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Howard M. Wiseman, Eric G. Cavalcanti

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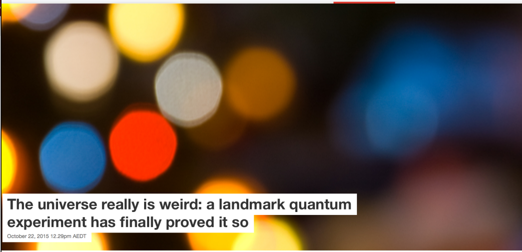

The universe really is weird: a landmark quantum experiment has finally proved it so

October 22, 2015 12.29pm AEDT

Measuring the photons in an entangled state was part of the experiment. Flickr/Alexandre Normand, CC BY

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Only last year the world of physics celebrated the 50th anniversary of Bell's theorem, a mathematical proof that certain predictions of quantum mechanics are incompatible with local causality. Local causality is a very natural scientific assumption and it holds in all modern scientific theories, except quantum mechanics.

Author

Howard Wiseman
Professor in Physics, Griffith

Ensembles of Bohmian trajectories: Real, Surreal, and Hyper-real

Howard M. Wiseman & (Michael J. Hall & Dirk-André Deckert)
& (Dylan Mahler & Lee Rozema & Kent Fisher & Lydia Vermeyden
& Kevin J. Resch & **Aephraim Steinberg**)

Centre for Quantum Dynamics

Griffith UNIVERSITY

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1. Orthodox Quantum Mechanics: who could ask for anything more?
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The Problems with Quantum Theory

"Quantum Theory has a lot of problems"

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Problems:

- The mathematical formalism is remote from the everyday world.
- Bell's theorem: it cannot be replaced by a local realistic (causal) process in space-time.

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The Problems with Quantum Theory

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Attitudes:

- **Operationalism:** QT describes only what we (macroscopic observers) expect to happen. But how can *we* be real if we are made up of quantum particles?
- **Realism:** Macroscopic observers are real because there is a reality for all quantum systems.

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Types of Realism

All about the quantum state $|\Psi(t)\rangle$ or wavefunction $\Psi(\mathbf{q}, t)$:

- For simplicity consider a D-dimensional universe comprising P scalar nonrelativistic distinguishable particles, and no fields.
- e.g. for $D = 3$ the pth particle has position $(q_{3p-2}, q_{3p-1}, q_{3p})^\top$, so the total configuration variable $\mathbf{q} = \{q_1, \cdots, q_K\}^\top$, $K = DP$.
- Then $i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{q}, t) = \left[V(\mathbf{q}) - \sum_{k=1}^{K} \frac{\hbar^2}{2m_k}\left(\frac{\partial}{\partial q_k}\right)^2\right]\Psi(\mathbf{q}, t)$.

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2. $\Psi(\mathbf{q}, t)$ or $|\Psi(t)\rangle$, *and something else* more connected with the everyday world, is real. **Hidden Variables Interpretations**
3. *Only something else*, which is connected with, but not limited to, the everyday world, is real. e.g. **Many Interacting Worlds**

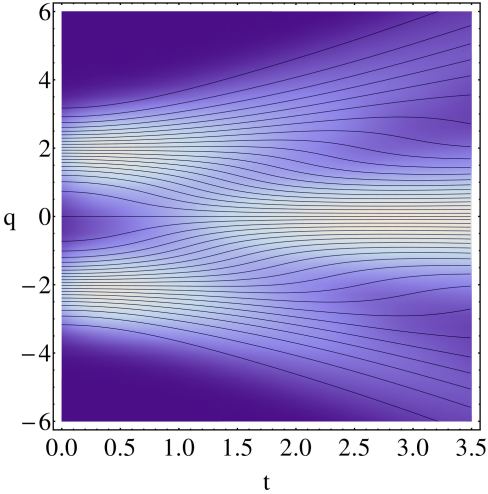
Realism Type 2: Hidden Variables Interpretations

e.g. the de Broglie–Bohm interpretation.

- $\Psi(\mathbf{q}, t)$ is a real "wave" in configuration space.
- In addition there is a *single* real configuration $\mathbf{x}(t)$.
- It is "piloted" by $\Psi(\mathbf{q}, t)$ (de Broglie, 1927):

$$\dot{x}_k(t) = \frac{\hbar}{m_k} \mathrm{Im} \frac{\frac{\partial}{\partial x_k} \Psi(\mathbf{x}; t)}{\Psi(\mathbf{x}; t)}$$

- The *a priori* probability distribution for $\mathbf{x}$ at $t = t_0$ is $P(\mathbf{x}; t_0) = |\Psi(\mathbf{x}; t_0)|^2$.



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Non-uniqueness of Bohmian mechanics

- Experientially adequate hidden variable theories can be formulated for all sorts of variables, not just position $\mathbf{x}$.
- In general they have to be stochastic (Bell, 1984).
- Even restricting to position $\mathbf{x}$ and deterministic dynamics,

$$\dot{\mathbf{x}} = \mathbf{v}_{\psi(t)}(\mathbf{x}),$$

there are infinitely many functional expressions for $\mathbf{v}_{\bullet}(\bullet)$:

$$\partial P_{\psi(t)}(\mathbf{x})/\partial t + \nabla \cdot [P_{\psi(t)}(\mathbf{x};t)\mathbf{v}_{\psi(t)}(\mathbf{x})] = 0,$$

with $P_{\psi(t)}(\mathbf{x}) = \langle\psi(t)|\mathbf{x}\rangle\langle\mathbf{x}|\psi(t)\rangle$.

- $\Longrightarrow$ why believe $\mathbf{x}$ and its Bohmian dynamics is **real**?

Outline

Motivating Bohmian mechanics

- If we require determinism then the HV must have a continuous spectrum like $\hat{q}$ or $\hat{p}$.
- If we assume the ability to do weak and strong measurements, and define (HMW, NJP, 2007)

$$\mathbf{v}_{\psi(t)}(\mathbf{x}) = \lim_{\tau\to 0} \tau^{-1}\,\mathrm{E}_{\psi(t)}[\mathbf{q}_{\rm strong}(t+\tau) - \mathbf{q}_{\rm weak}(t)|\mathbf{q}_{\rm strong}(t+\tau) = \mathbf{x}]$$

$$\text{or} = \lim_{\tau\to 0} \mathrm{E}_{\psi(t)}[(d\mathbf{q}/dt)_{\rm weak}(t)|\mathbf{q}_{\rm strong}(t+\tau) = \mathbf{x}],$$

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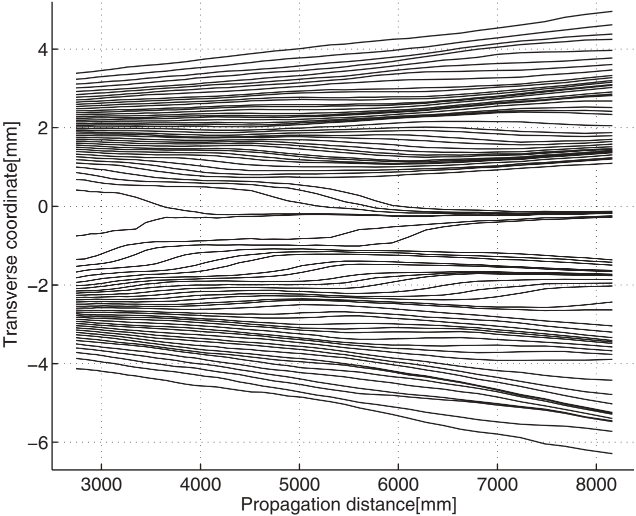
  then we get the standard Bohmian expression for $\mathbf{v}_{\psi(t)}(\mathbf{x})$ ...
- as long as $\hat{H}$ is at most quadratic in operators canonically conjugate to $\hat{\mathbf{x}}$ ...
- which is actually a *feature* because it forces us to choose $\hat{\mathbf{x}} = \hat{\mathbf{q}}$ rather than $\hat{\mathbf{x}} = \hat{\mathbf{p}}$.

Experiment [Kocsis & *al.* & Steinberg (Science, 2011)]

- ... and one can measure it (even as a "naive experimentalist")



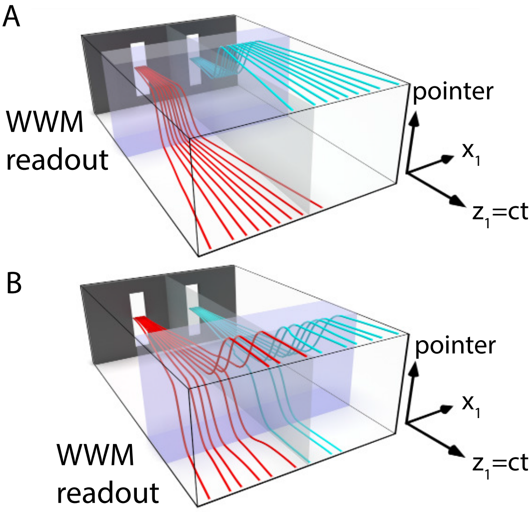
Note that it is **not** possible to follow an individual particle.

These trajectories are created by patching together little increments inferred from the weak velocities.

Outline

"Surreal Trajectories"

- Englert, Scully, Süssman, and Walther (1992).
- Three Q. systems:
  1. particle 1 (x_1 and $z_1 = ct$),
  2. the WWM device ("spin" $|H\rangle / |V\rangle$),
  3. particle 2 (x_2), the "pointer".
- In BM, the WWM information is not "real" until it has moved the pointer.



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Surreal trajectories, and "nonlocality"

With delayed readout, Bohmian theory says

- $\mathbf{v}_1(x_1, x_2; t) =$

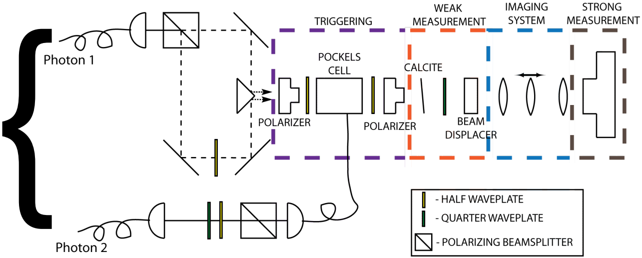
  $\frac{\mathbf{v}_1^{\text{left}}(x_1;t)+\mathbf{v}_1^{\text{right}}(x_1;t)}{2}$

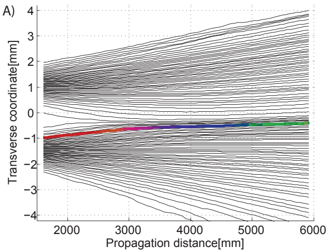
  = weak-valued velocity of particle 1 alone.

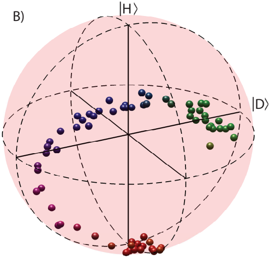
- $\mathbf{s}_2(x_1, x_2; t)$

  $= \mathbf{s}_2(x_1; t)$

  = weak-(or strong-)valued spin of particle 2.



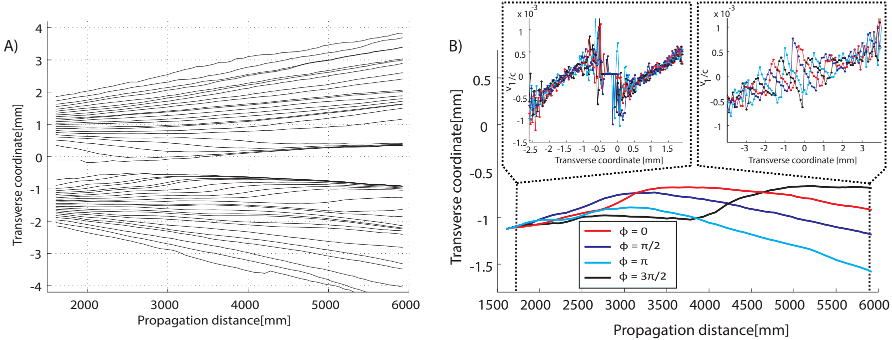




Real Nonlocality ("Setting Dependence")

With *immediate* readout, Bohmian theory says

- $\mathbf{v}_1(x_1, x_2; t) = \mathbf{v}_1(x_1, \text{outcome}; t)$
  = 1's w.v. velocity conditioned on readout of 2's polarization.
- To best see nonlocality, use two "quantum eraser" readouts i.e. $|\Theta\rangle / |\Theta + \pi\rangle$, where $|\Phi\rangle \equiv \frac{|H\rangle - e^{i\Phi}|V\rangle}{\sqrt{2}}$, for $\Theta = 0$ and $\Theta = \pi/2$.



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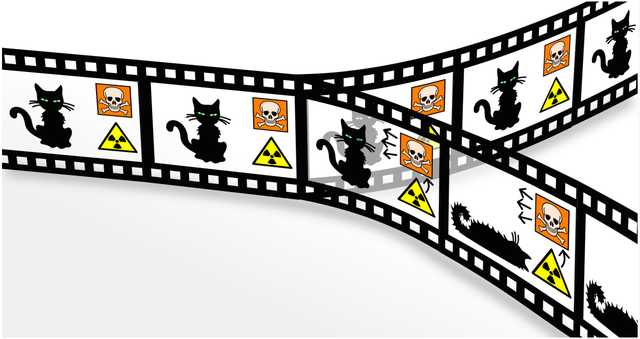
Realism Type 1: the "Many Worlds Interpretation"

- $\Psi(\mathbf{q}, t)$ is highly structured, and at any time t, $|\Psi(\mathbf{q}, t)|$, when smoothed out a bit, has local maxima at a vast number of macroscopically different configurations $\{\tilde{\mathbf{q}}_1, \tilde{\mathbf{q}}_2, \ldots\}$.
- These configurations, $\{\tilde{\mathbf{q}}\}$ are the "many worlds" (de Witt, 1973)
- As time increases, each local maximum is liable to split into one or more local maxima — a "branching" or "splitting" (Everett, 1957).



Issues with the Many Worlds Interpretation (MWI)

1. It is not clear exactly what is real.
   - Is it $\Psi(\mathbf{q};t)$? But in an abstract sense it is just a vector in Hilbert state $|\Psi(t)\rangle$, so how can it have any "structure"?
   - Is it the local maxima $\{\tilde{\mathbf{q}}\}$ of the coarse-grained $|\Psi(\mathbf{q},t)|$, the "worlds"? But this coarse-graining is vague; the number of worlds is not defined; and the timing of the splitting is also not defined.

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2. Some worlds are more real than others.
   - When a world splits, some daughter worlds are "bigger" than others:

$$|\Psi(t)\rangle \to \alpha|\Psi_1(t+\tau)\rangle + \beta|\Psi_2(t+\tau)\rangle \; ; \quad |\alpha| > |\beta|.$$

   - But each world will feel equally real to its respective inhabitants (our future selves, at time $t+\tau$).
   - So we should I care more about my future self in the world 1, and in particular why should I care in the ratio $|\alpha|^2 : |\beta|^2$?

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3. If the worlds really split, why not just postulate that the branches I don't experience get pruned? They have no effect on anything!

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Bohmian mechanics in the light of the MWI

Empty Waves

- If $\Psi(\mathbf{q}, t)$ is real in Bohmian mechanics, isn't it just "Many Worlds in denial"?
- The true configuration $\mathbf{x}(t)$ will typically be near one of the MWI-worlds $\tilde{\mathbf{q}}(t)$.
- What about all of the "empty" MWI-worlds? Won't their denizens still *feel* real even with no $\mathbf{x}$?

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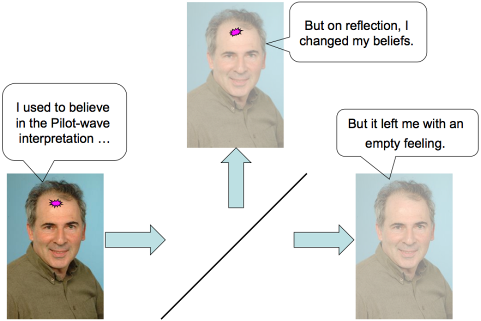

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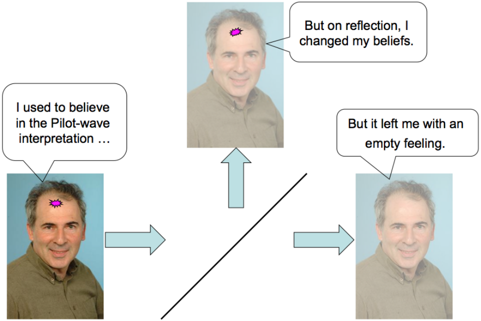

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Also, Probability

- Why should the wavefunction play this dual role of pilot wave and defining the *a priori* probability distribution for $\mathbf{x}$?

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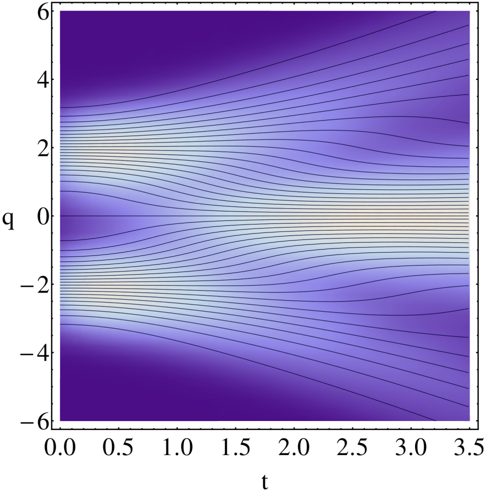
Repulsive trajectories?



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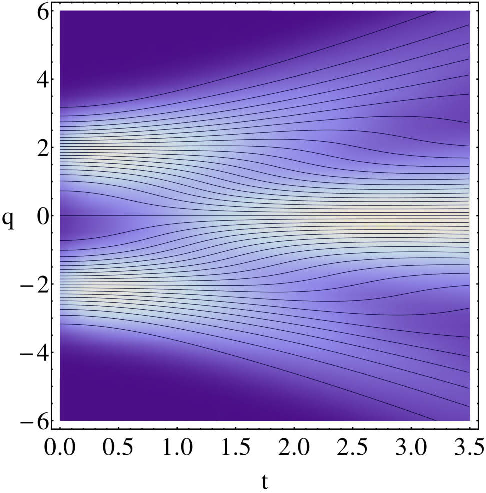

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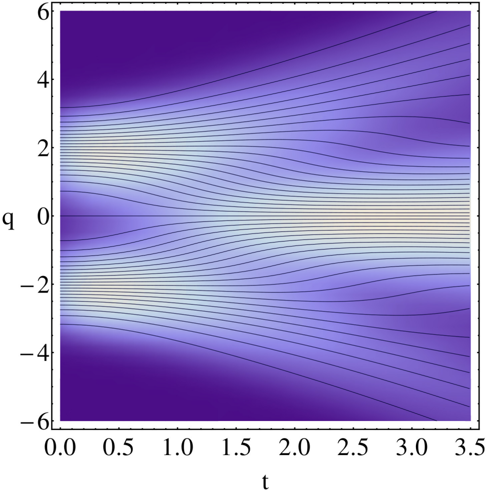
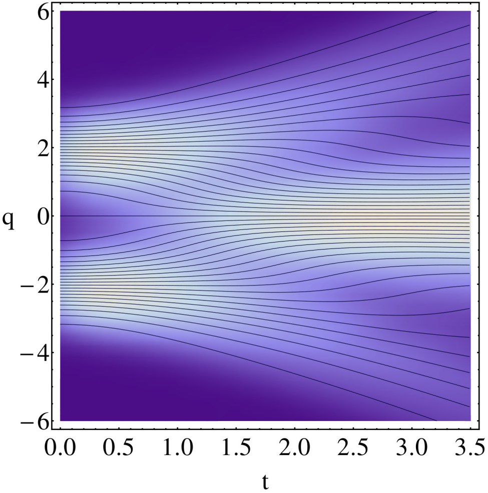


- Suggestive of trajectories for a bunch of particles which repel one another.
- Why not take this literally?
- Bill Poirier, “Bohmian mechanics without pilot waves” Chem. Phys. (2010) developed this theory for a *continuous* ensemble of particles.

Repulsive trajectories?



- Suggestive of trajectories for a bunch of particles which repel one another.
- Why not take this literally?
- Bill Poirier, “Bohmian mechanics without pilot waves” Chem. Phys. (2010) developed this theory for a *continuous* ensemble of particles.
- We think it is clearer to imagine a finite (but very large) ensemble: Phys. Rev. X **4**, 041013 (2014).

A single particle; many Bohmian worlds

- Consider a "world" comprising a *single* nonrelativistic *particle* of mass m, in one spatial dimension with potential $V(q)$.
- In Bohm's 1952 formulation a particle obeys a modified force law,

$$m\ddot{x}(t) = -\frac{\partial}{\partial q}[V(q) + Q(q)]\bigg|_{q=x(t)},$$

  with "quantum potential" $Q(q) = |\psi(q,t)|^{-1}\frac{-\hbar^2}{2m}|\psi(q,t)|''$.
- Let there be $N \gg 1$ worlds $\{x^n\}_{n=1}^{N}$: $x_n < x_{n+1}$, for all n.
- Say the $x^n(t_0)$ are arranged "evenly" according to the distribution $P(x;t_0) = |\psi(x;t_0)|^2$ and the $\dot{x}^n(t_0)$ obey de Broglie's formula

$$\dot{x}^n(t_0) = \frac{\hbar}{m}\mathrm{Im}\,\frac{\psi'(q;t_0)}{\psi(q;t_0)}\bigg|_{q=x^n(t_0)}$$

- Then by Bohm's force law, the $x^n(t)$ will remain arranged "evenly" according to $P(x;t) = |\psi(x;t)|^2$ for all times.

A single particle; many *interacting* worlds

- **Our idea:** If we approximate $|\psi(q,t)|^2$ by the local density of worlds, we can replace the quantum potential $Q(q)$ by a function of the positions of the nearby worlds.
- e.g. **toy model**: the world-positions evolve via Newton's equations

$$m\ddot{x}^n(t) = -\frac{\partial}{\partial x_n}\left[V(x^n) + \sum_{n'} Q_3^{uip}\left(x^{n'-1}, x^{n'}, x^{n'+1}\right)\right].$$

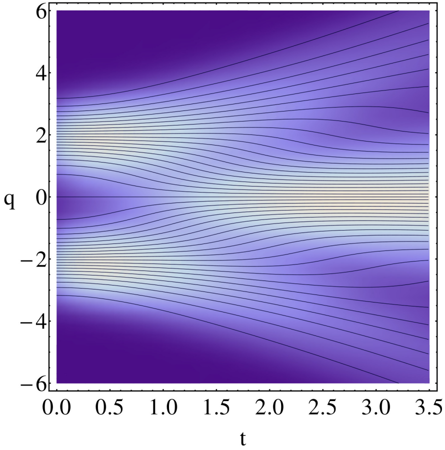
where the "3-body" (3-world) "local" potential can be chosen as

$$Q_3^{uip}\left(x^{n-1}, x^n, x^{n+1}\right) = \frac{\hbar^2}{8m}\left[\frac{1}{x_{n+1}-x_n} - \frac{1}{x_n - x_{n-1}}\right]^2.$$

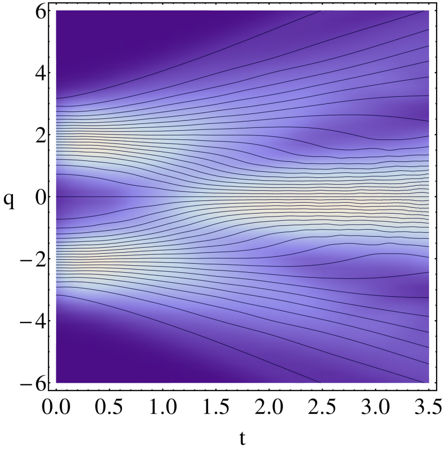
- As $N \to \infty$, we should recover the (virtual) Bohmian ensemble.
- However, *there is no wavefunction* in the ontology of our theory;
- our ensemble of worlds is *real*, not virtual.
- this is necessary because our worlds *interact*.

Realism Type 3: Many Interacting Worlds

dB-B virtual ensemble,
guided by real wavefunction.



MIW real ensemble,
reconstructed wavefunction.



What else have we done?

- Suggested a conservative inter-world potential that may work for the many-particles case.

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Phys. Rev. X **4**, 041013 – Published 23 October 2014
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What else have we done?

- Suggested a conservative inter-world potential that may work for the many-particles case.
- Using some generic properties of such inter-world potentials,
  1. given a qualitative explanation for quantum tunneling.
  2. derived Ehrenfest's theorem, as in CM and QM, for all *N*.
  3. derived quadratic-in-time wave-packet spreading.

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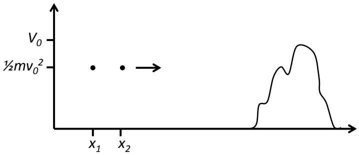

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  1. given a qualitative explanation for quantum tunneling.
  2. derived Ehrenfest's theorem, as in CM and QM, for all N.
  3. derived quadratic-in-time wave-packet spreading.
- Developed and tested an algorithm for finding ground states of a particle in a 1D potential.

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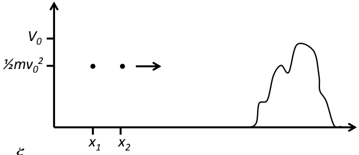

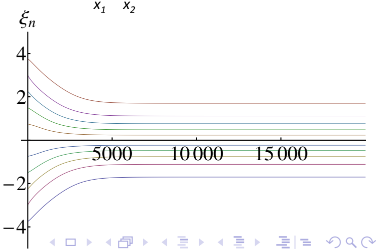

Open questions

1. Is the dynamics stable for excited state distributions and (more generally) distributions with nodes?
2. When is it useful as a numerical tool?
3. Can we deal with spin? Interacting spins (a quantum computer)?
4. Can we explain Bell-nonlocality with a simple, few-world model?
5. Can we deal with relativistic QM?

Recapitulation

1. Orthodox Quantum Mechanics: who could ask for anything more?
2. Bohmian Mechanics: who could ask for anything more?
   - Issue 1 with Bohmian mechanics: why believe it is **real**?
   - Addressing issue 1: theory and experiment
   - Issue 2 with Bohmian mechanics: it seems **surreal**
   - Addressing issue 2: theory and experiment
3. Many Worlds Interpretation: who could ask for anything more?
4. Bohmian mechanics and Many Worlds: better together?
   - Issue 3 with Bohmian mechanics: it should be **hyper-real**
   - Addressing issue 3 (&...): theory of *Many Interacting Worlds*

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Ontology and Epistemology

- All worlds are equally real.
- Your consciousness supervenes on only one of the worlds.
- Just as (here and in classical physics) your consciousness supervenes only on one part (i.e. you) of a world.
- There is no wavefunction and hence no collapse of the wavefunction.
- Effective wavefunction collapse is just Bayesian updating by some consciousness about *which world* it is likely to supervene upon.
- Agreement with standard QM emerges (in the $N \to \infty$ limit) much the same as in de Broglie–Bohm.
- *All* quantum effects are a consequence of interaction between worlds so they *are* observable!
- For finite N deviations from QM may be observable.

Analytical results from $E = \sum [m\dot{x}^2 + V + Q_3]$

- Ehrenfest's theorem, as in CM and QM, for all N,

$$\frac{d}{dt}\langle x\rangle = \frac{1}{m}\langle m\dot{x}\rangle, \quad \frac{d}{dt}\langle m\dot{x}\rangle = -\langle V'(x)\rangle$$

  for the (real!) ensemble averages e.g. $\langle x\rangle \equiv N^{-1}\sum_{n=1}^{N} x^n$.

- Ensemble spreading

$$V_t[x] = V_0[x] + \frac{2t}{m}\mathrm{Cov}_0[x, m\dot{x}] + \frac{t^2}{m}\left[2\langle E\rangle - m\langle\dot{x}\rangle^2\right]$$

  as in QM and CM, for all N.

- Qualitative explanation for nonclassical barrier transmission *and* nonclassical reflection, via the quantum repulsion for $N > 1$.
- The harmonic oscillator ground configuration has an energy

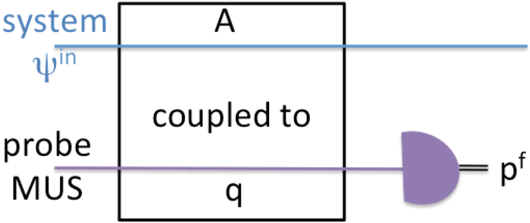
$$\langle E\rangle = \frac{N-1}{N}\frac{\hbar\omega}{2},$$

  as in CM for $N = 1$ and as in QM in the limit $N \to \infty$.

How the Result of a Measurement of a Component of the Spin of a Spin-$\frac{1}{2}$ Particle Can Turn Out to be 100

Yakir Aharonov, David Z. Albert, and Lev Vaidman

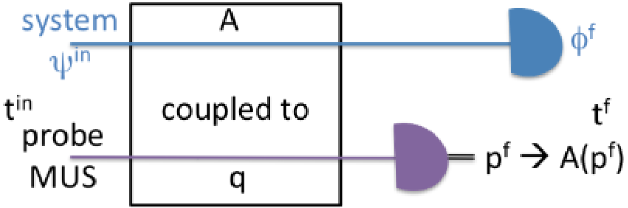
- PRL **60**, 1351 (1988).
- Consider an arbitrary system observable A.
- Assume a probe with $[\hat{q}, \hat{p}] = i$, initially in a MUS (minimum uncertainty state).



- The probe state is defined by σ_p^{in}, $\bar{p}^{\mathrm{in}}$, and $\bar{q}^{\mathrm{in}} = 0$.
- Assume (von Neumann) $\hat{H} = \delta(t)\hat{A} \otimes \hat{q}$, so that $\hat{p}^{\mathrm{f}} - \hat{p}^{\mathrm{in}} = \hat{A}$.
- By measuring p^{f} we can **estimate** A as $A(p^{\mathrm{f}}) = p^{\mathrm{f}} - \bar{p}^{\mathrm{in}}$.

Initial and Final States.

- For initial system state $|\psi^{\rm in}\rangle$, we can obtain, by repeating the experiment,
$$\mathrm{E}[A(p^{\rm f})|\psi^{\rm in}] = \langle\psi^{\rm in}|\hat{A}|\psi^{\rm in}\rangle.$$
- Now consider a final *strong* measurement on the system too.



- Consider the sub-ensemble where the final result corresponds to projecting onto state $|\phi^{\rm f}\rangle$.
- Then we can consider the *post-selected* average $\mathrm{E}[A(p^{\rm f})|\psi^{\rm in}, \phi^{\rm f}]$.

The Weak Measurement Limit

- In the **weak measurement limit**, $\sigma_p \to \infty$,

$$\mathrm{E}[A(p^{\mathrm{f}})|\psi^{\mathrm{in}}, \phi^{\mathrm{f}}] \to {}_{\phi^{\mathrm{f}}}\langle A^{\mathrm{w}} \rangle_{\psi^{\mathrm{in}}} \equiv \mathrm{Re} \frac{\langle \phi^{\mathrm{f}} | \hat{A} | \psi^{\mathrm{in}} \rangle}{\langle \phi^{\mathrm{f}} | \psi^{\mathrm{in}} \rangle}.$$

Q Why is this the weak measurement limit?

A Because very little information in any individual result

$$A(\hat{p}^{\mathrm{f}}) = \hat{A} + (\hat{p}^{\mathrm{in}} - \bar{p}^{\mathrm{in}})$$

and $\left\langle (\hat{p}^{\mathrm{in}} - \bar{p}^{\mathrm{in}})^2 \right\rangle = \sigma_p^2 \to \infty$.

A Because weak (*not no*) disturbance:

$$\hat{s}^{\mathrm{f}} = \hat{s}^{\mathrm{in}} - i[\hat{s}^{\mathrm{in}}, \hat{A}] \otimes \hat{q}^{\mathrm{in}}$$

and $\left\langle (\hat{q}^{\mathrm{in}})^2 \right\rangle = 1/(2\sigma_p)^2 \to 0$ in this limit.

- Note: the weaker the measurement, the larger the number of repetitions required to obtain a reliable average.