Title: Superdeterminism â€“ The Forgotten Solution

Speakers: Sabine Hossenfelder

Series: Quantum Foundations

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Abstract: What is a measurement? This, it turns out, is the most difficult question in physics today. In this talk, I will explain why the measurement problem is important and why all attempts to solve it so far have failed. I will then discuss the obvious solution to the problem that was, unfortunately, discarded half a century ago without ever being seriously considered: Superdeterminism. After addressing some common objections to this idea, I will summarize the existing approaches to develop a theory for it.

Zoom link

The Forgotten Solution

Superdeterminism

Sabine Hossenfelder

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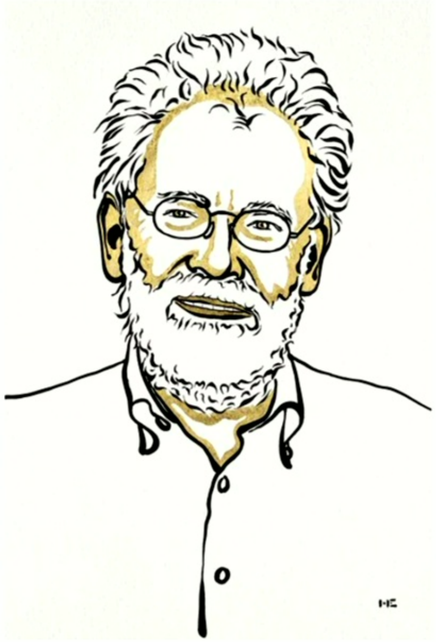
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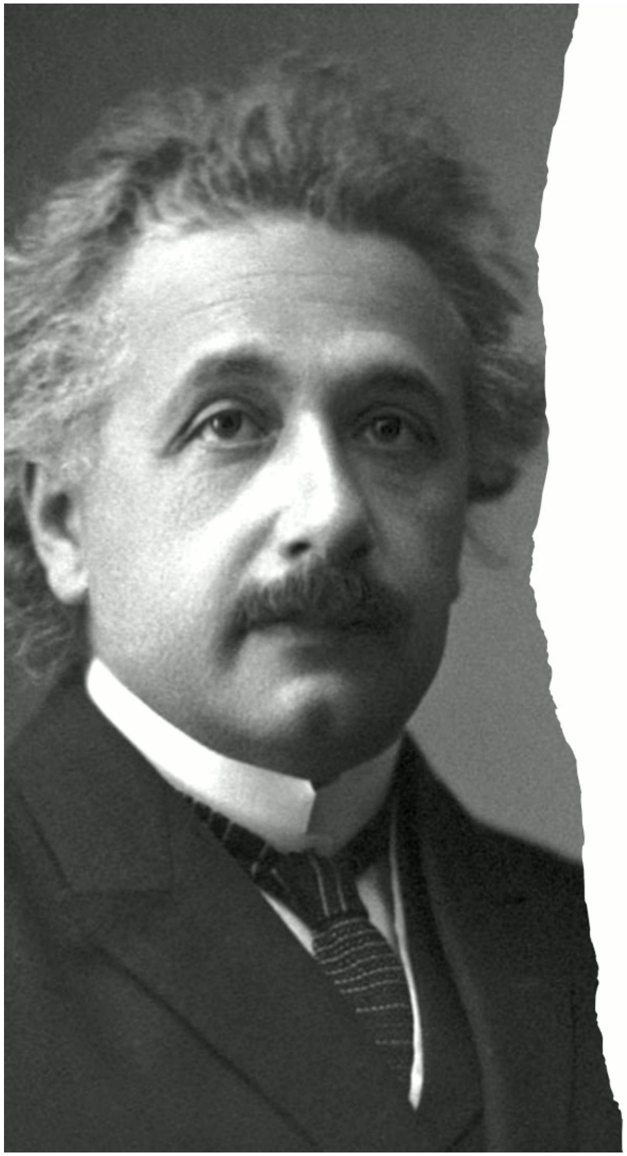
"for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"



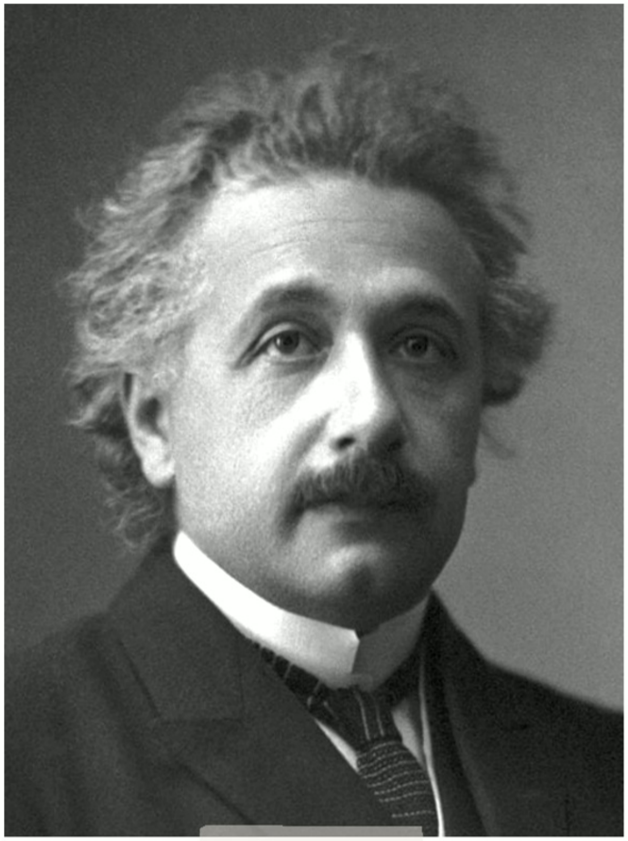
Spukhafte Fernwirkung

Einstein, March 1947, Letter to Max Born:

> "Ich kann aber deshalb nicht ernsthaft daran glauben, weil die Theorie mit dem Grundsatz unvereinbar ist, dass die Physik eine Wirklichkeit in Zeit und Raum darstellen soll, ohne spukhafte Fernwirkungen."

> "I cannot seriously believe [in quantum mechanics] because the theory is incompatible with the requirement that physics should represent reality in space and time without spooky action at a distance…"

This letter does not refer to entanglement.



Peculiar Action At a Distance

Einstein, 1927 Solvay Conference (quant-ph/0609184):

> "The interpretation, according to which [the square of the wave-function] expresses the probability that this particle is found at a given point, assumes an entirely peculiar mechanism of action at a distance, which prevents the wave continuously distributed in space from producing an action in two places on the screen."

This example does not refer to entanglement.

What is "Spooky Action"?

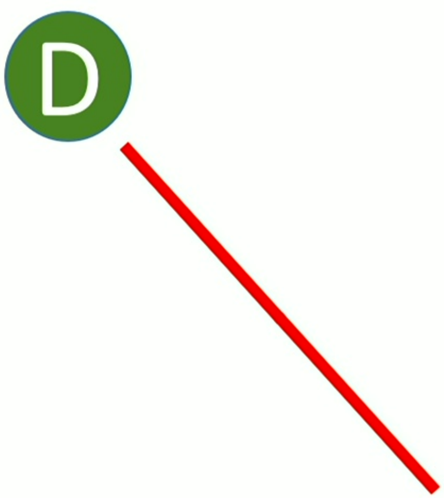
- I believe that Einstein was worried about the update (aka collapse aka reduction) of the wave-function.
- The collapse of the wave-function is instantaneous and generically faster-than light, worrisome ***if the wave-function is ontic*.***
- If the wave-function otoh is epistemic*, then the instantaneous update is nothing to worry about. In this case, so Einstein argued, quantum mechanics must be incomplete.

*not the Harrigans & Spekkens definition

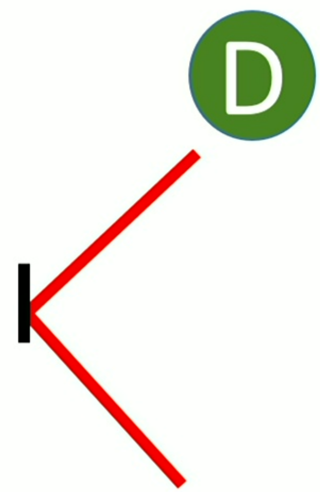
Modern Vintage

- The outcome of a measurement is determined by hidden variables (λ). The seemingly random outcome is due to our lack of knowledge of the precise state (as in classical systems).
- The wave-function is an ensemble (psi-epistemic).
- That the variables are "hidden" just means they don't appear in the formalism of quantum mechanics.

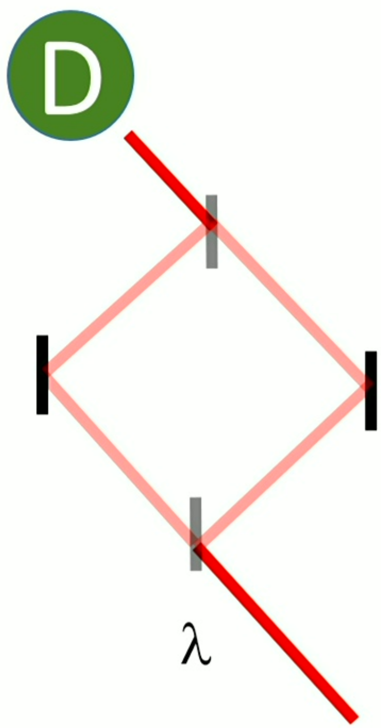
Why Superdeterminism



Why Superdeterminism

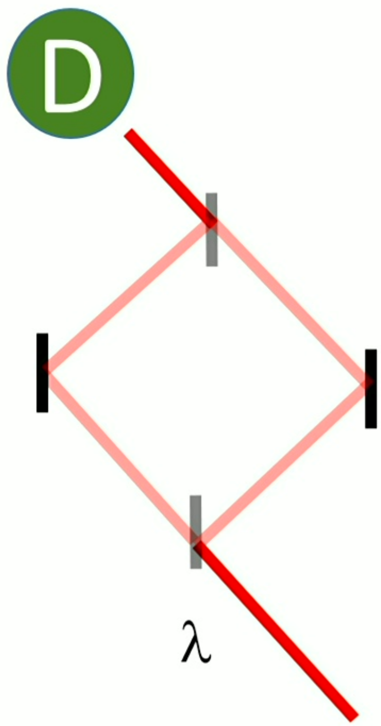


Why Superdeterminism



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

Why Superdeterminism



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

statistical independence is violated

Bell's Theorem in a Nutshell

Local Causality + Statistical Independence
⇒ Conflict with Observations

But we already know that to solve the measurement problem, statistical independence must be violated. Hence: All the interesting hidden variables theories violate the assumptions of Bell's theorem.

"for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

→ If nature is local, then it's superdeterministic.

Superdeterminism Definition

- Hidden variable theories which violate statistical independence are called "superdeterministic".
- Superdeterminism is not a theory, it's a property of a class of theories.
- Superdeterministic theories aren't any more deterministic than deterministic.
- Superdeterministic theories are not "classical" in any meaningful sense.

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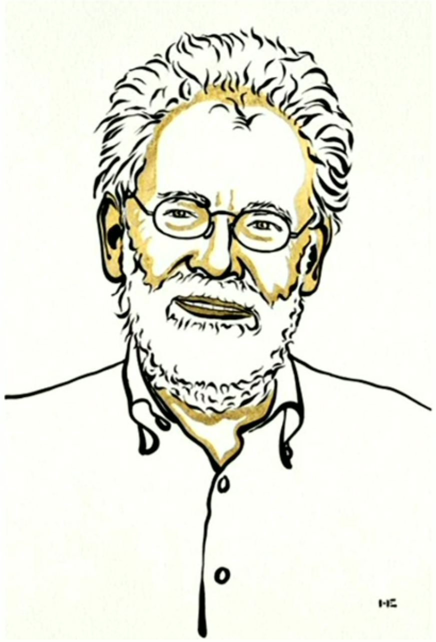

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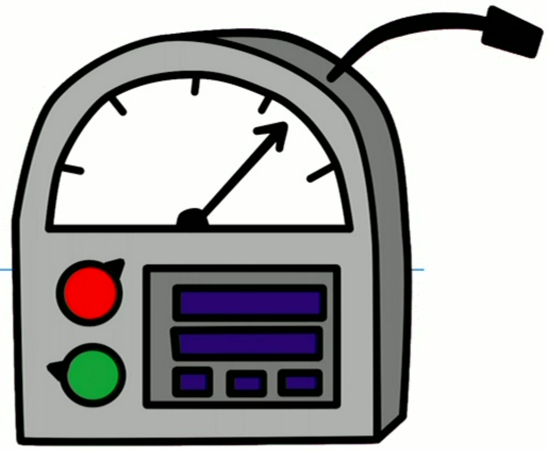
Unsolved Problems



The Heisenberg Cut
What's a detector? A fundamental theory should explain it.

The Collapse Problem
If interpreted as a physical process is not local. If not a physical process then what's the process?

Gravity
What happens with the source term if you "update" the wave-function?

Classical Limit
Chaotic systems are a problem.

Quantum Mechanics is Emergent

- The measurement postulate is an effective description for a process in an underlying, more fundamental, theory.
- This idea is supported by the apparent similarity between the classical Liouville equation and the v Neumann Dirac equation

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

- It is also supported by the fact that the $\hbar \to 0$ limit gives a statistical theory (see Klein 1201.0150 [quant-ph]).

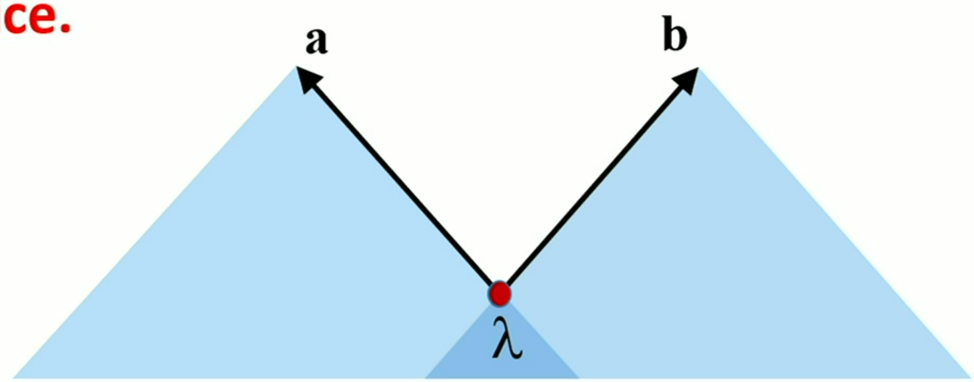
Locality

A violation of **statistical independence**:

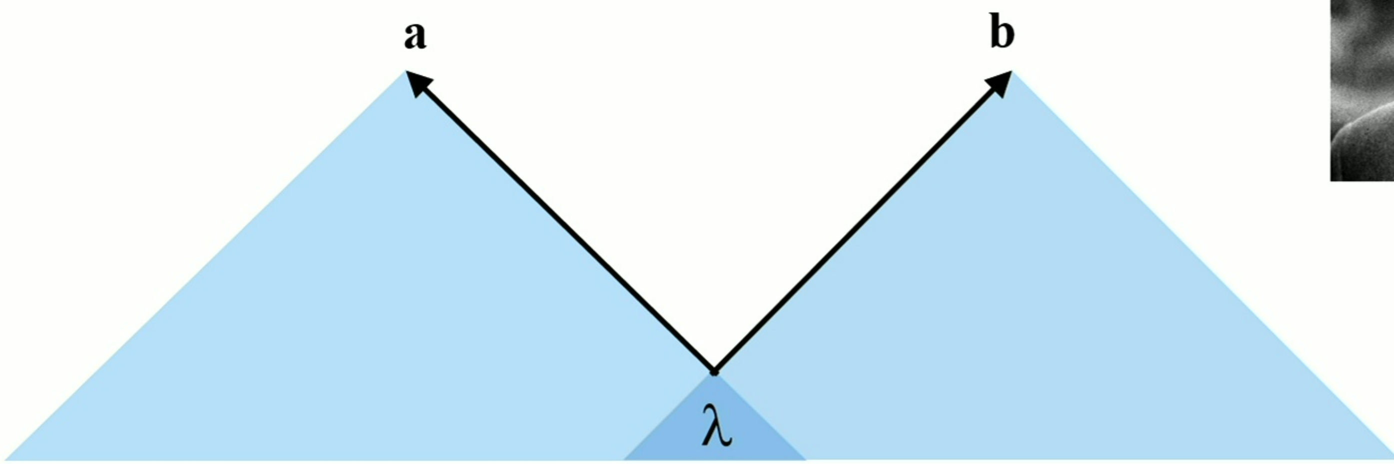
$$\rho(\lambda|\mathbf{a},\mathbf{b}) \neq \rho(\lambda)$$

Also sometimes called **measurement independence**, **free will** or **free choice.**

Does not violate local causality.



The Implicate Order

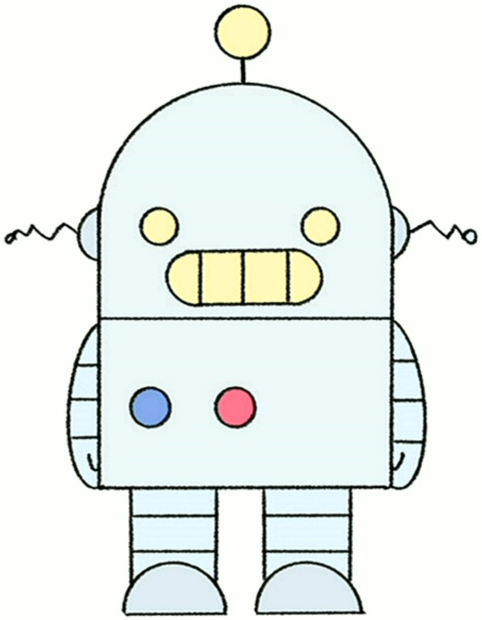


We can express the settings at the time of measurement by their initial state. The hidden variables therefore also correlate with this initial state. **This is why people think superdeterminism is a "conspiracy".** But we already know that the only degree of freedom that matters is the final setting. The initial state for the settings hence has an "implicate" order that becomes "explicate" at the measurement.

Free Will?

Statistical Independence is often referred to as **“Free Choice”** or **“Free Will”**. But fact is:

- Choosing detector settings does not necessarily require human actors.
- Free Will is hard to make sense of in any theory that is deterministic. This has nothing to do with superdeterminism in particular.
- The laws of nature always constrain what we can do. Again, that is not specific to superdeterminism.

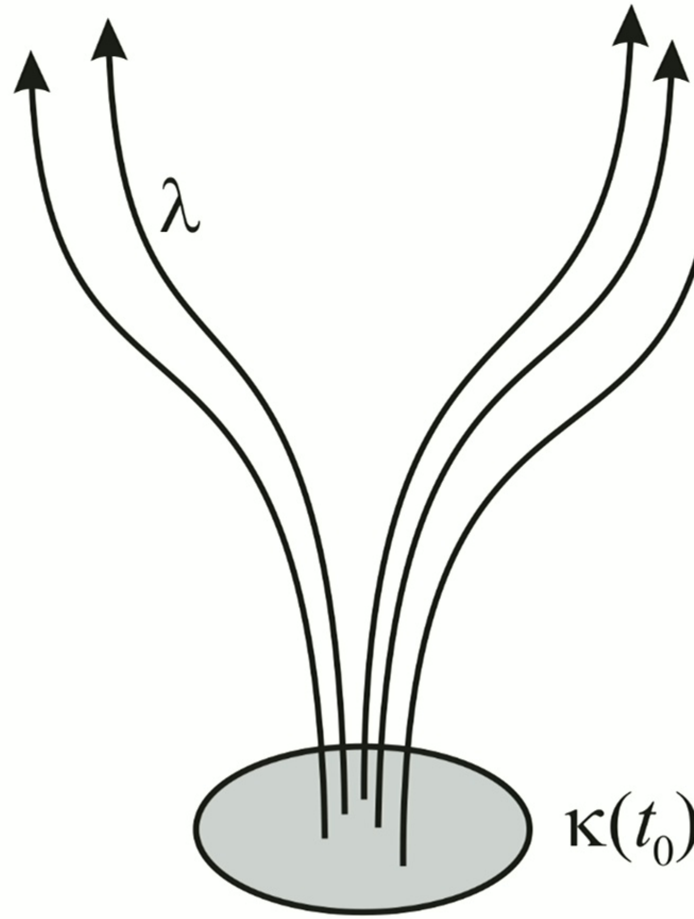


"Where" are the hidden variables?

The hidden variables are that what determines the outcome of the measurement. They are a combination of initial values and an evolution law (in the underlying theory).

⇒ **The hidden variables are labels for trajectories and not initial values.**

This means asking "where" they are makes no sense.



Does it destroy science?

- This notion of statistical independence which is relevant in quantum foundations has nothing to do with statistical independence in other areas of science.
- It is violated if and only if the Schrödinger evolution would lead to a superposition of detector eigenstates.
- It does not affect classical, macroscopic objects; it explains why we observe such objects in the first place!

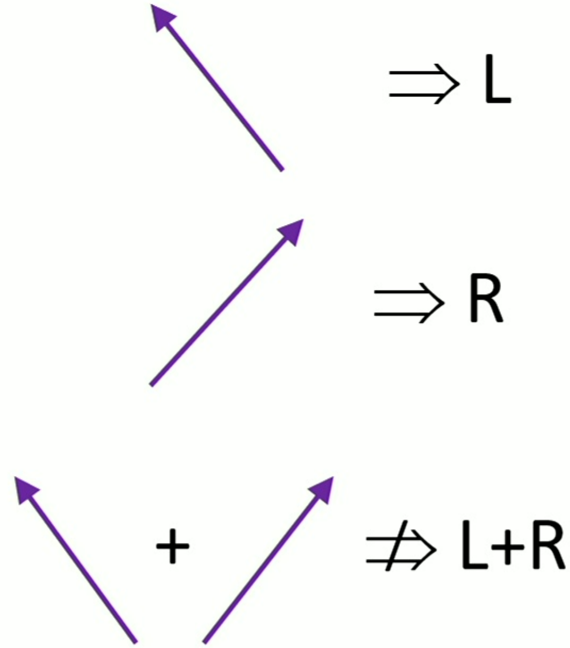
What does it mean?

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

Violating statistical independence means that what the prepared state does depends on the measurement settings at detection.

We don't know the setting, but we never do: We make predictions for all possible settings and then compare the prediction with the result. The theory has a "future input dependence" (Wharton & Argaman).

Most importantly…



The measurement process is not linear. Eigenstates of pointer states remain eigenstates, but superpositions of those Eigenstates don't remain superpositions.

This means **superdeterministic models are necessarily non-linear and quite possibly chaotic** (explaining why the hidden variables are hard to measure).

Sandro Donadi & SH, arXiv:2010.01327 [quant-ph]

Toy Model

- N-dimensional Hilbert space, define N complex hidden variables σ_N uniformly distributed in unit disk and from that

$$\lambda_N \quad := \quad |\alpha_N \sigma_N|^2 - \sum_{I=1}^{N-1} |\alpha_I|^2 (1 - |\sigma_N|^2) \qquad\qquad \alpha_I := \langle I | \Psi^*(t_\mathrm{d}) \rangle$$

- Define $N(N$-1)/2 Lindblad operators

$$L_{NM} \quad := \quad \theta(\lambda_N) |N\rangle\langle M| + \theta(-\lambda_N) |M\rangle\langle N|$$

- Add to master equation for density matrix:

$$\partial_t \rho(t) = -\mathrm{i}\,[H, \rho(t)] + \kappa \sum_{K>M=1}^{N} \left(L_{KM} \rho(t) L_{KM}^\dagger - \frac{1}{2} \{\rho(t), L_{KM}^\dagger L_{KM}\} \right)$$

Sandro Donadi & SH, arXiv:2010.01327 [quant-ph]

Toy Model (cont'd)

$$\partial_t \rho(t) = -\mathrm{i}\,[H, \rho(t)] + \kappa \sum_{K>M=1}^{N} \left(L_{KM}\rho(t)L_{KM}^{\dagger} - \frac{1}{2}\{\rho(t), L_{KM}^{\dagger}L_{KM}\} \right)$$

- The evolution of any initial prepared state ends up in a detector eigenstate.
- Exactly which eigenstate is determined by the hidden variables
- When averaged over the hidden variables, the probabilities agree with those predicted by quantum mechanics
- Ie: It's a deterministic, local, collapse process that reproduces quantum mechanics exactly → No finetuning necessary (duh)

Sandro Donadi & SH, arXiv:2010.01327 [quant-ph]

Toy Model

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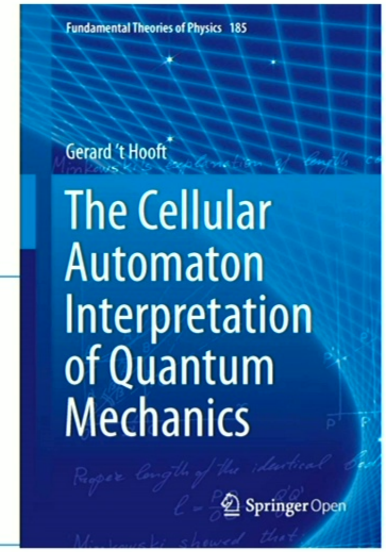
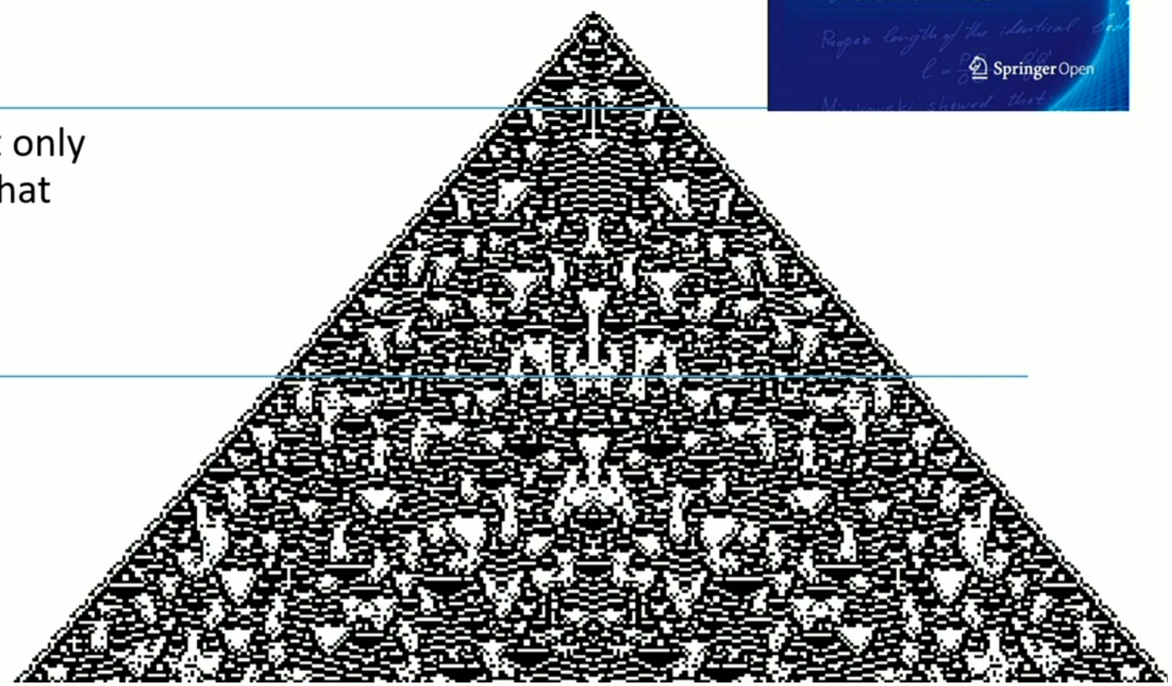
‘t Hooft’s Cellular Automata



A deterministic, local, quantum mechanical model with discrete space and time

Defeats Bell’s theorem by postulating that only some initial states are allowed, the ones that lead to results which agree with quantum mechanics

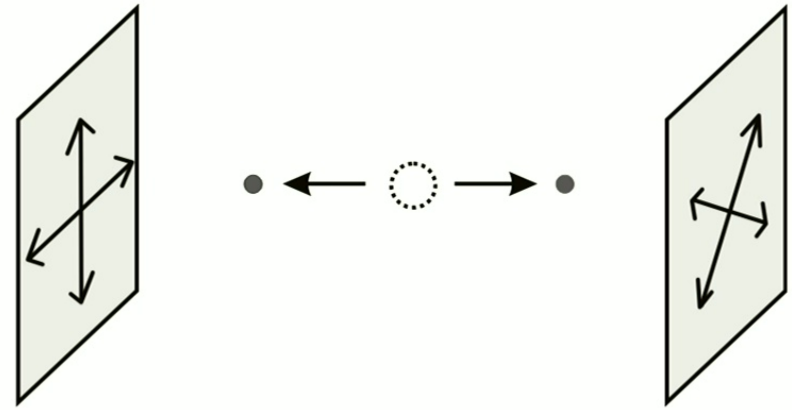
Problem: How to chose the initial state?
If it is chosen by the assumption that it reproduces observations, then the theory has no predictive power.



Palmer's Invariant Set

- State space is a fractal. It has *gaps* which are states that do not exist in physical reality.
- States that don't exist are close to those that do exist – using a Euclidean metric.
- Not all combinations of prepared states and detector settings exist, leading to correlations that violate Statistical Independence.
- Possible test: arXiv:2102.07795 [quant-ph]

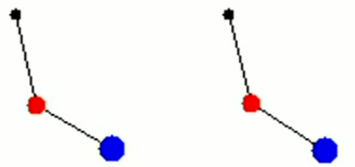
Bell-Type Tests



- 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.

→ Bell-type tests cannot rule out superdeterminism.

Remember it's non-linear



[animation: uwaterloo.ca]

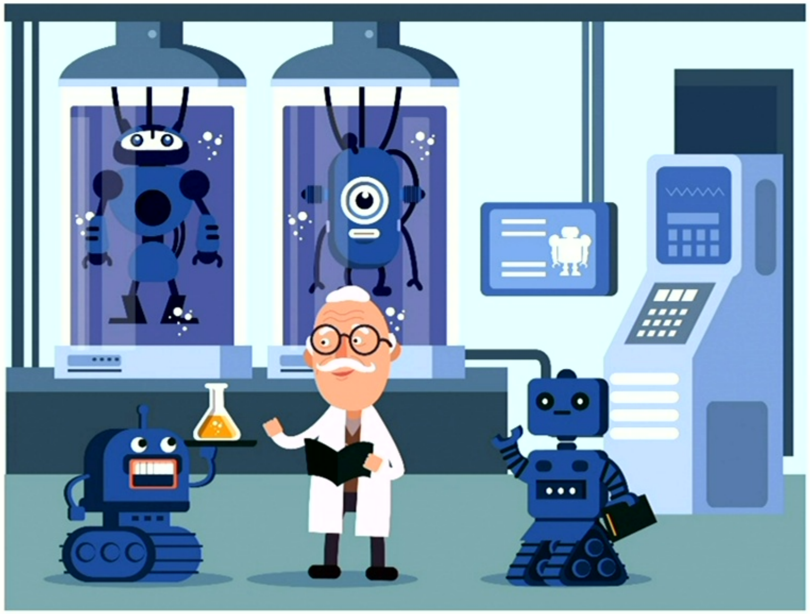
Quantum mechanics is the long-term average. That's the best we can do in the chaotic limit.

To find evidence for the deterministic part of the evolution we have to closely control initial conditions (this includes the detector!) and measure quickly.

Detailed predictions depend on the model.

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.



What is it good for?

If quantum mechanics is not fundamental, then its bounds and inequalities aren't fundamental either. This means the limitations posed by the uncertainty principle can be overcome.

Superdeterminism…

… is in my opinion our best chance to make progress in the foundations of physics.

Example of Path Integral

We* are currently trying the following:

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

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

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

* Sandro Donadi, SH 2110.07168 [quant-ph]