Are there rocks in your head?
Stephan LeBohec

ABSTRACT:

In 1935, A. Einstein, B. Podolsky, and N. Rosen challenged the understanding of quantum mechanics with a paradox known since then as the EPR paradox. It is only in 1964 that John S. Bell proposed a route for the experimental test of the EPR paradox in a way implemented in 1982 by A. Aspect establishing that the formulation of quantum mechanics provides a strange but accurate description of nature. I will tell you this story and how it may impact secret communication and even teleportation following the lines of the beautiful 1985 article by N.D. Mermin in which you can find the quote: “Anybody who’s not bothered by [all this] has to have rocks in his head!”

Relevant EPR paradox references can be found on http://www.physics.utah.edu/~lebohec
Are there rocks in your head?

Stephan LeBohec

After a paper by N. David Mermin(*) on
the Einstein-Podolsky-Rosen paradox

(*) “Is the moon there when nobody looks? Reality and the quantum theory”, Physics Today, April 1985, p 38-47

Note:
All the relevant papers can be found on http://www.physics.utah.edu/~lebohec
Randomly set the dials on A & B to 1, 2, or 3 independently.
Data sample

<table>
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<th>23GR</th>
<th>13RR</th>
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Data fact 1

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When A and B have the same dial setting, they flash the same colour.
When A and B have the same dial setting, they flash the same colour.
Disregarding the dial setting of A and B, 
The data is completely random. 
(i.e. A & B flash the same colour half the times)
A theory:

There are 8 types of particles. The source fires the same type of particles in both directions. The source randomly selects the type of particles it fires each time.
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There are 8 types of particles. The source fires the same type of particles in both directions. The source randomly selects the type of particles it fires each time.

The theory accounts for data fact 1.
Does the theory accounts for data fact 2?

RRR

Allways the same colour in A & B

GRG

Same colour for configurations:
(1,1); (2,2); (3,3) (1,3); & (3,1);

Different colours for configurations:
(1,2); (2,1); (2,3) & (3,2);

Fraction of same colour records > 5/9 > 1/2
Does the theory accounts for data fact 2?

**RRR**
Allways the same colour in A & B

**GRG**
Same colour for configurations: (1,1); (2,2); (3,3) (1,3); & (3,1);
Different colours for configurations: (1,2); (2,1); (2,3) & (3,2);

Fraction of same colour records > 5/9 > 1/2

**NO!**

Such data would imply that “something one cannot know anything about cannot exist!”
A theory: Quantum mechanics

Postulates:

(1) State vectors $| + \rangle$ or $| - \rangle$

$a| + \rangle + b| - \rangle$ also is a possible state

as well as $a'| \Delta \rangle + b'| \nabla \rangle$ with

$| \Delta \rangle = \alpha| + \rangle + \beta| - \rangle \quad \& \quad | \nabla \rangle = \delta| + \rangle + \gamma| - \rangle$

two identical systems would be in a state we can write as

$a| + \rangle| + \rangle + b| + \rangle| - \rangle + c| - \rangle| + \rangle + d| - \rangle| - \rangle$ or

$a'| \Delta \rangle| \Delta \rangle + b'| \Delta \rangle| \nabla \rangle + c'| \nabla \rangle| \Delta \rangle + d'| \nabla \rangle| \nabla \rangle$
A theory: Quantum mechanics

(2) Observables and operators

Observable $A \leftrightarrow$ linear operator $A$

Measurement of $A$ gives a solution of

$$A|\alpha\rangle = a|\alpha\rangle$$
A theory: Quantum mechanics

(3) Born postulate

State \( \psi \) = \( a_1 | \alpha_1 \rangle + a_2 | \alpha_2 \rangle \)

Measurement of A gives

- \( \alpha_1 \) with probability \( |a_1|^2 \)
- \( \alpha_2 \) with probability \( |a_2|^2 \)

\( A|\alpha_1\rangle = a_1 |\alpha_1\rangle \quad A|\alpha_2\rangle = a_2 |\alpha_2\rangle \)

Example: polarization of light, one photon at a time
A theory: Quantum mechanics

(4) von Neumann postulate:
Right after a measurement of A yielding $\alpha_1$, 
the system is in the state $|\alpha_1\rangle$. 
A theory: Quantum mechanics

(5) The observable energy $H$ drives the evolution of the state vector:

$$i\hbar \frac{d}{dt} |\psi\rangle = H |\psi\rangle$$

Note: At this point you know everything you will ever know about quantum mechanics. You can start considering applications.
\[ |\psi\rangle = |\uparrow\rangle |\downarrow\rangle + |\downarrow\rangle |\uparrow\rangle \]
\[ = |\Rightarrow\rangle |\Leftarrow\rangle + |\Leftarrow\rangle |\Rightarrow\rangle \]
\[ = |\Leftarrow\rangle |\Leftarrow\rangle + |\Leftarrow\rangle |\Leftarrow\rangle \]
\[ |\psi\rangle = |\uparrow\rangle |\uparrow\rangle + |\downarrow\rangle |\downarrow\rangle |\downarrow\rangle |\downarrow\rangle \]
\[ = |\nearrow\rangle |\nearrow\rangle + |\swarrow\rangle |\swarrow\rangle |\swarrow\rangle |\swarrow\rangle \]
\[ = |\nwarrow\rangle |\nwarrow\rangle + |\searrow\rangle |\searrow\rangle |\searrow\rangle |\searrow\rangle \]

Dial settings
Back to Data facts

✔️ (1) When A and B have the same dial setting, they flash the same colour.

✔️ (2) Disregarding the dial setting of A and B, The data is completely random. (i.e. A & B flash the same colour half the times)
Back to Data facts

✔️ (1) When A and B have the same dial setting, they flash the same colour.

✔️ (2) Disregarding the dial setting of A and B, the data is completely random. (i.e. A & B flash the same colour half the times)

Hurray! Bravo!
History:

1935 Einstein Podolsky & Rosen, Phys. Rev. 47, 777
“The bolt from the blue”

1964 J.S. Bell, Physics, 1, 195
Possibly “the most profound discovery of science”

1981 A.Aspect et al., PRL, 47, 460
“Magic! Unless you have rocks in your head”
Cryptography

\{ |\uparrow\rangle; |\uparrow\rangle; |\downarrow\rangle; |\uparrow\rangle; \cdots \}
Cryptography

Alice

Spy

Bob
Cryptography

Alice → Bob

\{ |↑\rangle; |←\rangle; |↓\rangle; |↔\rangle; |→\rangle; |↑\rangle; |←\rangle; \cdots \}
Cryptography

\[ \{ |\uparrow\rangle; |\leftarrow\rangle; |\downarrow\rangle; |\rightarrow\rangle; |\uparrow\rangle; |\leftarrow\rangle; \cdots \} \]

\[ \{ |\leftrightarrow\rangle; |\leftarrow\rangle; |\rightarrow\rangle; |\uparrow\rangle; |\rightarrow\rangle; |\uparrow\rangle; |\leftarrow\rangle; \cdots \} \]
Cryptography

Alice

\{ |\uparrow\rangle; |\leftarrow\rangle; |\downarrow\rangle; |\rightarrow\rangle; |\uparrow\rangle; |\leftarrow\rangle; \cdots \} \\
\{ |\leftrightarrow\rangle; |\leftarrow\rangle; |\uparrow\rangle; |\leftarrow\rangle; |\uparrow\rangle; |\leftrightarrow\rangle; \cdots \} \\
\{ |BAD\rangle; |\rightarrow\rangle; |GOOD\rangle; |\rightarrow\rangle; |BAD\rangle; |\rightarrow\rangle; |GOOD\rangle; \cdots \} \\

Bob
Cryptography

Alice

Spy

Bob

\{ |\uparrow\rangle; |\leftarrow\rangle; |\downarrow\rangle; |\leftrightarrow\rangle; |\rightarrow\rangle; |\uparrow\rangle; |\leftarrow\rangle; \cdots \}\n
\{ |\leftrightarrow\rangle; |\rightarrow\rangle; |\uparrow\rangle; |\leftarrow\rangle; |\downarrow\rangle; |\leftrightarrow\rangle; \cdots \}
No Clone theorem

A quantum copy machine ...

$|\uparrow\rangle|\Phi\rangle \rightarrow |\uparrow\rangle|\uparrow\rangle$

$|\downarrow\rangle|\Phi\rangle \rightarrow |\downarrow\rangle|\downarrow\rangle$

$|\psi\rangle = |\uparrow\rangle + |\downarrow\rangle$

... can not work!

$|\psi\rangle|\Phi\rangle \rightarrow |\uparrow\rangle|\uparrow\rangle + |\downarrow\rangle|\downarrow\rangle \neq |\psi\rangle|\psi\rangle$

Here is another problem with teleportation
Sheldon: Here's the problem with teleportation. Assuming a device could be invented, which would identify the quantum state of matter of an individual in one location and transmit that pattern to a distant location for reassembly. You would not have actually transported the individual, you would have destroyed him in one location and recreated him in another. Personally, I would never use a transporter because the original Sheldon would have to be dissintegrated in order to create a new Sheldon.

Leonard: Would the new Sheldon be in any way an improvement on the old Sheldon?
Sheldon: No, he would be exactly the same.
Leonard: That is a problem