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Six Possible Worlds of Quantum Mechanics[1]

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I suppose one could imagine laws of physics which would dictate that a world be exactly so, and not otherwise, allowing no detail to be varied. But what could dictate that those laws of physics be "the" laws of physics? By considering a spectrum of possible laws, one could again consider a spectrum of possible worlds.

In fact the laws of physics of our actual world, as presently understood, have no such dictatorial character. So that even with the laws given, a spectrum of different worlds is possible. There are two kinds of freedom. Although the laws say something about how a given state of the world may develop, they say nothing (or anyway very little) about in what state the world should start. So, to begin with, we have freedom as regards "initial conditions." To go on with, the future that can evolve from a given present is not uniquely determined, according to contemporary orthodoxy. The laws list various possibilities, and attach to them various probabilities.

The relation between the set of possibilities and the unique actuality which emerges is quite peculiar in modern "quantum theory"—the contemporary all-embracing basic physical theory. The absence of determinism, the probabilistic nature of the assertions of the theory, is already a little peculiar ... at least in the light of pre-twentieth-century "classical" physics. But after all everyday life, if not classical physics, prepares us very well for the idea that not everything is predictable, that chance is important. So it is not in the indeterminism that the real surprise of quantum theory lies. There are other aspects of quantum theory for which neither classical physics nor everyday life prepares us at all.

As a result some very different conceptions, and some very strange ones, have arisen about how the visible phenomena might be incorporated into a coherent theoretical picture. It is to several such very different

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possible worlds that the title of this essay refers, rather than the permissible variation of incidental detail within each. Before giving some account of these schemes, we recall some of the phenomena with which they have to cope.

Atoms of matter can be pictured, to some extent, as small solar systems. The electrons circulate about the nucleus as do the planets about the sun. Since Newton we have very accurate laws for the motion of planets about suns, and since Einstein laws more accurate still. Attempts to apply similar laws to electrons in atoms meet with conspicuous failure. It was such failure that led to the development of "quantum" mechanics to replace "classical" mechanics. Of course our ideas about electrons in atoms are arrived at only indirectly, from the behavior of pieces of matter containing many electrons in many atoms. But in extreme conditions quantum ideas are essential even for "free" electrons, extracted from atoms, such as those which create the image on a television screen. It is in this simpler context that we will introduce the quantum ideas here.

In the "electron gun" of a television set (Fig. 1) a wire W is heated, by passage of an electric current, so that some electrons "boil off." These are attracted to a metal surface, by an electric field, and some of them pass through a hole in it, H1. And some of those that pass through the hole H1 pass also through a second hole H2 in a second metallic surface, to emerge finally moving toward the center of a glass screen G. The impact of each electron on the glass screen produces a small flash of light, a "scintillation." In a television set in actual use the electron beam is redirected, by electric fields, to the various parts of the screen, with varying intensity, to build up a complete picture thereon. But we want to consider here the behavior of "free" electrons, and will suppose that between the second hole H2 and the

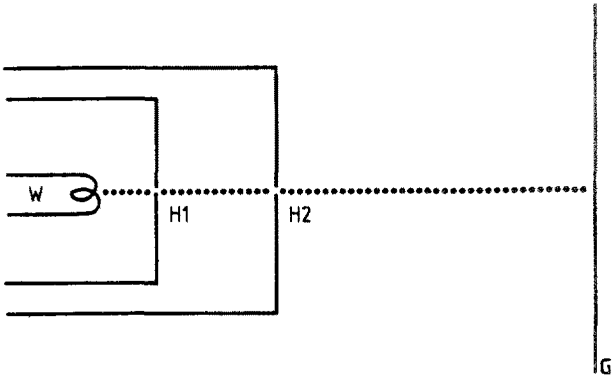

Fig. 1. Electron gun.

screen G there are no electric or magnetic fields, or any other obstacle to "free" motion.

Consider the following question: how accurately can we arrange that each electron reaching the glass screen does so exactly in the center? One thing to avoid, to this end, is that different electrons jostle one another. This can be done by "pulsing" (i.e., by applying for only a very short time) the electric field that attracts electrons from W towards H1, and by making H1 very small. Then it becomes very unlikely that more than one electron will emerge from the hole H1 on a given occasion. Then one might reasonably think that to avoid any particle striking the glass screen off center it is sufficient to make H2 as well as H1 sufficiently small and central. Up to a point that is true. But beyond that point there is a surprise. Further reducing the size of the holes does not reduce further the inaccuracy of the gun, but increases it. The pattern built up, by pulsing the gun many times and photographically recording the electron flashes, is something like Fig. 2. The flashes are scattered over a region which gets bigger, rather than smaller, when the holes by which we try to determine the electron trajectory are reduced beyond a certain magnitude.

There is a still greater surprise when the hole H2 is replaced by two holes close together, Fig. 3. Instead of the contributions of these two holes just adding together, as in Fig. 4, an "interference pattern" appears, as in Fig. 5. There are places on the screen that no electron can reach, when two holes are open, which electrons do reach when either hole alone is open. Although each electron passes through one hole or the other (or so we tend to think), it is as if the mere possibility of passing through the other hole influences its motion and prevents it going in certain directions. Here is the

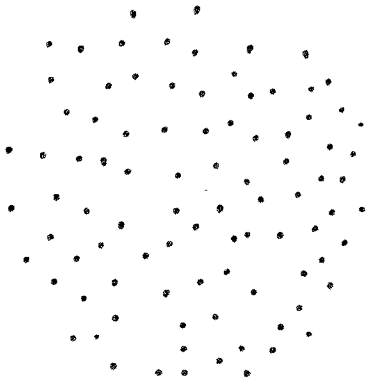

Fig. 2. Pattern built up by many pulses of electron gun of Fig. 1.

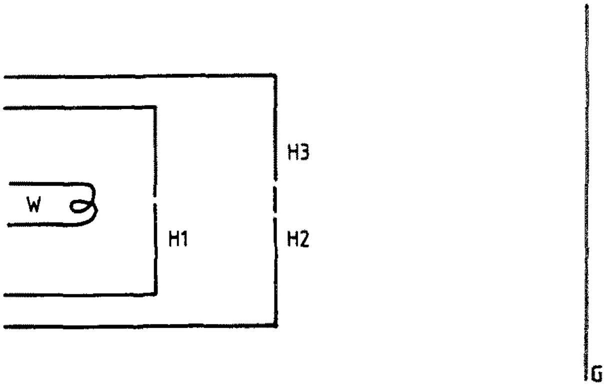

Fig. 3. Electron gun with two holes in second screen.

first hint of some queerness in the relation between possibility and actuality in quantum phenomena.

Forget for a moment that the pattern in Fig. 2 and Fig. 5 are built up from separated points (collected separately over a period of time) and look only at the general impression. Then these patterns become reminiscent of those which occur in classical physics in connection not with particles but with waves. Consider, for example, a regular train of waves on the surface of water. When they fall on a barrier with a hole, Fig. 6, they proceed more

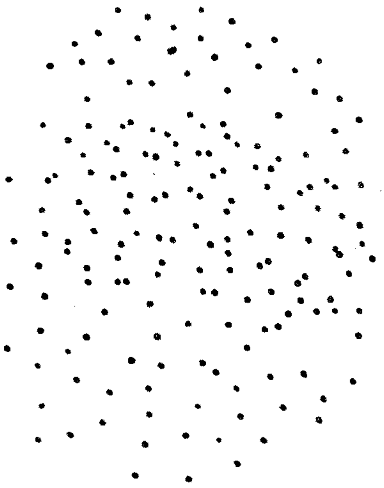

Fig. 4. Guess, on the bases of classical particle mechanics, for pattern built up by many pulses of electron.

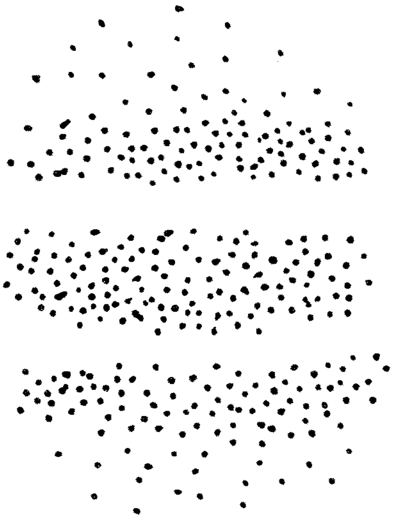

Fig. 5. Actual pattern from electron gun of Fig. 3.

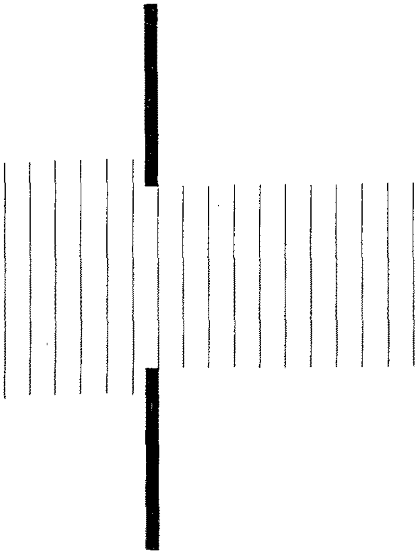

Fig. 6. Propagation of waves through hole much larger than wavelength.

or less straight on, on the other side, when the hole is large compared with the wavelength. But when the hole is smaller, they diverge after passing through, Fig. 7, and to a degree which is greater the smaller the hole. This is called "wave diffraction." And when the barrier has two small holes, Fig. 8, there are places behind the barrier where the surface of the water is undisturbed with both holes open, but disturbed when either separately is open. These are places where the waves from one hole try to raise the surface of the water while the waves from the other hole are trying to lower it, and vice-versa. This is called "wave interference."

Returning to the electron then, we cannot tell in advance at just which point on the screen it will flash. But it seems that the places where it is likely to turn up are just those which a certain wave motion can appreciably reach.

It is the mathematics of this wave motion, which somehow controls the electron, that is developed in a precise way in quantum mechanics. Indeed the most simple and natural of the various equivalent ways in which quantum mechanics can be presented is called just "wave mechanics." What is it that "waves" in wave mechanics? In the case of water waves it is the surface of the water that waves. With sound waves the pressure of the air oscillates. Light also was held to be a wave motion in classical physics. We were already a little vague about what was waving in that case ... and

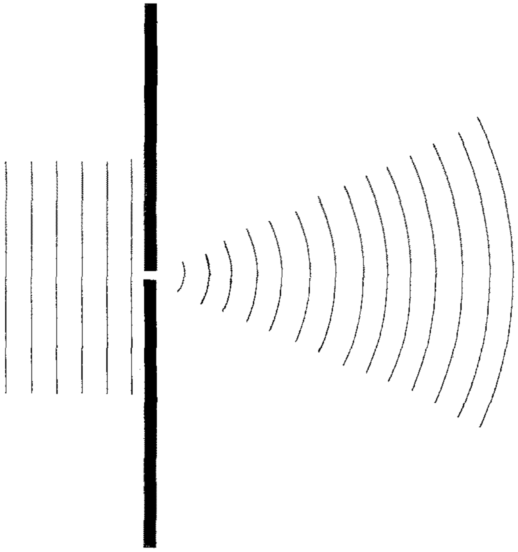

Fig. 7. Propagation of waves through hole much smaller than wavelength.

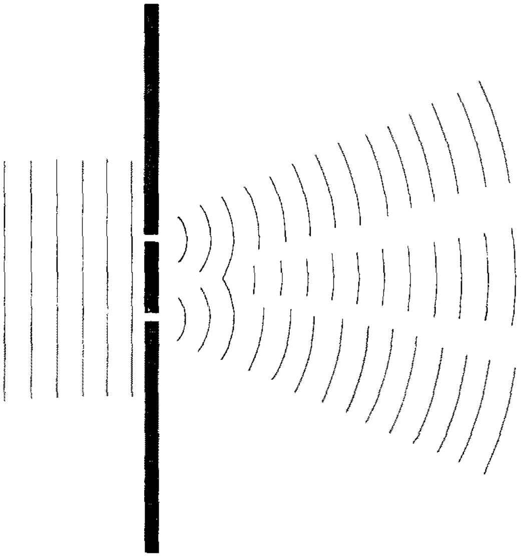

Fig. 8. Propagation of waves through two small holes.

even about whether the question made sense. In the case of the waves of wave mechanics we have no idea what is waving ... and do not ask the question. What we do have is a mathematical recipe for the propagation of the waves, and the rule that the probability of an electron being seen at a particular place when looked for there (e.g., by introducing a scintillation screen) is related to the intensity there of the wave motion.

In my opinion the following point cannot be emphasized too strongly. When we work out a problem in wave mechanics, for example that of the precise performance of the electron gun, our mathematics is entirely concerned with waves. There is no hint in the mathematics of particles or particle trajectories. With the electron gun the calculated wave extends smoothly over an extended portion of the screen. There is no hint in the mathematics that the actual phenomenon is a minute flash at some particular point in that extended region. And it is only in applying the rule, relating the probable location of the flash to the intensity of the wave, that indeterminism enters the theory. The mathematics itself is smooth, deterministic, "classical" mathematics ... of classical waves.

So far it was only the single electron, proceeding from the hole H2 to the detection screen G, that was replaced by a wave in the mathematics. The screen G, in particular, was not discussed at all. It was simply assumed to have the capacity to scintillate. Suppose we wish to explain this capacity. Suppose we wish to calculate the intensity, the color, or indeed the size of the scintillation (for it is not really a point)? We see that our treatment of the electron guns so far is neither complete nor accurate. If we wish to say more, and be more accurate, about its performance, then we have to see it as made of atoms, of electrons and nuclei. We have to apply to these entities the only mechanics that we know to be applicable ... wave mechanics. Pursuing this line of thought, we are led, in the quest for more accuracy and completeness, to include more and more of the world in the wavy quantum mechanical "system" ... the photographic plate that records the scintillations, the developing chemicals that produce the photographic image, the eye of the observer ....

But we cannot include the whole world in this wavy part. For the wave of the world is no more like the world we know than the extended wave of the single electron is like the tiny flash on the screen. We must always exclude part of the world from the wavy "system," to be described in a "classical" "particulate" way, as involving definite events rather than just wavy possibilities. The purpose of the wave calculus is just that it yields formulas for probabilities of events at this "classical" level.

Thus in contemporary quantum theory it seems that the world must be divided into a wavy "quantum system," and a remainder which is in some sense "classical." The division is made one way or another, in a particular application, according to the degree of accuracy and completeness aimed at. For me it is the indispensability, and above all the shiftiness, of such a division that is the big surprise of quantum mechanics. It introduces an essential ambiguity into fundamental physical theory, if only at a level of accuracy and completeness beyond any required in practice. It is the toleration of such an ambiguity, not merely provisionally but permanently, and at the most fundamental level, that is the real break with the classical ideal. It is this rather than the failure of any particular concept such as "particle" or "determinism." In the remainder of this essay I will outline a number of world views with physicists have entertained in trying to digest this situation.

First, and foremost, is the purely pragmatic view. As we probe the world in regions remote from ordinary experience, for example the very big or the very small, we have no right to expect that familiar notions will work. We have no right to insist on concepts like space, time, causality, or even perhaps unambiguity. We have no right whatever to a clear picture of what goes on at the atomic level. We are very lucky that we can form rules of calculation, those of wave mechanics, which work. It is true that in principle there is some ambiguity in the application of these rules, in deciding just how the world is to be divided into "quantum system" and the "classical" remainder. But this matters not at all in practice. When in doubt, enlarge the quantum system. Then it is found that the division can be so made that moving it further makes very little difference to practical predictions. Indeed good taste and discretion, born of experience, allow us largely to forget, in most calculations, the instruments of observation. We can usually concentrate on a quite minute "quantum system," and yet come up with predictions meaningful to experimenters who must use macroscopic instruments. This pragmatic philosophy is, I think, consciously or unconsciously the working philosophy of all who work with quantum theory in a practical way ... when so working. We differ only in the degree of concern or complacency with which we view ... out of working hours, so to speak ... the intrinsic ambiguity in principle of the theory.

Niels Bohr, among the very greatest of theoretical physicists, made immense contributions to the development of practical quantum theory. And when this took definitive form, in the years following 1925, he was foremost in clarifying the way in which the theory should be applied to avoid contradictions at the practical level. No one more than he insisted that part of the world (indeed the vastly bigger part) must be held outside the "quantum system" and described in classical terms. He emphasized that at this classical level we are concerned, as regards the present and the past, with definite events rather than wavy potentialities. And that at this level ordinary language and logic are appropriate. And that it is to statements in this ordinary language and logic that quantum mechanics must lead, however esoteric the recipe for generating these statements.

However, Bohr went further than pragmatism, and put forward a philosophy of what lies behind the recipes. Rather than being disturbed by the ambiguity in principle, by the shiftiness of the division between "quantum system" and "classical apparatus," he seemed to take satisfaction in it. He seemed to revel in the contradictions, for example between "wave" and "particle," that seem to appear in any attempt to go beyond the pragmatic level. Not to resolve these contradictions and ambiguities, but rather to reconcile us to them, he put forward a philosophy which he called "complementarity." He thought that "complementarity" was important not only for physics, but for the whole of human knowledge. The justly immense prestige of Bohr has led to the mention of complementarity in most textbooks of quantum theory. But usually only in a few lines. One is tempted to suspect that the authors do not understand the Bohr philosophy sufficiently to find it helpful. Einstein himself had great difficulty in reaching a sharp formulation of Bohr's meaning. What hope then for the rest of us? There is a very little I can say about "complementarity." But I wish to say one thing. It seems to me that Bohr used this word with the reverse of its usual meaning. Consider, for example, the elephant. From the front she is head, trunk, and two legs. From the back she is bottom, tail, and two legs. From the sides she is otherwise, and from top and bottom different again. These various views are complementary in the usual sense of the word. They supplement one another, they are consistent with one another, and they are all entailed by the unifying concept "elephant." It is my impression that to suppose Bohr used the word "complementary" in this ordinary way would have been regarded by him as missing his point and trivializing his thought. He seems to insist rather that we must use in our analysis elements which *contradict* one another, which do not add up to, or derive from, a whole. By "complementarity" he meant, it seems to me, the reverse: contradictoriness. Bohr seemed to like aphorisms such as: "the opposite of a deep truth is also a deep truth": "truth and clarity are complementary." Perhaps he took a subtle satisfaction in the use of a familiar word with the reverse of its familiar meaning.

"Complementarity" is one of what might be called the "romantic" world views inspired by quantum theory. It emphasizes the bizarre nature of the quantum world, the inadequacy of everyday notions and classical concepts. It lays stress on how far we have left behind naive 19th century materialism. I will describe two other romantic pictures, but will preface each by related unromantic notions.

Suppose that we accept Bohr's insistence that the very small and the very big must be described in very different ways, in quantum and classical terms, respectively. But suppose we are skeptical about the possibility of such a division being sharp, and above all about the possibility of such a division being shifty. Surely the big and the small should merge smoothly with one another? And surely in fundamental physical theory this merging should be described not just by vague words but by precise mathematics? This mathematics would allow electrons to enjoy the cloudiness of waves, while allowing tables and chairs, and ourselves, and black marks on photographs, to be rather definitely in one place rather than another, and to be described in "classical terms." The necessary technical theoretical development involves introducing what is called "nonlinearity," and perhaps what is called "stochasticity," into the basic "Schroedinger equation." There have been interesting pioneer efforts in this direction, but not yet a breakthrough. This possible way ahead is unromantic in that it requires mathematical work by theoretical physicists, rather than interpretation by philosophers, and does not promise lessons in philosophy for philosophers.

There is a romantic alternative to the idea just mentioned. It accepts that the "linear" wave mechanics does not apply to the whole world. It accepts that there is a division, whether sharp or smooth, between "linear" and "nonlinear," between "quantum" and "classical." But instead of putting this division somewhere between small and big, it puts it between "matter" (so to speak) and "mind." When we try to complete as far as possible the quantum theoretic account of the electron gun, we include first the scintillation screen, and then the photographic film, and then the developing chemicals, and then the eye of the experimenter ... and then (why not) her brain. For the brain is made of atoms, of electrons and nuclei, and so why should we hesitate to apply wave mechanics ... at least if we were smart enough to do the calculations for such a complicated assembly of atoms? But beyond the brain is ... the mind. Surely the mind is not material? Surely here at last we come to something which is distinctly different from the glass screen, and the gelatine film ... Surely it is here that we must expect some very different mathematics (if mathematics at all) to be relevant? This view, that the necessary "classical terms," and nonlinear mathematics, are in the mind, has been entertained especially by E. P. Wigner. And no one more eloquently than J. A. Wheeler has proposed that the very existence of the "material" world may depend on the participation of mind. Unfortunately it has not yet been possible to develop these ideas in a precise way.

The last unromantic picture that I will present is the "pilot wave" picture. It is due to de Broglie (1925) and Bohm (1952). While the founding fathers agonized over the question

"particle" *or* "wave"

de Broglie in 1925 proposed the obvious answer

"particle" *and* "wave"

It is not clear from the smallness of the scintillation on the screen that we have to do with a particle? And is it not clear, from the diffraction and interference patterns, that the motion of the particle is directed by a wave? De Broglie showed in detail how the motion of a particle, passing through just one of two holes in a screen, could be influenced by waves propagating through both holes. And so influenced that the particle does not go where the waves cancel out, but is attracted to where they cooperate. This idea seems to me so natural and simple, to resolve the wave–particle dilemma in such a clear and ordinary way, that it is a great mystery to me that it was so generally ignored. Of the founding fathers, only Einstein thought that de Broglie was on the right lines. Discouraged, de Broglie abandoned his picture for many years. He took it up again only when it was rediscovered, and more systematically presented, in 1952, by David Bohm. In particular Bohm developed the picture for many particles instead of just one. The generalization is straightforward. There is no need in this picture to divide the world into "quantum" and "classical" parts. For the necessary "classical terms" are available already for individual particles (their actual positions) and so also for macroscopic assemblies of particles.

The de Broglie Bohm synthesis, of particle and wave, could be regarded as a precise illustration of Bohr's complementarity ... if Bohr had been using this word in the ordinary way. This picture combines quite naturally both the waviness of electron diffraction and interference patterns, and the smallness of individual scintillations, or more generally the definite nature of large-scale happenings. The de BB picture is also, by the way, quite deterministic. The initial configuration of the combined wave–particle system completely fixes the subsequent development. That we cannot predict just where a particular electron will scintillate on the screen is just because we cannot know everything. That we cannot arrange for impact at a chosen place is just because we cannot control everything.

We come finally to the romantic counterpart of the pilot wave picture. This is the "many world interpretation," or MWI. It is surely the most bizarre of all the ideas that have come forth in this connection. It is most easily motivated, it seems to me, as a response to a central problem of the pragmatic approach ... the so-called "reduction of the wavefunction." In discussing the electron gun, I emphasized the contrast between the extension of the wave and the minuteness of the individual flash. What happens to the wave where there is no flash? In the pragmatic approach the parts of the wave where there is no flash are just discarded ... and this is effected by rule of thumb rather than by precise mathematics. In the pilot wave picture the wave, while influencing the particle, is not influenced by the particle. Flash or no flash, the wave just continues its mathematical evolution ... even where it is "empty" (very roughly speaking). In the MWI also the wave continues its mathematical way, but the notion of "empty wave" is avoided. It is avoided by the assertion that everywhere that there might be a flash ... there is a flash. But how can this be, for with one electron surely we see only one flash, at only one of the possible places? It can be because the world multiplies! After the flash there are as many worlds (at least) as places which can flash. In each world the flash occurs at just one place, but at different places in different worlds. The set of actual worlds taken together corresponds to all the possibilities latent in the wave. Quite generally, whenever there is doubt about what can happen, because of quantum uncertainty, the world multiplies so that all possibilities are actually realized. Persons of course multiply with the world, and those in any particular branch world experience only what happens in that branch. With one electron, each of us sees only one flash.

The MWI was invented by H. Everett in 1957. It has been advocated by such distinguished physicists as J. A. Wheeler, B. de Witt, and S. Hawking. It seems to attract especially quantum cosmologists, who wish to consider the world as a whole, and as a single quantum system, and so are particularly embarrassed by the requirement, in the pragmatic approach, for a "classical" part outside the quantum system ... i.e., outside the world. But this problem is already solved by the "pilot wave" picture. It needs no extra classical part, for "classical terms" are already applicable to the electron itself, and so to large assemblies of particles. The authors in question probably did not know this. For the pilot wave interpretation was rather deeply consigned to oblivion by the founding fathers, and by the writers of textbooks.

The MWI is sometimes put forward as a working out of the hypothesis: the wavefunction is everything, there is nothing else. (Then the parts of the wavefunction cannot be distinguished from one another on the grounds of corresponding to possibility rather than actuality.) But here the authors, in my opinion, are mistaken. The MWI does add something to the wavefunction. I stressed in discussing the electron gun that the extended wave has little resemblance to the minute flash. Inspection of the wave itself gives no hint that the experienced reality is a scintillation ... rather than, for example, an extended glow of unpredicted color. That is to say, the extended wave does not simply fail to specify one of the possibilities as actual ... it fails to list the possibilities. When the MWI postulates the existence of many worlds in each of which the photographic plate is blackened at a particular position, it adds, surreptitiously, to the wavefunction, the missing classification of possibilities. And it does so in an imprecise way, for the notion of the position of a black spot (it is not a mathematical point), and indeed the concept of the reading of any macroscope instrument, is not mathematically sharp. One is given no idea of how far down toward the atomic scale the splitting of the world into branch worlds penetrates.

There then are six possible worlds to choose from, designed to accommodate the quantum phenomena. It would be possible to devise hybrids between them, and maybe other worlds that are entirely different. I have tried to present them with some detachment, as if I did not regard one more than another to be pure fiction. I will now permit myself to express some personal opinions.

It is easy to understand the attraction of the three romantic worlds for journalists, trying to hold the attention of the man in the street. The opposite of a truth is also a truth! Scientists say that matter is not possible without mind! All possible worlds are actual worlds! Wow! And the journalists can write these things with good consciences, for things like this have indeed been said ... out of working hours ... by great physicists. For my part, I never got the hang of complementarity, and remain unhappy about contradictions. As regards mind, I am fully convinced that it has a central place in the ultimate nature of reality. But I am very doubtful that contemporary physics has reached so deeply down that that idea will soon be professionally fruitful. For our generation I think we can more profitably seek Bohr's necessary "classical terms" in ordinary macroscopic objects, rather than in the mind of the observer. The "many world interpretation" seems to me an extravagant, and above all an extravagantly vague, hypothesis. I could almost dismiss it as silly. And yet ... It may have something distinctive to say in connection with the "Einstein–Podolsky–Rosen puzzle," and it would be worthwile, I think, to formulate some precise version of it to see if this is really so. And the existence of all possible worlds may make us more comfortable about the existence of our own world ... which seems to be in some ways a highly improbable one.

The unromantic, "professional," alternatives make much less good copy. The pragmatic attitude, because of its great success and immense continuing fruitfulness, must be held in high respect. Moreover, it seems to me that in the course of time one may find that because of technical pragmatic progress the "problem of interpretation of quantum mechanics" has been encircled. And the solution, invisible from the front, may be seen from the back. For the present, the problem is there, and some of us will not be able to resist paying attention to it. The nonlinear Schroedinger equation seems to me to be the best hope for a precisely formulated theory which is very close to the pragmatic version. But while we get along so well without precision, the pragmatists are not going to help to develop it. The "pilot wave" picture is an almost trivial reconciliation of quantum phenomena with the classical ideals of theoretical physics ... a closed set of equations, whose solutions are to be taken seriously, and not mutilated ("reduced") when embarrassing. However, it would be wrong to leave the reader with the impression that, with the pilot wave picture, quantum theory simply emerges into the light of day, with the transparency of pure water. The very clarity of this picture puts in evidence the extraordinary "nonlocality" of quantum theory. But that is another story.

To what extent are these possible worlds fictions? They are like literary fiction in that they are free inventions of the human mind. In theoretical physics sometimes the inventor knows from the beginning that the work is fiction, for example when it deals with a simplified world in which space has only one or two dimensions instead of three. More often it is not known till later, when the hypothesis has proved wrong, that fiction is involved. When being serious, when not exploring deliberately simplified models, the theoretical physicist differs from the novelist in thinking that maybe the story might be true. Perhaps there is some analogy with the historical novelist. If the action is put in the year 1327, the pope must be located in Avignon, not Rome. The serious theories of theoretical physicists must not contradict experimental facts. If thoughts are put into the mind of pope John XXII, then they must be reasonably consistent with what is known of his words and actions. When we invent worlds in physics we would have them to be mathematically consistent continuations of the visible world into the invisible ... even when it is beyond human capability to decide which, if any, of those worlds is the true one. Literary fiction, historical or otherwise, can be professionally good or bad (I think). We could also consider how our possible worlds in physics measure up to professional standards. In my opinion the pilot wave picture undoubtedly shows the best craftsmanship among the pictures we have considered. But is that a virtue in our time?