What one should know (and remember) about Quantum Mechanics

Detlef Dürr

Mathematisches Institut
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Is Quantum Theory Exact?

Before asking that, we should be clear about

What is it that quantum physics is about?

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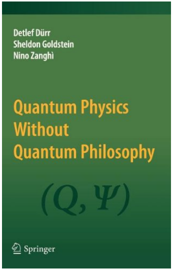
GALILEI:
THEY SHOULD NOT HAVE SAVED MONEY ON THE FOUNDATIONS

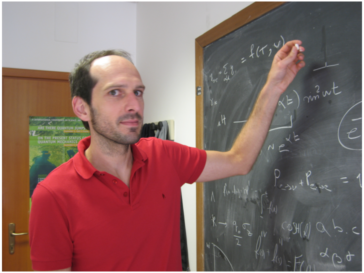
Acknowledgement

Thanks to my friends Shelly Goldstein and Nino Zanghì



and thanks to

GianCarlo Ghirardi here with John Bell in 1989 Erice



Angelo Bassi, Chair of the COST Action

and thanks to many of my students, coworkers and colleagues

I understand QM

although

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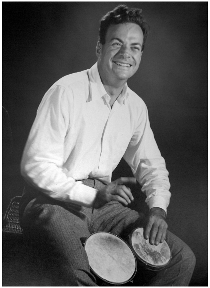
Nobody understands QM



Richard P. Feynman (1965) The Character of Physical Law

There was a time when the newspapers said that only twelve men understood the theory of relativity. I do not believe there ever was such a time. There might have been a time when only one man did, because he was the only guy who caught on before he wrote his paper. But after people read the paper, a lot of people understood the theory of relativity in some way or other, certainly more than twelve. On the other hand, I think I can safely say that nobody understands quantum mechanics.

Why?

There is Ψ

What is Ψ?

Why?

There is $\boldsymbol{\Psi}$

What is $\boldsymbol{\Psi}$?

Why?

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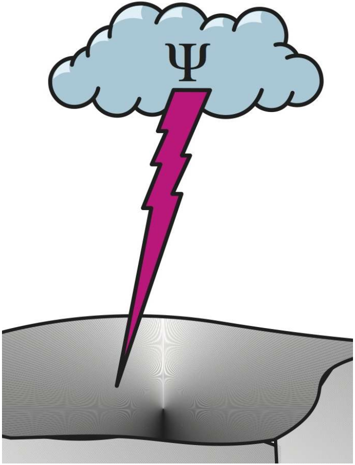
What is Ψ?



What is that grey stuff? Brains? Matter?

$$\boldsymbol{\Psi} : \mathbb{R}^n \times \mathbb{R} \mapsto \mathbb{C}$$

$\mathbb{R}$ is time, but

what is $\mathbb{R}^n$?

the essence of the debate about QM

$\mathbb{R}$ is time, but

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$n = 3N$ where N is the number of particles

$\mathbb{R}^{3N}$= configuration space of N particles

BUT

in QM particles do not exist

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why don't particles exist?

because says W. Heisenberg, there is no real world

...the idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist, independently of whether or not we observe them... is impossible....

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Feynman seems puzzled

Does this mean that my observations become real only when I observe an observer observing something as it happens? This is a horrible viewpoint. Do you seriously entertain the thought that without observer there is no reality? Which observer? Any observer? Is a fly an observer? Is a star an observer? Was there no reality before 10^9 *B.C. before life began? Or are you the observer? Then there is no reality to the world after you are dead? I know a number of otherwise respectable physicists who have bought life insurance.*

Mermin (in Physics Today) has the answer to that

Albert Einstein famously asked whether a wavefunction could be collapsed by the observations of a mouse. Bell expanded on that, asking whether the wavefunction of the world awaited the appearance of a physicist with a PhD before collapsing. The QBist answers both questions with "no." A mouse lacks the mental facility to use quantum mechanics to update its state assignments on the basis of its subsequent experience, but these days even an undergraduate can easily learn enough quantum mechanics to do just that.

QB= Quantum Baysianism (the grey stuff is brain)

How can physics go so bad?

Lakatos in Criticism and the Growth of Knowledge,

In the new, post-1925 quantum theory the ‘anarchist‘ position became dominant and modern quantum physics, in its ‘Copenhagen interpretation‘, became one of the main standard bearers of philosophical obscurantism. In the new theory Bohr’s notorious ‘complementarity‘ principle enthroned [weak] inconsistency as a basic ultimate feature of nature, and merged subjectivist positivism and antilogical dialectic and even ordinary language philosophy into one unholy alliance. After 1925 Bohr and his associates introduced a new and unprecedented lowering of critical standards for scientific theories. This led to a defeat of reason within modern physics and to an anarchist cult of incomprehensible chaos.

all that because of the simple question

$$\Psi : \mathbb{R}^n \mapsto \mathbb{C}$$

What is n and what is Ψ?

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$$\boldsymbol{\Psi} : \mathbb{R}^n \mapsto \mathbb{C}$$

What is n and what is $\boldsymbol{\Psi}$?

to which the simplest answer is

$n = 3N$ because there are N particles

and Ψ determines the law of motion
in the simplest way possible

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But again: Landau and Lifshitz say about the double slit experiment

It is clear that this result can in no way be reconciled with the idea that electrons move in paths.... In quantum mechanics there is no such concept as the path of a particle and Richard Feynman agrees

... the two-slit experiment for electrons is a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality it contains the only mystery.... How does it really work? What machinery is actually producing this thing? Nobody knows any machinery. Nobody can give you a deeper explanation of this phenomenon than I have given; that is, a description of it.

But John Stuart Bell after reading Bohm's 1952 paper caught on

Is it not clear from the smallness of the scintillation on the screen that we have to do with a particle? And is it not clear, from the diffraction and interference patterns, that the motion of the particle is directed by a wave? De Broglie showed in detail how the motion of a particle, passing through just one of two holes, could be influenced by waves propagating through both holes. And so influenced that the particle does not go where the waves cancel out, but is attracted to where they cooperate. This idea seems to me so natural and simple, to resolve the wave-particle dilemma in such a clear and ordinary way, that it is a great mystery to me that it was so generally ignored.

This man wrote the paper in 1952: (Q, ψ) is indeed the trivial solution to all the mysteries of quantum mechanics.

David Bohm (1917-1992)

and before him in 1927 at the Solvay conference

de Broglie (1892- 1987): wave **and** particle

de Broglie proposed that the wave guides the particles: (Q, ψ)

BUT he was ridiculed at the Solvay conference in 1927. WHY?

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(de Broglie-) Bohmian Mechanics (Q, Ψ)

Ψ is a solution of the Schrödinger equation

$Q = (Q_1, ... Q_N) \in \mathbb{R}^{3N}$ positions of N particles. $Q(t)$ solves the guiding equation

$$\frac{d}{dt} Q \sim \mathrm{i} \nabla \ln \Psi$$

Analyze this theory! That what physicists are trained to do but they wouldn't do it!

What does it give you? The quantum formalism, the Boson Fermion alternative, the quantum randomness ... but most importantly

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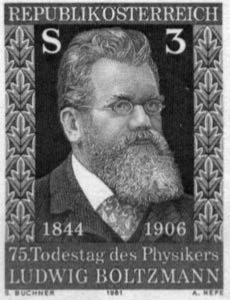
Insight: It is useful to know what you are talking about

You want Probability?

In a deterministic theory?

ask



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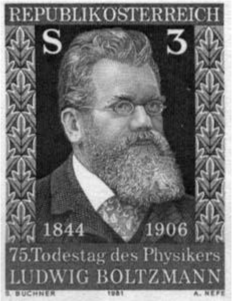

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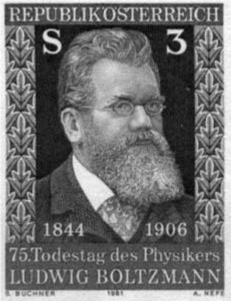

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QUANTUM EQUILIBRIUM AND THE ORIGIN OF ABSOLUTE UNCERTAINTY

Detlef Dürr,[1,2] Sheldon Goldstein,[1] and Nino Zanghí[1,3]

Dedicated to the memory of J. S. Bell.

Abstract. The quantum formalism is a "measurement" formalism—a phenomenological formalism describing certain macroscopic regularities. We argue that it can be regarded, and best be understood, as arising from Bohmian mechanics, which is what emerges from Schrödinger's equation for a system of particles when we merely insist that "particles" means particles. While distinctly non-Newtonian, Bohmian mechanics is a fully deterministic theory of particles in motion, a motion choreographed by the wave function. We find that a Bohmian universe, though deterministic, evolves in such a manner that an *appearance* of randomness emerges, precisely as described by the quantum formalism and given, for example, by "$\rho = |\psi|^2$." A crucial ingredient in our analysis of the origin of this randomness is the notion of the effective wave function of a subsystem, a notion of interest in its own right and of relevance to any discussion of quantum theory. When the quantum formalism is regarded as arising in this way, the paradoxes and perplexities so often associated with (nonrelativistic) quantum theory simply evaporate.

KEY WORDS: Quantum randomness; quantum uncertainty; hidden variables; effective wave function; collapse of the wave function; the measurement problem; Bohm's causal interpretation of quantum theory; pilot wave; foundations of quantum mechanics.

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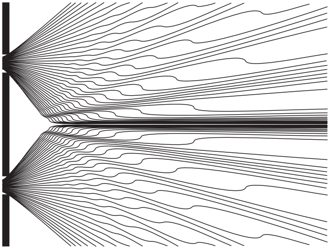

computer simulation of Bohmian trajectories by Chris Dewdney

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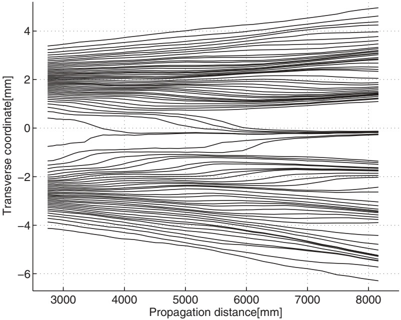

Experiment: S.Kocsis et al: Observing the Average Trajectories of Single Photons in a Two-Slit Interferometer. Science 2011

Ahead to the past: de Broglie formulated the idea of guided mechanics in 1927 and David Bohm in 1952 wrote the papers how the quantum formalism emerges

So why

after 1952, Feynman still said?: *But after people read the paper , a lot of people understood the theory of relativity in some way or other, certainly more than twelve. On the other hand, I think I can safely say that nobody understands quantum mechanics.*

Did nobody read Bohm's paper? Certainly more than 12 did. Why did nobody catch on?

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Ψ is not on physical space but on the high dimensional unphysical configuration space $\mathbb{R}^{3N}$

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Entanglement: ψ the "unphysical" wave function

Erwin Schrödinger 1887-1961

- de Broglie at the Solvay conference in 1927: "It seems a little paradoxical to construct a configuration space with the coordinates of points that do not exist."
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- Because a physical field on configuration space is a sin against relativity!

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BM is manifestly nonlocal because the wave function is nonlocal = entangled

Two particles at $X_1(t)$ and $X_2(t)$

$$\dot{X}_1(t) = \frac{\hbar}{m_1} \Im \left(\frac{\frac{\partial}{\partial \vec{x}} \psi(x, X_2(t))|_{x = X_1(t)}}{\psi(X_1(t), X_2(t))} \right),$$

- if $\psi = \psi_1(x_1)\psi_2(x_2)$ the evolution of X_1 is independent of X_2
- **Entanglement**: wave function ψ is **not** a product, it is a general function on configuration space, the evolution of X_1 is NOT independent of X_2

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Einstein, Schrödinger, ... and almost all physicists:
wave function (since entangled) is not a physical field!
the probability $|\psi(x_1, x_2)|^2$ makes sense on configuration space
The knowledge of Mr. Mermin about far away events may change instantaneously: Bertlmann's socks

But it must not happen, that a particle affects another over arbitrary distances and in no time – so BM is out?

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NONLOCALITY, the only true innovation of QM:

NATURE is nonlocal

John Stuart Bell 1928-1990, established nonlocality of nature in 1964

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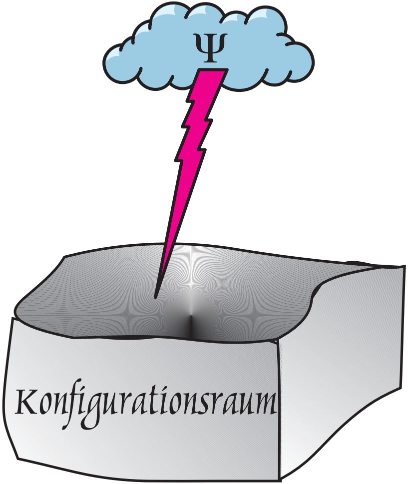
Bell's inequality argument is NOT about hidden variables

Local realism is not an assumption for Bell's inequalities!

Bell himself in Speakable...page 143

> *It is important to note that to the limited degree to which determinism plays a role in the EPR argument, it is not assumed but inferred. What is held sacred is the principle of "local causality" or "no action at a distance". . . . It is remarkably difficult to get this point across, that determinism is not a presupposition of the analysis.*

Bohmian mechanics is just what the doctor ordered



THE FUTURE

What will remain?

- Nonlocality, because that is how nature is
- particles, because that is the easiest way to present local real things
  perhaps will be replaced by other ontology $\sim \circ\diamond$
- "quantisation" of the mad hatter $X \to \hat{X}, P \to \hat{P}$? NO!
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Schrödinger's equation?

Linearity on all scales?

No, say Ghirardi, Bassi, Diosi... and...Weinberg

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  Schrödinger's equation false
- GianCarlo Ghirardi,Angelo Bassi, Stephen Adler, Lajos Diosi, Antony Leggett....: experiments must decide between GRW and BM

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