Title: Foundations of Quantum Mechanics - Lecture 15

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Abstract:

perimeter scholars

international

The Everett interpretation "Many Worlds"

Hugh Everett, III
(1930-1982)

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"Orthodox" postulates of quantum theory

Representational completeness of ψ. The rays of Hilbert space correspond one-to-one with the physical states of the system.

Measurement. If the Hermitian operator A with spectral projectors $\{P_k\}$ is measured, the probability of outcome k is $\langle\psi|P_k|\psi\rangle$. These probabilities are objective -- indeterminism.

Evolution of isolated systems. It is unitary, $|\psi\rangle \to U|\psi\rangle = e^{-\frac{i}{\hbar}Ht}|\psi\rangle$ therefore deterministic and continuous.

Evolution of systems undergoing measurement. If Hermitian operator A with spectral projectors $\{P_k\}$ is measured and outcome k is obtained, the physical state of the system changes discontinuously,

$$|\psi\rangle \to |\psi_k\rangle = \frac{P_k|\psi\rangle}{\sqrt{\langle\psi|P_k|\psi\rangle}}$$

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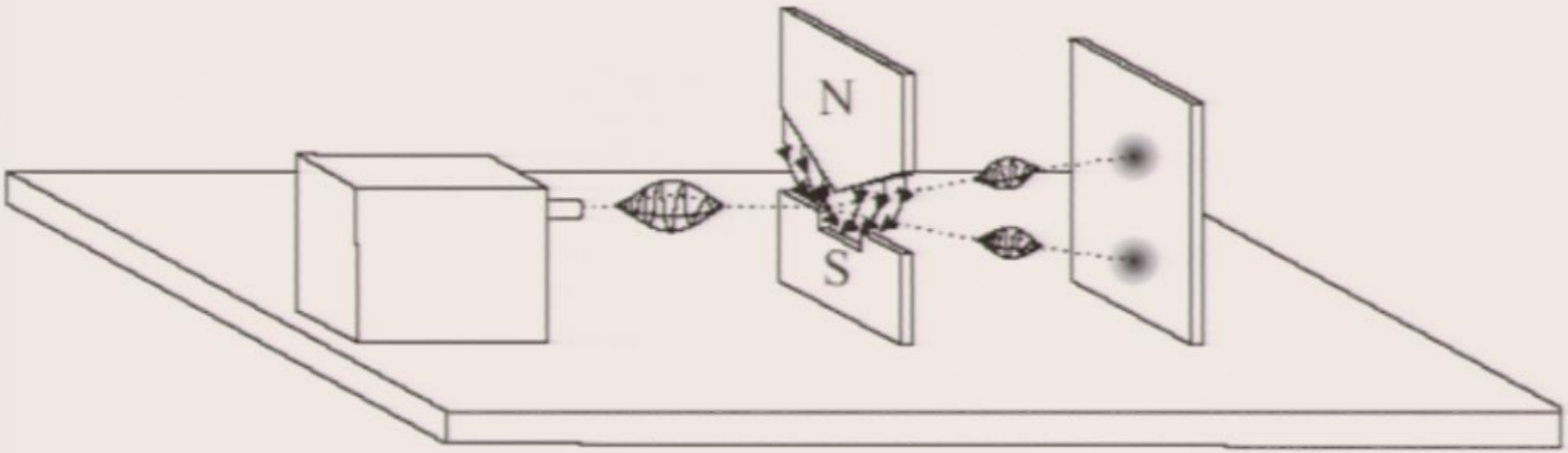
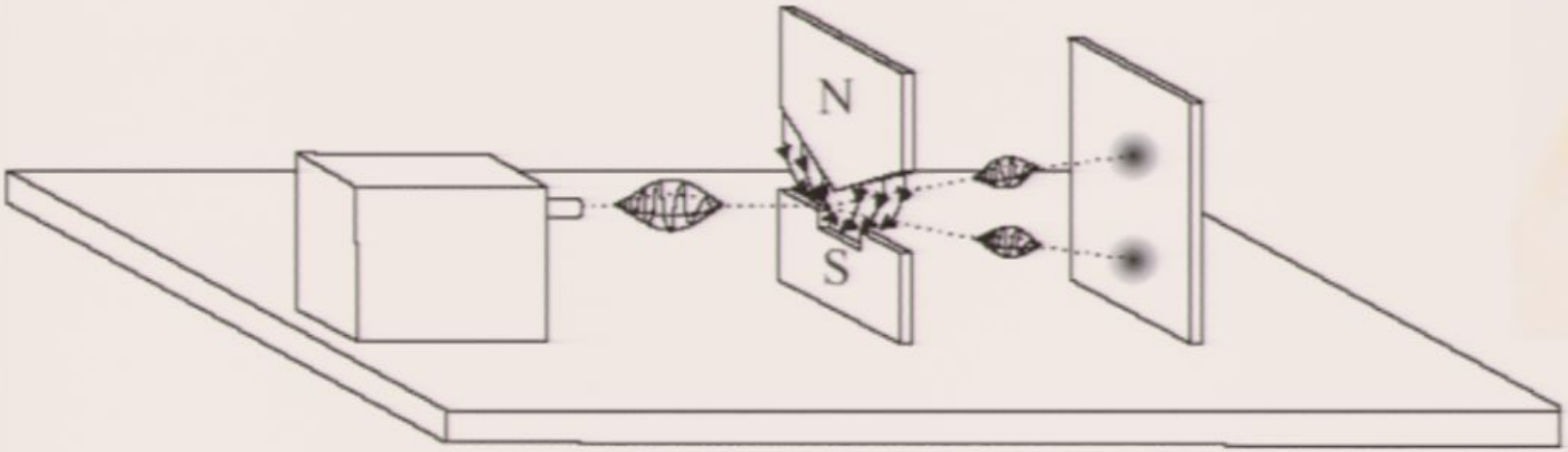
Quantum measurement



$$(a|\uparrow\rangle + b|\downarrow\rangle)|\text{“ready”}\rangle$$
$$\rightarrow a|\uparrow\rangle|\text{“up”}\rangle + b|\downarrow\rangle|\text{“down”}\rangle$$

Quantum measurement with observer



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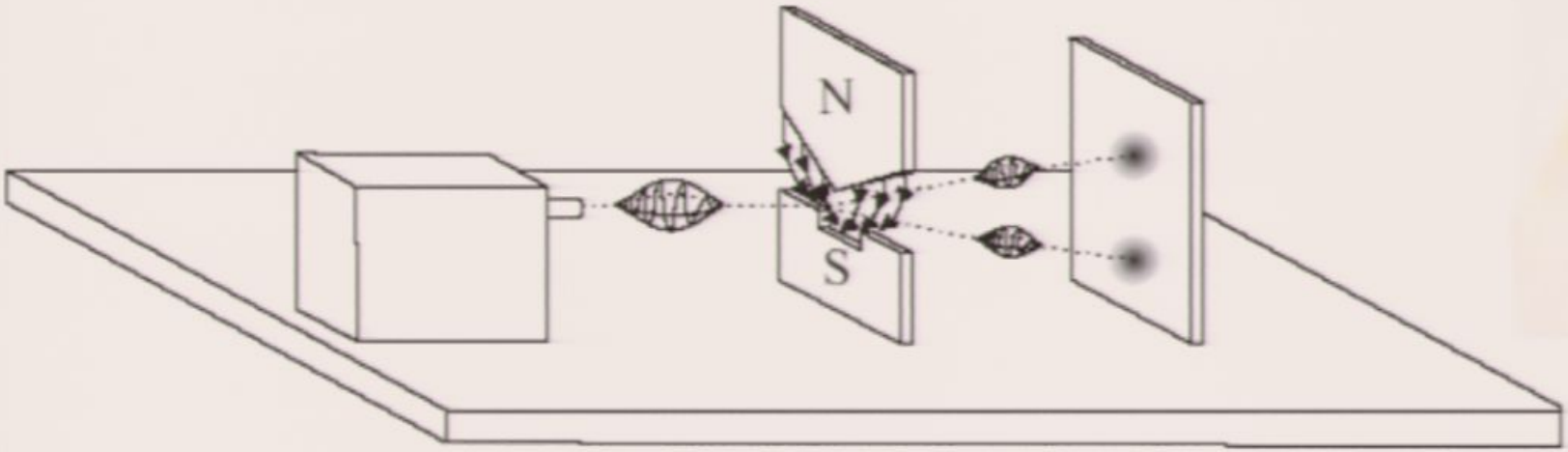

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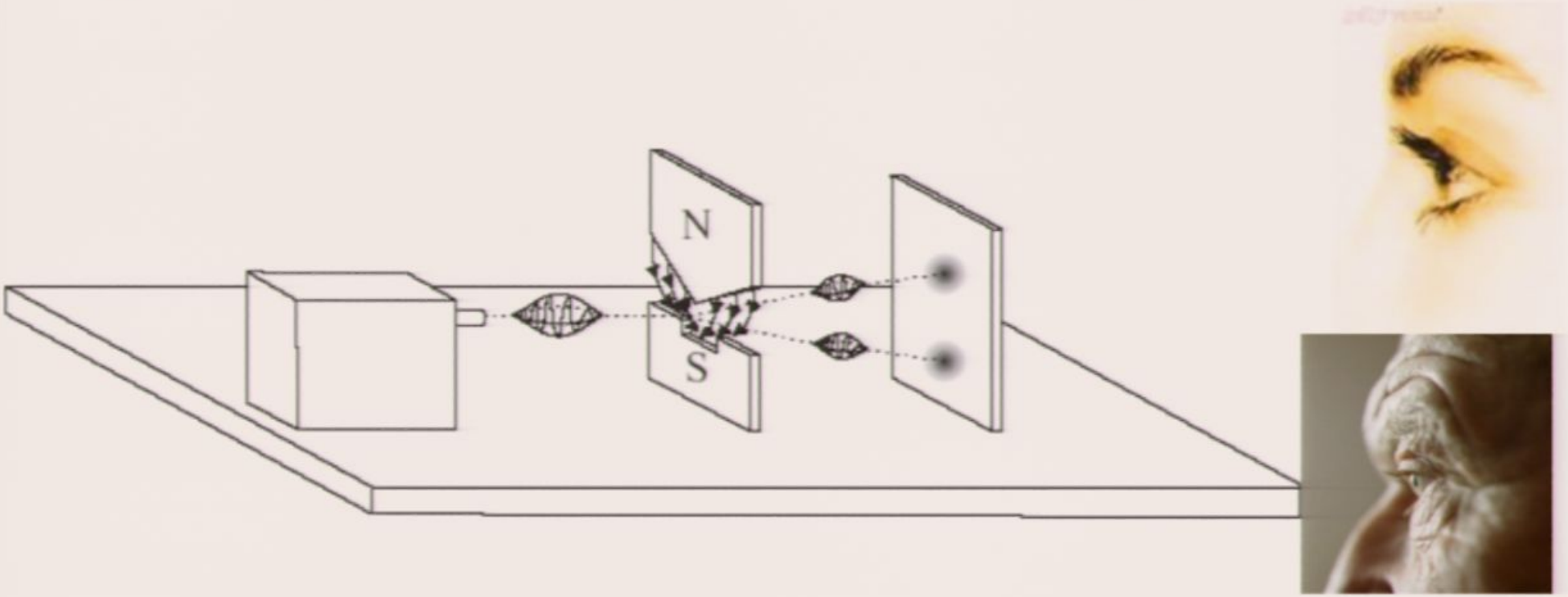
Note that in each branch, the observer will not report observing anything unusual

Quantum measurement with many observers



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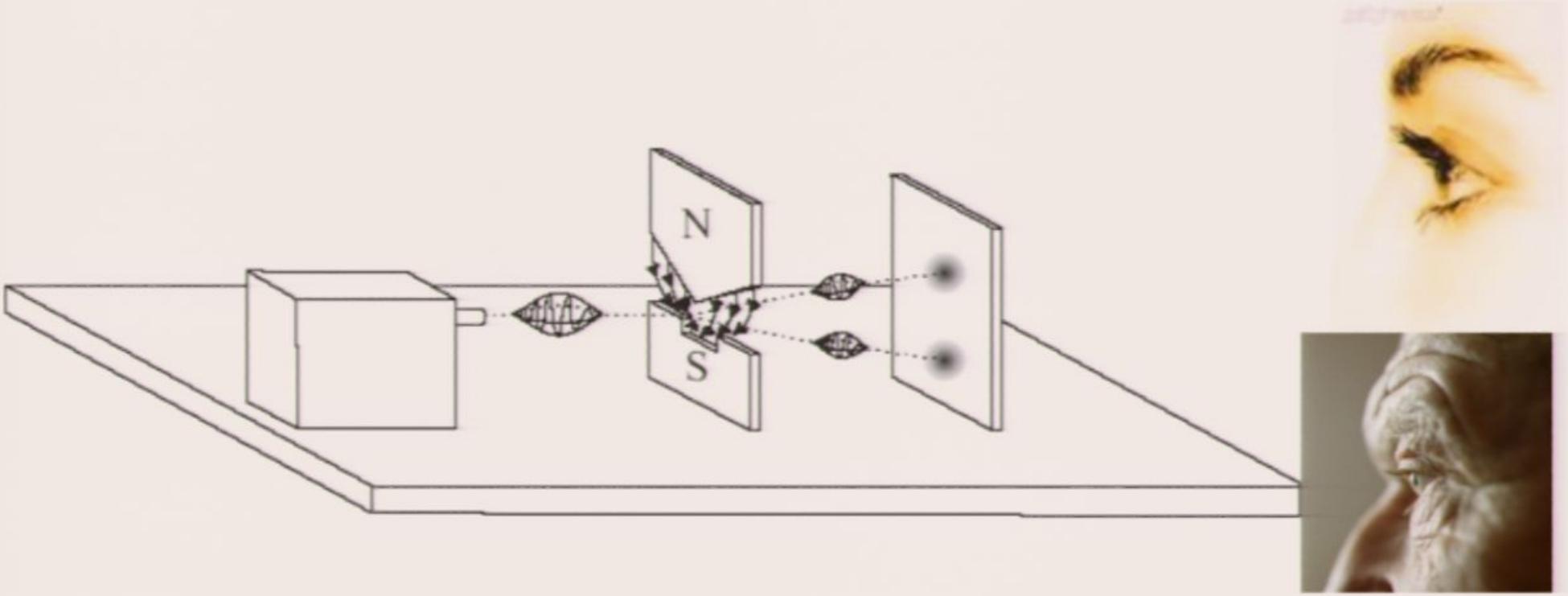

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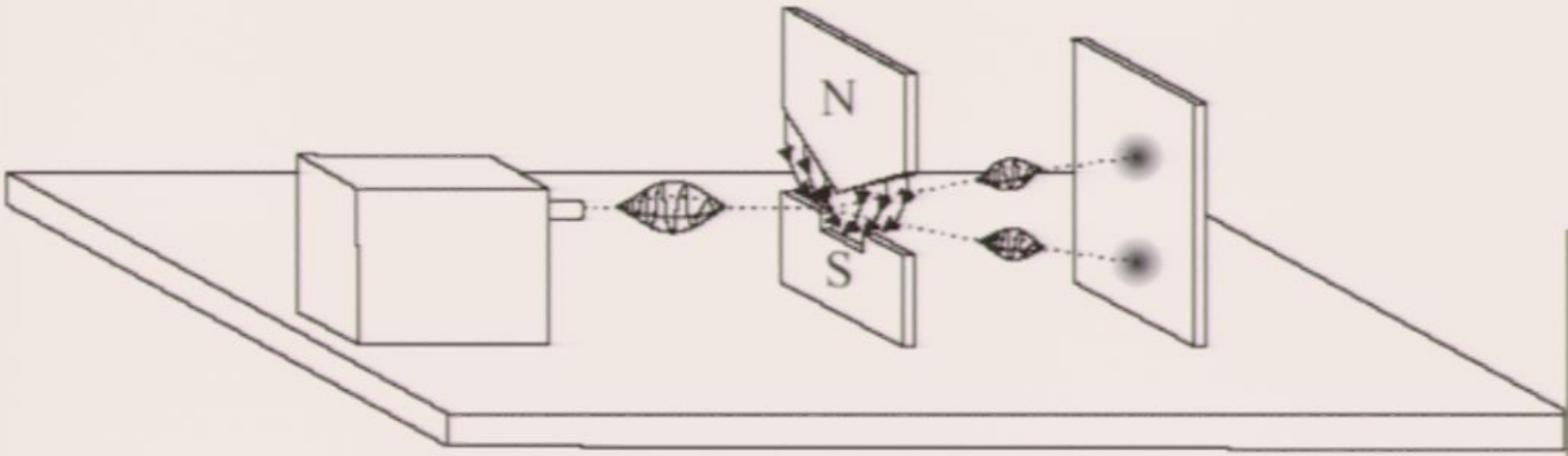

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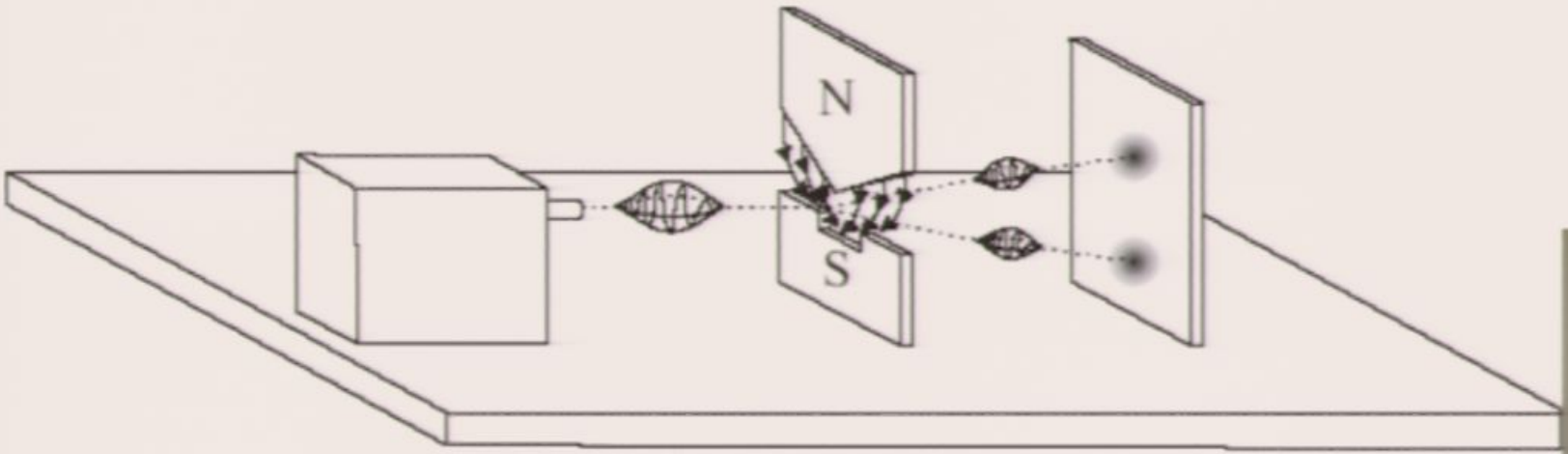

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"...we shall deduce the probabilistic assertions of [the collapse postulate] as *subjective* appearances to such observers, thus placing the theory in correspondence with experience. We are then led to the novel situation in which the formal theory is objectively continuous and causal, while subjectively discontinuous and probabilistic. (1973, p. 9).

Everett's relative states

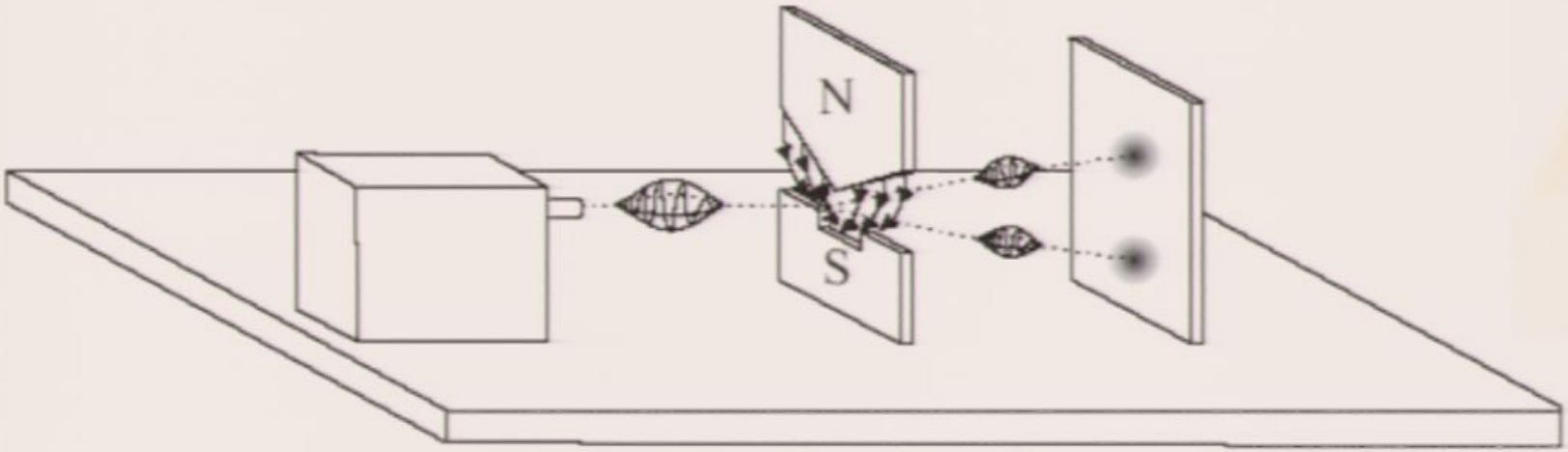
Neither system nor observer "has a state," as in the orthodox interpretation, ***but***

$|\uparrow\rangle$ is the state of the system *relative* to $|\text{"observe up"}\rangle$

$|\downarrow\rangle$ is the state of the system *relative* to $|\text{"observe down"}\rangle$

Everett: "The 'quantum jumps' exist in our theory as *relative* phenomena (*i.e.*, the states of an object-system relative to chosen observer states shows this effect), while the absolute states change quite continuously."

Quantum measurement with observer



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rewrite as

$$(a|+\rangle + b|-\rangle)|R\rangle \rightarrow a|+\rangle|E_+\rangle + b|-\rangle|E_-\rangle$$

Preferred basis problem

$$\left(a|+\rangle + b|-\rangle\right)|R\rangle \quad \rightarrow \quad a|+\rangle|F_+\rangle + b|-\rangle|F_-\rangle$$

$$= \left(\frac{a|+\rangle + b|-\rangle}{\sqrt{2}}\right)\left(\frac{|F_+\rangle + |F_-\rangle}{\sqrt{2}}\right)$$

$$+ \left(\frac{a|+\rangle - b|-\rangle}{\sqrt{2}}\right)\left(\frac{|F_+\rangle - |F_-\rangle}{\sqrt{2}}\right)$$

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$$\left(a|+\rangle|F_+\rangle + b|-\rangle|F_-\rangle\right)|E_0\rangle \quad \rightarrow \quad a|+\rangle|F_+\rangle|E_+\rangle + b|-\rangle|F_-\rangle|E_-\rangle$$

Decoherence:

- Rapid diagonalization in some basis of the reduced density operator of the system
- Effective impossibility of preparing superpositions of the basis states

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Kent's criticism: "no preferred basis can arise, from the dynamics or from anything else, unless some basis selection rule is given

Trans-temporal identity problem

In addition to a preferred basis, one needs a notion of how to connect basis elements at one time to those at another.

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Imagine removing the notion of trajectories from pilot-wave theories
Bell's criticism: Everett entails radical scepticism about the past

Response (drawn primarily from the work of David Wallace)

No axiom is needed for basis selection because real things (macroscopic objects and worlds) are emergent patterns.

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Dennett's Criterion: A macro-object is a pattern, and the existence of a pattern as a real thing depends on the usefulness --- in particular, the explanatory power and predictive reliability --- of theories which admit that pattern in their ontology.

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The branches picked out by decoherence admit of patterns that have explanatory and predictive power, such as tigers.

Patterns are not precisely defined, but this need not detract from their reality (consider a mountain, or a species)

Response to the transtemporal identity problem

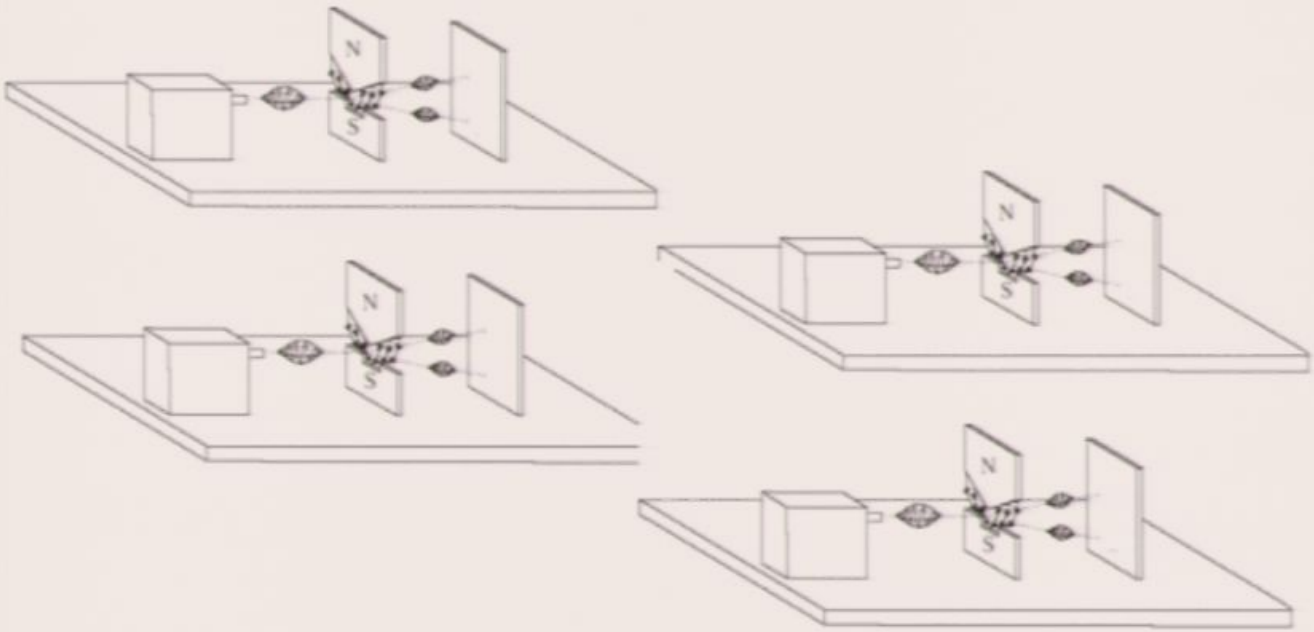
Similarity of a pattern across time allows for a pragmatic (and imprecise) notion of world identity across time (in certain circumstances)

The problem with probabilities

The Incoherence Problem:

How can anything "be probability" in a deterministic theory where all possible outcomes occur and there is nothing to be ignorant about?

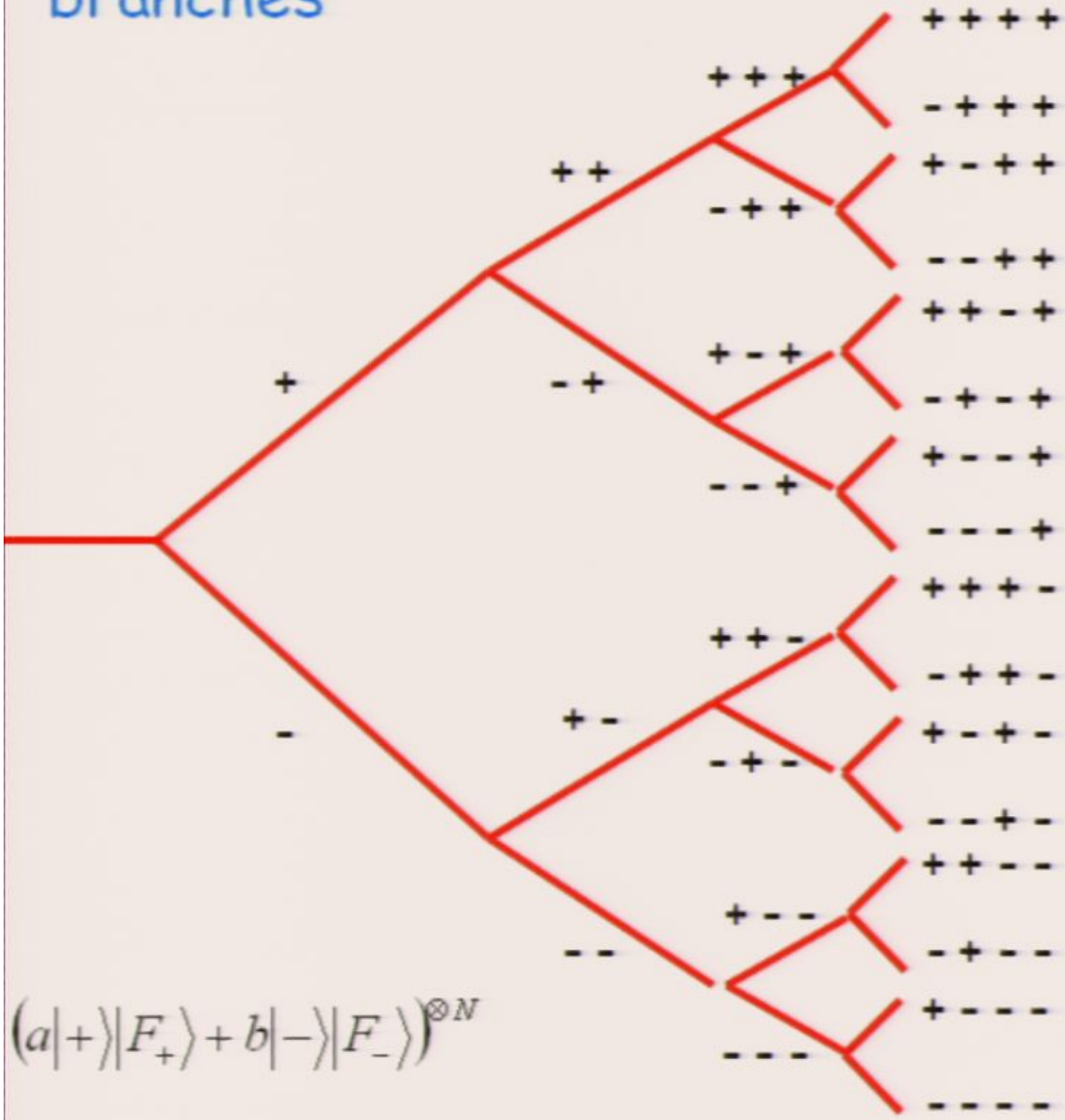
Sequence of measurements:



$$\left(a|+\rangle+b|-\rangle\right)^{IV}\left(a|+\rangle+b|-\rangle\right)^{III}\left(a|+\rangle+b|-\rangle\right)^{II}\left(a|+\rangle+b|-\rangle\right)^{I}\quad |R\rangle^{I}|R\rangle^{II}|R\rangle^{III}|R\rangle^{IV}\rightarrow$$

$$\left(a|+\rangle+b|-\rangle\right)^{IV}\left(a|+\rangle+b|-\rangle\right)^{III}\left(a|+\rangle+b|-\rangle\right)^{II}\left(a|+\rangle^{I}|F_{+}\rangle^{I}+b|-\rangle^{I}|F_{-}\rangle^{I}\right)\quad |R\rangle^{II}|R\rangle^{III}|R\rangle^{IV}\rightarrow$$

"branches"



$$\left(a|+\rangle|F_+\rangle + b|-\rangle|F_-\rangle\right)^{\otimes N}$$

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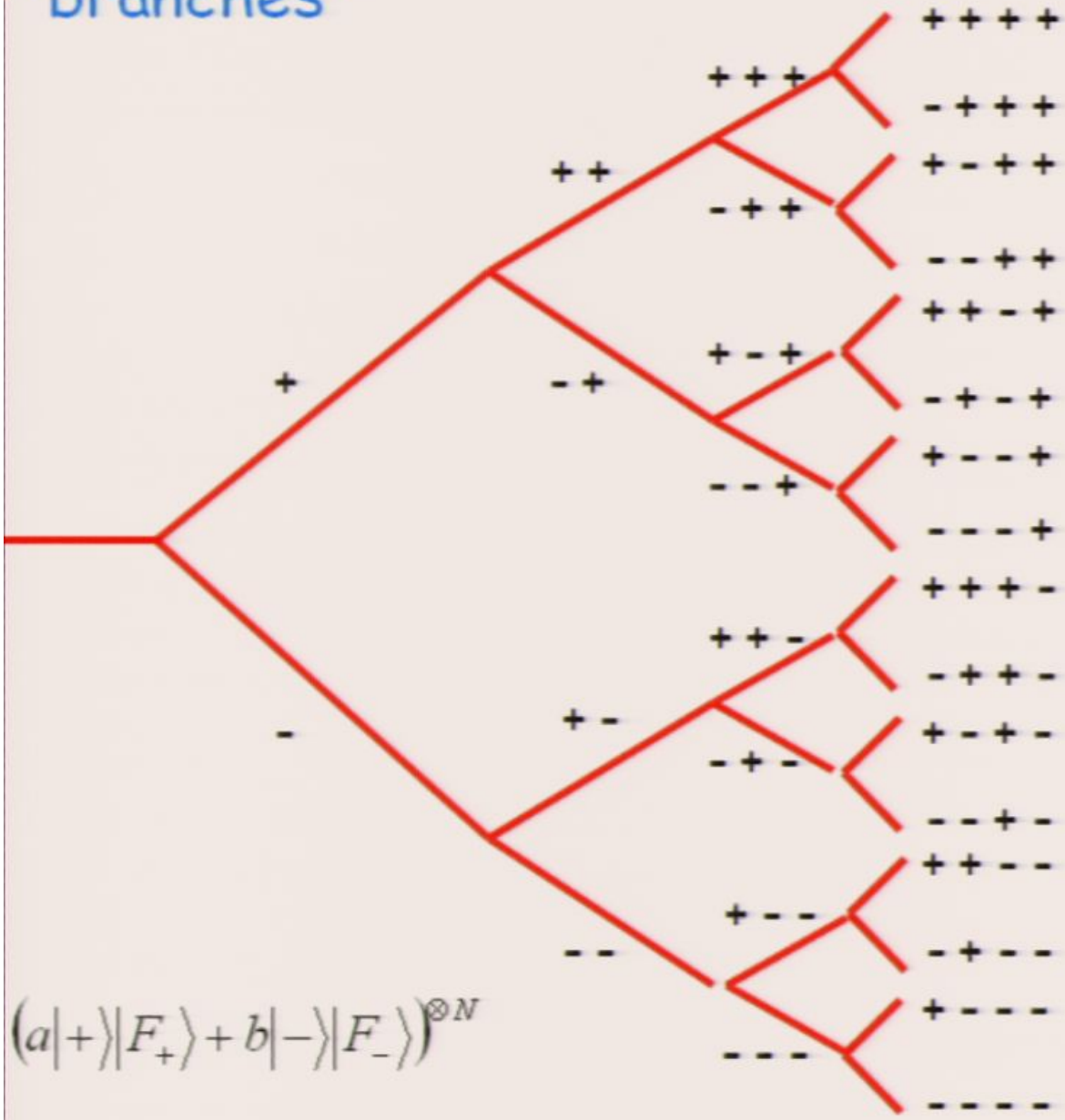

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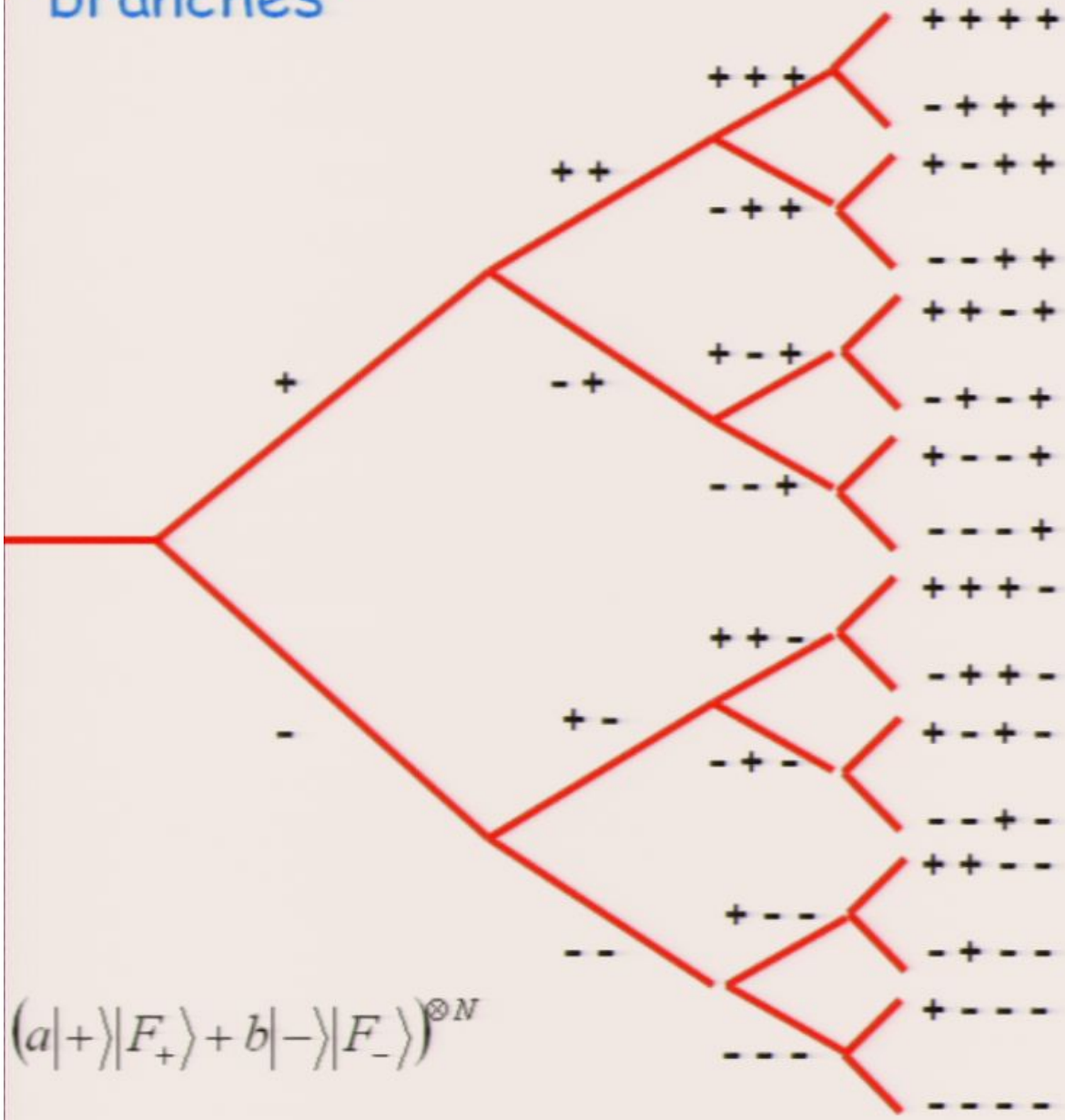

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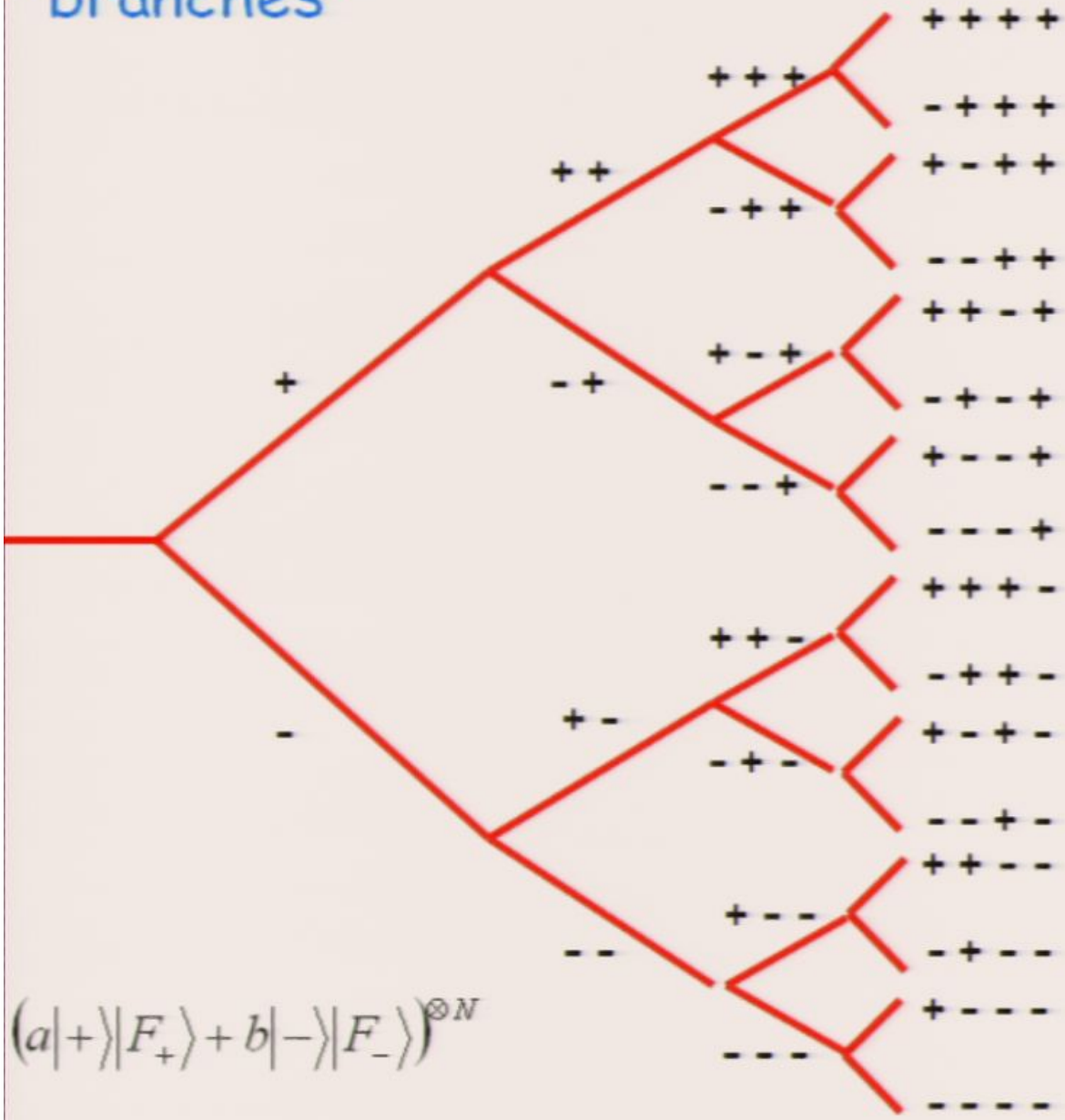

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Problem of theory confirmation:
Why should seeing all "+" cast any doubt on the theory?

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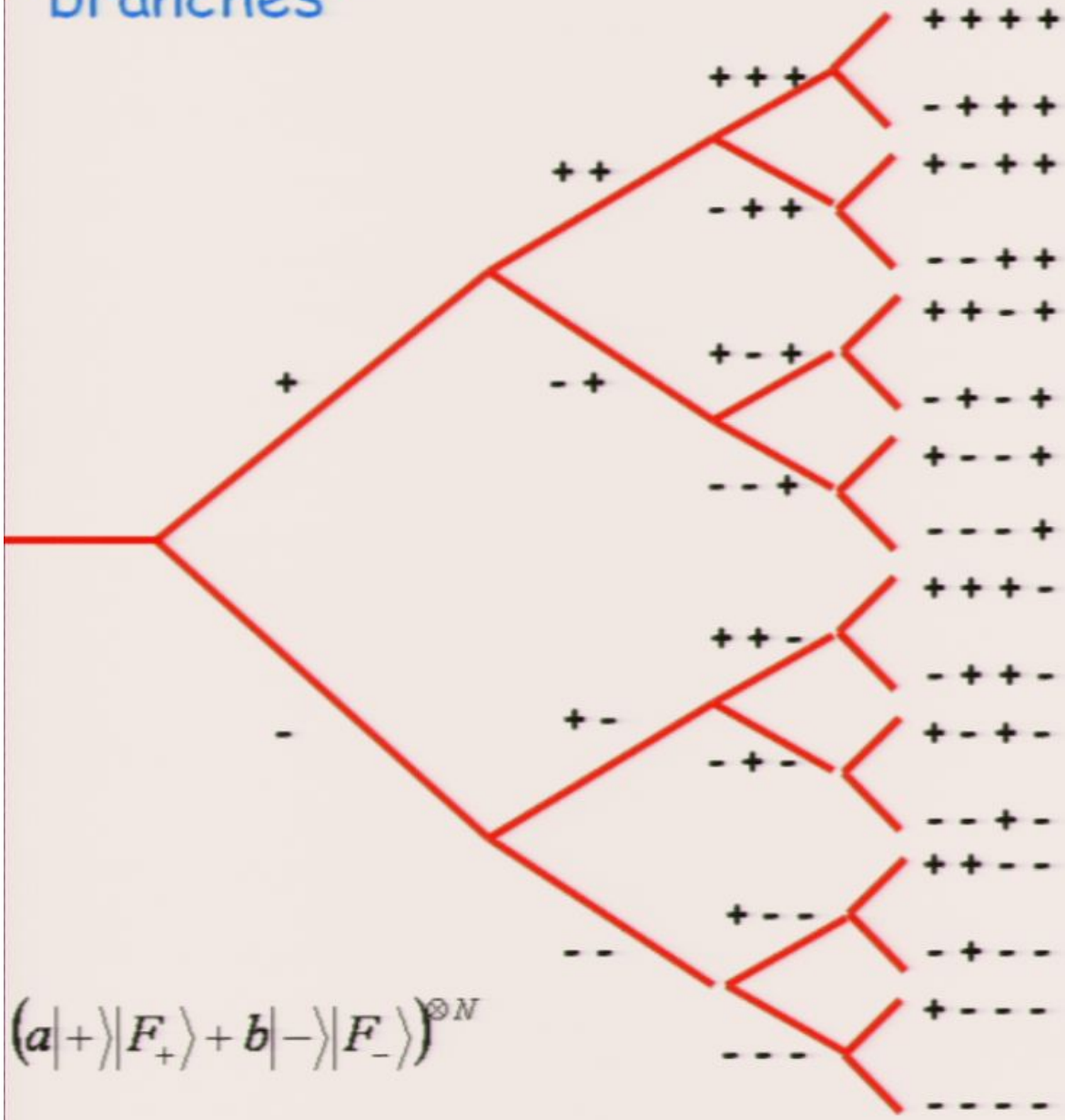

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In the limit $N \to \infty$, in all branches except a set of measure zero, the frequency of + results is the same.

What is this "typical" frequency?

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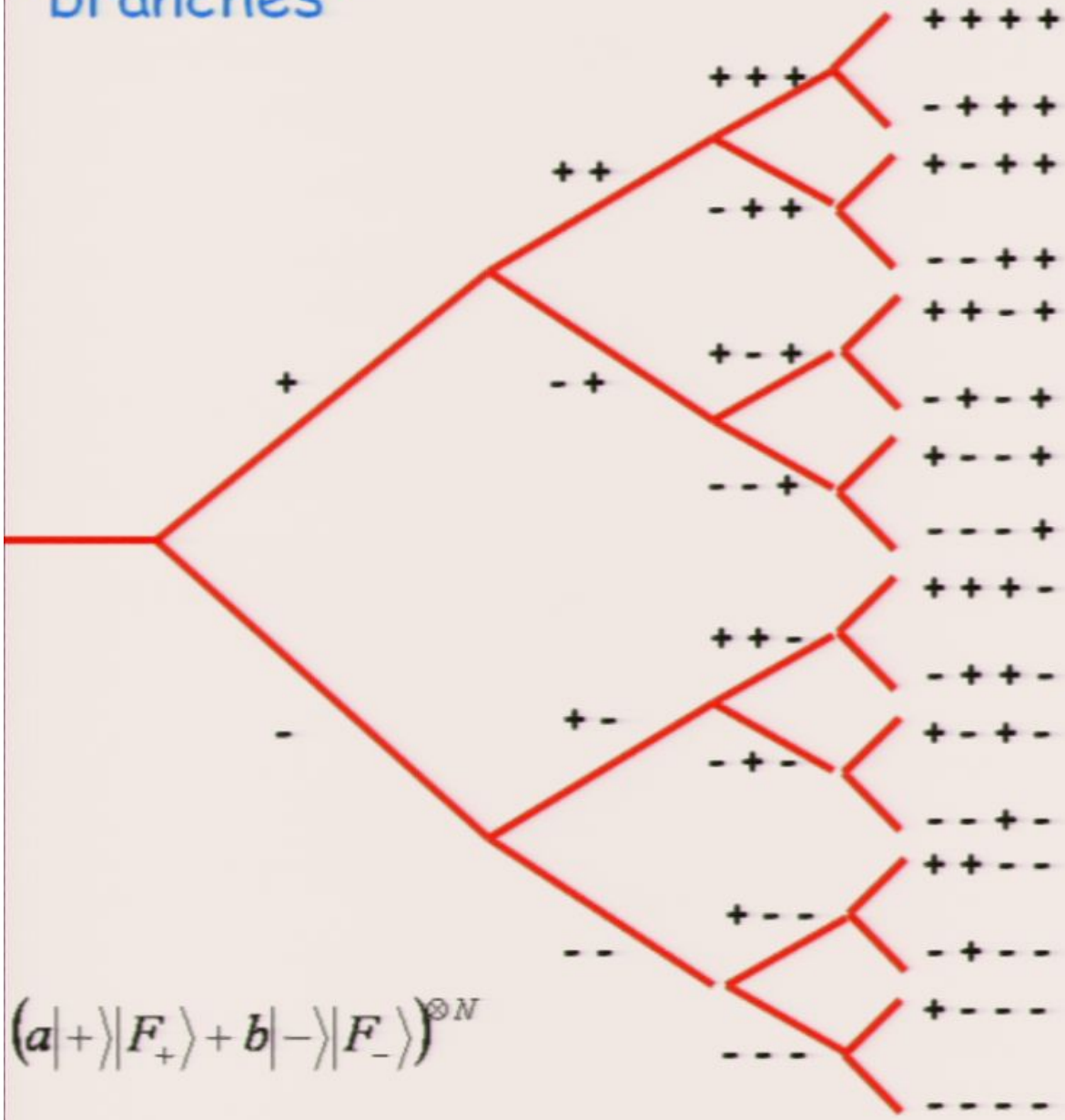

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For a counting measure over branches $\frac{1}{2}$

For the Born measure over branches $|a|^2$

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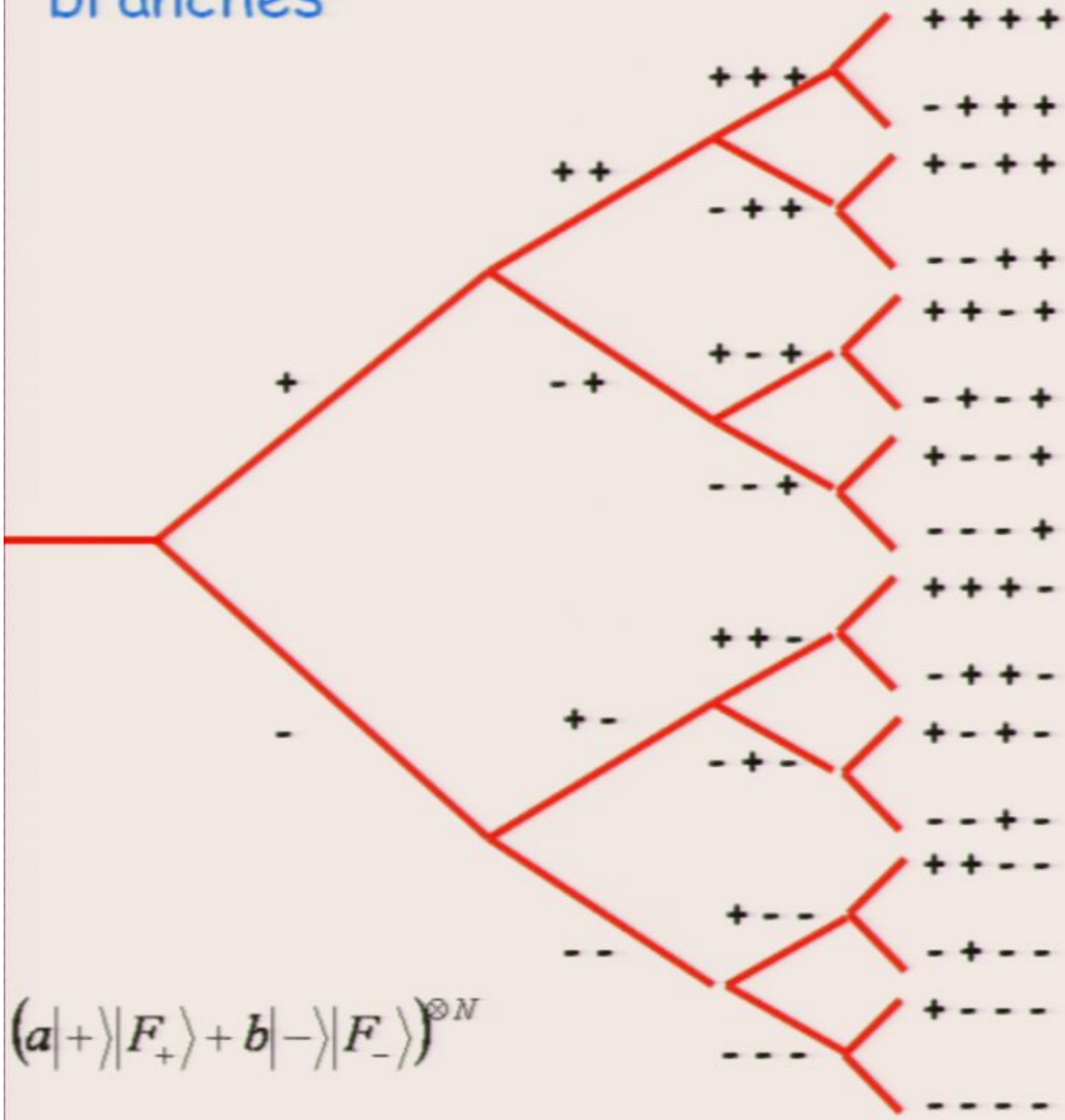

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Caves and Schack: In the law of large numbers, inferences run not from

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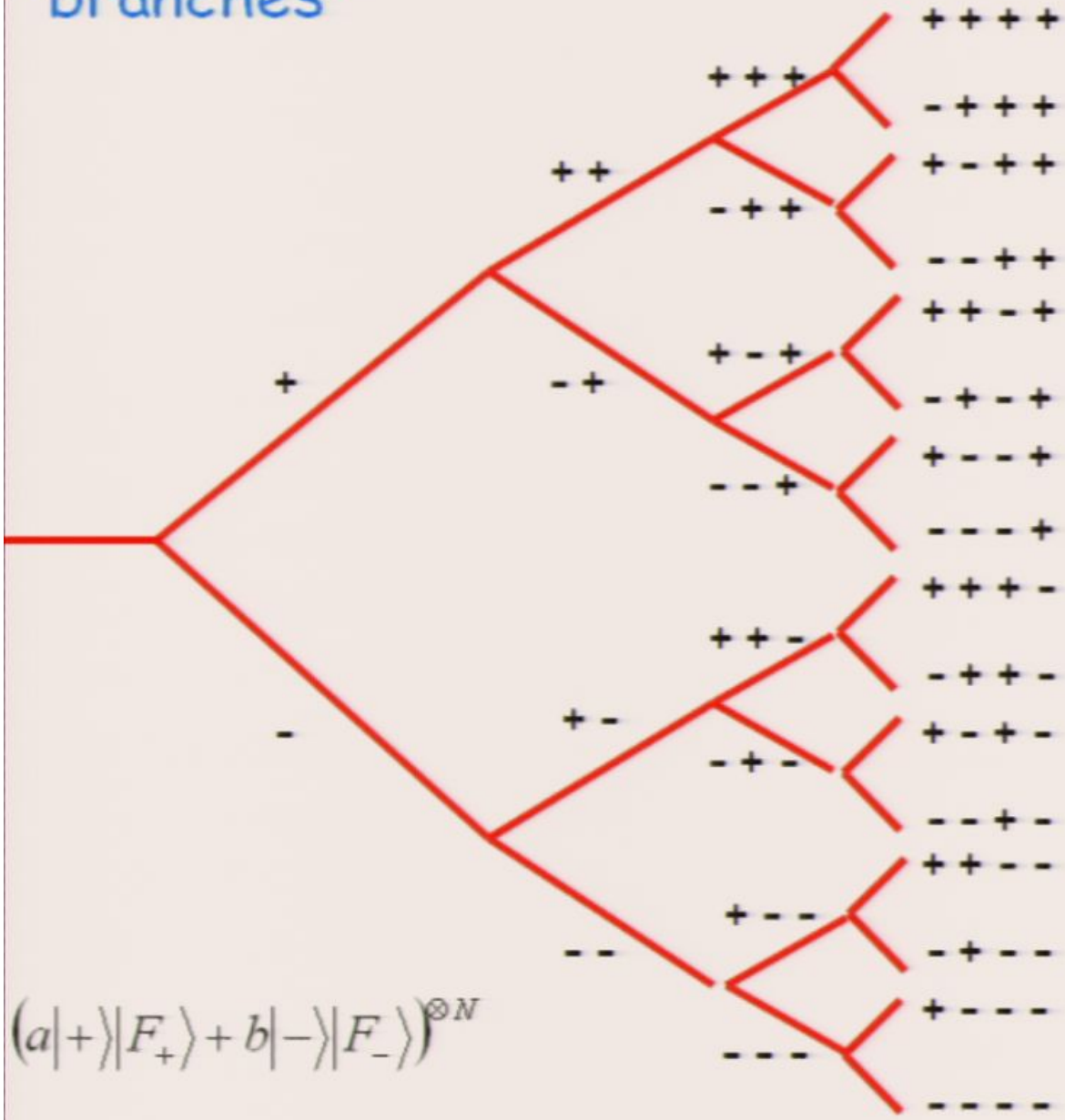

$$\left(a|+\rangle|F_+\rangle + b|-\rangle|F_-\rangle\right)^{\otimes N}$$

In any case, we need to reproduce a notion of probability for finite sequences of measurements

And the universal wavefunction will never be in an eigenstate of anyone performing a sequence of measurements

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The Quantitative Problem:

What kind of argument can be given to justify the claim that mod-squared amplitude is probability?

Response to the problem of probabilities

Deutsch's decision-theoretic strategy: Probability gets its meaning through the rational preferences of agents.
Born-rule weight in Everett plays the same role in weighting utilities in decision theory as probabilities do in one-world indeterministic theories.
A rational agent who knows that the Born-rule weight of an outcome is p is rationally compelled to act as if that outcome had probability p.

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Albert's criticism: It is not enough to show that agents who believed in the Everett picture would bet according to the Born measure, one must explain why we observe the particular relative frequencies that we do.

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Therefore, Ockham's razor prefers Everett to deBroglie-Bohm!

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For instance, the response of a measurement device to an impinging system is encoded in the wavefunction; the Bohmian particle's position only picks out a branch

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deBroglie-Bohm, unlike Everett, has no problem with probabilities

Responses to the measurement problem

1. Deny universality of quantum dynamics
   - Quantum-classical hybrid models
   - Collapse models

2. Deny representational completeness of ψ
   - ψ-ontic hidden variable models (e.g. deBroglie-Bohm)
   - ψ-epistemic hidden variable models

3. Deny that there is a unique outcome
   - Everett's relative state interpretation (many worlds)

4. Deny some aspect of classical logic or classical probability theory
   - Quantum logic and quantum Bayesianism

5. Deny some other feature of the realist framework?

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How do these ψ-ontic interpretations explain the success of the analogy between quantum states and epistemic states?

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