Dr. Schwinger's Paper -

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I must say I approached the idea of giving this lecture with great diffidence because being one who is neither trained nor particularly eloquent in the traditional modes of philosophical discourse, it was not entirely clear to me that I could say anything very helpful to this seminar. But on second thought, it seems, it had seemed to me, and I hope perhaps you will agree after tonight, that there are deep philosophical lessons to be learned in the way in which the practicing theoretical physicist thinks about the foundations of the subject; that is, the manner in which he approaches the problems, the general criteria that he brings to bear on what is a reasonable solution. Or perhaps you might say that the important thing then is to display the general world view, the world picture that the theoretical physicist has.

Now, this is particularly significant in connection with the specific topic of our seminar this evening, quantum physics and philosophy, because quantum physics or quantum mechanics, by which I think we mean finally the rational mode of understanding of microscopic or atomic phenomena, has perhaps had the greatest impact of any of the developments of physics upon the mode of thinking or the world picture of the physicist and thereby indirectly of the general citizen.

Now, to indicate that the topics we want to discuss today ever so briefly are not merely a matter of recording what is finished and settled in a dry subject, let me, perhaps just simply indicate to you that in the current line of research on this very area which is concerned with the attempt to understand the properties of the vast numbers of so-called elementary particles which have been discbsed in the course of investigations of high energy physics - - that there have emerged very deep philosophical questions concerning what the purpose of the theory should be. In other words, the class of theoretical physicists are split along rather deep lines of what they consider to be the proper mode of development, the proper means of finding a logical explanation. These are, at their foundations ~~are~~ philosophical questions and I think we can only understand ever so dimly how these deep philosophical cleavages among current practicing theoretical physicists have come about, if we try somehow to study the historical line of development which has led theoretical physics up to its current problems, its current dilemmas which must seem, at the present point, to be ever much more difficult than any of the things which have previously been considered. Obviously, every age thought that, but this is again the same situation.

Now, if we want to understand specifically the origins of quantum physics and its current line of development of high energy physics, I think we must go back to see how the stage has been set through the developments of what are called classical physics to compare with quantum physics. By classical physics, we mean essentially the precise formulation of all of the properties of matter as they were finally expressed in their essentially perfect form at the beginning of the 20th century and which are characterized by the fact that while the underlying conceptions are idealizations, it was no easy job to be a Galileo or to be a Newton; nevertheless, these conceptions still strike very close to common, ordinary everyday affairs. To understand the principles of physics, as they are expressed within these great generalizations of ~~these~~ classical physics, is not very difficult. Our school children manage it all the time. But quantum physics is something different. In quantum physics, and even more so in the current line of development of high energy physics, you go far beyond the ordinary situations of everyday life. We strike at a level of idealization that is hard to appreciate until you have seen how this historical line of development has come about.

Well to begin this historical development first, the first grand physical theory, of course, was that of Newtonian physics. This is a theory of massive point particles which interact by means of actions at a distance. The traditional theory of gravitation, of course, is the classic example of this. And to characterize this theory in a general way in terms of its philosophical foundations, let me say that Newtonian physics, or Newtonian mechanics is a causal, deterministic theory. Now, by this I mean the following things. By causal, one means essentially that when the state of the system is given at a definite time, and we must return to precisely what we mean by state, but when a state is given at a particular time, then the state is completely determined at any other time. This is what we mean by causality. Causality is inference in time. Given the state of affairs at one time, a state of affairs is uniquely determined at another time. What makes it deterministic is that the knowledge of the state also determines all possible physical phenomena precisely.

Now, the making of this distinction may not seem very important until we come up to the rather different situation that appears in quantum mechanics. I have spoken of the state within the framework of Newtonian physics or Newtonian mechanics. It surely is familiar to you that when you specify the state of the system of particles which interact with each other by means of instantaneous forces as the gravitational force was conceived at that time, that the full specification of state is the indicating of precisely where the particles are at a given instant of time and how they are moving;or perhaps in more technical language, it is the specification of the positions and the momenta of the particles, the momenta being their masses, their inertias and their velocities. If the positions and the masses of particles are known at a given instant of time, and it is known precisely under what law of force they are moving, such as the grand statement of the inverse square law of gravitation, then this is the specification of the state. Given the knowledge of the state, the state of any other time can be predicted and also, since this is a deterministic theory, the knowledge of the state is the origin of the full knowledge of the answer to all possible physical questions that can be asked.

Now, to indicate that Newtonian physicist is not something that lies completely behind us in the history of physics, let me perhaps remind you of the fact that the triump of Newtonian physics is indicated every-time, or should I say almost everytime, we have an announcement from Cape Canaveral, and certainly every time we have an announcement from Moscow. That is, Newtonian physics, as any general theory of physics must be, remains perfectly valid in its own domain and the domain, of course, is the motion of material bodies under the action of known laws of force which are instantaneous ~~in their~~ interactions and cover, therefore, fully the motion of artificial satellites in the perfectly well known field of force that is provided by the gravitational attraction of the earth, or more hopefully the moon, the planets, and so on. Physics introduces new theories not because the theories in a particular domain are found to be unsatisfactory, although they may be so also, if the technique of experiment becomes finer and finer and new phenomena are found which pass beyond the level of accuracy in the earlier theories, but primarily because the domains of physics which come into question are ever extended. For example, the next - - that is, to follow our line of historical development - - the introduction in the 17th century of the Newtonian concepts led to a steady development of these ideas, their applications primarily to astronomical phenomena, which lasted for essentially a full 200 years, while the technical means for the inference, in a precise sense, of the implications of these laws were drawn until one could fully carry out the calculations necessary to follow the paths of the planets, ~~their orbits~~ in all detail and so on. It was, however, during the 19th century that new areas of physical experience began to be met in particular in the domain of electromagnetism. And then we came finally ~~across~~ towards the second half of the 19th century to essantially a new physical theory going beyond anything that had been, so to speak, conceived within the framework of ~~the~~ a Newtonian physics.

This is Maxwell's field theory of electromagnetism. And let me say again, that as far as the broad ~~characteri~~categorization of these theories is concerned, that this was also a causal, deterministic theory. But what made it so very different was what was involved in the specification of state. Let me recall again that the Newtonian ~~physics~~ theories were concerned with point particles and the specification of state was the indication of where these particles were and how they were moving at any particular time. It is a discrete description; a finite number of particles; a finite number of quantities is needed to characterize everything about this physical system. By contrast, the field theory, and I have in mind of course the very specific example of the electromagnetic field, this requires, for the specification of state, we must give not a finite number of things; where the particles are and how they are moving, but an infinite number. We must in principle, at least, specify what the electromagnetic field is doing; how the electric field is pointed; and how the magnetic field is pointed at every point of space and this at a given time. And what makes this a causal theory is that if we know the state, if we know the distribution throughout space of the electric and magnetic field at a given time, then we can predict at any later time what the distribution of the electric and magnetic fields will be. Given the state at one time, the state is uniquely ~~employed~~ implied at another time. That makes it a causal theory.

Again, what makes it deterministic is the knowledge of the state, the knowledge of the electric and magnetic fields completely determines, supplies the deterministic answers to all questions that can be asked about the electromagnetic field. And again may I point out to you that while we are talking about a domain of classical physics, with the inference that this is not the final word, nevertheless, you have only to look about you at the ever expanding development of radio communication systems, and microwaves of radar, of television, to indicate that everyday the quantative success of Maxwell's theory is demonstrated. This is not a past history in the development of physics, it is something whose validity is confirmed everyday. The point, however, is that it refers to a limited domain of experience. It is not all of the physical world.

So, here then we have two very different kinds of physical theories, both causal, both deterministic but widely different in the nature of what characterizes the specification of a state. One line, so to speak, at one limiting domain of the spectrum, it is a discrete description. A finite number of quantities is specified. The other, at the other end, is a continuous description. Fields are involved, distributed throughout all space. And these, so to speak, are the models of the two limits of classical behavior: the discrete, the continuous. And it is particularly interesting to see how these two entirely different classical modes of description have in a sense become unified, or perhaps better transcended in the further developments of quantum physics.

And now, still continuing with our historical development, (of course, this is all familiar to you), that at the end, or shall we say the beginning of the 20th century, there were further very important developments associated with the name of Einstein - the developments of the special and general theory of relativity. But yet in a sense, these were not radically new developments in the sense that I mean quantum mechanics to be; they were rounding out the framework of classical physics. They were the recognition, so to speak, that once we had placed the field phenomena, the electromagnetic field specifically, on the same power - on the same foundation - as the theories of particles, that we had to recognize that there was a modification in the strict Newtonian point of view. In other words, while we certainly have still to deal within this framework with point particles, the point particles no longer interact by instantaneous forces. We now recognize within this framework, which is particularly emphasized by the relativity theory, that the interactions between particles are propagated through space by means of the intermediary of the field. And may I incidentally also emphasize this difference between the two classical modes. The strict Newtonian viewpoint was one of instantaneous interaction at a distance. The field point of view is one of local interaction propagated from one point of space to the contiguous points. There is no longer within the field concept any idea of instantaneous propagation. It is propagation through space and time by means of a mechanism which is, in fact, intrinsically limited in speed. This is, of course, the famous constancy of the speed of light, which is the starting point for all of the investigations on the special theory of relativity.

And so, what finally emerges from all of this is a theory in which there are particles and fields, standing side by side, neither explained in terms of the other. A dualistic theory, but in which the strict Newtonian point of view has been modified because we now recognize that the interactions between particles are not instantaneous but are propagated through the mechanism of the field. The field is there to supply the dynamical agency by which particles interact. This, then, is, so to speak, the dualistic point of view which is the culmination of classical physics; the point of view in which we have side by side, neither explained in terms of the other, the discrete point of view of particle, the continuous point of view of field; and a fundamental duality.

It was to be the purpose of further developments of quantum mechanics that these two distinct classical concepts, as I say, are merged and become transcended in something that has no classical counterpart - - is a new conception in its own, the idea ~~of~~ quanta as field. And we must try to trace the development of quantum mechanics, starting from this classical background, up to this much deeper quantum mechanical foundation and explanation - - a kind of replacing of the classical duality. (I presume here I am trampling somewhat on the domain of the next speaker but he ~~simply~~ must suffer ~~then for this intrusion~~.)

Now, so much then for a summary which can hardly do justice to several hundred years of hard work by many physicists in attempting to lay the foundations of these laws of what I will now call macroscopic phenomena because it was, of course, in the investigation of the micro~~scopic~~, of the atomic phenomena, that an entirely new world and a new system of order was opened up. It was here that it was found that the laws which served so very well to range from ordinary experience on the earth to extraterrestial experience in terms of the motions of the planets; when we turn not outward, but inward, we found new laws of motions, new laws of physics, new ways of thinking, new philosophical conceptions.

Now, how did this come about? First of all I must remind you - - I can hardly, of course, do justice to the tremendous development of physics which occurred during these years and the early part of the 20th century - - but these developments began in what may seem to be a paradox because we had pointed out the fact that in classical physics, we had two distinct laws of behavior, and one never trampled on the other. We either had particles, and they were discrete objects, or we had fields and there were continuous objects distributed throughout space. And the fields could be attenuated as much as you want - - a radio wave, as we travel out through space, becomes weaker and weaker and weaker in a perfectly continuous way. A particle, on the other hand, has discrete properties which it carries with it. And so the remarkable thing was the discovery, investigations of various atomic phenomena, of an apparent paradox. Objects such as light waves, for example, which were known ~~from the various phenomena - -~~ from various ~~experience~~ interference phenomena, to be essentially in the nature of waves, that is field phenomena; there are wave lengths associated with them and light is spread out through space in a characteristic field way. One now found that from performing suitable experiments, that these light waves now appeared to acquire, under certain experimental conditions, particle-like properties unlike the picture which the classical notion of a light wave which suggests that the energy of the light wave is simply distributed continuously throughout the area that it occupies, the light wave now apparently under some circumstances exhibited the ability to transfer definite and concrete amounts of energy, acting then as a particle whose characteristic, of course, is that a particle has associated with it, in a certain state of motion, a definite energy, a definite momentum. And now we found, in the early days of these developments, that light waves exhibited, under certain circumstances, definite particle-like behavior. This was a paradox. Here we found the two quite distinct classical notions, nevertheless in some sense, both being realized within the microscopic domain. This, for example, is the classic experiment of the ~~polar~~ photo- electric effect in which light waves, falling upon metals, would liberate electrons, transferring energy to the electrons, in which a definite amount of energy was absorbed every time, despite the picture of a classical field distributed throughout space in which you might absorb more or less energy, depending upon the accidental circumstances of that particular electron.

Now, here then was light, a characteristic example of a wave or a field phenomenon, acting in a particle-like manner. The converse was also true, although the experimental proof of this would have to wait for some 27 years. But at this distance in time, I think we can lump all these things together and say that experimentally, as an important aspect of this same development, the converse was true. Electrons were the characteristic example of microscopic particles. Electron beams could be produced in evacuated tubes and they would move in straight lines. And when exposed to electric and magnetic fields, they would change their direction just as material bodies were supposed to do. But, nevertheless, under appropriate circumstances, namely when electron beams are scattered from crystalline bodies, one now found interference rings which would be characteristic of the type of wave length or field phenomena that is characteristically associated with a distributed field. In other words, instead of being scattered as material objects would be, you found that the electrons moving through a crystal would be scattered in the way that would produce a characteristic interference ring much as light would do under conditions that would produce the same wave length. Here then were objects originally thought to be essentially classical particles which, under new experimental conditions, would exhibit continuum or wave-like phenomena. We had then a remarkable duality in which apparently the same objects could, under some circumstances, act as classical particles; under some other circumstances, could act as classical waves.

And here, of course, was something for which there was no preparation in any other phenomena of physics as they had been known.

Now, more than this, the further detailed investigation of the properties of atoms, as they were revealed by detailed spectroscopic experiments. (You know, of course, how throughout this time the possibility of producing atomic spectra in some suitable circumstances of high vacuo so that one could investigate the behavior of individual atoms, how this led to a detailed investigation of atomic spectroscopy, the attempt to understand this in terms of the motion of electrons within the atoms, and the complete failure of classical physics to account for these phenomena.) The mere existence of atoms and their ability to radiate precise spectral lines is a conflict with classical physics. This is, of course, a familiar illustration, but if we take any pictures of an atom as electrons move around some central nucleus, as Rutherford discovered to be the situation in 1911, that according to the classical laws of electromagnetism, the accelerated charges in their motions around the nucleus would always continue to radiate until finally, they had exhausted all possible energy and would fall into the nucleus. And in the course of this radiation, which first of all meant that atoms were not stable, a gross flagrant violation of simple experience; and more than that, as they did so, they would radiate spectral lines whose frequencies would change as they got closer and closer to the nucleus, and you would have nothing analogous to the empirical situation of sharp spectral lines, of definite frequencies, characteristic of individual atoms. So, that classical ~~the theory of~~ the laws of macroscopic physics ~~had~~ failed completely within the microscopic world.

Now in the detailed analysis as it was carried out, primarily in the hands of Neils Bohr, and others of this important Copenhagen School of Physics, it was found, in the course of attempting to understand it, by simply postulating new laws of physics; by struggling from one phenomenon to another of what was necessary to introduce; how one had to throw away the laws of classical physics and discover new hypotheses that could account for these facts; it was soon found, in terms of the analysis of these and other experiments, that the only explanation that could be given was by supposing that physical phenomena, or physical quantities such as energy, ~~and the~~ angular momentum - - are the two important examples, which according to classical mechanics could assume any possible values - - these are continuous objects - - a particle in ordinary life can be given any energy one wishes by simply providing the appropriate amount of energy. If you set a body into rotation, the angular momentum that this will have, to use an appropriate technical term, can be given any value. There is no particular selected set of values that are natural. But, nevertheless, the analysis of the facts of atomic spectroscopy indicated that the energy values that atoms or electrons in atoms could have were not continuous but assumed definite values. This was the only explanation that could be given of the discreteness of spectral lines. And the particular values that these spectral frequencies had could only be understood by supposing that the angular momenta of the atoms or the electrons rather had certain definite values, all of these values being given in terms of the new natural constant which is the so-called Planck constant of action, which was first discovered in connection with other attempts to understand particularly significant characteristics of atomic phenomena.

So here, then, we had first of all the major break with the phenomena of classical physics, quantities which classically were supposed to be - - would be given continuous values now had discrete values. This, in other words, is the general observation of the microscopic world that the phenomena of atomicity is all prevading. Not only must we account for the very existence of atoms, which after all is not a classical conception. Classically, there should be no limit to the extent to which you could subdivide matter. The fact that this subdivision cannot be carried out indefinitely, but ceases when we reach the atomic scale is, of course, the most fundamental statement that something new is involved. But here is the phenomenum of atomicity, not only in the mere existence of atoms but also in the laws of mechanical motion that an atomicity of angular momentum, an atomicity of action, to put it in the most general way, was a basic phenomena of microscopic physics. And we simply had - - I say, we - but of course I was not involved at the time; there is, nevertheless, the feeling of ~~future~~ kinship here - - that physics simply had to understand in terms of new laws which transcended anything that was familiar before. This was a new world.

Now, beyond this phenomenon of atomicity, which I mark as the one basic fact, the new fact of microscopic physics, there is another one which appears at the same time. This is the essentially statistical nature of microscopic phenomena. This is another fundamental feature which must be accepted as the way that the microscopic world operates. The fact that the microscopic world is necessarily statistical can perhaps be understood if we think back to what we have just said about the fact that, for example, an electron beam, interacting with a crystal, will exhibit a defraction phenomenom. Now, let's think about how this defraction phenomenon in fact would come about. In other words, suppose we had a crystal. A crystal is a regular arrangement of atoms with a characteristic distance separating them, and by virtue of this characteristic dimension, any wave phenomenom that falls upon this crytal - - in other words, if there is a characteristic distance associated with the crystal, shall we call it a - - and there is a wave with a characteristic wave length, that then, depending upon the relation of that wave length to this characteristic distance, there will be certain preferred definite directions of scattering. This is, for example, the phenomenon that was well known in the case of X-rays which, in fact, the demonstration of which represented one of the experimental proofs that X-rays are in fact wave phenomena. So that when we carry - - so to speak - that when we carry out an experiment in which a beam of say electrons falls upon this crystal, and then moves in various directions falling upon a screen, it will then produce a characteristic interference phenomenon; which is to say instead of the electrons falling more or less at random, with a uniform intensity all over this screen, you will find preferred places. If I may draw a sort of an intensity pattern, there would be something we can see that looks like this. In particular, if this is not a single crystal but a number of such crystals randomly oriented, then we will find rings, circular rings, forming an interference pattern - individual ~~understand,~~ electrons, if I make this beam so weak that one electron, so to speak, within a perfectly definite time interval moves through this crystal in some way, it will finally be detected by landing in a perfectly definite place on this screen. This may be a scintilation screen,

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for example, and if you have a weak ~~groups~~ beam of electrons and you look at the screen, you'll suddenly see a flash of light, not all over the screen but in one place. The electron exhibits its particle ~~light~~ like characteristics by finally detecting, by finally exhibiting its position by producing an appropriate chemical process, the result of which is a flash of light. And we observe that the electron is here. For one electron, in other words, there is certainly no interference pattern. The interferrnce pattern does not appear all at once. You have simply an individual electron. Now, a second electron arrives in the course of this very weak beam. What happens to it? Does it land here? No, it lands at random, relatively speaking, ~~to~~ this point. But now we continue more and more electrons, each arriving independently of the others. All coming under the same experimental conditions land upon this scintillation screen and as more and more come, (for the photographic plate perhaps to give a permanent record) as more and more ~~finally~~ come, finally the pattern of this interference behavior emerges. In other words, many electrons land here; none land there, and so on until the final picture of intensity is one which gives this overall pattern.

But nevertheless, this has come about as the result of the random landing of these electrons at various points on the screen. Put in another way, suppose we had carried through such an experiment ten to the tenth electron ~~that~~ have finally landed on a certain area, and the picture of intensity of relative numbers such as this. Now, I repeat the experiment. I prepare exactly the same circumstances, and I turn on the electron gun and see what happens. Now, again, the first electron moves through this ~~beam~~ medium. Will it land at this place; certainly not. We begin all over again but the pattern repeats itself in a random way. The first electron of the second experiment will land here; the second electron of the repeat experiment will land here. In other words, the individual particles arrive in a perfectly random statistical way. There is no possibility of controlling. This is, of course, a generalization from a half of a century of attempts to do so, but, nevertheless, the picture which we must accept is that within the domain of microscopic phenomena, we are unable to control within the framework of this particular experiment where the individual particles will land, but what is perfectly determinate, and will be repeated every time you repeat the experiment, is the picture of the interference pattern. In other words, we have, therefore, - - we have to accept - - I give you this one simple example - - that once we have this apparent duality of entities - - electrons - - behaving under some circumstances like discrete entities - - particles - -, landing at definite places on that screen, but in other respects acting as waves, producing in their overall intensity characteristics this interference wave phenomenon, we must accept the fact that the inteference pattern is not going to be repeated in miniature every time an electron lands. And, therefore, there must be an aspect of randomness about where the electrons do land; and that the intereference pattern is merely finally the statement of relative probabilities; that with endless repetitions, you will find many more particles here than here - - and in a perfectly regular way. So that it is in a sense almost an automatic inference of everything that we have said, but I would prefer to take it as really the more fundamental thing, that it is a basic characteristic of the laws of microscopic phenomena that they are statistical. It is not possible to predict, in general, the outcome of a specific event. But what one can predict, and what is the purpose of microscopic physics or quantum mechanics to predict, is the average result, the statistical result, the effect that the net situation for the repetition of a sufficiently large number of times of the same experiment. So here then ~~given~~ - - we have the basic situation of microscopic physics - - there are these two new phenomena which we must incorporate into a world picture: the fact that phenomena are atomistic and that they are statistical. But to be statistical, of course, does not mean that we have failed; in other words, that our physics is fundamentally different. We simply recognize what the nature of this new microscopic physics must be. It is not to predict the outcome of each individual event. It is to predict rather what the outcome must be on the average; what the probable outcome must be. And in this experiment - - or rather this simple description of the experiment - - indicates that this is something that we necessarily must put up with. In fact, as we will perhaps suggest in ~~future~~ further discussion, if we attempt in any way to control precisely where this first electron shall land, we can indeed do that; we can produce a new experimental situation in which with essential certainty, the electrons will land ~~over~~ always here. But then we shall have no interference pattern. In other words, the two situations that we're talking about: one in which ~~the~~ an interference pattern does appear is one definite experimental situation, and in that it is not possible to predict or control in any way where the individual electrons will appear. There are other experimental situations, however, in which, in fact, we can control and predict where the electrons will appear in the course of moving through some apparatus. It will be a different apparatus and that apparatus could never produce an interference pattern. In other words, we are dealing, so to speak, with two distinct aspects of the microscopic world and it requires a different experimental situation to display one or the other. Let me perhaps come back to say a little more about this because let's think now of how once having recognized that we have these two basic features of the microscopic world, the aspects of atomicity and of the statistical nature of microscopic events, we could now proceed to construct a theory that would in some way incorporate this very bizarre situation.

To indicate how this comes about, in other words we must have a mathematical theory. We must have a mathematical theory which in some way will represent a suitable mathematical model or idealization and enable us to predict in a coherent way, in much the same manner as physics has always done, what the outcome of experiments will be if we are given correctly all the conditions that fully characterize what the nature of the experiment is. To see what we have to do, I think we must go back and think a little more consciously of some of the fundamental principles, call them philosophical, if you like, which underlie ~~the~~ classical physics - - or shall I now say macroscopic physics - - because that's now the distinction. I now think specifically of the theory of measurement. And here, of course, we have to recognize a fundamental philosophical conception that physics is an experimental science and it is concerned only with those statements which in some sense can be verified by an experiment. And the purpose of this theory is to provide a unification a codification, or however you want to say it, of those results which can be tested by means of some experiment. In a sense, therefore, what is fundamental ~~in a~~ theory ~~is the theorem of any theory~~ of a specific department of nature is the theory of measurement within that domain.

Now, what was characteristic of the theory of measurement in the macroscopic classical physics? Well, the essential thing that was basic to it was the conception of a non-disturbing measurement. That is to say, of course, it's perfectly obvious to anyone who has ever come near a physics laboratory that in the process of measurement, which is to say an interaction between the physical object of interest and a measuring apparatus,(you may take as the simplest model the insertion of the thermometer into a body of water) the object, of course, is to determine the temperature of the water ideally as it would be without any disturbance by means of the thermometer,but without the presence of the thermometer, there is no means to determine what that temperature is.) In other words, we must - - to gain information about a particular object - - we must interact with it physically in some way but nevertheless we would like to be able to idealize that interaction in such a way that we could

~~immediately~~ meaningfully state what that property would be as though the interaction did not occur. Now, you know, of course, that whenever the interaction occurs, there must be some disturbance as a net effect of that interaction with the object in question. The insertion of a thermometer into a pail of water changes the mass of the water. It will change the temperature that is to be measured in some way. But what is characteristic of classical physics is that we state, and correctly, that it is meaningful to talk of an idealization in which that interaction can be made as small as we please without, however, it becoming zero; because if it is zero, we have no means of gaining information. To gain information, the interaction must be present, but we can meaningfully speak of that interaction being so small that it does not disturb the object of interest. Now, that is in fact not always necessary; that is, one fact of measurement that we can carry out in which, by means of a disturbance that is so slight that it can be neglected for all practical purposes; then we have carried out a measurement ~~we~~ of the thing we want. That is not always possible. For example, some measurements, shall we say, represent chemical changes, which are large alterations in the nature of the substance and these are certainly not negligible disturbances. It is here that a second aspect of macroscopic physics comes into play. We say that it may be necessary for some measurements to make large disturbances in the object of interest, but since classical physics is causal and deterministic, we can calculate as accurately as we please and correct for the effect of this disturbance.

Any of you who have taken classical physics will know that any measurement has a theory associated with it. A theory which represents the recognition within the framework of that practical experiment what the disturbance has been and the calculation, how to correct for that disturbance in order, therefore, to come back to what an idealized non-disturbing measurement would be. In other words, the two basic features are that we can either make the interaction so small that there is a negligible disturbance; or in a particular experimental circumstance, by the nature of the experiment we wish to perform, we cannot make the disturbance arbitrarily small, we can still calculate the effect of that disturbance and compensate for it with arbitrary precision.

This is, ~~the~~ simply stated, ~~it is~~ the theory of classical measurement; and associated with that, of course, corresponding to this idealization of non-disturbing measurements, either because there is no disturbance or ~~that~~ the effect of the disturbance can be precisely substracted that is accounted for, underlying this, of course, is the idea that there is then no limit to the accuracy with which we could make measurements simultaneously of any number of physical properties as in the very statement of the concept of state, for example, in Newtonian physics. When I assert that the state is the specification of the positions of the momenta of all these particles, of course, implicit in that is the assumption, consistent with the whole scheme, that in fact I can carry out the measurements necessary to give the numerical values that those quantities have at every time, or the distribution of electromagnetic fields throughout all of space.

So, the point is, therefore, that the classical theory of measurement says there is no limit to the accuracy with which we can assign numerical values to all the quantities that are needed to specify the state and since all of these are deterministic theories, that means to all physical properties at once. For this reason, since physical properties, so to speak, can be assigned numerical values, one has never in classical physics drawn any distinction between the physical properties and the numerical values which they have at any particular time because we are always in the position of being able to assign to the physical properties considered, if you like, as an abstract thing, a very concrete representation by means of numerical values which a non-disturbing measurement would assign to them at a particular time.

So, here we have again restated the foundations of classical physics: the idealization of non-disturbing measurements and the corresponding foundations of the mathematical representation; the identification of physical properties with numbers because nothing stands in the way of the continual assignment of numerical values to these physical properties.

Now, what is the situation of microscopic physics? Drawing upon the vast body of experimental data which finally accumulated in the course of several decades, and which I have finally summarized under these two basic headings as the properties of microscopic physics or, if you like, of microscopic measurement; the phenomena of atomicity and of the statistical nature of these phenomena.

What does this mean? First of all, atomicity: atomicity means, of course, that the microscopic entities come or have many of their properties carried in certain basic units. There is no half of an electron. The electron is a definite mass. It has a definite charge. If the interactions that I am concerned with are electrostatic in nature, I cannot reduce them arbitrarily in strength because there is no half of a unit of charge. This indicates to you immediately, I think, that the basic difference between the laws of microscopic measurement and macroscopic measurement. I must take into account the fact that the strength of the interaction, which must be present if I am to talk of measurement at all and, therefore, talk meaningfully of physical phenomena, the strengths of the interactions that are necessarily present if a measurement is to take place at all, cannot in general be made arbitrarily small because the physical phenomena that interact, the atoms, the electrons, in general have relevant physical properties which come in certain units - quanta, the origin of the name of the subject that we are discussing.

Now, that might seem as though this were still not an insupportable difficulty. We recognized, even in classical physics, that there might be circumstances in which the act of measurement produced definite disturbances in which we could not minimize the nature of the interaction because of the particular kind of measurement we carried out. In classical physics, we said the situation may be such that the measurement interaction is very strong; cannot be made arbitrarily weak, but this still does not upset the underlying philosophy of measurement because I can calculate with arbitrary precision what the effect of that interaction was and compensate for it, correct for it. Can I still do that now? The answer is no, because this is where the second fundamental aspect of microscopic measurement comes into play; namely, the phenomenom of statistics. The fact that we cannot predict in detail what each individual event will do but only make predictions on an average or statistical scale. In other words, we say if a measurement act involves a strong - - necessarily strong - -

on a microscopic scale interaction, because we cannot cut the strengths of the charges in half, we cannot change the properties of these fundamental particles, we must accept them as they are) If an act of measurement has produced a large disturbance, we might say we could, nevertheless, correct for it in each individual instance. But we cannot produce a control over what happens in each individual instance in any detail. We can only predict or control what happens on the average; never in any individual instance, which is to say, therefore, that the program of computing what the effect of the disturbance was and correcting for it is, in general, impossible. Impossible because we cannot control precisely what will happen in each individual circumstance. Then, the two basic tenets, therefore, of the theory of macroscopic measurement are both violated. Either the interactions cannot be made arbitrarily weak because of the phenomenon of atomicity, or if we wish to accept this and correct for it, we cannot do so because we do not have a detailed, deterministic theory of each individual event; we have only the ability to anticipate or control what happens on the average.

So, here then is the general indication from this mass of experimental data that for microscopic physics, if we are to construct a theory, we need a whole new theory of microscopic measurement. And to go with this, we need a whole new scheme of mathematics, which is to say that we can no longer, of course, speak meaningfully of the numerical values that physical properties have at a given time; that is, I wish now to point out that the failure of these fundamental assumptions means equally well a failure of the ability to represent physical phenomena in the microscopic realm by numbers which change in time as we do in the macroscopic or classical domain. Something of an entirely different mathematical nature is needed. And it must be of such a different mathematical nature that it represents or it mimics the basic facts of microscopic measurement. And to emphasize the relevent point, I may say this. Macroscopically, we can measure one physical property; we can assign a number to it. We measure a second physical property; we assign a number to it; and, in fact, we can now speak of this pair of numbers which are the values of this pair of physical properties at a given time. And there is no contradiction here. We can perfectly well go back and check that that first property has still the same value that it had if we could, in an idealized way, carry out these measurements rapidly enough or regenerate the physical circumstances in such a way that we could repeat that measurement. By contrast, suppose we have indeed succeeded in measuring in some way some one physical property of an atomic system. Now, we go on to make a measurement of the second physical property. That measurement necessarily will involve an interaction, the strength of which is not arbitrarily weak and the effect of which is not controllable, in such a way that it will, in general, produce changes in the physical circumstance that is involved, the physical results that were brought about by the first measurement. In other words, the system that is being measured, if you like, is disturbed in an uncontrollable way in such a manner that if we now went back and asked for the value of the first physical property, checking to see that it still had the same value, we would now find not at all the same value but a random assortment of all the possible values that it could ~~have had~~ assume with various probabilities that depend in detail upon precisely what we have done because the second measurement has introduced a new physical situation; has disturbed or has interacted with the physical system of interest in such a way that we can in no way be sure, except under very special circumstances, that the system has been left in precisely the same physical situation that would enable us to say that the first physical property still has the same value. In other words, if we once recognize that the act of measurement introduces in the object of measurement changes which are not arbitrarily small, and which cannot be precisely controlled, or shall we - - I say anticipated, then everytime we make a measurement, we introduce a new physical situation and we can no longer be sure that the new physical situation corresponds to the same physical properties which we had obtained by an earlier measurement. In other words, if you measure two physical properties in one order, and then the other, which classically, of course, would make absolutely no difference, these in the microscopic realm are simply two different experiments. You have two different physical situations which come about depending upon whether you first measure property "A" and then property "B", two successions of disturbances which have this microscopic character, or do it in the reverse order, which is an entirely different physical situation. A different array of disturbances have been brought to bear on the physical system. In other words, depending upon the order in which the microscopic measurements are performed, you will have in the final result a different physical situation; that is, in general it is no longer possible to say that properties "A" and "B" have these values because that would only have meaning if you could get the same numerical values no matter in which order the measurement was carried out. Only then could you meaningfully speak of properties "A" and "B" as compared to first the measurement of "A" and then the measurement "B"; as compared to first the measurement of "B" and then the measurement of "A". These are simply different physical situations.

So, therefore, the mathematical scheme can certainly not be the assignment, the association, or the representation of physical properties by numbers because numbers do not have this property of depending upon the order in which the measurements are carried out. The assignment of a pair of numbers to two physical properties introduces no sense of order, no sense of sequence. We must instead look for a new mathematical scheme in which the order of performance physical operations is represented by an order of performance of mathematical operations. Now that, clear to those of you who may be mathematically sophisticated but perhaps not aware of the actual course of development, may suggest to you that in fact the development of quantum mechanics, which was the final culmination in the sense of the erection of a logical scaffolding to incorporate these new laws of microscopic physics; that the mathematical scheme that was finally found to be necessary and successful is the representation in a very abstract way of physical phenomena - - physical properties -- not by numbers but by elements of an algebraic scheme which are non-commutative in the sense of multiplication. In other words, the multiplication of these symbols was found to be the proper counterpart of the successive performance of measurements. And the fact that the order of measurements in consequence of these disturbances is significant means that correspondingly, the sense of multiplication of these symbols must be significant.

And so we are led to a much more sophisticated and deep mathematical scheme in which physical properties are set into correspondence with the non-commutative elements of an algebra or hypercomplex number system as compared to the very elementary representation of physical properties=numbers. So here then, is so to speak, the way in which the laws of microscopic physics led to a deepening, a much more sophisticated level of mathematical representation in terms of a system of non-commutative physical quantities or, as they often are referred to, non-commutative operators, because the full development of this scheme of mathematical representation showed that the proper development was to be done by associating to every physical property an abstract symbol or operator, and to associate with every physical state - - the idea of state reoccurs - - to associate with every physical state a vector in a suitable abstract space on which these operators acted. In other words, you have a kind of geometry now, a geometrization of physics in which you now have an association between vectors in an abstract space and states, operators in this abstract vector space and physical properties.

And as a result of all of this, a very beautiful mathematical scheme which gives a wonderful account of all these seemingly bizarre and incomprehensible facts of microscopic physics has emerged. This is quantum mechanics as it is known and this development took place essentially in the years 1925 to 1927, still very distant from our present point of view.

Let me describe, within the same general framework what the nature of quantum mechanics is. It is still a causal theory. Given the state at one time, the state at any other time is uniquely determined but what makes it different is that it is not a causal, deterministic theory. It is a causal, statisticallly determinate → deterministic theory. In other words, while the knowledge of the state at one time fixes the state at another time, what information is obtainable from this knowledge of the state? Classically, if you knew the state, you knew everything. If you knew where the particles were and how they were moving, you could predict any other physical property you happened to be concerned with with arbitrary precision, but as we have just said, of course, arbitrary precision of individual predictions cannot exist in the microscopic world. Nevertheless, as a science, as a science of observation, we must be able to make precise predictions. But the precise predictions are of a statistical nature. The knowledge of the state enables you to predict the statistical, the average outcome of the result of the result of the measurement of any physical property, but never the result of any specific event. In other words, if you know the state, you can then predict what the result of repeated trials of measurement of particular physical property will be. You will have perfectly determinate, statistical predictions but no longer individual predictions. And so in this sense, then, I say that the theory is still causal. The connections between states at different time is still present. This apparently seems to be fundamental in any physics as we know it; at least up to this point. But what has changed drastically is the fact that the knowledge of the state does not imply a detailed knowledge of every physical property but merely, in general, of what the average or statistical behavior of physical properties may be. And so this, in a sense, has been the final understanding of these remarkable - - what appear to be paradoxes in the earlier developments of the theory. They are now resolved in terms of this statistical determinate rather than individually determinate theory.

Now, in particular, however, within the framework of these states, I have spoken of states but have in no way indicated how a state is to be defined. The answer to this can be given if we think of kind of a model of a physical system which still comes very close to classical models. For example, we began by thinking that atoms were to be understood simply by electrons with the idea of small material bodies moving in a certain definite field of force; that field of force to be the Coulomb law of attraction between the electrons, as negatively charged bodies, and the nucleus as positively charged bodies. Here is a situation which seems to fit the Newtonian mold; a definite law of force, a finite definite number of material bodies. What failed was not that the dynamical picture was not correct but that the laws of microscopic physics were different. They were not such as to permit a detailed, deterministic prediction but they have this character of the statistical deterministic theory. But now here, at least, we have a physical model which is classical in picture. When we describe an atom, we say how many electrons there are and what the nuclear charge is and the picture is still classical, at least as far as our minds are concerned. It is very different, of course, in how we go about calculating. And the difference is that while, for example, where we talked about the hydrogen atom we would say, in a very simple picture, here is one electron and the electron has associated with it physical properties of position and physical properties of momenta and classically we would say that there is no limit to the accuracy with which we could measure these positions and momenta simultaneously. The net outcome of this -- the distillation of what physicists have learned throughout this line of development is that this is not the proper definition of a state or an electron in an atom. The best we can do to specify a state is not to assign numerical values simultaneously to all of these classical properties of position and momenta but to only half of them. We can, in fact, produce experimental situations in which we know precisely where an electron is. It ~~might~~ lands on an a scintilation screen that is essentially the position of it; or we can produce experimental situations in which we know precisely what the momentum of the particle is. That, in fact, is what I had in mind when I started this beam experiment. Here is the particle, moving in a definite direction with a definite speed, and having a definite mass. That means I know the momentum, but when I know the momentum, in a sense I cannot know where the position is and the appearance of the interference pattern and the random falling of the particles on the screen is the sign of that effect. On the other hand, if I produce a very different experimental situation, of course, in which I arrange matters so the electrons always land here; so that I have a position measurement, I can predict precisely what the result of such a measurement would be; then we will never have an interference pattern which is characteristic of a very different physical situation where the momenta are perfectly definite. In other words, what has changed basically is what is the nature of a state. If we have a certain number of particles, electrons, for example, and the specification of the state is the specification of where the particles are at a given time or alternately, how they are moving at a given time, but never both together. And this fact -- that in a sense, by comparison with what would be a full specification of state in classical physics, that in quantum mechanics, the specification of state is the ability to specify with arbitrary precision what the result of the measurement would be of half of those properties. But then we are completely incapable of predicting the individual values of the other half. They will then simply have random probability distributions.

If you make measurements again and again on this state, about which you know precisely the positions, you will always find that position, of course, comes out precisely as it should be. But if, on that state, you make momenta measurements, you will find never a definite value. You will find a random statistical distribution which is the wider variance -- at wider variance -- the more precise is the accuracy with which you specify the position.

Now in fact, this simple situation is essentially a statement of what is perhaps the widest philosophical principle that has emerged from these studies of microscopic physics. This is what is known as Bohr's principle of complementarity. And by the idea of complementarity we mean the final unification within these general principles of what began by seeming to be a paradox. The fact that electrons which, under certain perfectly definite experimental situations, acted as particles would, under other experimental situations, act as waves - - this is now, so to speak, what we have expressed in a more precise way by the fact that the definition of state never refers to all of these physical properties but to only half of them. You have the privilege of designing experiments in which different choices are made as to which will be the physical properties whose values are precisely known and *

waves represent the option - the choice on the part of the experimenter to produce an

*Interruption due to changing of tapes.

experimental situation in which the momenta are selected to have definite values, the position can then not be controlled. In other words, Bohr's principle is the statement we have in microscopic physics first of all a new world (that's the important thing to recognize), in which classical analogies fail but, nevertheless, there are, so to speak, certain situations in which analogies of a classical nature do hold in which it is possible to speak meaningfully of particles with regard to certain circumstances and certain measurements; other situations where electrons, or what have you, can be spoken of as waves. In other words, in which there are two distinct classical pictures which can hold under different physical situations, never simultaneously, And in which the applicability of one picture prevents the applicability of the other. If we have an experimental situation like this, this is the experimental situation -- the picture is one in which the electrons act as waves and then the classical picture is inapplicable. We cannot predict precisely what the particles will do. If we do attempt to use the classical picture, the result is simply a statistical prediction of what the result of position measurement will be. In other words, we never have, we never can have this as a resolution of the paradox: the wave picture holding, this is the interference pattern; and the particle picture holding, the prediction of a definite position simultaneously. We can produce experimental situations in which one picture is relevant and the other is not but both pictures are on the same footing. We can produce experimental situations in which either classical picture can be applied, and the other is then inapplicable. The idea of complementarity, however, is that a full understanding of this microscopic world comes only from the possibility of applying both pictures; neither in itself is complete. Both must be present but when one is applied, the other is excluded.

This is, so to speak, the entirely new situation which has no counterpart in any of the classical philosophical modes of thought. It is something that simply must be accepted or, at least all physicists have accepted it - - it is simply the way in which the laws of microscopic physics have been understood and as the result of which an enormously successful development of quantum mechanics has arisen. The net result of the applicability of these understandings in microscopic phenomena has represented within the space of a few years the complete sweeping away of what was traditionally regarded, at least as far as the fine work of fundamentals of all of the classical problems of physics; in other words, an understanding of the state of matter in all its various common manifestations has been completely refuted? ~~reputed~~. A reduction of chemistry to physics has been brought about. The understanding of all of the various diverse properties of matter in all its forms under all ordinary circumstances is reduced to a few simple facts. The laws of quantum mechanics and the specification, if you like, of which particular configuration you happen to be talking about - - you must give, of course, ~~some of the~~ - what the nature of the nuclei are and various other matters. And then the laws of quantum mechanics, in principle at least, and to a large successful manner ~~have been~~ in practice~~d~~, as indicated by the enormous developments of the underlying theory of the solid state and many other applications.

All of these are in large measure the direct understanding, or an expression of the understanding. of the laws of atomic physics ~~that account for~~ - that have been codified - and unified in quantum mechanics.

But now in a fundamental sense, this was completed by 1927. This is by no means the end, however, of physicists' investigation of the physical world. The development has gone on and gone on in the direction of looking for entirely new realms of physical experience within the domain of higher energies, smaller distances - -. We have spoken again and again of the atom but within the center of the atom is the nucelus, and within the nucleus are the nucleons, and as we are now beginning to understand, the nucleons are made up of other still more fundamental primordial entities. The search goes on. But to understand it a little bit, I think, in what language this development has continued; to understand the language in which this is continued, I must come back to an idea that I mentioned rather earlier, the notion of the quantized field because here we have perhaps the deepest expression of what has been learned, so to speak, what has been learned within the framework of these microscopic phenomena. Let me perhaps introduce this in terms of another basic philosophical idea which is given an entirely new turn within the phenomena of microscopic physics. This is the idea, or the concept, if you like, of identity or indistinguishability. It is, of course, perfectly clear to you that when we speak even in classical physics of electrons that mere terminology indicates that we understand that one electron is just like another. If we measure any of the properties of this electron, or that electron, that is the fundamental non-accidental properties its mass, its charge, and whatever more sophisticated properties you may be concerned with, these are invariably the same. This is, if you like, the fundamental conception of the uniformity of nature without which physics could never begin to operate. We must assume that one sample of a particular substance is like any other sample if no irrelevant circumstances are involved. So that if we take any two electrons, describing them classically as we might have if we had two beams of electrons moving in some evacuated chamber, then we understand that one electron is just like another but in classical physics, there are no particular implications in this, because despite the identity, the indiscernability in principle of the two electrons, in classical physics we are never in any difficulty of being able to specifically distinguish them. We can say this electron originated from this region of space; the second electron from the second region of space. Classically, in the sense of being able to follow in detail the projectories of these particles, I can at every instance say precisely where this electron came from and trace its path back continuously to the point of origin and indicate no matter how these electrons may interact in some complicated way within a vacuum chamber or a radio tube, for example, in principle, at least, if I were making use of nothing but the classical laws of physics, I could always identify at any stage precisely which each electron is.

Now, I think you may see from that that the situation must be very different when we recognize the laws - - when you recognize the reality of the microscopic world; that it is not governed by those laws. If we have, for example, a collision experiment. Suppose I have two beams of electrons. I set them into collision, an experiment which, incidentally, will hopefully be done in the not too distant future - - you could make them protons just as well, in which case there is no difficulty in performing the experiment.

It is, of course, important to realize that the laws of nature which I am speaking about govern all of the various manifestations of matter. If I choose a particular example - - if I speak of electrons, that is historical convention. Those could be protons, neutrons, hyperons, pi-mesons, the laws of physics are the same. Now, if we imagine such a collision, if it is to be a collision, these particles must come into intimate interaction and, of course, what they do not do now is carry out, as they would do classically, a detailed trajectory because for that to be meaningful, I must be able to always, without disturbing the nature of this experiment, check precisely what this particle is doing at every instant of time. That calls for a degree of control or of determinism which is impossible in the microscopic world. If I have produced an experimental situation in which the particles head toward each other, then they have rather definite momenta. Then, as I have tried to suggest, the complementary physical measurement no longer can be specified in detail. I have no way of knowing, nor can I give any meaning to precisely where these particles are.

In other words, to draw this on the board, I must indicate a fuzzy indication, I must indicate that I have only a fuzzy knowledge of where these particles ~~are~~ can be, which is to say that I can no longer tell what has happened here. And when finally these beams separate, so I no longer have any doubt about which is which, I have no right or ability to tell whether this electron is that one - - or that one - - because I have not been able to follow in detail precisely what has happened. In other words, these basic physical phenomena, the atomicity, the statistical nature of things, the inability to control in detail individual events, implies correspondingly the absence of an ability in the fundamental experimental sense to tell in detail which particle is which at every stage of the interaction, which means, therefore, that my description must take into account, in a fundamental way, of this fundamental failure of being able to place a tag on every particle because there is no experiment I can perform that gives reality to that label because to do so would represent ~~the~~ an intervention ~~vation~~ into this experiment, the performance of a detailed microscopic localization experiment which would change completely the nature of the experiment. It would no longer be a simple collision, there would be something else there, equally important, interacting with these particles. It is a different experiment. And this is the whole point, of course, the recognition that I must indicate in detail precisely every experiment I have in mind because every measurement I wish to perform changes the conditions of the experiment, produces a strong, non-controllable interference in the other things that are going on.

The net result of all of this is to recognize that the description of the states of several particles necessarily could only be done in a way which would incorporate from the very beginning the fact that they were indistinguishable; that particular labels have no significance; and to simply state the results - - and we certainly can't go into the details here - - this simply means that when we have several indistinguishable particles, the states can only be described in a way that is perfectly symmetrical among all the particles that contribute to it.

Now the word symmetrical is to be understood in a more general sense. That means in particular that if I had several particles and I had a specification of the state, let me use what is traditionally a matter in which the state is specified, I ~~speak~~ spoke of vectors but the vectors are described by numerical quantities and the numerical quantities are what is known as wave functions. These are the wave functions associated with these waves, if you like. Here I have several particles and here are their positions; for example, say that at a particular time, the only description which is tenable is one in which this wave function is either completely symmetrical among all these positions, which puts them on exactly the same footing. In other words, in which these arbitrary labels are deprived of any distinguishing significance by insisting that no matter how the labels are given, the wave function or the state is the same. But this can be done either by making them completely symmetrical or complktely anti-symmetrical. And in this way we recognize the existence of two very distinct types of systems of identical particles. And, in fact, of the two basic examples we have used, the proton~~s~~ and the electrons, the detailed properties of physical phenomena show that the proton belongs to this class of symmetrical state; the electron, of course, and the other particles fall into the framework of anti-symmetrical states.

Now, the concept of the field is something else. The concept of the quantas field is something rather different. Here you see, perhaps I might - - I have written an "X" but, of course, what is really involved in "X-Y-Z" - the position of the particle in three-dimensional space of particle 1.; "X-Y-Z", the position of particle 2. according to this arbitrary labelling, a symmetry of which is removed by these requirements of symmetry. Here similarly is particle 3. Here you might say that I have in a sense a field. A field is after all physically a distributed object in space and time. Now, say if I were talking about one particle, which in a sense is what I am doing; then I would have a specification of state, or a wave function which tells me what the state is at a given time is in terms of position measurements on the particle.

Now, we have something which is very much analogous, as far as its structure is concerned, to say a Maxwell field, an electromagnetic field, a function of space and time. And it might seem that what we were really talking about here is a field. But I trust that perhaps a rather technical way, the fact that I now have the function of several positions in space and time indicates that this is not a field in the conventional sense. In other words, here I have rather a much more abstract, multi-dimensional configuration space - - a way of indicating what several particles are doing at once in a highly hypothetical mathematical space which has nothing to do with ordinary three-dimensional space because there are many three-dimensional spaces now being considered at the same time. The idea of quantized field is a deeper unification of what has been achieved by the new principles - - is something else again. It is now a much more sophisticated notion, or at least at the time in which it was introduced it appeared to be. It was soon given experimental confirmation in the sense that the idealization that was introduced was soon found to be the all-prevading phenomenon of high energy physics. I speak of the following idea. Suppose, let me so to speak, - - may I come back again to this wave function except instead of writing "X-Y-Z" I will write a position vector - - that, here are several particles at the time T. Let me introduce a new concept which is the following. If I wish to speak of three particles; say in a certain experimental situation, let me imagine, and at the moment it is nothing but imagining, an idealized - - an abstract physical situation in which I will create a particle. What makes this important is that if I am concerned with various experimental situations with varying numbers of particles, whatever situation I am interested in with several particles can be imagined as being brought about by an uniform process, the creation abstractly of whatever particles I am concerned with. And let me, for example, describe this act of creation in this way. This now means something entirely different. It is a creation operator. An operator because it symbolizes a physical property but something beyond what we are accustomed to thinking of, and an operator because it acts on a state, the state being the state in which nothing is present, or physically a vacuum. And so I will imagine, for example, simply writing here the vacuum state, and now I will create to this wave function except instead of writing "X-Y-Z" I will write a position vector - - that, here are several particles at the time T. Let me introduce a new concept which is the following. If I wish to speak of three particles; say in a certain experimental situation, let me imagine, and at the moment it is nothing but imagining, an idealized - - an abstract physical situation in which I will create a particle. What makes this important is that if I am concerned with various experimental situations with varying numbers of particles, whatever situation I am interested in with several particles can be imagined as being brought about by an uniform process, the creation abstractly of whatever particles I am concerned with. And let me, for example, describe this act of creation in this way. This now means something entirely different. It is a creation operator. An operator because it symbolizes a physical property but something beyond what we are accustomed to thinking of, and an operator because it acts on a state, the state being the state in which nothing is present, or physically a vacuum. And so I will imagine, for example, simply writing here the vacuum state, and now I will create particle 1. at the time T; I will then create particle 2. at the time T, or any number of additional particles and in this way, by the repeated action of this operator, (here I have written 2.), I will produce something which is essentially in the nature of that wave function which involves both position and the time T. And the important thing is that these requirements of symmetry and anti-symmetry on this wave function can now be converted into algebraic statements on these operators. If the situation is one of symmetry, as in the case of photons, then I assert that whether these are multiplied in one order or the other, the result is the same. That produces symmetry. If it is anti-symmetry, as in the case of electrons, I assert that if they are multiplied in one order, the result is ~~indicative~~ the negative of what occurs when they are multiplied in the reverse order. In other words, the properties of these two classes of identical particles, or statistics as it usually is referred to, becomes replaced by an algebraic property of these operators. In short, we now, instead of talking about a system of a definite number of particles, are led to think of physical systems with ~~in~~ an indefinite number of particles because we can produce whatever number we are interested in by the application of this creation operator. We now then, so to speak, transfer our attention to this operator as the basic physical object. And this is what I mean by the quantized field because it is on the one hand a field, it is a mathematical quantity which varies continuously in time and space. On the other hand, it is certainly not a classical field because these, as operators, are not things which can be measured simultaneously and in the operator character, in the fact that the sense of multiplication or in a much deeper way than I have been able to describe it, is significant, we have the elements of discontinuity which is essentially the particle concept.

In fact, I have described, I have obtained, a field - - and I have described it to you in terms of physical operations on particles; namely, this is the symbolized - - the operation of creating a particle at a certain point in time but since I can do this anywhere in space, at any time, a field conception is introduced. In other words, the two entirely unrelated classical conceptions of discreteness of particles, of continuity of the field, now are unified in in this entirely new conception; if not unified, then transcended because the new conception, which is beyond either, because the two are after all incompatible in the classical sense because there is nothing that is both discrete and continuous. We point to something which has neither of those properties but which, in limited domains, can be characterized in terms of either of these conventional concepts.

So, here is, so to speak, the fundamental unification, the idea of the quantized field. The fact that we can sort of speak meaningfully - - think of processes in which particles are created and then correspondingly, we must also have the inverse process in which they are destroyed at various points in space and time.

This, as it arose historically was simply a convenient way of summarizing the mathematical properties of indistinguishable particles but soon, through the ever broadening developments of experimental ~~times~~ science, what was here conceived of simply as a convenient mathematical idealization became reality. The ability, as enough energy was available, to produce the rest energy of particles according to the Einstein relation: given the energy that corresponds to the mass, a physical particle can be produced. It may be necessary for other reasons to produce them in pairs as in fact is the case of the electron and its counterpart the positron.

But by the early thirties, these experiments had been performed. In much more recent years, the ability to create pairs of protons and anti-protons, neutrons and anti-neutrons regarding vastly much greater amounts of energy and hopefully experiments are now on the way to creating pairs of all the other particles known to be the building blocks of nature. These alone then give the field then - so to speak - in ~~his~~ its interpretation of symbolizing an act of creation, an element of physical reality.

But now in the course of the development, it soon became realized you see that the moment you have introduced the field in direct correspondence and in direct association with particles as we know them, inevitably this situation could not persist. A new level of abstraction had to be reached and was reached.

It occurred essentially within the past 15 years in the course of attempting to understand in more detail, more detail demanded by the refinement of experimental data, to understand more of the properties of atomic phenomena than were successfully accounted for in the first flush of the development of quantum mechanics. The experiments went on. More and more refined properties became known. More and more sharper applications of the theory were required. And, for example, in the case of electrons in atoms, in which from the field point of view we are really concerned with the dynamics of two fields. There is the field which is associated with the electrons and also their counterpart the positrons; there is the field which is associated with the electromagnetic field, to use its classical name, the field of photon. The photon field, the electron [illegible] are in interaction. But now, the identification of each field by these physical names has only been an approximate one. Only if the interaction between the two fields is weak, as to a large extent it is in that example, can we use physical names in relation to these mathematical objects. But in a more refined theory in which the interaction between them must now be taken into account, we have to recognize that what we call physically an electron is only partially to be associated with that electron field. It is also partially to be associated with the photon field, because the two are an interaction. Physically, an electron can sometimes radiate a photon. It can then re-radiate - - also reabsorb it. In other words, what we physically call an electron would, at a deeper level, be described as sometimes the action of the electron field only but other times another fraction of the total history also involves the action of the photon field. And conversely, what we call a photon, propogating through empty space, is not merely the result of the creation act of an analogous photon field because that photon can occasionally materialize itself in space and become replaced by an electron and a positron which then, in the course of time, recombine to reform the photon.

In other words, the physical object we call the photon is not what is created all the time by the mathematical operator. The other operators, the quantities that represent the creation of electrons and photons, also come into play. In other words, once you recognize this, you now say that we draw a distinction between two levels of physical description. There is the phenomenological level, in which we recognize the properties of electrons and photons as we see them, ~~and we have~~ Ontic, of course, the enormously detailed analysis of microscopic experiments. There is now the attempt to deepen the understanding in terms of more primitive objects which are these fields, which are no longer placed in immediate correspondence but through a chain of dynamical development. And, in fact, this program as it was applied specifically to the case of electrons and photons, or through the development of what is called quantum electrodynamics, represented a prediction for more fundamental levels of some of the finer features of electron and photon behavior. What were once considered to be anomalies, things that were unexpected, now became the predicted outcome of this deepening level of understanding of what the observed particles of nature were; that our level of understanding is not to be found in terms of what we actually see but something at a more fundamental level. So it has always gone throughout the history of physics.

We began with atoms as fundamental objects and then we attempt to understand the properties of atoms in terms of electrons and a nucleus, which is taken as un-analyzable. Then we move down to the level of the nucleus, and analyze it in terms of the properties of nucleons and so on and on. Well, that is a very simple conception of how we go about it in terms of smaller and smaller particles, smaller and smaller regions of space.

Here is something quite different. The analysis of particles as we know them and as we associate them with fields in terms of yet more fundamental fields at a deeper level which have fewer properties because this attempt at understanding is always to strive for a simpler level, to have deeper, more symbolic laws, with fewer arbitrary constants, if you like. In other words, unlike the experimental situation in which the charge of the electron, the mass of the electron, the magnetic moment of the electron, are all unrelated constants. The deeper understanding attempts to explain one or more of these in terms of a fewer number of fundamental things.

So it has gone in the case of quantum electrodynamics. This has been very successful application of this idea that it is the quantized field conception which is the statement at the moment of our deepest level of understanding of microscopic phenomena, but as I mentioned, and it must be familiar to you to some extent, in the course of the development of higher and higher energy machines, more and more particles have become known and these have appeared in a bewildering array of properties. Some of them are stable. Some of them are unstable. They decay into each other in all possible conceivable ways. They are produced as sufficient energy is available very copiously as the result of obviously strong interactions. They then proceed very slowly to die successively, moving down to the final stable particles that we know.

In other words, entirely different mechanisms are in operation, depending upon whether the creation of these particles in impact or their successive decay or cascading down to the final stable particles we know, which are still the electrons, protons, plus a few others.

Now, the interactions which are involved here in the basic studies of nuclear phenomena are of an entirely different level than the electro-magnetic ones. The electro-magnetic forces are essentially rather weak. And on the basis of this, one has been able to develop technical methods of handling these interactions. But when one comes to the very much stronger bonds that hold - that not only hold the nucleus together but hold together the particles that compose the nucleons, that make up the nucleus, here we are at a much more difficult level in the sense that not only are the phenomena bewilderingly complicated but we also lack the mathematical means to draw the implications of any particular hypothesis about what is going on. And as a result of this, and I think I am going to stop finally at this point, there has come about a very deep schism between two schools of thought about what should be the fundamental nature of an explanation at this level. Should it be the continuation of this point of view of the searching for deeper understandings in terms of ideally a very small number of fundamental fields, who in their dynamic interplay and as a result of the complexity of that dynamics, finally bring about the manifold nature of the world as we see it; or must we really abandon this attempt completely? In other words, replacing the difficulties by the anticipation of a fundamental ~~end~~ impossibility. Must we abandon this attempt altogether and simply describe nature in terms of what happens when we take various microscopic particles, perform experiments on them. We send electrons in, protons equal to the various kinds of nucleons, in which we perform experiments in which these particles enter a certain region. We make no attempt to describe what goes on there and simply attempt to finally characterize what emerges when the particles are separated again. Is ~~this~~ the purpose of theoretical physics, to be no more than a cataloguing of all the things that can happen when particles interact with each other and separate? Or is it to be an understanding at a deeper level in which there are things that are not directly observable as the underlying fields are, but in terms of which we shall have a more fundamental understanding. Well, this idealized, frankly beyond all recognition, is in a sense the deep philosophical problem that confronts theoretical physics at this current frontier of high energy physics. The attempt to understand the structure of matter as matter has been revealed to us in all of its complexity with the ever rising level of the energy that is available to create new kinds of matter.