FIAS Frankfurt Institute for Advanced Studies

Fetzer Franklin Fund — Exploring Frontiers. Breakthroughs. Science.

Gefördert durch DFG Deutsche Forschungsgemeinschaft

The Forgotten Solution

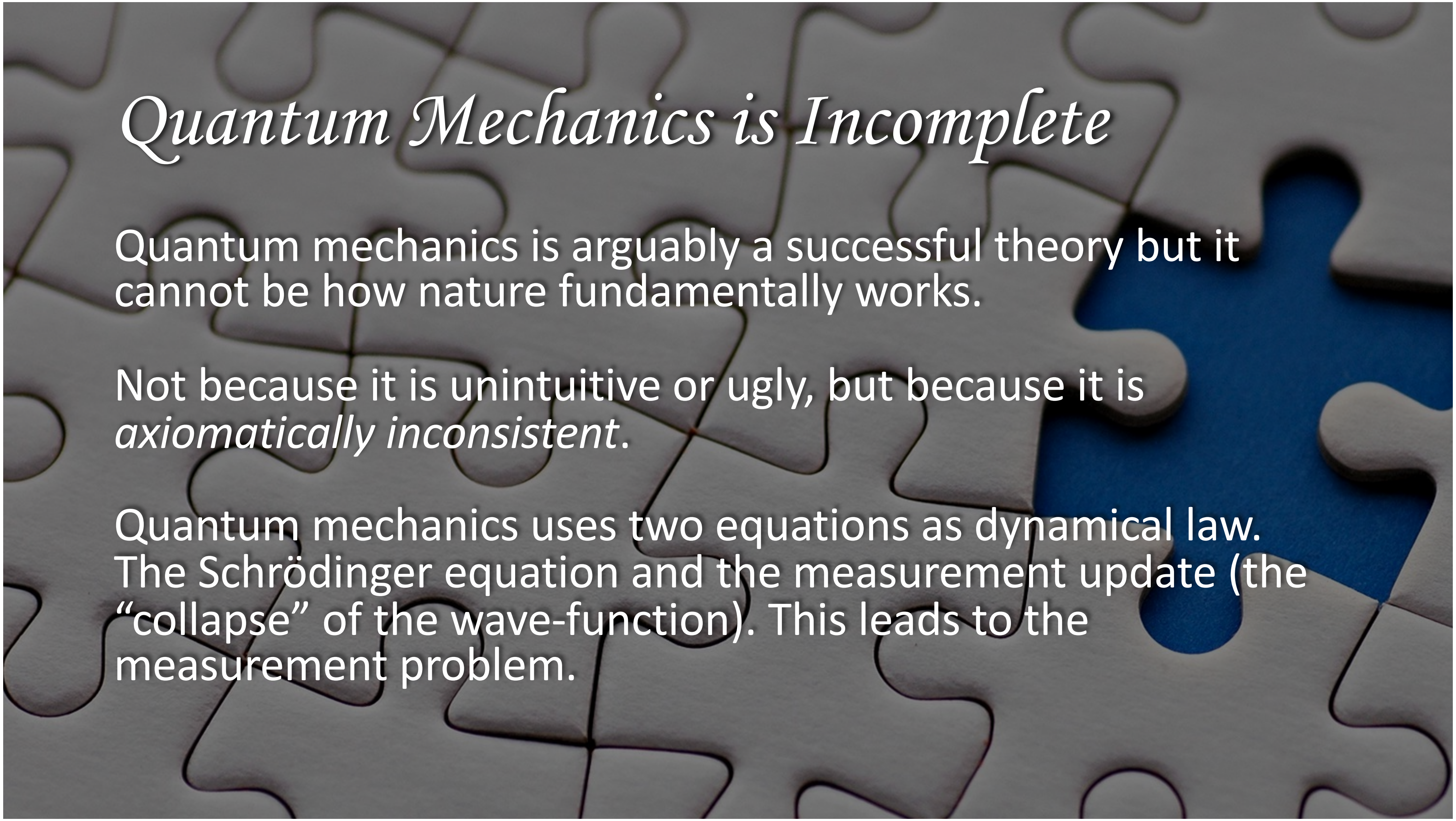
Sabine Hossenfelder

Superdeterminism

This is a talk about the *foundations* of quantum mechanics, not about *interpretations* of quantum mechanics.

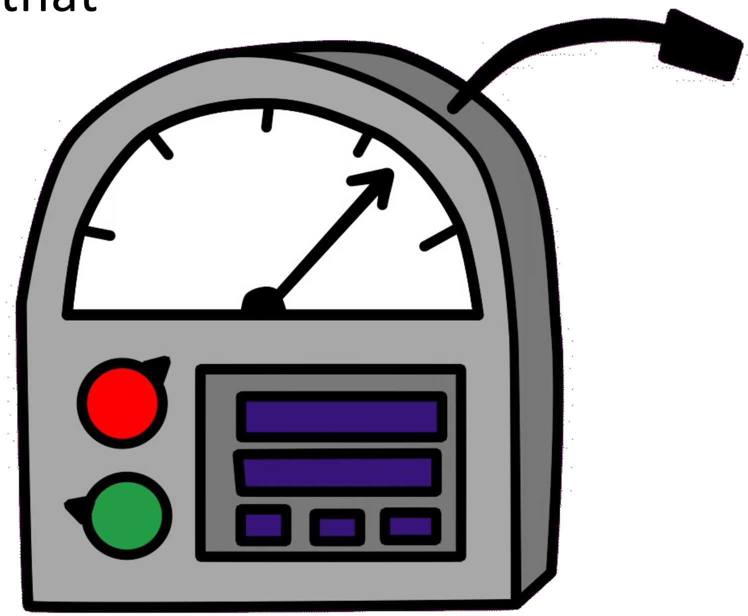
For details and references, see:

SH, Tim N. Palmer "Rethinking Superdeterminism," arXiv:1912.06462 [quant-ph]


Quantum Mechanics is Incomplete
Quantum mechanics is arguably a successful theory but it cannot be how nature fundamentally works.
Not because it is unintuitive or ugly, but because it is *axiomatically inconsistent*.
Quantum mechanics uses two equations as dynamical law. The Schrödinger equation and the measurement update (the “collapse” of the wave-function). This leads to the measurement problem.

The Measurement Problem

Quantum mechanics is not an ensemble theory. It is a theory for individual particles. But a particle that is 50% measured is not a thing.



This means the update of the wave-function is *necessary* to describe what we observe.

Decoherence does not solve the problem.

The Measurement Problem (cont'd)

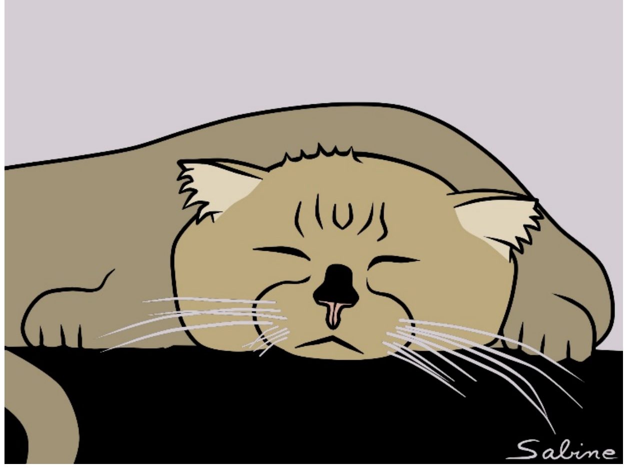
The measurement process in quantum mechanics is **not linear.** This means it is incompatible with the Schrödinger equation. It cannot be derived from it.

But if quantum mechanics was a fundamental theory, the measurement postulate should be unnecessary. The behavior of macroscopic objects like detectors should be derivable.

(This, or one has to give up reductionism for which there isn't even a theory.)

The Measurement Problem is Unsolved

- (Neo-)Copenhagen approaches bring back the problem in new clothes by referring to terms like “knowledge” held by “agents”.



- Many Worlds requires a postulate equivalent to the measurement postulate. No improvement.
- Collapse models solve the problem only after specifying what state to collapse into.
- Pilot wave theories solve the problem but require an explicitly non-local ontology that is hard to make compatible with QFT and GR.

Quantum Mechanics is Emergent

- The measurement postulate is an effective* description for a process in an underlying, more fundamental, theory.
- The underlying theory is deterministic but has to be non-linear. It is what goes under the name "hidden variables theory".
- This idea is supported by the apparent similarity between the classical Liouville equation and the v Neumann Dirac equation

$$\frac{\partial \rho}{\partial t} = \{H, \rho\} \qquad\qquad i\hbar \frac{\partial \rho}{\partial t} = [H, \rho]$$

* a technical term meaning it's coarse-grained and omits details on small structures.

But That's Obvious!

And if it's so obvious, why hasn't anyone looked at this before?

- Any theory that is deterministic, local, and solves the measurement problem must violate a condition known as statistical independence

$$\rho(\lambda|\mathbf{a},\mathbf{b}) \neq \rho(\lambda)$$

- Violating statistical independence means essentially that the time-evolution of the prepared state depends on the detector settings.
- Such theories are called "superdeterministic" and have a bad rep.

What is Superdeterminism?

A superdeterministic theory is a **hidden variables theory** that solves the measurement problem and

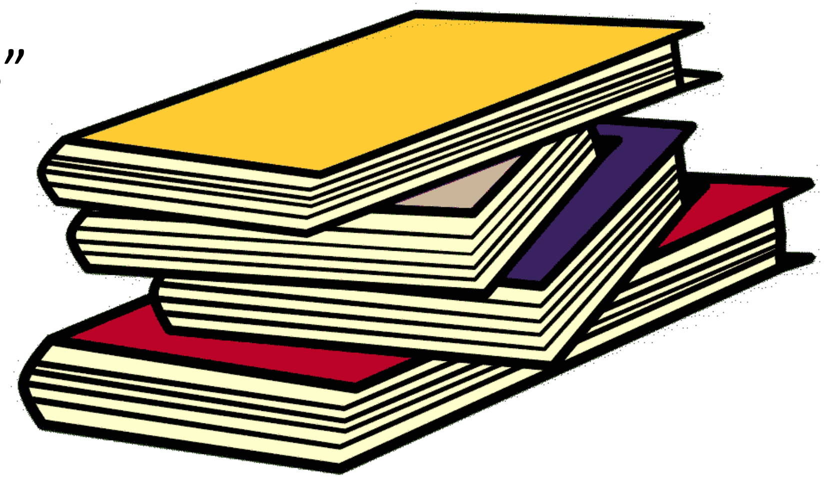
a) reproduces quantum mechanics on the average ("**psi-epistemic**")
b) is **deterministic**
c) is **local** in the sense of not having "spooky action at a distance"

It ***follows*** from this that the theory must violate Statistical Independence and be non-linear. (Need I say it follows that it reproduces quantum mechanics on the average?)

The Literature is Full with Misconceptions

Multiple authors have erroneously claimed that violating Statistical Independence in the preparation of quantum states would have the following consequences:

1. It's unscientific.
2. It would make science impossible.
3. It would require fine-tuned "conspiracies"
4. It would eradicate free will.



Misconception #1: It's unscientific

- The most common argument is that a supe… …heory is unscientific because it is necessarily … …ver.
- But: Superdeterminism gives ri… …s and hence makes the same predicti…
- If it makes the sa… …assumptions, it has more explanatory…
- If it r… …s, it should give rise to more pred… …does one can only find out by writing down a concre…

Non Sequitur

Misconception #2: Would make science impossible

If we would allow calling correlations between [illegible] and detector an “explanation,” science would [illegible]

- First mistake of the argument to [illegible] tions cannot explain anything. That’s as [illegible]
- Second mistake is to [illegible] s of the assumption of Statistical Inde [illegible] periments that it must also hold for [illegible] at’s not an allowed inference.

Besides, [illegible] rks just fine regardless of whether anyone talks abou [illegible] inism.

Plain Nonsense

Misconception #3: It's a conspiracy ("fine-tuned").

Similar to the first argument: The claim is impl[illegible]eeds a lot of detailed information to obtain a predic[illegible]eory non-predictive.

Again: One needs a conc[illegible]tell whether this is the case. A vanilla-i[illegible].

The intui[illegible]notion of what states are probable or "close". [illegible]ure. The measure of superdeterminism must mad[illegible]genstates a likely outcome.

Appeal to Intuition

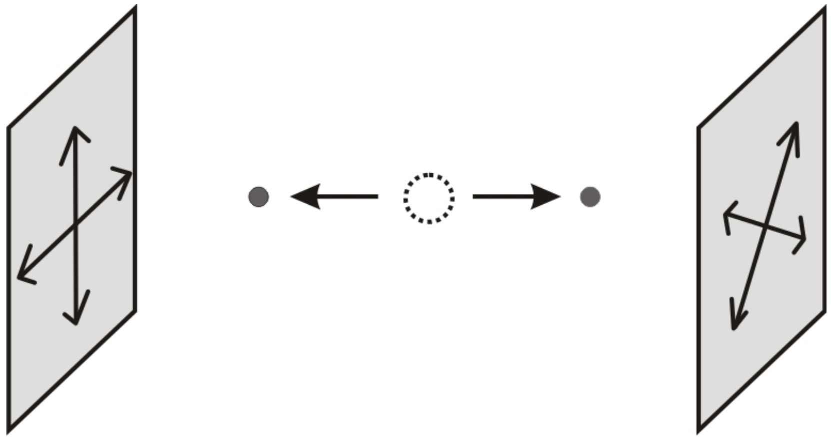
Misconception #4: It would eradicate free will

Statistical Independence is often referred to as [illegible]e” or “Free Will” assumption (to Bell’s theorem[illegible] unfortunate because it raises the im[illegible]inism puts outrageous constraints o[illegible]act is:

- Choosing detector se[illegible]y require human actors.
- Free Wil[illegible]n any theory that is deterministic. This ha[illegible]uperdeterminism in particular.
- The laws[illegible]ways constrain what we can do. Again, that is not specific t[illegible]determinism.

Red Herring

Bell-Type Tests



- Violating Bell's inequality tells us that at least one of the assumptions of the theorem must be violated.
- They cannot tell us which one.
- Superdeterministic theories by assumption give rise to exactly the same violations of Bell's inequality.

→ Doing the same experiment over and over again will not teach us anything new.

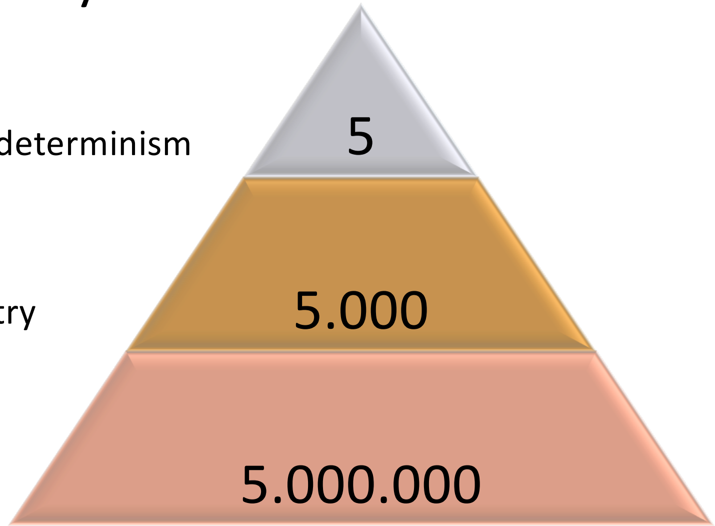
Models and Theories

- A variety of toy-models for simple situations (2 q-bits and such) that demonstrate quantum mechanics can be reproduced deterministically when violating Statistical Independence
- But theory approaches to superdeterminism? Very few.

approximate number of people working on superdeterminism

approximate number of people working on supersymmetry

approximate number of people working for superman franchise



Future-bounded Path Integrals

- The system of prepared state and detector takes one optimal path to the measurement outcome.
- Just which path is optimal depends on the degrees of freedom of the detector (including the measurement setting).
- The function to optimize gives a low weight to states that contain macroscopic entangled states.

Example of Path Integral

We* are currently trying the following:

$$Z := \int_{a^{\mathrm{i}}}^{a^{\mathrm{e}}} \prod_{i,j,k\ldots} [\mathrm{d}a_{ijk\ldots}(t)] \exp\left(-\mathrm{i}\int \mathrm{d}t \left(\langle\Phi|\mathrm{i}\partial_t - \hat{H}/\hbar|\Phi\rangle - \text{“Quantumness”}\right)\right)$$

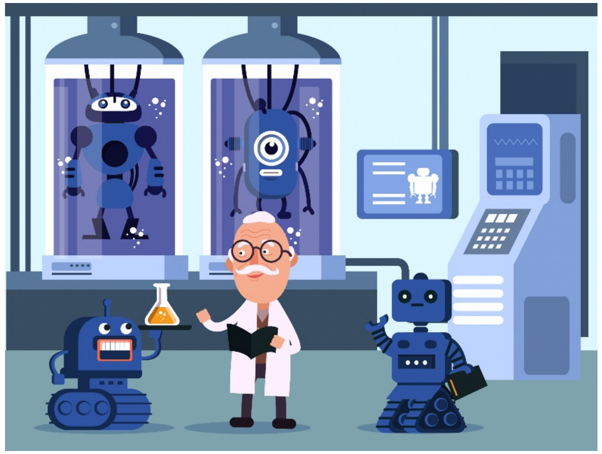
$$\mathcal{H}_N \ni |\Phi(t)\rangle := \sum_{i,j,k\ldots}^{D} a_{ijk\ldots}(t)|\Psi_A^i\rangle \otimes |\Psi_B^j\rangle \otimes |\Psi_C^k\rangle \ldots$$

Idea: State will need to balance Schrödinger evolution with minimizing “quantumness” that is some measure of entanglement.

* w/ Sandro Donadi

Experiment

- For all superdeterministic theories identical measurement setups will lead to identical measurement outcomes
- This is not the case in quantum mechanics!
- Look for autocorrelation in time-series of measurement outcomes that, according to quantum mechanics, should be uncorrelated



- This generally requires small, cold, systems in which measurements can be repeated in rapid sequence.

Superdeterministic Theories…

… are *not* interpretations of quantum mechanics. They are more fundamental theories from which quantum mechanics derives.