Abstract: In accordance with Betteridge's Law of Headlines, the answer to the question in the title is "no." I will argue that the usual norms of Bayesian inference lead the conclusion that quantum states are features of physical reality. The argument will involve both existing $\psi$-ontology results and extension of them that avoids the use of the Cartesian Product Assumption. As the usual norms of Bayesian inference lead to the conclusion of the reality of quantum state, rejecting it requires abandonment of virtually all of Bayesian information theory. This, I will argue, is unwarranted.
Can quantum states be understood as Bayesian states of belief?

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Algorithmic Information and Observers in Physics
Perimeter Institute for Theoretical Physics
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Betteridge’s Law of Headlines

Betteridge's law of headlines
From Wikipedia, the free encyclopedia

Betteridge's law of headlines is an adage that states: "Any headline that ends in a question mark can be answered by the word no." It is named after Ian Betteridge, a British technology journalist, although the principle is much older.

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Can quantum states be understood as Bayesian states of belief?

- Of course, one can, without getting into an outright contradiction, maintain that quantum states correspond to nothing in physical reality.
- But is that the conclusion that we will come to if we examine what we know with an eye to understanding what it is telling us about the world?
A well-motivated research programme

- A research programme with a distinguished history:
  - To understand quantum states as analogous to statistical mechanics probability distributions, and quantum probability as epistemic.
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- Among the things that give impetus to this research programme:
  - Common features of quantum states and classical probability distributions.
  - Fragments of QM that can be recovered by a classical theory with restrictions on preparation and access to information.

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- Among the things that give impetus to this research programme:
  - Common features of quantum states and classical probability distributions.
  - Fragments of QM that can be recovered by a classical theory with restrictions on preparation and access to information.
  - Phenomena that might be thought of as peculiarly quantum that can be recovered in such theories.
Status of these considerations?

- If taken as considerations motivating a research programme, they serve their purpose well.
- But they don’t count as *strong evidence* in favour of the conclusion for quantum state irrealism.
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- But they don’t count as strong evidence in favour of the conclusion for quantum state realism.
- The difference matters, because:
  - If we had strong evidence quantum states are not physically real, then, faced with an argument starting from assumptions of the sort usually taken for granted in science, it might become reasonable to reject those assumptions.
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- But they don’t count as strong evidence in favour of the conclusion for quantum state irrealism.
- The difference matters, because:
  - If we had strong evidence quantum states are not physically real, then, faced with an argument starting from assumptions of the sort usually taken for granted in science, it might become reasonable to reject those assumptions.
- It seems to me that we are not in such a situation.
Where I’m headed

I will present a variant of the argument of Pusey, Barrett, and Rudolph (PBR). (Nat. Phys. 8, 475, 2012). This variant is in WCM, arXiv:1803.04023v2[quant-ph].
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I will then outline the ontological models framework (Harrigan and Spekkens Found. Phys. 40, 125, 2010), which forms the background for the PBR argument and mine.
Information transfer schema

- Alice wants to send a message to send to Bob.
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- Shared presupposition:
  - Readout at Bob’s end is informative about Alice’s choice of operation.

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The physical content

- What we add to the bare schema on the previous slide: the folks who designed the protocol used a physical theory about the system to produce gadgets that can be expected to serve the purpose reliably.
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  - Upon receiving readout Y, Bob’s credence goes to certainty that Alice’s operation was X.
  - It is natural to attribute to Bob a belief that operation X produces physical states that the other choices of operations don’t.
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The ontological models framework

- Associate with a physical system \( S \) a measurable space \( \langle \Omega, \mathcal{L} \rangle \). \( \Omega \) is the ontic state space.
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- Associate with each preparation $\psi$ of $S$ a probability distribution $P_\psi$ on $\langle \Omega, \mathcal{L} \rangle$.
- For an $n$-outcome experiment, there are $n$ functions $f_k : \Omega \rightarrow [0, 1]$. $f_k(\omega)$ is the probability of obtaining outcome $k$ in ontic state $\omega$. 

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- Probability of outcome $k$, given preparation $\psi$: $\langle f_k \rangle P_\psi$. 

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  - Disregarding the previous state of the system!
- A preparation is a very special sort of operation, as it screens off the past of the system.
- Local preparation: screens off correlations with other things.
The ontological models framework

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- Associate with each preparation $\psi$ of $S$ a probability distribution $P_\psi$ on $\langle \Omega, \mathcal{L} \rangle$.
- For an $n$-outcome experiment, there are $n$ functions $f_k : \Omega \rightarrow [0, 1]$. $f_k(\omega)$ is the probability of obtaining outcome $k$ in ontic state $\omega$.
- For all $\omega \in \Omega$, $\sum_k f_k(\omega) = 1$.
- Probability of outcome $k$, given preparation $\psi$: $\langle f_k \rangle_{P_\psi}$.
- Nothing at all rides on whether these probability functions, $P_\psi$ and $f_k$, are thought of as physical or subjective.
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"if I consider the physical phenomena with which I am acquainted, and especially those which are so successfully comprehended by means of quantum mechanics, then, nevertheless, I nowhere find a fact which makes it appear to me probable that one has to give up" this assumption.

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Can quantum states be understood as Bayesian states of belief?
Distinguishability, etc.

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- A pair of preparations \( \psi, \phi \) is \textit{ontologically distinct} iff there is no overlap in the probability distributions \( P_\psi, P_\phi \).
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- **Lemma:** A distinguishable set of preparations is pairwise ontologically distinct.
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- **Lemma**: A distinguishable set of preparations is pairwise ontologically distinct.

- A set of preparations \( \{\psi_i\} \) is antidistinguishable iff there is an experiment \( E \) such that each outcome of \( E \) has zero probability on some preparation in the set.
Distinguishability, etc.

- A set of preparations \( \{\psi_i\} \) is *distinguishable* iff there is an experiment \( E \) such that each outcome of \( E \) has nonzero probability on only one preparation.

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- *Lemma:* A distinguishable set of preparations is pairwise ontologically distinct.

- A set of preparations \( \{\psi_i\} \) is *antidistinguishable* iff there is an experiment \( E \) such that each outcome of \( E \) has zero probability on some preparation in the set.

- *Lemma:* An antidistinguishable set of preparations has null joint overlap of all the corresponding probability distributions.
In any ontological model of quantum mechanics, orthogonal states are ontologically distinct.
ψ-ontology

- In any ontological model of quantum mechanics, orthogonal states are ontologically distinct.
- Non-orthogonal pure states are not distinguishable. Are they ontologically distinct, or are they more like classical probability distributions, whose indistinguishability is due to overlap of the distributions on ontic state space?
No ontological model of QM is fully $\psi$-epistemic

An ontological model is fully $\psi$-epistemic iff indistinguishability of states is fully accounted for by overlap of the corresponding probability distributions.
The PBR argument, I

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- We have a pair of systems $A$, $B$.
- Consider a pair of states $|\psi\rangle$, $|\phi\rangle$, with $|\langle\psi|\phi\rangle| \leq 1/\sqrt{2}$. 
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- We have a pair of systems $A, B$.
- Consider a pair of states $|\psi\rangle, |\phi\rangle$, with $|\langle\psi|\phi\rangle| \leq 1/\sqrt{2}$.
- The set of states,

$$\{|\psi\rangle_A |\psi\rangle_B, |\psi\rangle_A |\phi\rangle_B, |\phi\rangle_A |\phi\rangle_B, |\phi\rangle_A |\psi\rangle_B\}$$

is antidistinguishable.
The PBR argument, I

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$$

is antidistinguishable.
- Therefore, the corresponding set of probability distributions have null joint support.
The PBR argument, II

Now impose the *Preparation Independence Postulate* (PIP):
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  - (CPA) $\Omega_{AB} = \Omega_A \times \Omega_B$.
  - (NCA) Probability distribution is a product distribution:
    $$P_{AB}(\Delta_A \times \Delta_B) = P_A(\Delta_A)P_B(\Delta_B).$$
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      $$P_{AB}(\Delta_A \times \Delta_B) = P_A(\Delta_A)P_B(\Delta_B).$$
  - From this, plus antidistinguishability, it follows that the states $|\psi\rangle$, $|\phi\rangle$ are ontologically distinct.
Two attitudes towards the PBR Theorem

- Results of this sort can be regarded either as:
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- I want to know about our world!
- Assumptions we use should hold in successor theories to QM: QFT and beyond.

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- Assumptions we use should hold in successor theories to QM: QFT and beyond.
- Theorem should also be robust under relaxation of idealizations.

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QFT: it is a consequence of the Reeh-Schlieder theorem that, in any state of bounded energy, there is entanglement between any two spacelike separated open sets.
A worry about the Cartesian Product Assumption

- **QFT**: it is a consequence of the Reeh-Schlieder theorem that, in any state of bounded energy, there is entanglement between any two spacelike separated open sets.
- We should not assume that *any* product states are preparable!
Preparation Uninformativeness Condition

Consider a pair of systems, \( A, B \), with a choice of local preparations on each.
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- Consider a pair of systems, \( A, B \), with a choice of local preparations on each.
- Preparation chosen independently on each, with probabilities \( \{p_i^A\}, \{q_i^B\} \).
Preparation Uninformativeness Condition

- Consider a pair of systems, $A$, $B$, with a choice of local preparations on each.
- Preparation chosen independently on each, with probabilities $\{p_i^A\}$, $\{q_i^B\}$.
- Preparations having been chosen and performed, you are presented with the ontic state of the joint system.
The Preparation Uninformativeness Condition

- PIP implies PUC.
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- PUC is strictly weaker:
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The Preparation Uninformativeness Condition

- PIP implies PUC.
- PUC is strictly weaker:
  - It does not presuppose the CPA.
  - Even in the presence of the CPA, there can be models that satisfy PUC but not NCA.

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- It is *not* assumed to hold for arbitrary operations.
- Example: For a pair of systems $A, B$, let $|\psi\rangle$ be any entangled state in $\mathcal{H}_A \otimes \mathcal{H}_B$. 
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    - $I \otimes U_B |\psi\rangle \neq |\psi\rangle$
    - $U_A \otimes U_B |\psi\rangle = |\psi\rangle$
- Suppose now, that, starting with $|\psi\rangle$, Alice and Bob each make a choice between doing nothing and applying their unitaries.
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    - $U_A \otimes U_B |\psi\rangle = |\psi\rangle$
- Suppose now, that, starting with $|\psi\rangle$, Alice and Bob each make a choice between doing nothing and applying their unitaries.
- If I tell you that the resulting state is $|\psi\rangle$, you are undecided between $I \otimes I$ and $U_A \otimes U_B$. 

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A $\psi$-ontology result using the PUC, I

Suppose that we have two systems, and a choice of preparations $\psi$, $\phi$ on each, such that the resulting set of four alternatives is an antidistinguishable set.
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This entails: no 4-way joint overlap between the probability distributions $\{P_{\psi,\psi}, P_{\psi,\phi}, P_{\phi,\phi}, P_{\phi,\psi}\}$. 
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- This entails: no 4-way joint overlap between the probability distributions $\{P_{\psi,\psi}, P_{\psi,\phi}, P_{\phi,\phi}, P_{\phi,\psi}\}$.
- PUC entails that the ontic state $\omega$ always permits unique determination of at least one of the subsystem preparations.

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Can quantum states be understood as Bayesian states of belief?
A $\psi$-ontology result using the PUC, II

- Suppose that, given the ontic state $\omega$, you are undecided about both subsystem preparations.
  - $\omega$ is in overlap of $P_{\psi,\psi}$ and $P_{\phi,\phi}$, or of $P_{\psi,\phi}$ and $P_{\phi,\psi}$.
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- If $\omega$ is in joint overlap of $P_{\psi,\psi}$ and $P_{\phi,\phi}$, it can’t also be in overlap of $P_{\psi,\phi}$ and $P_{\phi,\psi}$.
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  - Suppose $\omega$ is incompatible with $P_{\psi,\phi}$.
  - You are undecided between $\psi, \psi$ and $\phi, \phi$, but certain it’s not $\psi, \phi$. 

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  - Suppose $\omega$ is incompatible with $P_{\psi,\phi}$.
  - You are undecided between $\psi$, $\psi$ and $\phi$, $\phi$, but certain it’s not $\psi$, $\phi$.
  - Learning that the $B$-preparation was $\phi$ tells you that the $A$-preparation was $\phi$, contradicting PUC.
- Same if $\omega$ is incompatible with $P_{\phi,\psi}$.
- Conclusion: PUC + antidistinguishability entails no overlap between $P_{\psi,\psi}$ and $P_{\phi,\phi}$.

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Can quantum states be understood as Bayesian states of belief?
A $\psi$-ontology result using the PUC, III

- From previous slide: PUC + antidistinguishability entails that the ontic state $\omega$ always permits unique determination of the preparation of at least one of the subsystems $A$, $B$.
- Now consider a system $\Sigma_N$ composed of a large number of subsystems, each subjected to either $\psi$ or $\phi$.
A $\psi$-ontology result using the PUC, III

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- For each pair, it is possible to perform an experiment that antidistinguishes the four possibilities of preparations.
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- For each pair, it is possible to perform an experiment that antidistinguishes the four possibilities of preparations.
- Assume PUC.
  - Ontic state of $\Sigma_N$ must be such that, for each pair, it uniquely determines the preparation of at least one member of the pair.

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- For each pair, it is possible to perform an experiment that antidistinguishes the four possibilities of preparations.
- Assume PUC.
  - Ontic state of $\Sigma_N$ must be such that, for each pair, it uniquely determines the preparation of at least one member of the pair.
  - That is, ontic state of $\Sigma_N$ leaves the preparation of at most one subsystem undecided.
  - Probability of correctly identifying a randomly chosen subsystem is at least $1 - 1/N$.

Wayne C. Myrvold

Can quantum states be understood as Bayesian states of belief?
A $\psi$-ontology result using the PUC, IV

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- Principle of extendibility: the ontic state of $\Sigma_N$ must be compatible with its being part of a larger system $\Sigma_{N'}$, for arbitrarily large $N'$. 

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Can quantum states be understood as Bayesian states of belief?
Convinced?

- If you aren’t convinced that pure quantum states to which the theorem applies are ontologically distinct, what assumptions do you reject? And what are your reasons?