Title: Foundations of Quantum Mech. (PHYS 639) - Lecture 15

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Abstract:

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, $|\psi\rangle \rightarrow U|\psi\rangle = e^{-\frac{i}{\hbar}Ht}|\psi\rangle$ 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,

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

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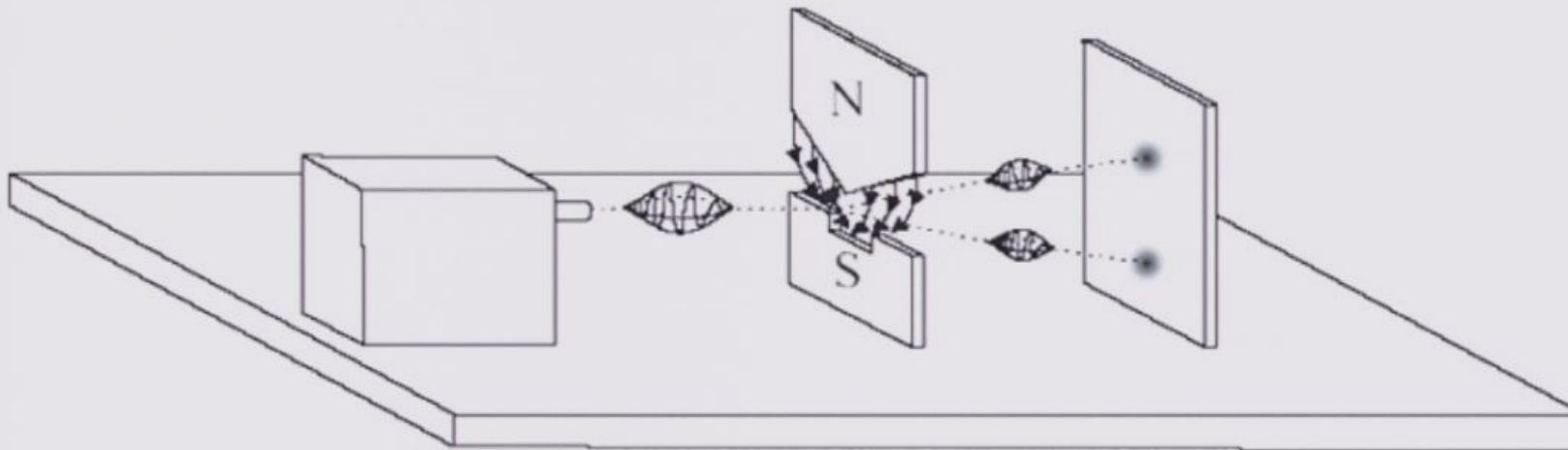
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Quantum measurement
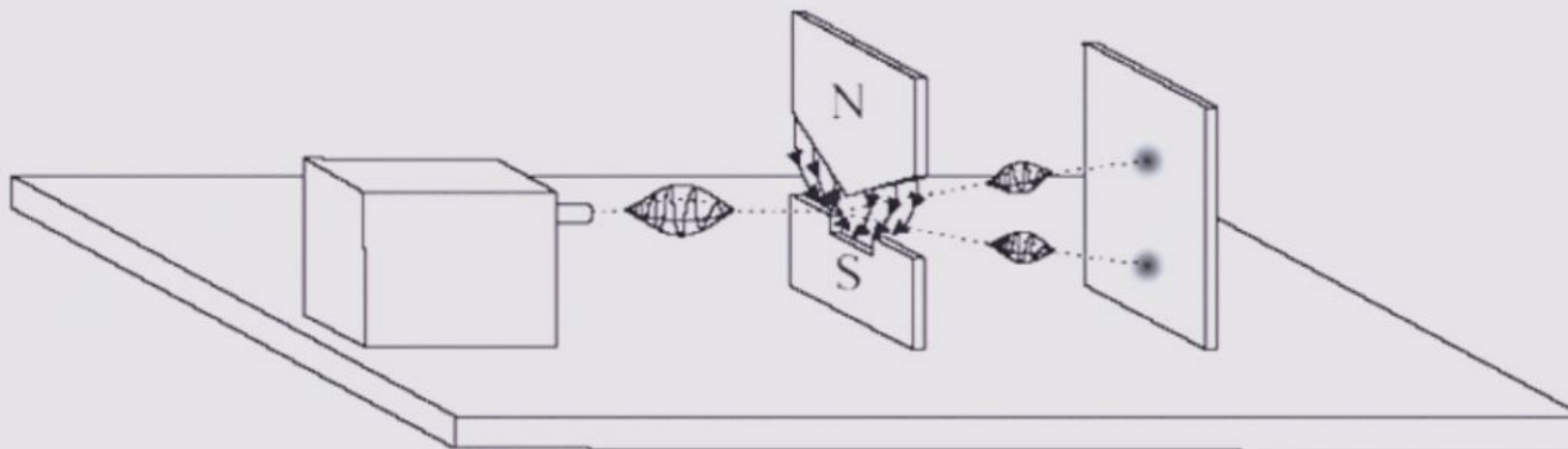
$(a|\uparrow\rangle + b|\downarrow\rangle)|\text{``ready''}\rangle$

$\rightarrow a|\uparrow\rangle|\text{``up''}\rangle + b|\downarrow\rangle|\text{``down''}\rangle$

Quantum measurement with observer

$$(a|\uparrow\rangle + b|\downarrow\rangle)|\text{``ready''}\rangle|\text{``ready to observe''}\rangle$$

$$\rightarrow a|\uparrow\rangle|\text{``up''}\rangle|\text{``observe up''}\rangle + b|\downarrow\rangle|\text{``down''}\rangle|\text{``observe down''}\rangle$$
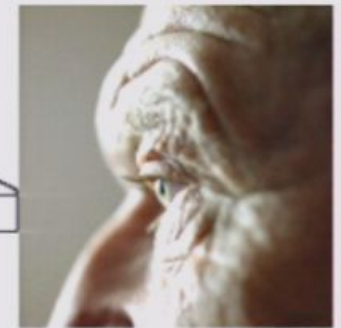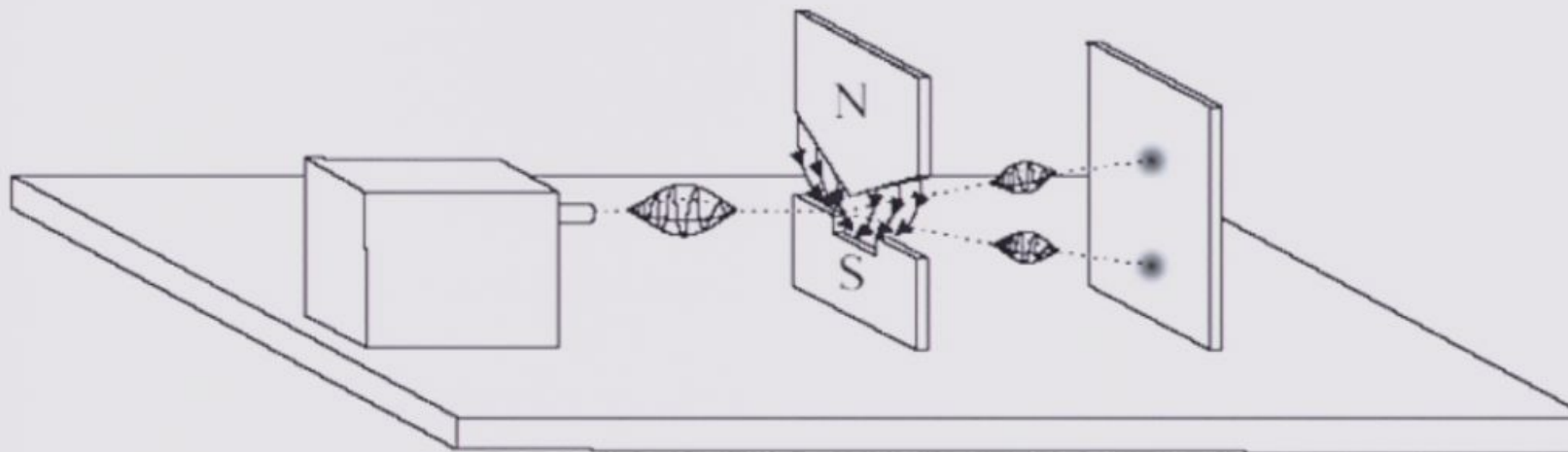
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"...we shall deduce the probabilistic assertions of [the collapse postulate] as *subjective* appearances to such observers, thus placing the theory in correspondence with experience. We are then led to the novel situation in which the formal theory is objectively continuous and causal, while subjectively discontinuous and probabilistic. (1973, p. 9).

Quantum measurement with many observers

$$(a|\uparrow\rangle + b|\downarrow\rangle)|\text{``ready''}\rangle|\text{``ready to observe''}\rangle|\text{``ready to observe''}\rangle$$

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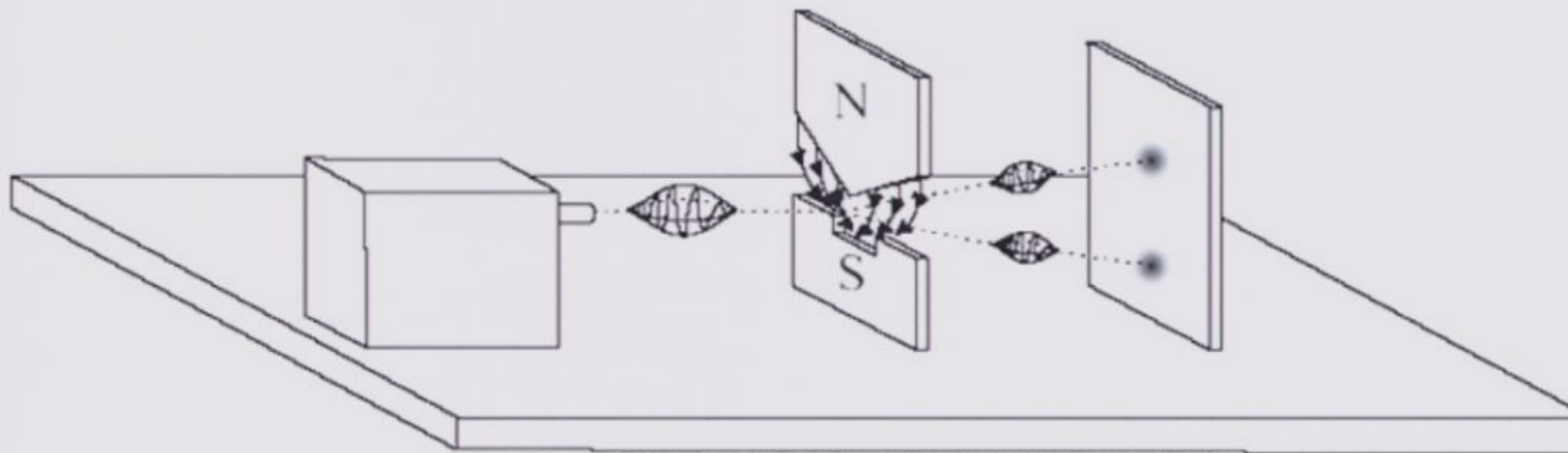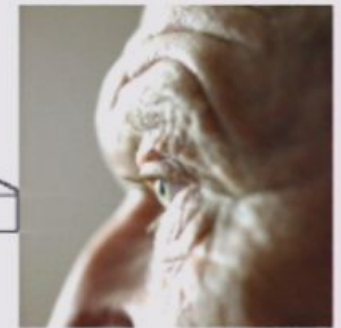$$\otimes|\text{``ready to observe''}\rangle$$

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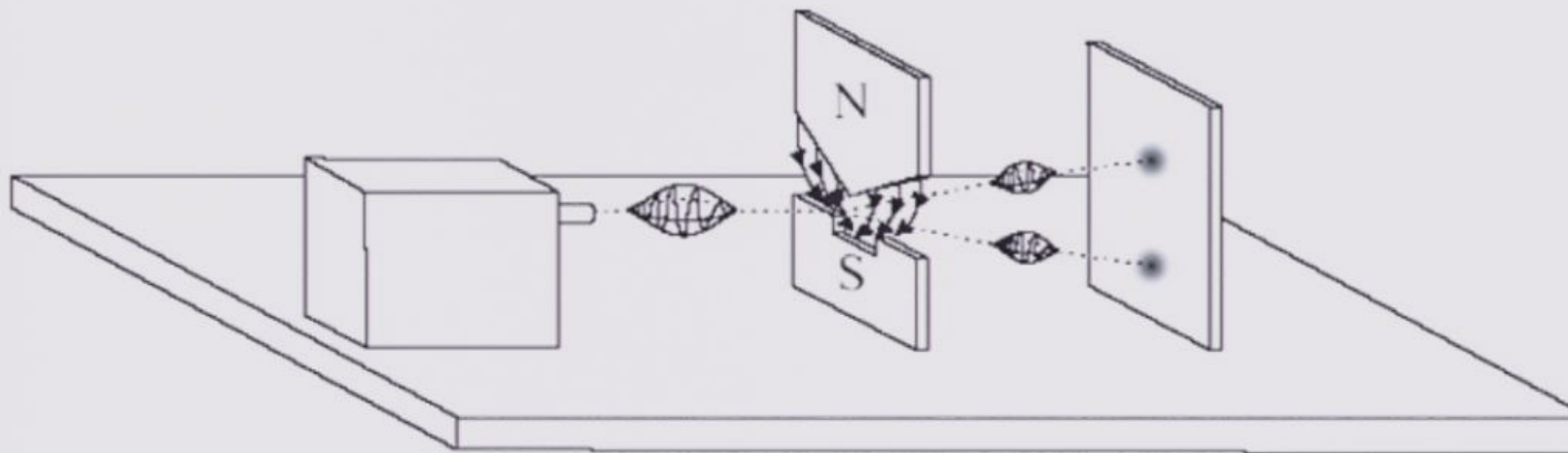
$$(a|\uparrow\rangle + b|\downarrow\rangle)|\text{"ready"}\rangle|\text{"ready to observe"}\rangle|\text{"ready to observe"}\rangle$$

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$$\rightarrow a|\uparrow\rangle|\text{"up"}\rangle|\text{"observe up"}\rangle|\text{"observe up"}\rangle$$

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
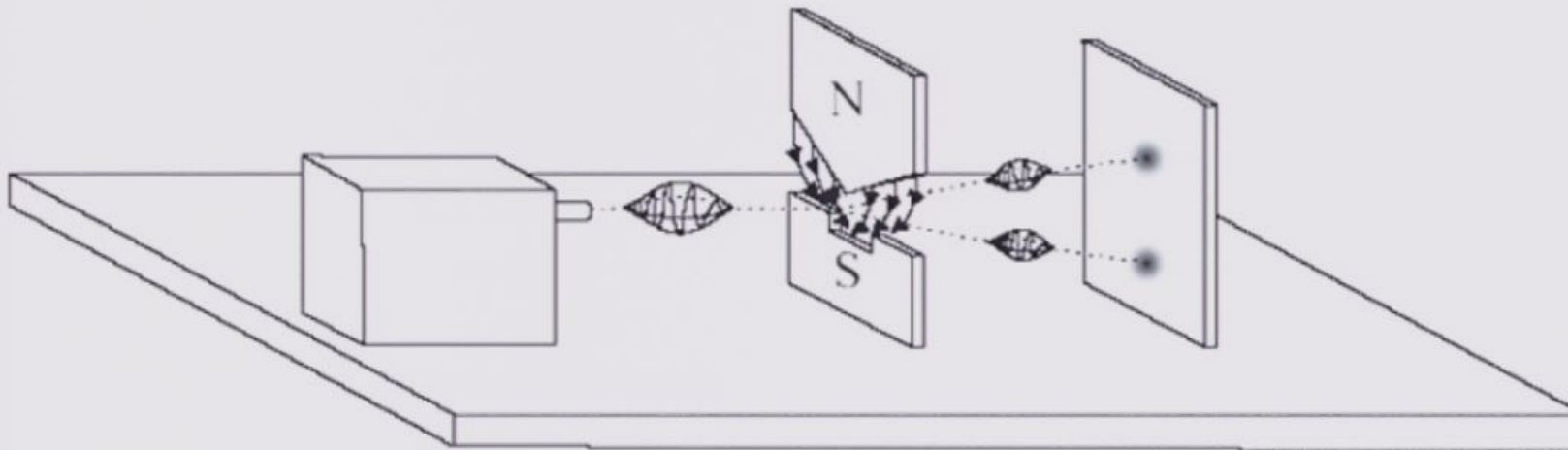
$$(a| \uparrow \rangle + b| \downarrow \rangle)| \text{``ready''} \rangle | \text{``ready to observe''} \rangle$$

$$\rightarrow a| \uparrow \rangle | \text{``up''} \rangle | \text{``observe up''} \rangle + b| \downarrow \rangle | \text{``down''} \rangle | \text{``observe down''} \rangle$$

rewrite as

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

Preferred basis problem

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

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

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

Preferred basis problem

$$\left(a|+\rangle|F_{+}\rangle + b|-\rangle|F_{-}\rangle \right)|E_{0}\rangle \;\;\rightarrow\;\; a|+\rangle|F_{+}\rangle|E_{+}\rangle + b|-\rangle|F_{-}\rangle|E_{-}\rangle$$

Decoherence:

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

Preferred basis problem

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

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Kent's criticism: "no preferred basis can arise, from the dynamics or

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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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.

By Dennett's criterion there is a real tiger in each branch.

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?

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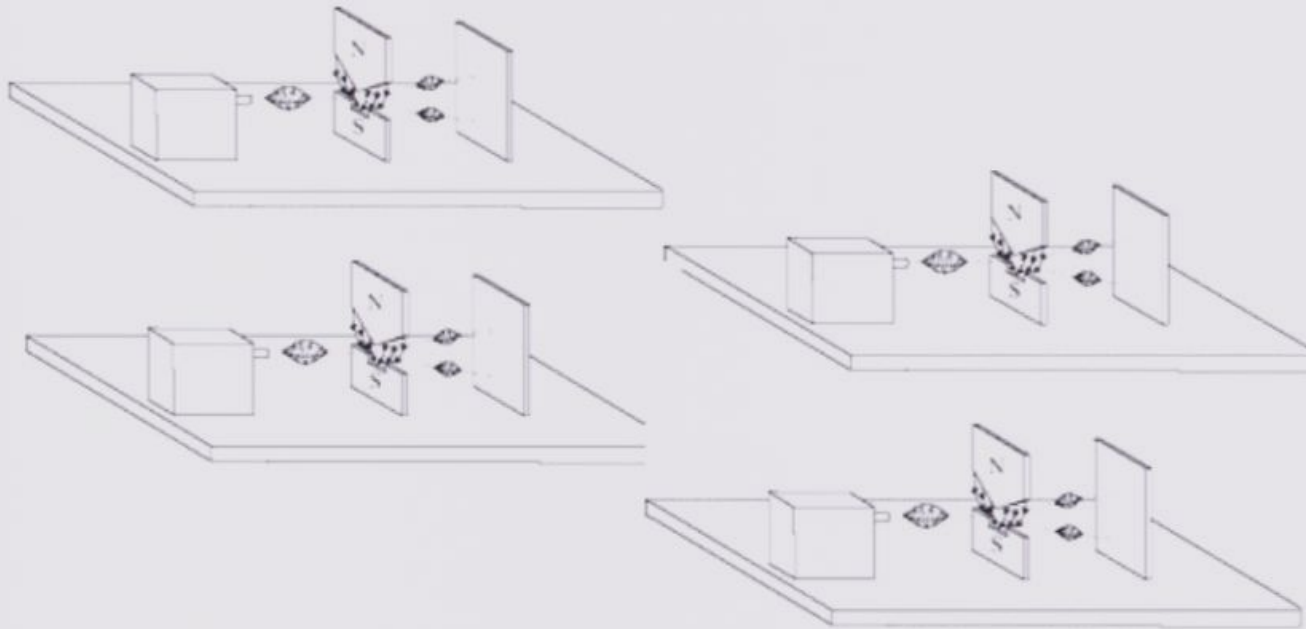
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Sequence of measurements:

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

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

"branches"

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

+ + + +
+ + +
- + + +
+ +
+ - + +
- + +
- - + +
+
+ + - +
+ - +
- + - +
- +
+ - - +
- - +
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"branches"
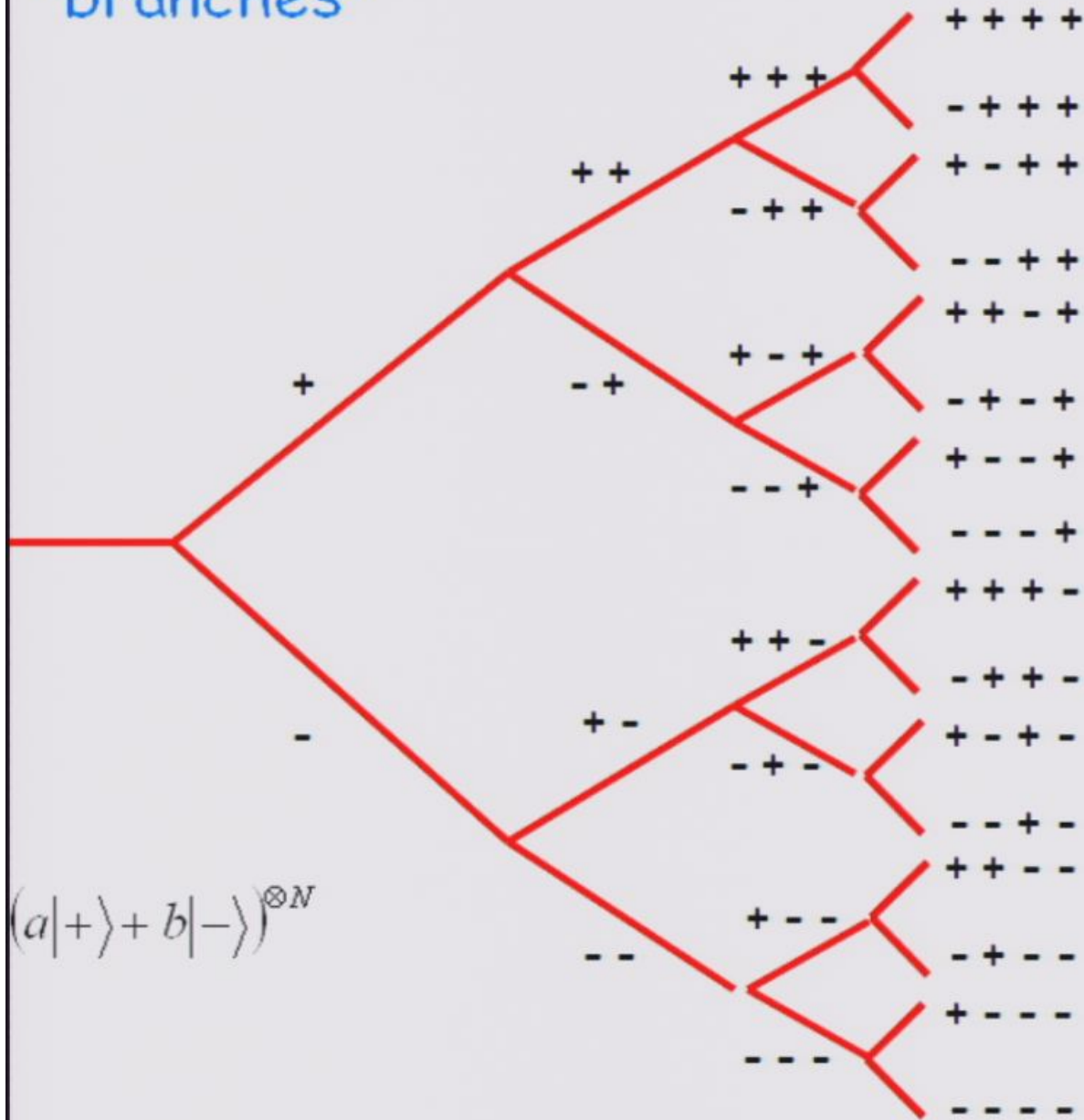
+ + + +
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$$\big(a\ket{+} + b\ket{-}\big)^{\otimes N}$$

Different branches correspond to different subjective experiences
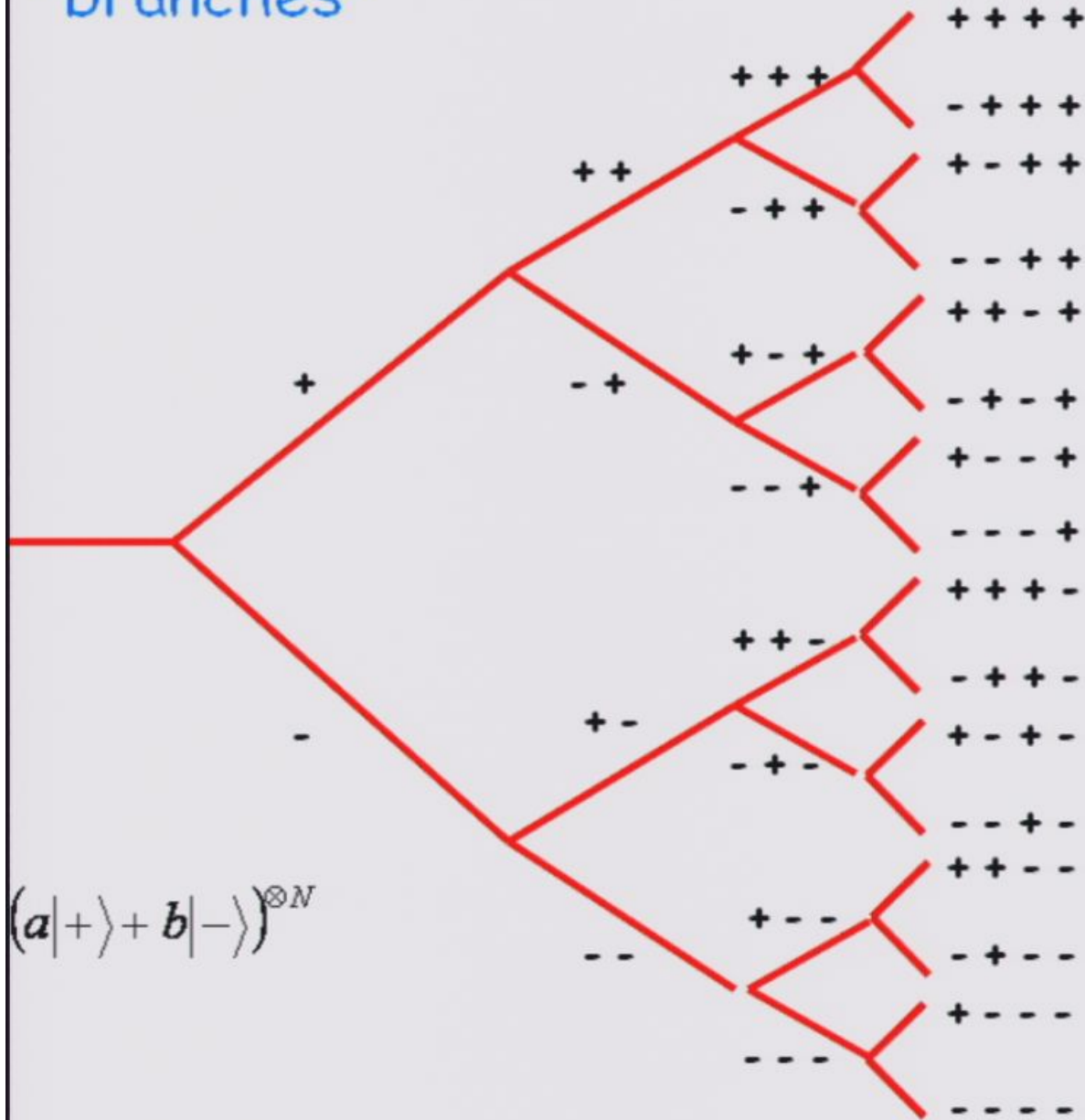
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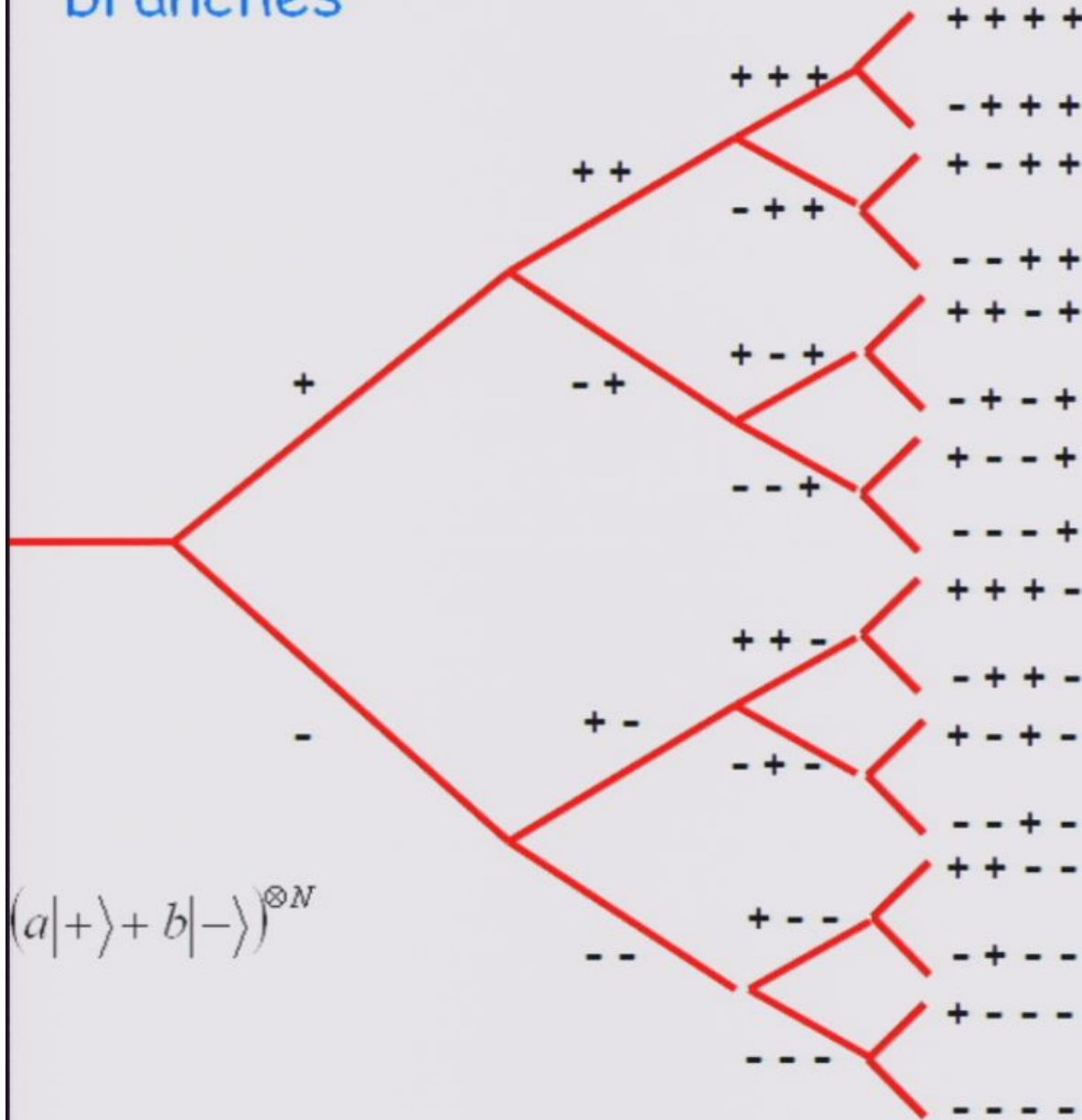
All branches are actual → all experiences occur

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

"branches"

+ + + +

+ + +

+ +   - + + +

+ - + +

- + +

- - + +

+   ++ - +

+ - +

- +   - + - +

+ - - +

- - +   - - - +

+ + + -

+ + -

- + + -

+ -   + - + -

-                - + -

- - + -

+ + - -

+ - -

- -   - + - -

+ - - -

- - -

- - - -

$\left(a \vert + \rangle + b \vert - \rangle \right)^{\otimes N}$
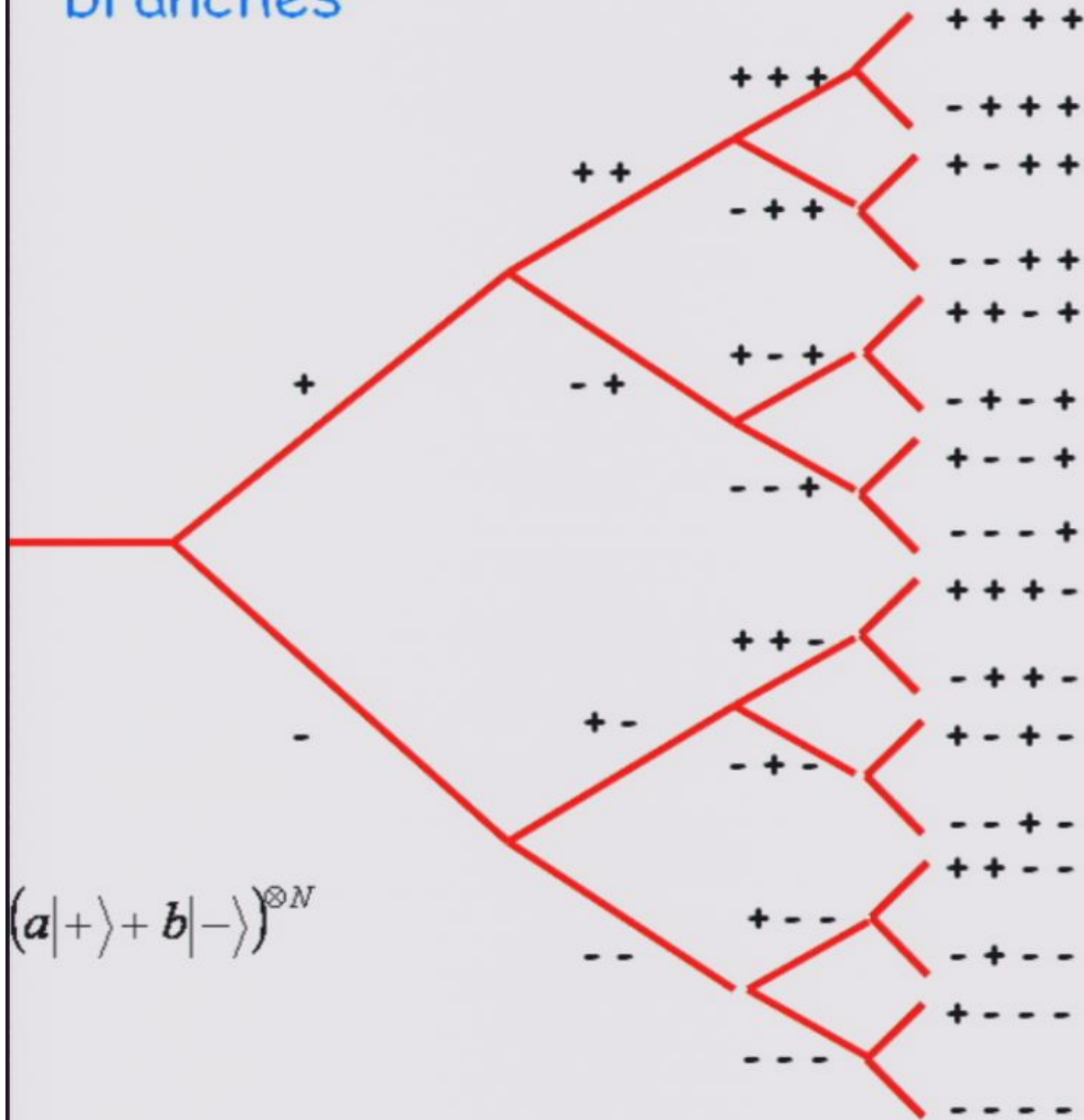
In the limit $N \rightarrow \infty$, in all branches except a set of measure zero, the frequency of + results is the same.

What is this "typical" frequency?

"branches"


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

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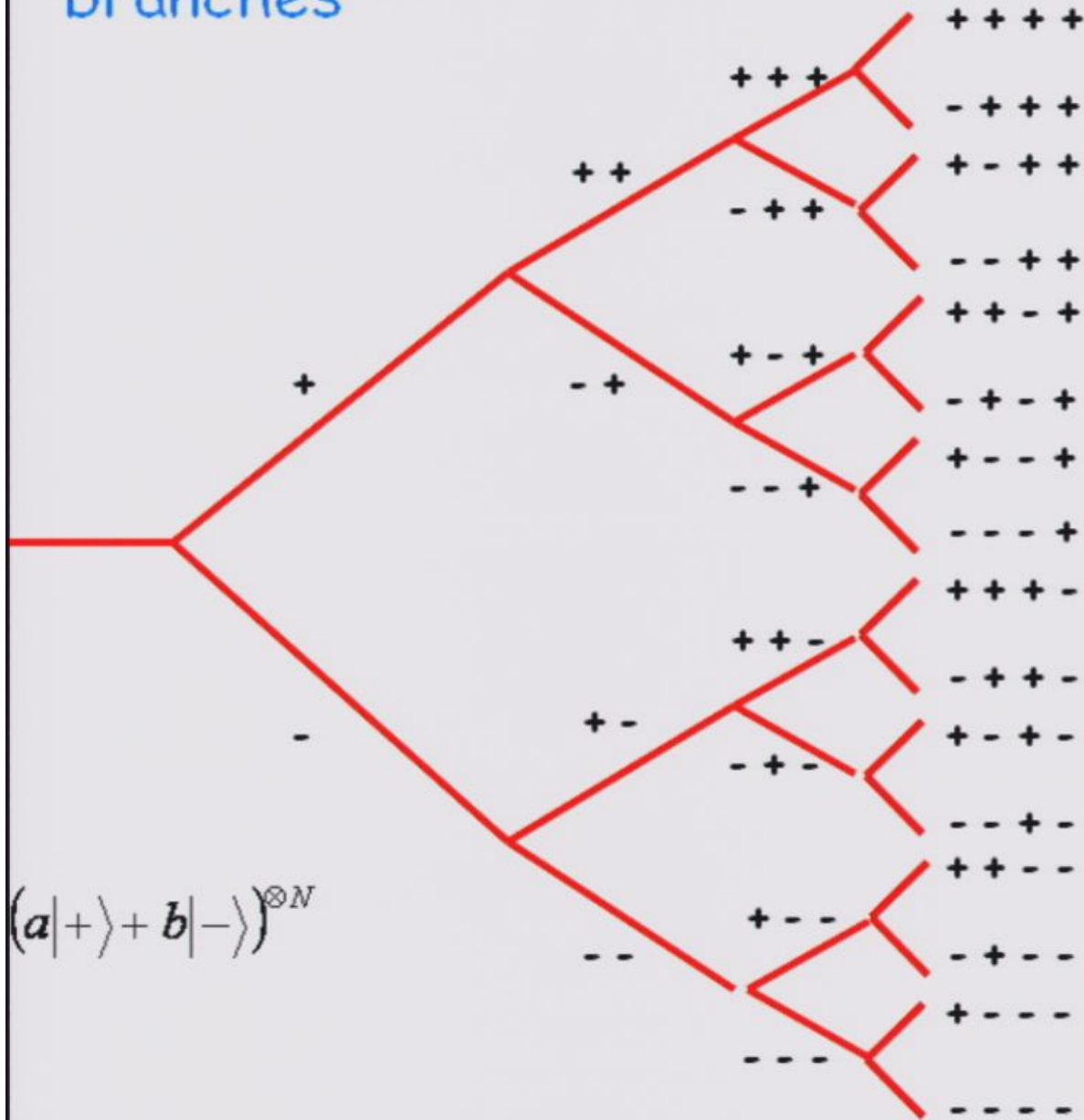
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For the Born measure over branches $|a|^2$

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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 in quantum mechanics through the rational preferences of agents. In particular, 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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In any case, how do any of these interpretations explain the success of the analogy between quantum states and epistemic states?