at the same time he looks vaguely as if he hasn't the faintest idea what she is talking about.

In order to capture this complicated facial expression I have wasted 38 sheets of paper. And I certainly cannot pronounce this 39th a success either.

(7) In hotel dining rooms Mrs. Einstein always takes charge of ordering our meals. Tonight, however, because of a headache she cannot join us at the table.

Dr. Einstein, placing the menu in front of him, says he will order in her stead, and flexing his muscles, declares: "Under the pressures of the responsibility, I feel strong." We all laughed.

It is quite dangerous, however, to be fed by Dr. Einstein. He has no respect for the proper sequence of courses; the poultry dishes will come out first, then the fish dishes later.

And he himself is eating potatoes, which Mrs. Einstein does not allow him because she considers them too vulgar. (The foreign lady seated at the table in my sketch is not Mrs. Einstein, but Mr. Inagaki's wife.)

(8) Dr. Einstein comes to join us in Mr. Inagaki's room for a chat. He is incessantly cleaning his beloved pipe.

I offer an observation:

"Professor, it's hard for me to tell whether you smoke for the pleasure of smoking, or you smoke in order to engage in unclogging and refilling your pipe."

He replies, "My aim lies in smoking, but as a result things tend to get clogged up, I'm afraid. Life, too, is like smoking, especially marriage.

When the pipe cleaning is over he says the next job is going to be a little handicraft operation. With his knife he cuts away worn pieces of leather from the soles of his shoes and feeds them to the charcoal fire. It smells to high heaven.

No matter how many times we plead with him to stop, he just looks over at us, grinning, and continues to put pieces of old leather to the flames. Dr. Einstein has a certain devilish streak in him.

Bringing home the atomic world: Quantum mysteries for anybody

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A simple device is described, based on a version of Bell's inequality, whose operation directly demonstrates some of the most peculiar behavior to be found in the atomic world. To understand the design of the device one has to know some physics, but the extraordinary implications of its behavior should be evident to anyone. Except for a preface and appendix for physicists, the paper is addressed to the general reader.

PREFACE

The 1935 thought experiment of Einstein, Podolsky, and Rosen[1] challenged the quantum-mechanical doctrine that simultaneous values of incompatible observables are not only impossible to know, but also meaningless to contemplate. The correlations revealed by that experiment underly much of Einstein's subsequent insistence that the quantum theory, though it might well account correctly for all measurements, was only a step toward a more complete theory that would give meaning to the values of unmeasured properties.

For almost three decades the objections to Einstein's views on the reality of unmeasured properties were entirely philosophical. "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."[2] In 1964, however, J. S. Bell[3] showed that such assumptions of existence can have observable consequences. These can be at odds with quantitative numerical predictions of the quantum theory, and thus, if the theory is correct, with observable physical behavior.

Experiments since Bell's paper[4] indicate that nature behaves consistently with quantum mechanics, but not with the concept of reality Einstein demanded from a satisfactory theory. The metaphysical conundrum with which Einstein, Podolsky, and Rosen attacked the accepted interpretation of quantum mechanics can now be extracted directly from a few simple facts, without any reference at all to the conceptual apparatus of the quantum theory. The point is no longer that quantum mechanics is an extraordinarily (and, for Einstein, unacceptably) peculiar theory, but that the world is an extraordinarily peculiar place.

In the paper that follows I present the Einstein–Podolsky–Rosen conundrum,[5] without mention of wave functions, superposition, wave–particle duality, the uncertainty principle, incompatible observables, electron spin, or any other quantum-mechanical notions. The argument is addressed to readers who know nothing of the quantum theory or, for that matter, of classical physics either. My aim is to bring such readers directly up against one of the most strikingly odd ways the world can behave. Those who follow the argument should be as able as practicing physicists to ponder the metaphysical implications of the Einstein–Podolsky–Rosen conundrum.

I begin by describing a certain device. The device contains some black boxes, but the relevant features of its behavior are fully described, just as one can fully describe what comes out of a radio when the knobs turn, without delving into electromagnetic theory.

In the second half of the paper I point out the conundrum posed by the existence of such a device. No resolution of the conundrum is offered. Many physicists simply deny that it is a conundrum,[6] a position readers can accept or reject for themselves.

There is an Appendix for physicists that explains what is in the black boxes. Understanding the explanation is no more essential to appreciating the wonders of the device

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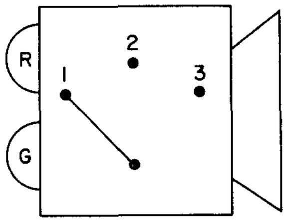

Fig. 1. Detector. Particles enter on the right. The red (R) and green (G) lights are on the left. The switch is set to position 1.

than a grasp of Maxwell's equations is prerequisite to enjoying a broadcast of the Waldstein Sonata. Instructions on how to make the device are appended only because no specimens have yet been built that would demonstrate its behavior directly.

I. THE DEVICE AND WHAT IT DOES

I shall describe a device that achieves a rather remarkable effect by exploiting the known behavior of matter on the atomic level. Although this device has not been built, there is no reason in principle why it could not be, and probably no insurmountable practical difficulties. The device has three unconnected parts. By "unconnected" I mean that there are neither mechanical connections (e.g., pipes, rods, strings, or wires) nor electromagnetic connections (e.g, radio, radar, or light signals) nor any other known relevant connections. Irrelevant connections may be hard to avoid. For example, all three parts might sit on the same table top.

Two of the parts (A and B) are detectors. Each detector has a switch that can be set in one of three positions (labeled 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 not matter how the 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 the observer; marks on a ribbon of tape would serve as well. I mention this only to emphasize that the unconnectedness of the parts of the device prohibits any mechanism in either detector, that can modify its behavior according to the color that may have flashed on the other.

The third piece 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. Things are aimed and adjusted so that within a second or two of every push of the button, each detector flashes one or the other of its two colored lights.

Because there are no connections between parts of the device, the link between pressing the button on the box and the subsesquent flashing of the detectors can only be provided by the passage of the particles from the box to the detectors. This passage could be confined 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 any other communication between the box and the two detectors, or between the detectors themselves (Fig. 3).

The device is operated repeatedly in the following way: the switch on either detector is set at random to one of its three possible positions; this gives 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 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 one flashes first.It also does not matter whether the switches are set to their random positions before or after the particles leave the box, as long as each is set before a particle actually reaches the detector. 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 setting of the switches and the colors that flashed are recorded using the following notation: 31 GR indicates 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 whch A was at 1, B at 2, and both flashed red; and so on. A typical fragment from a record of many runs is shown in Fig. 4.

The accumulated data have a random character, but like the data collected in many tossings of a coin (where the division of cases between heads and tails gets closer and closer to 50–50 as the number of tosses increases) certain features emerge clearly when enormously many runs are examined. These features reveal two main types of behavior:

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 with equal frequency; RG and GR never occur.

Case (b). In those runs 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 with equal frequency); the other three quarters of the time the detectors flash different colors (RG and GR occurring with equal frequency).

These results are subject to the fluctuations that accompany any statistical predictions, but, as in the case of

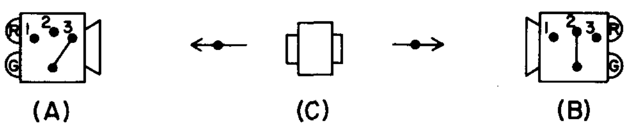

Fig. 2. Complete device. A and B are the two detectors. C is the box from which the two particles emerge.

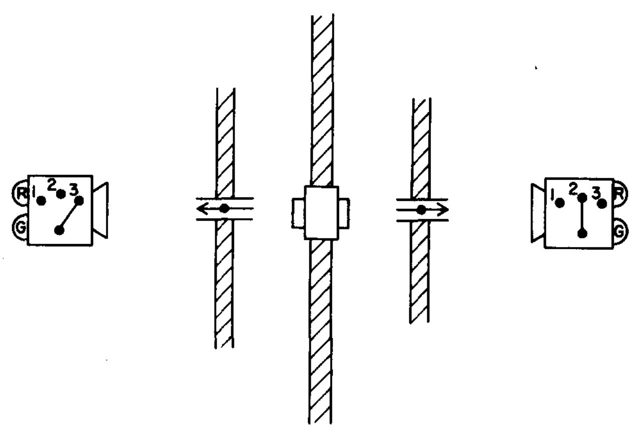

Fig. 3. Possible refinement of the device. The box is embedded in a wall tht cuts off one detector from the other. Subsidiary detectors confirm the passage of the particles to the main detectors.

a coin tossing experiment, the observed ratios differ less and less from the predicted ones as the number of runs becomes larger and larger.

This is all one needs to know about the device and how it operates.

II. THE CONUNDRUM OF THE DEVICE

The statistics of the data produced by the device may seem harmless enough, but some scrutiny reveals them to be as surprising as a conjurer's trick. My emphasis that no pieces of the device could communicate with any others except through the particles, was precisely to forestall the search for hidden wires, mirrors, or cards up the sleeve that one feels impelled to embark upon, once the implications of the data are grasped.

Consider first the behavior in the runs of case (a). Why do the detectors always flash the same color when the switches are in the same positions? Since the two detectors are unconnected there is no way for one to "know" that the switch on the other is set in the same position as its own; 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).

There is, however, a very simple way to explain the results 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 is does not matter; it is enough 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 encompass all possible cases. The detector extracts from each type of state a definite set of instructions for what color to flash for each of the three possible settings of its switches; thus each particle can be viewed as carrying such a set of instructions to its detector through the value of the relevant property.

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 carry identical instruction sets. Thus if both particles in a run are 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, that the particles in a run carry identical instruction sets, is the obvious way to account for what happens in case (a). It cannot be proved that there is no other way, but I challenge the reader to suggest any.

And therein lies a conundrum, because this hypothesis, the only apparent way to account for case (a), is quite incompatible with what happens in case (b).

If the hypothesis were correct, then both particles in a given run would have to carry the same instructions whether or not the switches on the detectors were set the same. The box producing the particles has no way to "know" how the switches are going to be set, since there is no way to communicate such information from the detectors to the box; in any event, the switches need not be set to their random positions until after the particles have left the box. To insure that the detectors invariably flash the same color every time the switches end up with the same settings, the particles leaving the box must each carry the same instructions even in those runs [case (b)] where the switches have different settings.

Consider now a run of type (b). Even after the run is over, we can never know what the full instruction sets were, since the data only reveal the colors assigned to two of the three settings. We can nevertheless draw important conclusions about type (b) runs by examining all possible instruction sets. Suppose both particles were produced with instruction sets *RRG*. Then out of the six possible settings of type (b) only 12 and 21 will result in both detectors flashing the same color (red); 13, 31, 23, and 32 will all result in one red light and one green. Both detectors will therefore flash the same color for two of the six possible case (b) switch settings. Since the switch settings are completely random, the various case (b) settings occur with equal frequency. Thus both detectors will 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 these instruction sets, the detectors will flash the same color.

The only remaining instruction sets are *RRR* and *GGG;* for these, both detectors will obviously flash the same color in every case (b) run

Thus regardless of how the instruction sets are distributed among different runs, in the runs of type (b) both detectors must flash the same color at least a third of the time. (The same color will flash more than a third of the time unless the instruction sets *RRR* and *GGG* never occur.) As stated at the end of Sec. I, however, when the device actually op-

23GR	12GR	11GG	13GR	23RG	33GG	12RG	21GR
11RR	31RG	22GG	11GG	22GG	11RR	32RG	23RG
31RG	32GR	22RR	31RG	13RG	22GG	22RR	12GG
33RR	22RR	21GR	32RG	11GG	32GR	33GG	21GR
32GG	22GG	11RR	11GG	23GG	12RR	32GR	11GG
32RG	12RG	13RG	33GG	21RG	13GR	31RR	32GR
31GR	13GR	21RG	33RR	13GR	11RR	11GG	13RG
12GG	32GR	33GG	21GR	21GG	33RR	23RG	21GG
13GR	11GG	32GG	31GR	32RG	33RR	13RR	13RG
11GG	31RG	33RR	12RG	21GR	11GG	22GG	33GG
33RR	21GG	21RG	12RG	11GG	12RG	11GG	23GG
11GG	12RR	12RG	31GR	23GR	12GR	33GG	31GG
11RR	22RR	12RG	22GG	23GR	12GR	23RG	21RR
13GR	21RR	33RR	33RR	13RG	23RG	33GG	32RR
13RR	32RG	11RR	11RR	11RR	32RG	12RG	21RG
23RG	23RR	21RG	33RR	13GR	12GR	23RG	21RR
13RR	21GR	12RR	31GR	12RG	13GR	13RG	22RR
21RG	23GR	11RR	12RR	33RR	21RG	13GR	21RR
31GR	23GG	13RG	21RG	11GG	12GR	23GR	13GG
11RR	31RG	11GG	31GR	32GR	32RG	32GR	11GG

Fig. 4. Fragment of a page of a volume from the set of notebooks recording a long series of runs.

erates the same color is flashed only a quarter of the time when the switches have different settings.

The observed facts in case (b) are thus incompatible with our explanation of the observed facts in case (a), and we are left with the profound problem of how else to account for them. This is the conundrum posed by the device: there is no other obvious explanation for why the same colors always flash when the switches are set the same.

I shall not describe how contemporary physical theory accounts for the behavior of the device except to note that although, in its own way, the explanation is very simple, it is far from obvious and, some might argue, hardly an explanation at all. Instead, I only emphasize again that we live in a world in which such a device can be built; nature is stranger and more wonderful than we had once thought or could possible have imagined. Ponder the device a little more, if that seems too extreme a conclusion.

APPENDIX: INSIDE THE BLACK BOXES

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 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 of each particle yielding opposite values is $\cos^2(\frac{1}{2}\theta)$. This probability is unity when $\theta = 0$ [case (a)] and 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.

It is left as a challenging exercise to the physicist reader to translate the elementary quantum-mechanical reconciliation of cases (a) and (b) into terms meaningful to a general reader struggling with the dilemma raised by the device.

ACKNOWLEDGMENT

This work was supported in part by the National Science Foundation under Grant No. DMR-77-18329. It is a pleasure to thank E. M. Purcell for moral and intellectual support.

[1] A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev. **47**, 777 (1935).

[2] Attributed to O. Stern by W. Pauli in a letter to M. Born, *The Born Einstein Letters* (Walker, New York, 1971), p.223.

[3] J. S. Bell, Phys. **1**, 195 (1964)

[4] For a review see J. F. Clauser and A. Shimony, Rep. Prog. Phys. **41**, 1991 (1978).

[5] A nontechnical aproach, which partly inspired mine, has been given by B. D'Espagnat, Sci. Am. **241** (5), 158 (November 1979). I have bypassed such arcane notions as vectors or spin, and have used a specific geometry that makes the counting argument simple and explicit. I stress, however, that what I give is neither an analogy nor a simplification; it is the pure Einstein–Podolsky–Rosen conundrum.

[6] In one sense they are obviously right. Compare Tovey's remark that "the Waldstein Sonta has no more business than sunsets and sunrises to be paradoxical." [Donald Francis Tovey, *A Companion to Beethoven's Pianoforte Sonatas* (Associated Board of the Royal Schools of Music, London, 1931), p. 150].

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

HEAT CONDUCTION AS A DISSIPATIVE PROCESS

CONTEXT

Any nonequilibrium thermodynamics text[1] shows that heat conduction and mass diffusion are dissipative processes, but the demonstration is usually rather formal and unintuitive—the entropy source is given as a product of a chemical potential gradient and its conjugate flux. Physically, this seems only obscurely related to the heat and mechanics principles underlying thermodynamics. Here is a simple example of heat conduction converting mechanical energy into heat. The problem is suitable for homework or a take-home exam in a course involving heat conduction, diffusion, or nonequilibrium thermodynamics. It is given in two dimensions because it is then easily solved in closed form.

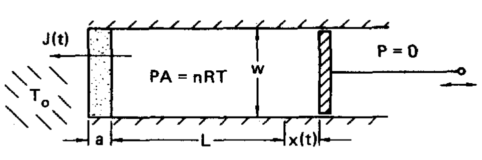

Fig. 1. Schematic diagram of the two-dimensional piston and cylinder.

PROBLEM

A two-dimensional "cylinder" and piston arrangement, shown in Fig. 1, contains n moles of two-dimensional ideal gas. Recall that such a gas has internal energy $E = nRT$ and that $PA = nRT$, where A is its area. The piston, which is frictionless, is made to undergo the oscillation $x(t) = \alpha L \times \sin\omega_0 t$, where $\alpha < 1$. The piston and side walls of the cylinder are insulating, but the end of the cylinder conducts heat into a bath at T_0 according to Fourier's law (thermal conductivity λ independent of T). Assume that the gas is always well mixed, so that its temperature is uniform, but ignore any associated viscous heating. Make the approximation (tantamount to neglecting the wall's heat capacity[2]) that the end wall temperature is linear.

(a) Solve for the steady-state gas temperature $T_s(t)$ (i.e., the oscillatory part remaining after the initial transients die out).

(b) Integrate the heat flux $J(t)$ over one cycle to obtain the average thermal power $\dot{Q}_{av}$ generated by this machine at steady state.

(c) Using the expression $\sigma = -T^{-2}\mathbf{J}\cdot\mathrm{grad}\,T$ for the entropy production source, explain the instantaneous entropy balance[1] for this system.

(Solution on page 949.)