Quantum Entanglement,
Bell’s Theorem,
and Reality
in 12 minutes

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*Perspectives on Science Research Symposium 2006*
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Randomness in QM: Subjective or Objective?

- **Uncertainty Principle** predicts **incompatible observables** (e.g., position and momentum)

- Measuring one **randomizes** any subsequent measurement of the other

- But before the first measurement, don’t both have **definite values**?
But before the measurement, don’t both have definite values?

Partial Answer: **Bell’s Theorem** (JS Bell, 1964):

Two possibilities…
either:
Incompatible observables **don’t** both have definite values
or:
Incompatible observables **do** both have definite values, but, those values **depend on** simultaneous events, at far away locations
Quantum Entanglement

Interaction between two objects

Objects separate

Objects correlated after separation

Space

Time
Quantum Entanglement

If the interaction includes quantum entanglement, then: after separating, the objects are more strongly correlated than any separated non-quantum objects can be.
Making linear operations nonlinear, with entanglement

Box is a simple quantum computer. Need linear algebra to understand its operation. Therefore we make an analogy:

**Quantum computational process** →
Flow of information through **separate pipes** where the information is altered by **machinery**; followed by a **coupling stage**.

**Quantum randomness in the computation** →
**Mice** are stuck in the pipes. They cause random fluctuations in the pipe-machinery. But the box is designed to work anyway (it computes $f$).
Inside the black box: Pipes isolate input streams, then combine

INPUTS

A
B
C
D

“Black Box”
Computes function: \( f \)

f(A,B,C,D)

A → Pipe 1
B → Pipe 2
C → Pipe 3
D → Pipe 4

Combiner, L

f(A,B,C,D)
Inside the black box: Pipes isolate input streams, then combine

Assumption: Mouse behavior is deterministic

There are “random” fluctuations in the pipes from use to use, but, during any given use, each pipe outputs a definite function of its input.

(Note: Mouse behavior too complex to predict which function.)
There are “random” fluctuations in the pipes from use to use, but, during any given use each pipe outputs a definite function of its input.

During any single use:

Each pipe has one, determined output, for a given input.
There are “random” fluctuations in the pipes from use to use, but, during any given use each pipe outputs a definite function of its input.

L DESIGNED SO THAT:
No matter which functions G, H, I, J are: L outputs a linear function of A, B, C, D
L DESIGNED SO THAT: No matter what functions G, H, I, J are, L outputs a linear function of A, B, C, D

BUT: In our box, the mice have been entangled with one another in the past, and f becomes a nonlinear function of A, B, C, D

Even if we don’t change the nature of the combiner at all….
If the mice have been entangled with one another in the past, L outputs a nonlinear function of A, B, C, D... even though the mice never interact after the machine is constructed.
A PARADOX?

No matter what functions G, H, I, J are:
L always outputs a linear function of A, B, C, D

BUT: If the mice have prior entanglement,
L outputs a nonlinear function of A, B, C, D….
Even though the mice never interact after the machine is constructed

Made one key assumption:

“There are random fluctuations in the pipes from use to use, but, during any given use, each pipe outputs a definite function of its input.”

i.e., mouse behavior deterministic
A PARADOX?

Made one key assumption:

“There are random fluctuations in the pipes from use to use, but, at any given time, each pipe outputs a definite function of its input.”

Resolutions of Paradox?:

1) Behavior of mouse in one pipe is affected by input to other pipes. Therefore a pipe’s output is a function both of its own input and of the inputs to other pipes.
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Faster than light “causation”, without interaction. Only affects the random fluctuations in the pipes. Therefore doesn’t violate special relativity.
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Resolutions of Paradox?:

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2) Behavior of mouse is non-deterministic. No definite function maps pipe input to pipe output. i.e., randomness in the computational process is objective
We’ve designed such a quantum-computational “box”, thus proving a variant of:

Bell’s Theorem:

Either:

1) The hidden determinants of measured values in one location are *instantaneously* affected by events elsewhere.

Or:

2) Quantum randomness is *objective*. There are no hidden determinants of the values of all observables ….