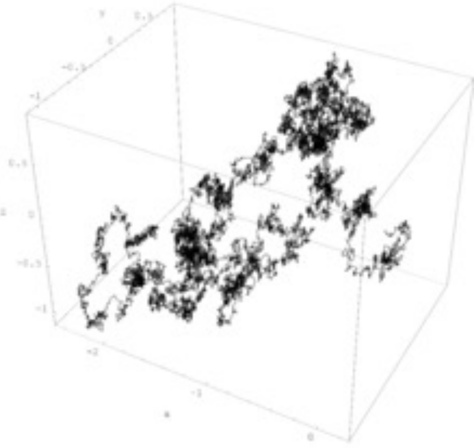
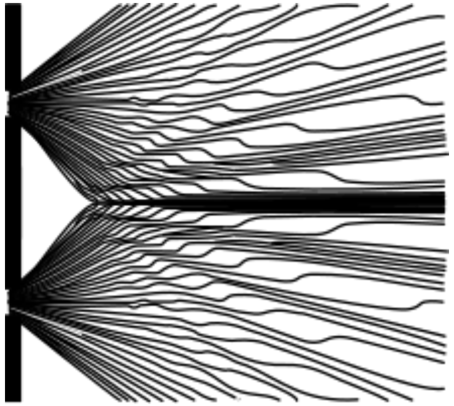
Interpreting quantum mechanics

John B. DeBrota

August 14, 2024





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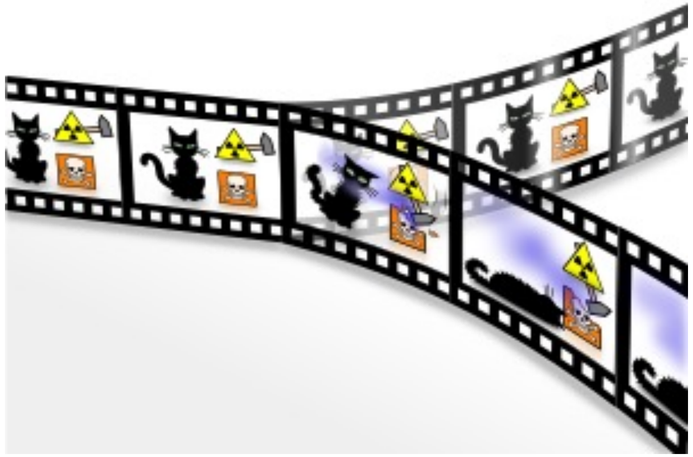


Outline

- A motivating rant
- Looking back at what we covered
- Some of the most prominent interpretations of quantum theory

Why did you want to be a physicist?

- For me, it was the idea that we could get a deeper notion of what reality is by studying what we can find in it and what it lets us do
- The theory takes the form it does because nature has certain characteristics

- Some people are happy to study models alone, but I think many of us were interested in the models *because* they promise to tell us something about reality
  - Reality = model? Maybe. “All models are wrong.” Confusing the map for the territory?

What is real?

- The success of classical physics seemed to imply that reality is made of some “stuff” (particles, fields, forces) *intrinsically detached from observation* or “secondary qualities”
- It works. Making this judgment was a large part of unlocking the explosion of scientific progress beginning in the Renaissance

- It was only after incredible technological advances that any possible reason to doubt it appeared
  - Actually, some Western philosophers doubted it already, e.g. James, Whitehead, Husserl.
  - Much of the East never really believed it in the first place!)

The measurement problem

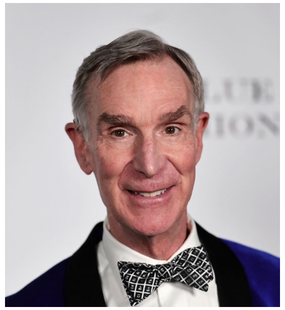
- Quantum theory strains this picture. The basic object, a quantum state, seems to rope-in an observer
- There are two fundamental kinds of state change: evolution without measurement and evolution upon a measurement

- Although the form is different, the former is familiar from classical physics, but the latter challenges the idea that we can really be “detached” as measurement is our empirical hook onto reality!
- How do we make sense of all this? This is *the measurement problem*

So what’s real then?

- The measurement problem is the central guiding question of quantum foundations
- The very nature of reality is at stake!
- What kind of characteristics of nature could make it so that *this* theory is right? If we’re roped-in, the classical picture needs at least some revision
- Should we try to salvage as much of our pre-quantum intuitions as possible or could it be that reality is profoundly different than we supposed?

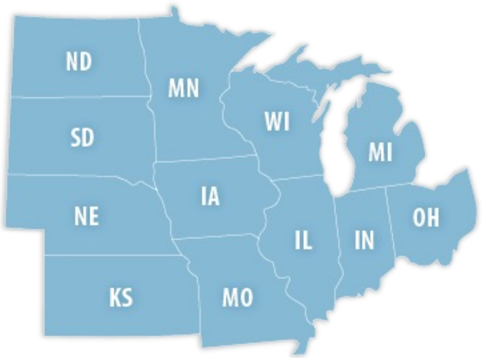
Don’t worry, be happy



- Or maybe all this philosophizing is unhelpful?
- Shut up and calculate!

- Who are we to suppose anything about nature?
- Science reveals approximate truths about reality and thereby replaces any need to philosophize
- If quantum theory or any physical theory seems weird, you just need to adjust your expectations to fit
- And anyway, prior to a Theory of Everything why bother even trying to interpret it?

You're not alone



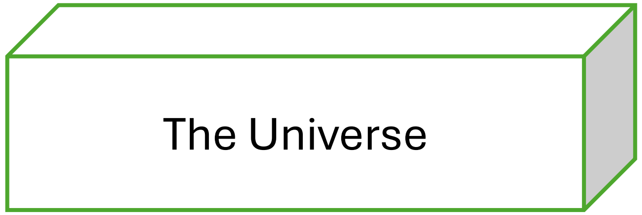
- Early on I thought every physicist shared my motivation but eventually realized *I* was the minority!
- I felt there had been a bait and switch, that physics isn't really about what I thought

- But just because you're in the minority doesn't mean you're wrong. And I know many of you agree this is important stuff.
- For the rest of you, consider this: thinking you don't have a philosophy is very much like thinking you don't have an accent!

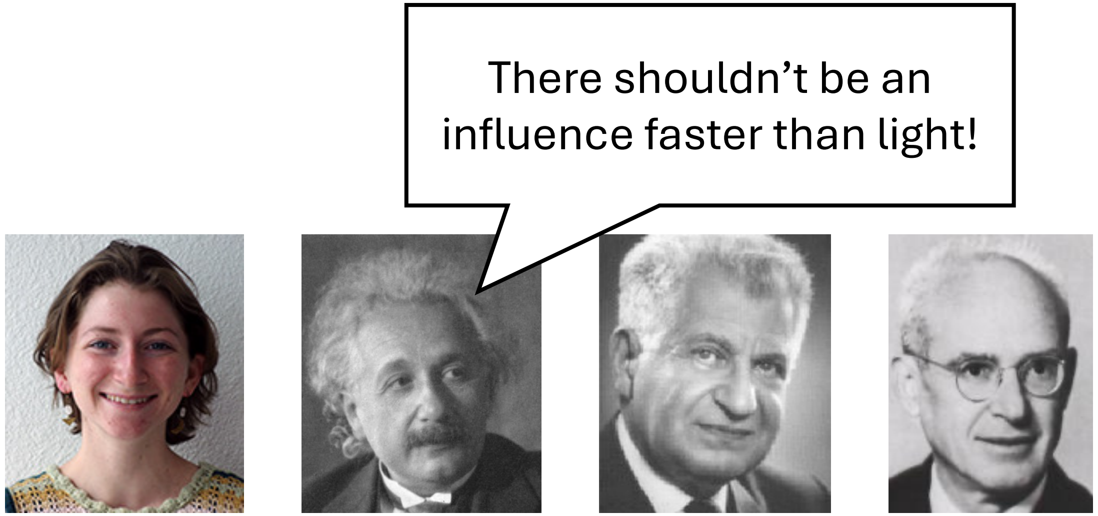
</rant> (mostly 😬)

- This course has been for those who don’t want to shut up and calculate
- We toured several of the technical landmarks of foundations research. The purpose was to get everyone thinking, to organize those thoughts, and in some cases to question preconceived notions
- Armed with concepts like these, we are better situated to have informed opinions about proposed ways to interpret quantum theory
- We will review what was covered and weave in some of these interpretations along the way

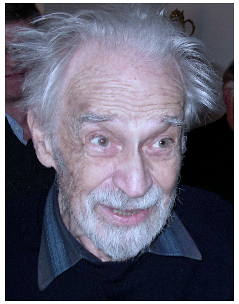
The block universe



- All of space-time is an unchanging four-dimensional block. The past and future are written; time and “now” are illusions. A God’s-eye perspective on the universe
- Most physicists have something like this in mind. Certainly Einstein did, along with the insistence that physics is *local*



- If states are real, then the choice of measurement at A affects the real state at B, violating locality
- QM is correct, but not complete
- There should be an underlying story of other variables interacting locally

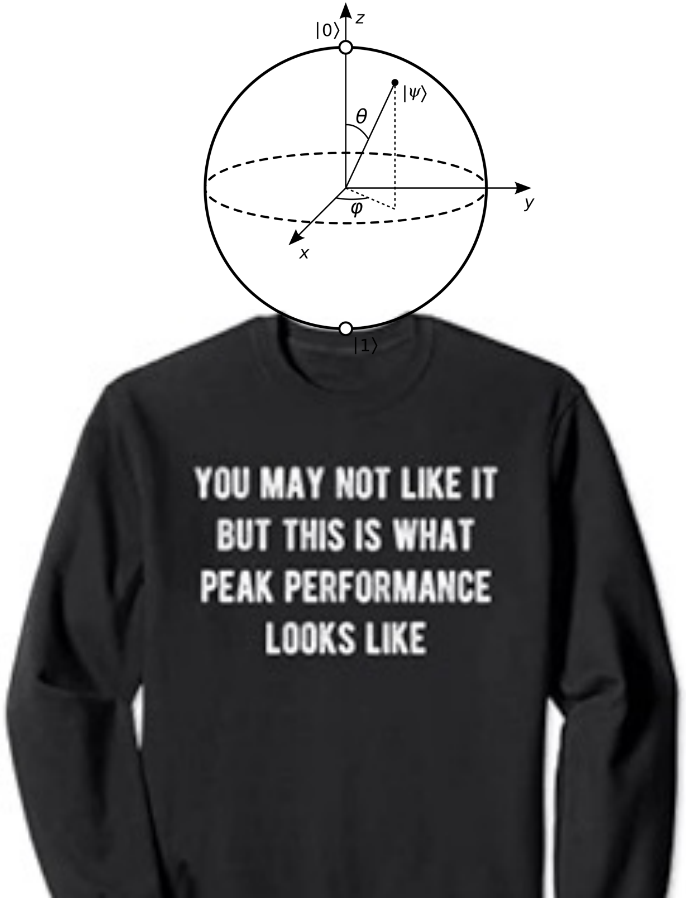
  

- Bell showed this is impossible. The consequence is you must reject either locality or “reality” (essentially the block picture)
- The impossibility to have both is often simply called “quantum nonlocality”

- More generally: quantum theory is simply inconsistent with simultaneously ascribing elements of reality to different contexts
  - Nonlocality is a special case in which measurement contexts contain measurements that are distributed over spacelike separated regions

So what do we do?

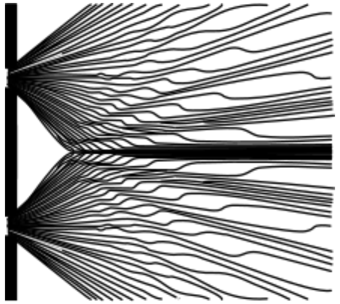
- Since quantum theory is not incomplete, should we conclude that its objects are real even if “spooky”?



So what do we do?

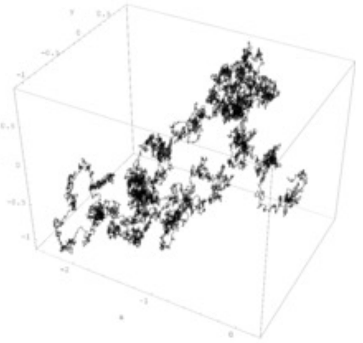
- Since quantum theory is not incomplete, should we conclude that its objects are real even if “spooky”?
- You *can* fit all of this in the block, but it’s getting larger and more unwieldy
  - My take is that it’s better to conclude that measurements are generative, not revealing! But there’s no accounting for taste…
- Roughly speaking, interpretations fall into one of two categories
  - *Psi-ontic* interpretations take the wavefunction to be a real physical thing. We call believers “psi-ontologists”
  - *Psi-epistemic* interpretations regard the state to be a measure of our knowledge, information, or belief

De Broglie—Bohm (Bohmian) mechanics



- Our first interpretation is actually a modification of quantum theory: “So reality has to be nonlocal? That’s fine, let’s construct a model”
- Wavefunction of the universe is a “pilot wave” that guides motion of real physical particles evolving in a non-Newtonian way. Whole universe participates in determining behavior of every particle
- Physical properties like position and momentum are deterministic; outcomes preexist revealing measurement
- Requires extensions to go beyond simple settings, but may be possible

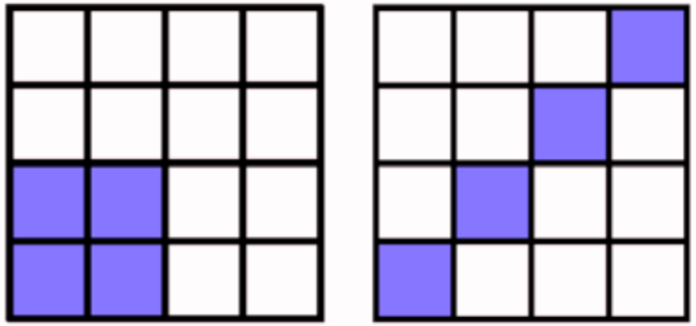
Spontaneous collapse models



- Directly tackle the measurement problem by modifying QM so that collapse *is* part of the dynamics
- Unitarity is approximate. Schrödinger equation is supplemented with additional nonlinear stochastic terms which localize wavefunctions
  - Any interaction can trigger a collapse and as the number of interactions increases, the probability of collapse approaches certainty
- Many distinct models exist
- Two open problems:
  - How to combine nonlocal collapse with relativitistic locality
  - Energy is not conserved even for isolated particles

But how is epistemics an option?

- We know a state is not simply equivalent to a probability distribution over a true state of affairs, hidden variable, or ontic state
- But Leroy gave us a powerful argument that quantum theory is nonetheless at least partly of epistemic character



The evidence for epistemics

- Explicitly local and real toy model to which we simply impose an *epistemic* restriction produces analogies of most “quantum” phenomena
  - Noncommutativity
  - Interference
  - No-cloning
  - Entanglement monogamy
  - Teleportation
  - Dense coding
- We want to isolate what is truly special and different, not wade around in a theory which is “in part realities of Nature, in part incomplete human information about Nature”

“The” Copenhagen interpretation

- Not a single interpretation. Term refers to collection of ideas and perspectives associated with some of the founders
  - Heisenberg, Born, Pauli, Wigner, and most significantly Bohr
- State is of epistemic character and measurement (“irreversible amplification”) leads to information update and objective knowledge
- However, knowledge is context dependent; “experimental arrangement” cannot be taken out of the picture
  - Classical realm of classical physics and “ordinary language” essential to any discussion of the distinct quantum realm

- Takeaway: QM profoundly changes how we should understand the relationship between system and observer

Teasing out what's special

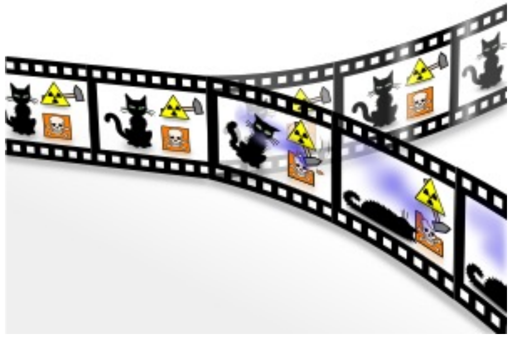
- Cole and Robby went deeper into the idea of foil theories and reconstructions
- Popescu—Rorlich box provides non-signaling foil which is *more nonlocal* than QM
  - Why precisely this much nonlocality?
- The GPT framework allows for constructing any of a landscape of epistemic foils based on whatever convex state space you wish
  - What makes quantum theory special among these?
- Modal QM foil cuts things differently from the Spekkens toy model

Wigner’s former roommates

- Andrew and Mohsin managed to enrage all of CQuIC with their coverage of an extension of the Wigner’s friend paradox
  - Essentially folds in a CHSH inequality violation into the original thought experiment thereby forcing us to confront our beliefs
- One must reject either (Q), (S), or (C)! How you answer depends crucially on what you think quantum theory is

	(Q)	**(S)**	**(C)**
Copenhagen	✓	✓	×
HV theory applied to subsystems	✓	✓	×
HV theory applied to entire universe	×	✓	✓
Many worlds	?	×	?
Collapse theories	×	✓	✓
Consistent histories	✓	✓	×
QBism	✓	✓	×
Relational quantum mechanics	✓	✓	×
CSM approach	×	✓	✓
ETH approach	×	✓	✓

Many worlds



- Wavefunction simply doesn't collapse; all you need is unitary dynamics. Universe is a deterministically evolving state vector
- At moments of measurement, universe "splits" into worlds where observer records different outcomes (violates S)
- Also a family of interpretations: does branching *objectively* happen? (Q) and (C) depend on this, hence the ?s
- Decoherence sometimes invoked to explain why world splitting is effectively irreversible
- Similarity with Bohmian mechanics except swapping particles for worlds

Rant 2: Electric Boogaloo

- MWI is motivated to save “reality” (the block universe)
- Preskill justifies his belief in MWI by saying “I believe in reality” as if believing in reality implies psi-ontology!
- This misses the point. Just because someone doesn’t think a state is real doesn’t mean they think nothing is
- For MWI the state is real despite being a ghostly thing in the theory by everyone’s admission whereas measurement, the only part of the theory that connects us to experiment, is the illusion!?

- Jalan also argued today that without extrinsic factors, a state evolving alone cannot provide its own interpretation

Causal curiosities

- Ivy drew our attention to the asymmetric way in which quantum theory treats time and space
- Nevertheless, one can collect everything into a single *process matrix* formalism which uses the usual form
- Working in operational terms one can see that the theory seems to *not prohibit* exotic causal behavior. The situation is reminiscent of but distinct from entanglement

- Another interesting quantum phenomenon…what do we make of this?

Auditing the epistemic side

- Even if states are epistemic, it seems like we can get them *right*
  - Similarly, we have "unknown" states. *Knowledge* rather than belief
- De Finetti gives operational meaning to "unknown" probabilities and quantum states
  - Exchangeable joint prior: you believe the order of data is irrelevant and that this would be true regardless of how much data you plan to collect
- *If* you hold an exchangeable joint prior, you may reason *as if* you have many copies of the "same" system with a prior density
  - Quantum states need not be (and perhaps cannot be) *properties* of a system just as a bias is not a property of a coin

QBism

- “Radical” epistemic (doxastic) interpretation. Takes the agent's actions and experiences with the world as the central concerns of the theory
- Some similarities to Copenhagen interpretations
- Strict adherence to Bayesian interpretation of all probabilities renders QM a normative addition to decision theory
- States, measurements, even outcomes are personal (subjective). Measurement apparatus is conceptual extension of agent. Overall structure is *same* for anyone (objective)
- Measurement is fundamental, dynamics is derived (see my paper!)
- Rejects block universe. We wish to develop a replacement ontology, not assume one

Relational Quantum Mechanics

- Somewhere between epistemic and ontic. An attempt to make QM like relativity
- States are epistemic, but essentially *relative* to another system. Description of the objective correlation of some degrees of freedom in the observer w.r.t. the observed system
- Physical systems have intrinsic properties like position and momentum, but *only in interaction with other systems*
- Any system can be an “observer”; measurements are just interaction. In between interactions, nothing can be said about properties
- “Different observers can give different accounts of the same sequence of events.”

Comparisons with RQM

- Like MWI, indexes branches of superposition. Unlike MWI, only one world
- Like Copenhagen, focuses on interaction between observer and system. Unlike Bohr, no special role for macro-world
- Like QBism, emphasizes essential role of perspective and similarly rejects block universe (no God's eye view). Unlike QBism, probabilities are objective and any system can be observer

- However, there appear to be inconsistencies in RQM* (and it has historically been a moving target)

* J. Pienaar, "A Quintet of Quandaries: Five No-Go Theorems for Relational Quantum Mechanics." *Found Phys* **51**, 97 (2021).

There are *many* more interpretations

- Consider how they fit into the concerns we've raised during this course
- Always be auditing your own philosophy. Is it consistent? Is it useful?
- Be open to the possibility that things aren't what they seemed
- *Don't forget about reality!*

Thank you for your attention!