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David Mermin is director of the Laboratory of Atomic and Solid State Physics at Cornell University. A solid-state theorist, he has recently come up with some quasithoughts about quasicrystals. He is known to PHYSICS TODAY readers as the person who made "boojum" an internationally accepted scientific term. With N. W. Ashcroft, he is about to start updating the world's funniest solid-state physics text. He says he *is* bothered by Bell's theorem, but may have rocks in his head anyway.

Is the moon there when nobody looks? Reality and the quantum theory

Einstein maintained that quantum metaphysics entails spooky actions at a distance; experiments have now shown that what bothered Einstein is not a debatable point but the observed behavior of the real world.

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

N. David Mermin

A. Pais, Rev. Mod. Phys. **51**, 863 (1979).

statistical. But the EPR paper, his most powerful attack on the quantum theory, focuses on quite a different aspect: the doctrine that physical properties have in general no objective reality independent of the act of observation. As Pascual Jordan put it[3]

> Observations not only disturb what has to be measured, they produce it. . . . We compel [the electron] to assume a definite position. . . . We ourselves produce the results of measurement.

Jordan's statement is something of a truism for contemporary physicists. Underlying it, we have all been taught, is the disruption of what is being measured by the act of measurement, made unavoidable by the existence of the quantum of action, which generally makes it impossible even in principle to construct probes that can yield the information classical intuition expects to be there.

Einstein didn't like this. He wanted things out there to have properties, whether or not they were measured[4]:

> 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.

The EPR paper describes a situation ingeniously contrived to force the quantum theory into asserting that properties in a space–time region **B** are the result of an act of measurement in another space–time region **A**, so far from **B** that there is no possibility of the measurement in **A** exerting an influence on region **B** by any known dynamical mechanism. Under these conditions, Einstein maintained that the properties in **A** must have existed all along.

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[3] Quoted by M. Jammer, *The Philosophy of Quantum Mechanics*, Wiley, New York (1974) p. 151.

The Born–Einstein Letters, with comments by M. Born, Walker, New York (1971).

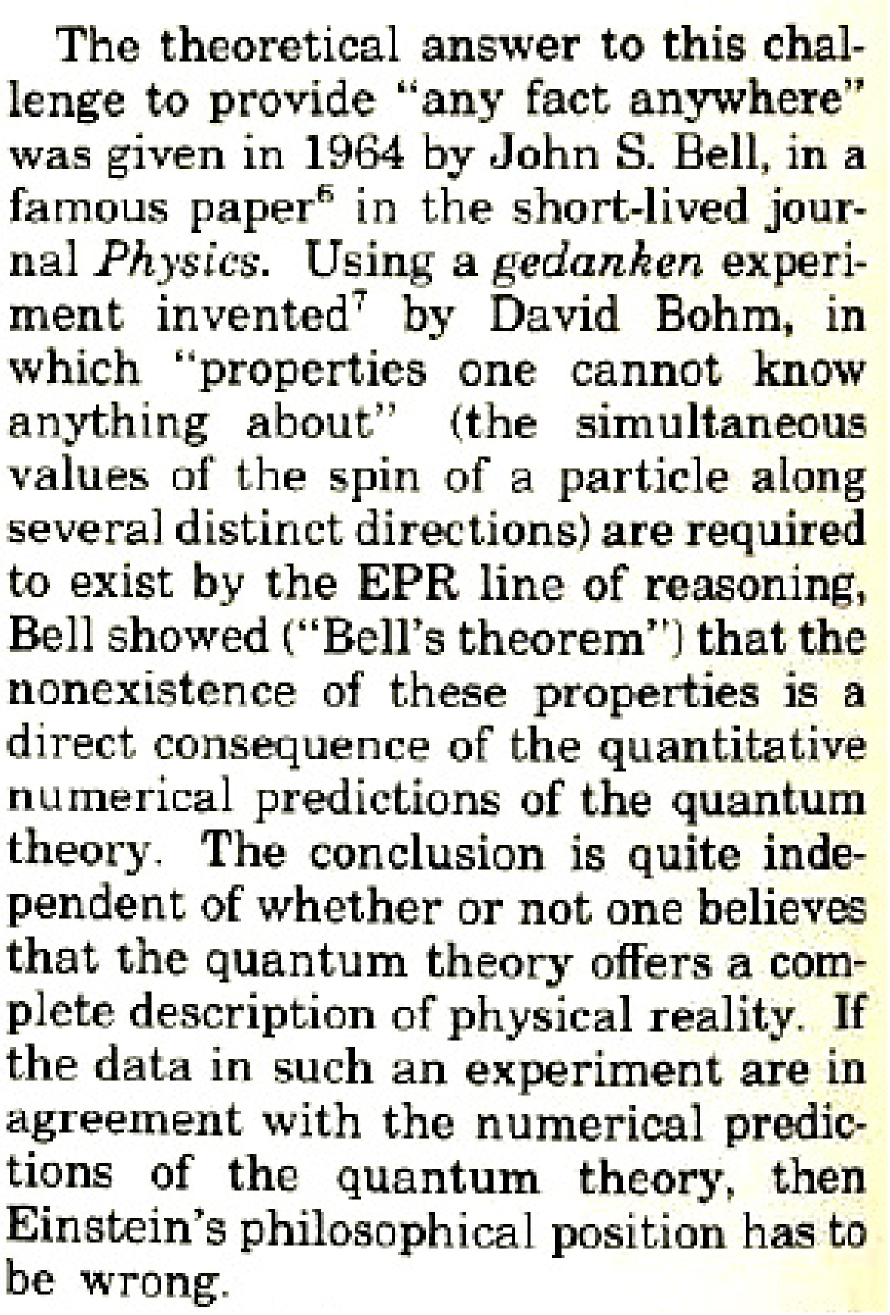
Or, in March 1947,

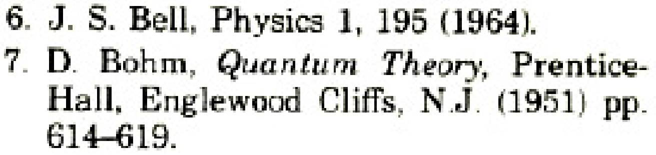
> I cannot seriously believe in [the quantum theory] because it cannot be reconciled with the idea that physics should represent a reality in time and space, free from spooky actions at a distance.

exist all the same. In April 1948 he wrote to Born:

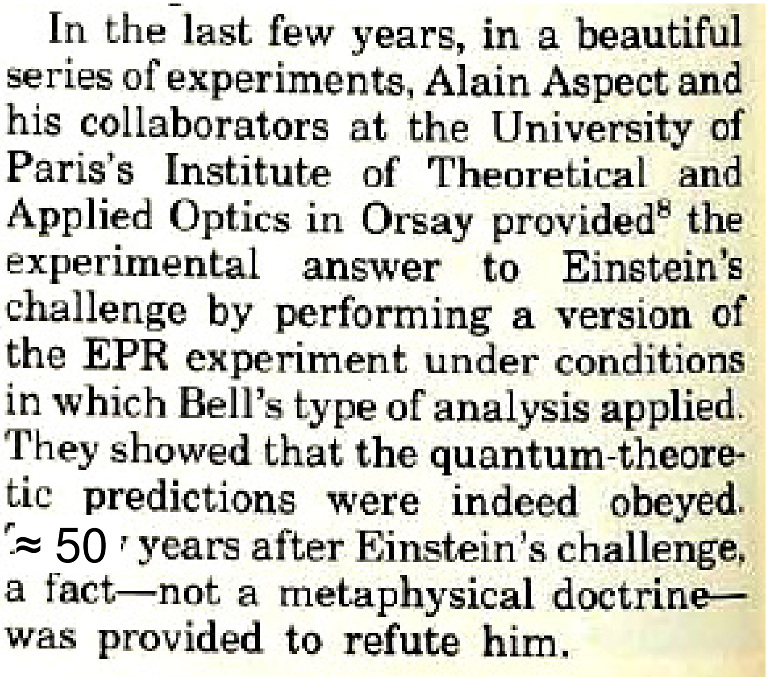
> Those physicists who regard the descriptive methods of quantum mechanics as definitive in principle would . . . drop the requirement for the independent existence of the physical reality present in different parts of space; they would

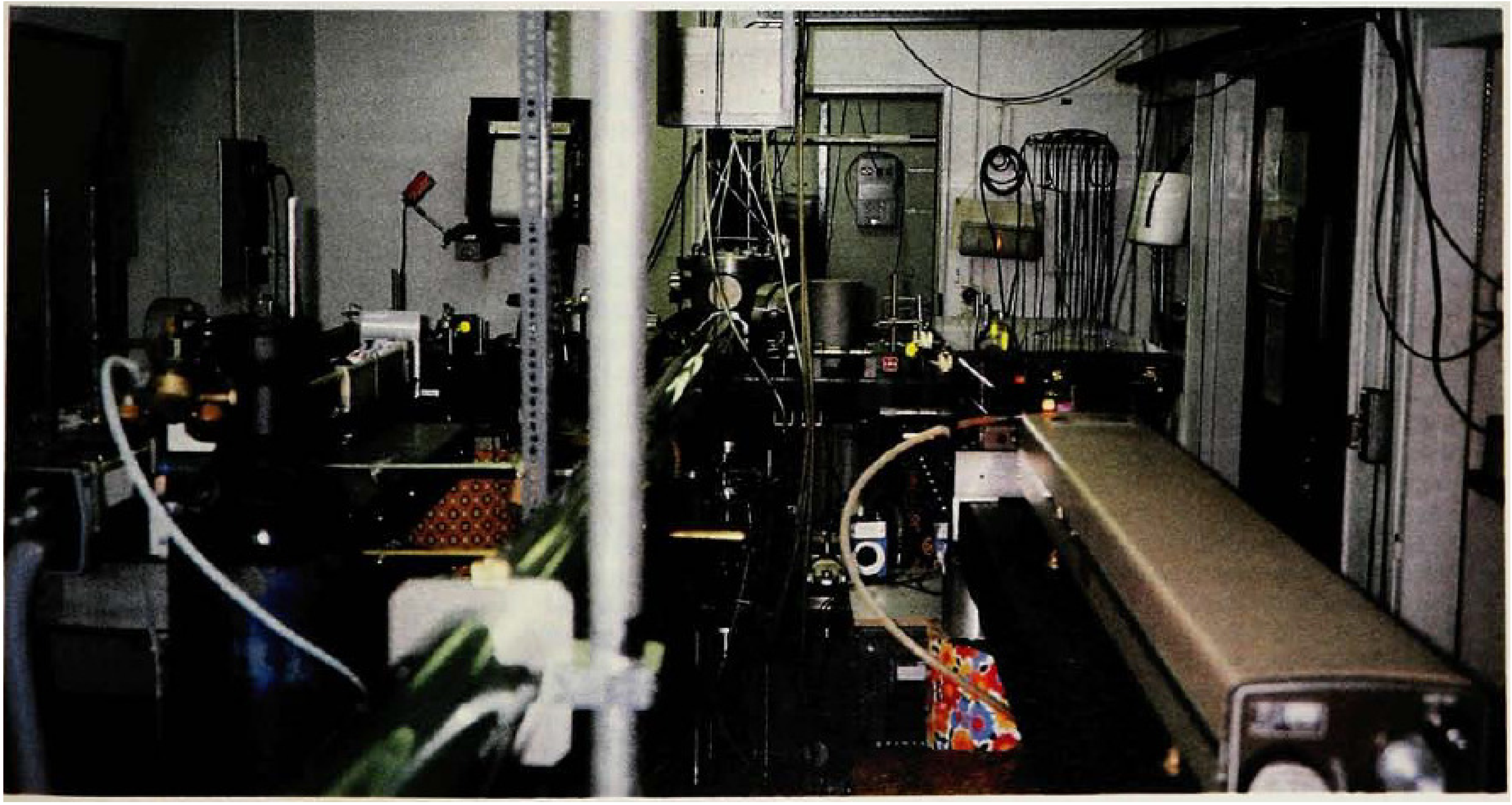
The "spooky actions at a distance" (*spukhafte Fernwirkungen*) are the acquisition of a definite value of a property by the system in region **B** by virtue of the measurement carried out in region **A**. The EPR paper presents a wavefunction that describes two correlated particles, localized in regions **A** and **B**, far apart. In this particular two-particle state one can learn (in the sense of being able to predict with certainty the result of a subsequent measurement) either the position or the momentum of the particle in region **B** as a result of measuring the corresponding property of the particle in region **A**. If "that which really exists" in region **B** does not depend on what kind of measurement is carried out in region **A**, then the particle in region **B** must have had both a definite position and a definite momentum all along.


The theoretical answer to this challenge to provide "any fact anywhere" was given in 1964 by John S. Bell, in a famous paper[6] in the short-lived journal *Physics*. Using a *gedanken* experiment invented[7] by David Bohm, in which "properties one cannot know anything about" (the simultaneous values of the spin of a particle along several distinct directions) are required to exist by the EPR line of reasoning, Bell showed ("Bell's theorem") that the nonexistence of these properties is a direct consequence of the quantitative numerical predictions of the quantum theory. The conclusion is quite independent of whether or not one believes that the quantum theory offers a complete description of physical reality. If the data in such an experiment are in agreement with the numerical predictions of the quantum theory, then Einstein's philosophical position has to be wrong.


6. J. S. Bell, Physics 1, 195 (1964).
7. D. Bohm, *Quantum Theory*, Prentice-Hall, Englewood Cliffs, N.J. (1951) pp. 614–619.

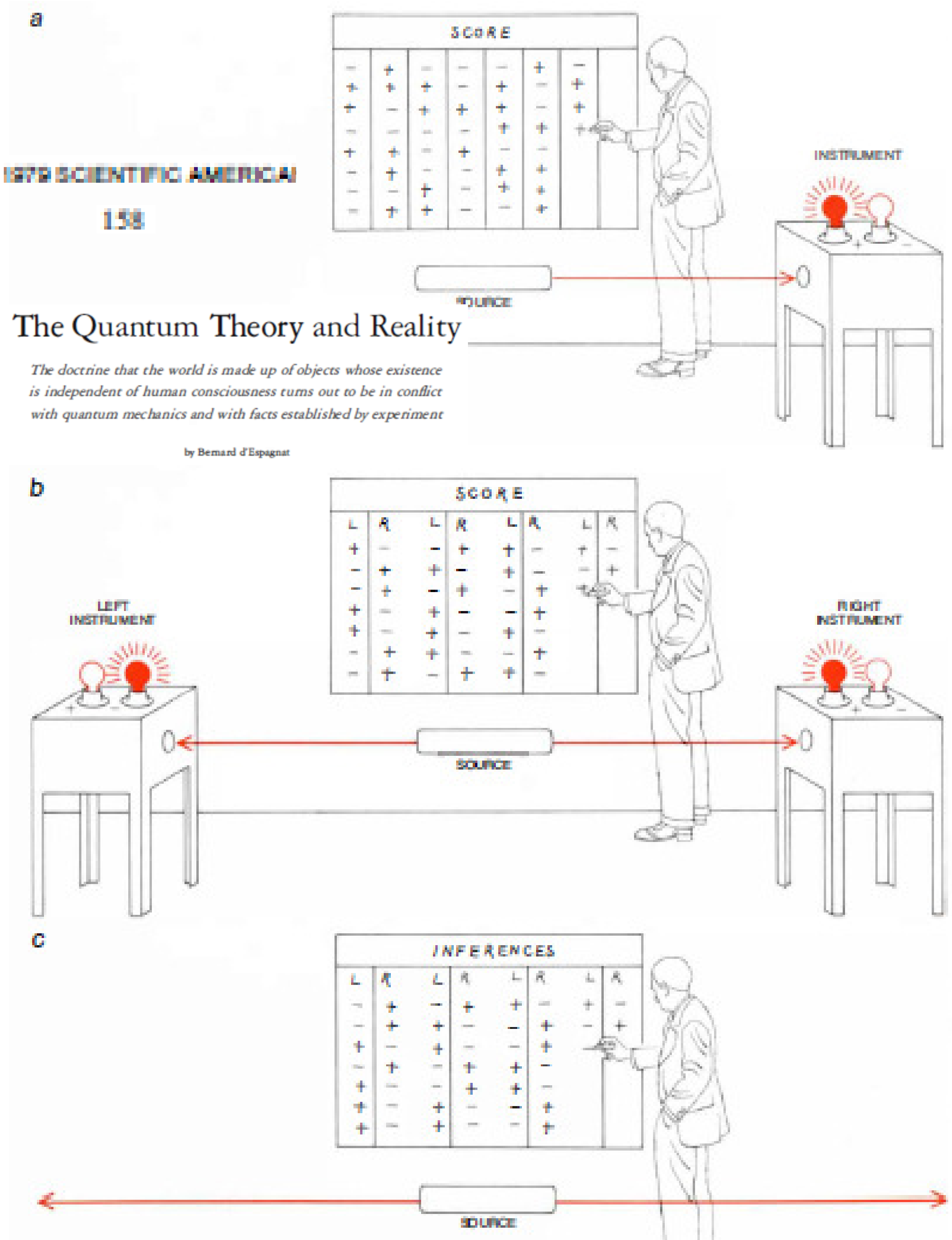
Early 1980s


In the last few years, in a beautiful series of experiments, Alain Aspect and his collaborators at the University of Paris's Institute of Theoretical and Applied Optics in Orsay provided[8] the experimental answer to Einstein's challenge by performing a version of the EPR experiment under conditions in which Bell's type of analysis applied. They showed that the quantum-theoretic predictions were indeed obeyed. ≈ 50 years after Einstein's challenge, a fact—not a metaphysical doctrine—was provided to refute him.



A. Aspect, J. Dalibard, and G. Roger, "Experimental test of Bell's inequalities using time-varying analyzers," Phys. Rev. Lett. **49**(25), 1804–1807 (1982).
A. Aspect, "Trois tests expérimentaux des inégalités de Bell par mesure de corrélation de polarisation de photons," Ph.D. thesis No. 2674, Université de Paris-Sud, Centre d'Orsay, France, 1983.

Two detectors more than 13 m apart, detector can be switched after particle has left source



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The Quantum Theory and Reality

The doctrine that the world is made up of objects whose existence is independent of human consciousness turns out to be in conflict with quantum mechanics and with facts established by experiment

by Bernard d'Espagnat

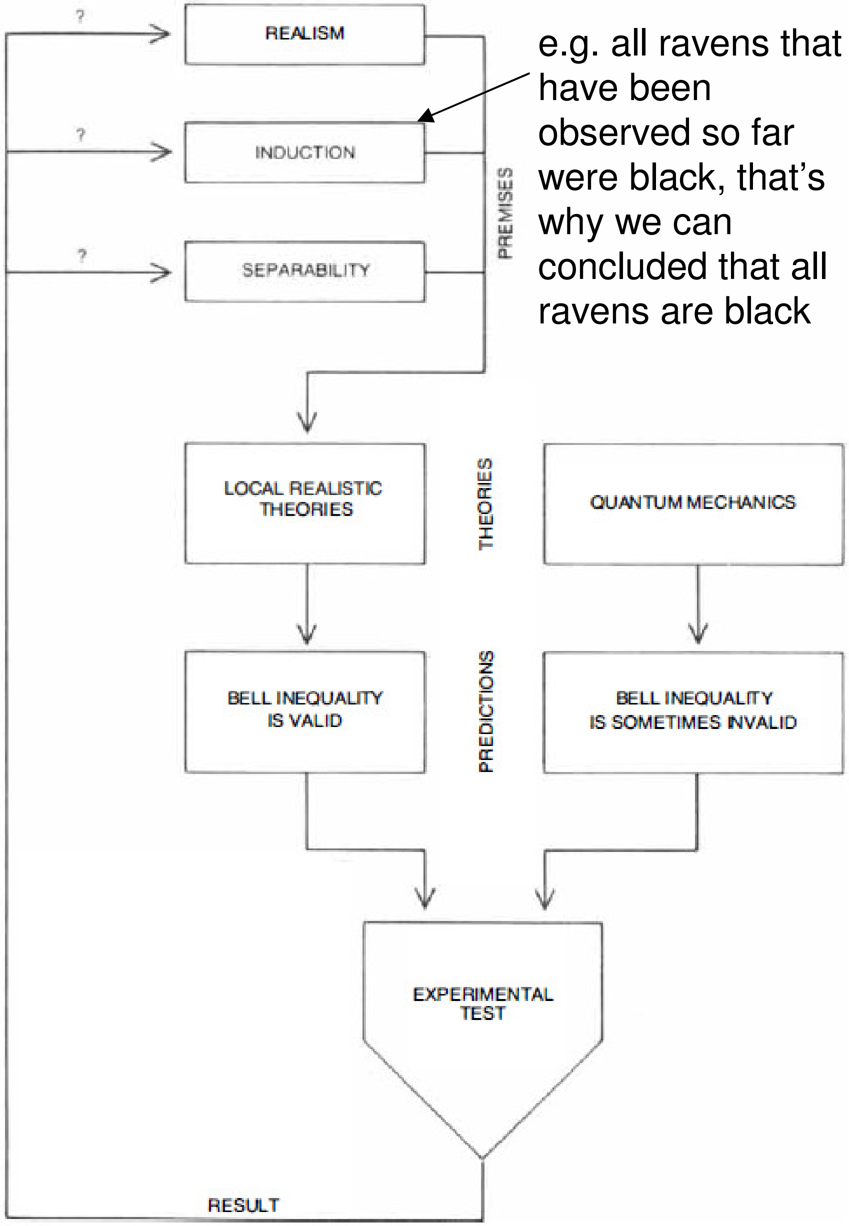
Putting the detectors very far apart makes sure there is no connection between the two of them

Complete randomness is observed if there is only one detector, half of the time the + bulb flashes, half of the time the – bulb flashes

If there are two identical detectors, each of them taken separately observed complete randomness as well, i.e. same number of + and - flashes

When one makes a correlation between the result sequences from both detectors, one observes that when there is a plus on one side there is always a minus on the other side, **perfect anti-correlation**

Change the + and – signs on one detector and you will observe perfect correlations, in the correlation setting/sign convention, replace the bulbs at + with a green bulb, then you will observe correlated green or red flash pairs, the + and – signs can then be removed



e.g. all ravens that have been observed so far were black, that's why we can concluded that all ravens are black

LOCAL REALISTIC THEORIES and quantum mechanics make conflicting predictions for certain experiments in which distant events are correlated. In particular, local realistic theories predict that a relation called the Bell inequality will be obeyed, whereas quantum mechanics predicts a violation of the inequality. There is strong experimental evidence that the inequality is violated in the way predicted by quantum mechanics. Local realistic theories therefore seem to be untenable, and at least one of the premises underlying those theories must be in error.

Observing perfect correlations of two distant detectors that have no connection between them can be explained simply by the assumption that the particle carries an instruction set that is identical to each of the identical appearing detectors,

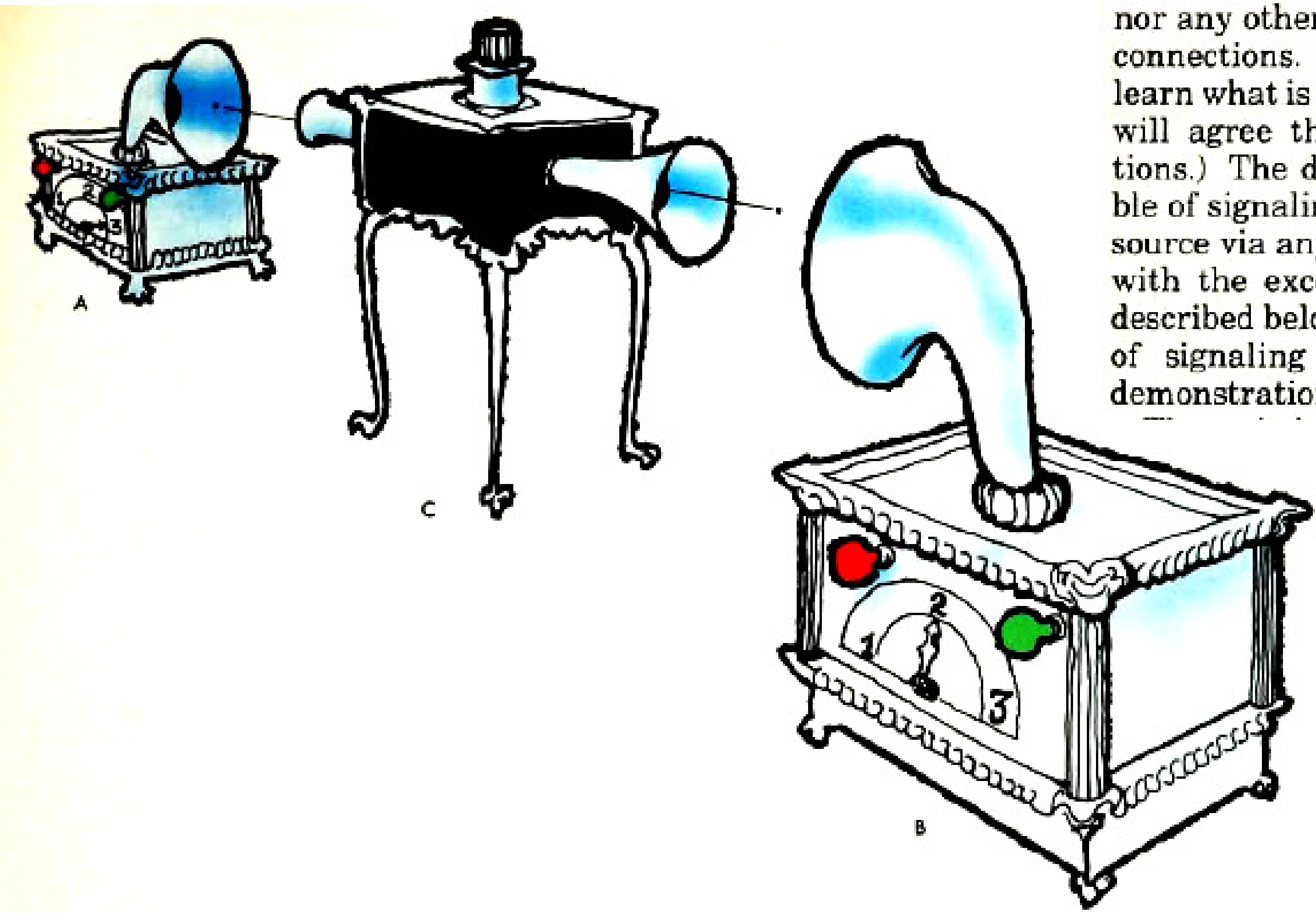
(or if anti-correlation is observed, the natural conclusion is that the instruction set must simply be opposite, it is still one set of instructions, a two value thing, only)

Now we need to have a more complicated detector with three different settings, 1, 2, 3, so there are the nine (3^2) different cases

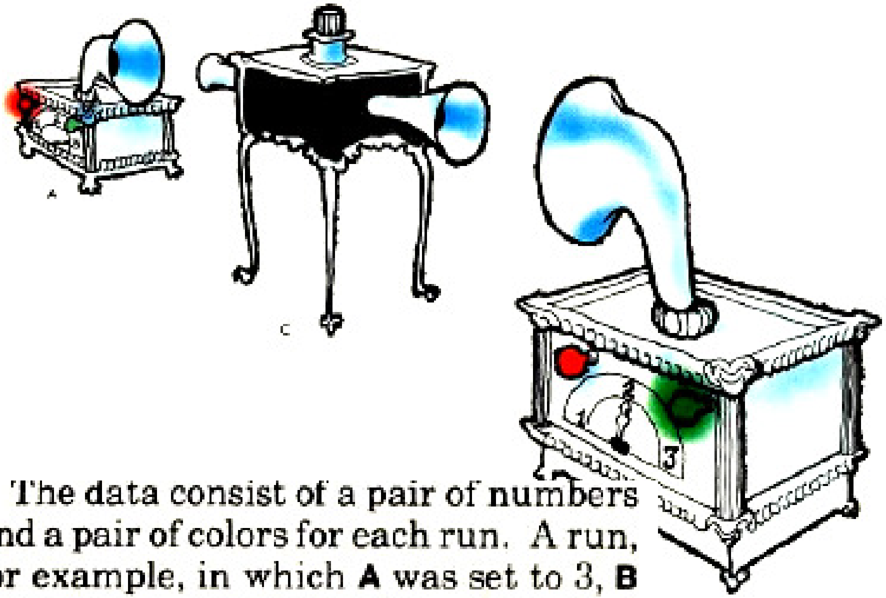
11, 22, 33, when we will observe perfect correlation,

12, 21, 13, 31, 23, 32 when we will observed correlation one quarter of the time

There are no connections between the pieces—no mechanical connections, no electromagnetic connections, nor any other known kinds of relevant connections. (I promise that when you learn what is inside the black boxes you will agree that there are no connections.) The detectors are thus incapable of signaling to each other or to the source via any known mechanism, and with the exception of the "particles" described below, the source has no way of signaling to the detectors. The demonstration proceeds as follows:



An EPR apparatus. The experimental setup consists of two detectors, **A** and **B**, and a source of something ("particles" or whatever) **C**. To start a run, the experimenter pushes the button on **C**; something passes from **C** to both detectors. Shortly after the button is pushed each detector flashes one of its lights. Putting a brick between the source and one of the detectors prevents that detector from flashing, and moving the detectors farther away from the source increases the delay between when the button is pushed and when the lights flash. The switch settings on the detectors vary randomly from one run to another. Note that there are no connections between the three parts of the apparatus, other than via whatever it is that passes from **C** to **A** and **B**. The photo below shows a realization of such an experiment in the laboratory of Alain Aspect in Orsay, France. In the center of the lab is a vacuum chamber where individual calcium atoms are excited by the two lasers visible in the picture. The re-emitted photons travel 6 meters through the pipes to be detected by a two-channel polarizer. Figure 1



The result of a run. Shortly after the experimenter pushed the button on the source in figure 1, the detectors flash one lamp each. The experimenter records the switch settings and the colors of the lamps and then repeats the experiment. Here, for example, the record reads 32RG—the switches are in positions 3 and 2 and the lamps flashed R and G, respectively. Figure 2

The data consist of a pair of numbers and a pair of colors for each run. A run, for example, in which **A** was set to 3, **B** was set to 2, **A** flashed red, and **B** flashed green, would be recorded as "32RG," as shown in figure 2.

Typical data from a large number of runs are shown in figure 3. There are just two relevant features:

- ▶ If one examines only those runs in which the switches have the same setting (figure 4), then one finds that the lights always flash the same colors.
- ▶ If one examines all runs, without any regard to how the switches are set (figure 5), then one finds that the pattern of flashing is completely random. In particular, half the time the lights flash the same colors, and half the time different colors.

That is all there is to the *gedanken* demonstration.

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

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

11
21
21
2
3
3
3
3
2
21
1
3
3
3
31
1
1
3
31

GR
RR

23RR
33RR

33RR
11RR

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

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

Data produced by the apparatus of figure 1. This is a fragment of an enormous set of data generated by many, many runs: Each entry shows the switch settings and the colors of the lights that flashed for a run. The switch settings are changed randomly from run to run. Figure 3

Switches set the same: the data of figure 3, but highlighted to pick out those runs in which both detectors had the same switch settings as they flashed. Note that in such runs the lights always flash the same colors. Figure 4

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

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

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

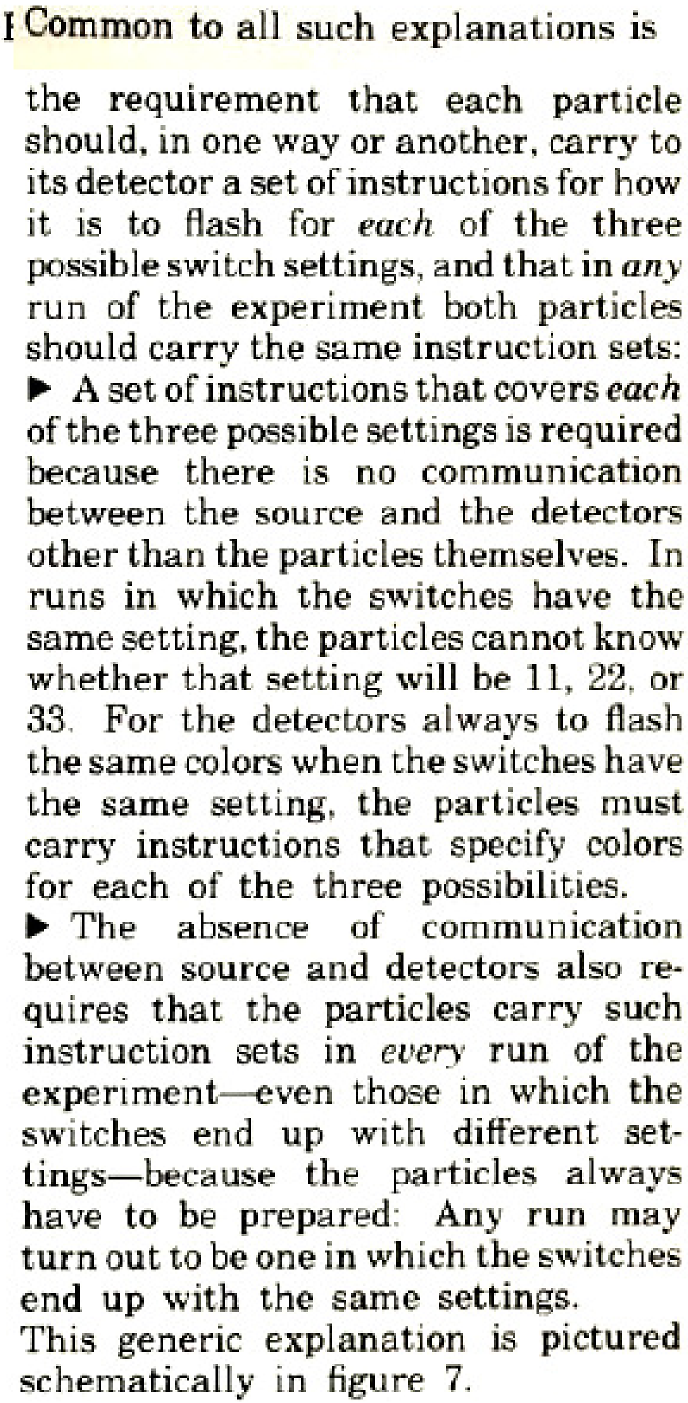
More facts

Each of the four lights flashes just about half of the time green and half of the time red given a long enough run to be statistically sound. The difference between the number of red or green flashes diminishes as the number of test runs increases.

It is not possible to transmit any kind of information from one detector to the other, even if one tried, the separated observer on the other end will always observe about as many red flashes at green flashes

it is only after the experiment has been made and the observations are compared that the remarkable correlations are revealed !!!

by relativity, the question which detector detected his particle first is meaningless as simultaneity in 4 dimensional space time means an event is only simultaneous if it is observed at the same 3D space and 3+1D time. Hence there will always be an observer standing closer to detector A who observes A going off before detector B which is much further away from him. He cannot argue about this with an observer that stands much closer to detector B, who just observes the opposite. By special relativity, both are correct.



Common to all such explanations is the requirement that each particle should, in one way or another, carry to its detector a set of instructions for how it is to flash for *each* of the three possible switch settings, and that in *any* run of the experiment both particles should carry the same instruction sets:

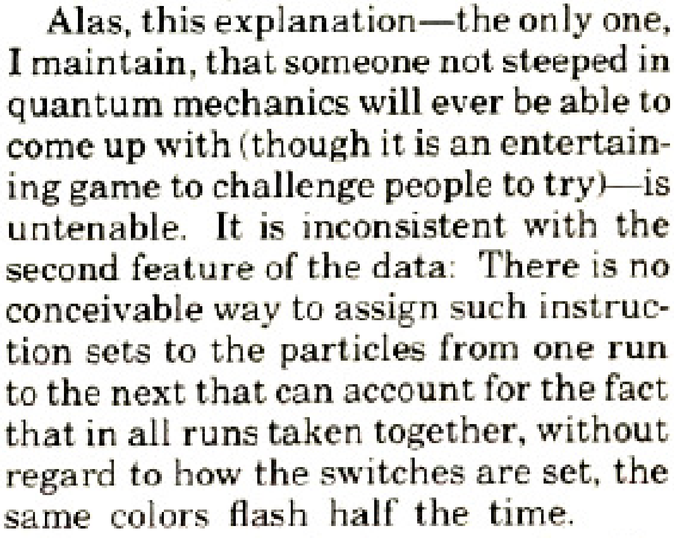
▶ A set of instructions that covers *each* of the three possible settings is required because there is no communication between the source and the detectors other than the particles themselves. In runs in which the switches have the same setting, the particles cannot know whether that setting will be 11, 22, or 33. For the detectors always to flash the same colors when the switches have the same setting, the particles must carry instructions that specify colors for each of the three possibilities.

▶ The absence of communication between source and detectors also requires that the particles carry such instruction sets in *every* run of the experiment—even those in which the switches end up with different settings—because the particles always have to be prepared: Any run may turn out to be one in which the switches end up with the same settings.

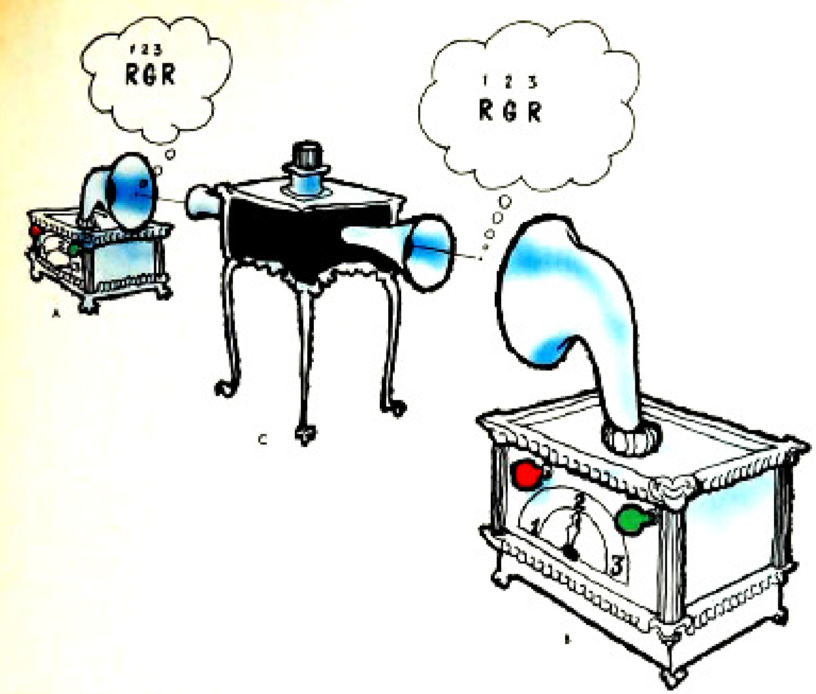
This generic explanation is pictured schematically in figure 7.

Just eight (2^3) instruction sets would do,

RRR, GGG, i.e. two where there is the same color for the three identical switch settings 11, 22, and 33, ..



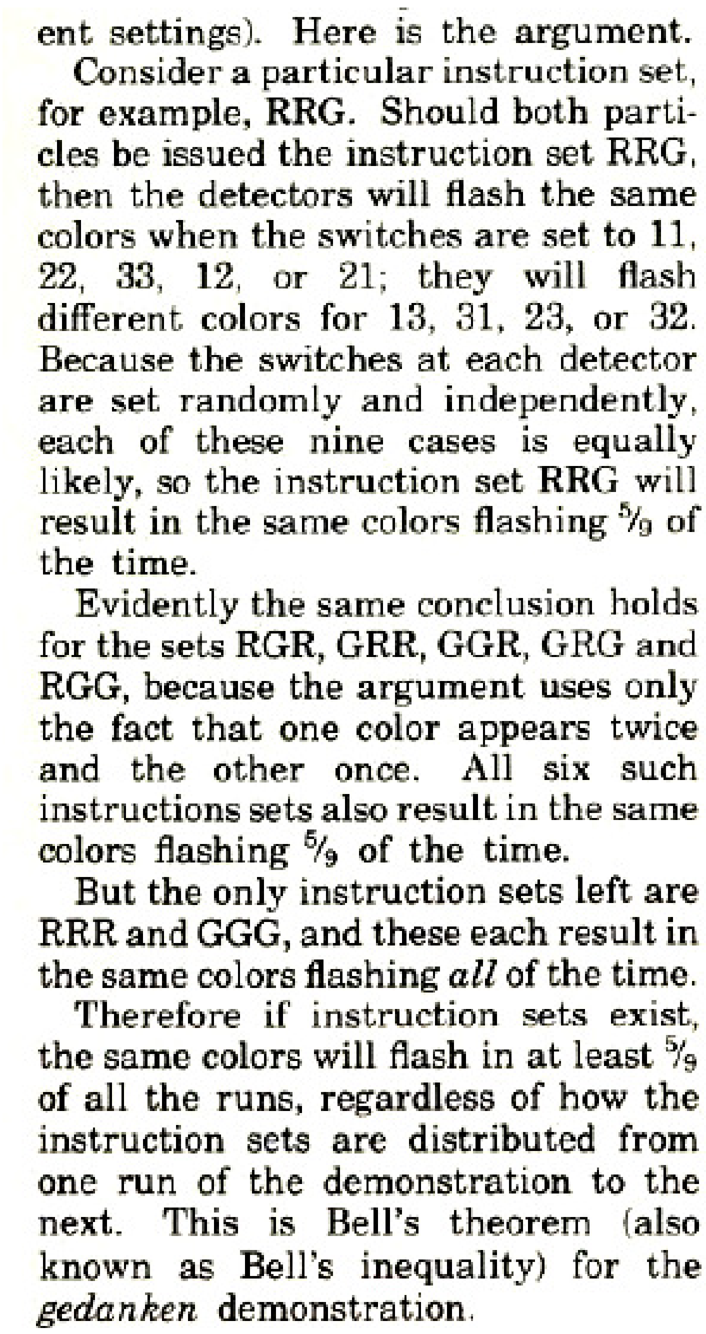
Alas, this explanation—the only one, I maintain, that someone not steeped in quantum mechanics will ever be able to come up with (though it is an entertaining game to challenge people to try)—is untenable. It is inconsistent with the second feature of the data: There is no conceivable way to assign such instruction sets to the particles from one run to the next that can account for the fact that in all runs taken together, without regard to how the switches are set, the same colors flash half the time.



Instruction sets. To guarantee that the detectors of figure 6 flash the same color when the switches are set the same, the two particles must in one way or another carry instruction sets specifying how their detectors are to flash for each possible switch setting. The results of any one run reveal nothing about the instructions beyond the actual data; so in this case, for example, the first instruction (1R) is "something one cannot know anything about," and I've only guessed at it, assuming that "it exists all the same." Figure 7

and six mixed instruction sets for the other six mixed switch settings:

RRG, RGR, GRR, GGR, GRG, and RGG for the



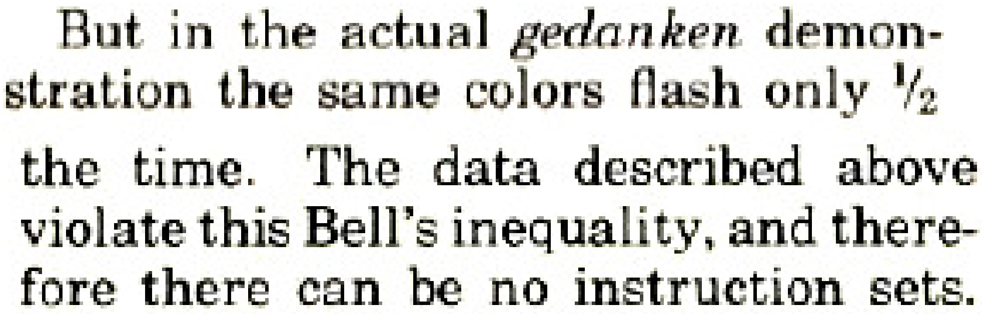
ent settings). Here is the argument.

Consider a particular instruction set, for example, RRG. Should both particles be issued the instruction set RRG, then the detectors will flash the same colors when the switches are set to 11, 22, 33, 12, or 21; they will flash different colors for 13, 31, 23, or 32. Because the switches at each detector are set randomly and independently, each of these nine cases is equally likely, so the instruction set RRG will result in the same colors flashing $^5/_9$ of the time.

Evidently the same conclusion holds for the sets RGR, GRR, GGR, GRG and RGG, because the argument uses only the fact that one color appears twice and the other once. All six such instructions sets also result in the same colors flashing $^5/_9$ of the time.

But the only instruction sets left are RRR and GGG, and these each result in the same colors flashing *all* of the time.

Therefore if instruction sets exist, the same colors will flash in at least $^5/_9$ of all the runs, regardless of how the instruction sets are distributed from one run of the demonstration to the next. This is Bell's theorem (also known as Bell's inequality) for the *gedanken* demonstration.



But in the actual *gedanken* demonstration the same colors flash only $^1/_2$ the time. The data described above violate this Bell's inequality, and therefore there can be no instruction sets.

Note that the particles must carry three instruction sets, e.g. RRG, i.e. possess three kinds of properties, e.g. two different colors, small or big sizes, tetrahedral or cubic shapes

Only two of these properties get ever measured, i.e. must really exist, while the third is never measured, may as well not exist!!! Actually it is one of the hidden variables that EPR required, but the experiment shows that the prediction on the assumption that there are three properties, including a hidden variable that is never measured, are not borne out in experiments !!!

Quantum mechanics has no problem to predict the experimental outcome, one just has to accept that [Sx,Sz] ǂ [Sz,Sx], i.e. do not commute just like momentum and position, in a sense, spin does not exist before it is measured

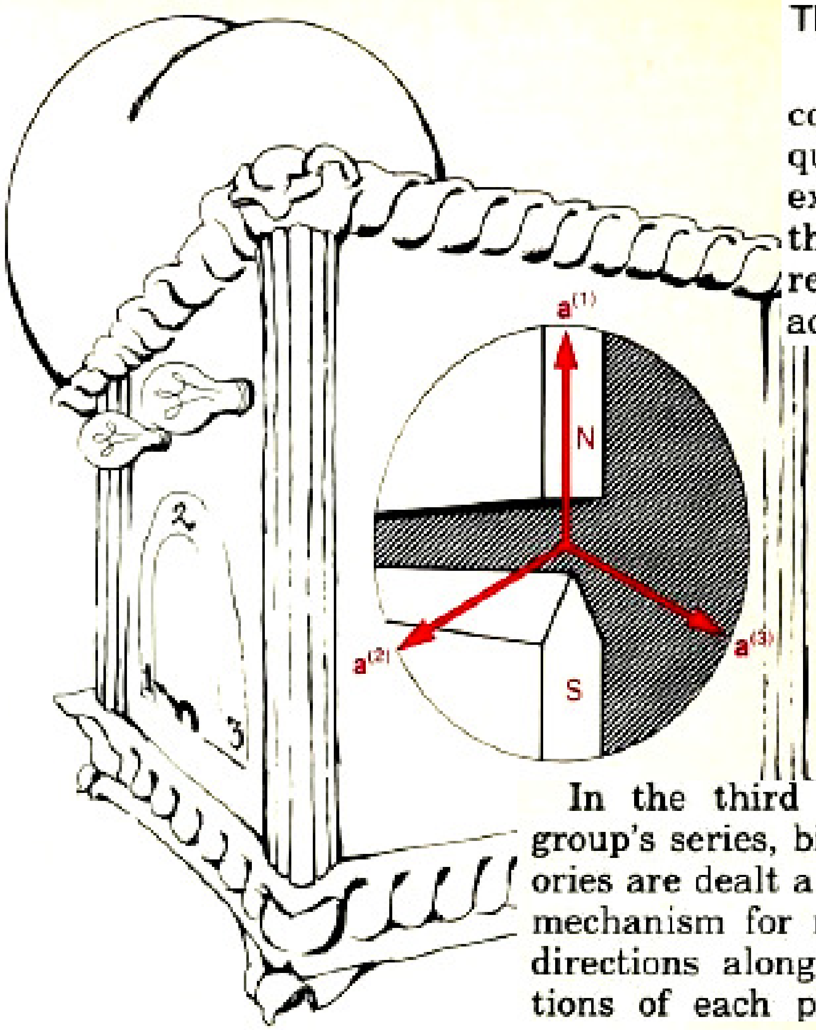
The experiments

The experiments of Aspect and his colleagues at Orsay confirm that the quantum-theoretic predictions for this experiment are in fact realized, and that the conditions for observing the results of the experiment can in fact be achieved. (A distinguished colleague

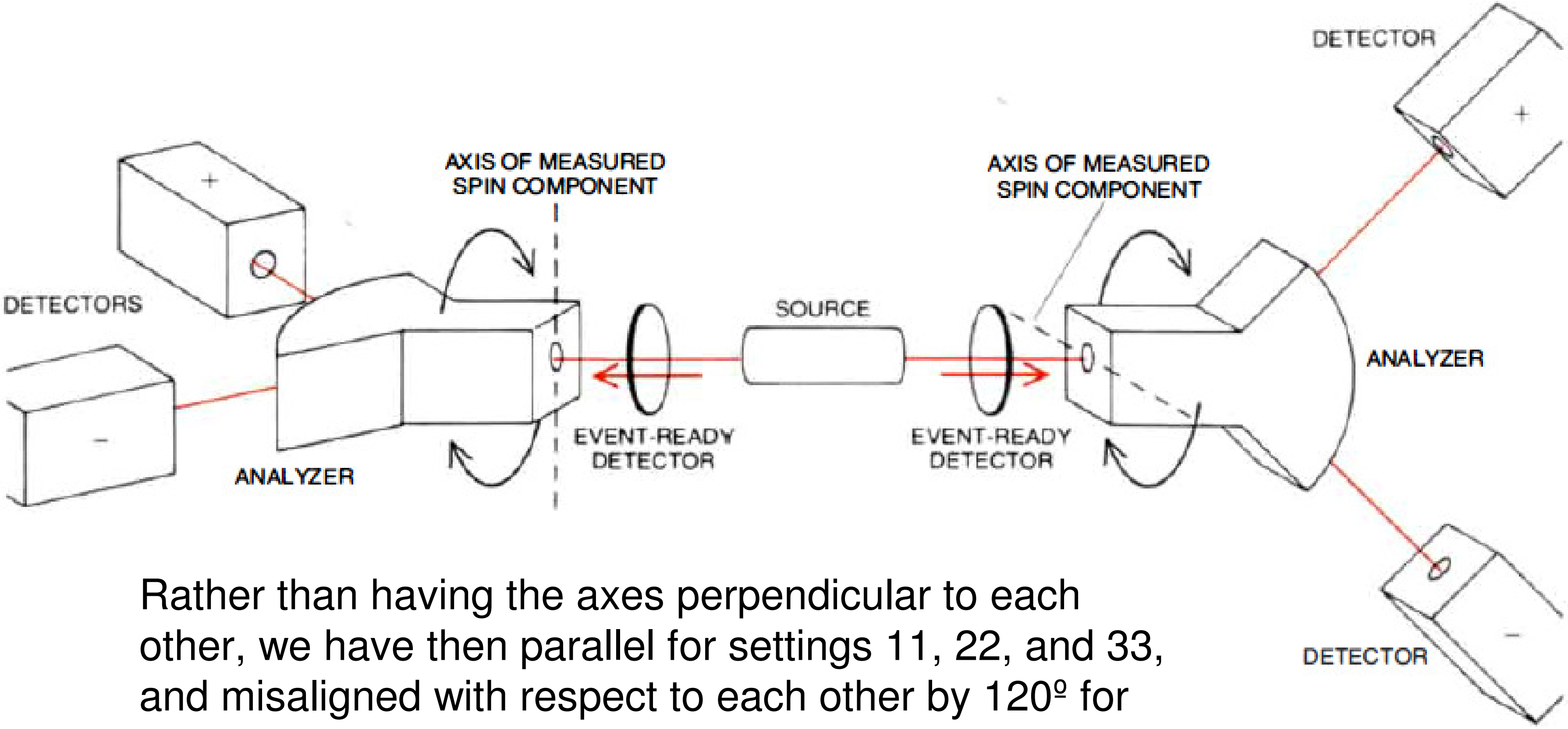
In these experiments the two spin-$\frac{1}{2}$ particles are replaced by a pair of photons and the spin measurements become polarization measurements.

The photon pairs are emitted by calcium atoms in a radiative cascade after suitable pumping by lasers. Because the initial and final atomic states have $J = 0$, quantum theory predicts (and experiment confirms) that the photons will be found to have the same polarizations (lights flashing the same colors in the analogous *gedanken* experiment) if they are measured along the same direction—feature number 1. But if the polarizations are measured at 120° angles, then theory predicts (and experiment confirms) that they will be the same only a quarter of the time $[\frac{1}{4} = \cos^2(120°)]$. This is precisely what is needed to produce the statistics of feature number 2 of the *gedanken* demonstration: The randomly set switches end up with the same setting (same polarizations measured) $\frac{1}{3}$ of the time, so in all runs the same colors will flash $\frac{1}{3} \times 1 + \frac{2}{3} \times (\frac{1}{4}) = \frac{1}{2}$ the time.

In the third paper of the Orsay group's series, bizarre conspiracy theories are dealt a blow by an ingenious mechanism for rapidly switching the directions along which the polarizations of each photon are measured.

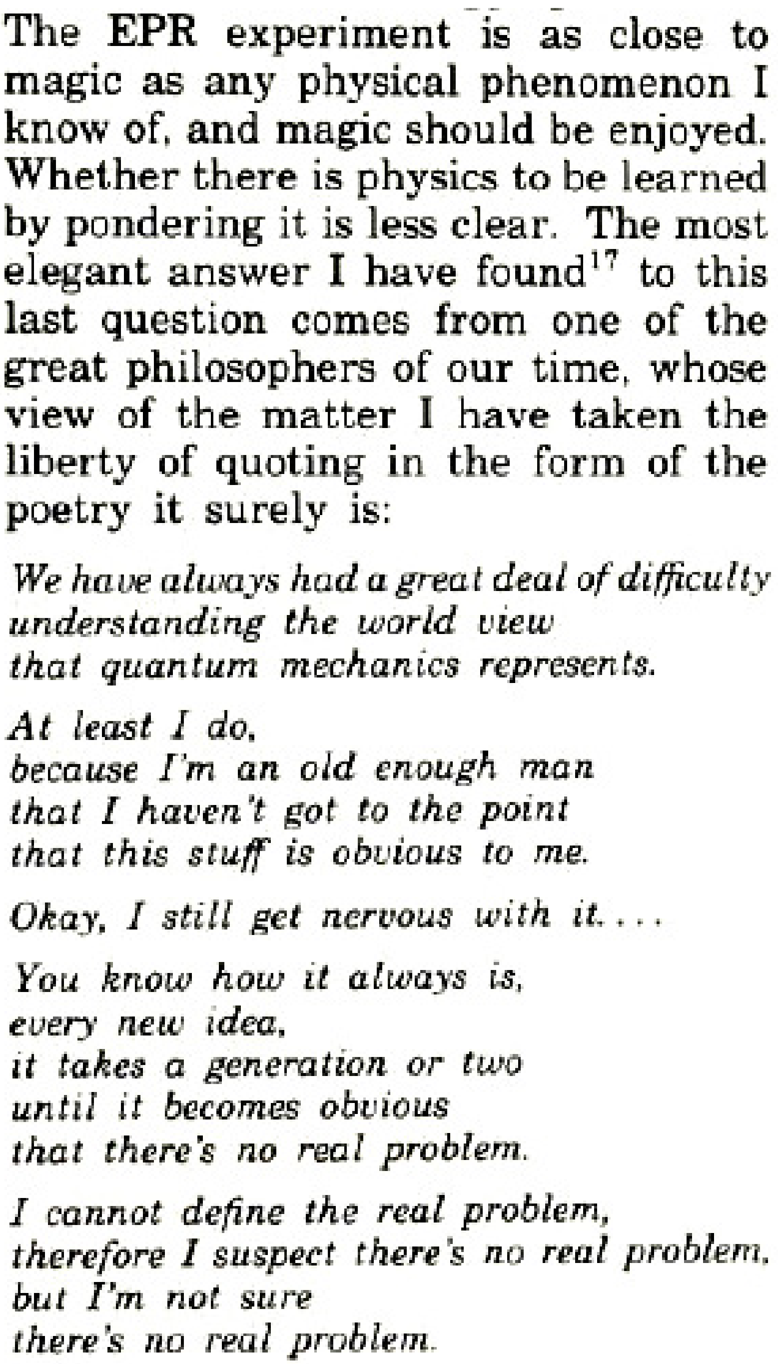


A realization of the detector to produce the data of figure 3. The particles have a magnetic moment and can be separated into "spin up" and "spin down" particles by the Stern–Gerlach magnet inside the detector. Setting the switch to positions 1, 2, or 3 rotates the north pole of the magnet along the coplanar unit vectors $a^{(1)}$, $a^{(2)}$, or $a^{(3)}$, separated by 120°. The vector sum of the three unit vectors is, of course, zero. The switch positions on the two detectors correspond to the same orientations of the magnetic field. One detector flashes red for spin up, green for spin down; the other uses the opposite color convention. Figure 8



Rather than having the axes perpendicular to each other, we have then parallel for settings 11, 22, and 33, and misaligned with respect to each other by 120º for settings 12, 21, 13, 31, 23, and 32

http://phet.colorado.edu/sims/stern-gerlach/stern-gerlach_en.html


The EPR experiment is as close to magic as any physical phenomenon I know of, and magic should be enjoyed. Whether there is physics to be learned by pondering it is less clear. The most elegant answer I have found[17] to this last question comes from one of the great philosophers of our time, whose view of the matter I have taken the liberty of quoting in the form of the poetry it surely is:

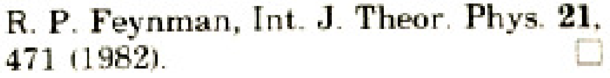
We have always had a great deal of difficulty
understanding the world view
that quantum mechanics represents.

At least I do,
because I'm an old enough man
that I haven't got to the point
that this stuff is obvious to me.

Okay, I still get nervous with it. . . .

You know how it always is,
every new idea,
it takes a generation or two
until it becomes obvious
that there's no real problem.

I cannot define the real problem,
therefore I suspect there's no real problem,
but I'm not sure
there's no real problem.


R. P. Feynman, Int. J. Theor. Phys. **21**, 471 (1982).

"There are more things in heaven and earth, Horatio,
than are dreamt of in your philosophy."

William Shakespeare