

# Philosophy of quantum mechanics

VU University Amsterdam: W\_MASP\_TF013 Lecture 6: 19/2/2015

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# Today's lecture

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- ▶ **Recap: measurement problem and research essay questions.**
- ▶ **The Everett interpretation**
  - ▶ Linear dynamics and wave function only.
- ▶ **Many worlds: Albert's two objections**
  - ▶ The basis problem
  - ▶ The probability problem
- ▶ **Albert's versions of Everett**
  - ▶ Bare theory: Everett interpretation plus eigenstate-eigenvalue link.
  - ▶ Many (many) minds theory
- ▶ **Many worlds: The Oxford view**
  - ▶ Response to basis problem: decoherence and emergence.

# The problem of outcomes

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- ▶ The following three claims are mutually inconsistent.
  - ▶ A. The wave-function of a system is complete i.e. the wave-function specifies (directly or indirectly) all of the physical properties of a system.
  - ▶ B. The wave-function always evolves in accord with a linear dynamical equation (e.g. the Schrödinger equation).
  - ▶ C. Measurements always (or at least usually) have determinate outcomes, i.e., at the end of the measurement the device indicates a definite physical state.

# Illustrating the inconsistency

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- ▶ A. Imagine the complete wave function is:

$$\frac{1}{\sqrt{2}} | \text{"ready"} \rangle_m | \text{hard} \rangle_e + \frac{1}{\sqrt{2}} | \text{"ready"} \rangle_m | \text{soft} \rangle_e$$

- ▶ B. Then given the linearity of the dynamics inserting electron e into device m yields:

$$\frac{1}{\sqrt{2}} | \text{"hard"} \rangle_m | \text{hard} \rangle_e + \frac{1}{\sqrt{2}} | \text{"soft"} \rangle_m | \text{soft} \rangle_e$$

- ▶ C. But this is not a determinate outcome such as:

$$| \text{"soft"} \rangle_m | \text{soft} \rangle_e$$

# Taxonomy of solutions

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- ▶ **Deny A. – wave function is incomplete.**
  - ▶ Additional variables theories
    - ▶ (Not our focus)
- ▶ **Deny B. – dynamics is not (always) linear.**
  - ▶ Dynamical collapse theories
    - ▶ Triggered collapse theories (e.g. CCC).
    - ▶ Spontaneous collapse theories (e.g. GRW).
- ▶ **Deny C. – measurements don't have single outcomes.**
  - ▶ Everett interpretation (many-worlds theory)

# The philosophical issues

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- ▶ Should we remove the collapse postulate?
  - ▶ But then how do we make sense of probability?
- ▶ Or: Should we make the collapse postulate more precise?
  - ▶ By spontaneous collapses?
    - ▶ Tails problem – why is this not a many worlds theory?
  - ▶ By defining consciousness as the cause?
    - ▶ How is ‘consciousness’ better than ‘measurement’?
    - ▶ Does this idea exploit the mind-body problem, or contribute to its solution?
    - ▶ Is there still a problem of tails?

# The Everett Interpretation

Historical background and contemporary status

# Hugh Everett III (1930-1982)

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- ▶ Entered graduate school at Princeton in 1953.
- ▶ One night in 1954, “after a slosh or two of sherry,” he had a conversation with Charles Misner and Aage Peterson (Bohr’s assistant) during which he discovered the basic idea of many-worlds theory.
- ▶ Began to work these ideas into a PhD dissertation under the supervision of J.A.Wheeler.
- ▶ Spring 1956: Wheeler takes the draft to Copenhagen...





Princeton, 1955: Everett (second from right) with Niels Bohr and Charles Misner (first from left).

# The drama of Everett's PhD thesis

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- ▶ **Wheeler wrote back to Everett:**
  - ▶ “Your beautiful wave-function formalism of course remains unshaken; but all of us feel that the real issue is the words that are to be attached to the quantities of the formalism.”
- ▶ **E.g. a footnote from Everett's dissertation reads:**
  - ▶ “From the viewpoint of the theory, all elements of a superposition (all ‘branches’) are ‘actual,’ none any more ‘real’ than the rest.”
- ▶ **In a letter to Stern (Bohr's associate in Copenhagen), Wheeler excused Everett's theory as an extension, not a refutation of the standard Copenhagen interpretation...**

# Wheeler to Stern

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- ▶ “I think I may say that this very fine and able and independently thinking young man had gradually come to accept the present approach to the measurement problem as correct and self-consistent, despite a few traces that remain in the present thesis of a past dubious attitude. So, to avoid any possible misunderstanding, let me say that Everett’s thesis is not meant to question the present approach, but to accept and generalize it.”
  - ▶ In 1957, Wheeler made Everett delete all unorthodox passages from his draft, cutting it to one quarter the original length, before submitting. The committee then accepted the abridged version.
  - ▶ Discouraged, Everett left academia to work on military and industrial mathematics and computation.
  - ▶ Bryce DeWitt who had corresponded with Everett in 1957, edited an anthology on many-worlds and included Everett's unpublished 1956 paper *The Theory of the Universal Wavefunction*. The book was published late in 1973 and sold out completely.
    - ▶ ‘The origin of the Everettian heresy’. 2009. Osnaghi et. al. *SHPMP* Vol. 40(2): 97-123

# Nowadays...

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- ▶ **The view was still initially not well received because:**
  - ▶ **Technical problem: the basis problem**
    - ▶ Now widely considered to have been solved by a technical development: decoherence (today's lecture).
  - ▶ **Philosophical problem: the probability problem**
    - ▶ This is still a moot point (next week's lectures).
- ▶ **Nowadays, we don't have definite data, but:**
  - ▶ Poll of 72 "leading cosmologists" in 1995 showed 58% agreement with "Yes, I think MWI is true".
    - ▶ Including Stephen Hawking and Nobel Laureates Murray Gell-Mann and Richard Feynman.
  - ▶ In philosophy it is widely believed that if the probability problem can be solved, then Everett wins.
    - ▶ The "Oxford Everettians" have tried to solve this problem.

# The Everett Interpretation

A.K.A. many worlds theory

# The problem of outcomes

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- ▶ The following three claims are mutually inconsistent.
  - ▶ A. The wave-function of a system is complete i.e. the wave-function specifies (directly or indirectly) all of the physical properties of a system.
  - ▶ B. The wave-function always evolves in accord with a linear dynamical equation (e.g. the Schrödinger equation).
  - ▶ **C. Measurements always (or at least usually) have determinate outcomes, i.e., at the end of the measurement the device indicates a definite physical state.**
    - ▶ **Can we deny C?**

# The Everett interpretation (definition)

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- ▶ The Everett interpretation is *defined* in terms of A and B:
  - ▶ The physical universe is *completely* described by the wave-function and the wave function *only* ever evolves linearly (e.g. via the Schrödinger equation).
- ▶ This is what all “Everett-views” have in common.
  - ▶ As we shall see, many ways of developing this basic idea.
  - ▶ I will ignore the question of what Everett’s (1957) intended idea was (it’s controversial exegesis).

# The problem with denying C

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- ▶ A. Imagine the complete wave function is:

$$\frac{1}{\sqrt{2}} | \text{"ready"} \rangle_m | \text{hard} \rangle_e + \frac{1}{\sqrt{2}} | \text{"ready"} \rangle_m | \text{soft} \rangle_e$$

- ▶ B. Then given the linearity of the dynamics inserting electron e into device m yields:

$$\frac{1}{\sqrt{2}} | \text{"hard"} \rangle_m | \text{hard} \rangle_e + \frac{1}{\sqrt{2}} | \text{"soft"} \rangle_m | \text{soft} \rangle_e$$

- ▶ C. This is not a determinate outcome. But determinate outcomes are what we see when we perform such measurements e.g.

$$| \text{"soft"} \rangle_m | \text{soft} \rangle_e$$

# The “canonical” Everettian solution

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- ▶ The linear dynamics guarantees that “the observer O” sees a determinate outcome...

$$\frac{1}{\sqrt{2}} |"hard">_o |"hard">_m |hard>_e$$
$$+ \frac{1}{\sqrt{2}} |"soft">_o |"soft">_m |soft>_e$$

- ▶ ..because observer O literally splits into *two* observers post-measurement!
  - ▶ One observes a hard result the other observes a soft result.
- ▶ This is the *many worlds* interpretation.
  - ▶ Albert thinks this is not the best way to understand the Everett interpretation...

Many worlds: Albert's two objections

# Albert's two objections

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## ▶ Objection 1: The basis problem:

- ▶ If a “world” is *identified* with an individual term in a state vector (i.e. a superposition component)...
  - ▶ (and *how else* could a world be defined by the formalism?)
- ▶ ...then the number and the content of the world varies depending on which basis we write the state vector down in.

## ▶ Objection 2: The probability problem:

- ▶ The previous experiment (hardness measurement on black electron) gave both possible outcomes (in different worlds).
- ▶ So no sense can be made of the claim that the measurement will give one or the other outcome *with 0.5 probability*.

# The basis problem

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- ▶ What “worlds” there are (at a time) will depend on what separate terms there are in the state vector (at that time).
- ▶ But: what separate terms there are (at a time) depend on what basis we write that vector down in.
- ▶ And (according to Albert 1992): **there isn’t anything in the formalism that picks out any basis as the “right” one.**
- ▶ So many worlds theory needs to “add something” to define worlds (but it’s not clear what).
  - ▶ Albert pp. 113-4.

# The basis problem: simple illustration

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- ▶ Consider only the spin state of a single electron:
  - ▶  $|\text{soft}\rangle$ 
    - ▶ So there's one world containing a soft electron.
- ▶ But we can write this down in the colour basis:
  - ▶  $\frac{1}{\sqrt{2}}|\text{black}\rangle - \frac{1}{\sqrt{2}}|\text{white}\rangle$ 
    - ▶ So now there's two worlds, one containing a black electron, another containing a white electron.
- ▶ The formalism does not privilege either basis as “more correct”.

# The basis problem: Albert's illustration

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- ▶ Albert considers the result of a colour measurement on a hard electron (h for human)...

$$\frac{1}{\sqrt{2}}(|\text{believes } e \text{ black}\rangle_h |\text{"black"}\rangle_m |\text{black}\rangle_e + |\text{believes } e \text{ white}\rangle_h |\text{"white"}\rangle_m |\text{white}\rangle_e)$$

- ▶ ...presumably two worlds, one with a black e, one with a white e. He then rewrites it as:

$$\frac{1}{\sqrt{2}}(|Q+\rangle_{h+m} |\text{hard}\rangle_e + |Q-\rangle_{h+m} |\text{soft}\rangle_e)$$

- ▶ ...where...

$$|Q+\rangle_{h+m} = \frac{1}{\sqrt{2}}(|\text{believes } e \text{ black}\rangle_h |\text{"black"}\rangle_m + |\text{believes } e \text{ white}\rangle_h |\text{"white"}\rangle_m)$$

$$|Q-\rangle_{h+m} = \frac{1}{\sqrt{2}}(|\text{believes } e \text{ black}\rangle_h |\text{"black"}\rangle_m - |\text{believes } e \text{ white}\rangle_h |\text{"white"}\rangle_m)$$

- ▶ ...which looks like there's two worlds (or four?), one where e is hard the other where e is soft.

# Many-minds physicalism

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- ▶ A way of bypassing the basis problem treats only minds as branching.

- ▶ No matter how we write:

$$\frac{1}{\sqrt{2}}(|\text{believes } e \text{ black}\rangle_b |\text{“black”}\rangle_m |\text{black}\rangle_e + |\text{believes } e \text{ white}\rangle_b |\text{“white”}\rangle_m |\text{white}\rangle_e)$$

- ▶ The measurement generated a mind that experiences a black result and a mind that experiences a white result.
  - ▶ This basis simply makes the supervenience of minds on quantum states more transparent.
- ▶ “Physicalism” because it’s consistent with physicalism.
  - ▶ Albert’s (1992) favoured version of “many minds” (designed to solve the probability problem) is dualist.

# The probability problem

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- ▶ Let the pre-measurement state be:

$$| \text{"ready"} \rangle_m \left( \frac{1}{\sqrt{2}} | \text{hard} \rangle_e + \frac{1}{\sqrt{2}} | \text{soft} \rangle_e \right)$$

- ▶ According to Many Worlds (or many minds), the linearity of the dynamics entails that the microscopic superposition bifurcates the measuring device, giving *both possible* outcomes:

$$\frac{1}{\sqrt{2}} | \text{"hard"} \rangle_m | \text{hard} \rangle_e + \frac{1}{\sqrt{2}} | \text{"soft"} \rangle_m | \text{soft} \rangle_e$$

- ▶ But if we know both outcomes will occur, then surely they occur with probability 1 rather than 0.5?

# Whither many worlds?

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- ▶ Albert (1992) thinks there are better ways of developing the Everett interpretation.
  - ▶ We shall consider these:
    - ▶ The bare theory
    - ▶ The many (many) minds theory.
- ▶ We will then look at how modern (Oxford) many worlds theory responds to the basis problem.
  - ▶ Probability problem discussed next week.



# The bare theory

# The bare theory

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- ▶ Albert thinks Many Worlds is not the most interesting interpretation of Everett's (1957) paper.
- ▶ Note that reading properties off of specific terms in the state vector is going directly against the standard (Copenhagen) understanding of superposition...
  - ▶ Macro-superpositions don't entail multiple macrosuperpositions.
  - ▶ Superpositions are *meaningless* states.
- ▶ So what happens if we apply the standard interpretive principles to the Everett interpretation?

# The standard interpretive principles

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- ▶ **The eigenstate-eigenvalue link entails:**
  - ▶ A physical system only has a value for a given property when it is in an eigenstate of that property.
  
- ▶ **The interpretation of superposition:**
  - ▶ When a physical system is in a superposition of distinct values for a given property, there is no fact of the matter as to whether or not the system has or does not have that property.

# Albert's strategy for analysing this view

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- ▶ Albert wants to analyse the implications of asking our superposed observers questions about what they've measured ...without triggering further branching.
- ▶ However this is to be done in practice, the in principle possibility of doing so will (for Albert) teach us something important about the measurement problem.
- ▶ E.g. it will teach us something about what it might be like to actually be in a superposition!

# What it's like to be in a superposition

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- ▶ Let's ask the human in state...

$$\frac{1}{\sqrt{2}}(|\text{believes } e \text{ black}\rangle_h |\text{"black"}\rangle_m |\text{black}\rangle_e + |\text{believes } e \text{ white}\rangle_h |\text{"white"}\rangle_m |\text{white}\rangle_e)$$

- ▶ ...“what is your belief about the electron's colour?”
  - ▶ Not helpful: h evolves into a superposition of giving distinct answers.
- ▶ Let's instead ask h this: do you have a determinate belief about the colour of the electron?
  - ▶ It's like asking: do you believe e is black or white?
  - ▶ If h believes e is black she answers “yes”.
  - ▶ If h believes e is white she answers “yes”.
    - ▶ So linearity of dynamics entails h answers “yes” even when she's in a superposition of contradictory beliefs!

# What it's like to be in a superposition

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- ▶ So when  $h$  is in this state:

$$\frac{1}{\sqrt{2}}(|\text{believes } e \text{ black}\rangle_b |\text{“black”}\rangle_m |\text{black}\rangle_e + |\text{believes } e \text{ white}\rangle_b |\text{“white”}\rangle_m |\text{white}\rangle_e)$$

- ▶ ... the linearity of the dynamics entails that  $h$  will believe that she has a determinate belief about the electron's colour.
  - ▶  $H$  is in an eigenstate of the “answering the colour question” observable with eigenvalue “yes”.
- ▶ So the linearity of the dynamics entails that  $h$  is radically deceived about her own mental state!

# The measurement problem

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- ▶ Consider one of the key formulations of the problem:
  - ▶ The dynamics entails that (given colour measurements on hard electrons) the observer ends up in a superposition of believing she measured “black” and believing she measured “white”.
  - ▶ But introspection tells us that we have *determinate* beliefs not indeterminate superposed beliefs after such measurements, so the dynamics must be wrong.
- ▶ But the dynamics also entails that certain introspective beliefs are false!
  - ▶ So perhaps we should trust the dynamics and not introspection.
  - ▶ And so perhaps there is no measurement problem at all...

# Could the bare theory be true?

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## ▶ Problems:

- ▶ Hard to understand how we could have any reason to believe this view:
  - ▶ There can't realistically ever be matters of fact about what we take the outcomes of measurements to be.
  - ▶ So no matter of fact about whether we take the relative frequencies of any set out of measurement outcomes to confirm quantum mechanics.
- ▶ There also appears to be no matter of fact as to whether there are measuring devices or even observers.
- ▶ Let's try something else...

# Many (many) minds: disclaimer

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- ▶ In what follows I will briefly cover Albert's (1992) alternative developments of Everettian quantum mechanics.
  - ▶ Also published elsewhere with Barry Loewer.
- ▶ In his 2015 he describes these developments as “bad, silly, tasteless, hopeless, [and] explicitly dualist.” (163)
  - ▶ So why bother looking at it?
    - ▶ One reason: it gives us an idea as to what Albert thinks it would take to solve the probability problem with the Everett framework.
  - ▶ We will consider his 2015 objection to the modern many worlds theory next week.



Many (many) minds



# Varieties of many minds theory

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## ▶ Many minds physicalism

- ▶ Arguably avoids the basis problem.
- ▶ But suffers from the probability problem.
  - ▶ According to Albert, at least.

## ▶ Dualist Everettian theories

- ▶ Designed to solve the probability problem: minds evolve probabilistically.
  - ▶ Single minds dualism
  - ▶ Many minds dualism
  - ▶ Universal mind dualism

# Prelim: phenomenal dynamics

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- ▶ **Guiding idea behind dualist Everettian theories:**
  - ▶ **Physical reality** (i.e. the wave function) evolves deterministically in accordance with the linear dynamics.
  - ▶ **Phenomenal reality** (i.e. conscious minds) evolve in probabilistically in accordance with psychophysical laws and the Born rule.
  
- ▶ **Is this ad hoc or extravagant or refuted by philosophy of mind?**
  - ▶ Ad hoc / extravagant: but why is it any worse

# Single minds dualism (SMD)

See Albert & Loewer (1988), Barrett (1995).

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- ▶ Consider the deterministic wave-function evolution:

$$t1: |"ready">_b \left( \frac{1}{2} |"b">_m |black>_e + \frac{\sqrt{3}}{2} |"w">_m |white>_e \right)$$

$$t2: \frac{1}{2} |"b">_b |"b">_m |black>_e + \frac{\sqrt{3}}{2} |"w">_b |"w">_m |white>_e$$

- ▶ The single conscious mind associated with brain b (at t1) evolves into **one of either** the “black” branch or the “white” branch.
- ▶ The chance that the mind experiences “b” is 0.25 while the chance that it experiences “w” is 0.75.

# Single minds dualism (SMD)

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## ▶ Problems:

- ▶ Imagine the conscious mind goes down the “black” branch. What exactly is in the “white” branch?
- ▶ “The dualism of this sort of picture is pretty bad. On this proposal all but one of the terms in a superposition represent (as it were) *mindless hulks*; and *which one* of those terms is *not* a mindless hulk can’t be deduced from the physical state of the world; or from any experiment; and it will follow that most of the people we take ourselves to have met in our lives have *been* such hulks and not really people at all!” (Albert p 130)
  - ▶ Albert proposes to fix this up as follows...

# Many minds dualism (MMD)

See Albert & Loewer (1988, 1989), Albert (1992 chapter 6).

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- ▶ Consider (again) the deterministic wave-function evolution:

$$t1: |"ready">_b \left( \frac{1}{2} |"b">_m |black>_e + \frac{\sqrt{3}}{2} |"w">_m |white>_e \right)$$

$$t2: \frac{1}{2} |"b">_b |"b">_m |black>_e + \frac{\sqrt{3}}{2} |"w">_b |"w">_m |white>_e$$

- ▶ At  $t1$  brain  $b$  is associated with a continuous infinity of minds and each evolves into **one of either** the “black” branch or the “white” branch.
- ▶ The chance that any one mind experiences “b” is 0.25 while the chance that any one mind experiences “w” is 0.75.

# Many minds dualism (MMD)

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## ▶ Problems:

- ▶ This is Albert (and Loewer's) favoured position, but it's not clear why it's an improvement on SMD!
- ▶ Why is infinitely many minds per brain better than “mindless hulks”?

# Universal mind dualism (UMD)

See Euan Squires (1991, 1993).

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- ▶ Consider (again) the deterministic wave-function evolution:

$$t1: |"ready">_b \left( \frac{1}{2} |"b">_m |black>_e + \frac{\sqrt{3}}{2} |"w">_m |white>_e \right)$$

$$t2: \frac{1}{2} |"b">_b |"b">_m |black>_e + \frac{\sqrt{3}}{2} |"w">_b |"w">_m |white>_e$$

- ▶ At  $t1$  brain  $b$  is associated with one mind that evolves into **one of either** the “black” branch or the “white” branch, *and all other minds follow.*
- ▶ The chance that *all* minds go down the “b” branch is 0.25 while the chance that all minds go down the “w” branch is 0.75.

# Universal mind dualism (UMD)

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## ▶ Problems:

- ▶ Still hard to believe, but perhaps does less damage to our self conceptions than SMD or MMD.
- ▶ Everett views are plausible because they leave the physics as is: quantum physics itself solves the measurement problem.
  - ▶ But it's not clear that these dualist views retain this theoretical virtue.

# Consequences of Everettian dualism

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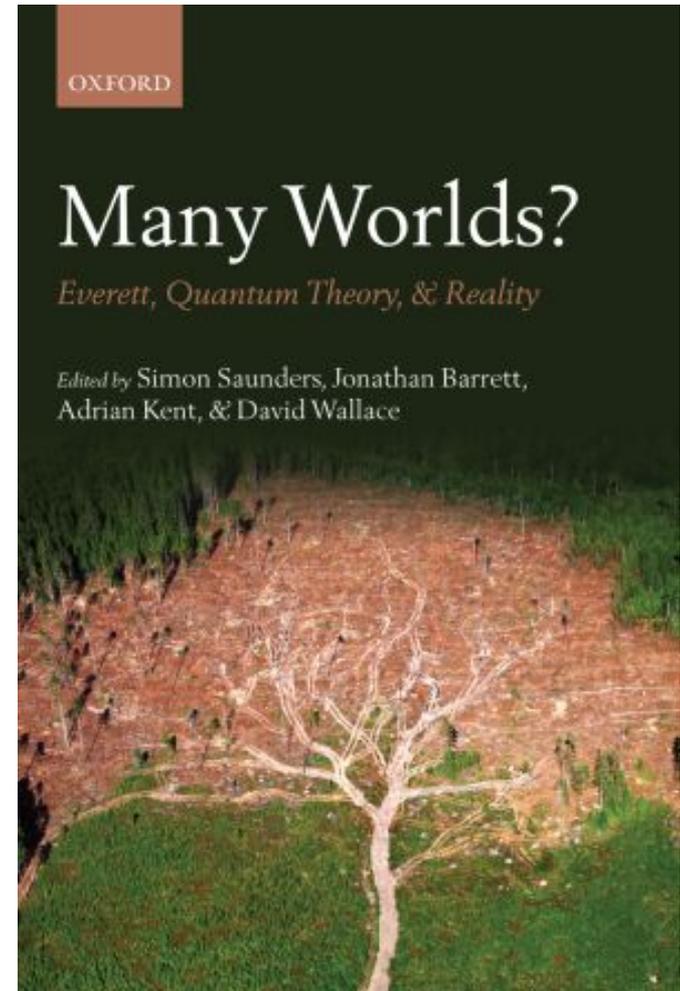
- ▶ They are local.
  - ▶ Bell showed that there is no local way of accounting for the correlations between the outcomes of measurements of entangled particles.
  - ▶ But on such theories measurements don't have determinate outcomes!
    - ▶ Think: are the minds nonlocally correlated?
- ▶ They entail that we are radically deceived about physical states of affairs.
  - ▶ At least if we stick with the usual interpretive principles, experiences of determinate measurement outcomes correspond to situations in which there are no determinate measurement outcomes.

# Many worlds: the Oxford view

# The Oxford view

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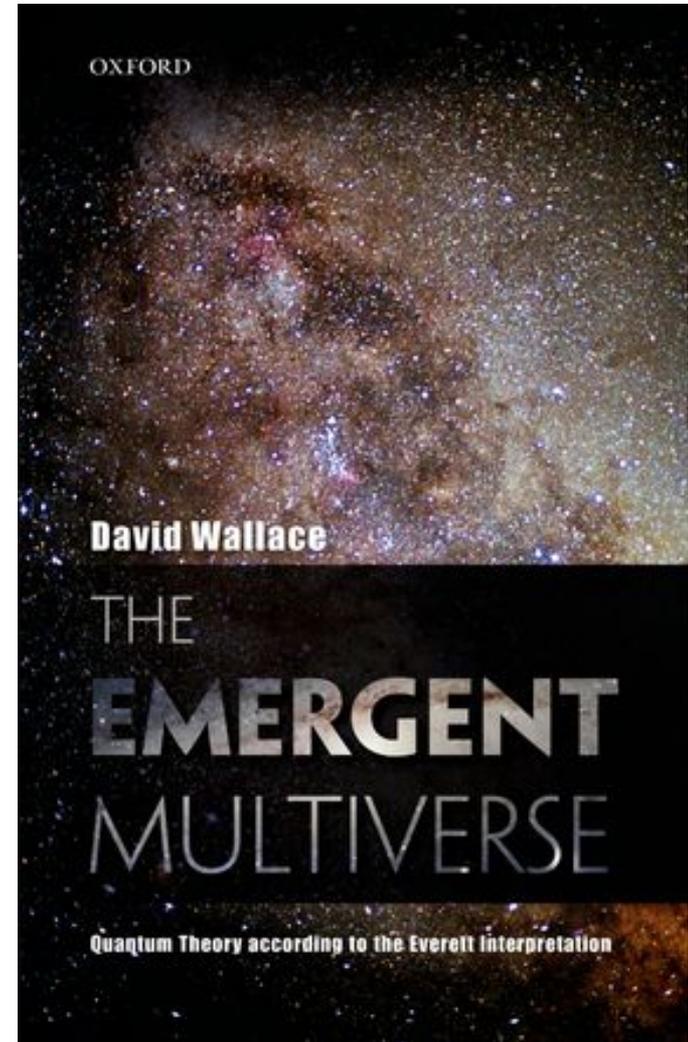
- ▶ The modern view is captured in “Many Worlds?” (2010).
  - ▶ Chapters 1-3 concern the basis problem.
    - ▶ Though these articles get very technical.
  - ▶ In what follows I try to express the basic idea, drawing mostly upon David Wallace’s essay (chapter 1).



# The Oxford view

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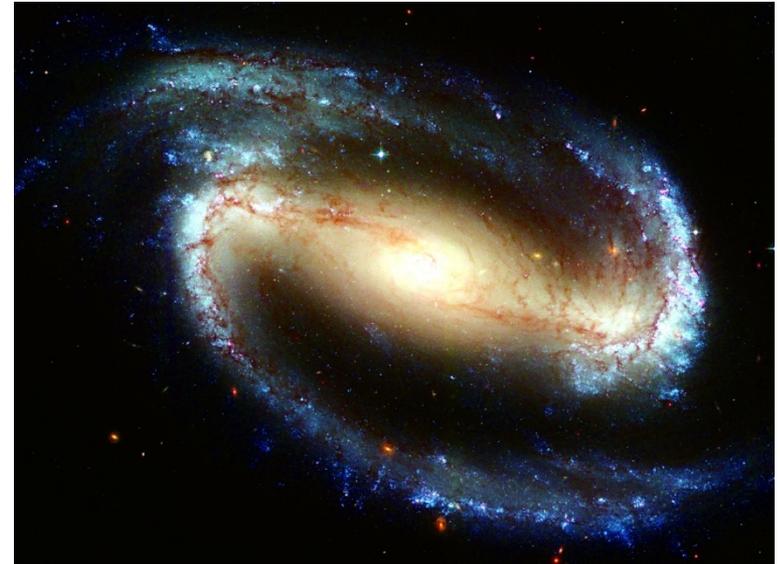
- ▶ See also David Wallace's (2012) "The Emergent Multiverse".
- ▶ The most thorough defence of the many worlds interpretation available.
- ▶ A newer version of Wallace's response to the basis problem is also here (chapter 2), which I also draw on.



# The basic idea

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- ▶ Wallace likens alternative “worlds” to alternative (distant) galaxies.
- ▶ We will never go to NGC 1300 and we’ve seen it only as a hazy glow (pictured).
- ▶ However, our best theory of planetary formation tells us a lot about this galaxy.
- ▶ Similarly (for Wallace) our best physics (QM) tells us a lot about alternative worlds.



- ▶ So postulating many worlds is no more ontologically extravagant than postulating many galaxies!

# The basis problem

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- ▶ What about the basis problem?
- ▶ The combination of two ideas arguably solve this problem:
  - ▶ Technical idea: decoherence
  - ▶ Philosophical idea: emergence
- ▶ “Twenty years of decoherence theory, together with the philosophical recognition that a “world” is not necessarily part of the fundamental mathematical formalism, now allow us to resolve the preferred basis problem.”
  - ▶ David Wallace “Decoherence and Ontology”.

# Emergence

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- ▶ Philosophers distinguish between what's “fundamental” and what's “merely emergent”.
- ▶ The quantum mechanical formalism describes what's fundamental.
  - ▶ E.g. the possible physical states and interactions of the particles postulated in the standard model.
- ▶ But so much more exists other than what fundamental physics postulates!
  - ▶ Cats
  - ▶ Festivals
  - ▶ Worlds?

# Emergence

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- ▶ An object not among the basic posits of the standard model.

# Emergence

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- ▶ Emergent entities cannot be *identified* with anything fundamental.
  - ▶ Fundamental entities (and collections of them) are precisely defined, emergent entities are vaguely defined.
- ▶ How do emergent entities relate to fundamental entities?
  - ▶ Wallace: emergent entities are “patterns” within the microphysics.
  - ▶ It is often extraordinarily difficult to find such patterns within a “microphysical soup”.
    - ▶ So how can we tell when some macro-object exists as a pattern within the fundamental microphysics?

# Emergence

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- ▶ Special sciences (biology, geology, psychology etc.) do not delineate natural patterns (natural kinds) in nature by deducing them from microphysics.
- ▶ **Dennett's criterion:** A macro-object is a pattern, and the existence of a pattern as a real thing depends on the explanatory power and predictive reliability of theories which admit that pattern in their ontology.
  - ▶ From Daniel Dennett's "Real Patterns" (1991).
  - ▶ Example: "fish'" (a grouping that includes whales) do not exist whereas "fish'" (that leave out all mammals) do.

# Decoherence

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- ▶ Why think worlds are emergent entities?
- ▶ Basic idea of decoherence theory:
  - ▶ As terms (or collections of terms) in the state vector (in certain bases) become complex enough the probability they will interfere (interact) becomes very low.
  - ▶ In such circumstances the terms (or collections of terms) evolve independently from the other terms (or collections of terms) and *exhibit quasi-classical dynamics*.
    - ▶ Stable recognisable macro-worlds!
- ▶ The emergent multiverse:
  - ▶ The bases in which decoherence occurs are the bases that approximately define many quasi-classically evolving worlds.

# How many branches (worlds) are there?

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- ▶ Consider Schrödinger's cat again..
  - ▶ A crucial assumption in the set up is that the dynamical laws allow for the cat to evolve from alive to dead (when the atom definitely decays).
    - ▶ Crucial for the linearity step!
  - ▶ But how does a cat evolve from alive to dead?
    - ▶  $|\text{Alive}\rangle \rightarrow |\text{Dead}\rangle$
    - ▶ Recall that the dynamics continuously rotates the state vector; only the collapse postulate allows for discontinuous “jumps”.
    - ▶ So to get from  $|\text{Alive}\rangle$  to  $|\text{Dead}\rangle$  don't we need intermediate superpositions?

# How many branches (worlds) are there?

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- ▶ ...so to get from  $|\text{Alive}\rangle$  to  $|\text{Dead}\rangle$  don't we need intermediate superpositions?
  - ▶ Yes, but since dying itself is an *approximately continuous process* the superpositions are “negligible”.
  - ▶ The process involves transitions between:
    - ▶  $|\text{Alive}'\rangle \rightarrow |\text{Alive}''\rangle \rightarrow |\text{Alive}'''\rangle \rightarrow |\text{Dead}\rangle$  etc.
      - Where apostrophe number designates closeness to death.
    - ▶ To evolve from  $|\text{Alive}'\rangle$  to  $|\text{Alive}''\rangle$  we move through superpositions:
      - ▶  $\#|\text{Alive}'\rangle + \#|\text{Alive}''\rangle$
      - ▶ But due to the similarity between  $|\text{Alive}'\rangle$  and  $|\text{Alive}''\rangle$  the state is effectively a definite aliveness state.
  - ▶ But there is no *privileged* “coarse graining” so there can be no definite number of branches / worlds!

# How often does branching occur?

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- ▶ Wallace: branching is caused by any process which magnifies microscopic superpositions up to the level where decoherence kicks in (i.e. the “macro-level”).
- ▶ Three kinds of these processes:
  - ▶ (i) Deliberate human experiments: Schrödinger’s cat, the two-slit experiment, two path experiments, and the like.
  - ▶ (ii) ‘Natural quantum measurements’, such as occur when radiation causes cell mutation.
  - ▶ (iii) ‘Classically chaotic’ processes: that is: processes governed by Hamiltonians whose classical analogues are chaotic.
- ▶ Measurements are a new phenomenon.
- ▶ But chaos is everywhere, and where there is chaos there is branching.
  - ▶ The weather, for instance, is chaotic, so there will be different weather in different branches.

# Decoherence

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- ▶ Wallace offers a metaphor:
  - ▶ 1. Imagine a world consisting of a thin, infinitely long and wide, slab of matter, exhibiting complex internal processes (e.g. that support life).
  - ▶ 2. Stack thousands of such slabs atop each other without allowing them to interact (think: David Lewis' modal realism).
  - ▶ 3. Introduce a weak force normal to the plane of the slabs with a range of only 2-3 slabs (think: science fiction style many worlds allowing inter-world travel?).
  - ▶ 4. Turn up the interaction sharply: forces have a range of several thousand slabs. Dynamical processes (e.g. evolutionary processes) are not confined only to single slabs, living creatures are spread across many. Now slab-boundaries are vague, but can be drawn based on the dynamical processes of interest.
    - ▶ Decoherence theory shows how we can approximately distinguish many quasi-classical macro-worlds in certain bases. These define the emergent multiverse.

# Response to Albert (1992)

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## ▶ David Albert (p113-4):

- ▶ “The trouble is that ***what worlds there are will depend on what separate terms there are in the state vector*** [which is basis dependent] so if there’s going to be an objective matter of fact about what worlds there are then ***some new general principle will have to be added to the formalism***”

## ▶ David Wallace:

- ▶ What worlds there are DO NOT depend on what separate terms there are in the fundamental formalism.
- ▶ There is no exact matter of fact as to *how many* worlds there are because worlds are vaguely defined emergent entities.
  - ▶ Compare: no exact matter of fact as to how many particles compose a cat because cats are vaguely defined emergent entities.
  - ▶ Wallace: asking how many worlds there are at a time is like asking how many experiences you had yesterday.

# Response to the simple example

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- ▶ The simple example:
  - ▶ Consider only the spin state of a single electron:
    - ▶  $|\text{soft}\rangle$
    - ▶ So there's one world containing a soft electron.
  - ▶ But we can write this down in the colour basis:
    - ▶  $\frac{1}{\sqrt{2}}|\text{black}\rangle - \frac{1}{\sqrt{2}}|\text{white}\rangle$
    - ▶ So now there's two worlds, one containing a black electron, another containing a white electron.
- ▶ This objection does not even speak to the modern Oxford view.

# Response to the complex example

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- ▶ Albert considers the result of a colour measurement on a hard electron (h for human)...

$$\frac{1}{\sqrt{2}}(|\text{believes } e \text{ black}\rangle_h |\text{“black”}\rangle_m |\text{black}\rangle_e \\ + |\text{believes } e \text{ white}\rangle_h |\text{“white”}\rangle_m |\text{white}\rangle_e)$$

- ▶ ...presumably two worlds, one with a black e, one with a white e. He then rewrites it as:

$$\frac{1}{\sqrt{2}}(|Q+\rangle_{h+m} |\text{hard}\rangle_e + |Q-\rangle_{h+m} |\text{soft}\rangle_e)$$

- ▶ **Response:** “If the system Albert describes was (impossibly) alone in an empty spacetime, not interacting with any fields etc, then there wouldn't be any preferred basis in the picture even according to Wallace. We only get an emergent preferred basis with sufficiently complex systems, e.g. once we embed Albert's system into a radiation bath like the cosmic microwave background radiation.” (Alastair Wilson)

# Summary

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- ▶ The Everett interpretation treats the wave-function and linear dynamics as complete, and adds nothing to the physics.
- ▶ In doing so it faces the basis problem and the probability problem.
- ▶ Albert (1992) and others claim that these problems are so severe that Everett theories require bizarre additions.
- ▶ Nowadays the basis problem is not seen to support this claim (decoherence plus emergence).
- ▶ But the probability problem is still very controversial (next week).