Bohr to Bohm: Surveying Quantum Interpretations

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Why Care?

- They make vastly different statements about the fundamental building blocks of nature

- Some interpretations do have unique predictions

- Agnostic stance for the talk

- Forewarning: mainly philosophizing
- (You’ll know about as much as me by the end)

References and Resources

- “Quantum Theory and Measurement” by John Wheeler
- “What is Real?: The Unfinished Quest for the Meaning of Quantum Physics” by Adam Becker
- “Philosophy of Quantum Physics” by Tim Maudlin
- Stanford Encyclopedia of Philosophy

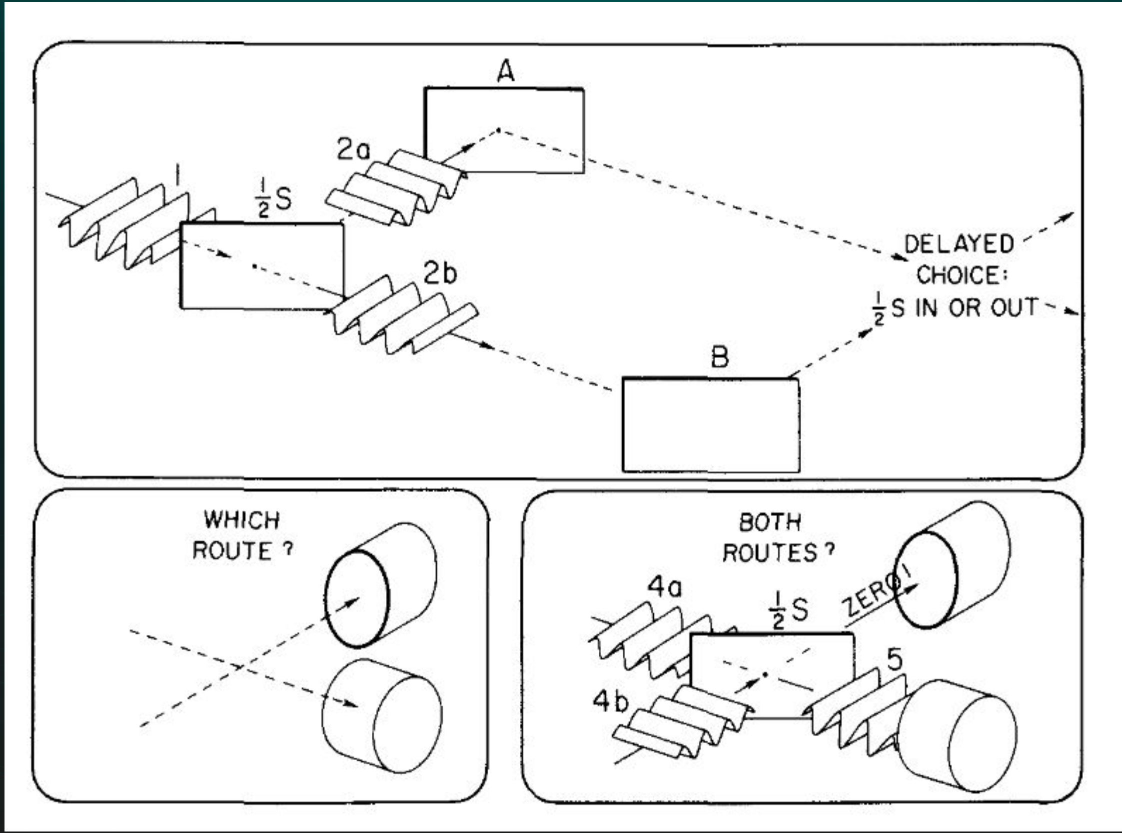
What’s Weird About Quantum?

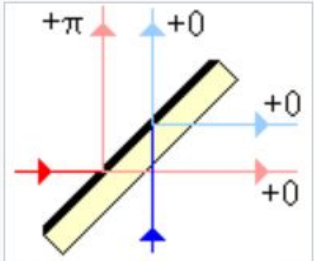
- Stochastic measurement, Schrodinger otherwise

What is a Measurement?

- Deterministic evolution of wavefunction: measurement is stochastic collapse
- Measurement: When quantum object interacts with classical object
- If quantum is fundamental: classical objects made of quantum objects
- Are wavefunctions real? Or just an update of our information?

Delayed-Choice Experiment





Phase shift through a beam splitter with a dielectric coating.

What’s Weird About Quantum?

- Stochastic measurement, Schrodinger otherwise
- Entanglement

Bell's Inequality

1. If A measures S_z and B measures S_x, there is a completely random correlation between the two measurements.
2. If A measures S_x and B measures S_x, there is a 100% (opposite sign) correlation between the two measurements.
3. If A makes no measurement, B's measurements show random results.

Spin component measured by A	A's result	Spin component measured by B	B's result
z	$+$	z	$-$
z	$-$	x	$+$
x	$-$	z	$-$
x	$-$	z	$+$
z	$+$	x	$-$
x	$+$	x	$-$
z	$+$	x	$+$

Bell's Inequality

Population	Particle 1	Particle 2
N_1	$(\hat{\mathbf{a}}+, \hat{\mathbf{b}}+, \hat{\mathbf{c}}+)$	$(\hat{\mathbf{a}}-, \hat{\mathbf{b}}-, \hat{\mathbf{c}}-)$
N_2	$(\hat{\mathbf{a}}+, \hat{\mathbf{b}}+, \hat{\mathbf{c}}-)$	$(\hat{\mathbf{a}}-, \hat{\mathbf{b}}-, \hat{\mathbf{c}}+)$
N_3	$(\hat{\mathbf{a}}+, \hat{\mathbf{b}}-, \hat{\mathbf{c}}+)$	$(\hat{\mathbf{a}}-, \hat{\mathbf{b}}+, \hat{\mathbf{c}}-)$
N_4	$(\hat{\mathbf{a}}+, \hat{\mathbf{b}}-, \hat{\mathbf{c}}-)$	$(\hat{\mathbf{a}}-, \hat{\mathbf{b}}+, \hat{\mathbf{c}}+)$
N_5	$(\hat{\mathbf{a}}-, \hat{\mathbf{b}}+, \hat{\mathbf{c}}+)$	$(\hat{\mathbf{a}}+, \hat{\mathbf{b}}-, \hat{\mathbf{c}}-)$
N_6	$(\hat{\mathbf{a}}-, \hat{\mathbf{b}}+, \hat{\mathbf{c}}-)$	$(\hat{\mathbf{a}}+, \hat{\mathbf{b}}-, \hat{\mathbf{c}}+)$
N_7	$(\hat{\mathbf{a}}-, \hat{\mathbf{b}}-, \hat{\mathbf{c}}+)$	$(\hat{\mathbf{a}}+, \hat{\mathbf{b}}+, \hat{\mathbf{c}}-)$
N_8	$(\hat{\mathbf{a}}-, \hat{\mathbf{b}}-, \hat{\mathbf{c}}-)$	$(\hat{\mathbf{a}}+, \hat{\mathbf{b}}+, \hat{\mathbf{c}}+)$

$$N_3 + N_4 \leq (N_2 + N_4) + (N_3 + N_7)$$

$$P(\hat{\mathbf{a}}+; \hat{\mathbf{b}}+) = \frac{(N_3 + N_4)}{\sum_i^8 N_i}$$

$$P(\hat{\mathbf{a}}+; \hat{\mathbf{b}}+) \leq P(\hat{\mathbf{a}}+; \hat{\mathbf{c}}+) + P(\hat{\mathbf{c}}+; \hat{\mathbf{b}}+).$$

$$\sin^2\left(\frac{\theta_{ab}}{2}\right) \leq \sin^2\left(\frac{\theta_{ac}}{2}\right) + \sin^2\left(\frac{\theta_{cb}}{2}\right)$$

Assumptions for Bell’s Inequality

- Local Causal hidden variables
- Measurement independence: experimental settings are free parameters
- Unique Outcomes

Who's Playing?

Copenhagen

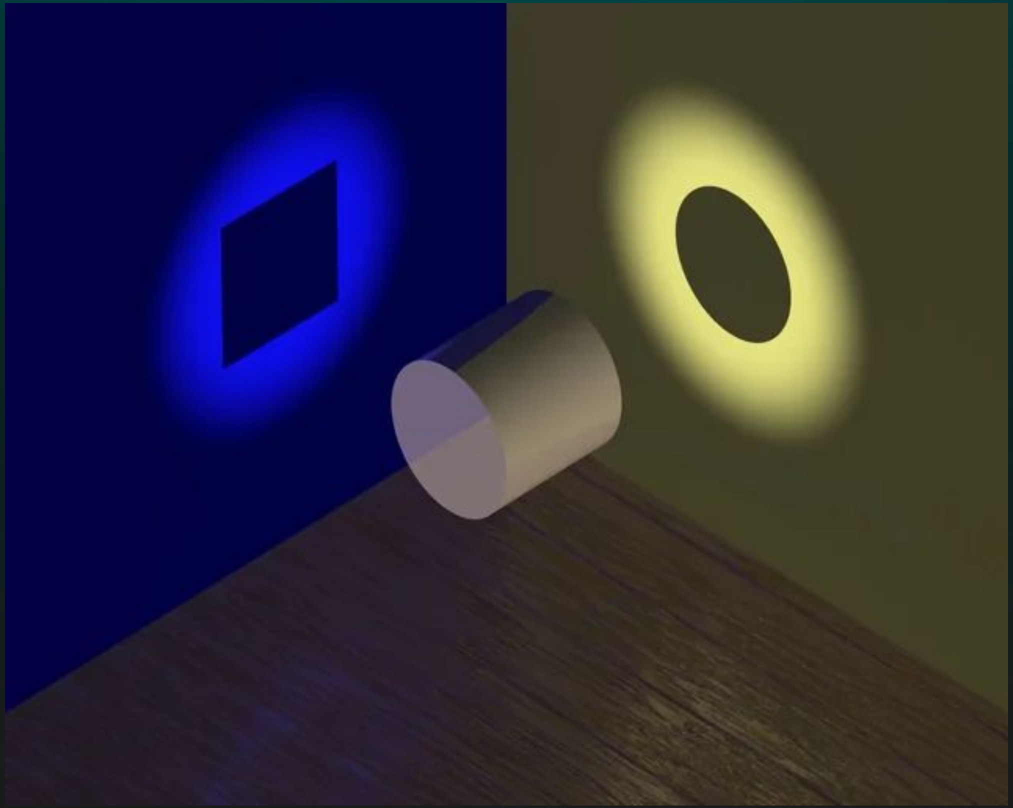
Pilot Wave

Many Worlds

Spontaneous Collapse

QBism

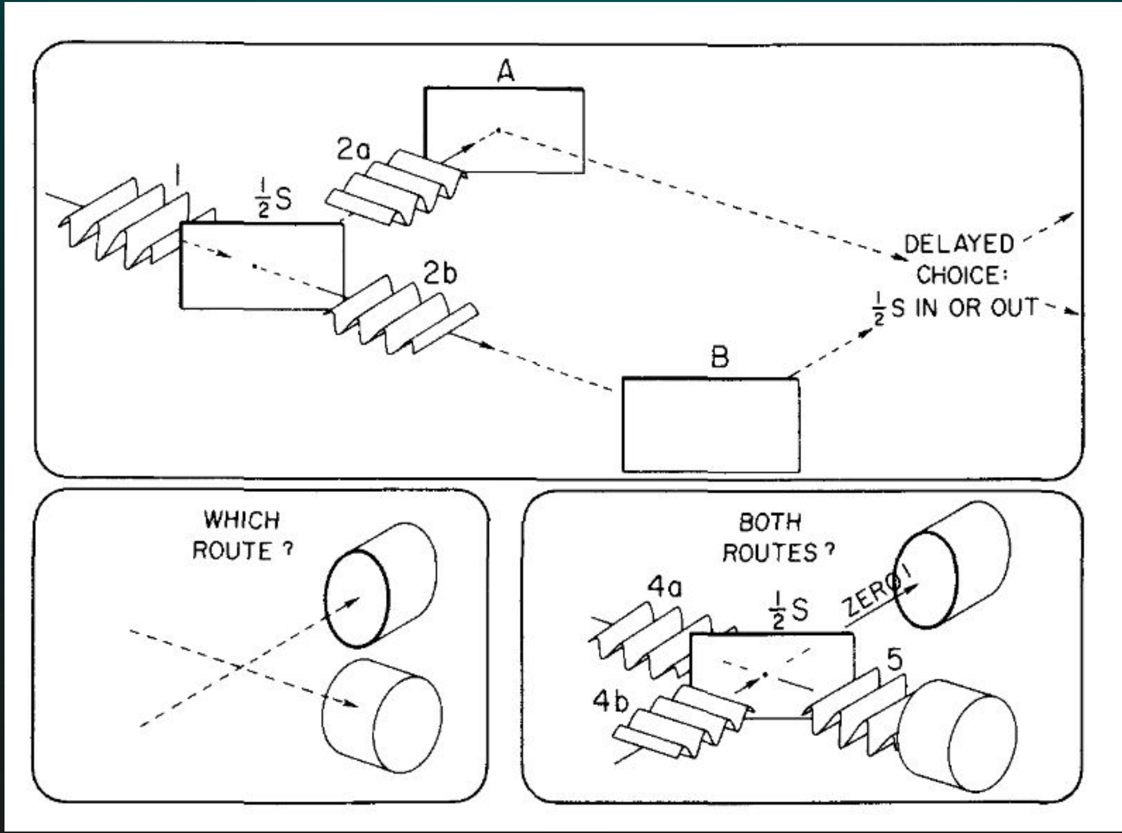
Complementarity



Copenhagen (Bohr)

- Different aspects of reality can never be seen in totality
- Experimental arrangement is not independent
- Must always frame things in idealized, “classical” language (“electron-positron interaction”, CM->QM)
- Bohr-Heisenberg Cut

Delayed-Choice Experiment



Delayed-Choice Copenhagen

- "…we must conclude that our very act of measurement not only revealed the nature of the photon's history on its way to us, but in some sense *determined* that history. The past history of the universe has no more validity than is assigned by the measurements we make—now!"

Copenhagen Criticisms

- "...conventional formulations of quantum theory, and of quantum field theory in particular, are unprofessionally vague and ambiguous. Professional theoretical physicists ought to be able to do better." – John Bell
- "Was the wavefunction of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer, for a better qualified system . . . with a Ph.D.?"

de Broglie–Bohm

- Initially developed by de Broglie in 1927, Bohm reinvented in 1952 after dissatisfaction with QM
- Bohm was stripped of US citizenship while in Brazil due to past communist affiliations
- Same from Aharonov-Bohm
- Theory: non-local, deterministic
- Disliked by mainstream: Einstein for non-local, Bohr for circumventing complementarity

Mathematics

Decomposition: $\psi(\mathbf{x},t) = R(\mathbf{x},t)e^{iS(\mathbf{x},t)/\hbar}$. Note that $R^2(\mathbf{x},t)$ corresponds to the probability density $\rho(\mathbf{x},t) = |\psi(\mathbf{x},t)|^2$

Continuity equation: $-\frac{\partial \rho(\mathbf{x},t)}{\partial t} = \nabla \cdot \left(\rho(\mathbf{x},t)\frac{\nabla S(\mathbf{x},t)}{m}\right)$.

Hamilton–Jacobi equation: $\frac{\partial S(\mathbf{x},t)}{\partial t} = -\left[\frac{1}{2m}(\nabla S(\mathbf{x},t))^2 + V - \frac{\hbar^2}{2m}\frac{\nabla^2 R(\mathbf{x},t)}{R(\mathbf{x},t)}\right]$.

For a spinless single particle moving in $\mathbb{R}^3$, the particle's velocity is given by

$$\frac{d\mathbf{Q}}{dt}(t) = \frac{\hbar}{m}\operatorname{Im}\left(\frac{\nabla\psi}{\psi}\right)(\mathbf{Q},t).$$

For many particles, we label them as $\mathbf{Q}_k$ for the k-th particle, and their velocities are given by

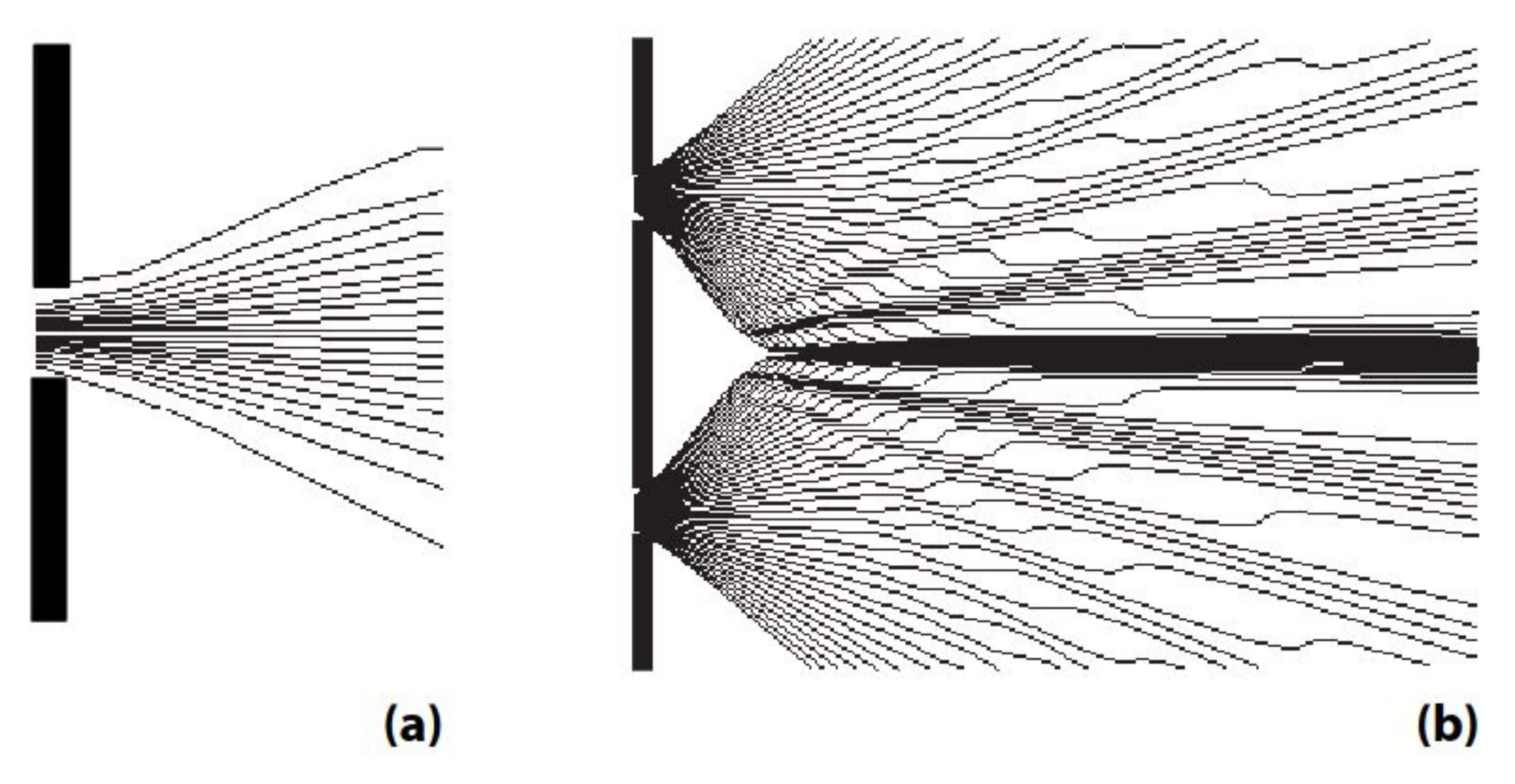
$$\frac{d\mathbf{Q}_k}{dt}(t) = \frac{\hbar}{m_k}\operatorname{Im}\left(\frac{\nabla_k\psi}{\psi}\right)(\mathbf{Q}_1,\mathbf{Q}_2,\ldots,\mathbf{Q}_N,t).$$

The main fact to notice is that this velocity field depends on the actual positions of all of the N particles in the universe.

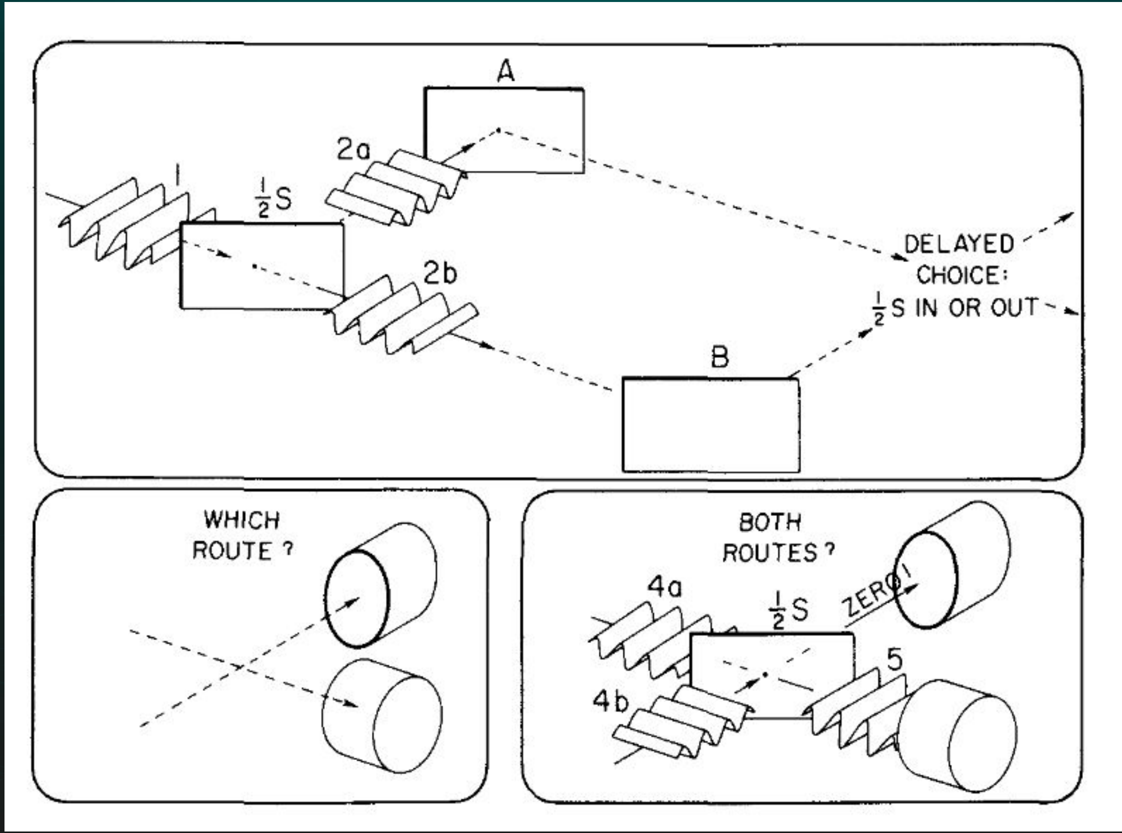
Properties

- Requires initial wave function, initial position
- Probabilities are really our lack of knowledge
- Supposedly shown $|\Psi|^2$ is “typical” probability distribution of particles in region
- Particle trajectories don’t cross (for single particle)
- Space is R^{3N}, not R^3

Double Slit



Delayed-Choice Experiment



Criticisms

- Particle doesn't backreact. Mass, charge spread over pilot wave
- Why have a particle?
- Non-relativistic
- + or -: Super non-local

Decoherence

- How interference effects are suppressed when analyzing large degrees of freedom
- Entanglement makes distinct measurement outcomes no longer interfere, appear “classical-like”
- Doesn’t solve measurement problem, how does one pick possible measurement outcomes?

Hugh Everett III

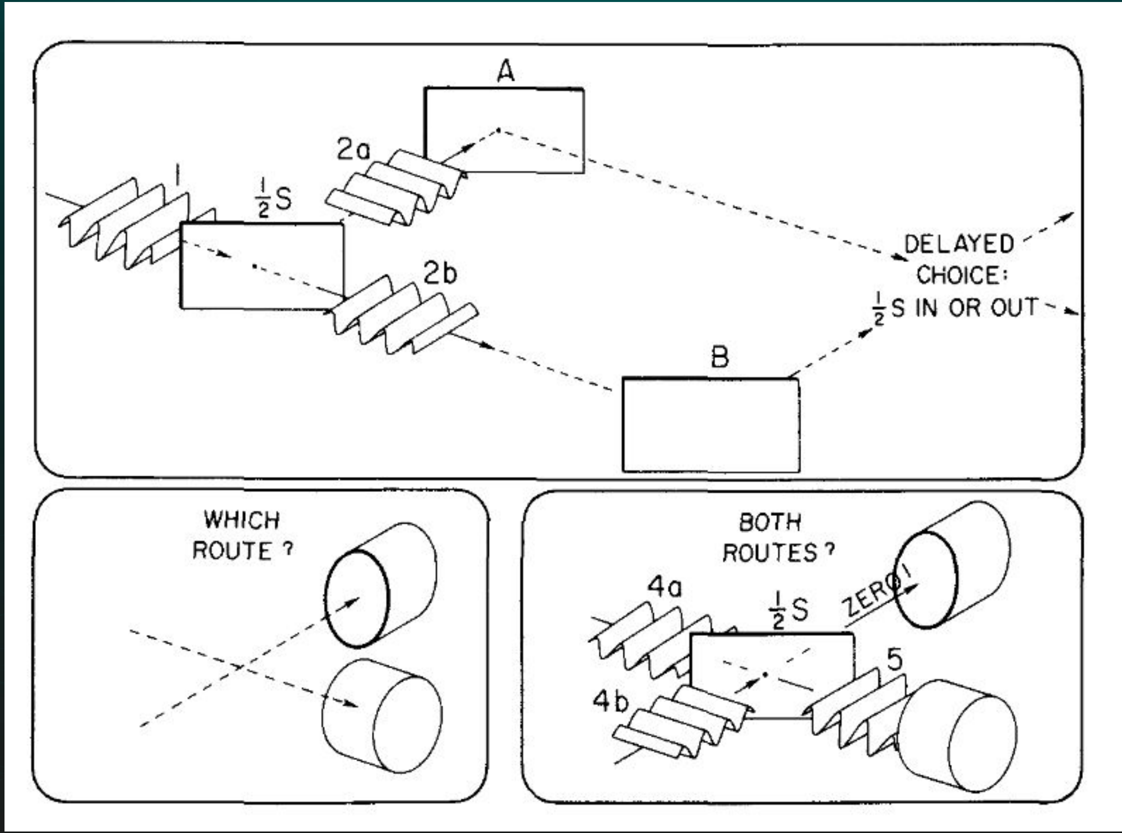
- PhD at Princeton under John Wheeler
- Thesis edited greatly due to pressure from Bohr, later full account released
- “Many-Worlds” interpretation popularized by Bryce DeWitt
- Everett left academia, joined Pentagon

Formalism

$$|\Psi_{\text{UNIVERSE}}\rangle = \sum \alpha_i |\Psi_{\text{WORLD }i}\rangle$$

- What if everything evolved according to the Schrodinger equation? What if we didn't discard parts due to "measurement"?
- "Theory of the Universal Wavefunction"
- Measurement by decoherence: interactions "split" wavefunction
- These split realities are perceived by us as the "true" world, but there are many

Delayed-Choice Experiment



Pros

- There is no measurement problem, or measurement at all
- Just one universal wavefunction, predictably evolves
- Consistent with relativity
- “Resolves” most quantum paradoxes
- A “better” Pilot Wave theory

Cons

- Assigning probabilities to branches
- Preferred basis: why do measurement outcomes align with separation of “worlds”?
- Existential/scientific questions

Testability

- The wavefunction never collapses
- Macroscopic interference from coherent superposition
- “Wigner’s Friend”

Spontaneous Collapse

- All quantum wavefunctions spontaneously collapse with a very small probability
- Only when object have decoherence, large degrees of freedom become entangled independently
- One degree of freedom bound to collapse, collapsing everything
- Bound on collapse makes it semi-testable
- What if probability too low?

QBism

- Quantum Bayesianism
- Quantum is inherently subjective, probabilities are personal beliefs
- Subsequently states are not real, but constructions

That’s All

Hope you enjoyed