the theory considers only electron beams. The existence of the elementary charge e is presumably a quantum phenomenon. Therefore, there is no e to set equal to zero. The first approximation of the usual classical theory sets $e = 0$ and then introduces the electromagnetic interaction as a perturbation. In Dirac's theory the motion of electron streams only is considered, and a velocity distribution given by his potentials is associated with them.

I have stressed the importance of the dynamic or interacting properties of empty space with respect to matter and radiation fields. One may ask, in the spirit of classical physics, whether it is not possible to analyze and isolate these interacting properties with neither matter nor field present. Completely empty space with neither matter nor field present is an idealized condition and can never be actually realized. However, the perfect vacuum—empty space—in the light of the implications of contemporary quantum field theory, is not exactly equivalent to nothing. Because of its dynamic or interacting properties, empty space may be equated to mere activity. For instance, there is the interaction between the electromagnetic field oscillations with the latent electron pairs of the vacuum. But this character of empty space, as discussed previously, can become manifest only by measurements involving wavelengths of the order of $\frac{h}{mc}$. Nevertheless, it may be instructive, or at least suggestive, to inquire whether the dynamic character of vacuous space can be carried over in some guise to classical theory and clothed with a classical concept. In the opinion of the author, something of this nature is what seems to have been accomplished by Dirac in his attempts to formulate an adequate classical theory with one eye on the quantum theory and in his ensuing rediscovery of the ether (*10, 11*).

Because it is interaction with which we are dealing, one may apply the knowledge gained by quantum mechanics to the interacting properties of the vacuum, or empty space. Quantum mechanics is made possible by the existence of the natural constant of interaction h, just as relativity exists because of the natural constant c. One could set up a wave function that would describe a state which could not be physically identified, but which represents the vacuum. A wave function of this type is one that would yield all motion or velocity values and directions as equally probable, which is the symmetry property demanded by relativity for the existence of an ether. This ether of Dirac, which is fashioned out of the knowledge gained from quantum mechanics, is not amenable to mechanical description. It may be looked upon as a property of space-time. For this reason, it bears little resemblance to the old-fashioned ether. It may be defined as *hypostatized interaction*, or interaction considered as a thing in itself. It may occur to many that this abstraction is too much, even for contemporary physics. On the other hand, in the light of quantum electrodynamics, an isolated particle or a field is not a closed system, as in the classical definition, but it is constantly interacting with the vacuum fluctuations of its associated fields. The classical concepts of particle and field are as much an abstraction as the concept of isolated interaction. That the concept of interaction has not been treated separately as "action," in the manner of particle and field in the Newtonian and Maxwellian physics, may be a matter of psychology. Isolated particle, field, or action may be legitimately viewed only as theoretical idealizations. In the view presented here, one of the functions of the ether is to give interaction a fundamental role in classical theory that would place it on an equal footing with particle and field.

It is of interest to note that the properties of the vacuum in Dirac's classical theory are somewhat suggestive of its properties in the quantum domain. His theory involves a velocity field that exists even in empty space. The velocity field, which is a continuum of velocity values, because of its omnipresence will not permit the field quantities to be zero, even—to use Dirac's connotation—in a "perfect vacuum." Consequently, it is not surprising that one of the fundamental equations of Dirac's theory giving his potentials in terms of velocity can be fulfilled for a vacuum as well. This equation yields a definite velocity throughout space-time, which may be interpreted as the velocity of an ether. Dirac (*12*) interprets the ether velocity in the vacuous regions of space as the velocity of a small charge, were it introduced, although the introduction of a charge in the vacuum would violate the conservation of electricity. However, in the equations of his theory, a small charge may be introduced in the guise of initial conditions. And so, even in the classical domain, empty space, because of its ether and velocity properties, and its function as a site for charge creation, exhibits a dynamism somewhat suggestive of its role in quantum theory. Would a final classical theory yielding an adequate quantum theory be as different, conceptually, from present classical electron theories as Dirac's is?

In any event, one of the significant results of recent investigation in quantum field theory, and even in classical field theory, as just indicated, is the recognition of the complexity behind the ultimately simple. And so a new chapter in physics opens, with overtones suggesting that the simplicity of this fundamental intellectual discipline may reside principally in the aesthetic character of its mathematical elegance.

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Ralph Stayner Lillie: 1875-1952

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THE SCIENTIFIC LIFE of Ralph Stayner Lillie neatly spanned the first half of this century, his first paper appearing in 1901 and his last, just fifty years (and some 125 publications) later. In this period he and a handful of other leaders effectively created the subdiscipline of general physiology. For Lillie had an integrating or generalizing mind; he had little concern for the particular—although his experiments revealed many important facts—and he probed unceasingly for the deeper import and broader impact of the phenomena that engaged his attention. Not the effect of some ion on some function, but the nature of ion action on the colloids and membranes of protoplasm interested him; not fertilization or contraction or conduction, but the whole problem of irritability and response. Few acres of the field of general physiology were not plowed by his sharp understanding and seeded by his generalizing insight.

A complete bibliography of Lillie's papers was prepared for me by Deborah Harlow, librarian of the Marine Biological Laboratory at Woods Hole, and from this alone emerge many interesting lights on his work and his period. In his first decade of publication (1901–10) six papers appeared in such journals as *Biological Bulletin* and *Journal of Experimental Zoology*, and 14 appeared in the *American Journal of Physiology*—the latter including articles on *Arenicola* larvae, the swimming plate of Ctenophora, and the eggs of *Asterias* and *Arbacia*. Two decades later (1921–30) only four of 27 papers reached the *American Journal of Physiology* (and these by 1923), the others being distributed in such new publications as *Journal of General Physiology* and *Journal of Cellular and Comparative Physiology*, the second a journal he helped found and edit. The dozen papers of Lillie's last decade were mostly in philosophical journals—he published in 24 different periodicals over his professional life span—but this represented a shift in emphasis, whereas the earlier change reflected the altered interest of physiology and the growth of its cellular and general offspring.

Only nine of Lillie's papers had a joint author, and five of them were students. In part this reflected the times, for multiple authorship was the exception earlier in the century; in part it may have represented an inclination to have students publish separately; but largely it must have resulted from his personal qualities of mind and manner. Omnivorous in his reading, eager always to discuss (despite some hearing difficulty) or to correspond about an interesting problem, generous in instructing students, at which he was most successful outside the classroom, Lillie was still a solitary worker. His thoughts and labors were his own, and his main influence on others, including the oncoming generation, was exerted by way of the written word, despite the long, busy, and happy summers he spent throughout his adult life in the teeming scientific community of Woods Hole.

The first paper Lillie published established the basic themes of his scientific work. "On the Differences of the Effects of Various Salt-Solutions on Ciliary and on Muscular Movements in *Arenicola* Larvae" touched upon ion action and antagonism, colloids and membranes, irritability and response. The dramatic actions of the common ions of protoplasm never exhausted his interest, and one of his last experimental reports dealt with "The Influence of Neutral Salts on the Photodynamic Stimulation of Muscle." He related ions to the dispersion state of colloidal particles and so to osmotic pressure and membrane permeability, to fertilization and mitosis, to stimulation and anesthesia, to contraction and conduction, to the action of drugs and radiations.

Lillie was perhaps most widely known for his contributions to neurophysiology, especially his provoca-