QUANTUM MECHANICS

Get real

Do quantum states offer a faithful representation of reality or merely encode the partial knowledge of the experimenter? A new theorem illustrates how the latter can lead to a contradiction with quantum mechanics.

Scott Aaronson

You might think that, since the legendary Bohr–Einstein debates of the 1920s, questions concerning the foundations of quantum mechanics have been picked over so thoroughly that little meat is left. The theory works, no one intuitively understands it — what else is there to say? Yet from time to time, people have found new aspects of quantum mechanics — from Bell's inequality to Shor's factoring algorithm — which gave debaters some fresh ammunition. These discoveries (and countless others) have obviously not settled the debate about the reality of the wavefunction, but they have sparked hope that progress might be possible on these matters.

For some, that hope was reignited in November 2011, when Matthew Pusey, Jon Barrett and Terry Rudolph announced (via preprint[1]) what has already come to be known as the PBR theorem in quantum foundations. Emotions about this theorem ran high, this time not in the cafés of Copenhagen but on news sites and blogs. At one extreme, Antony Valentini told *Nature News*[2] that he thought the word 'seismic' seemed apt, and 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 (http://go.nature.com/3vZqkM). But now, Pusey *et al.*[3] have their findings formally published in *Nature Physics*. I personally think the theorem is correct, original, interesting and possibly important — although your take on its importance may depend on whether the ideas ruled out by the theorem ever appealed to you in the first place.

In a nutshell, the PBR theorem concerns whether the quantum wavefunction, ψ, is uniquely determined by the state of reality, or the so-called ontic state. Of course, if you believed both that the wavefunction truly exists and that nothing else does, then you could simply declare it equal to the ontic state and be done. However, we do not want to presuppose that equality, as the whole point of this game is to see how close we can come to deducing it from the experimental predictions of quantum mechanics. It is crucial to understand that we're not discussing whether the same wavefunction can be compatible with multiple states of reality, but a different and less familiar question: whether the same state of reality can be compatible with multiple wavefunctions. Intuitively, the reason we're interested in this question is that the wavefunction seems more 'real' if the answer is no, and more 'statistical' if the answer is yes.

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For Pusey *et al.*[3], an observable is called ontic if it is completely determined by the ontic state, and is otherwise called epistemic. To illustrate this, in a Newtonian universe, the positions, velocities and masses of the particles would be ontic, but the probability of a given future event would be epistemic. For example, Alice and Bob might reasonably assign different probabilities to the same event, simply because Alice knows something that Bob doesn't.

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In the quantum world, it seems clear that mixed states — being, after all, just the quantum version of probability distributions — are similarly epistemic. By contrast, pure states seem stubbornly ontic. If Alice thinks that a qubit is in the state $|0\rangle$, whereas Bob thinks it is in the state $|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$, then intuition suggests that at least one of them must be flat-out mistaken.

On reflection, though, what exactly goes wrong if Alice and Bob try to describe the same physical system using different pure states? In the previous example, suppose someone measured the qubit in the basis $\{|0\rangle, |1\rangle\}$, and the outcome was $|1\rangle$. Then Alice would be unmasked as irrational: her belief that the state was $|0\rangle$ corresponds to a zero probability for the actual outcome. On the other hand, we could imagine hidden variables dictating that for this measurement, on this qubit, the outcome would be $|0\rangle$ — in which case there would be no obvious problem. If you can invent such a hidden-variable story, and show that it perfectly reproduces all the predictions of standard quantum mechanics, while still (sometimes) letting Alice and Bob describe the same system with different pure states, then you have what Pusey *et al.* call a ψ-epistemic theory.

Perhaps you consider such a theory outlandish, or even in conflict with earlier theorems such as Bell's inequality. And yet, at least for special cases, non-trivial ψ-epistemic theories have been explicitly constructed[4,5]. However, Pusey *et al.* show that, if we make one further assumption — basically, that rational beliefs behave well under tensor product — then ψ-epistemic theories are impossible.

To understand this, consider the previous example, where Alice described a qubit using the state $|0\rangle$, and Bob described the same qubit using $|+\rangle$. It seems reasonable to suppose that if we just repeat the experiment in two separate labs then we'll get a joint state of two qubits, which could be described by four different people as any one of $|0\rangle|0\rangle$, $|0\rangle|+\rangle$, $|+\rangle|0\rangle$ or $|+\rangle|+\rangle$. Yet Pusey *et al.* describe an entangled measurement on this joint state such that, whatever the measurement's outcome, one of the four people will be unmasked as irrational. (In general, we might need more than two qubits to make the argument, but the basic idea remains the same.) The conclusion is that Alice and Bob cannot rationally assign different pure states to the same physical system, even if their pure states are non-orthogonal. If one or both of them were uncertain about which pure state to assign, then they should have used a mixed state instead.

The consequences this theorem has for the interpretation of quantum mechanics depend on which camp you reside in. If you favour the many-worlds or Bohm interpretations, then the PBR theorem shouldn't trouble you in the least — the wavefunction is an explicit part of your ontology (in many-worlds, it is your ontology), so the ontic state uniquely determines ψ.

Likewise if you adhere to the shut-up-and-calculate philosophy or the Copenhagen interpretation (which I think of as shut-up-and-calculate minus the shutting-up part) then the PBR result shouldn't trouble you. You don't have an ontology: you consider it uninteresting or unscientific to discuss reality before measurement. For you, ψ is indeed an encoding of human knowledge, but it's merely knowledge about the probabilities of various measurement outcomes, not about the state of the world before someone measures.

If, like Roger Penrose, you believe quantum mechanics itself is just an approximation to some deeper theory, then again PBR shouldn't trouble you. For in that case, you're free to adopt a shut-up-and calculate attitude about ψ, while also holding out hope that the yet-undiscovered deeper theory will grant you your ontology.

But if you think that the rules of quantum mechanics are fine and the wavefunction is merely a summary of human knowledge about underlying objects that are not themselves quantum states — then, and only then, the PBR theorem spells big trouble for you. In this case, you have two choices: you can either deny the PBR tensor product assumption, or you can change your belief. Personally, I'd opt for the latter. ❐

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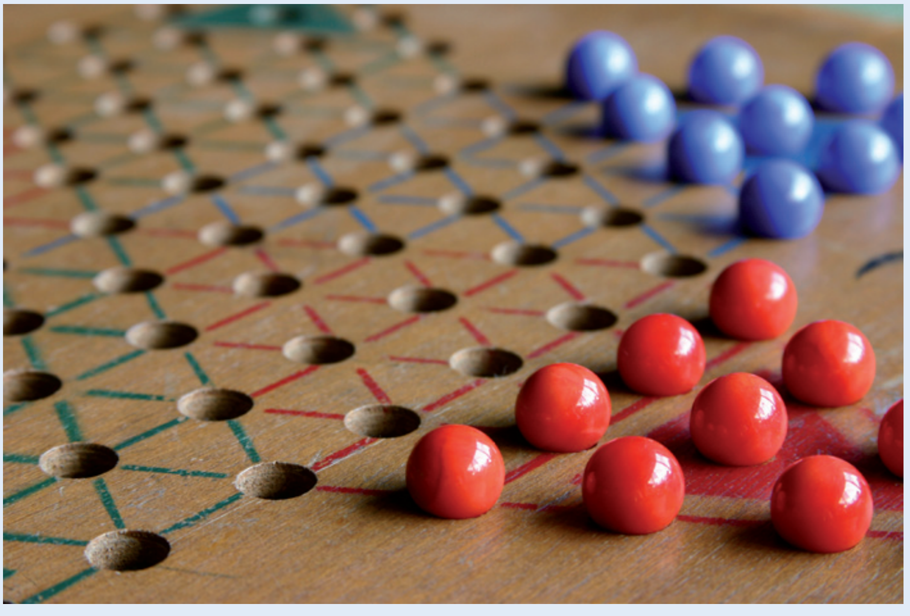
QUANTUM SIMULATION

Toy model

To understand the physics of complicated systems, physicists choose to work with simplified models that can be easily manipulated and observed: from eighteenth-century orreries to the twentieth-century Feynman quantum simulator, the toy models may have grown in complexity, but the principle remains the same. Now, using cold trapped ions — as though in a game of marbles on a lattice board — Joseph Britton and colleagues demonstrate such a toy model for quantum magnetism (*Nature* **484,** 489–492; 2012).

Spin frustration is one of the tricky problems in quantum magnetism that cannot be efficiently tackled using computer simulation. The challenge is to find the minimum-energy configurations for spins on a triangular lattice — however, the lattice geometry forbids the simultaneous minimization of the interaction energies at a given site. In analogy with marbles on a board, the problem corresponds to trying to fill the board with blue and red marbles such that no marble has two neighbours of the same colour.



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An alternative to this difficult computation is to actually construct a triangular lattice of interacting spins and have them evolve into various configurations. This can be done by trapping neutral atoms in periodic optical potentials; but, although the method is elegant, inducing the required type of interactions between the atoms is not straightforward. Ion interactions, on the other hand, are stronger and easier to control.

Britton *et al.* trapped hundreds of beryllium ions using electric and magnetic fields. The laser-cooled ions crystallized into a two-dimensional triangular lattice structure — an ion 'marble' at each site, with its electronic ground and excited states representing the 'colour': spin up or spin down. Using a pair of off-resonance laser beams, the researchers excited the collective motion of the ions. Then, through the entanglement of the ions' motion and their electronic states, this excitation could be translated into an effective ion–ion Ising-type interaction.

Several proof-of-concept experiments on spin interactions and quantum phase transitions have already been performed by other researchers, using few ions. But Britton and colleagues' work using hundreds of ions has created a new playground in which to explore quantum magnetism, far beyond simple computable scenarios.

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