Science & Humanism — SCHRÖDINGER

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SCIENCE AND HUMANISM

Physics in Our Time

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It comes to pass that he, secluded in the narrowness of his field of vision, actually succeeds in discovering new facts and in promoting his science (which he hardly knows) and promoting along with it the integrated human thought—which he with full determination ignores. How has anything like this been possible, and how does it continue to be possible? For we must strongly underline the inordinateness of this undeniable fact: experimental science has been advanced to a considerable extent by the work of fabulously mediocre and even less than mediocre persons.

I shall not continue the quotation, but I strongly recommend you to get hold of the book and continue for yourself. In the twenty-odd years that have passed since the first publication, I have noticed very promising traces of opposition to the deplorable state of affairs denounced by Ortega. Not that we can avoid specialization altogether; that is impossible if we want to get on. Yet the awareness that specialization is not a virtue but an unavoidable evil is gaining ground, the awareness that all specialized research has real value only in the context of the integrated totality of knowledge. The voices become fainter and fainter that accuse a man of dilettantism who dares to think and speak and write on topics that require more than the special training for which he is 'licensed' or 'qualified'. And any loud barking at such attempts comes from very special quarters of two types—either very scientific or very unscientific quarters—and the reasons for the barking are in both cases translucent.

In an article on 'The German Universities' (published on 11 December 1949 in *The Observer*) standing the strange empirical dependence of my mental processes on the physical data of a certain portion of matter, viz. my brain).

During the second half of the nineteenth century matter seemed to be the permanent thing to which we could cling. *There* was a piece of matter that had never been created (as far as the physicist knew) and could never be destroyed! You could hold on to it and feel that it would not dwindle away under your fingers.

Moreover this matter, the physicist asserted, was with regard to its demeanour, its motion, subject to rigid laws—every bit of it was. It moved according to the forces which neighbouring parts of matter, according to their relative situations, exerted on it. You could *foretell* the behaviour, it was rigidly determined in all the future by the initial conditions.

This was all quite pleasing, anyhow in physical science, in so far as external inanimate matter comes into play. When applied to the matter that constitutes our own body or the bodies of our friends, or even that of our cat or our dog, a well-known difficulty arises with regard to the apparent freedom of living beings to move their limbs at their own will. We shall enter on this question later (see p. 58 ff.) At the moment I wish to try and explain the radical change in our ideas about matter that has taken place in the course of the last half-century. It came about gradually, inadvertently, without anybody aiming at such a change. We believed we moved still within the old 'materialistic' frame of ideas, when it turned out that we had left it.

Our conceptions of matter have turned out to be 'much less materialistic' than they were in the second half of the nineteenth century. They are still very imperfect, very hazy, they lack clearness in various respects; but this can be said, that matter has ceased to be the simple palpable coarse thing in space that you can follow as it moves along, every bit of it, and ascertain the precise laws governing its motion.

Matter is constituted of particles, separated by comparatively large distances; it is embedded in empty space. This notion goes back to Leucippus and Democritus, who lived in Abdera in the fifth century B.C. This conception of particles and empty space (ἄτομοι καὶ κενόν) is retained today (with a modification that is just the thing I wish to explain now)—and not only that, there is complete historical continuity; that is to say, whenever the idea was taken up again it was in full awareness of the fact that one was taking up the concepts of the ancient philosophers. Moreover it experienced the greatest thinkable triumphs in actual experiment, such as the ancient philosophers would hardly have hoped for in their boldest dreams. For instance, O. Stern succeeded in determining the distribution of velocities among the atoms in a jet of silver vapour by the simplest and most natural means, of which figure 1 gives a rough schematical sketch. The outer circle (carrying the letters A, B, C) represents the cross-section of a closed cylindrical box, exhausted to perfect vacuum. The point S marks the cross-section to the end of the nineteenth century, though they had never traced the effect of an individual atom (and probably did not hope ever to be able to), were yet convinced that the atoms *are* individuals, identifiable, small bodies just like the coarse palpable objects in our environment. It seems almost ludicrous that precisely in the same years or decades which let us succeed in tracing single, individual atoms and particles, and that in various ways, we have yet been compelled to dismiss the idea that such a particle is an individual entity which in principle retains its 'sameness' for ever. Quite the contrary, we are now obliged to assert that the ultimate constituents of matter have no 'sameness' at all. When you observe a particle of a certain type, say an electron, now and here, this is to be regarded in principle as an *isolated event*. Even if you do observe a similar particle a very short time later at a spot very near to the first, and even if you have every reason to assume a *causal connection* between the first and the second observation, there is no true, unambiguous meaning in the assertion that it is *the same* particle you have observed in the two cases. The circumstances may be such that they render it highly convenient and desirable to express oneself so, but it is only an abbreviation of speech; for there are other cases where the 'sameness' becomes entirely meaningless; and there is no sharp boundary, no clear-cut distinction between them, there is a gradual transition over intermediate cases. And I beg to emphasize this and I beg you to believe it: It is not a question of our being able to ascertain the identity in some instances and not being able to do so in others. It is beyond doubt that the question of 'sameness', of identity, really and truly has no meaning.

FORM, NOT SUBSTANCE, THE FUNDAMENTAL CONCEPT

The situation is rather disconcerting. You will ask: What are these particles then, if they are not individuals? And you may point to another kind of gradual transition, namely that between an ultimate particle and a palpable body in our environment, to which we do attribute individual sameness. A number of particles constitute an atom. Several atoms go to compose a molecule. Molecules there are of various sizes, small ones and big ones, but without there being any limit beyond which we call it a big molecule. In fact there is no upper limit to the size of a molecule, it may contain hundreds of thousands of atoms. It may be a virus or a gene, visible under the microscope. Finally we may observe that any palpable object in our environment is composed of molecules, which are composed of atoms, which are composed of ultimate particles . . . and if the latter lack individuality, how does, say, my wrist-watch come by individuality? Where is the limit? How does individuality arise at all in objects composed of non-individuals?

It is useful to consider this question in some detail, for it will give us the clue to what a particle or an as in many others how in palpable bodies, composed of many atoms, individuality arises out of the structure of their composition, out of shape or form, or organization, as we might call it in other cases. The identity of the *material*, if there is any, plays a subordinate role. You may see this particularly well in cases when you speak of 'sameness' though the material has definitely changed. A man returns after twenty years of absence to the cottage where he spent his childhood. He is profoundly moved by finding the place unchanged. The *same* little stream flows through the *same* meadows, with the cornflowers and poppies and willow trees he knew so well, the white-and-brown cows and the ducks on the pond, as before, and the collie dog coming forth with a friendly bark and wagging his tail to him. And so on. The shape and the organization of the whole place have remained the same, in spite of the entire 'change of material' in many of the items mentioned, including, by the way, our traveller's own bodily self! Indeed, the body he wore as a child has in the most literal sense 'gone with the wind'. Gone, and yet not gone. For, if I am allowed to continue my novelistic snapshot, our traveller will now settle down, marry, and have a small son, who is the very image of his father as old photographs show him at the same tender age.

Let us now return to our ultimate particles and to small organisations of particles as atoms or small molecules. The *old* idea about them was that *their* individuality was based on the identity of matter in

them. This seems to be a gratuitous and almost mystical addition that is in sharp contrast to what we have just found to constitute the individuality of macroscopic bodies, which is quite independent of such a crude materialistic hypothesis and does not need its support. The *new* idea is that what is permanent in these ultimate particles or small aggregates is their shape and organization. The habit of everyday language deceives us and seems to require, whenever we hear the word 'shape' or 'form' pronounced, that it must be the shape or form of *something*, that a material substratum is required to take on a shape. Scientifically this habit goes back to Aristotle, his *causa materialis* and *causa formalis*. But when you come to the ultimate particles constituting matter, there seems to be no point in thinking of them again as consisting of some material. They are, as it were, *pure shape*, nothing but shape; what turns up again and again in successive observations is this shape, not an individual speck of material.

THE NATURE OF OUR 'MODELS'

In this we must, of course, take shape (or *Gestalt*) in a much wider sense than as geometrical shape. *Indeed there is no observation concerned with the geometrical shape* of a particle or even of an atom. It is true that in *thinking* about the atom, in drafting theories to meet the observed facts, we do very often draw geometrical pictures on the black-board, or on a piece of paper, or more often just only in our mind, the details of the picture being given by a mathematical formula with much greater precision and in a much handier fashion than pencil or pen could ever give. That is true. But the geometrical shapes displayed in these pictures are not anything that could be directly observed in the real atoms. The pictures are only a mental help, a tool of thought, an intermediary means, from which to deduce, out of the results of experiments that have been made, a reasonable expectation about the results of new experiments that we are planning. We plan them for the purpose of seeing whether they confirm the expectations—thus whether the expectations were reasonable, and thus whether the pictures or models we use are *adequate*. Notice that we prefer to say *adequate*, not *true*. For in order that a description be *capable* of being true, it must be capable of being compared *directly* with actual facts. That is usually not the case with our models.

But we do use them, as I said, to deduce observable features from them. It is these that constitute the permanent shape or form or organization of the material object, and they have usually nothing to do with 'tiny specks of material, constituting the object'.

Take for instance the atom of iron. A very interesting and highly complicated part of its organization can be displayed again and again, whenever you like and with unalterable permanence, in the following manner. You bring a small amount of iron (or of an iron salt) into the electric arc and take a photograph of its spectrum, produced by a powerful optical

grating. You find tens of thousands of sharp spectral lines, that is to say tens of thousands of definite wave-lengths contained in the light that an iron atom emits at these high temperatures. And they are always the same, exactly the same, so much so that as is well known, you can tell from the spectrum of a star that it contains certain chemical elements. While you are unable to find out anything about the geometrical shape of an atom—even with the most powerful microscope—you are able to discover its typical permanent organization, displayed in its spectrum, at a distance of thousands of light-years!

You may say the typical line spectrum of an element like iron is a macroscopic property, a property of the glowing vapour, it has nothing to do with its coarse-grained structure (its being composed of single atoms)—and nobody has yet observed the light emitted by a single, a truly isolated, atom. That is true. But, of course, I must remind you that the theory of matter, as it is accepted at present, does ascribe the emission of all these various monochromatic beams of light to the single atom; the geometrical-mechanical-electrical constitution of the single atom is deemed responsible for every single wave-length we observe in the glowing vapour. To confirm this, the physicist most emphatically points to the fact that these line spectra are only observed in the rarefied vaporous state where the atoms are so far apart from each other that they do not disturb each other. Glowing solid or liquid iron emits a continuous spectrum, much the same as every other solid or liquid facts - truth ?

at the same temperature—the sharp lines have entirely disappeared, or, better, they are entirely blurred, owing to the mutual disturbance of neighbouring atoms.

Would you then say—so you might ask me—would you then say that we are to regard the observed line spectra (which, broadly speaking, conform to the theory) as part of the *circumstantial evidence*, that the iron atoms of our theoretical description actually *exist* and that they constitute the vapour in the way the theory of gases maintains it—small specks of matter (of that peculiar constitution that makes them emit the spectral lines)—small specks of *something*, wide apart, embedded in the *nothing*, flying hither and thither, occasionally colliding with the walls, etc., etc.? Is that a *true* picture of glowing iron vapour?

I keep to what I said earlier in a more general context: it is certainly an *adequate* picture; but as regards its *truth* the appropriate question to ask is not whether it is true or not, but whether it is at all capable of being either true or false. Probably it is not. Probably we cannot ask for more than just adequate pictures capable of synthesizing in a comprehensible way all observed facts and giving a reasonable expectation on new ones we are out for. Very similar declarations have been made again and again by competent physicists a long time ago, all through the nineteenth century and in the early days of our own. They were aware that the desire for having a *clear* picture necessarily led one to encumber it with unwarranted details. It is, so to speak,

'infinitely improbable' that those gratuitous additions should, by good luck, turn out to be 'correct'. L. Boltzmann strongly emphasized the point; let me be quite precise, he would say, childishly precise about my model, even though I know that I cannot guess from the ever incomplete circumstantial evidence of experiments what nature really is like. But without an absolutely precise model thinking itself becomes imprecise, and the consequences to be derived from the model become ambiguous.

Yet the attitude at that time—except perhaps in a very few philosophically foremost minds—was different from what it is now, it was still a little too naïve. While asserting that any model we may conceive is sure to be deficient and would surely be modified sooner or later, one still had at the back of one's mind the thought that a true model exists—exists so to speak in the Platonic realm of ideas—that we approach to it gradually, without perhaps ever reaching it, owing to human imperfections.

This attitude has now been abandoned. The failures we have experienced no longer refer to details, they are of a more general kind. We have become fully aware of a situation that may perhaps be summarized as follows. As our mental eye penetrates into smaller and smaller distances and shorter and shorter times, we find nature behaving so entirely differently from what we observe in visible and palpable bodies of our surrounding that *no* model shaped after our large-scale experiences can ever be 'true'. A completely satisfactory model *of this type* is not only practically inaccessible, but not even thinkable. Or, to be precise, we can, of course, think it, but however we think it, it is wrong; not perhaps quite as meaningless as a 'triangular circle', but much more so than a 'winged lion'.

CONTINUOUS DESCRIPTION AND CAUSALITY

I shall try to be a little clearer about this. From our experiences on a large scale, from our notion of

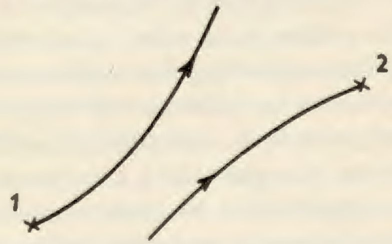

Figure 2

geometry and of mechanics—particularly the mechanics of the celestial bodies—physicists had distilled the one clear-cut demand that a truly clear and complete description of any physical happening has to fulfil: it ought to inform you precisely of what happens at any point in space at any moment of time—of course, within the spatial domain and the period of time covered by the physical events you wish to describe. We may call this demand the *postulate of continuity of the description.* It is this

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postulate of continuity that appears to be unfulfillable! There are, as it were, gaps in our picture.

This is intimately connected with what I called earlier the lack of individuality of a particle, or even of an atom. If I observe a particle here and now, and observe a similar one a moment later at a place very near the former place, not only cannot I be sure whether it is 'the same', but this statement has no absolute meaning. This *seems* to be absurd. For we are so used to thinking that at every moment between the two observations the first particle must have been *somewhere*, it must have followed a *path*, whether we know it or not. And similarly the second particle must have come from somewhere, it must have *been* somewhere at the moment of our first observation. So in principle it must be decided, or decidable, whether these two paths are the same or not—and thus whether it *is* the same particle. In other words we assume—following a habit of thought that applies to palpable objects—that we could have kept our particle under *continuous observation*, thereby ascertaining its identity.

This habit of thought we must dismiss. *We must not admit the possibility of continuous observation.* Observations are to be regarded as discrete, disconnected events. Between them there are gaps which we cannot fill in. There are cases where we should upset everything if we admitted the possibility of continuous observation. That is why I said it is better to regard a particle not as a permanent entity but as an instantaneous event. Sometimes these events form chains that give the illusion of permanent beings—but only in particular circumstances and only for an extremely short period of time in every single case.

Let us go back to the more general statement I made before, namely that the classical physicist's naïve ideal cannot be fulfilled, his demand that in principle information about every point in space at every moment of time should at least be *thinkable*. That this ideal breaks down has a very momentous consequence. For in the times when this ideal

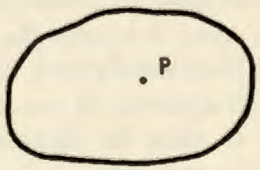

Figure 3

of continuity of description was not doubted, the physicists had used it to formulate the *principle of causality* for the purposes of their science in a very clear and precise fashion—the only one in which they could use it, the ordinary enouncements being much too ambiguous and imprecise. It includes in this form, the principle of 'close action' (or the absence of *actio in distans*) and runs as follows: The exact physical situation at *any* point P at a given moment t is unambiguously determined by the exact physical situation within a certain surrounding of P at any previous time, say $t-\tau$. If τ is large, that is, if that previous time lies far back, it may be necessary to

know the previous situation for a wide domain around P. But the 'domain of influence' becomes smaller and smaller as τ becomes smaller, and becomes infinitesimal as τ becomes infinitesimal. Or, in plain, though less precise, words: what happens anywhere at a given moment depends only and unambiguously on what has been going on in the immediate neighbourhood 'just a moment earlier'. Classical physics rested entirely on this principle. The mathematical instrument to implement it was in all cases a system of partial differential equations —so-called field equations.

Obviously, if the ideal of continuous, 'gap-less', description breaks down, this precise formulation of the principle of causality breaks down. And we must not be astonished to meet in this order of ideas with new, unprecedented difficulties as regards causation. We even meet (as you know) with the statement that there are gaps or flaws in strict causation. Whether this is the last word or not it is difficult to say. Some people believe that the question is by no manner of means settled (among them, by the way, is Albert Einstein). I shall tell you a little later about the 'emergency exit', used at present to escape from the delicate situation. For the moment I wish to attach some further remarks to the classical ideal of continuous description.

THE INTRICACY OF THE CONTINUUM

However painful its loss may be, by losing it we probably lose something that is very well worth times our series equals 2, the series equals $\frac{2}{3}$; that is to say, the number $\frac{3}{4}$ of the 'remaining set' corresponds (or 'is mated') to the number $\frac{2}{3}$ in the original set.]

The remarkable fact about our 'remaining set' is that, though it covers no measurable interval, yet it has still the vast extension of any continuous range. This astonishing combination of properties is, in mathematical language, expressed by saying that our set has still the 'potency' of the continuum, although it is 'of measure zero'.

I have brought this case before you, in order to make you feel that there is something mysterious about the continuum and that we must not be all too astonished at the apparent failure of our attempts to use it for a precise description of nature.

THE MAKESHIFT OF WAVE MECHANICS

Now I shall try to give you an idea of the way in which physicists at present endeavour to overcome this failure. One might term it an 'emergency exit', though it was not intended as such, but as a new theory. I mean, of course, wave mechanics. (Eddington called it 'not a physical theory but a dodge—and a very good dodge too'.)

The situation is about as follows. The observed facts (about particles and light and all sorts of radiation and their mutual interaction) appear to be *repugnant* to the classical ideal of a continuous description in space and time. (Let me explain myself to the physicist by hinting at one example: Bohr's famous theory of spectral lines in 1913 had to assume that the atom makes a *sudden* transition from one state into another state, and that in doing so it emits a train of light waves several feet long, containing hundreds of thousands of waves and requiring for its formation a considerable time. No information about the atom during this transition can be offered.)

So the facts of observation are irreconcilable with a continuous description in space and time; it just seems impossible, at least in many cases. On the other hand, from an incomplete description—from a picture with gaps in space and time—one cannot draw clear and unambiguous conclusions; it leads to hazy, arbitrary, unclear thinking—and that is the thing we must avoid at all costs! What is to be done? The method adopted at present may seem amazing to you. It amounts to this: we do give a complete description, continuous in space and time without leaving any gaps, conforming to the classical ideal—a description *of something*. But we do not claim that this 'something' is the observed or observable facts; and still less do we claim that we thus describe what nature (matter, radiation, etc.) really *is*. In fact we use this picture (the so-called wave picture) in full knowledge that it is *neither*.

There is no gap in this picture of wave mechanics, also no gap as regards *causation*. The wave picture conforms with the classical demand for complete determinism, the mathematical method used is that

of field-equations, though sometimes they are a highly generalized type of field-equations.

But what is the use of such a description, which, as I said, is not believed to describe observable facts or what nature really is like? Well, it is believed to give us *information* about observed facts and their mutual dependence. There is an optimistic view, viz. that it gives us *all* the information obtainable about observable facts and their interdependence. But this view—which may or may not be correct—is *optimistic* only inasmuch as it may flatter our pride to possess in principle all obtainable information. It is pessimistic in another respect, we might say epistemologically pessimistic. *For the information we get as regards the causal dependence of observable facts is incomplete.* (The cloven hoof must show up *somewhere*!) The gaps, eliminated from the wave picture, have withdrawn to the connection between the wave picture and the observable facts. The latter are *not* in one-to-one correspondence with the former. Plenty of ambiguity remains, and, as I said, some optimistic pessimists or pessimistic optimists believe that this ambiguity is essential, it cannot be helped.

This is the logical situation at present. I believe I have depicted it correctly, though I am quite aware that without examples the whole discussion has remained a little bloodless—just purely logical. I am also afraid that I have given you too unfavourable an impression of the wave theory of matter. I ought to amend both points. The wave theory is not of yesterday and not of 25 years ago. It made its first appearance as the wave theory of light (Huygens 1690). For the better part of 100 years[1] light waves were regarded as an incontrovertible reality, as something of which the real existence had been proved beyond all doubt by experiments on the diffraction and interference of light. I do not think that even today many physicists—certainly not experimentalists—are ready to endorse the statement

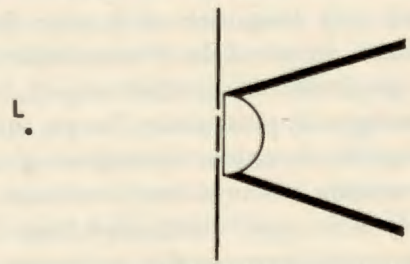

Figure 8

that 'light waves do not really exist, they are only waves of knowledge' (free quotation from Jeans).

If you observe a narrow luminous source L, a glowing Wollaston wire, a few thousandths of a millimetre thick, by a microscope whose objective lens is covered by a screen with a couple of parallel slits, you find (in the image plane conjugate to L) a system of coloured fringes which conform exactly and quantitively to the idea that light of a given colour is a wave motion of a certain small wave-

[1] Not the immediately following hundred years. Newton's authority eclipsed Huygens' theory for about a century.

length, shortest for violet, about twice as long for red light. This is one out of dozens of experiments that clinch the same view. Why, then, has this *reality* of the waves become doubtful? For two reasons:

(a) Similar experiments have been performed with beams of cathode rays (instead of light); and cathode rays—so it is said—*manifestly* consist of single electrons, which yield 'tracks' in the Wilson cloud chamber.

Figure 9

(b) There are reasons to assume that light itself also consists of single particles—called photons (from the Greek φῶς = light).

Against this one may argue that nevertheless in *both* cases the concept of waves is unavoidable, if you wish to account for the interference fringes. And one may also argue that the particles are not identifiable objects, they might be regarded as explosion like events within the wave-front—just the events by which the wave-front manifests itself to observation. These events—so one might say—are to a certain only other alternative is to assume that a particle flying through the opening No. 1 is influenced also by the opening No. 2, and that in an extremely mysterious fashion.

We must, so it seems, give up the idea of tracing back to the source the history of a particle that manifests itself on the plate by reducing a grain of silver-bromide. *We cannot tell where the particle was before it hit the plate.* We cannot tell through which opening it has come. This is one of the typical gaps in the description of observable events, and very characteristic of the lack of individuality in the particle. We must *think* in terms of spherical waves emitted by the source, parts of each wave-front passing through both openings, and producing our interference pattern on the plate—but this pattern manifests itself to *observation* in the form of single particles.

THE ALLEGED BREAK-DOWN OF THE BARRIER BETWEEN SUBJECT AND OBJECT

It cannot be denied that the new physical aspect of nature of which I have tried to give you some idea by this example is very much more complicated than the old way which I called 'the classical ideal of uninterrupted, continuous description'. The very serious question arises naturally: Is this new and unfamiliar way of looking at things, which is at variance with the habits of everyday thinking—is it deeply rooted in the facts of observation, so that it has *come to stay* and will never by got rid of again; or is this new aspect perhaps the mark, not of objective nature, but of the setting of the human mind, of the stage that our understanding of nature has reached at present?

This is an extremely difficult question to answer, because it is not even absolutely clear what this antithesis means: objective nature and human mind. For on the one hand I undoubtedly form part of nature, while on the other hand objective nature is known to me as a phenomenon of my mind only. Another point that we must keep in mind in pondering this question is this: that one is very easily deceived into regarding an acquired habit of thought as a peremptory postulate imposed by our mind on any theory of the physical world. The famous instance of this is Kant, who, as you know, termed *space* and *time, as he knew them*, the form of our mental intuition (*Anschauung*)—space being the form of external, time that of internal, intuition. Throughout the nineteenth century most philosophers followed him in this. I will not say that Kant's idea was completely wrong, but it was certainly too rigid and needed modification when new possibilities came to light, e.g. that space may be (and probably is) closed in itself, yet without boundaries; and that two events may happen in such a way that *either of them* may be regarded as the earlier one (this was the most amazing novel aspect in Einstein's 'Restricted' Theory of Relativity).

But let us return to our question, however poorly

it may be formulated: Is the impossibility of a continuous, gapless, uninterrupted description in space and time really founded in incontrovertible facts? The current opinion among physicists is, that this *is* the case. Bohr and Heisenberg have put forward a very ingenious theory about it, which is so easy to explain that it has entered most popular treatises on the subject—I should say, unfortunately; for its philosophical implication is usually misunderstood. I am going to argue against it, but first I must summarize it briefly.

It runs as follows. We cannot make any factual statement about a given natural object (or physical system) without 'getting in touch' with it. This 'touch' is a real physical interaction. Even if it consists only in 'looking at the object', the latter must be hit by light-rays and reflect them into the eye, or into some instrument of observation. This means that the object is *interfered with* by observing it. You cannot obtain any knowledge about an object while leaving it strictly isolated. The theory goes on to assert that this disturbance is neither irrelevant nor completely surveyable. Thus after any number of painstaking observations the object is left in a state of which *some* features (the last observed ones) are known, but *others* (those interfered with by the last observation) are not known, or not accurately known. This state of affairs is offered as the explanation why no complete, gapless description of a physical object is possible.

But obviously these inferences, even when granted, tell me so far only that such a description cannot be actually accomplished, but they do *not* convince me that I should not be able to form *in my mind* a complete, gapless *model*, from which everything I can observe can be correctly inferred or foreseen, to the degree of certainty which the incompleteness of my observations allows. The situation *might* be such as in the beginning of a game of whist. By the rules of the game I can only have knowledge of one quarter of all the 52 cards. Still I know that each of the other players also has a certain lot of 13 cards, which will not change during the game; that nobody else can have a queen of hearts (because I have it); that there are exactly 6 clubs among the cards I do not know (because I happen to have 7)—and so on.

I say this interpretation suggests itself: that there *is* a fully determined physical object in existence, but I can never know all about it. However, this would be a complete misunderstanding of what Bohr and Heisenberg and those who follow them actually mean. They mean that the object has no existence independent of the observing subject. They mean that recent discoveries in physics have pushed forward to the mysterious boundary between the *subject* and the *object*, which thereby has turned out not to be a sharp boundary at all. We are to understand that we never observe an object without its being modified or tinged by our own activity in observing it. We are to understand that under the impact of our refined methods of observation, and of thinking

about the results of our experiments, that mysterious boundary between the subject and the object *has broken down*.

The opinion of what may be called our two foremost quantum theorists deserves, of course, careful attention; and the further fact that several other prominent scientists do not reject their opinion, but seem rather satisfied with it, adds to its claim to be thoroughly weighed. But in doing so, I cannot suppress certain objections.

I do not think I am prejudiced against the importance that science has from the purely human point of view. I had expressed by the original title of these lectures, and I have explained in the introductory passages, that I consider science an integrating part of our endeavour to answer the one great philosophical question which embraces all others, the one that Plotinus expressed by his brief: τίνες δὲ ἡμεῖς; —*who are we*? And more than that: I consider this not only one of the tasks, but *the* task, of science, the only one that really counts.

But with all that, I cannot believe (and this is my first objection)—I cannot believe that the deep philosophical enquiry into the relation between subject and object and into the true meaning of the distinction between them depends on the quantitative results of physical and chemical measurements with weighing scales, spectroscopes, microscopes, telescopes, with Geiger-Müller-counters, Wilson-chambers, photographic plates, arrangements for measuring the radioactive decay, and whatnot. It is not very easy to say *why* I do not believe it. I feel a certain incongruity between the applied means and the problem to be solved. I do *not* feel quite so diffident with regard to other sciences, in particular biology, and quite especially *genetics* and the facts about *evolution*. But we shall not talk about this here and now.

On the other hand (and this is my second objection), the mere contention that every observation depends on both the subject and the object, which are inextricably interwoven—this contention is hardly new, it is almost as old as science itself. Though but scarce reports and quotations of the two great men from Abdera, Protagoras and Democritus, have come down to us across the twenty-four centuries that separate us from them, we can tell that they both in their way maintained that all our sensations, perceptions, and observations have a strong personal, subjective tinge and do not convey the nature of the thing-in-itself (the difference between them was that Protagoras dispensed with the thing-in-itself, to him our sensations were the only truth, while Democritus thought differently). Since then the question has turned up whenever there was science; we might follow it through the centuries, speaking of Descartes', Leibnitz', Kant's attitudes towards it. We shall not do this. But I must mention one point, in order not to be accused of injustice towards the quantum physicists of our days. I said their statement that in perception and observation subject and object are inextricably interwoven is hardly new.

But they could make a case that something about it *is* new. I think it is true that in previous centuries, when discussing this question, one mostly had in mind two things, viz. (a) a direct physical *impression caused* by the object in the subject, and (b) the *state* of the subject that receives the impression. As against this, in the present order of ideas the direct physical, causal, influence between the two is regarded as *mutual*. It is said that there is also an unavoidable and uncontrollable impression from the side of the *subject* onto the *object*. This aspect *is* new, and, I should say, more adequate anyhow. For physical action always is *inter*-action, it always *is* mutual. What remains doubtful to me is only just this: whether it is adequate to term one of the two physically interacting systems the 'subject'. *For the observing mind is not a physical system, it cannot interact with any physical system.* And it might be better to reserve the term 'subject' for the observing mind.

ATOMS OR QUANTA—THE COUNTER-SPELL OF OLD STANDING, TO ESCAPE THE INTRICACY OF THE CONTINUUM

Be this as it may, it seems worth our while to try to examine the matter from various angles. A point of view that I have previously touched on in these lectures and that does suggest itself is this, that our present difficulties in physical science are bound up with the notorious conceptional intricacy inherent in the idea of the *continuum*. But this does not tell you much. How are they bound up? What precisely is the mutual relationship?

If you envisage the development of physics in *the last half-century*, you get the impression that the discontinuous aspect of nature has been forced upon us *very much against our will*. We seemed to feel quite happy with the continuum. Max Planck was seriously frightened by the idea of a discontinuous exchange of energy, which he had introduced (1900) in order to explain the distribution of energy in black-body-radiation. He made strong efforts to weaken the hypothesis, and, if possible, to get away from it, but in vain. Twenty-five years later the inventors of wave mechanics indulged for some time in the fond hope that they had paved the way of return to a classical continuous description, but again the hope was deceptive. Nature herself seemed to reject continuous description, and this refusal seemed to have *nothing* to do with the mathematicians' *aporia* in dealing with the continuum.

This is the impression you get from the last 50 years. But quantum theory dates 24 centuries further back, to Leucippus and Democritus. They invented the first discontinuity—isolated atoms embedded in empty space. Our notion of the elementary particle has historically descended from their notion of the atom and is conceptionally derived from their notion of the atom; *we have simply held on to it*. And these *particles* have now turned out to be *quanta of energy*, because—as Einstein discovered in 1905—

mass and energy are the same thing. So the idea of discontinuity is very old. How did it arise? I wish to establish that it originated precisely from the intricacy of the continuum, so to speak as a weapon in defence against it.

How did the ancient atomists come by the idea of atomism of matter? This question gains now a more than merely historical interest, it becomes epistemologically relevant. The question is sometimes asked in the following form—in a mood of utter amazement: How did those thinkers, with an extremely scanty knowledge of the laws of physics, indeed in complete ignorance of all the relevant experimental facts—how did they hit on the *correct* theory of the composition of material bodies? Occasionally you find people so bewildered by this 'lucky strike' that they actually declare it to be a chance-event and refuse to give the ancient atomists any credit for it. They declare that their atomic theory has been a completely unfounded guess which might just as well have turned out a mistake. Needless to say, it is always a scientist, never a classical scholar, who reaches this strange conclusion.

I reject it. But then I must answer the question. That is not very difficult. The atomists and their ideas did not emerge suddenly out of nothing, they were preceded by the great development that began with Thales of Miletus (floruit 585 B.C.) more than a century earlier; they continue the awe-inspiring line of Ionian physiologoi. Their immediate predecessor in this line was Anaximenes, whose principal doctrine consisted in underlining the all-importance of 'rarefaction and condensation'. From a careful consideration of everyday experience he abstracted the thesis that every piece of matter can take on the solid, the liquid, the gaseous and the 'fiery' state; that the changes between these states do not imply a change of nature, but are brought about geometrically, as it were, by the spreading of the same amount of matter over a larger and larger volume (rarefaction), or—in the opposite transitions—by its being reduced or compressed into a smaller and smaller volume. This idea is so absolutely to the point that a modern introduction into physical science could take it over without any relevant change. Moreover it is certainly not an unfounded guess, but the outcome of careful observation.

If you try to assimilate Anaximenes' idea, you naturally come to think that the change of properties of matter, say on rarefaction, must be caused by its parts receding at greater distances from each other. But it is extremely difficult to accomplish this in your imagination, if you think of matter as forming a gapless continuum. What should recede from what? The mathematicians of the same epoch considered a geometrical line as consisting of points. That is perhaps all right if you leave it alone. But if it is a *material* line and you begin to stretch it—would not its points recede from each other and leave gaps between them? For the stretching cannot *produce* new points and the same set of points cannot go to cover a greater interval.

From these difficulties, *which reside in the mysterious character of the continuum*, the easiest escape is the one taken by the atomists, namely to regard matter as consisting from the outset of isolated 'points' or rather of small particles, which recede from each other on rarefaction and approach to closer distances on condensation, while remaining themselves unchanged. The latter is an important by-product. Without it, the contention that in these processes matter stays intrinsically unchanged would remain very hazy. The atomist can tell what it means: the particles remain unchanged; only their geometrical constellation changes.

It would thus seem that physical science in its present form—in which it is the direct offspring, the uninterrupted continuation, of ancient science—was from its very beginning ushered in by the desire to avoid the haziness inherent in the conception of the continuum, the precarious side of which was then more felt than in modern times, until quite recently. Our helplessness vis-à-vis the continuum, reflected in the present difficulties of quantum theory, is not a late arrival, it stood godmother to the birth of science—an evil godmother, if you please, like the thirteenth fairy in the tale of the Sleeping Beauty. Her evil spell had for a long time been stemmed by the genial invention of atomism. *This explains why atomism has proved so successful and durable and indispensable.* It was not a happy guess by thinkers who 'really did not know anything about it'—it was the powerful counter-spell which naturally cannot be dispensed with as long as the difficulty it is to exorcise survives.

By this I will not say that atomism will ever go by the board. Its invaluable findings—especially the statistical theory of heat—certainly never will. Nobody can tell the future. Atomism finds itself facing a serious crisis. Atoms—our modern atoms, the ultimate particles—must no longer be regarded as identifiable individuals. This is a stronger deviation from the original idea of an atom than anybody had ever contemplated. We must be prepared for anything.

WOULD PHYSICAL INDETERMINACY GIVE FREE WILL A CHANCE?

On p. 12 I briefly touched upon that old crux, the apparent contradiction between the deterministic view about material events and what is called in Latin *liberum arbitrium indifferentiae*, in modern language free will. I suppose you all know what I mean: since my mental life is obviously bound up very closely with the physiological goings on in my body, more especially in my brain, then, if the latter are strictly and uniquely determined by physical and chemical natural laws, what about my inalienable feeling that *I* take decisions to act in this or that way, what about my feeling responsibility for the decision I actually do take? Is not everything I do mechanically determined in advance by the material state of affairs in my brain, including modifications

caused by external bodies, and is not my feeling of liberty and responsibility deceptive?

This does strike us as a true *aporia*, which occurred for the first time to Democritus, who realised it fully —but left it alone; very wisely, I think. He fully realised it. While he adhered to his 'atoms and the void' as the only reasonable way of understanding objective nature, we have some definite utterances of his preserved, to the effect that he also realised that this whole picture of the atoms and the void was formed by the human mind on the evidence of sense perceptions, and nothing else; and other utterances where he states, almost in the words of Kant, that we know nothing about what any thing really is in itself, the ultimate truth remaining deeply in the dark.

Epicurus took over Democritus' physical theories (by the way, without acknowledgement); however, less wise, and very keen on conveying to his disciples a fair and sound and incontrovertible *moral* attitude, he tampered with physics and invented his famous (or ill-famed) swerves—strongly reminiscent of modern ideas about 'uncertainty' of physical events. I will not enter on details here; suffice it to say that he broke away from physical determinism in a rather childish way, which was not based on any experience and therefore had no consequences.

The problem itself never left us. It turned up very prominently—or at least a problem of closely similar *logical* structure turned up—with St Augustine of Hippo, as a theological *aporia*. The part of the Law of Nature is taken by the omniscient and quantum laws, though they leave the single event undetermined, predict a quite definite *statistics* of events when the same situation occurs again and again. If these statistics are interfered with by any agent, this agent violates the laws of quantum mechanics just as objectionably as if it interfered —in pre-quantum physics—with a strictly causal mechanical law. Now we know that *there is no statistics* in the reaction of the same person to precisely the same moral situation—the rule is that the same individual in the same situation acts again precisely in the same manner. (Mind you, in *precisely* the same situation; this does not mean that a criminal or addict cannot be converted or healed by persuasion and example or whatnot—by strong external influence; but this, of course, means that the situation is changed.) The inference is that Jordan's assumption—the direct stepping in of free will to fill the gap of indeterminacy—does amount to an interference with the laws of nature, even in their form accepted in quantum theory. But at *that* price, of course, we can have everything. This is not a solution of the dilemma.

The moral objection was strongly emphasized by the German philosopher Ernst Cassirer (who died in 1945 in New York as an exile from Nazi Germany). Cassirer's extended criticism of Jordan's ideas is based on a thorough familiarity with the situation in physics. I shall try to summarize it briefly; I would say, it amounts to this. Free will in man includes as its most relevant part man's ethical behaviour. Supposing the physical events in space and time actually are to a large extent not strictly determined but subject to pure chance, as most physicists in our time believe, then this haphazard side of the goings-on in the material world is certainly (says Cassirer) *the very last to be invoked as the physical correlate of man's ethical behaviour*. For this is anything but haphazard, it is intensely determined by motives ranging from the lowest to the most sublime sort, from greed and spite to genuine love of the fellow creature or sincere religious devotion. Cassirer's lucid discussion makes one feel so strongly the absurdity of basing free will, including ethics, on physical haphazard that the previous difficulty, the antagonism between free will and determinism, dwindles and almost vanishes under the mighty blows Cassirer deals to the opposite view. 'Even the reduced extent of predictability' (Cassirer adds) 'still granted by Quantum Mechanics, would amply suffice to destroy ethical freedom, if the concept and true meaning of the latter were irreconcilable with predictability'. Indeed, one begins to wonder whether the supposed paradox is really so shocking, and whether physical determinism is not perhaps quite a suitable correlate to the mental phenomenon of will, which is not always easy to predict 'from outside', but usually extremely determined 'from inside'. To my mind this is the most valuable outcome of the whole controversy: the scale is turned in favour of a possible reconciliation of free will with physical determinism, when we realise how inadequate a basis physical

Wallenstein's devout belief in astrology, which we are not inclined to share. But is not the very lure of astrology, the irresistible attraction it has for scores of centuries exerted on men's minds, witness to the fact that we are not prepared to regard our fate as the outcome of pure chance, even though, or rather just because, it largely depends on our taking the right decision in the right moment? (We usually lack the full information needed for this purpose; and that is where astrology comes in!)

THE BAR TO PREDICTION, ACCORDING TO NIELS BOHR

But let us return to our subject proper. A much more serious and interesting attempt to explain the difficulty away was founded by Bohr and Heisenberg on the idea, mentioned above, that there is an unavoidable and uncontrollable mutual interaction between the observer and the observed physical object. Their ratiocination is briefly as follows. The alleged paradox consists in this, that according to the mechanistic view, by procuring an exact knowledge of the configuration and velocities of all the elementary particles in a man's body, including his brain, one could predict his voluntary actions—which thereby cease to be what he believes them to be, namely voluntary. The fact that we cannot *actually* procure this detailed knowledge is no great help. Even the theoretical predictability shocks us.

To this Bohr answers that the knowledge cannot

even be procured *in principle*, not even in theory, because such accurate observation would involve so strong an interference with 'the object' (the man's body) as to dissociate it into single particles—in fact kill him so efficiently that not even a corpse would be left for burial. At any rate, no prediction of behaviour would result, before the 'object' is far beyond the state of exhibiting any voluntary behaviour.

The emphasis is of course on the phrase 'in principle'. That the said knowledge cannot *actually* be procured, not even for the simplest living organism, let alone a higher animal like man, is clear also without quantum theory and uncertainty relation.

Bohr's consideration is no doubt interesting. Yet, I should say, we are more convicted by it than convinced, as in some mathematical proofs: you must grant A and B, then follows C and D, and so on, you cannot object to any single step; finally follows the interesting result Z. You have to accept it, but you cannot see how it really comes about, the proof gives no hint of that. In the present case I would say: Bohr's considerations show you that the present views in physics—mainly on account of the lack of strict causality (or on account of the uncertainty relation) —bar the objectionable predictability *in principle*. But you cannot see how this comes about. In view of the close relation Bohr's reasoning has to the lack of observable strict causality, you even incline to suspect that it is only Jordan's suggestion over again, but in a more careful disguise, so as to be shielded from Cassirer's arguments.

that later time—the more so, the longer the time that has elapsed.

It would thus appear that Bohr's considerations adduce a *physical* unpredictability of the behaviour of a living body again precisely from the lack of strict causation, maintained by quantum theory. Whether or no this physical indeterminacy plays any relevant role in organic life, we must, I think, sternly refuse to make it the physical counterpart of voluntary actions of living beings, for the reasons outlined before.

The net result is that quantum physics has nothing to do with the free-will problem. If there is such a problem, it is not furthered a whit by the latest development in physics. To quote Ernst Cassirer again: 'Thus it is clear . . . that a possible change in the physical concept of causality can have no immediate bearing on ethics'.