On the Reality of the Quantum State

M.F. Pusey, J. Barrett, & T. Rudolph, Nature Physics 8, 476–479 (2012).

¿$|\psi\rangle$?

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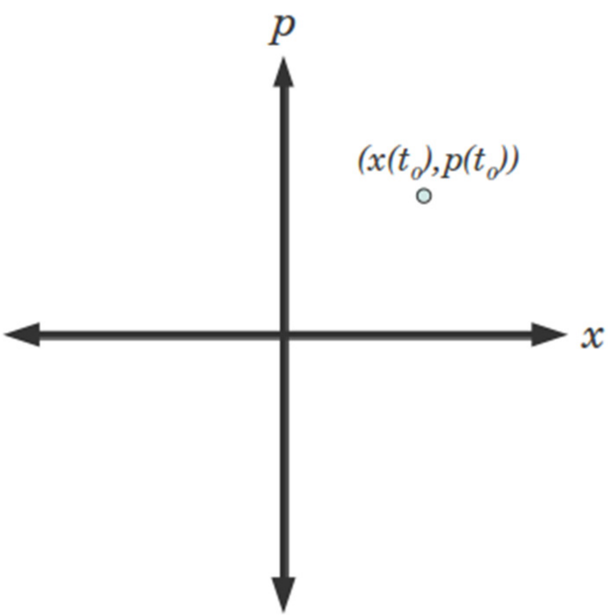
DEC 7 2012

What is a Classical State?

"Real" (ontic) state:
Contains known properties of a system.



Ex: Particle position, momentum. We know what it is doing precisely.

src: Matt Leifer @ mattleifer.info

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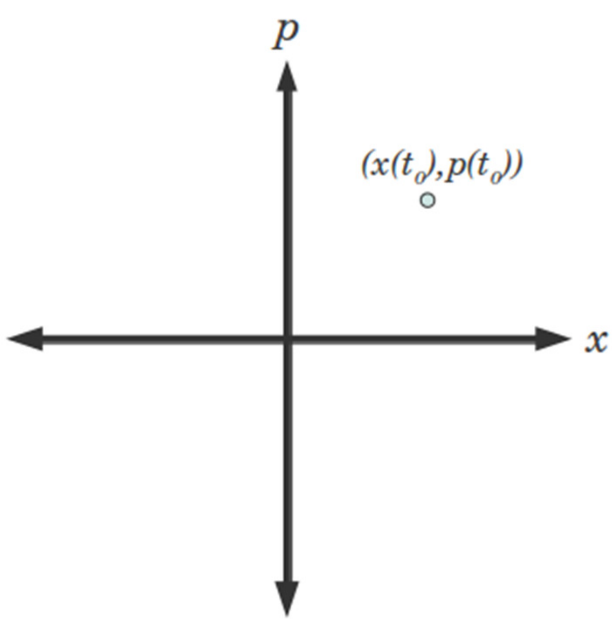

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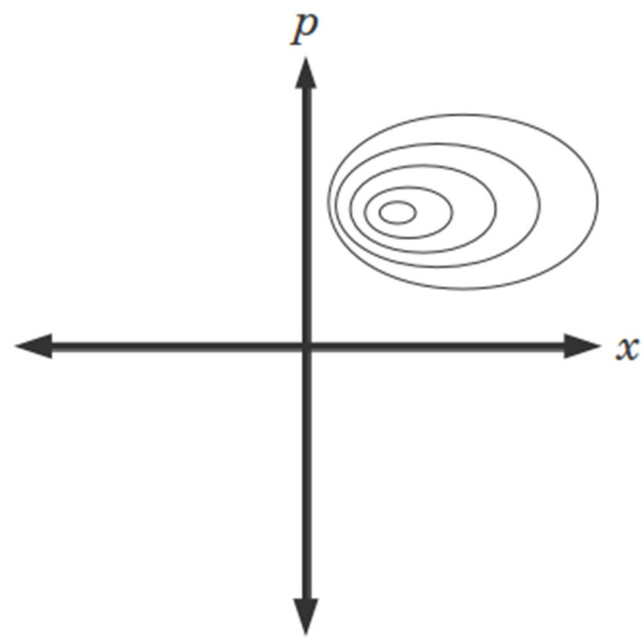
State of knowledge (epistemic):

Represents uncertainty (statistical distribution).



Ex: Thermodynamical systems (gasses, etc). Distributions of particle properties (position, momentum)

Previous conclusions reject state reality

- The famous paper by *Einstein, Podolsky, and Rosen (EPR)*
- *Popper*'s book on "Quantum Theory and Reality"
- "Quantum probabilities as Bayesian probabilities" by *C.M. Caves, C. A. Fuchs, & Schack*

Conclude →

- Quantum state (QS) is not real.
- QS corresponds to experimenter's knowledge/uncertainty about system.
- Wavefunction collapse is a statistical (Bayesian) process of information update.

“Need to unscramble the omelet”

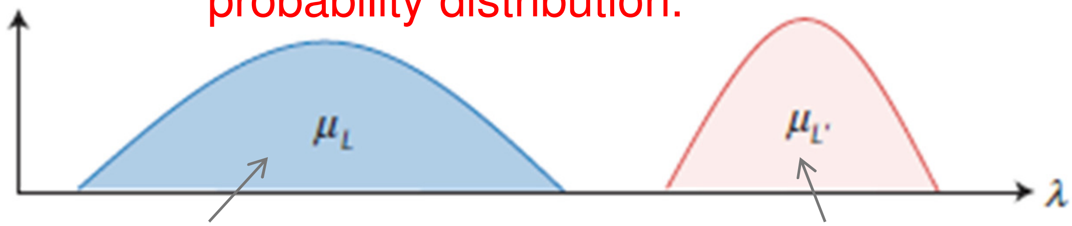
As *Edwin T. Jaynes* said, “for, if we cannot separate the subjective and objective aspects of the formalism, we cannot know what we are talking about.”

According to *Harrigan* and *Spekkens*:

Ψ-ontic models :

Example of non-overlapping probability distribution.

If we measure variable *L*, we will obtain a state λ with probability μ_L



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$\mu_{L'}$ is the same for variable *L'.*

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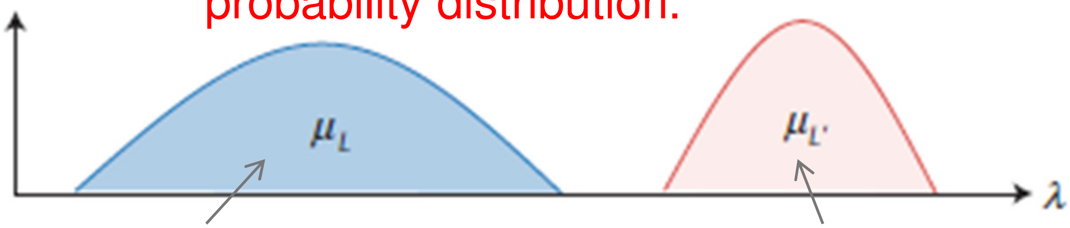

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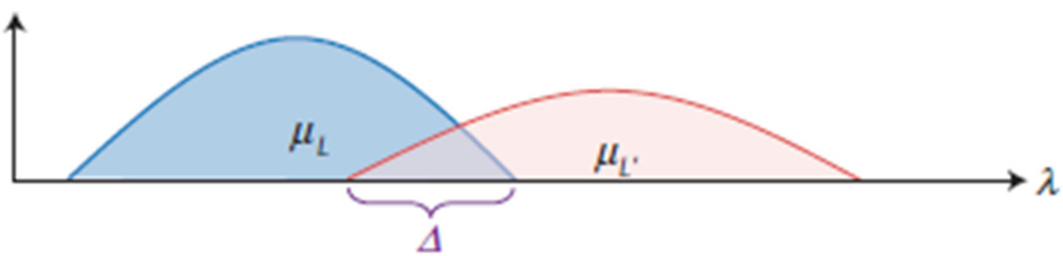
Ψ-epistemic models:



Only in the latter case can the quantum state be considered to be truly epistemic, that is, a representation of an observer's knowledge of reality rather than reality itself

The quantum state under fire

Question to answer:

What kind of *knowledge* is the quantum state?

Testing a "No-go" theorem about state reality:

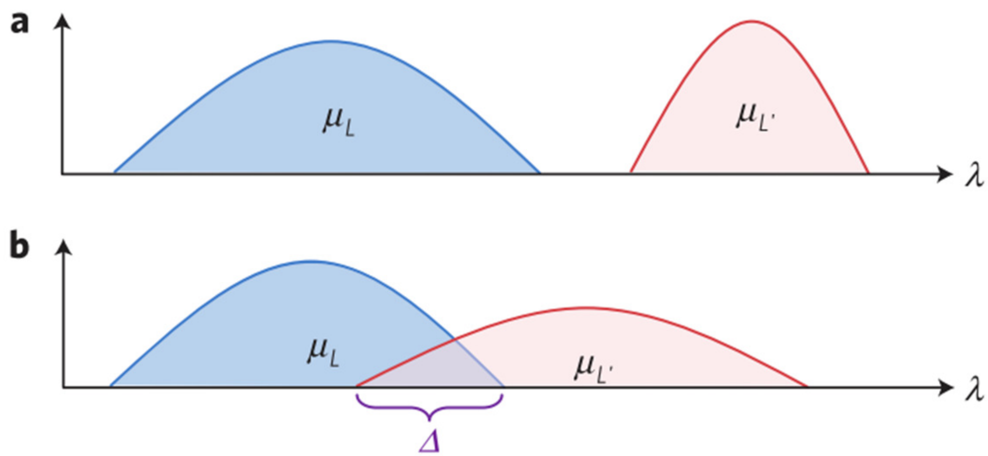
→ 1) Knowledge about underlying 'real state' (like the classical epistemic state). Not quite 'hidden variable.'

2) Knowledge with no underlying 'real state.' (Copenhagen)

3) A 'real' state of the system (i.e., the wavefunction is a real wave).

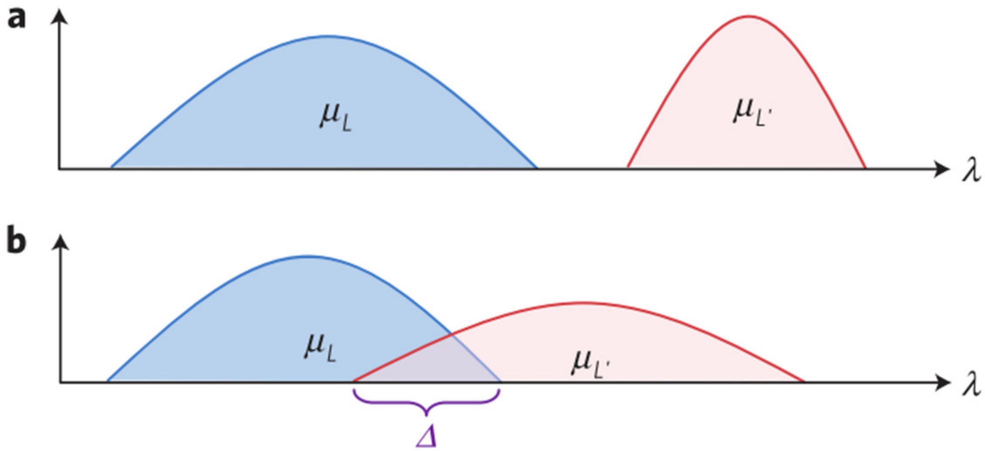
Is this just a semantic issue?

Distributional overlap is the key



Epistemic state distributions overlap, thereby containing a possibly infinite number of ‘real’ states in a wishy-washy property purgatory.

Distributional overlap is the key



Epistemic state distributions overlap, thereby containing a possibly infinite number of ‘real’ states in a wishy-washy property purgatory.

•Given only a system’s energy, an experimenter knows only a distribution of the state $\mu_E(x,p)$ in phase space.

•Energy is a physical property so different energies E and E’, refer to disjoint state distributions $\mu_E(x,p)$ and $\mu_{E'}(x,p)$.

•If two state distributions $\mu_L(x,p)$ and $\mu_{L'}(x,p)$ have an overlapping region L and L’ cannot be physical properties.

No-go theorem demonstrating that quantum state as information leads to contradiction.

Assumptions:

1: A quantum system has a real physical state. (Only needs to hold for isolated and not entangled systems.)

2: Systems prepared independently have independent physical states.

Pusey, Barrett, Rudolph say:

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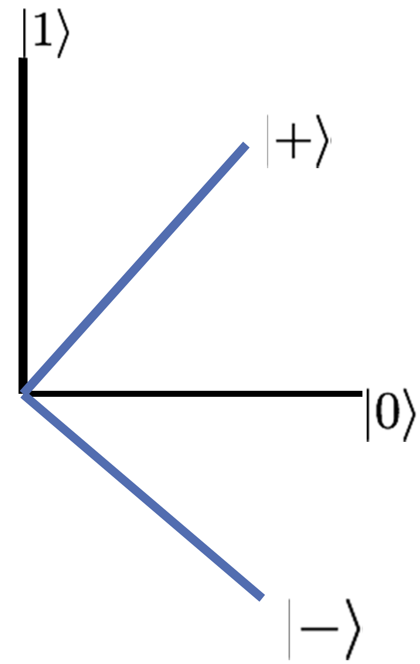
Prepare a quantum system

- Quantum theory gives a unique quantum state $|\psi\rangle$.
- The physical state may be described by a distribution function $\mu_\psi(\lambda)$
- Given two quantum states $|\psi_0\rangle$ and $|\psi_1\rangle$, let their corresponding distributions $\mu_0(\lambda)$ and $\mu_1(\lambda)$ overlap by some amount q > 0.

Preparation of states



Consider a two-state system with eigenvectors $|0\rangle$ and $|1\rangle$ along with a rotated basis given by

$$|\pm\rangle = \frac{|0\rangle \pm |1\rangle}{\sqrt{2}}$$

Prepare a state with two particles, e.g. $|0+\rangle = |0\rangle \otimes |+\rangle$

Possible preparations:

$$|0\rangle \otimes |0\rangle$$

$$|0\rangle \otimes |+\rangle$$

$$|+\rangle \otimes |0\rangle$$

$$|+\rangle \otimes |+\rangle$$

Basis for possible outcomes:

$$|\xi_1\rangle = \frac{1}{\sqrt{2}}(|0\rangle \otimes |1\rangle + |1\rangle \otimes |0\rangle)$$

$$|\xi_2\rangle = \frac{1}{\sqrt{2}}(|0\rangle \otimes |-\rangle + |1\rangle \otimes |+\rangle)$$

$$|\xi_3\rangle = \frac{1}{\sqrt{2}}(|+\rangle \otimes |1\rangle + |-\rangle \otimes |0\rangle)$$

$$|\xi_4\rangle = \frac{1}{\sqrt{2}}(|+\rangle \otimes |-\rangle + |-\rangle \otimes |+\rangle)$$

Entangled measurements and zero-probability outcomes

Looking at our possible measurements:

$$|\xi_1\rangle = \frac{1}{\sqrt{2}}(|0\rangle \otimes |1\rangle + |1\rangle \otimes |0\rangle)$$

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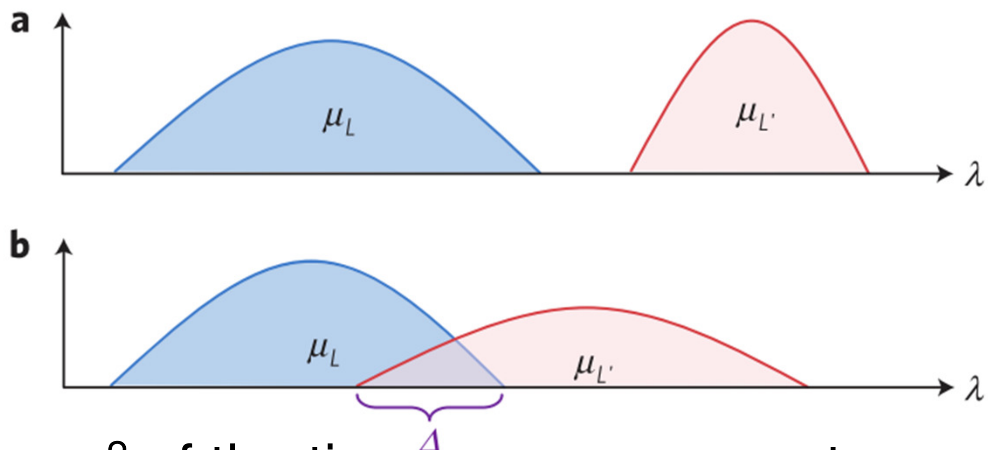
$$|\xi_4\rangle = \frac{1}{\sqrt{2}}(|+\rangle \otimes |-\rangle + |-\rangle \otimes |+\rangle)$$

There is a zero probability of measuring final state starting with state

starting state	final state
$\|0\rangle \otimes \|0\rangle$	$\|\xi_1\rangle$
$\|0\rangle \otimes \|+\rangle$	$\|\xi_2\rangle$
$\|+\rangle \otimes \|0\rangle$	$\|\xi_3\rangle$
$\|+\rangle \otimes \|+\rangle$	$\|\xi_4\rangle$

This leads to a contradiction with quantum theory



Remembering q^2 of the time a measurement corresponds to λ_1 or λ_2:

-At least q^2 of the time the measuring device does not know which of the four preparations was made originally.

-During this time a measurement can be made that quantum theory predicts has zero probability (a contradiction).

-This means the distributions $\mu_1(\lambda)$ and $\mu_2(\lambda)$ cannot overlap.

-Furthermore $|\psi_1\rangle$ and $|\psi_2\rangle$ can be uniquely determined from their distributions.

Pusey, Barrett, Rudolph (PBR) Polemic

Luboš Motl (Harvard):

…let me say that this is such a remarkable claim that if it is wrong, and it is obviously wrong, as I will discuss below, you should only be able to do it once in your life, especially if it gets to Nature, as long as the system of institutionalized science is functional. It's clearly not. You don't need to be competent at all. You may produce nothing else than garbage throughout your life and you will do just fine…

Matt Leifer (University College London):

…I find the use of the word "Statistically" [in preprint] in the title to be a rather unfortunate choice. It is liable to make people think that the authors are arguing against the Born rule (Luboš Motl has fallen into this trap in particular), whereas in fact the opposite is true. The result is all about reproducing the Born rule within a realist theory.

Criticism

1) Paper attempts to be precise in terminology, but does not go far enough (uses ‘loaded’ words and concepts/variables foreign to physics readership).

2) Philosophically interesting but touchy, semantic, and almost irrelevant to physics at-large.

3) Present three separate arguments for the same idea; why is one insufficient?

Citations

- Cites 23 papers

- Has been cited 5 times, 2 of them by the authors – 3 published in PRL, 1 in Nature Physics and 1 in Phys. Rev. A

Citations

Implications of the PBR No-Go Theorem (PRL):

- *They "make precise the class of models targeted and construct equivalent models that evadethe theorem".*
- *They say that "The theorem can be seen as showing that some measurements on composite systems must have built-in inefficiencies, complicating its testing".*

Citations

Distinct Quantum States Can Be Compatible with a Single State of Reality (PRL) :

- *They show that “not only is the 'preparation independence' assumption of the PBR no-go theorem necessary, but also any similar no-go theorem will also require nontrivial assumptions beyond those required for a well formed ontological model.*

Citations

Get real (Nature Physics News & Views):

- Notes that *“at one extreme, Antony Valentini called the PBR theorem the most important advance in the field since Bell’s inequality. At the other extreme, the paper has been labelled garbage and anti-quantum-mechanics”.*
- The author personally thinks *“the theorem is correct, original, interesting and possibly important.”*

Summary

1) **We can rule out quantum state as a representation of knowledge of an underlying state.**

2) **Still no proof regarding the existence of a ‘real’ state.**

3) **Pusey/Barrett/Rudolph’s research is very controversial.**