BELL AND NONLOCALITY

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Quantum Theory Without Observers III

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THE CLASSICAL OR EPISTEMIC VIEW OF PROBABILITIES:

Laws are deterministic

$\Rightarrow$ probabilities are ONLY due to our ignorance.

The curve described by a single molecule in air or vapor is regulated in a manner just as certain as the planetary orbits; the only difference between them is that which comes from our ignorance. Probability is relative, in part to this ignorance, in part to our knowledge. ...

P.S. LAPLACE

WHAT ABOUT QUANTUM MECHANICS?

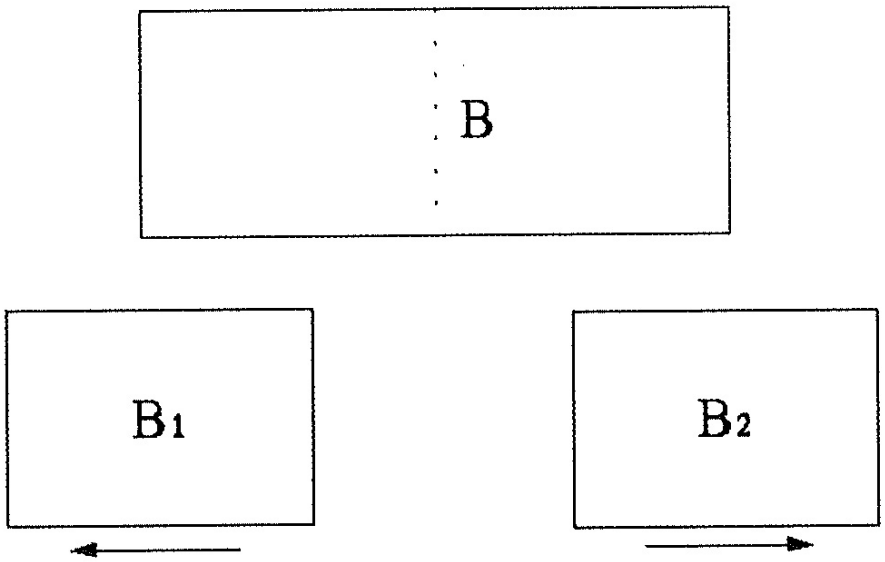
$|\Psi|^2$ = probabilistic interpretation

But is it only ignorance ?

If so, why does it evolve according to a physical law ?

What about the reduction or collapse of Ψ during a measurement?

Einstein's boxes



A single particle is in Box B. One cuts the box in two half-boxes,

$$| \text{ state} > = | \ B >$$

The state becomes

$$\longrightarrow \frac{1}{\sqrt{2}}(|B_1> + |B_2>)$$

where $|B_i> =$ particle "is" in box B_i, $i = 1, 2$.

The two half-boxes B_1 and B_2 are then separated and sent as far apart as one wants.

If one opens one of the boxes (say B_1) and that one does *not* find the particle, one *knows* that it is in B_2. Therefore, the state "collapses" instantaneously and in a non local way.

One opens box $B_1 \longrightarrow$ nothing

This is a "measurement", therefore state $\longrightarrow |B_2>$

(and, if one opens the box B_2, one will find the particle !).

Is the reduction or collapse of the

$|$ state $>$ a real (= physical) operation

or does it represent only our knowledge (= epistemic), as in the classical view ?

If physical $\longrightarrow$ A non local form of causality exists

If epistemic $\longrightarrow$ QM "incomplete" : there exists other variables than the quantum state that describe the system.

These variables would tell in which half-box the particle **IS** *before one opens either of them.*

Let us put aside the issue of completeness and *prove* non locality

What is non locality ?

Non local causality (causality NOT mere correlation)

Properties

1. Instantaneous
2. a. Extends arbitrarily far

   b. The effect does not decrease with the distance
3. Individuated
4. Can be used to transmit messages

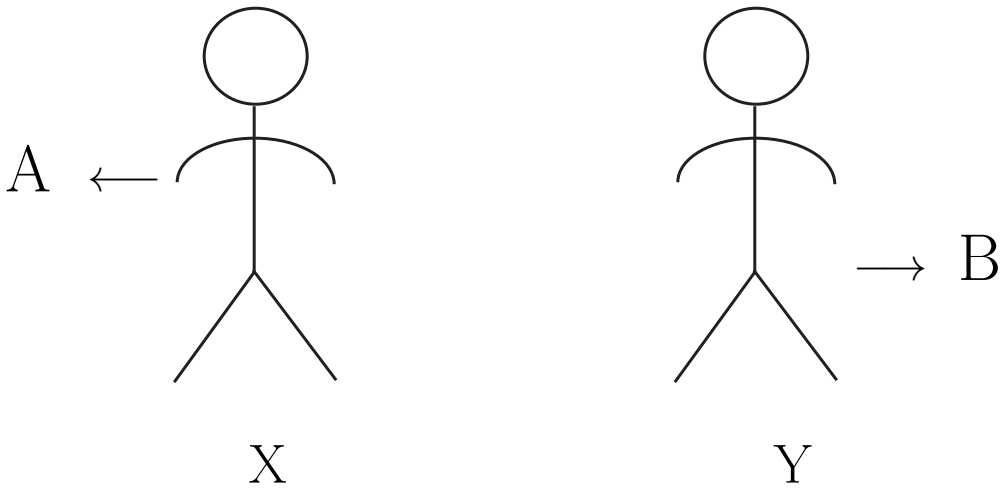
Newton's gravity : 1, 2a and 4

Post-Newtonian physics (e.g. field theories) : 2a and 4

Is there a phenomenon with properties : 1-3 ?

(Not 4 $\rightarrow$ pseudoscience).

HOW TO PROVE NON LOCALITY ,



3 questions 1,2,3

2 answers yes/no

Questions and answers vary. But when the same question is asked at A and B, one always gets the same answer.

Only one possibility : either the answers are predetermined *or* there exists a form of causality at a distance *after* one asks the questions.

This is the Einstein Podolsky and Rosen (EPR-1935) argument (in Bohm's formulation).

BUT

This assumption

(alone)

leads to a contradiction with observations made when the questions are different.

Bell (1964)

PROOF

3 Questions 1 2 3

2 Answers Yes/No

If the answers are given in advance, there exists $2^3 = 8$ possibilities :

1	2	3
Y	Y	Y
Y	Y	N
Y	N	Y
Y	N	N
N	Y	Y
N	Y	N
N	N	Y
N	N	N

In *each case* there are at least *two questions* with the same answer.

Therefore,

$$\begin{aligned}
&\text{Frequency (answer to 1 = answer to 2)} \\
&+ \text{Frequency (answer to 2 = answer to 3)} \\
&+ \text{Frequency (answer to 3 = answer to 1)} \geq 1
\end{aligned}$$

BUT,

in some experiments,

$$\begin{aligned}
&\text{Frequency (answer to 1 = answer to 2)} \\
&= \text{Frequency (answer to 2 = answer to 3)} \\
&= \text{Frequency (answer to 3 = answer to 1)} \\
&= \frac{1}{4}
\end{aligned}$$

$$\Rightarrow \frac{3}{4} \geq 1$$

FALSE !

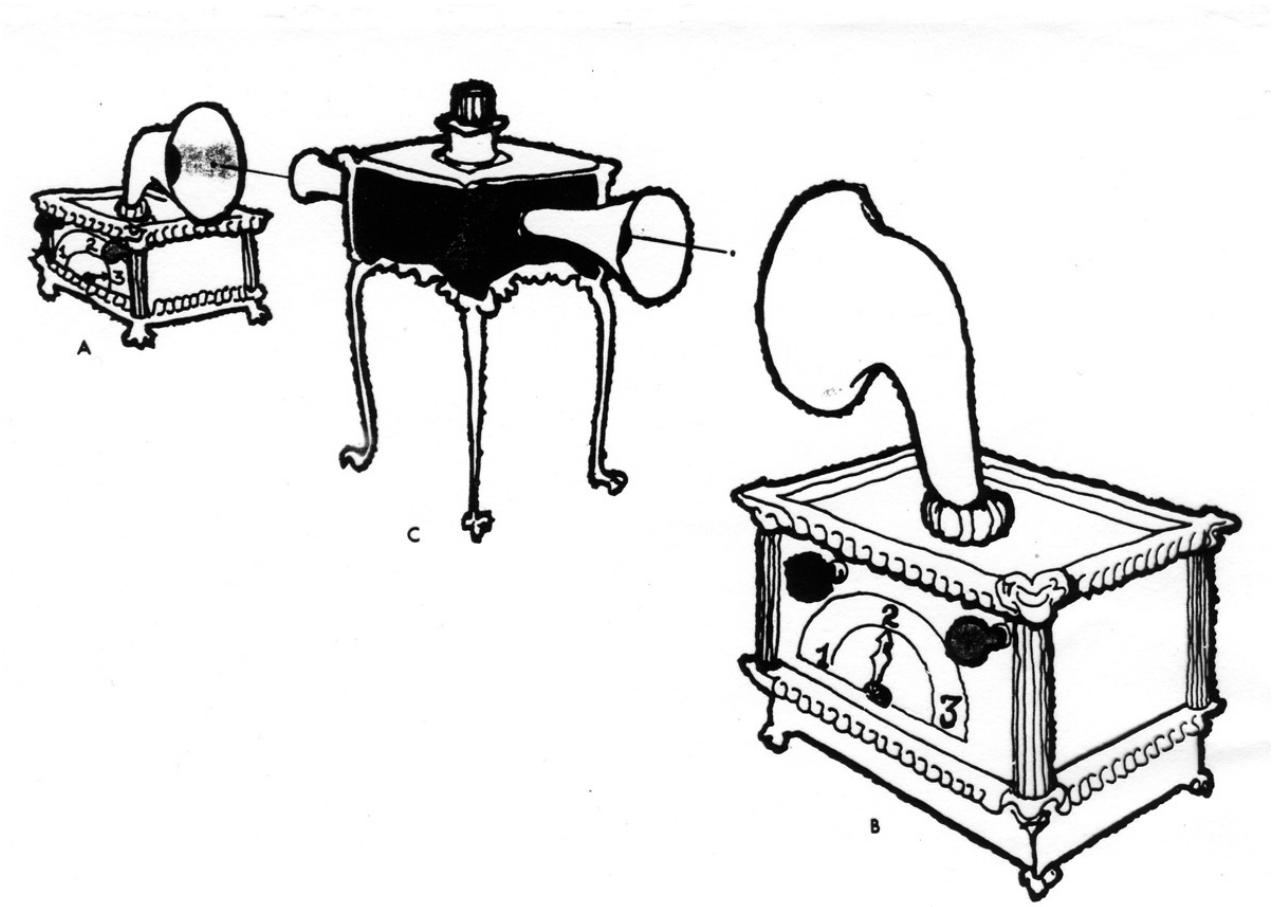
$\Rightarrow$ CONTRADICTION

That's all. That's the difficulty. That's why quantum mechanics can't seem to be imitable by a local classical computer.

I've entertained myself always by squeezing the difficulty of quantum mechanics into a smaller and smaller place, so as to get more and more worried about this particular item. It seems to be almost ridiculous that you can squeeze it to a numerical question that one thing is bigger than another.

R. FEYNMAN, in "Simulating physics with computers" (1982)

EXPERIMENTS



1, 2, 3 =

QUESTIONS

(left/right)

Red

Green

≈ 2 ANSWERS

(Yes/No)

31RR	2200	3300
3300	11RR	21GR
33RR	3300	13GR
12GR	31GR	2300
3300	12GG	22RR
21GR	21GR	11RR
21RR	3300	21GR
22RR	21RR	21RR
3300	12GR	2300
1100	22RR	32GR
23RR	13RG	33RR
32GR	12RG	33GG
12GR	23GG	33GG
12RG	1100	23GR
1100	13RG	21GR
31RG	21RG	12RR
12RG	33RR	32GR
13GR	32GR	32GR
2200	32GG	3300
12RG	3300	31RG
12GR	21RR	13RR
2200	12RG	13RG
23GR	2200	32RG
33RR	1100	31GR
3300	23GR	23RR
31RG	22RR	33RR
31RR	1100	13GR
33RR	32GR	1100
32RG	13RG	31GR
31RG	13GR	31RG
11RR	2300	13GR
23GR	33RR	23RG
12GG	31GR	3100
1100	13RG	23RG
13RG	23RR	21RR
31RG	12GR	23RG
23GR	31RG	1100
31GR	32RG	2200
23RG	21GR	1100
22RR	2200	1100
12GR	22RR	21RG
32GR	13RR	11RR
22RR	21GG	12RG
12GG	2300	23GR
33RR	2200	32GR
11RR	2200	21GG
2300	3100	21RG
2300	13GR	13RG
33RR	21GR	13RG
23GR	33RR	13RG
21GG	23RR	13GR
13GR	22RR	2300
3300	12RR	1100
1100	2300	11RR
12RR	23RG	31RG
12GG	32GR	23RR
3100	31RG	2300
32RG	2200	11RR
21GR	1100	32RG
2200	1100	32GR
22RR	21RG	13GG
13RR	11RR	23GR
21GG	12RG	32GR
23GR	23GR	22RR

35 out of ≈ 130

QUANTUM DESCRIPTION

X and Y are replaced by particles

A and B are Stern-Gerlach apparatuses that "measure the spin" along some direction.

$1, 2, 3 = 3$ possible directions for that "measurement".

Yes/No = Up/Down.

$|$ state of the two particles $>$

$$= \frac{1}{\sqrt{2}}(|A\ 1 \uparrow> |B\ 1 \downarrow> - |A\ 1 \downarrow> |B\ 1 \uparrow>)$$

$$= \frac{1}{\sqrt{2}}(|A\ 2 \uparrow> |B\ 2 \downarrow> - |A\ 2 \downarrow> |B\ 2 \uparrow>)$$

$$= \frac{1}{\sqrt{2}}(|A\ 3 \uparrow> |B\ 3 \downarrow> - |A\ 3 \downarrow> |B\ 3 \uparrow>)$$

$|$ state of the two particles $>$

$= \frac{1}{\sqrt{2}}(|A\ 1 \uparrow> |B\ 1 \downarrow> - |A\ 1 \downarrow> |B\ 1 \uparrow>)$

If one measures the spin in direction 1 at A, and one sees $\uparrow$, the state becomes $|A\ 1 \uparrow> |B\ 1 \downarrow>$.

If one sees $\downarrow$, the state becomes $|A\ 1 \downarrow> \ |B\ 1 \uparrow>$.

Similar result if one measures the spin in direction 2 or 3 at A.

But then the state changes *non locally* at B.

Same dilemma as for Einstein's boxes :

reduction of the $|$ state $>$ = physical or epistemic ?

If physical $\longrightarrow$ non locality

If epistemic $\longrightarrow$ "answers" are given in advance, i.e. the particle at B *is* $1\uparrow$ or $1\downarrow$, $2\uparrow$ or $2\downarrow$, $3\uparrow$ or $3\downarrow$, *before* any measurement at A.

BUT (Bell 1964) this leads to a contradiction with observations made when the directions in which the spin is "measured" are *different* at A and B.

SO, the perfect correlations (here, we have perfect anti-correlations, but that is a matter of conventions for YES/NO) are not merely correlations, but the result of a subtle form of nonlocality. In other words, the reduction of the quantum state, which is non local, is not merely epistemic, but related to something physical.

One cannot use this to send messages

If one could, then relativity implies that one could send messages into one's own past.

— Each side sees a perfectly random sequence of YES/NO or RED/GREEN

— BUT if each person tells the other which "measurements" have been made (1, 2 or 3), then, they both know which result has been obtained on the other side when the same measurement is made on both sides.

$\Rightarrow$ Then, they both share a common sequence of YES/NO or RED/GREEN, which is form of "information". Since that information cannot possibly come from the source (Bell), some sort of nonlocal transmission of information has taken place.

BELL WAS QUITE EXPLICIT ABOUT WHAT THIS MEANS

Let me summarize once again the logic that leads to the impasse. The EPRB correlations are such that the result of the experiment on one side immediately foretells that on the other, whenever the analyzers happen to be parallel. If we do not accept the intervention on one side as a causal influence on the other, we seem obliged to admit that the results on both sides are determined in advance anyway, independently of the intervention on the other side, by signals from the source and by the local magnet setting. But this has implications for non-parallel settings which conflict with those of quantum mechanics. So we cannot dismiss intervention on one side as a *causal* influence on the other.

J. BELL

BUT BELL WAS WIDELY MISUNDERSTOOD

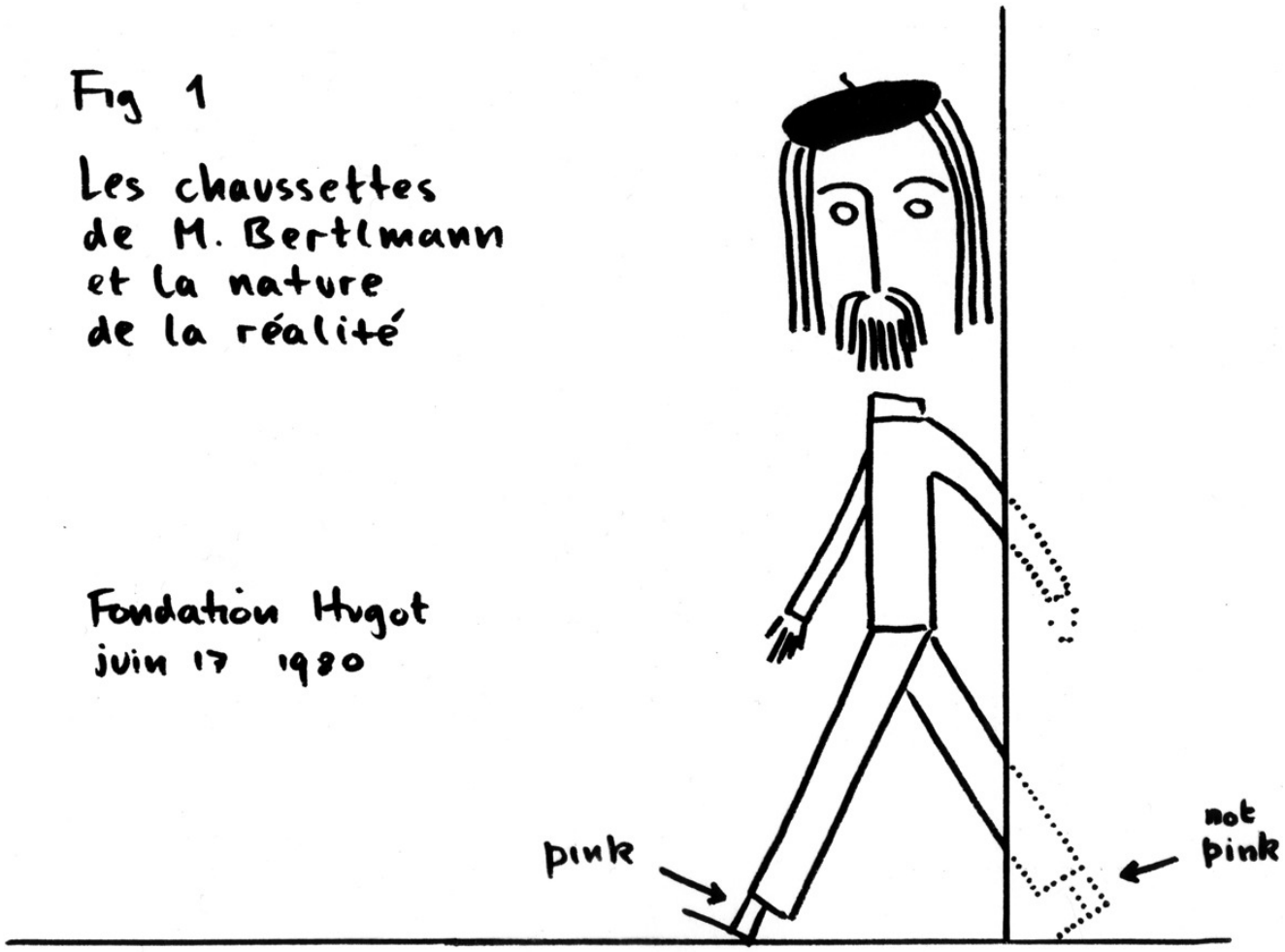
Some theoretical work of John Bell revealed that the EPRB experimental setup could be used to distinguish quantum mechanics from hypothetical hidden variable theories... After the publication of Bell's work, various teams of experimental physicists carried out the EPRB experiment. The result was eagerly awaited, although virtually all physicists were betting on the corrections of quantum mechanics, which was, in fact, vindicated by the outcome.

M. GELL-MANN

Fig 1

Les chaussettes
de M. Bertlmann
et la nature
de la réalité

Fondation Hugot
juin 17 1980



The situation is like that of Bertlmann's socks, described by John Bell in one of his papers. Bertlmann is a mathematician who always wears one pink and one green sock. If you see just one of his feet and spot a green sock, you know immediately that his other foot sports a pink sock. Yet no signal is propagated from one foot to the other. Likewise no signal passes from one photon to the other in the experiment that confirms quantum mechanics. No action at a distance takes place.

MURRAY GELL-MANN

The proof he [von Neumann] published... though it was made much more convincing later on by Kochen and Specker, still uses assumptions which, in my opinion, can quite reasonably be questioned... In my opinion, the most convincing argument against the theory of hidden variables was presented by J.S. Bell.

E. WIGNER

Bell's theorem establishes that the value assigned to an observable must depend on the complete experimental arrangement under which it is measured, even when two arrangements differ only far from the region in which the value is ascertained – a fact that Bohm theory exemplifies, and that is now understood to be an unavoidable feature of any hidden-variables theory. To those for whom nonlocality is anathema, Bell's Theorem finally spells the death of the hidden-variables program.

D. MERMIN

EINSTEIN WAS ALSO MISUNDERSTOOD

An essential aspect of this arrangement of things [physical objects] in physics is that they lay claim, at a certain time, to an existence independent of one another, provided these objects "are situated in different parts of space". The following idea characterizes the relative independence of objects far apart in space (A and B) : external influence on A has no direct influence on B.

A. EINSTEIN

The root of the difference between Einstein and me was the axiom that events which happens in different places A and B are independent of one another, in the sense that an observation on the states of affairs at B cannot teach us anything about the state of affairs at A.

M. BORN

Contemporary physicists come in two varieties. Type 1 physicists are bothered by EPR and Bell's theorem. Type 2 (the majority) are not, but one has to distinguish two subvarieties. Type 2a physicists explain why they are not bothered. Their explanations tend either to miss the point entirely (like Born's to Einstein) or to contain physical assertions that can be shown to be false. Type 2b are not bothered and refuse to explain why. Their position is unassailable. (There is a variant of type 2b who say that Bohr straightened out the whole business, but refuse to explain how.)

D. MERMIN

CONCLUSION

I know that most men, including those at ease with problems of the highest complexity, can seldom accept even the simplest and most obvious truth if it be such as would oblige them to admit the falsity of conclusions which they have delighted in explaining to colleagues, which they have proudly taught to others, and which they have woven, thread by thread, into the fabric of their lives.

TOLSTOY