

Title: Foundations of Quantum Mechanics - Lecture 1

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Abstract:

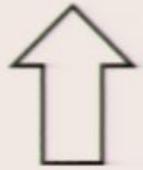
# Foundations of Quantum Theory

Provide an adequate interpretation

Explore nonclassical phenomena

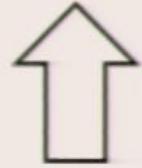
Determine principles from which the quantum formalism may be derived

Lorentz transformations



Relativity Principle  
Light Postulate

Lorentz transformations



Relativity Principle  
Light Postulate

Mathematical Formalism  
of Quantum Theory



Some physical principles

# Foundations of Quantum Theory

Provide an adequate interpretation

Explore nonclassical phenomena

Determine principles from which the quantum formalism may be derived

What's the problem?

## “Orthodox” postulates of quantum theory

Representational completeness of  $\psi$ . 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**,

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

**First problem:** the term “measurement” is not defined in terms of the more primitive “physical states of systems”. Isn’t a measurement just another kind of physical interaction?

Two strategies:

- (1) **Realist strategy:** Eliminate measurement as a primitive concept and describe everything in terms of physical states
- (2) **Operational strategy:** Eliminate “the physical state of a system” as a primitive concept and describe everything in terms of operational concepts

“It would seem that the theory is exclusively concerned about "results of measurement", and has nothing to say about anything else. What exactly qualifies some physical systems to play the role of "measurer"? ”

- John Bell

# The realist strategy

## Inconsistencies of the orthodox interpretation

By the collapse postulate  
(applied to the system)

Indeterministic and  
discontinuous evolution

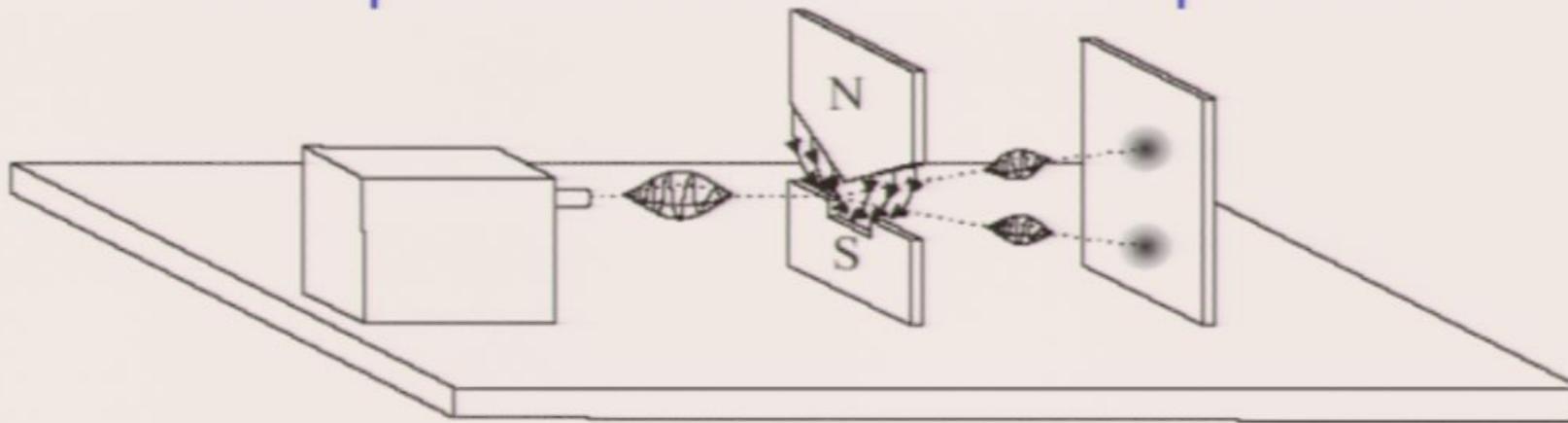
Determinate properties

By the unitary evolution postulate  
(applied to the isolated composite that  
includes the system and apparatus)

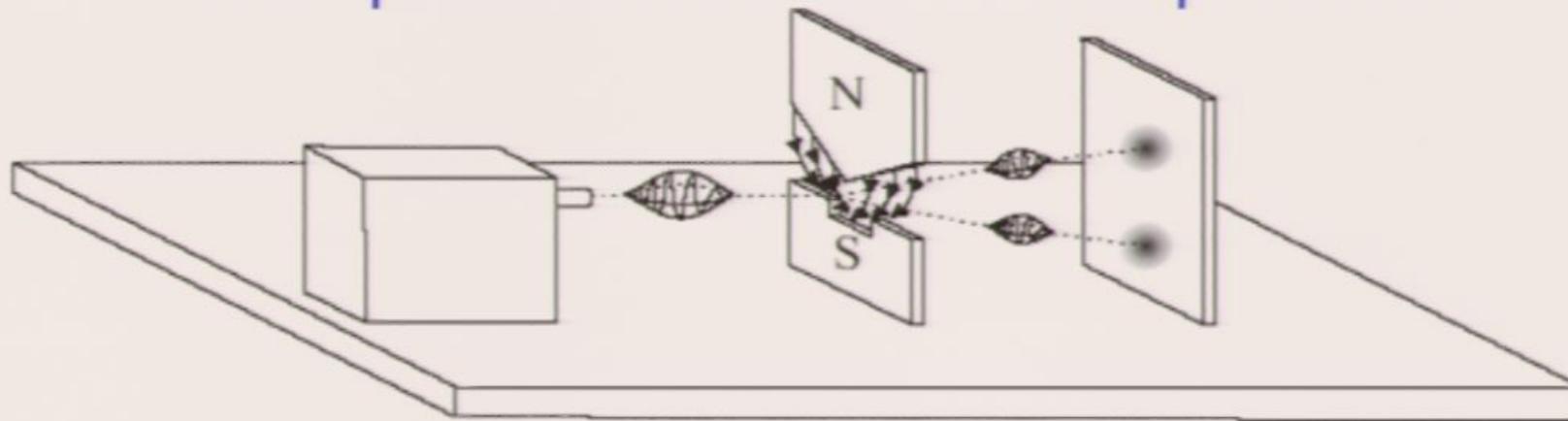
Deterministic and  
continuous evolution

Indeterminate properties

# The quantum measurement problem



## The quantum measurement problem

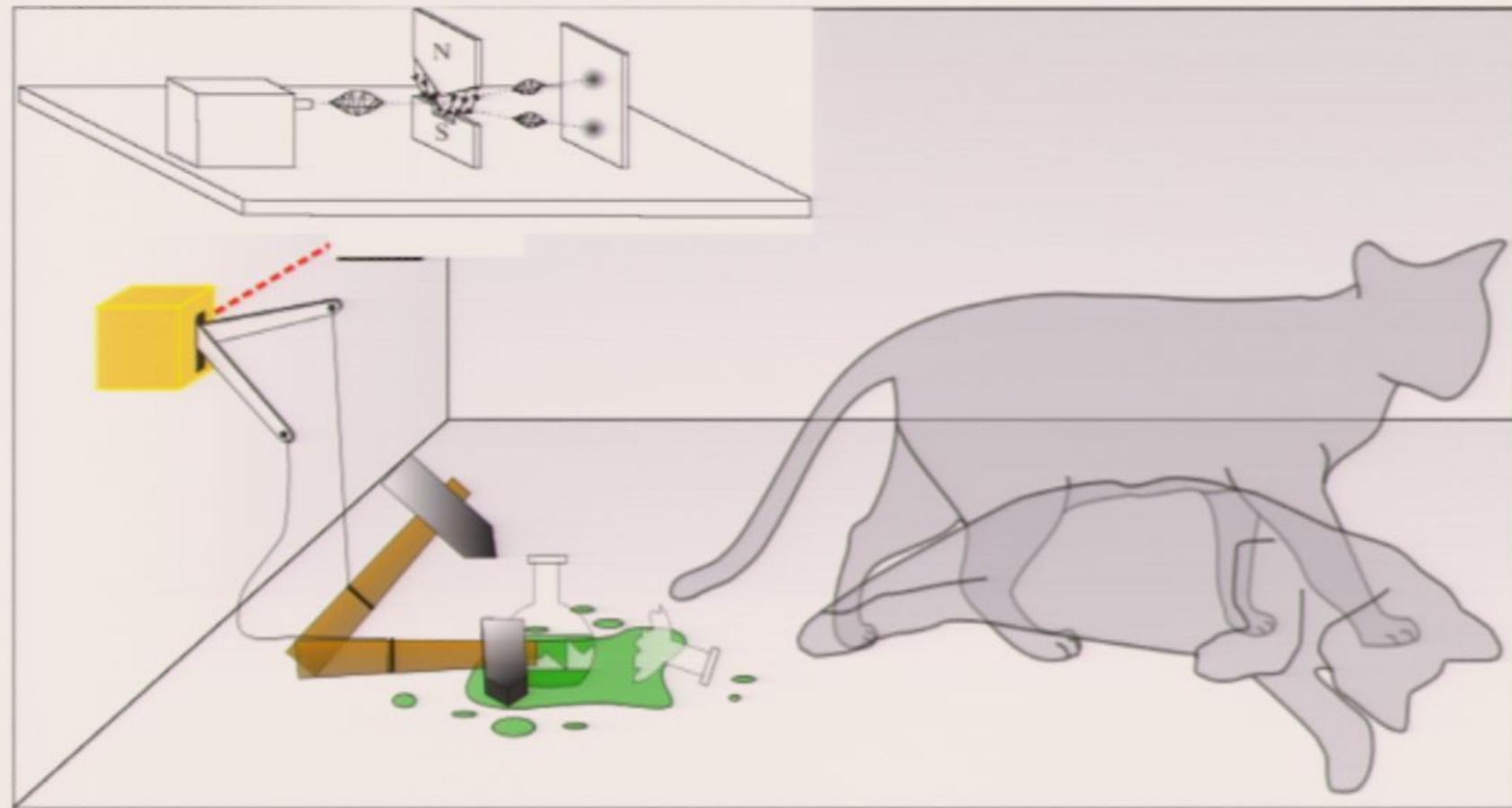


If the measurement apparatus is treated **externally**

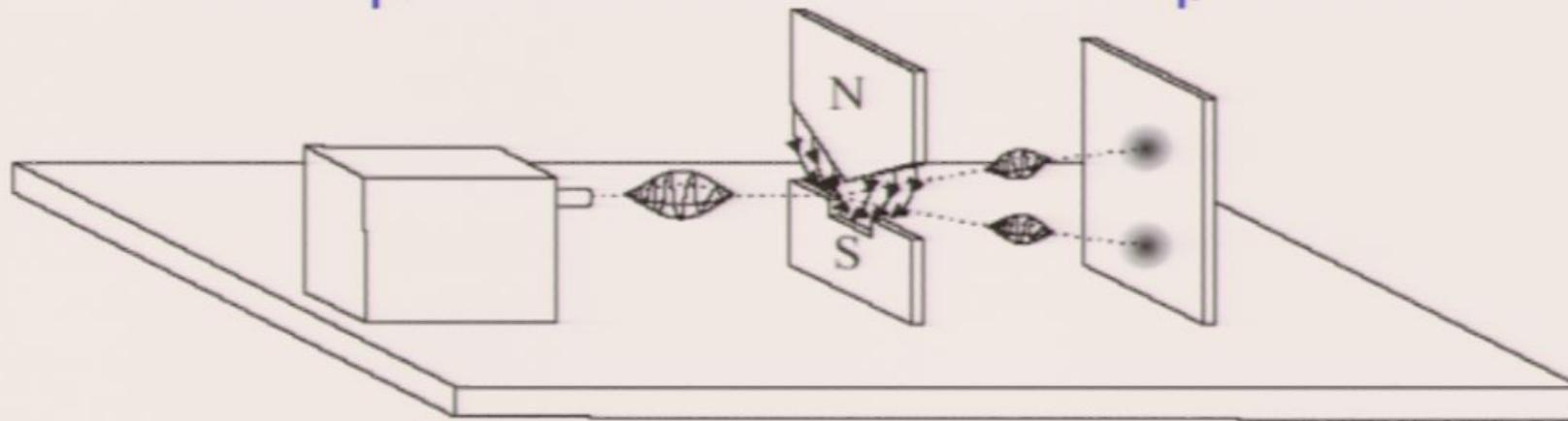
$$\begin{aligned} a|\uparrow\rangle + b|\downarrow\rangle &\rightarrow |\uparrow\rangle \text{ with probability } |a|^2 \\ &\rightarrow |\downarrow\rangle \text{ with probability } |b|^2 \end{aligned}$$

If the measurement apparatus is treated **internally**

$$\begin{aligned} |\uparrow\rangle \otimes |\text{"ready"}\rangle &\rightarrow U(|\uparrow\rangle \otimes |\text{"ready"}\rangle) = |\uparrow\rangle \otimes |\text{"up"}\rangle \\ |\downarrow\rangle \otimes |\text{"ready"}\rangle &\rightarrow U(|\downarrow\rangle \otimes |\text{"ready"}\rangle) = |\downarrow\rangle \otimes |\text{"down"}\rangle \end{aligned}$$



## The quantum measurement problem



If the measurement apparatus is treated **externally**

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If the measurement apparatus is treated **internally**

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$$|\downarrow\rangle \otimes |\text{"ready"}\rangle \rightarrow U(|\downarrow\rangle \otimes |\text{"ready"}\rangle) = |\downarrow\rangle \otimes |\text{"down"}\rangle$$

U is a linear operator  $U(a|\psi\rangle + b|\phi\rangle) = aU|\psi\rangle + bU|\phi\rangle$

$$\begin{aligned} (a|\uparrow\rangle + b|\downarrow\rangle) \otimes |\text{"ready"}\rangle &\rightarrow U[a|\uparrow\rangle \otimes |\text{"ready"}\rangle + b|\downarrow\rangle \otimes |\text{"ready"}\rangle] \\ &= a|\uparrow\rangle \otimes |\text{"up"}\rangle + b|\downarrow\rangle \otimes |\text{"down"}\rangle \end{aligned}$$



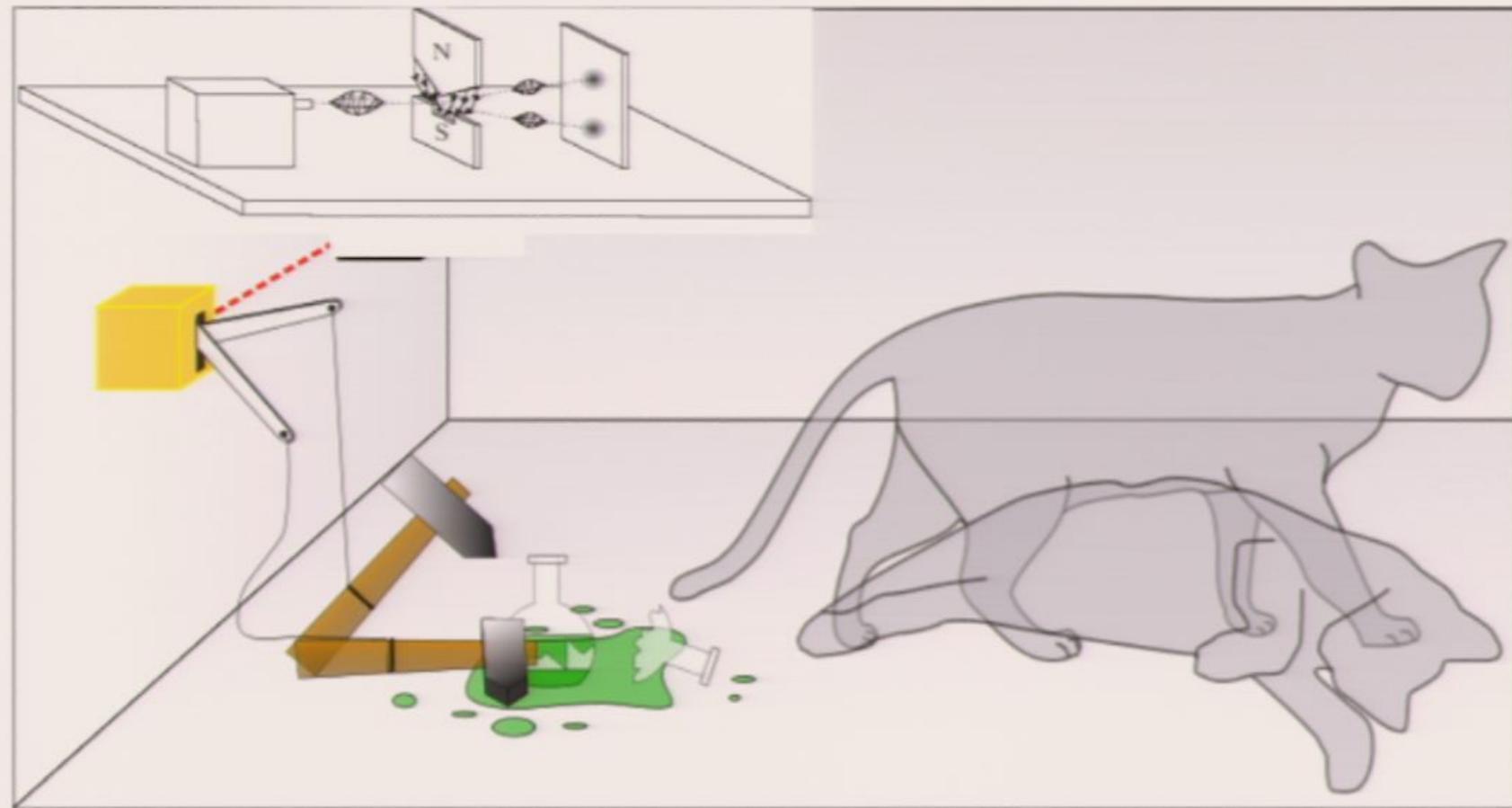
## False starts on the measurement problem

- Interpret coherent superposition as disjunction

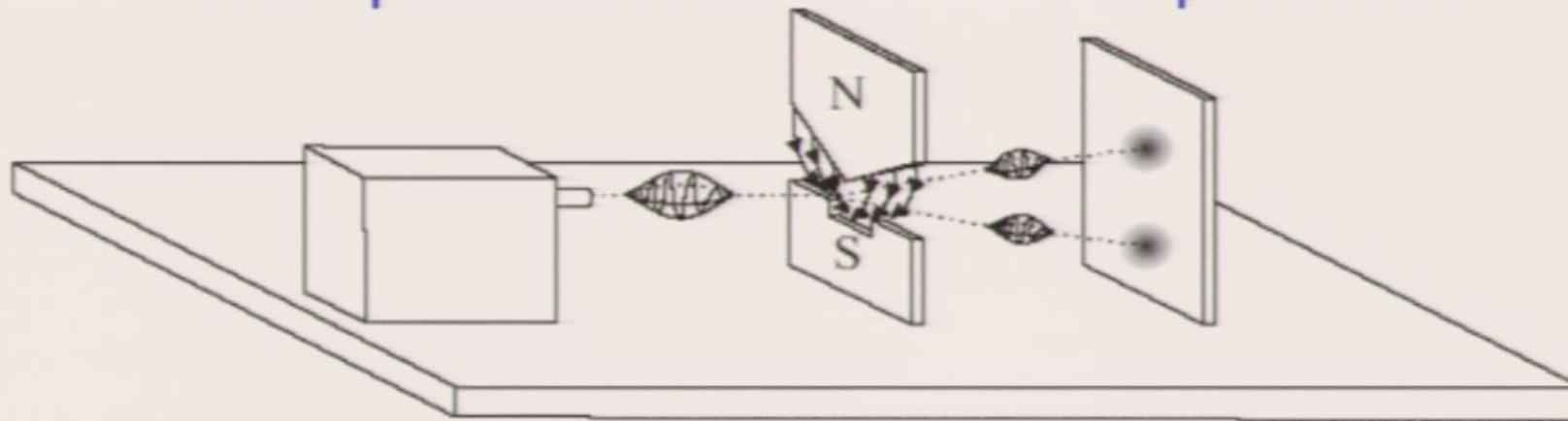
$$a|\uparrow\rangle \otimes |\text{"up"}\rangle + b|\downarrow\rangle \otimes |\text{"down"}\rangle$$

Means either  $|\uparrow\rangle \otimes |\text{"up"}\rangle$   
or  $|\downarrow\rangle \otimes |\text{"down"}\rangle$

with probabilities  $|a|^2$  and  $|b|^2$   
respectively



## The quantum measurement problem



If the measurement apparatus is treated **externally**

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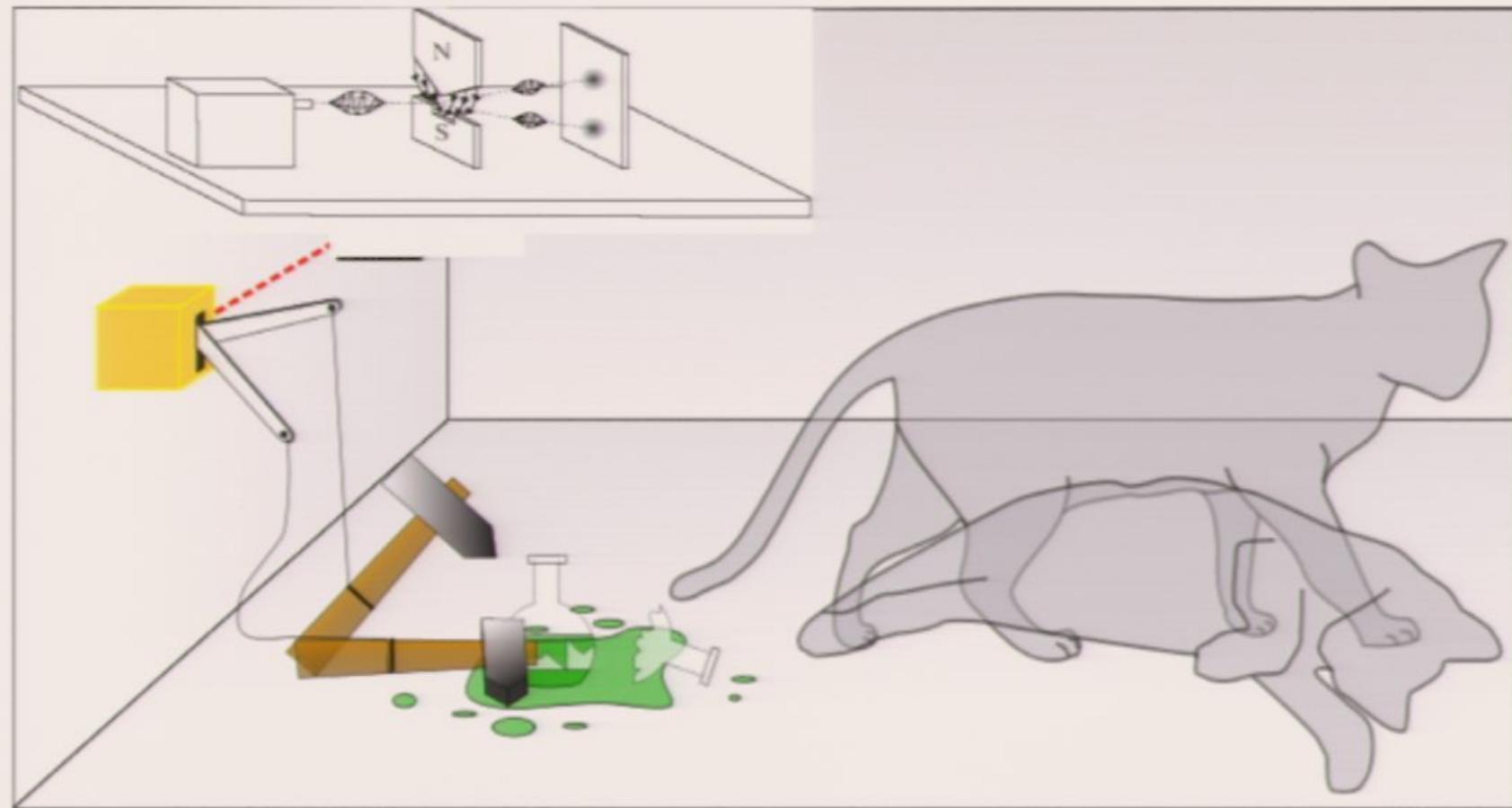
If the measurement apparatus is treated **internally**

$$|\uparrow\rangle \otimes |\text{"ready"}\rangle \rightarrow U(|\uparrow\rangle \otimes |\text{"ready"}\rangle) = |\uparrow\rangle \otimes |\text{"up"}\rangle$$

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$U$  is a linear operator  $U(a|\psi\rangle + b|\phi\rangle) = aU|\psi\rangle + bU|\phi\rangle$

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## False starts on the measurement problem

- Interpret coherent superposition as disjunction

$$a|\uparrow\rangle \otimes |\text{"up"}\rangle + b|\downarrow\rangle \otimes |\text{"down"}\rangle$$

Means either  $|\uparrow\rangle \otimes |\text{"up"}\rangle$   
or  $|\downarrow\rangle \otimes |\text{"down"}\rangle$

with probabilities  $|a|^2$  and  $|b|^2$   
respectively

## False starts on the measurement problem

- Interpret the reduced density operator as a proper mixture

$$a|\uparrow\rangle\otimes|\text{"up"}\rangle + b|\downarrow\rangle\otimes|\text{"down"}\rangle$$

$$\rho = |a|^2|\text{"up"}\rangle\langle\text{"up"}| + |b|^2|\text{"down"}\rangle\langle\text{"down"}|$$

## False starts on the measurement problem

- Appeal to environment-induced decoherence

$$\begin{aligned}(a|\uparrow\rangle + b|\downarrow\rangle) \otimes |\text{"ready"}\rangle \otimes |E_0\rangle \\ \rightarrow (a|\uparrow\rangle \otimes |\text{"up"}\rangle + b|\downarrow\rangle \otimes |\text{"down"}\rangle) \otimes |E_0\rangle \\ \rightarrow a|\uparrow\rangle \otimes |\text{"up"}\rangle \otimes |E_1\rangle + b|\downarrow\rangle \otimes |\text{"down"}\rangle \otimes |E_2\rangle\end{aligned}$$

## Responses to the measurement problem

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

## Responses to the measurement problem

1. Deny universality of quantum dynamics
  - Quantum-classical hybrid models
  - Collapse models
2. Deny representational completeness of  $\psi$ 
  - $\psi$ -ontic hidden variable models (e.g. Bohmian mechanics)
  - $\psi$ -epistemic hidden variable models
3. Deny that there is a unique outcome
  - Everett's relative state interpretation (many worlds)