Title: Quantum Mechanics as Classical Physics

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Abstract: On the face of it, quantum physics is nothing like classical physics. Despite its oddity, work in the foundations of quantum theory has provided some palatable ways of understanding this strange quantum realm. Most of our best theories take that story to include the existence of a very non-classical entity: the wave function. Here I offer an alternative which combines elements of Bohmian mechanics and the many-worlds interpretation to form a theory in which there is no wave function. According to this theory, all there is at the fundamental level are particles interacting via Newtonian forces. In this sense, the theory is classical. However, it is still undeniably strange as it posits the existence of many worlds. Unlike the many worlds of the many-worlds interpretation, these worlds are fundamental, not emergent, and are interacting, not causally isolated. The theory will be presented as a fusion of the many-worlds interpretation and Bohmian mechanics, but can also be seen as a foundationally clear version of quantum hydrodynamics. A key strength of this theory is that it provides a simple and compelling story about the connection between the amplitude-squared of the wave function and probability. The theory also gives a natural explanation of the way the wave function transforms under time reversal and Galilean boosts.

Quantum Mechanics as Classical Physics

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A Strange Interpretation of QM

- Deterministic, no collapse
- No wave function, no Schrödinger equation
- Many worlds
- Worlds do not branch
- The number of worlds is finite
- Particles follow Bohmian trajectories
- Equation of motion of the form $F = ma$

The theory proposed is a version of the hydrodynamic interpretation, originally proposed by Madelung (1927) and developed by Takabayasi (e.g., 1952).

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3

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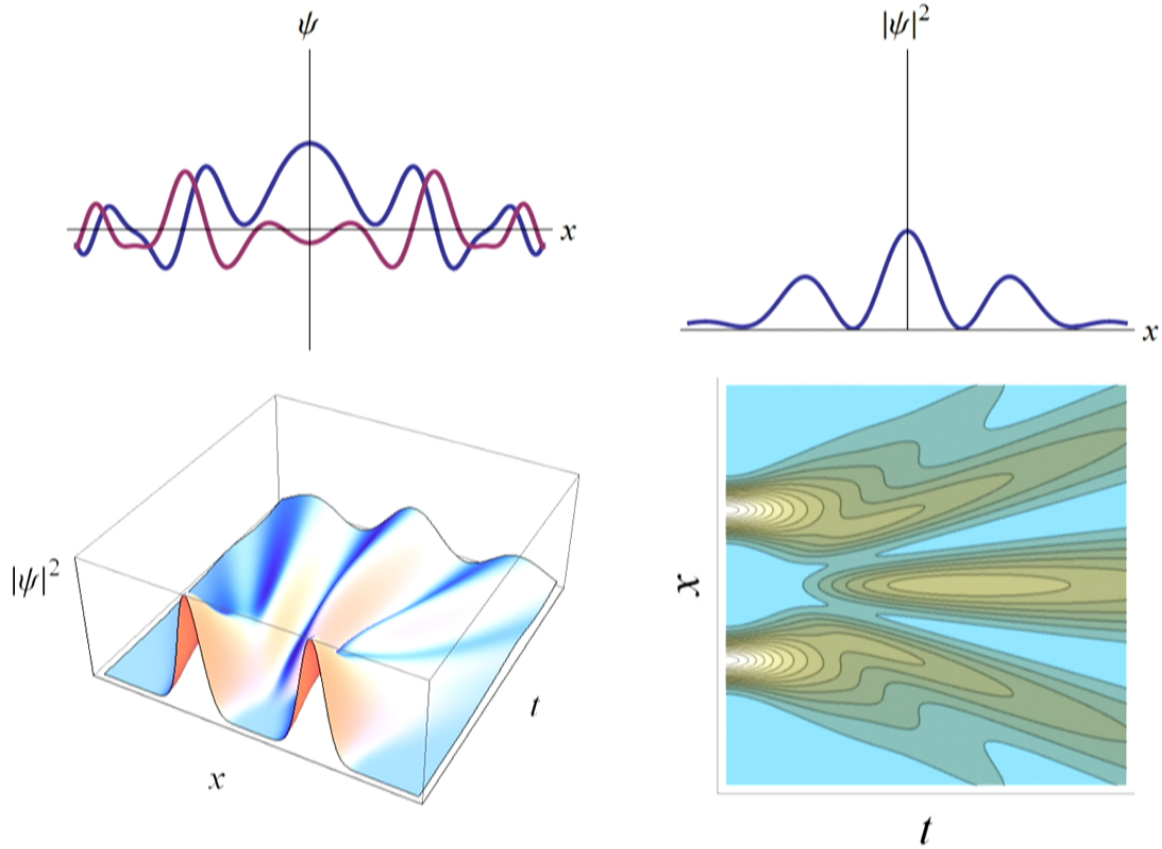
Outline

I. A Series of Solutions to the Measurement Problem
   a) The Many-worlds Interpretation
   b) Bohmian Mechanics
   c) Prodigal QM
II. Newtonian Quantum Mechanics
   a) Probability
   b) Time Reversal
III. A Weakness: Non-quantum States

Refresher: The Double-slit Experiment



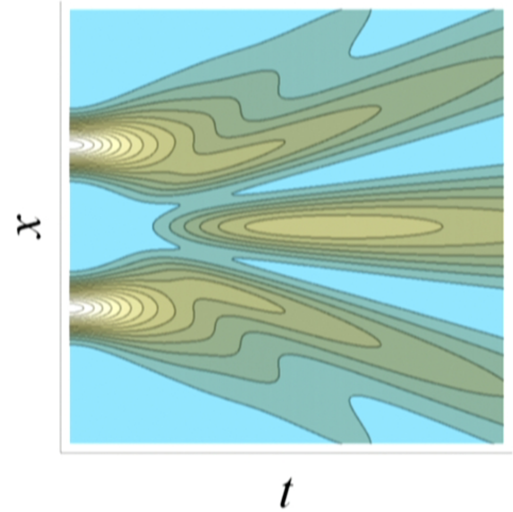
5

Solution 1: Everettian QM

What there is (Ontology):

The Wave Function

$$\Psi(\vec{x}_1, \vec{x}_2, ..., t)$$



What it does (Laws):

Schrödinger Equation

$$i\hbar\frac{\partial}{\partial t}\Psi(\vec{x}_1, \vec{x}_2, ..., t) = \widehat{H}\Psi(\vec{x}_1, \vec{x}_2, ..., t)$$

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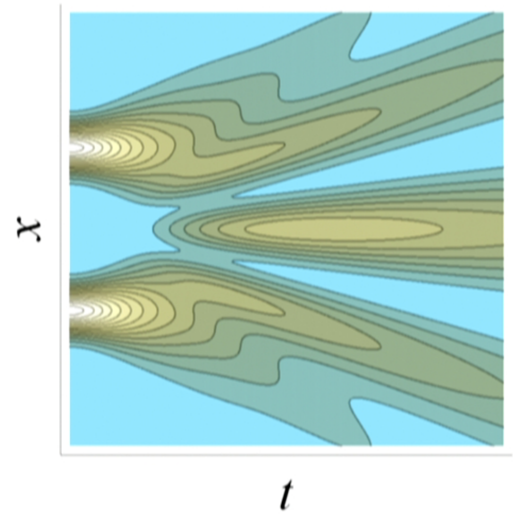

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6

Solution 2: Bohmian QM

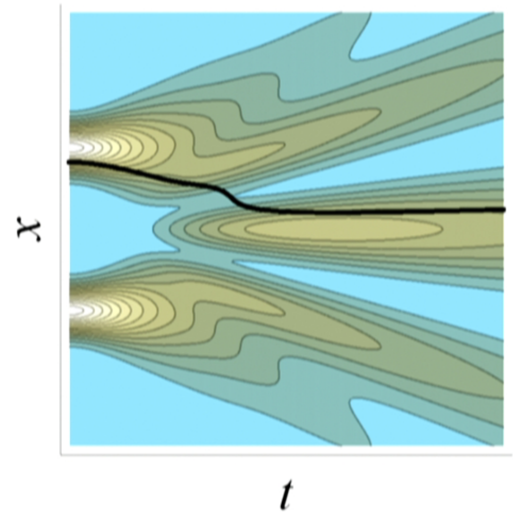
Ontology:

The Wave Function

$$\Psi(\vec{x}_1, \vec{x}_2, ..., t)$$

Particles

$$\vec{x}_k(t) \qquad \vec{v}_k(t)$$



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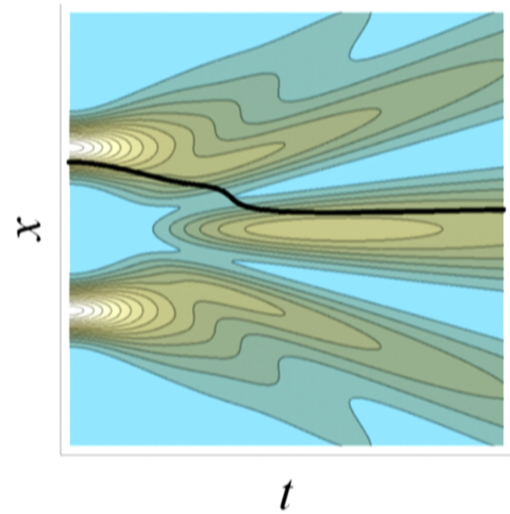

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Solution 3: Prodigal QM

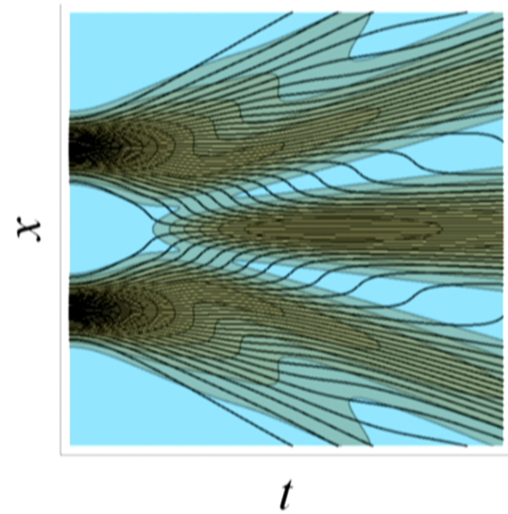
Ontology:

The Wave Function

$$\Psi(\vec{x}_1, \vec{x}_2, ..., t)$$

Particles (in many worlds)

$$\rho(\vec{x}_1, \vec{x}_2, ..., t) \quad \vec{v}_k(\vec{x}_1, \vec{x}_2, ..., t)$$



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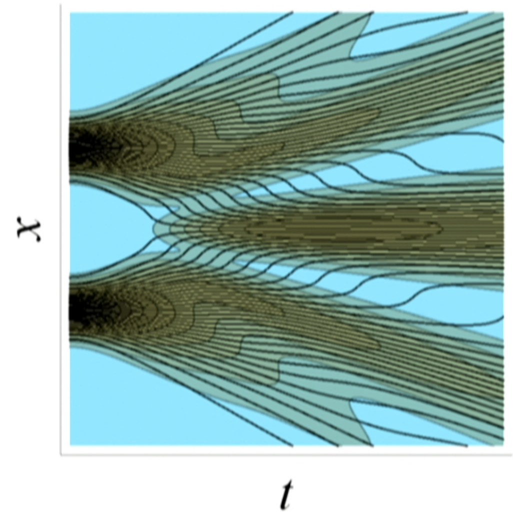

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8

Two Important Characters: ρ & $\vec{v}_k$

- $\rho(\vec{x}_1, \vec{x}_2, ..., t)$ is the **density of worlds** in configuration space, scaled so that $\int dV_1 dV_2 ... \rho = 1$.
- By hypothesis, $\rho = |\Psi|^2$.
- $\vec{v}_k(\vec{x}_1, \vec{x}_2, ..., t)$ gives the velocity of the k-th particle in the world where particles are arranged $\langle \vec{x}_1, \vec{x}_2, ... \rangle$.
- The evolution of ρ is determined by the velocities of the particles in the various worlds by a *continuity equation*: $$\frac{\partial \rho}{\partial t} = -\sum_k \vec{\nabla}_k \cdot (\rho \vec{v}_k)$$

Parallel: Fluid Dynamics

- $\rho(\vec{x}, t)$ is the density of the fluid.
- $\vec{v}(\vec{x}, t)$ gives the velocity of a particle at $\vec{x}$.
- The continuity equation for the fluid is: $$\frac{\partial \rho}{\partial t} = -\vec{\nabla} \cdot (\rho \vec{v})$$

9

The Evolution of $\vec{v}_k$

From the following facts one can derive the double boxed equation below.

- Worlds are distributed in accordance with psi-squared: $\rho = |\Psi|^2$
- The Schrödinger equation:

$$i\hbar\frac{\partial}{\partial t}\Psi(\vec{x}_1, \vec{x}_2, ..., t) = \left(\sum_k \frac{-\hbar^2}{2m_k}\nabla_k^2 + V(\vec{x}_1, \vec{x}_2, ..., t)\right)\Psi(\vec{x}_1, \vec{x}_2, ..., t)$$

- The guidance equation:

$$\vec{v}_k(\vec{x}_1, \vec{x}_2, ..., t) = \frac{\hbar}{m_k}\mathrm{Im}\left[\frac{\vec{\nabla}_k\Psi(\vec{x}_1, \vec{x}_2, ..., t)}{\Psi(\vec{x}_1, \vec{x}_2, ..., t)}\right]$$

$$\boxed{\boxed{m_k\vec{a}_k = -\vec{\nabla}_k\left[\sum_j \frac{-\hbar^2}{2m_j}\left(\frac{\nabla_j^2\sqrt{\rho}}{\sqrt{\rho}}\right) + V\right]}}$$

This equation gives a way of calculating the evolution of $\vec{v}_k$, and hence ρ, which never references the wave function Ψ.

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The quantum potential Q.

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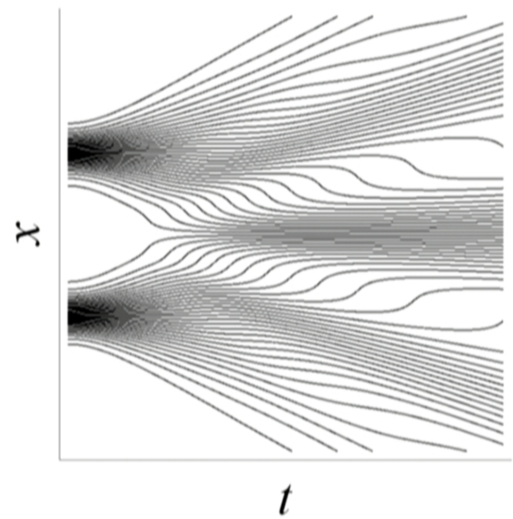
Solution 4: Newtonian QM

Ontology:

Particles (in many worlds)

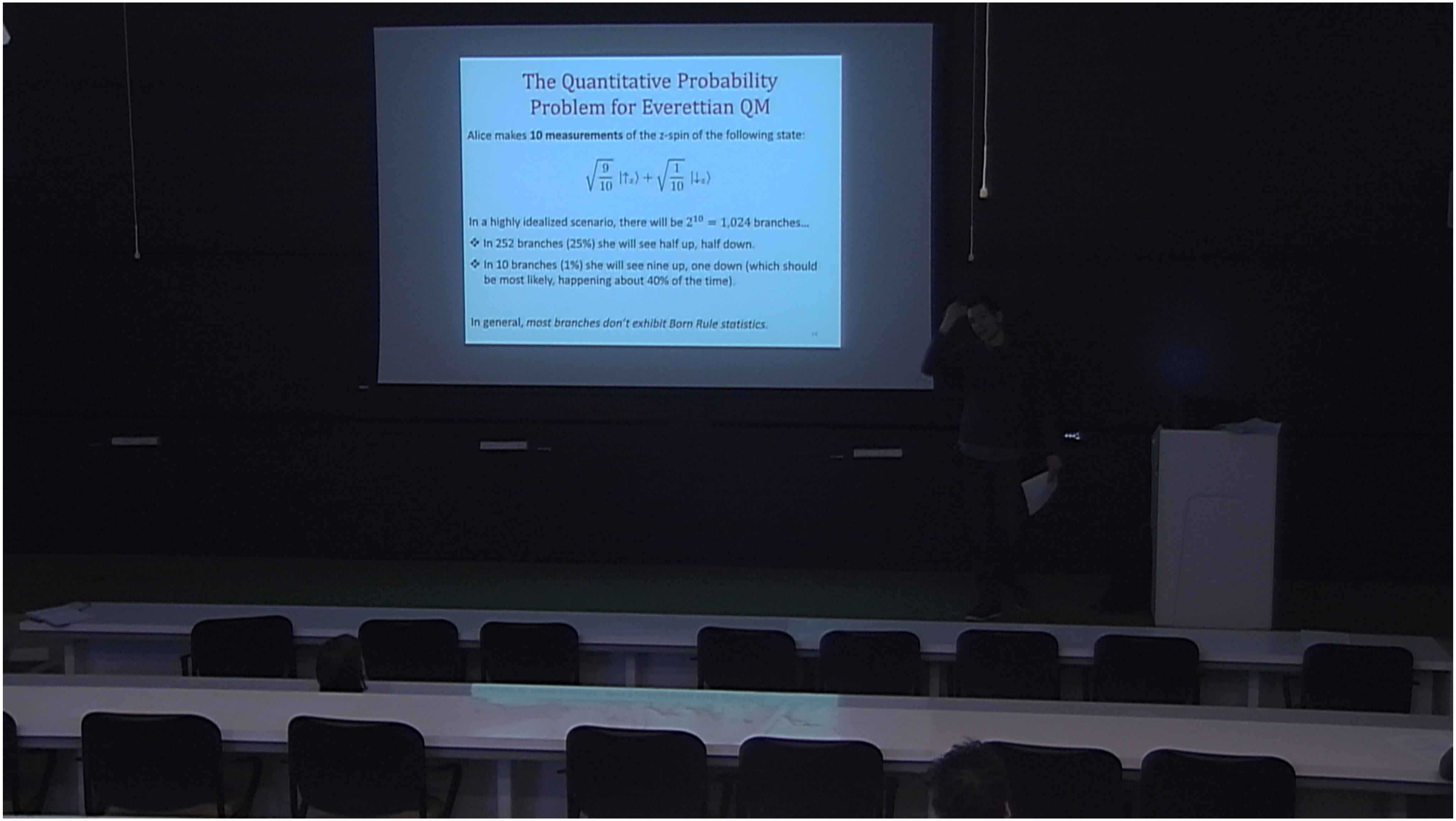
$$\rho(\vec{x}_1, \vec{x}_2, ..., t) \quad \vec{v}_k(\vec{x}_1, \vec{x}_2, ..., t)$$



Law:

Newtonian Force Law

$$m_j \vec{a}_j = -\vec{\nabla}_j \left[\sum_k \frac{-\hbar^2}{2m_k} \left(\frac{\nabla_k^2 \sqrt{\rho}}{\sqrt{\rho}} \right) + V \right]$$


The Quantitative Probability Problem for Everettian QM
Alice makes 10 measurements of the z-spin of the following state:
$\sqrt{\frac{9}{10}}\,|\uparrow_z\rangle + \sqrt{\frac{1}{10}}\,|\downarrow_z\rangle$
In a highly idealized scenario, there will be $2^{10} = 1{,}024$ branches...
In 252 branches (25%) she will see half up, half down.
In 10 branches (1%) she will see nine up, one down (which should be most likely, happening about 40% of the time).
In general, most branches don't exhibit Born Rule statistics.

Versus Bohmian Mechanics

- In Newtonian QM, each world follows a Bohmian trajectory through configuration space. So, if Bohmian mechanics can reproduce the predictions of textbook QM, Newtonian QM should be able to also.
- Some Bohmian trajectories don't predict quantum statistics.
- The correct long-run quantum statistics will be observed if the universe satisfies the **quantum equilibrium hypothesis**.

Quantum Equilibrium Hypothesis (Teufel 2013, *rough version*):

"The initial wave function $\Psi(0)$ and configuration $Q(0)$ of the "universe" are such that the empirical distributions of subsystem configurations $X_i(t_i)$ of (different) subsystems at (different) times t_i with the same conditional wave function φ_{cond} are close to the $|\varphi_{cond}|^2$-distribution."

16

Neat Features of Newtonian QM

- Wave function is a mere summary of the properties of particles
- No superpositions
- No entanglement
- No collapse
- No mention of "measurement" in the laws
- All dynamics arise from Newtonian forces
- The theory is deterministic
- Worlds are fundamental, not emergent (so avoids the need to explain how people and planets arise as structures in the WF)
- Worlds do not branch (so avoids concerns about personal identity)
- No incoherence probability problem
- No quantitative probability problem
- Immune to Everett-in-denial objection,* not in denial

* See Deutsch (1996), Brown & Wallace (2005)

Ontological Options

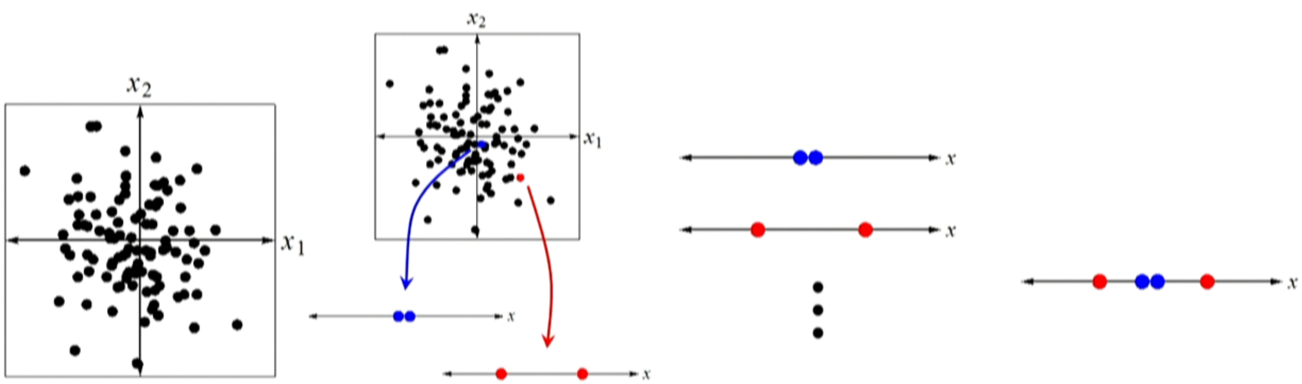
Option 1: World-particles in Configuration Space

Option 2: World-particles in Configuration Space and 3D Worlds

Option 3: Distinct 3D Worlds

Option 4: Overlapping 3D Worlds

Shown below for two particles in one dimensional space…



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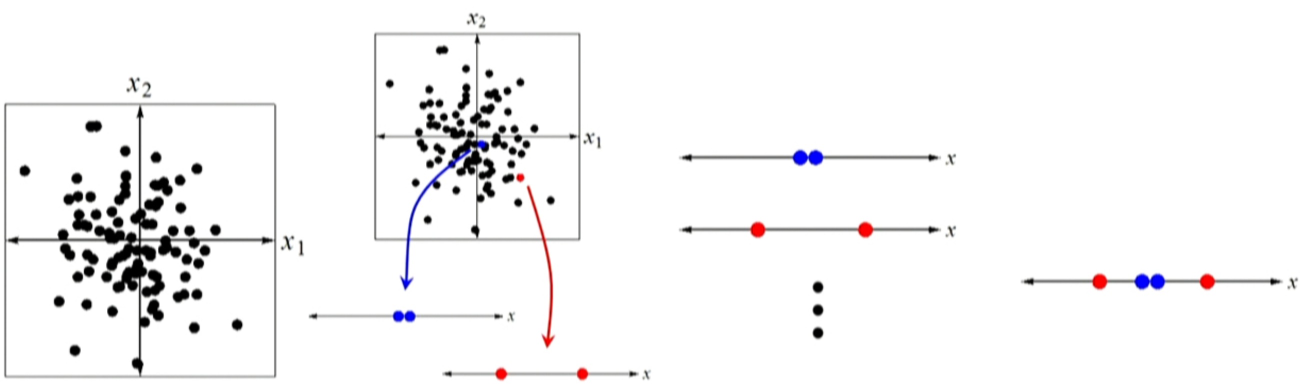

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29