logic); others might see it as injunction against speaking in the way we do in natural language, of arbitrary scenes and situations.

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QUANTUM MYSTERIES FOR ANYONE

We often discussed his notions on objective reality. I recall that during one walk Einstein suddenly stopped, turned to me and asked whether I really believed that the moon exists only when I look at it.

A. Pais[1]

As O. Stern said recently, one should no more rack one's brain about the problem of whether something one cannot know anything about exists all the same, than about the ancient question of how many angels are able to sit on the point of a needle. But it seems to me that Einstein's questions are ultimately always of this kind.

W. Pauli[2]

PAULI and Einstein were both wrong. The questions with which Einstein attacked the quantum theory do have answers; but they are not the answers Einstein expected them to have. We now know that the moon is demonstrably not there when nobody looks.

The impact of this discovery on philosophy may have been blunted by the way in which it is conventionally stated, which leaves it fully accessible only to those with a working knowledge of quantum mechanics. I hope to remove that barrier by describing this remarkable aspect of nature in a way that presupposes no background whatever in the quantum theory or, for that matter, in classical physics either. I shall describe a piece of machinery that presents without any distortion one of the most strikingly peculiar features of the atomic world. No formal training in physics or mathematics is needed to grasp and ponder the extraordinary behavior of the device; it is only necessary to follow a simple counting argument on the level of a newspaper braintwister.

Being a physicist, and not a philosopher, I aim only to bring home some strange and simple facts which might raise issues philosophers would be interested in addressing. I shall try, perhaps

[1] *Reviews of Modern Physics*, LI, 863 (1979): 907.

[2] From a 1954 letter to M. Born, in *The Born-Einstein Letters* (New York: Walker, 1971), p. 223.

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without notable success, to avoid raising and addressing such issues myself. What I describe should be regarded as something between a parable and a lecture demonstration. It is less than a lecture demonstration for technical reasons: even if this were a lecture, I lack the time, money, and particular expertise to build the machinery I shall describe. It is more than a parable because the device could in fact be built with an effort almost certainly less than, say, the Manhattan project, and because the conundrum posed by the behavior of the device is no mere analogy, but the atomic world itself, acting at its most perverse.

There are some black boxes within the device whose contents can be described only in highly technical terms. This is of no importance. The wonder of the device lies in what it does, not in how it is put together to do it. One need not understand silicon chips to learn from playing with a pocket calculator that a machine can do arithmetic with superhuman speed and precision; one need not understand electronics or electrodynamics to grasp that a small box can imitate human speech or an orchestra. At the end of the essay I shall give a brief technical description of what is in the black boxes. That description can be skipped. It is there to serve as an existence proof only because you cannot buy the device at the drugstore. It is no more essential to appreciating the conundrum of the device than a circuit diagram is to using a calculator or a radio.

The device has three unconnected parts. The question of connectedness lies near the heart of the conundrum, but I shall set it aside in favor of a few simple practical assertions. There are neither mechanical connections (pipes, rods, strings, wires) nor electromagnetic connections (radio, radar, telephone or light signals) nor any other relevant connections. Irrelevant connections may be hard to avoid. All three parts might, for example, sit atop a single table. There is nothing in the design of the parts, however, that takes advantage of such connections to signal from one to another, for example, by inducing and detecting vibrations in the table top.

By insisting so on the absence of connections I am inevitably suggesting that the wonders to be revealed can be fully appreciated only by experts on connections or their lack. This is not the right attitude to take. Were we together and had I the device at hand, you could pick up the parts, open them up, and poke around as much as you liked. You would find no connections. Neither would an expert on hidden bugs, the Amazing Randi, or any physicists you called in as consultants. The real worry is unknown connections. Who is to say that the parts are not connected by the transmission of unknown Q-rays and their detection by unrecognizable Q-detectors? One can only offer affidavits from the manufacturer testifying to an ignorance of Q-technology and, in any event, no such intent.

Evidently it is impossible to rule out conclusively the possibility of connections. The proper point of view to take, however, is that it is precisely the wonder and glory of the device that it impels one to doubt these assurances from one's own eyes and hands, professional magicians, and technical experts of all kinds. Suffice it to say that there are no connections that suspicious lay people or experts of broad erudition and unimpeachable integrity can discern. If you find yourself questioning this, then you have grasped the mystery of the atomic world.

Two of the three parts of the device (A and B) function as detectors. Each detector has a switch that can be set in one of three positions (1, 2, and 3) and a red and a green light bulb (Fig. 1). When a detector is set off it flashes either its red light or its green. It does this no matter how its switch is set, though whether it flashes red or green may well depend on the setting. The only purpose of the lights is to communicate information to us; marks on a ribbon of tape would serve as well. I mention this only to emphasize that the unconnectedness of the parts prohibits a mechanism in either detector that might modify its behavior according to the color that may have flashed at the other.

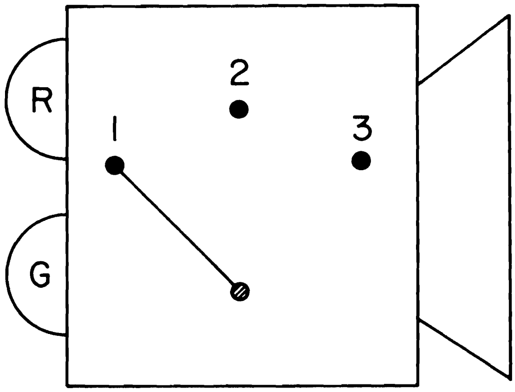

Fig. 1. A detector. Particles enter on the right. The red (R) and green (G) lights are on the left. The switch is set to 1.

The third and last part of the device is a box (C) placed between the detectors. Whenever a button on the box is pushed, shortly thereafter two particles emerge, moving off in opposite directions toward the two detectors (Fig. 2). Each detector flashes either red or green whenever a particle reaches it. Thus within a second or two of every push of the button, each detector flashes one or the other of its two colored lights.

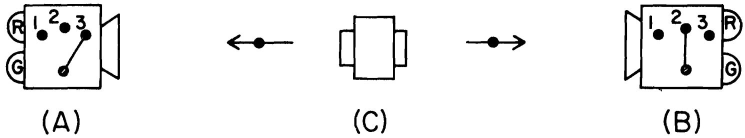

Fig. 2. The complete device. A and B are the two detectors. C is the box from which the two particles emerge.

Because there are no connections between parts of the device, the link between pressing the button on the box and the subsequent flashing of the detectors can be provided only by the passage of the particles from the box to the detectors. This passage could be confirmed by subsidiary detectors between the box and the main detectors A and B, which can be designed so as not to alter the functioning of the device. Additional instruments or shields could also be used to confirm the lack of other communication between the box and the two detectors or between the detectors themselves (Fig. 3).

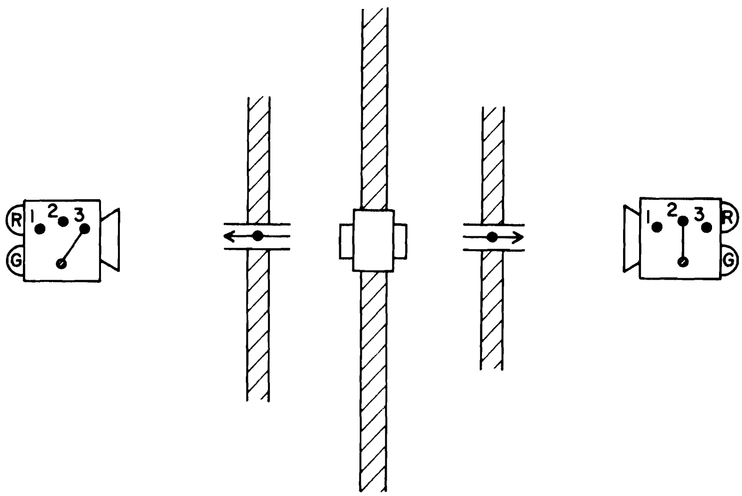

Fig. 3. Possible refinement of the device. The box is embedded in a wall that cuts off one detector from the other. Subsidiary detectors confirm the passage of the particles to the main detectors.

The device is operated repeatedly in the following way. The switch on each detector is set at random to one of its three possible positions, giving nine equally likely settings for the pair of detectors: 11, 12, 13, 21, 22, 23, 31, 32, and 33. The button on the box is then pushed, and somewhat later each detector flashes one of its lights. The flashing of the detectors need not be simultaneous. By changing the distance between the box and the detectors we can arrange that either flashes first. We can also let the switches be given their random settings either before or after the particles leave the box. One could even arrange for the switch on B not to be set until after A had flashed (but, of course, before B flashed).

After both detectors have flashed their lights, the settings of the switches and the colors that flashed are recorded, using the following notation: 31 GR means that detector A was set to 3 and flashed green, while B was set to 1 and flashed red; 12 RR describes a run in which A was at 1, B at 2, and both flashed red; 22 RG describes a run in which both detectors were set to 2, A flashed red and B flashed green; and so on. A typical fragment from a record of many runs is shown in Fig. 4.

```
                    GG 22GG
               2RR 31RG 13RG 22GG 22R
           R 21GR 32RG 11GG 32GR 33GG 2
        22GG 11RR 11GG 23GG 12RR 32GR 11GG
      G 12RG 13RG 33GG 21RG 13GR 31RR 32GR
   GR 13GR 21RG 33RR 13GR 11RR 11GG 13RG 31
  2GG 32GR 33GG 21GR 21GG 33RR 23RG 21GG 21R
 13GR 11GG 32GG 31GR 32RG 33RR 13RR 13RG 12R
 11GG 31RG 33RR 12RG 21GR 11GG 22GG 33GG 23G
 11RR 22RR 12RG 22GG 23GR 12GR 33GG 31GG 13G
 13GR 21RR 33RR 33RR 13RG 23RG 33GG 32RR 12R
  3RR 32RG 11RR 11RR 11RR 32RG 12RG 21RG 11G
   RG 23RR 21RG 33RR 13GR 12GR 23RG 21RR 32
    R 21GR 12RR 31GR 12RG 13GR 13RG 22RR 1
      23GR 11RR 12RR 33RR 21RG 13GR 21RR
         R 12RR 23GG 13RG 21RG 11GG 12
              2RG 32RG 32GR 11GG 22R
                      31RG 21
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Fig. 4. Fragment of a page of a volume from the set of notebooks recording a long series of runs.

The accumulated data have a random character, but, like data collected in many tossings of a coin, they reveal certain unmistakable features when enormously many runs are examined. The statistical character of the data should not be a source of concern or suspicion. Blaming the behavior of the device on repeated, systematic, and reproducible accidents, is to offer an explanation even more astonishing than the conundrum it is invoked to dispel.

The data accumulated over millions (or, if you prefer, billions or trillions) of runs can be summarized by distinguishing two cases:

Case a. In those runs in which each switch ends up with the same setting (11, 22, or 33) both detectors always flash the same color. RR and GG occur in a random pattern with equal frequency; RG and GR never occur.

Case b. In the remaining runs, those in which the switches end up with different settings (12, 13, 21, 23, 31, or 32), both detectors flash the same color only a quarter of the time (RR and GG occurring randomly with equal frequency); the other three quarters of the time the detectors flash different colors (RG and GR occurring randomly with equal frequency).

These results are subject to the fluctuations accompanying any statistical predictions, but, as in the case of a coin-tossing experiment, the observed ratios will differ less and less from those predicted, as the number of runs becomes larger and larger.

This is all it is necessary to know about how the device operates. The particular fractions $\frac{1}{4}$ and $\frac{3}{4}$ arising in case b are of critical importance. If the smaller of the two were $\frac{1}{3}$ or more (and the larger $\frac{2}{3}$ or less) there would be nothing wonderful about the device. To produce the conundrum it is necessary to run the experiment sufficiently many times to establish with overwhelming probability that the observed frequencies (which will be close to 25% and 75%) are not chance fluctuations away from expected frequencies of $33\frac{1}{3}$% and $66\frac{2}{3}$%. (A million runs is more than enough for this purpose.)

These statistics may seem harmless enough, but some scrutiny reveals them to be as surprising as anything seen in a magic show, and leads to similar suspicions of hidden wires, mirrors, or confederates under the floor. We begin by seeking to explain why the detectors invariably flash the same colors when the switches are in the same positions (case a). There would be any number of ways to arrange this were the detectors connected, but they are not. Nothing in the construction of either detector is designed to allow its functioning to be affected in any way by the setting of the switch on the other, or by the color of the light flashed by the other.

Given the unconnectedness of the detectors, there is one (and, I would think, only one) extremely simple way to explain the behavior in case a. We need only suppose that some property of each particle (such as its speed, size, or shape) determines the color its detector will flash for each of the three switch positions. What that property happens to be is of no consequence; we require only that the various states or conditions of each particle can be divided into eight types; RRR, RRG, RGR, RGG, GRR, GRG, GGR, and GGG. A particle whose state is of type RGG, for example, will always cause its detector to flash red for setting 1 of the switch, green for setting 2, and green for setting 3; a particle in a state of type GGG will cause its detector to flash green for any setting of the switch; and so on. The eight types of states encompass all possible cases. The detector is sensitive to the state of the particle and responds accordingly; putting it another way, a particle can be regarded as carrying a specific set of flashing instructions to its detector, depending on which of the eight states the particle is in.

The absence of RG or GR when the two switches have the same settings can then be simply explained by assuming that the two particles produced in a given run are both produced in the same state; i.e., they carry identical instruction sets. Thus if both particles in a run are produced in states of type RRG, then both detectors will flash red if both switches are set to 1 or 2, and both will flash green if both switches are set to 3. The detectors flash the same colors when the switches have the same settings because the particles carry the same instructions.

This hypothesis is the obvious way to account for what happens in case a. I cannot prove that it is the only way, but I challenge the reader, given the lack of connections between the detectors, to suggest any other.

The apparent inevitability of this explanation for the perfect correlations in case a forms the basis for the conundrum posed by the device. For the explanation is quite incompatible with what happens in case b.

If the hypothesis of instruction sets were correct, then both particles in any given run would have to carry identical instruction sets whether or not the switches on the detectors were set the same. At the moment the particles are produced there is no way to know how the switches are going to be set. For one thing, there is no communication between the detectors and the particle-emitting box, but in any event the switches need not be set to their random positions until after the particles have gone off in opposite directions from the box. To ensure that the detectors invariably flash the same color every time the switches end up with the same settings, the particles leaving the box in each run must carry the same instructions even in those runs (case b) in which the switches end up with different settings.

Let us now consider the totality of all case b runs. In none of them do we ever learn what the full instruction sets were, since the data reveal only the colors assigned to two of the three settings. (The case a runs are even less informative.) Nevertheless we can draw some nontrivial conclusions by examining the implications of each of the eight possible instruction sets for those runs in which the switches end up with different settings. Suppose, for example, that both particles carry the instruction set RRG. Then out of the six possible case b settings, 12 and 21 will result in both detectors flashing the same color (red), and the remaining four settings, 13, 31, 23, and 32, will result in one red flash and one green. Thus both detectors will flash the same color for two of the six possible case b settings. Since the switch settings are completely random, the various case b settings occur with equal frequency. Both detectors will therefore flash the same color in a third of those case b runs in which the particles carry the instruction sets RRG.

The same is true for case b runs where the instruction set is RGR, GRR, GGR, GRG, or RGG, since the conclusion rests only on the fact that one color appears in the instruction set once and the other color, twice. In a third of the case b runs in which the particles carry any of these instruction sets, the detectors will flash the same color.

The only remaining instruction sets are RRR and GGG; for these sets both detectors will evidently flash the same color in every case b run.

Thus, regardless of how the instruction sets are distributed among the different runs, in the case b runs *both detectors must flash the same color at least a third of the time.* (This is a bare minimum; the same color will flash more than a third of the time, unless the instruction sets RRR and GGG never occur.) As emphasized earlier, however, when the device actually operates the same color is flashed only a quarter of the time in the case b runs.

Thus the observed facts in case b are incompatible with the only apparent explanation of the observed facts in case a, leaving us with the profound problem of how else to account for the behavior in both cases. This is the conundrum posed by the device, for there is no other obvious explanation of why the same colors always flash when the switches are set the same. It would appear that there must, after all, be connections between the detectors—connections of no known description which serve no purpose other than relieving us of the task of accounting for the behavior of the device in their absence.

I shall not pursue this line of thought, since my aim is only to state the conundrum of the device, not to resolve it. The lecture demonstration is over. I shall only add a few remarks on the device as a parable.

One of the historic exchanges between Einstein and Bohr,[3,4] which found its surprising denouement in the work of J. S. Bell nearly three decades later,[5] can be stated quite clearly in terms of the device. I stress that the transcription into the context of the device is only to simplify the particular physical arrangement used to raise the issues. The device is a direct descendant of the rather more intricate but conceptually similar *gedanken* experiment proposed in 1935 by Einstein, Podolsky, and Rosen. We are still talking physics, not descending to the level of analogy.

The Einstein, Podolsky, Rosen experiment amounts to running the device under restricted conditions in which both switches are required to have the same setting (case a). Einstein would argue (as was argued above) that the perfect correlations in each run (RR or GG but never RG or GR) can be explained only if instruction sets exist, each particle in a run carrying the same instructions. In the Einstein, Podolsky, Rosen version of the argument the analogue of case b was not evident, and its fatal implications for the hypothesis of instruction sets went unnoticed until Bell's paper.

The *gedanken* experiment was designed to challenge the prevailing interpretation of the quantum theory, which emphatically denied the existence of instruction sets, insisting that certain physical properties (said to be complementary) had no meaning independent of the experimental procedure by which they were measured. Such measurements, far from revealing the value of a preexisting property, had to be regarded as an inseparable part of the very attribute they were designed to measure. Properties of this kind have no independent reality outside the context of a specific experiment arranged to observe them: the moon is *not* there when nobody looks.

In the case of my device, three such properties are involved for each particle. We can call them the 1-color, 2-color, and 3-color of the particle. The n-color of a particle is red if a detector with its switch set to n flashes red when the particle arrives. The three n-colors of a particle are complementary properties. The switch on

[3] A. Einstein, B. Podolsky, and N. Rosen, *Physical Review*, XLVII, 777 (1935).
[4] N. Bohr, *Physical Review*, XLVIII, 696 (1935).
[5] J. S. Bell, Physics, I, 195 (1964).

a detector can be set to only one of the three positions, and the experimental arrangements for measuring the 1-, 2-, or 3-color of a particle are mutually exclusive. (We may assume, to make this point quite firm, that the particle is destroyed by the act of triggering the detector, which is, in fact, the case in many recent experiments probing the principles that underly the device.)

To assume that instruction sets exist at all, is to assume that a particle has a definite 1-, 2-, and 3-color. Whether or not all three colors are known or knowable is not the point; the mere assumption that all three have values violates a fundamental quantum-theoretic dogma.

No basis for challenging this dogma is evident when only a single particle and detector are considered. The ingenuity of Einstein, Podolsky, and Rosen lay in discovering a situation involving a *pair* of particles and detectors, where the quantum dogma continued to deny the existence of 1-, 2-, and 3-colors, while, at the same time, quantum theory predicted correlations (RR and GG but never RG or GR) that seemed to require their existence.

Einstein concluded that, if the quantum theory were correct, i.e., if the correlations were, as predicted, perfect, then the dogma on the nonexistence of complementary properties—essentially Bohr's doctrine of complementarity—had to be rejected.

Pauli's attitude toward this in his letter to Born is typical of the position taken by many physicists: since there is no known way to determine all three n-colors of a particle, why waste your time arguing about whether or not they exist? To deny their existence has a certain powerful economy—why encumber the theory with inaccessible entities? More importantly, the denial is supported by the formal structure of the quantum theory which completely fails to allow for any consideration of the simultaneous 1-, 2-, and 3-colors of a particle. Einstein preferred to conclude that all three n-colors did exist, and that the quantum theory was incomplete. I suspect that many physicists, though not challenging the completeness of the quantum theory, managed to live with the Einstein, Podolsky, Rosen argument by observing that though there was no way to establish the existence of all three n-colors, there was also no way to establish their nonexistence. Let the angels sit, even if they can't be counted.

Bell changed all this, by bringing into consideration the case b runs, and pointing out that the quantitative numerical predictions of the quantum theory ($\frac{1}{4}$ vs. $\frac{1}{3}$) unambiguously ruled out the existence of all three n-colors. Experiments done since Bell's paper confirm the quantum-theoretic predictions.[6] Einstein's attack, were he to maintain it today, would be more than an attack on the metaphysical underpinnings of the quantum theory—more, even, than an attack on the quantitative numerical predictions of the quantum theory. Einstein's position now appears to be contradicted by nature itself. The device behaves as it behaves, and no mention of wave-functions, reduction hypotheses, measurement theory, superposition principles, wave-particle duality, incompatible observables, complementarity, or the uncertainty principle, is needed to bring home its peculiarity. It is not the Copenhagen interpretation of quantum mechanics that is strange, but the world itself.

As far as I can tell, physicists live with the existence of the device by implicitly (or even explicitly) denying the absence of connections between its pieces. References are made to the "wholeness" of nature: particles, detectors, and box can be considered only in their totality; the triggering and flashing of detector A cannot be considered in isolation from the triggering and flashing of detector B—both are part of a single indivisible process. This attitude is sometimes tinged with Eastern mysticism, sometimes with Western know-nothingism, but, common to either point of view, as well as to the less trivial but considerably more obscure position of Bohr, is the sense that strange connections are there. The connections are strange because they play no explicit role in the theory: they are associated with no particles or fields and cannot be used to send any kinds of signals. They are there for one and only one reason: to relieve the perplexity engendered by the insistence that there are no connections.

Whether or not this is a satisfactory state of affairs is, I suspect, a question better addressed by philosophers than by physicists.

I conclude with the recipe for making the device, which, I emphasize again, can be ignored:

> The device exploits Bohm's version[7] of the Einstein, Podolsky, Rosen experiment. The two particles emerging from the box are spin $\frac{1}{2}$ particles in the singlet state. The two detectors contain Stern-Gerlach magnets, and the three switch positions determine whether the orientations of the magnets are vertical or at $\pm 120°$ to the vertical in the plane perpendicular to the line of flight of the particles. When the

[6] Theoretical and experimental aspects of the subject are reviewed by J. F. Clauser and A. Shimony, *Reports on Progress in Physics*, XLI, 1991 (1978). For a less technical survey see B. d'Espagnat, *Scientific American*, CCXL, 5 (November 1979): 158.

[7] D. Bohm, *Quantum Theory* (Englewood Cliffs, N.J.: Prentice-Hall, 1951), pp. 614-619.

switches have the same settings the magnets have the same orientation. One detector flashes red or green according to whether the measured spin is along or opposite to the field; the other uses the opposite color convention. Thus when the same colors flash the measured spin components are different.

It is a well-known elementary result that, when the orientations of the magnets differ by an angle θ, then the probability of spin measurements on each particle yielding opposite values is $\cos^2(\theta/2)$. This probability is unity when $\theta = 0$ (case a) and $\frac{1}{4}$ when $\theta = \pm 120°$ (case b).

If the subsidiary detectors verifying the passage of the particles from the box to the magnets are entirely nonmagnetic they will not interfere with this behavior.

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BOOK REVIEWS

Philosophical Perspectives in Artificial Intelligence. MARTIN D. RINGLE, ed. New York: Humanities Press, 1979. x, 244 p. $17.50.

There is no gadget more characteristic of our age than the computer. Computers and all fields and organizations that serve them arouse an interest that seems insatiable. Prestige and recognition naturally follow. Among the alphabet soup of acronyms, how many enjoy the recognition afforded IBM? So, when a discipline appears that presents itself as the theoretical arm of this new wave, it is only natural to find the metatheoretical impulses of philosophers aroused. This natural urge is further compounded when the discipline in question is generally unencumbered by even the faintest hint of modesty. Artificial intelligence—AI for short—has tantalized the philosophical community (as well as many psychologists and linguists) by announcing the discovery of both new principles of human understanding and new methods for the study of mind, behavior, and intelligence—new methods leading to *real* precise understanding in contradistinction to the sterile approaches of yesteryear.[1]

This book aims to introduce the philosophically inclined to both the substance and the metasubstance of AI. As reviewer I have some

[1] Some have likened the degree of understanding to the breakthroughs that Newton and the calculus spurred in physics. Minsky public lecture, Martin Luther King day, M.I.T., spring 1975.

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