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ABSTRACT

The evolution of concepts of space, time, and elementary particles is traced from their early forms to those embodied in modern S-matrix theory.

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† Address delivered April 20, 1964, at ceremonies commemorating the founding of the Institute for Mathematical Sciences, Madras, India.

Being in India it is not unfitting that I speak of transmigration. The transmigration I shall refer to is not of souls, however, but of ideas. Regardless of the destinies of souls it is the fate of ideas to be born, to die and to be born again in different guises. The topic is relevant today because ancient and cherished ideas about the nature of space, time, and elementary particles are being severely challenged by current developments in elementary particle physics, and their deaths may be imminent.

John Kenneth Galbraith, the recent American Ambassador to India emphasized in his book, 'The Affluent Society', that events and the ideas that interpret them are capable of quite independent lives. The vested interest in basic ideas is so great that they become self-sustaining; even though in their independent lives they may lose touch with reality and become obsolete, they remain virtually impregnable to the attack of fresh ideas. The fatal blow comes only when they, in the words of Galbraith, "...fail signally to deal with some contingency to which their obsolescence has made them palpably inapplicable".

Early Concepts of Space

Inquiry into the nature of space and time can be traced in the Western traditions back to Parmenides, who "proved" that empty space could not exist. He argued on the following lines: (1) A thing either exists or it doesn't exist; it is either real or not real; (2) Empty space is devoid of every real thing; (3) A thing cannot be both a real thing and devoid of every real thing; (4) Hence empty space is not a real thing — it does not exist.

Motion is the shifting of a thing from an occupied space into a formerly empty space. As empty space is not real, motion is not real. Parmenides concludes from these considerations that the world must be regarded as one solid lump of matter, forever immutable and unchanging.

This view of the world has attractive features. It has undeniable simplicity. It has logical unity and compactness. It is aesthetically neat. It may appear a little at odds with experience, but it is well-known, and readily demonstrated, that things are not always what they seem. Since the laws of logic are absolute one must accept their consequence and regard the appearances as deceptive.

In spite of their attractiveness, Parmenides' views were not universally accepted among the Greeks. However, they were definitely taken seriously and other thinkers had to reconcile their views with Parmenides' arguments. The most important counter-proposal from the point of view of science was that of Democritus. He accepted Parmenides' arguments regarding the nature of the world, but proposed that there can be many worlds. These worlds, which are the solid immutable objects of Parmenides, were called atoms. They moved about in an otherwise empty space. It is interesting that even in these early beginnings the nature of particles was closely tied to the nature of space.

The beginning of modern science seemed to validate these ideas. The contributions of Dalton, Newton, and others were most readily understood in terms of the idea of indestructible atoms moving in an otherwise empty space. Thus the views of Democritus, if not reborn, were at least revitalized.

Wave Concept of Light

The triumph was not to endure, however. Even in Newton's time the strange behaviour of light was difficult to reconcile with the particle viewpoint. If light is allowed to travel from a source to a screen via two alternative paths then the distribution of light falling on the screen is not the same as the sum of the distributions when the two paths are individually opened; the net amount falling at a point when both paths are simultaneously open for one minute is not the same as when the paths are consecutively opened for a minute. This interference between the two possible paths cannot be understood as an interference between different particles traveling along different paths because such an effect would vanish when the source became so weak that only one particle at a time was being transmitted. But the interference effect is in fact independent of the source strength.

The interference phenomena is easily understood if light is assumed to be kind of wave motion, like waves upon the sea. However, a medium to transmit these waves is needed. This medium would fill space, which would then be nowhere empty.

This wave picture of light seemed unquestionably confirmed when Maxwell's theory of electromagnetic phenomena was found to automatically give a detailed quantitative description of all the known properties of light, including the interference phenomena. In Maxwell's theory, light is a wave motion. The medium transmitting this wave was called ether, and was computed to be millions of times harder than steel. Since particles such as electrons are most easily pictured as merely local irregularities in this medium one is brought back to a view similar to that of Parmenides: space is filled with a hard solid substance — empty space does not exist.

Relativity

This view was destroyed in its turn by the theory of relativity. When efforts to detect the motion of the earth relative to the ether failed, Einstein suggested that the laws of nature were such as to make detection of motion relative to the ether impossible in principle. This idea was validated in many areas. But to say that the state of motion of the ether is undetectable in principle comes close to saying that the notion of ether is meaningless. In any case, it was not a useful idea, and it withered.

The theory of relativity did not however lead back to the notion of empty space as a simple "void". In the first place space became partially interchangeable with time. Formerly the two ideas were quite distinct; time referred to an ordering of events, space referred to their location. But in relativity two events that one man regards as simultaneous, hence separated only in space, will be regarded as separated in both space and time, in another man's view. Neither viewpoint can be regarded as preferred, insofar as physics can tell. Thus the distinction between "before" and "after" becomes enmeshed with "here" and "there", and a more general concept of space-time separation emerges.

Because the instant of time now has only a local significance in relativity theory, one can no longer think of the history of the universe as a whole as gradually unfolding; this requires a preferred definition of "now". Rather, the whole history of the universe is laid out like a map and the idea that the past and future are separated by what is "happening now" is just a matter of limited perspective; Parmenides' distrust in appearances seemed borne out.

In general relativity there is a still further departure from the concept of empty space as a simple void. For there empty space has nonuniform properties. Space is basically a framework supporting a system of distances. In general relativity, distance relationships vary from point to point, even in empty spaces. Thus empty space, while devoid of all matter is not devoid of every real thing; relationships regarding distances, although not matter, are nonetheless real. This distinction provides for an alternative not considered by Parmenides, and hence a way out of his dilema: empty space is devoid of all substance, but is not devoid of every real thing.

Quantum Mechanical Ideas

A somewhat similar but independent solution is provided by quantum mechanics. In quantum mechanics a particle is represented by a function defined at every point in space-time. Thus space is completely filled. Yet the function represents only a probability that some event will occur. Now a probability is not a substance, and the wave function cannot be considered to represent a substance, because it is subject to sudden changes in the far reaches of the universe due to changes in available information. Yet in quantum mechanics there is, besides mental events, nothing but the wave function.

As the wave function is defined throughout space, and there is nothing else in space, and the wave function represents nothing that can be considered a substance, we have a space completely filled with something but completely devoid of substances; space is completely filled but totally void.

Particle and Field Concepts

As the concept of space developed through these various stages the picture of the elementary particle in that space was correspondingly changed. For Democritus, each particle was a hard, solid, indestructible object. They interacted with one another by collisions, like billiard balls. In Newtonian mechanics, particles could interact at a distance, without coming into actual contact. Thus it was not necessary to ascribe to them any finite size; they could be confined to points. Instead of size the important property of a Newtonian particle was its mass; each particle has a unique well-defined mass. Since mass was measured by weight, the mass could be considered a measure of the "amount of matter" carried by the particle. Mass was a concept independent of the spatial properties of position and size.

For Maxwell it was not clear whether a particle was confined to a point or not. If it were a point-particle then the theory would imply that its mass be infinite, unless there were some unknown compensating factor. But in relativity theory it seemed that particles must be confined to points, for if extended in space they must be extended also in time. This led to awkwardness, if not actual inconsistency.

In both Maxwell's theory and relativity theory there were, in addition to particles also fields. Whereas particles were localized, fields were defined over all space. Thus nature was represented as a compromise between Parmenides and Democritus.

This compromise was unified by the quantum theory in which a particle is represented by a wave function, which like a field is defined over all space. This function is associated with the event of "finding the particle" at the various points in space. Because the probability of finding the particle simultaneously at two different points is zero, one can conclude that the wave function refers to the "center" of the particle. As there are (in standard treatments) no extra parameters corresponding to other parts of the particle, one has, in effect, a point particle, which is described however by a wave function defined over all of space.

Quantum Field Theory

A minor miracle occurs when the (same) quantum principles are applied to fields. If the fields are non-interacting, then the quantum principles imply that each field can be associated with a function that is the wave function of a particle. Thus the distinction between particles and fields disappears; both are aspects of a single entity, at least for the noninteracting case. The two classical concepts merge into a single quantum concept.

This elegant result is obtained for the case of non-interacting particles — for an idealized world in which every particle moves forever in a straight line. One possible way to extend the theory to more realistic cases is to add a contact interaction between the point particles. This procedure has had some remarkable successes and also some serious difficulties. The difficulties seem due basically to the necessarily singular nature of the contact interaction between point particles; the interaction has to be infinitely large to give any effect at all, and this infinity, when compounded, leads to difficulties. One difficulty is that the observable quantities are not defined in terms of the original quantities in a proper mathematical way; the theory is apparently not mathematically consistent.

A related problem is the unobservability of fields. The theory is built upon the concept of a field, which is a mathematical object defined at every point of space and time. In Maxwell's theory a field represents a quantity whose value at any point of space and time can be experimentally determined. But Maxwell's theory does not correspond to reality, because of quantum effects. Yet when the quantum effects are introduced one finds that fields in small space-time regions are not observable; if one tries to measure such a quantity the effect of the space-time constraint causes the apparatus to disintegrate, due to the phenomena of particle creation inherent in a relativistic quantum theroy. Thus, one is left then in the position of having built a theory to explain measurements of a quantity which the theory then shows impossible to measure.

The quantities that can be related to experience are probabilities associated with the presence or absence of particles. The defining characteristic of a particle is its mass. In the case of no interaction there is a close connection between fields and particles. The subsequent introduction of the interaction destroys this connection; particles correspond to eigenstates, and fields correspond to nothing — they are certain abstract entities.

In view of this, the possibility suggests itself that maybe a wrong move was made at the passage to the interacting case, namely that one should have stuck with the particles rather than going off with the fields.

S-Matrix Theory

The theory associated with the "particle alternative" is called S-matrix theory. The S matrix is essentially the collection of all quantities referring to the particles. These constitute only an infinitely small subset of the quantities appearing in the field-theory approach.

In the past few years it has been convincingly demonstrated, if not actually proved, that one can deduce all the results concerning the S-matrix that were formerly obtained from field theory directly from considerations involving only the S-matrix itself. That is, the very strong requirements imposed in the field theory upon the connection between the field-theoretic quantities and the S-matrix and between the various field-theoretic quantities themselves can be ignored; one can deal solely with relationships among the S-matrix quantities themselves. The calculations are in fact greatly simplified because none of the difficulties associated with the apparent inconsistencies of field theory arise. That is, the results come out in automatically renormalized form without use of special techniques for avoiding divergences. Moreover the new methods seem much more powerful than the old; they are being pursued with success in the area of strong interactions, where field theory had been completely ineffectual. Also the S-matrix approach seems to provide for a calculation of masses and coupling constants. This was outside the realm of conventional field theory.

In view of these impressive achievements let us adopt the view that the S-matrix or particle alternative is right and that the field alternative is wrong, and inquire as to the impact of this on the concepts of space and time.

In S-matrix theory the basic variable is not the space-time coordinate x , but is rather the momentum-energy variable k . The relationship between these two resides in the fact that two systems differing from each other by a translation by an amount x are represented by functions that differ by a phase factor exp (ikx) . In field theory where states corresponding to all values of k are allowed, one can find a superposition of these that has the property of being orthogonal to a translation of itself by any finite amount. One can therefore build up a system of orthogonal states, with one for each space-time point. These can be identified with the physical situation where the particle is at the corresponding point.

The basic difference between S-matrix and field theory is that in S matrix theory the value of k is restricted by the mass shell constraint, $k^2 = m^2$. The notion that there should be something corresponding to this particle, but with a nonphysical value of the mass is rejected; an eigenvector is associated with its eigenvalue, not with a continuum of noneigenvalues. A consequence of the mass constraint is that the construction of the space-time continuum from momentum space can no longer be carried out. In this sense space-time does not exist; there is no framework of points corresponding to the possible positions of the particles. Space-time is not, then, a framework of possible positions of a particle. It is rather a framework of possible translations of a particle. Thus, the notion of a particle's being at a point is lost, one can speak only of the shifting of a particle by a certain amount.

This sounds a little like the old idea of relativity of position — only relative position can be defined. Certainly this idea is at least contained. But we are referring to a situation where all particles but one are fixed, and hence can serve as a reference. Even then, the space-time coordinates do not define a set of possible positions of the particle but a set of possible translations of it.

How does the argument of Parmenides fare now? Previously we got around his assertion that empty space was devoid of every real thing by noting that it could be just devoid of every material thing, yet not devoid of every real thing. This circumvention was a consequence essentially of a better understanding of the possible kinds of things. But space was essentially, as before, a system of possible positions. In the S-matrix view, space is a set of possible translations. The concept of empty space simply does not arise. There are translations and other translations but no idea of emptiness.

Although from today's perspective Parmenides' conclusions are invalid, his rejection of the naive concept of space as a simple void seems supported. But who would dare say that the final word has now been said.