Interpreting the Wavefunction
(Based on “The life of psi” – Physics World, May 2013)

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Everything has a wavefunction: electrons, atoms, people, planets, even the entire universe.

Psi is a probability amplitude.  
Psi^2 is a probability density.

Hermitian operators extract information about measurable observables when acting on a wavefunction.
**Historical Development**

<table>
<thead>
<tr>
<th>Year</th>
<th>Name</th>
<th>Contribution</th>
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<tbody>
<tr>
<td>1900</td>
<td>Planck</td>
<td>light can be interpreted as both a wave and a stream of photons</td>
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<tr>
<td>1905</td>
<td>Einstein</td>
<td>first complete representation of quantum mechanics</td>
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<tr>
<td>1923</td>
<td>de Broglie</td>
<td>general “wave-particle duality”</td>
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<tr>
<td>1923</td>
<td>Debye</td>
<td>postulates existence of wave equation</td>
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<tr>
<td>1926</td>
<td>Schrödinger</td>
<td>wave equation/equation of motion</td>
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- Is $\psi$ a physical wave?
- What about nondeterministic wavefunction collapse?

1925 – Heisenberg, Born and Jordan:
- explained the structure of an atom using matrix mechanics
- first complete representation of quantum mechanics
- Schrödinger wanted a less abstract approach...
- ...something more continuous and visualizable, like classical physics

Psi (physical wave) would have to exist in a numerous (sometimes an infinite) number of dimensions.

Copenhagen/orthodox interpretation:
- wavefunction evolves deterministically
- measurement leads to wavefunction collapse
- system randomly acquires definite properties
- mechanism unknown
Interpretations of the Wavefunction

1) Does quantum theory describe an objective reality, independent of the observer?
   realists v. anti-realists

2) Does the wavefunction represent partial knowledge about reality or is it actually part (or all) of reality?
   epistemic view v. ontic view

Realists (intuitive) – reality exists even when we are not observing it or have no knowledge of it.
Anti-realists (pragmatic) – nothing can be said of nature when we are not looking, the job of physicists is to make sure that predictions match up with observation, nothing more.

Mermin: “Is the moon really there when nobody looks?”, Physics Today, 1985

Will the future bring a deeper underlying theory that will leave the wavefunction redundant?

“Epistemic” comes from the Greek ‘episteme’ = “knowledge”.
- state of partial knowledge (“hidden variables” view – system is hiding information)

“Ontic” comes from the Greek ‘on’ = “being”.
- completely specifies the particle’s situation
Consider a classical one-dimensional particle in phase space.
What is the difference between Einstein’s wavefunction, which represents partial knowledge about reality, and Bohm’s wavefunction, which is part (but not all) of reality?

The distinction between ontic and epistemic realist views needs to be made more precise.
Defining Reality

For example:
- **Energy** – definitely a part of reality
- A value of energy does not uniquely define an ontic state.
- However, an ontic state uniquely defines an energy.

Let this **many-to-one mapping** define a “part of reality”.

**Definition:** If a single ontic state only ever corresponds to a single wavefunction, then the wavefunction must *at least* be part of reality.

2010 - Robert Spekkens (Cambridge) & Nicholas Harrigan (Imperial): energy example.
The PBR Thought Experiment
– the dice analogy (I)

• 2 identical die rolling machines, each with 2 buttons:
  – ‘E’ **even number** is guaranteed
  – ‘P’ **prime number** is guaranteed
• Put these 2 machines side by side and let them roll dice simultaneously into a measurement box
• Measurement box displays a complete list of possible initial states that can be ruled out
• Measurement lamps start off **red** but any lamp corresponding to the actual outcome turns **green**

“*Will the measurement box always be able to turn at least one bulb green?*”

Matthew Pusey (Imperial), Johnathan Barratt (Royal-Holloway) & Terry Rudolph (Imperial): “On the reality of the quantum state”, Nature 2012
What if you roll a pair of twos?

The PBR Thought Experiment
– the dice analogy (II)

- If a pair of twos are rolled, no results can be ruled out.
- E and P buttons are preparing epistemic states, since they can sometimes correspond to the same ontic state: 2.

Now consider two wavefunctions, $\psi_1$ and $\psi_2$:

“Will the measurement box always be able to turn at least one bulb green?”
Quantum mechanics predicts that it is impossible to prepare an ontic state that corresponds to both $\psi_1$ and $\psi_2$, no matter what pair of wavefunctions are chosen.

This is derived from calculating the quantum probabilities of each state. Therefore, a single ontic state only ever corresponds to a single wavefunction.
There were already reasons to be sceptical of the epistemic view. E.g. experimental evidence that particles interfere with one another – a truly wave-like property, which suggests that particles are not merely partial knowledge of reality.

Terry Rudolph (Imperial) – supports an epistemic interpretation!
- believes that there is physics beyond the wavefunction
- we are working with implicit assumptions of space and time: “I prepare this and then I measure that, etc.”

**The PBR Theorem**

“If quantum mechanics is correct, then the wavefunction cannot be epistemic”

- **Assumption:** independently prepared systems have independent physical states
- In all its history, no prediction of quantum mechanics has ever been exposed as false.
- PBR have offered an experimental blueprint to test their theorem.
### Conclusion

If our current understanding of quantum mechanics is correct, the wavefunction is either part of reality or reality in full.

| Bohmian | Everettian |

- Bohm $\rightarrow$ pilot-wave theory
- Everett $\rightarrow$ many-worlds interpretation

**Pilot-wave theory:**
- reality consists of waves and particles
- the waves pilot the particles’ motion (“Bohm trajectories”)

**Many-worlds interpretation:**
- all alternative outcomes of physical processes happen in (a possibly infinite number of) myriad alternative universes
- each wavefunction collapse leads to the universe splitting