Title: What de Broglie--Bohm Mechanics tells us about the Nature of the Quantum State

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Abstract: TBA

What de Broglie–Bohm Mechanics tells us about the Nature of the Quantum State

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The Nature of the Quantum State, Perimeter Institute, September 2009

Outline

1. Preliminaries
   - Apologia
   - Terms and Concepts
   - On Instrumental States
2. The de Broglie(1926)–Bohm(1952) Interpretation
   - Single-particle B–B mechanics
   - General B–B Mechanics
   - Relating to Orthodox Quantum Theory
3. The Elephant in the Room: Probability
4. The Nature of Ψ
   - Nomic?
   - Ontic?
5. Conclusions

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Mere Bohmianity

- I do not believe de Broglie–Bohm mechanics is true.
- I do not believe de Broglie–Bohm mechanics is false.
- I do believe de Broglie–Bohm mechanics should be understood by everyone professing quantum foundations, with the following motivations:

1. to lessen the number of blatantly wrong statements that are made in the field
2. to act as a foil for intuition
3. to provoke new ways of thinking about quantum foundations
4. to suggest or perhaps constrain new fundamental theories

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Despite discouragement from Rob and Huw ...

To demonstrate my impartiality I hereby disavow all six interpretations of quantum mechanics :-)

I used to believe ...

1. in Everett's interpretation; now I'm in two minds.
2. in the Barbourverse; but that was a different world.
3. in Fuchs' interpretation; but no-one else was of like mind.
4. that Bohr's tenets were true; now I see they were profound.
5. in Pilot-wave theory; now my beliefs have drifted.
6. in Retrocausality; but there was no future in it.

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What does "the quantum state" apply to?

1. **objects**: A state vector $|\psi\rangle$, or more likely a state matrix ρ, applicable to a small (in some sense) physical system which is the object of laboratory enquiry.
2. **objects and subjects**: A state vector $|\Psi'\rangle$, or more likely a state matrix R', applicable to the whole universe *except me* (for a suitable value of "me"). That is, it applies to "other" subjects.
3. **totality**: A state vector $|\Psi\rangle$ (or possible a state matrix R, if that makes any sense), applicable to the whole universe, perhaps even the multiverse.

What is the “nature” of a given construct in our physical theories?

1. instrumental (=operational; ≈statistical): It encapsulates what I/we expect in the future, depending on how I/we interact with whatever it is that the construct in question applies to.
2. epistemic: It encapsulates what I/we believe/know about the configuration of whatever it applies to.
3. ontic: It encapsulates, at least partly, the configuration of whatever it applies to.
4. nomic: It defines, at least partly, the most fundamental laws of nature; that which is least contingent.

Instrumental versus Epistemic

- "The **instrumental state** of a **system** is defined to be that thing ... which uniquely determines the probability associated with every outcome of every measurement that may be performed on the system." (Hardy, 2003).
- Define $K_{\text{instrumental}} - 1$ as the number of positive numbers (probabilities) required to specify the instrumental state.
- In quantum theory, $K_{\text{instrumental}} = D^2$.
- Define $K_{\text{ontic}} - 1$ as the number of positive numbers (probabilities) required to specify the epistemic state, or *by definition*, the number of ontic states different from any particular ontic state.
- In classical probability theory, $K_{\text{instrumental}} = K_{\text{ontic}}$.
- In quantum theory, $K_{\text{ontic}} \gtrsim \#$ different ψs, and $\frac{K_{\text{ontic}}}{K_{\text{instrumental}}} = \infty$.
- This is the "Ontological excess baggage theorem". (Hardy, 2003).

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But aren't ρ or ψ closely analogous to $P(x)$?

Carl Caves (PIAF, Sydney, 2008) says yes, in that for the following questions, ρ, ψ, and $P(x)$ answer together; x answers differently:

1. Can the outcome of a fine-grained measurement on this sort of state be predicted with certainty, in general? (N; Y)
2. Can a state of this sort be verified from a single measurement? (N; Y)
3. Does this sort of state necessarily change upon measurement, in general? (Y; N)
4. Is there always a unique decomposition of a state into an ensemble of this sort of states? (N; Y)
5. With this sort of state, does a measurement here change the state for over there, in general? (Y; N)

The moral: the fine-grained **instrumental state** ψ of an **object** is neither closely analogous to a classical ontic state x **nor** to a classical epistemic state $P(x)$.

Yes, but no ...

There is a corresponding list of questions in which ρ and $P(x)$ answer together; ψ and x also answer together, but differently:

1. Given a state of this sort, is there a fine-grained measurement whose outcome can be predicted with certainty? (N; Y)
2. Is it possible to unambiguously distinguish any two states of this sort with a single measurement? (N; Y)
3. Given a state of this sort, is there a fine-grained measurement which does not change the state? (N; Y)
4. Is this equal to a non-trivial mixture of other states of the same sort? (Y; N)
5. Does knowledge of this guarantee that no other parties have more information? (N; Y)

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My attitudes

- Designing quantum gadgets is fun and lucrative, and requires only the **instrumental** interpretation of the **object**-state ρ.
- But the serious business of philosopher-physicists is to follow Einstein:

  > *I am not interested in this phenomenon or that phenomenon. I want to know God's thoughts; the rest are details.*

- Therefore, I am not interested in the instrumental interpretation, except in so far as it *emerges* from more fundamental (epistemic, ontic, and nomic) considerations.
- Also, to treat subjects (e.g. other people) as fundamentally different from objects is to retreat into Cartesian dualism.
- Therefore, I am not interested in the object-only application of states. I will consider states describing totality (or possibly totality excluding me).

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Why consider Hidden Variables?

1. Many, perhaps most, quantum physicists believe in hidden variables even if they don't admit it.
   - Everyone (except a solipsist) needs an ontology. Then either:
   1. Ψ, and nothing else, is ontic; or
   2. something else instead of, or in addition to, Ψ, is ontic.
   - If you accept (2), then you believe in hidden variables.
2. To *explain* the probabilities that appear in the instrumental theory.
3. To *explain* the existence of people who perform preparations, choose measurements, and observe results. That is, to explain the things that are *assumed* in the instrumental theory.
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Single-particle B–B mechanics

Consider scalar particles for simplicity, and for the moment just a single particle with state $|\psi\rangle$ and $\hat{H} = \hat{\mathbf{p}}^2/2m + V(\hat{\mathbf{x}})$. Then the Bohmian HV is the value $\mathbf{x}$ of the particle's position and

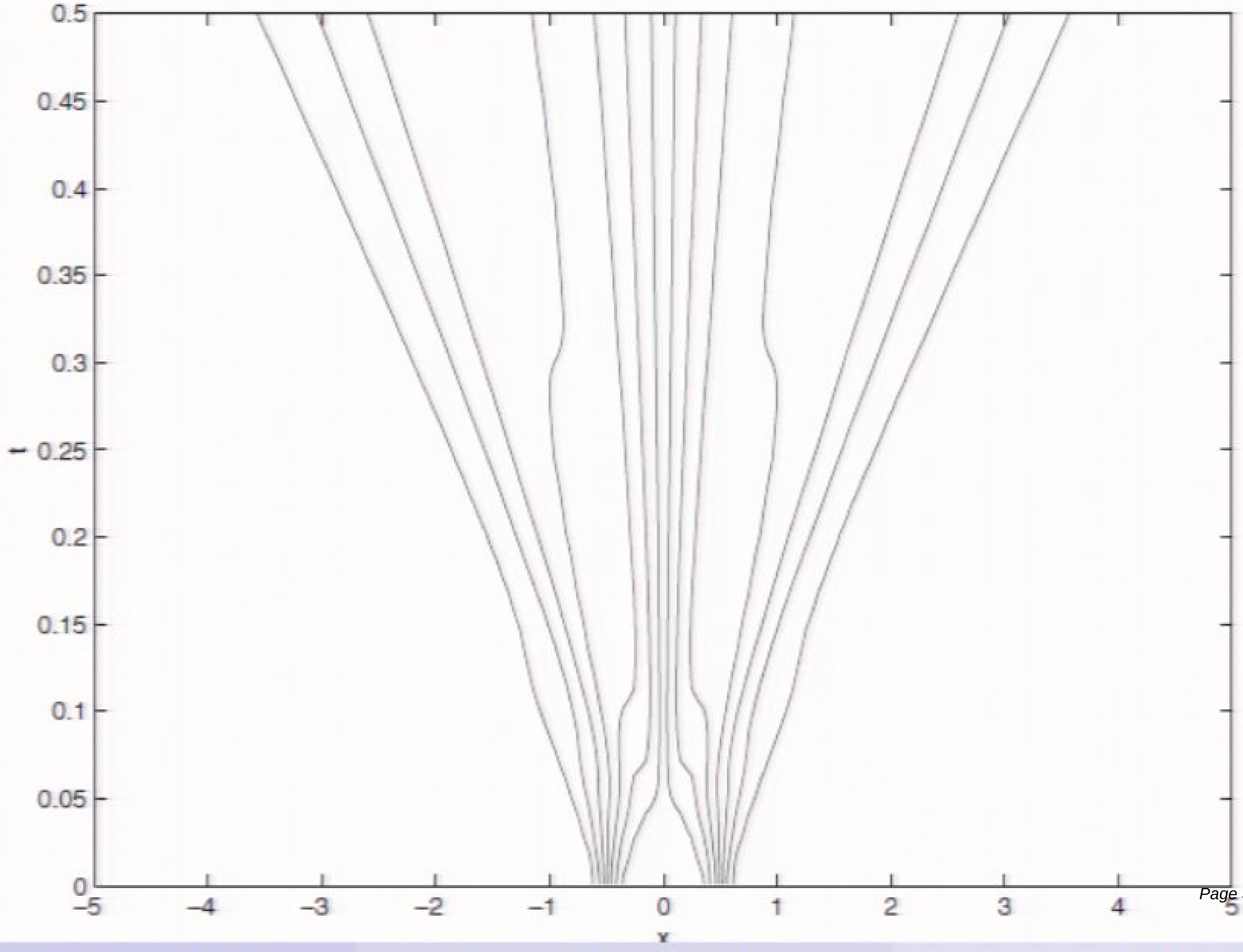
$$
\begin{aligned}
\dot{\mathbf{x}} &= \mathbf{v}(\mathbf{x};t) \equiv \mathbf{j}(\mathbf{x};t)/P(\mathbf{x};t), \\
P(\mathbf{x};t) &= \langle\psi(t)|\mathbf{x}\rangle\langle\mathbf{x}|\psi(t)\rangle, \\
\mathbf{j}(\mathbf{x};t) &= (\hbar/m)\mathrm{Im}\,\langle\psi(t)|\mathbf{x}\rangle\nabla\langle\mathbf{x}|\psi(t)\rangle.
\end{aligned}
$$

This $\mathbf{j}(\mathbf{x};t)$ is the standard *probability current* (flux), which satsifies

$$
\frac{\partial}{\partial t}P(\mathbf{x};t) + \nabla\cdot\mathbf{j}(\mathbf{x};t) = 0.
$$

This guarantees that if the probability distribution for $\mathbf{x}$ at time t_0 is $P(\mathbf{x};t_0)$ then at time t it will be $P(\mathbf{x};t)$.

An example of Bohmian trjaectories



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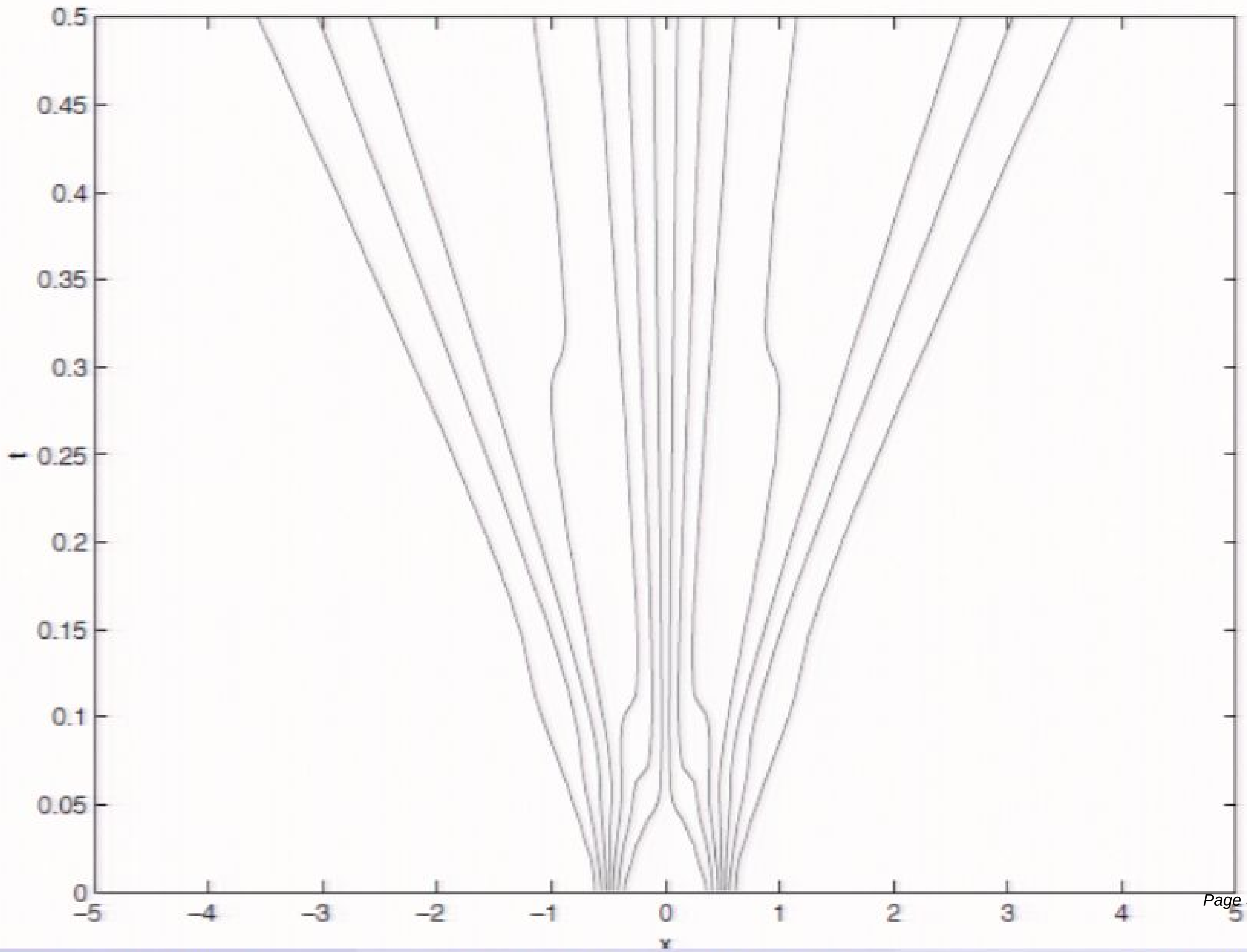

General B–B Mechanics

There are many ways to generalize BBM to deal with the fundamental Hamiltonian of the universe (well, at least that of the standard model). My favourite is as follows.

Rather than a 3-vector, **x** is now an ∞-vector including the 3-positions of all the (infinitely many) fermionic *particles* in the universe. Each one of these particles is associated with a finite-dimensional Hilbert space that encodes the spin, lepton number, colour, flavour etc.

x also contains the values of all the quantized gauge fields (electromagnetic, weak$\times$3, strong$\times$8) at every point in space.

$$\dot{x}_n = v_n(\mathbf{x};t) = \mathrm{Re}\frac{\langle\Psi(t)|\mathbf{x}\rangle\langle\mathbf{x}|i[\hat{H},\hat{x}_n]|\Psi(t)\rangle}{\hbar\langle\Psi(t)|\mathbf{x}\rangle\langle\mathbf{x}|\Psi(t)\rangle}.$$

Here $|\Psi\rangle$ is a *universal* wavefunction or guiding function.

Aside: Nonlocality in B–B Mechanics

BBM dynamics is *nonlocal* because $\dot{x}_n$ in general depends on *all* the co-ordinates in $\mathbf{x}$. That is, all the particles in the universe, and the values of the fields at every point in space.

Bell (1980): "It is a merit of the de Broglie-Bohm version to bring this [nonlocality] out so explicitly that it cannot be ignored."

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Aside: Why this is my favourite formulation

Given that position measurements are known to affect the *instrumental* quantum state of a system, the most natural *operational* way to define the velocity of the configuration of a subsystem is (Wiseman, 2007):

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

For the Hamiltonians that appear in the standard model, which are at most quadratic in the variables *conjugate* to $\hat{\mathbf{x}}$, this evaluates to

$$v_n(\mathbf{x};t) = \mathrm{Re}\frac{\langle\Psi(t)|\mathbf{x}\rangle\langle\mathbf{x}|i[\hat{H},\hat{x}_n]|\Psi(t)\rangle}{\hbar\langle\Psi(t)|\mathbf{x}\rangle\langle\mathbf{x}|\Psi(t)\rangle}.$$

This formulation also suggests *why* the HV should be chosen to be $\mathbf{x}$: because of the special functional dependence of the Hamiltonian on the conjugate variable.

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Here $|\Psi\rangle$ is a *universal* wavefunction or guiding function.

Aside: Why this is my favourite formulation

Given that position measurements are known to affect the *instrumental* quantum state of a system, the most natural *operational* way to define the velocity of the configuration of a subsystem is (Wiseman, 2007):

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

For the Hamiltonians that appear in the standard model, which are at most quadratic in the variables *conjugate* to $\hat{\mathbf{x}}$, this evaluates to

$$v_n(\mathbf{x};t) = \mathrm{Re}\frac{\langle\Psi(t)|\mathbf{x}\rangle\langle\mathbf{x}|i[\hat{H},\hat{x}_n]|\Psi(t)\rangle}{\hbar\langle\Psi(t)|\mathbf{x}\rangle\langle\mathbf{x}|\Psi(t)\rangle}.$$

This formulation also suggests *why* the HV should be chosen to be $\mathbf{x}$: because of the special functional dependence of the Hamiltonian on the conjugate variable.

Orthodox QT emerges from BBM (Bohm, 1952)

The simplest example: say the universe comprised only an observer *o* and a system *s*, and *o* could assign an **instrumental** pure state to *s*. Then that state would be

$$|\psi_s\rangle \propto \langle \mathbf{x}_o|\Psi\rangle.$$

Unlike OQT, BBM defines the observer unambiguously, being made of particles and fields with a definite configuration $\mathbf{x}_o$, which is **known** (to some approximation) to the observer by in(tro)spection.

Thus the **instrumental** state an observer assigns to *s is derived from* (but is quite distinct from) that observer's **epistemic** state for $\mathbf{x}_o$.

There is also an (unknown) $\mathbf{x}_s$, guided by $|\psi_s\rangle$, to which the observer will assign the distribution

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Provocative ways to think about B–B Mechanics

1. It is like the Everett interpretation in having no ad-hoc collapse, only better because you don't have to worry about how to define "worlds", or what the weightings of different "worlds" means, or what determines "which world" you end up in. Rather, there is something else (**x**) in the theory which picks out a unique world.

2. It is like the Copenhagen interpretation in having a classical world, only better because you don't have to worry about the "cut" between quantum and classical. Rather, classical variables are coarse-grainings of x, the configuration for *all* systems.

3. It is like Fuchs' interpretation in that instrumental quantum states have an epistemic interpretation, only better in that your ontology (that to which your epistemic state refers) is not *hypothetical events that have not yet happened to you*. Rather, your ontology is *presently existing stuff* x which, describes your mind (and, as a bonus, those of other people as well!).

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Outline

The probability problem in B–B Mechanics

B–B Mechanics reproduces all of OQT given the kinematics **x**, the dyanamics

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and the probability assignment

$$P(\mathbf{x};t_0) = \langle\Psi(t_0)|\mathbf{x}\rangle\langle\mathbf{x}|\Psi(t_0)\rangle.$$

But why should $|\Psi\rangle$ play this dual role?

A deeper question: What is probability?

The radical Bayesian (de Finetti) answer: *Probability is not real.*

$P(\mathbf{x}; t_0)$ is only an expression of one observer's *beliefs* about $\mathbf{x}$. It is known as the prior probability distribution, or *prior*.

How do the (apparently) objective probabilities of OQT arise?

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Is determinism the problem?

de Broglie–Bohm mechanics is a deterministic theory.

We can easily make the dynamics stochastic as in Nelson's (1966) theory, in which

$$dx_n = v_n(\mathbf{x})dt + O(\hbar)dw_n,$$

where $P(dw_n) = (2\pi dt)^{-1/2} \exp[-(dw)^2/2dt]$.

But this just introduces an infinitude of more hidden variables (one per component of $\mathbf{x}$, per "instant of time"), which begs the question:

How does the objective probability $P(dw_n(t))$ arise? In reality, there is a true value of $dw_n(t)$ for all n and all t, so $P(dw_n(t))$ merely expresses my ignorance of the true value. Why should $P(dw_n) = (2\pi dt)^{-1/2} \exp[-(dw)^2/2dt]$ express my ignorance?

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A Proposal: (Jaynes') Principle of Indifference

"If the statement of a statistical problem is invariant under some transformation, then choose a prior that respects this indifference."

Recall that the problem is specified by the (unkown) $\mathbf{x}(t_0)$ and the (known) $|\Psi(t_0)\rangle$. But there is no particular significance to the time t_0. Therefore the prior should be covariant with respect to translation in time. That is,

$$\frac{\partial}{\partial t} P_{\text{prior}}(\mathbf{x};t) = \sum_n \frac{\partial}{\partial x_n}[P_{\text{prior}}(\mathbf{x};t)\dot{x}_n(\mathbf{x};t)].$$

The only distribution known to obey this, which can be constructed using only the obviously relevant inputs $[|\Psi(t)\rangle$, $\hat{H}$ and $\{|\mathbf{x}\rangle\}]$, is

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Prior and Posterior Distributions

Remember the simple example of a universe comprised only *o* and *s*, with an instrumental state for the system of $|\psi_s\rangle \propto \langle \mathbf{x}_o|\Psi\rangle$.

Here it is as if the observer knows her own configuration $\mathbf{x}_0$. Such a degree of self-knowledge is neither realistic nor required.

Nevertheless, because the observer is part of the universe in BBM, her knowledge of $\mathbf{x}$ is certainly *not* limited to the prior distribution:

$$P(\mathbf{x}; t) \neq \langle\Psi(t)|\mathbf{x}\rangle\langle\mathbf{x}|\Psi(t)\rangle,$$

where $\mathbf{x}$ incorporates $\mathbf{x}_o$. The right-hand-side is what a totally innocent observer believes. The left-hand-side is the *posterior* distribution.

Episteme, Onts, and Instrumentalism (again)

As soon as an innocent observer opens her eyes she collapses her state of belief about $\mathbf{x}$ from $P_{\text{prior}}(\mathbf{x}; t)$ to a much sharper $P(\mathbf{x}; t)$, conditioned on her observing the location of macroscopic objects.

This "collapse" is classical/epistemic/psychological. The configuration $\mathbf{x}$ does not suddenly change, and neither does $|\Psi(t)\rangle$.

Whatever knowledge $\mathbf{x}_o$ encodes about $\mathbf{x}$ defines what she expects to happen in the future. Thus, the **instrumental state** of any subsystem, ρ_s, is determined by the **epistemic state**:

$$\rho_s = \mathrm{Tr}_{\text{not-}s} \int d\mathbf{x} P(\mathbf{x}; t) \langle \mathbf{x} | \Psi(t) \rangle \langle \Psi(t) | \mathbf{x} \rangle.$$

This guarantees that $\mathrm{Tr}_s \left[\rho_s | \mathbf{x}_s \rangle \langle \mathbf{x}_s | \right] = \int d\mathbf{x}_{\text{not-}s} P(\mathbf{x}; t) = P(\mathbf{x}_s; t)$.

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Outline

Could $|\Psi\rangle$ be Nomic?

$|\Psi(t)\rangle$ guides the configuration $\mathbf{x}(t)$, but is unaffected by it.

This suggests $|\Psi(t)\rangle$ is more fundamental, less contingent, than $\mathbf{x}(t)$. That is, it and $\hat{H}$ constitute the the law of motion.

This nomic interpretation would be much stronger if

1. $|\Psi(t)\rangle$ were *time-independent*: $|\Psi\rangle$.
2. $|\Psi\rangle$ was *uniquely determined*, e.g. by $\hat{H}$.

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On the other hand ...

Consider Classical Mechanics, formulated in terms of action.

$$S(q_1;t_1) = \int_{q_0,t_0}^{q_1,t_1} L(q,\dot{q})dt,$$

where $q(t_0) = q_0$, $q(t_1) = q_1$ and $q(t)$ is the *actual* path of the particle that minimizes the action between these two points.

The action function provides the dynamical information missing from x alone. Clearly it carries the same information as $x(t_0) = q_0$, or as $p(t)$, which is found from $x(t)$ by

$$p(x) = \left[\frac{\partial}{\partial q} S(q;t)\right]_{q=x}.$$

This suggests it has the same (contingent) nature.

Classical and Quantum look almost the same

Define a classical complex wave $\psi(q) = \exp[-iS(q)/\hbar]$. Then

	Classical Mechanics	B–B Mechanics
$i\hbar\frac{\partial}{\partial t}\psi(q) =$	$\psi(q)H\left(q, \left[-i\hbar\frac{1}{\psi(q')}\frac{\partial\psi(q')}{\partial q'}\right]_{q'=q}\right)$	$\psi(q)\left[H\left(q, -i\hbar\frac{1}{\psi(q')}\frac{\partial\psi(q')}{\partial q'}\right)\right]_{q'=q}$
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The only other difference is that classically the form of $\psi(q; t_0)$ is highly constrained.

This analogy suggests that $\psi(q, t_0)$ in B–B mechanics is also contingent, an initial (*or final*) condition. That is, that it is **ontic** rather than **nomic**.

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1. Why is it that

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but no instantaneous signalling ?

2. Can we gain insight into this question by constructing toy theories with other guiding wave equations?

3. e.g. What happens to classical mechanics if we drop any requirements on $\psi(q;t_0)$, even that $|\psi(q;t_0)| = 1$ by defining

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What does BBM tell us about the Nature of the Quantum State?

1. We should not expect to have *just one sort of state* in our best theory. BBM has
   - an ontic state $\mathbf{x}(t)$
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2. A big question is what is the nature of $|\Psi\rangle$.
3. Another big question: when CM and BMM can be formulated almost identically, why can we make do with just an ontic state in the former case, but not in the latter?
4. And further: can toy dynamical theories help us to understand the origin of quantum weirdness?

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3. Another big question: when CM and BMM can be formulated almost identically, why can we make do with just an ontic state in the former case, but not in the latter?
4. And further: can toy dynamical theories help us to understand the origin of quantum weirdness?

Guiding field formulation of Classical Mechanics

The initial conditions $S(q;t_0)$ are highly restricted in form. e.g. for a free particle,

$$S(q;t) = -\frac{m}{2}\left(\frac{q-q_0}{t-t_0}\right)^2.$$

But given this, the system kinematics can be taken to be $\{x(t), S(q;t)\}$, with the following dynamics:

$$\frac{\partial}{\partial t}S(q) = -H\left(q, \frac{\partial}{\partial q}S(q)\right)$$

$$\dot{x} = \left[\frac{\partial}{\partial p}H(x,p)\right]_{p=p(x)}$$

$$\text{where } p(x) = \left[\frac{\partial}{\partial q}S(q;t)\right]_{q=x}$$

That is, $S(q;t)$ seems to *guide* the configuration x.

On the other hand ...

Consider Classical Mechanics, formulated in terms of action.

$$S(q_1; t_1) = \int_{q_0, t_0}^{q_1, t_1} L(q, \dot{q}) dt,$$

where $q(t_0) = q_0$, $q(t_1) = q_1$ and $q(t)$ is the *actual* path of the particle that minimizes the action between these two points.

The action function provides the dynamical information missing from x alone. Clearly it carries the same information as $x(t_0) = q_0$, or as $p(t)$, which is found from $x(t)$ by

$$p(x) = \left[\frac{\partial}{\partial q} S(q; t)\right]_{q=x}.$$

This suggests it has the same (contingent) nature.

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Classical and Quantum look almost the same

Define a classical complex wave $\psi(q) = \exp[-iS(q)/\hbar]$. Then

	Classical Mechanics	B–B Mechanics
$i\hbar\frac{\partial}{\partial t}\psi(q) =$	$\psi(q)H\left(q, \left[-i\hbar\frac{1}{\psi(q')}\frac{\partial\psi(q')}{\partial q'}\right]_{q'=q}\right)$	$\psi(q)\left[H\left(q, -i\hbar\frac{1}{\psi(q')}\frac{\partial\psi(q')}{\partial q'}\right)\right]_{q'=q}$
$p(x) =$	$\left[-i\hbar\frac{1}{\psi(q)}\frac{\partial\psi(q)}{\partial q}\right]_{q=x}$	$\mathrm{Re}\left[-i\hbar\frac{1}{\psi(q)}\frac{\partial\psi(q)}{\partial q}\right]_{q=x}$
$\dot{x} =$	$\left[\frac{\partial}{\partial p}H(x,p)\right]_{p=p(x)}$	$\left[\frac{\partial}{\partial p}H(x,p)\right]_{p=p(x)}$

The only other difference is that classically the form of $\psi(q; t_0)$ is highly constrained.

This analogy suggests that $\psi(q, t_0)$ in B–B mechanics is also contingent, an initial (*or final*) condition. That is, that it is **ontic** rather than **nomic**.

This also leads to interesting questions:

1. Why is it that

$$H\left(q, \left[-i\hbar\frac{1}{\psi(q')}\frac{\partial\psi(q')}{\partial q'}\right]_{q'=q}\right) \implies \text{predictability and locality,}$$

$$\left[H\left(q, -i\hbar\frac{1}{\psi(q')}\frac{\partial\psi(q')}{\partial q'}\right)\right]_{q'=q} \implies \text{unpredictability and nonlocality}$$

but no instantaneous signalling ?

2. Can we gain insight into this question by constructing toy theories with other guiding wave equations?

3. e.g. What happens to classical mechanics if we drop any requirements on $\psi(q; t_0)$, even that $|\psi(q; t_0)| = 1$ by defining

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Outline

What does BBM tell us about the Nature of the Quantum State?

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Could $|\Psi\rangle$ be Nomic?

$|\Psi(t)\rangle$ guides the configuration $\mathbf{x}(t)$, but is unaffected by it.

This suggests $|\Psi(t)\rangle$ is more fundamental, less contingent, than $\mathbf{x}(t)$. That is, it and $\hat{H}$ constitute the **the law of motion**.

This **nomic** interpretation would be much stronger if

1. $|\Psi(t)\rangle$ were *time-independent*: $|\Psi\rangle$.
2. $|\Psi\rangle$ was *uniquely determined*, e.g. by $\hat{H}$.

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General B–B Mechanics

There are many ways to generalize BBM to deal with the fundamental Hamiltonian of the universe (well, at least that of the standard model). My favourite is as follows.

Rather than a 3-vector, $\mathbf{x}$ is now an ∞-vector including the 3-positions of all the (infinitely many) fermionic *particles* in the universe. Each one of these particles is associated with a finite-dimensional Hilbert space that encodes the spin, lepton number, colour, flavour etc.

$\mathbf{x}$ also contains the values of all the quantized gauge fields (electromagnetic, weak$\times$3, strong$\times$8) at every point in space.

$$\dot{x}_n = v_n(\mathbf{x};t) = \mathrm{Re}\frac{\langle\Psi(t)|\mathbf{x}\rangle\langle\mathbf{x}|i[\hat{H},\hat{x}_n]|\Psi(t)\rangle}{\hbar\langle\Psi(t)|\mathbf{x}\rangle\langle\mathbf{x}|\Psi(t)\rangle}.$$

Here $|\Psi\rangle$ is a *universal* wavefunction or guiding function.

But aren't ρ or ψ closely analogous to $P(x)$?

Carl Caves (PIAF, Sydney, 2008) says yes, in that for the following questions, ρ, ψ, and $P(x)$ answer together; x answers differently:

1. Can the outcome of a fine-grained measurement on this sort of state be predicted with certainty, in general? (N; Y)
2. Can a state of this sort be verified from a single measurement? (N; Y)
3. Does this sort of state necessarily change upon measurement, in general? (Y; N)
4. Is there always a unique decomposition of a state into an ensemble of this sort of states? (N; Y)
5. With this sort of state, does a measurement here change the state for over there, in general? (Y; N)

The moral: the fine-grained **instrumental state** ψ of an **object** is neither closely analogous to a classical ontic state x **nor** to a classical epistemic state $P(x)$.

Yes, but no ...

There is a corresponding list of questions in which ρ and $P(x)$ answer together; ψ and x also answer together, but differently:

1. Given a state of this sort, is there a fine-grained measurement whose outcome can be predicted with certainty? (N; Y)
2. Is it possible to unambiguously distinguish any two states of this sort with a single measurement? (N; Y)
3. Given a state of this sort, is there a fine-grained measurement which does not change the state? (N; Y)
4. Is this equal to a non-trivial mixture of other states of the same sort? (Y; N)
5. Does knowledge of this guarantee that no other parties have more information? (N; Y)

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Why consider Hidden Variables?

1. Many, perhaps most, quantum physicists believe in hidden variables even if they don't admit it.
   - Everyone (except a solipsist) needs an ontology. Then either:
     1. Ψ, and nothing else, is ontic; or
     2. something else instead of, or in addition to, Ψ, is ontic.
   - If you accept (2), then you believe in hidden variables.
2. To *explain* the probabilities that appear in the instrumental theory.
3. To *explain* the existence of people who perform preparations, choose measurements, and observe results. That is, to explain the things that are *assumed* in the instrumental theory.
4. To suggest research towards a theory that might supersede quantum theory.

Orthodox QT emerges from BBM (Bohm, 1952)

The simplest example: say the universe comprised only an observer *o* and a system *s*, and *o* could assign an **instrumental** pure state to *s*. Then that state would be

$$|\psi_s\rangle \propto \langle \mathbf{x}_o|\Psi\rangle.$$

Unlike OQT, BBM defines the observer unambiguously, being made of particles and fields with a definite configuration $\mathbf{x}_o$, which is **known** (to some approximation) to the observer by in(tro)spection.

Thus the **instrumental** state an observer assigns to *s is derived from* (but is quite distinct from) that observer's **epistemic** state for $\mathbf{x}_o$.

There is also an (unknown) $\mathbf{x}_s$, guided by $|\psi_s\rangle$, to which the observer will assign the distribution

$$\langle\psi_s|\mathbf{x}_s\rangle\langle\mathbf{x}_s|\psi_s\rangle,$$

but that is **irrelevant** to deriving OQT from BBM.

Provocative ways to think about B–B Mechanics

1. It is like the Everett interpretation in having no ad-hoc collapse, only better because you don't have to worry about how to define "worlds", or what the weightings of different "worlds" means, or what determines "which world" you end up in. Rather, there is something else (**x**) in the theory which picks out a unique world.
2. It is like the Copenhagen interpretation in having a classical world, only better because you don't have to worry about the "cut" between quantum and classical. Rather, classical variables are coarse-grainings of **x**, the configuration for *all* systems.
3. It is like Fuchs' interpretation in that instrumental quantum states have an epistemic interpretation, only better in that your ontology (that to which your epistemic state refers) is not *hypothetical events that have not yet happened to you.* Rather, your ontology is *presently existing stuff* **x** which, describes your mind (and, as a bonus, those of other people as well!).

Outline

A deeper question: What is probability?

The radical Bayesian (de Finetti) answer: *Probability is not real.*

$P(\mathbf{x}; t_0)$ is only an expression of one observer's *beliefs* about $\mathbf{x}$. It is known as the prior probability distribution, or *prior*.

How do the (apparently) objective probabilities of OQT arise?

Is determinism the problem?

de Broglie–Bohm mechanics is a deterministic theory.

We can easily make the dynamics stochastic as in Nelson's (1966) theory, in which

$$dx_n = v_n(\mathbf{x})dt + O(\hbar)dw_n,$$

where $P(dw_n) = (2\pi dt)^{-1/2} \exp[-(dw)^2/2dt]$.

But this just introduces an infinitude of more hidden variables (one per component of $\mathbf{x}$, per "instant of time"), which begs the question:

How does the objective probability $P(dw_n(t))$ arise? In reality, there is a true value of $dw_n(t)$ for all n and all t, so $P(dw_n(t))$ merely expresses my ignorance of the true value. Why should $P(dw_n) = (2\pi dt)^{-1/2} \exp[-(dw)^2/2dt]$ express my ignorance?

A Proposal: (Jaynes') Principle of Indifference

"If the statement of a statistical problem is invariant under some transformation, then choose a prior that respects this indifference."

Recall that the problem is specified by the (unkown) $x(t_0)$ and the (known) $|\Psi(t_0)\rangle$. But there is no particular significance to the time t_0. Therefore the prior should be covariant with respect to translation in time. That is,

$$\frac{\partial}{\partial t} P_{prior}(\mathbf{x}; t) = \sum_n \frac{\partial}{\partial x_n} [P_{prior}(\mathbf{x}; t) \dot{x}_n(\mathbf{x}; t)].$$

The only distribution known to obey this, which can be constructed using only the obviously relevant inputs $[|\Psi(t)\rangle$, $\hat{H}$ and $\{|\mathbf{x}\rangle\}]$, is

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Prior and Posterior Distributions

Remember the simple example of a universe comprised only *o* and *s*, with an instrumental state for the system of $|\psi_s\rangle \propto \langle \mathbf{x}_o|\Psi\rangle$.

Here it is as if the observer knows her own configuration $\mathbf{x}_0$. Such a degree of self-knowledge is neither realistic nor required.

Nevertheless, because the observer is part of the universe in BBM, her knowledge of $\mathbf{x}$ is certainly *not* limited to the prior distribution:

$$P(\mathbf{x}; t) \neq \langle \Psi(t)|\mathbf{x}\rangle\langle \mathbf{x}|\Psi(t)\rangle,$$

where $\mathbf{x}$ incorporates $\mathbf{x}_o$. The right-hand-side is what a totally innocent observer believes. The left-hand-side is the *posterior* distribution.

Episteme, Onts, and Instrumentalism (again)

As soon as an innocent observer opens her eyes she collapses her state of belief about $\mathbf{x}$ from $P_{\text{prior}}(\mathbf{x};t)$ to a much sharper $P(\mathbf{x};t)$, conditioned on her observing the location of macroscopic objects.

This "collapse" is classical/epistemic/psychological. The configuration $\mathbf{x}$ does not suddenly change, and neither does $|\Psi(t)\rangle$.

Whatever knowledge $\mathbf{x}_o$ encodes about $\mathbf{x}$ defines what she expects to happen in the future. Thus, the **instrumental state** of any subsystem, ρ_s, is determined by the **epistemic state**:

$$\rho_s = \text{Tr}_{\text{not-}s} \int d\mathbf{x} P(\mathbf{x};t) \langle \mathbf{x}|\Psi(t)\rangle\langle\Psi(t)|\mathbf{x}\rangle.$$

This guarantees that $\text{Tr}_s\left[\rho_s|\mathbf{x}_s\rangle\langle\mathbf{x}_s|\right] = \int d\mathbf{x}_{\text{not-}s} P(\mathbf{x};t) = P(\mathbf{x}_s;t)$.

In BBM the **pilot "wave"** $|\Psi(t)\rangle$ is completely different in nature even from a pure instrumental quantum state $|\psi(t)\rangle$.