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REALITY IN PHYSICS[1]

By Dr. W. F. G. SWANN

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I SUPPOSE there are few things concerning which one could find so many differences of opinion as the question of what constitutes a theory in physical science. The pure mathematician would probably be content with a procedure of the following kind. He will set up a branch of mathematics founded upon certain postulates having to do with quantities, letters, etc., that he chooses to be talking about. In this mathematical scheme, there will appear relationships between certain quantities which occur in the mathematics, and it will be his hope to invent a scheme of mathematics of this kind which shall form an analogue of the regularities of nature in the sense that there may be a one-to-one correspondence between certain things in the mathematics and the observable phenomena in nature. It has been said that the pure mathematician is never as happy as when he does not know what he is talking about; and, in the foregoing method, he establishes contacts with the physical world with a minimum degree of shock to his own conscience, by a procedure in which he ceases to think of anything physical until he has completed his mathematical structure, and confines all physical contamination of that structure to the act of setting up the correspondence to which I have already referred. When the correspondence has been set up, the postulates of his mathematics become the laws of nature in the physics. It is possible that he may choose his postulates in various ways. In the journeys which he takes from his postulates as starting points, he arrives at multitudes of conclusions. He might gather together a suitable collection of these at any stage and

[1] Address of the president of the American Physical Society given at New Orleans on December 30, 1931.

take them as his starting point, and continue his reasoning backwards and forwards over the whole realm of logical regularity which he traversed before. In his journey through the realm of the abstract mathematical thought of his theory, he may stop or start at various stations. Where will he prefer to start? He will probably prefer to start at the place where the number of his postulates is a minimum. To him, a good theory will be one in which by saying few things he can deduce, as their consequence, many things. The value of his theory to the physicist will lie in the fact that it not only correlates the phenomena which he, the physicist, has discovered, but suggests multitudes of other phenomena which he may look for, and also suggests ways of viewing the interrelationships between the phenomena already studied other than those which he has already adopted. The physicist may have taken an intellectual journey from the set of phenomena "A" to the set of phenomena "B," analogous to my taking a journey from Philadelphia to Washington via the Rocky Mountains, California and New Orleans, and the complete mathematical structure may show that shorter journeys, analogous to my going from Philadelphia to Washington through Baltimore could be made.

The postulates which are agreeable to the pure mathematician will not necessarily be agreeable to the physicist, because the latter thinks that he knows what he is talking about and glories in the fact. It will be little consolation to the physicist to know that by the assumption of few things he may deduce many, provided that he is not content as to the reason for those few things. He would like to start with the idea that the few things are not purely arbitrary postulates but, after all, are very reasonable. He likes to adorn those postulates with some kind of a raiment which makes them seem as though they had come from somewhere, even though he does not know where. When he is presented with Newton's law of gravitation in the cold-blooded form that the acceleration of a particle is to be calculated as the sum of a number of contributions associated with the various elements of matter in the universe, each element producing an effect inversely proportional to the square of its distance from the particle in question, it is not enough for him that in this simple postulate he has said something from which very many beautiful things may be deduced. It is not enough that this postulate gives for him the orbits of the planets, the times of recurrence of eclipses, the times when comets return, and a hundred other things. He must adorn it with physical significance, so he calls the left-hand side the rate of change of momentum and the right-hand side the force, and having called the right-hand side the force he naturally inquires, "Why should there be a force?" "Now," he says, "I will look for the reason for this force in some of the other things that I know about." And he thinks of a piece of elastic, and he sees how that exerts a force, and he wishes he could see that force which the planets exert on each other as arising in the same way as a piece of elastic exerts a force upon a stone which is fastened to one end of it when the stone is swung around in a circle with the other end of the elastic held in the hand. If I ask him why the elastic pulls, he will probably tell me that, while we do not know all about that, we believe that it is due to the fact that the elastic is composed of a lot of little molecules, and when they are separated from each other they tend to come back again. But I proceed to inquire why they tend to come back again when they are separated from each other. He tells me, "Well, although we say *separated,* we do not really mean separated. We believe that between the molecules there is a medium, and when this medium is stretched it tends to return to its original condition." But I inquire why it does this, and he tells me that it is because the medium is endowed with elastic properties. But I ask him what he means by that, and he tells me that it acts like a piece of elastic, and so I ask him why a piece of elastic pulls, and he tells me that it is because it is composed of a lot of little molecules, and so on, *ad infinitum.* You see all that even a successful appeal to the elastic could hope to do would be to show that this thing, gravitation, which we think we do not understand, acts in the same sort of way as that other thing about the elastic, which we also do not understand but think we do. There is a sort of a unification of ignorance in the matter; but this unification of ignorance is not something which should be despised—it is one of the plans and purposes of physics. Thus, we like to picture the atom working as a dynamo works, or as a motor works, or as the ripples on a bowl of water work—something which has become familiar to us in our youth and concerning which we have become accustomed to be satisfied. We met the elastic at an age when we were too young to question its actions, and when we had become old enough seriously to think about it, it had become so familiar to us that there seemed no necessity to think about it any further. The elastic was a little god, the origin of all things, who himself needed no explanation for his origin. And so physics, like everything else, has its starting point, its postulates, and the postulates of physics are its gods. Some appear artificial, as did the plain statement of the Newtonian law, and others mask in a guise of reasonableness, as did the elastic, but a reasonableness which very frequently evaporates in the sunshine of more complete thought.

In order that certain postulates shall be agreeable to a physicist of limited sophistication, it is necessary that they should be of the same kind as those associated with the behavior of circumstances and things to which the physicist has become accustomed and which he has been willing to accept on the basis of long acquaintance, formulated, probably, at a time before he had decided seriously to think about the matter. Then they must be associated with things which he calls "real." And what does he mean by the "reality" of things? We get a crude notion of his feeling in this matter by asking him to accompany us to a spiritualistic séance and seeing what he is willing to accept as to the reality of the ghost. It is not sufficient that the ghost has properties and produces phenomena. It is not sufficient, even, that the ghost shall produce material phenomena, such as the ringing of tambourines or the feeling of a draft. It is not sufficient that this entity, the ghost, shall merely be defined so as to account for all the phenomena that we are primarily interested in. It is necessary for his reality in the rather ill-defined accepted view of the matter that he shall have certain other properties which are not concerned with the activities which are the main purposes of his function. He must be capable of being seen; he must have weight; he must be felt when he is touched, etc. As a matter of fact, we should be more impressed with a ghost who had these properties and who did not do anything than we should be with one who was without them but was possessed in other respects of all sorts of remarkable powers. In our search for reality in physics, we do very much the same kind of thing. Bodies which are separated from each other appear to have effects upon each other. We discover the laws according to which these effects operate. We should like these laws to be interpretable in terms of a medium which we can think of as real. We shall be able to think of it as real if it has inertia and elasticity in the sense that a solid has inertia and elasticity, even though we have to take these properties as fundamental starting points in the case of the solid, and are unable to trace them to some ultimate source which of itself needs no explanation. At one end of our scale of satisfaction, we have a case where it is possible to account for the properties of the hypothetical medium without any departure whatsoever from the properties of the things that we have heard, smelled and felt, and ranging from this end of the scale to the other extreme end of complete expression in terms of abstract formulation, we have a graded sequence of possibilities which are apt to content us less and less, the further they are removed from the end of complete satisfaction. The other receives a slight blow to its prestige of reality when it is found that though it can operate according to inertia and elasticity, the elasticity is of a different type from anything that we happen to know of in the things that we have touched, seen, etc.

I have often been impressed by what I have sometimes called "the irrelevance of the obvious." I can illustrate the point by considering the case of a problem which I present to a small boy concerning a ball which is hurled vertically into the atmosphere with a certain speed. I ask him how long a period will elapse before it reaches its highest point. The boy comes back to me and tells me that he can not work out the problem, because I have not given him enough information. I ask him what information he would like to have, and he tells me that he would like to know the color of the ball. I tell him the color does not matter, but he probably does not like that, because some of the substantiality of the ball has vanished with its color. He asks for the weight of the ball, and I tell him that that does not matter. And I add that I will even withdraw my statement that it was a nice, round ball and will refuse to state what its shape actually is. Then, if he is materialistically minded, he will blow up entirely and demand how he is to work out the problem at all if I will not tell him anything about it. I finally tell him that the ball is red, that it weighs ten pounds, and that it is really a nice, round ball. He then goes to the blackboard, draws a circle, paints it red in his mind's eye, puts a "10" inside it, and works out the problem. When he brings up the result, I ask him where he utilized the redness of the ball. He looks through the calculations and finds that he did not use it. I ask him where the weight comes in. He looks through his calculations again and finds that he did not use that either, or if he did, it canceled out. And so with the roundness of the ball. Then I admonish him not to ask me a lot of unnecessary questions again. But I think I hear you sympathizing with this poor student. You will say to me, "What harm does it do to tell him that the ball is red, since the redness does not matter? Why did he sin in thinking that it weighed ten pounds, if, after all, its weight is irrelevant?" Well, I agree that in this case, perhaps, no particular harm was done; and yet I have a suspicion that if I allow him to think that the ball is red, some day he will come back to me with a problem which he is unable to solve, because, perchance, the ball in that problem may be blue. Then I shall have the trouble of bringing up past history to explain why it was that the redness of the ball really did not matter in the original problem. But if he has had this vision of redness for a sufficiently long time, it will have become so ingrained in his consciousness that he may be totally unable to think if he is deprived of it.

It would be very difficult to give a definition of what constitutes reality in a general sense which would satisfy everybody. For few who desire reality the greatest could state in words just what it is that they do desire. The best one could probably do would be to make a list of things and phenomena which he would agree were real. Then if one would take any of these things and gradually remove from it all the appendages which even our disciple of reality himself would admit were unnecessary for its function, it is probable that he would gradually find his conviction of reality vanishing with these appendages, until by the time that he had left all that he himself would claim were necessary, he would have something which, in terms of his own mode of thought, he would have to call "unreal." Even as the sight of the ghost, of his flowing robe, of his obvious weight, are the symbols of reality to the onlooker—though they perform no part of his function —so, frequently, in the physical world, those things which constitute that vague thought of reality are things which play no part in the phenomena which are the main interest of discussion. Sometimes, when systems and phenomena are of such an abstract nature as to shock our material senses, we even go to the extent of providing a curious kind of comfort for ourselves by garbing them in the very clothes of what constitutes reality to us, and then deny to those clothes themselves any of the ordinary properties of clothes, in order that they may not give any trouble. Thus, in the Bohr atom, we are apt to feel that we have something approaching reality in our model of electrons going around a nucleus in planetary orbits. We know that the laws according to which the electrons must operate are different from those of classical electrodynamics; but I think it safe to say that a great many physicists feel much happier in thinking of the Bohr picture than in thinking of the picture of wave mechanics, for example. And yet, what a curious situation we have here. In the Bohr atom, the only model that we have of anything is the model of the part that does not do anything. The Bohr theory gives us a beautiful picture of electrons moving in planetary orbits. The thing is delightful to look at on the blackboard; but, unfortunately, this beautiful model—what is going on on the blackboard —is just the part which is totally unobservable to our senses or in our apparatus. Only when the atom radiates do we get anything observable, but of the radiation mechanism the Bohr theory says nothing. It is true that by talking about the different states of the atom when it does not do anything we can set up a formal procedure for calculating what results follow when it does do something, but there is no picture of the process. In fact, everything which the picture would suggest in the matter of radiation is forbidden to happen. The planetary orbits are not a picture of the process any more than a conglomeration of railway stations presents pictures of the scenery on the journeys between them. A process of calculation we have, it is true; but, for the rest, it is simply a picture thrown in on the side to make us happy.

Let me cite a parable to indicate the condition of mind of one who thinks that in the Bohr atom he has a real, satisfying model. Suppose that I should encounter a strange monstrosity whom I was pleased to call a man, because he looks something like one. But suppose the monstrosity has all sorts of peculiarities. I look at him and exclaim, "See what muscles he has; such a being should be able to swing a five-hundred-pound hammer with ease. See how large his eyes are; such a being should be able to see the most distant stars without a telescope. See the length of his legs; such a man should have a stride which would carry him along at the rate of fifty miles an hour." And suppose that when we came to examine this being, we found that he could not lift a pepper pot, and that what he could lift in comparison with others of his kind depended not upon the size of his muscles, but upon the length of his hair multiplied by the diameter of his eyeballs. Suppose that his vision was no keener than ours, and such as it was, depended not upon his eyes at all but upon the distance between his toes divided by the diameter of one of his eyelashes. Suppose that his speed in walking depended not upon his legs but upon the length of his little finger. It might be that from his arms, legs, eyes, etc., we could make up a way of deducing what he would do under given circumstances, just as we can from the planetary orbits of the Bohr model make calculations about the radiation; but we should delude ourselves if we took comfort in thinking of this monstrosity as a man. And, if we take comfort from the resemblance between the pictures we draw from the Bohr atom and for the planets, we shall assuredly delude ourselves as to the significance of that resemblance also.

One who starts with certain preconceived pictures of how nature works may usually, with sufficient trouble, force those pictures to fit the frame of nature to some extent, but very likely there will be many loose joints and bizarre fits. If one takes two landscape paintings and superposes them by painting one over the other, he will get something which looks unlike any landscape. It is, of course, conceivable that by superposing a sufficiently large number of suitable landscapes, one might get something which looked like a circle, or a straight line, but to hold to the dogma that straight lines and circles are all fundamentally built up out of landscapes is to invite trouble.

If I should define the number of dimensions to be associated with a system as the number of numbers which it is necessary to assign to the system in order that, by writing down differential equations between them in terms of some arbitrary parameter, I could set up a satisfactory scheme of mathematics with a one-one correspondence to the facts of nature, it would probably be contended by many that I was talking in a very abstract manner and that such a definition of the number of dimensions of a system was highly artificial. The materialist will probably tell me that these dimensions are not real dimensions at all but merely mathematical abstractions. I shall ask him what he means by "real dimensions"—in what sense, for instance, does he regard space as three-dimensional? He will probably illustrate what he means by telling me that he sees me standing here, a three-dimensional being, with length, breadth and thickness, and that in this sense I have very obviously three dimensions. Alas! I shall have to point out to him that the impression which he gets of me is obtained through a two-dimensional image on the retinas of his eyes; that he sees me twice over, once in each eye; that he sees me upside down and that what the left eye sees the right-hand side of his brain interprets. The interpretation of the phenomenon of seeing your president here delivering this address is really a terribly complicated business.

Frequently, the development of a subject—such a subject as electrodynamics, for example, takes place in the first instance through experiments of a large-scaled nature performed upon more or less crude apparatus. As a result of this, we form concepts of a subject founded upon large-scale phenomena. We form concepts of electric and magnetic fields as the forces on magnetic poles and on unit charges. We form the concept of forces on the charges in the sense defined as the product of the masses associated with the bodies on which those charges exist, multiplied by their acceleration, etc. Later, as science develops, it becomes necessary to extend and generalize the mathematical equations which are the basis of the theory. They become generalized to apply to situations where the quantities cease to have meaning in the sense of their original definitions. There is no meaning to the field at a point inside an electron when defined as the force on a unit pole, nor, indeed, is there meaning to the force on the unit pole itself, even if we had it and could put it in the electron, when the force is defined as the mass of the pole multiplied by the acceleration. There arises a whole new formulation of the theory, in which these fields become defined in different ways in relation to a new set of starting points, etc. The things which were before the simple concepts, the masses of the bodies on which the charges were placed, now become quite complicated and elaborate parts of the theory. Those things which seemed to endow the subject with such elements of tangibility when considered on an engineering scale dissolve in meaning, leaving only the fundamental concepts which, as a matter of fact, were the only things which really counted in the engineering problems themselves, where, however, they remained hidden in the glittering robes of a spurious reality. And so, to the critically minded, there appears a reality in the new artificiality and an artificiality in the old reality. The process of generalization is not apt to become one in which the new forms a complication or extension of the old, but rather one in which the old is a rather vague, somewhat incomplete and illogical application of the principles of the new. When, as the result of a merciless stripping of irrelevant adornment from the laws of physics, we arrive at a spectacle unpalatable to the intellectual taste, let us ask ourselves whether this cold remnant does not contain the whole essence of the laws in the sense in which they are actually used. There is no harm in stimulating our intellectual activities by adorning our thoughts with irrelevant appendages, provided we use these appendages as our servants and not as our masters. It is true that the human mind is a mechanism which requires a spark to set it off. The mere assurance that it has all the necessary wherewithal to think with is not of itself sufficient to set the thinking going. If one man finds that a glass of wine is good for his mental activity, let him take it. If another finds that a model accelerates his thoughts, let him use it, however illogical and fantastic it may be, so long as he uses it only as a stimulant to thought and does not impose upon the structure which he has created some of the requirements of the model itself which may be inconsistent with the fundamentals of that structure. It is in the trouble caused by the requirements of these irrelevant characteristics of the model that the danger of an artificially created reality lies. Thus, in pondering upon the physical nature of an ether, for example, while we would strenuously deny that our picture of the all-prevading medium was anything like that of water, many of us will supplement the cold statement of the properties of the medium with vague shadows of substantiality, concerning which only the most dire intellectual torments would bring us to confess, even to ourselves, that we were semi-consciously thinking of the taste of ether, of the smell of ether, of its boiling point, etc.

I have spoken of a theory in mathematical physics as comprising the formulation of a branch of mathematics in which there is a one-one correspondence between the essential elements in the mathematics and the observable phenomena of nature. One of the main differences between the materialistic forms of theory and the more abstract forms is that in the former we seek this one-one correspondence between every stage of the mathematical work and some phenomena of the observable kind, while in the latter form of theory the correspondence only exists between the mathematics and nature at certain isolated points. I may perhaps illustrate this matter in a very simple way as follows. Suppose that a mathematician wants to write the equation of a parabola in what he calls the parametric form. He writes:

$$x = us, \tag{1}$$

$$y = \tfrac{1}{2}gs^2. \tag{2}$$

We then know that by eliminatings from these two equations, we can obtain the result,

$$y = \frac{g}{2u^2}x^2,$$

which is the equation of a parabola. But, for some purposes, it is convenient to leave the equation in a parametric form as expressed by (1) and (2). Now, if the physicist were presented with equations (1) and (2), he would ask what s was. The mathematician would tell him that s was nothing in particular, but simply an intermediate symbol, introduced for the convenience in relating x and y. But the physicist would be very unhappy about this. He would want a correspondence between this symbol s and something in nature. Happily, in this case, he has it. If he changes s to t, he can think of the whole problem as one of a falling body initially projected horizontally in the horizontal direction x with a velocity u, so that x equals ut, and allowed to fall vertically with an acceleration g, so that $y = \frac{1}{2}gt^2$. It is not always possible in physics to do what was done for s in this case, namely, to find a real correspondence between every symbol in the mathematics and some similar measurable quantity in the physics. At least, it is not possible to find it in a direct way. One can usually express one of the abstract quantities itself in terms of some of the measurable things in such a way as to evaluate it, but this usually does not satisfy the materialist. He likes to have the meaning of the quantity staring him in the face. Most of the quantities which cause trouble in mathematical physics, because of their abstract nature, may really be regarded, in a sense, as parameters in the equations—parameters introduced for the convenience of expressing the relationship between the observable quantities in a more convenient form than by some direct relationship. Considering, for example, the case of electrodynamics, it would be perfectly possible, but extremely cumbersome to express the motion of one electron as a function of the positions and motions of all the other electrons. The whole scheme of relationships assumes a much more elegant and convenient form when intermediate quantities called electric and magnetic fields are introduced as intermediaries. The electric and magnetic fields are really defined by the circuital relations in terms of the motions of the entities themselves; and then, by additional equations, those motions are again expressed in terms of the fields, the whole process being the equivalent of expressing the motion of the electrons in terms of each other.

If you should wish to force me to say what I would deem to constitute reality in a theory or in the conceptions which form a part of a theory, if you should demand of me a statement as to whether the concepts involved in a certain theory were real or artificial, it would, first of all, be necessary for me to ask for a precise definition of reality. I surmise that you will have difficulty in giving such a definition. Or, if you gave one which was satisfactory to yourself, I doubt whether it would be satisfactory to every one else. We should all probably find ourselves in the position of the group of statesmen who were discussing what Mr. Balfour meant when, at the time when tariff reform was a very touchy matter, he had ventured one of his customary non-committal phrases concerned with what he called "broadening the basis of taxation." Every one wanted to know what it meant and how it affected his own particular interests. A cartoon represents Politician A asking B what he understands by Mr. Balfour's statement, "broadening of the basis of taxation." B says, "Well, I mean exactly what Mr. C means." So they go to Mr. C, who says, "Well, I mean just what Mr. D means." Finally, they go to Mr. Balfour, who gives another of his famous statements: "Well, I mean exactly what we all mean." One might make definitions galore. He might define a quantity as real, provided that it obeyed the equation of continuity. He would then be comforted for the moment by thinking of a gas and would say, "Ah! My quantity now behaves just like a gas. If the amount that goes out of the room is greater than the amount that comes in, then the quantity in the room must decrease by an amount equal to the difference. Such stuff is really real. He tells that to the high-school boy who is quite satisfied about it until he is told that momentum also obeys the same relation. He is not so happy about the reality of momentum. We tell him that he will feel that that is also real when he gets older. We, at any rate, glory in a sophistication where momentum satisfies our mathematical criterion of reality and also our undefined sense of the fitness of things. Then the specialist in wave mechanics comes along with the mysterious quantity $\psi\psi^*$, concerning which he also has an equation of continuity. He may wish to present this quantity as a candidate for reality, but the materialist feels that he has been caught and that the claim is not fair. The wave-mechanical person demands to know why the claim is not fair. The materialist fishes around a bit and then thinks that he sees why the claim was not fair. He says, "You can not measure $\psi\psi^*$, whereas I can measure the density of a gas." But the wave-mechanical person contends that he can measure $\psi\psi^*$. It is a quantity which he can express in terms of the probability of the existence of an electron at a certain place. The materialist claims that this isn't any sort of a quantity at all—nothing like as tangible a quantity as is density. But, after all, if I ask him what is meant by density, he will probably tell me, "it is the mass per unit volume." Then I must ask what the mass is. If he defines mass by a momentum specification in which the measure of the mass is obtained through the velocity that it imparts to a standard of mass when it collides with it with an assigned velocity, then I begin to doubt whether the quantity "mass" is any less mysterious than the one called $\psi\psi^*$. On the other hand, if he defines it in terms of the weight, he has to rely upon a comparison with another body made through the agency of the mysterious force of gravitation, in order that he shall be able to say what he means by the mass. Of course, I am quite well aware of the fact that he has in his mind that high-school-text-book definition of mass as the quantity of matter in a body, but I fear that he would be hard put to it if I demanded an explanation of what he meant by "the quantity of matter," apart from such rather abstract definitions as I have cited. But perhaps our materialist, having been driven into a tight corner in the matter of the mass or in the matter of the density, will return to the conflict on the basis of the velocity. He will say, "for an equation of continuity, you need a velocity, but what on earth can be the velocity of the quantity $\psi\psi^*$?"[2] I tell him that in the wave-mechanical theory this quantity is defined in a certain way in terms of $\psi\psi^*$, and in a way, moreover, calculated to insure that the equation of continuity shall hold, the only element which finally remains as proved by the properties of the $\psi\psi^*$ function itself being the fact that the space integral of it throughout all space is constant with the time. I point out to the materialist that whenever I have a condition of that kind I can always associate with the quantity, in this case $\psi\psi^*$, a velocity u such that

$$\operatorname{div} \psi\psi^* u + \frac{\partial \psi\psi^*}{\partial t} = 0$$

holds throughout all space and does not require an influx through the infinite boundary to keep matters in order. "Ha, ha!" says the materialist. "Now I have caught you. Your equation of continuity was a bluff. You merely painted this $\psi\psi^*$ in the colors of reality by providing it with a meaningless velocity which enabled it to masquerade as something moving about and retaining its identity on the way. The materialist will claim that the velocity of a gas falls in a very different category. He points out that those little particles of gas are moving about in such a way that he can think of actually measuring their velocity with a meter stick. I could quarrel with him on this basis if I chose. However, I have plenty of ammunition in my pocket and will allow him this much rope; but I must ask him whether he really limits his idea of the equation of continuity as applicable only to situations of this kind. If he is old enough, he will probably remember the days when there were no electrons, at least in the minds of the physicists. He will remember the days when people used to think in terms of homogeneous distributions of electricity moving about in space or in conductors. I ask him whether he ever pondered upon the significance of the velocity of a homogeneous distribution of electricity or of anything else for that matter. I think he will have to confess to me that he did, but if he did, what was he really thinking about when he spoke of the velocity? He will probably ask me to picture one of the particles of the electricity and talk about that. However, I join with him in refusing to admit that there are any particles to talk about. Then he will probably ask me to imagine a little piece of cork placed in the homogeneous distribution of electricity, I confess that I find difficulty in this. However, if he forces me to do so or to let him do so, and talks about the velocity of that piece of cork, I shall never allow him to depart from his definition, and he will have to carry the velocities of corks with him for the rest of his life in all his discussions about electrodynamics. I shall never be willing to let him dissolve that cork and lead me to the stage of deceiving myself that I understand what is meant by the velocity of the electricity at the point at which it disappears. Finally, when the materialist has exhausted himself with his corks, etc., I shall ask him whether in the sense in which he thinks of velocity, the velocity really came in at all in his calculations about electrodynamics in those pre-electron days. He will say, "Certainly, it did! Consider, for example, the equation

$$\frac{1}{c}\left(\rho u + \frac{\partial E}{\partial t}\right) = \operatorname{curl} H. \qquad (3)$$

I ask him whether by any conceivable process he could arrive at the velocity used. He may see the equation of continuity staring him in the face and be tempted to use it, but after our discussion of a little while ago, in which he accused me of doing the same thing, he will not have the face to do that. It will probably occur to him that it is necessary, first of all, to come to a conclusion as to whether he knows what he means by E and H. Well, in those days of

[2] For simplicity, we confine our attention to a three-dimensional case.

macroscopic phenomena, I will allow him to use his unit poles and unit charges for the purpose of talking about E and H. Then, I think, he will have to confess to me that in order to get the quantity u, he will have to get, first of all, the current density, which is the quantity that he is going to regard as the product of ρ into the unknown velocity of u, and he will have to get this current density through equation (3) or its equivalent. As a matter of fact, limiting ourselves to the case of steady currents we all know that when we measure a current we are apt to use a tangent galvanometer and measure it by the magnetic field which it produces, which process is the equivalent of our measuring it by this equation (3) for the particular case where the conditions are steady. Then, having obtained this current density, it will be necessary for him to get the charge density. He will then have to get the charge density by a process which is the equivalent of defining that density through the equation $\rho = \operatorname{div} E$. We are confining our attention to the case where only one kind of electricity is involved. If his picture of the phenomenon is one where there are positive and negative densities moving in different directions, then the argument requires elaboration, but what I have said about it so far is sufficient to indicate the principle which I wish to enforce, namely, that in the sense in which even our materialist would be driven to define his density and his velocity, these qualities would depart very greatly from the concepts which he thought he was thinking about when he thought of the density and velocity of a gas. They would, in fact, involve, in their definition, a degree of what he would call "abstractness" which was in every way comparable with the abstractness involved in the definition of similar quantities in the case of wave mechanics, for example. The difference between the two lies not in the subject, but in the materialist himself. When he thought he was thinking about the electricity, he really was thinking about a gas or water. As the result of this mental stimulation, he was encouraged to carry out the analytical processes permitted by his mathematical equations, with the confidence that he knew what he was doing as he went along. This concept inspired him to make many steps and do many things which he ought to have based on purely analytical procedure, but in which he short-circuited much mathematics by using his intuition. In the case where he was dealing, let us say, with a charge distribution of limited extent which, in his language, was in motion, he has no difficulty in making the calculations necessary to find the time that it takes to go from the point A to the point B. He divides the element of distance ds by the velocity u and integrates. However, he should have been much more careful about this procedure. He ought really to have investigated through his electromagnetic equations the story of the gradual disappearance of the density in one place and its appearance in another, or, at any rate, if he did use the concept of a velocity, he ought to have used it in the sense in which we have conceived of it as being defined.[3] But he does no such thing; he uses his intuition and gets a simple solution to the problem. He, as it were, writes a check based on what he thinks is the intuitional balance of his account in his brain, but it is because of the strength and consistency of his mathematical securities that the check becomes honored. In the whole realm of a mathematically consistent structure, we may think of a multitude of cases which represent conclusions of value. These are linked by paths—sometimes tortuous to follow—of logical reasoning. If we take a lot of different mathematical structures, we shall find that many of the "stations of conclusions" look alike and the railroads that run between them have great similarity. In certain of these mathematical structures, the mind has become so familiar with the relationship of the stations that it can jump from one to the other with alacrity. The jump is philosophically hazardous. It is nearly always right, but the mind little realizes the chances that it has to take. When a similar set of stations makes its appearance in some other mathematical structure, and when the mathematical "railroads of logical thought connections" are the same, our materialist can still jump from one to the other with perfect security. He may be more frightened in his jump, so that in fact he has no confidence to jump at all, because he may be under the illusion that when he jumped before he jumped for certain reasons inherent in what he regarded as the physical significance of the things he was talking about, whereas the only thing which really justified his jump was the mathematical railroad which he had discarded. If he can delude himself with a sufficiently large dose of reality to have confidence to jump in the new realm, he will again avoid breaking his neck, but not for the reasons which he thinks are guiding him, but again on account of the guardian angel in the shape of the mathematical substratum which guards his intellectual adventures. Most of us stimulate our brains to action by the vision of an ill-defined reality at the back of our mental processes. So long as we treat it as a means to an end, all is well, but for him who thinks it has fundamental significance apart from the logical scheme of laws which represent the story to be told, there is trouble ahead. For you who seek reality as something characteristic of certain concepts in physics as distinct from others will find that such reality is but a will-

[3] Complicated now to an even greater extent by the inclusion of the $\frac{\partial E}{\partial t}$ term of Maxwell in equation (3).

o'-the-wisp of philosophy. You may think you have it in your hand but will find that you have merely the shadow of something else. You will pursue that something else; you will touch it, and again it will feel real until you find that your consciousness of its touch is no more than the tingle of your own blood as your hands clasp upon it. Reality is the most alluring of all courtesans, for she makes herself what you would have her at the moment; but she is no rock on which to anchor your soul, for her substance is of the stuff of shadows; she has no existence outside your own dreams and is often no more than the reflection of your own thoughts shining upon the face of nature.

THE CHANGING BACTERIA[1]

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I HAVE been asked to sum up the discussion on bacterial variability to which we have listened this morning chiefly as a compliment to my years, because I have lived through more radical changes in our concept of the bacterial cell than have fallen within the lifetime of many of those present. I am here in the capacity of the innocent bystander, as a witness to the assault which the younger generation of bacteriologists are making on the concepts which in the past were held most sacred.

I happen to have been born in the year 1877, the year in which Nägeli published his famous book emphasizing his concept of pleomorphism, which assumed an almost unlimited variability, involving mutual transmutations between bacteria of the most widely separated groups. His extreme position was quickly overthrown by the work of Koch, Cohn and Migula and their followers, and for a period of thirty years bacteriology was ruled by the concept of relatively fixed and simple bacterial types.

We did know all along that certain variations occurred in the physiological reactions of bacteria, but these variations were for the most part closely and directly related to environmental conditions. We knew, for example, that *Bacillus prodigiosus* produces no red pigment at 37°. We knew that the virulence of many organisms could be enhanced by passage through suitable animal hosts. We knew, too, that virulence could be attenuated by exposure to unfavorable environmental conditions, as in the production of anthrax vaccine by Pasteur. Such variations as this, however, variations which were held to be gradual in their development, quantitative in nature and directly dependent upon the maintenance of the environment which called them forth, did not materially disturb our concepts of bacterial stability.

The first real threat to the older ideas was in the work of Neisser (1906) and Massini (1907) upon *B. coli-mutabile* and in the simultaneous work of Twort on the acquisition of new fermentative powers by organisms of the colon-typhoid group. These observations were confirmed but still regarded as representing exceptional phenomena. Twort's work was, however, continued and broadened by Penfold and elaborated by Ledingham in England, while Eisenberg in Germany was bringing forward convincing evidence of new types of bacterial variability. In 1917, came the work of Weil and Felix on Proteus X 19, in 1921, the recognition of rough and smooth forms by Arkwright; and very shortly the universality of the phenomenon of bacterial dissociation was demonstrated beyond any question. No one can read Hadley's magnificent monograph on this subject without being convinced that we are dealing here with a wide-spread and fundamental characteristic of the bacterial cell.

It is an extraordinary evidence of the fact that we see with our minds and not our eyes that this phenomenon should have remained so long undiscovered. For thirty years, bacteriologists had had rough and smooth colonies staring them in the face and had refused to see them because they did not fit into preconceived concepts of what should be there.

It is now at any rate clear that bacteria of very widely separated groups in pure line cultures, sometimes cultivated from a single cell, break up into two or more different strains with characteristics clearly differentiating them from each other. These characteristics may manifest themselves in cell morphology and capsule formation, in colony type, in biochemical characters and in virulence. The variants may breed true for generations, but in a vast majority of instances they tend in whole or in part to revert to the parent type or to change from one type to another, if suitable environmental stimuli are provided. There is no wild or random variation, for certain fundamental characteristics remain constant and the behavior of a rough or a smooth dissociant of a given species may be just as characteristic as that of the parent strain from which it was derived. The process is not one of mutation in the ordinary biological sense, since it is generally reversible and a true mutation is not. Dissociation is also markedly influenced both in

[1] Address delivered before the Society of American Bacteriologists, Baltimore, December 28, 1931.