Title: Foundations of Quantum Mech. (PHYS 639) - Lecture 1

Date: Nov 30, 2009 11:00 AM

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Abstract:

Foundations of Quantum Theory

Provide an adequate interpretation

Explore nonclassical phenomena

Determine principles from which quantum theory may be derived

What's the problem?

"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,

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

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

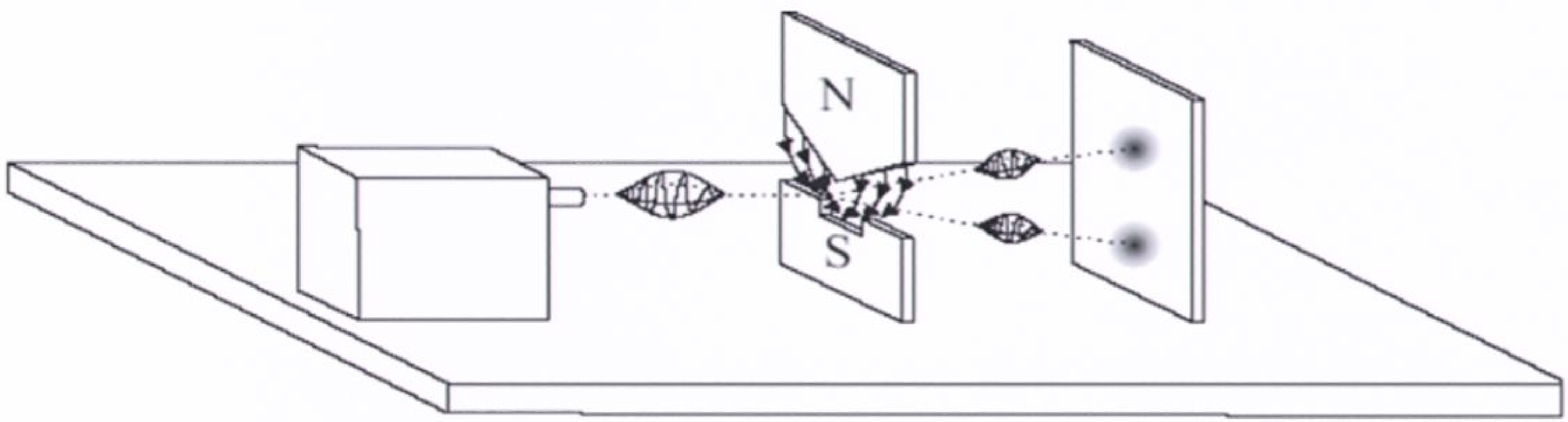
“It would seem that the theory is exclusively concerned about "results of measurement", and has nothing to say about anything else. What exactly qualifies some physical systems to play the role of "measurer"? ”

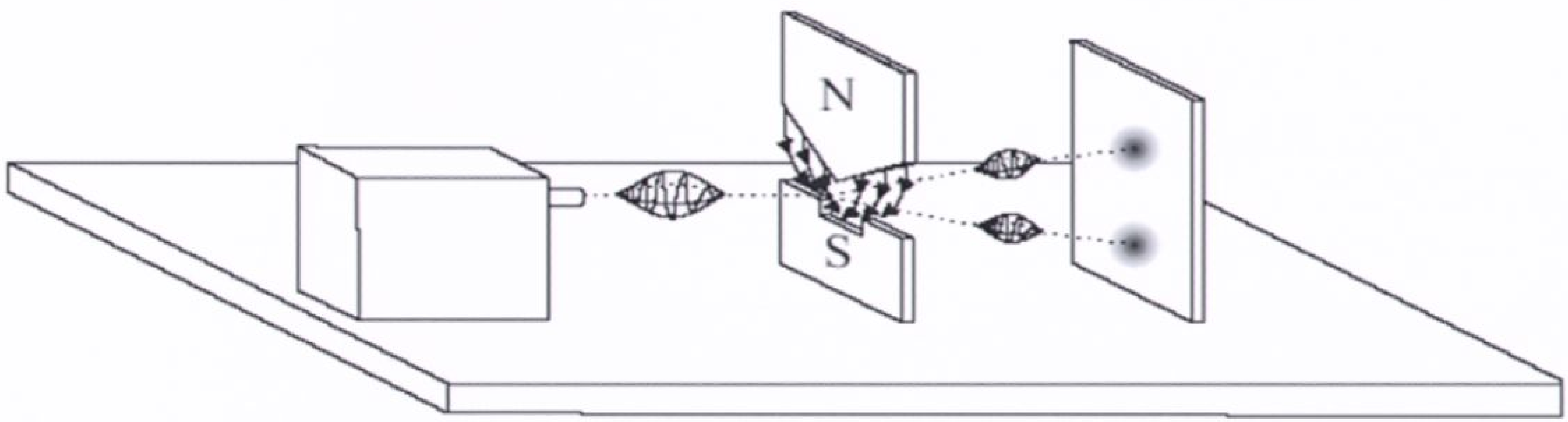
- John Bell

“In a strict sense, quantum theory is a set of rules allowing the computation of probabilities for the outcomes of tests which follow specified preparations.”

- Asher Peres

The operational strategy


N
S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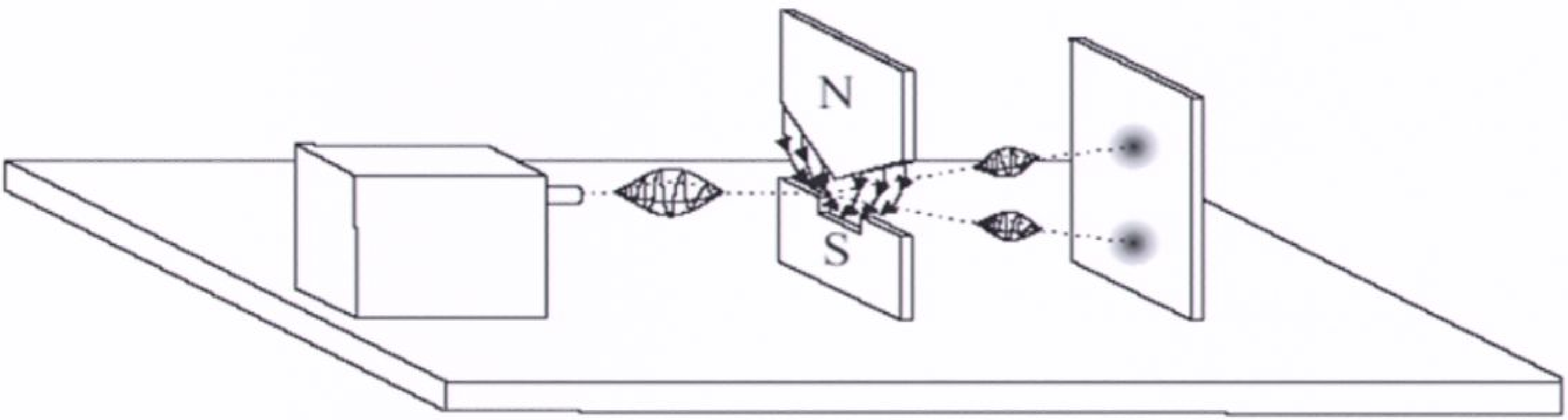

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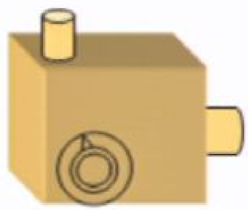
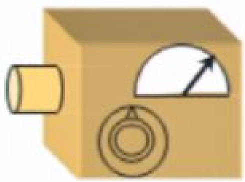
Operational Quantum Mechanics





Preparation

P

Measurement

M

Vector

$|\psi\rangle$

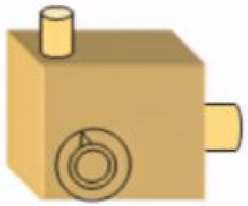
Hermitian operator

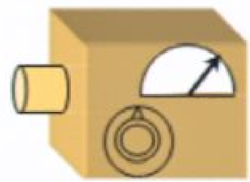
A

$A = \sum_k a_k P_k$

$$\boxed{Pr(k|\mathsf{P},\mathsf{M}) = \langle\psi|P_k|\psi\rangle}$$

Operational Quantum Mechanics





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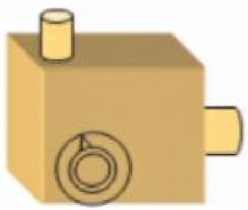

Preparation

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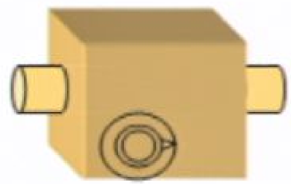
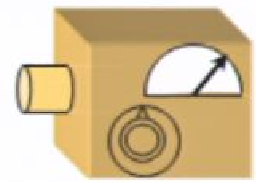


Transformation

T



Measurement

M

Vector

$|\psi\rangle$

Unitary map

U

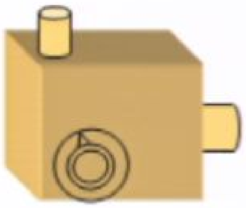
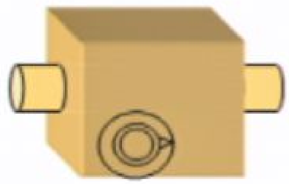
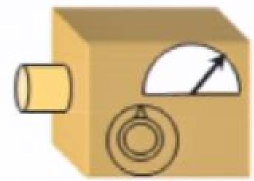
Hermitian operator

A

$A = \sum_k a_k P_k$

$$\boxed{Pr(k|\mathsf{P}, \mathsf{T}, \mathsf{M}) = \langle\psi|U^\dagger P_k U|\psi\rangle}$$

Operational Quantum Mechanics

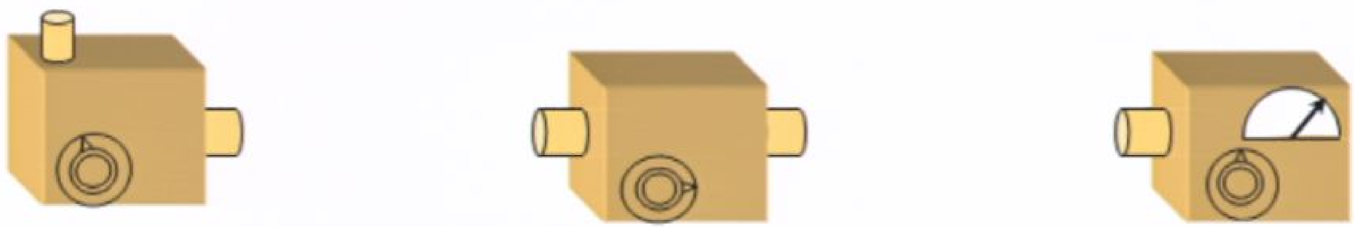
Preparation — Transformation — Measurement

$$\underbrace{\mathsf{P} \qquad\qquad \mathsf{T}}_{\text{Effective preparation } \mathsf{P}'} \qquad\qquad \mathsf{M}$$

$$|\psi\rangle \rightarrow |\psi'\rangle = U|\psi\rangle$$

$$\boxed{Pr(k|\mathsf{P}', \mathsf{M}) = \langle\psi'|P_k|\psi'\rangle = \langle\psi|U^\dagger P_k U|\psi\rangle}$$

Operational Quantum Mechanics



Preparation | Transformation | Measurement
P | T | M

Effective preparation

P′

$$|\psi\rangle \rightarrow |\psi'\rangle = U|\psi\rangle$$

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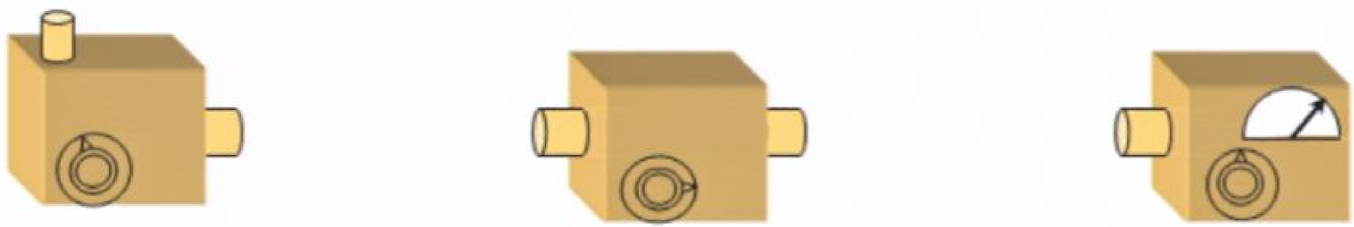
Operational Quantum Mechanics



Preparation

P

Transformation

T

Measurement

M

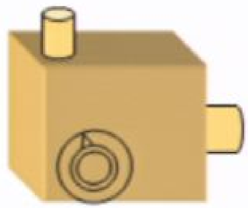
$\underbrace{\text{T} \qquad \text{M}}_{\text{Effective Measurement}\ \text{M}'}$

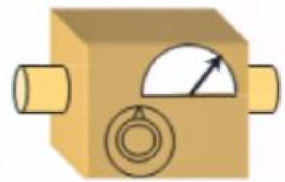
$$A \to A' = U^\dagger A U$$

$$A' = \sum_k a_k P'_k$$

$$\text{Pr}(k|\text{P}, \text{M}) = \langle\psi| P'_k |\psi\rangle = \langle\psi| U^\dagger P_k U |\psi\rangle$$

Operational Quantum Mechanics





Preparation

P

Measurement

M

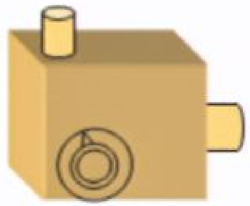
Effective preparation

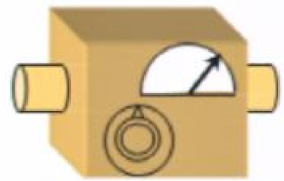
P_k

Update map

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

Operational Quantum Mechanics





Preparation Measurement

$$\underbrace{\mathsf{P} \qquad\qquad\qquad \mathsf{M}}$$

Effective preparation

P_k

Update map

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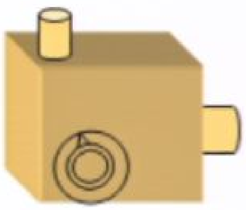
Operational Quantum Mechanics



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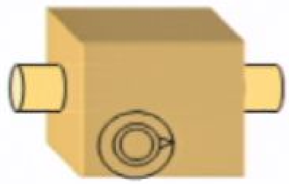

Transformation

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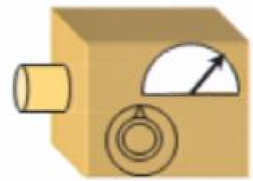


Measurement

M

Density operator

ρ

Trace-preserving completely positive linear map (CP map)

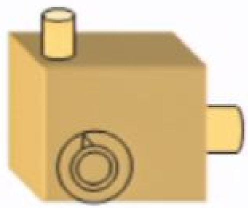
$\mathcal{T}$

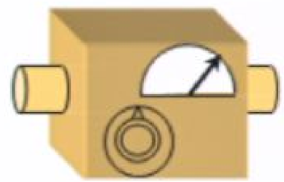
Positive operator-valued measure (POVM)

$\{E_k\}$

$$\boxed{Pr(k|\mathsf{P},\mathsf{T},\mathsf{M}) = \mathrm{Tr}[E_k \mathcal{T}(\rho)]}$$

Operational Quantum Mechanics





$$\underbrace{\text{Preparation } \mathsf{P} \qquad\qquad \text{Measurement } \mathsf{M}}_{\text{Effective preparation } \mathsf{P}_k}$$

Update map

$$\rho \to \rho_k = \frac{\mathcal{T}_k(\rho)}{\mathrm{Tr}[\mathcal{T}_k(\rho)]}$$

Trace-decreasing completely positive linear map

Operational postulates of quantum theory

Every preparation P is associated with a density operator ρ

Every measurement M is associated with a positive operator-valued measure $\{E_k\}$. The probability of M yielding outcome k given a preparation P is $p_k = \mathrm{Tr}(E_k \rho)$.

Every transformation is associated with a trace-preserving completely-positive linear map $\rho \rightarrow \rho' = T(\rho)$,

Every measurement outcome k is associated with a trace-nonincreasing completely-positive linear map T_k such that $\rho \rightarrow \rho_k = T_k(\rho)/\mathrm{Tr}[T_k(\rho)]$.

No mention of "physical states" or their evolution

Is the operational interpretation satisfactory?

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Inconsistencies of the orthodox interpretation

By the collapse postulate (applied to the system)	By unitary evolution postulate (applied to isolated system that includes the apparatus)
Indeterministic and discontinuous evolution	Deterministic and continuous evolution
Determinate properties	Indeterminate properties

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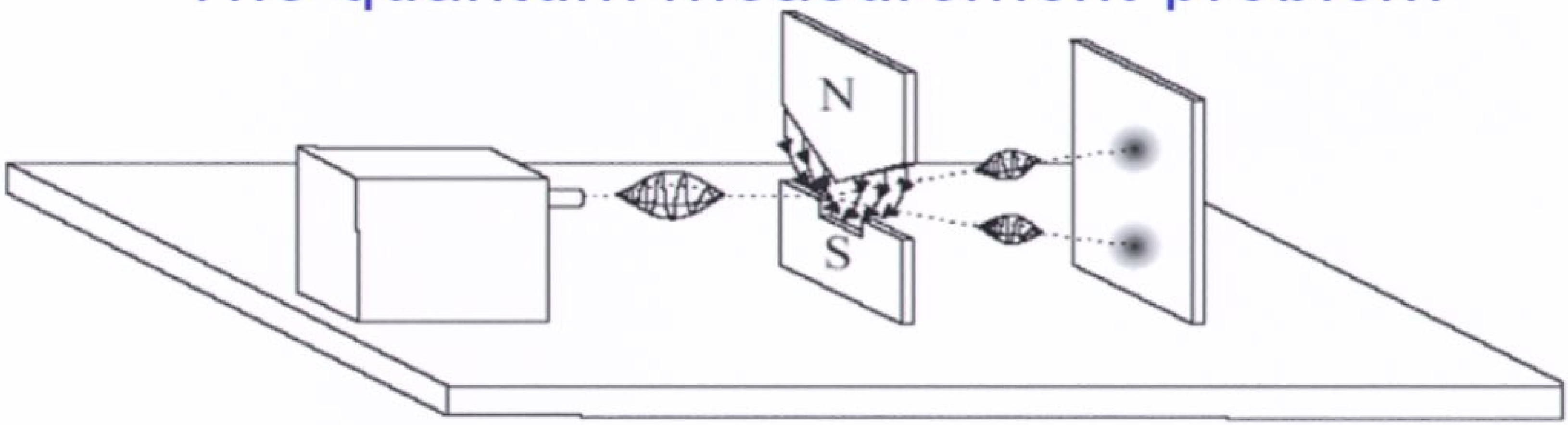
The quantum measurement problem



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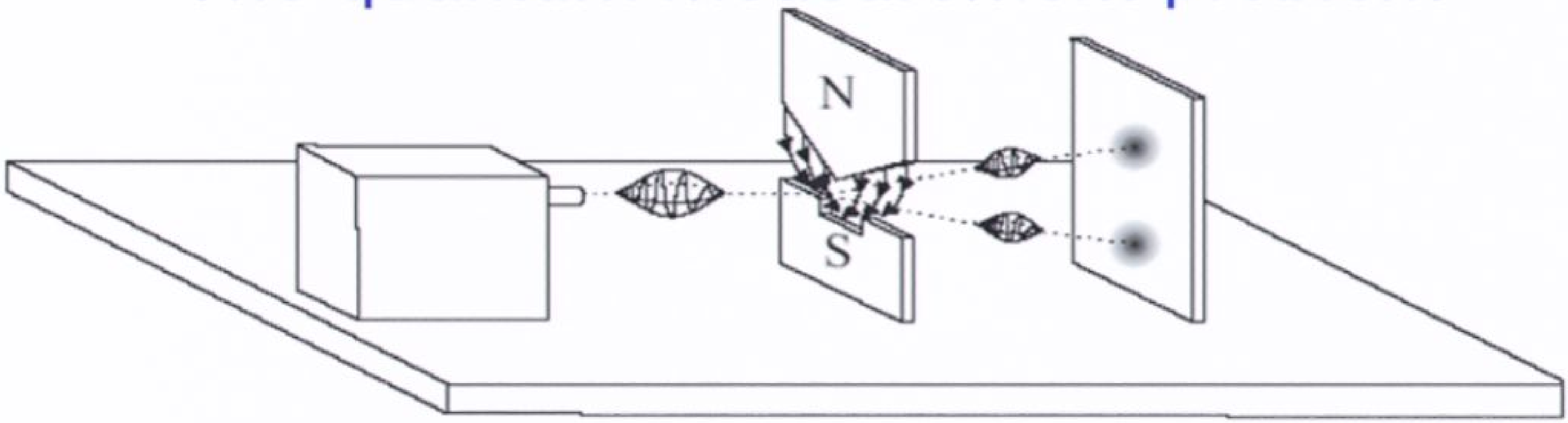
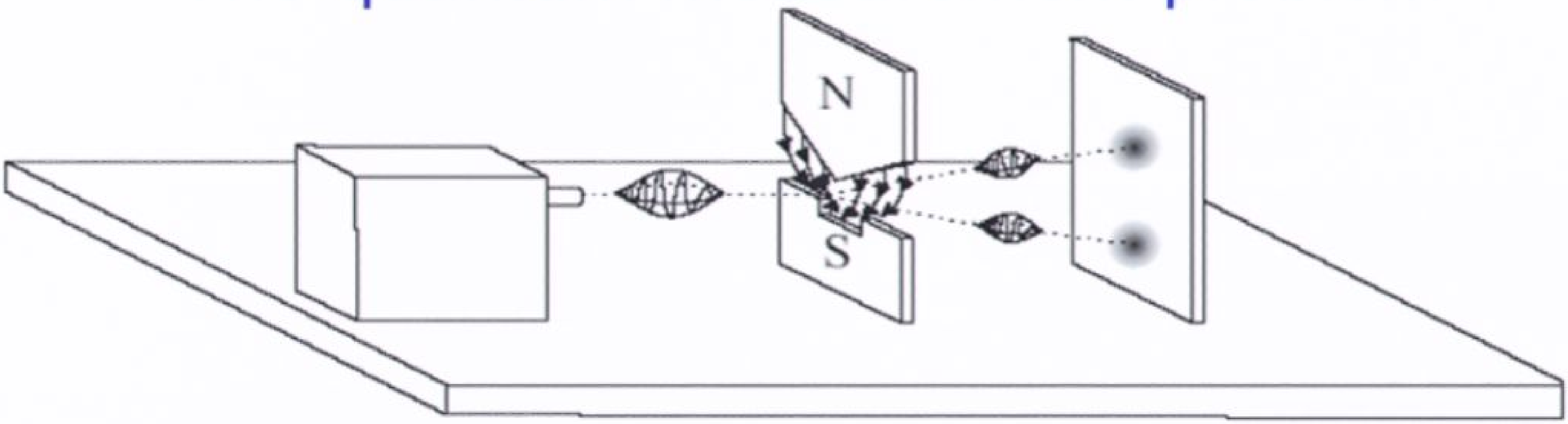


If the measurement apparatus is treated externally

$$a|\uparrow\rangle + b|\downarrow\rangle \;\to |\uparrow\rangle \text{ with probability } |a|^2$$
$$\to |\downarrow\rangle \text{ with probability } |b|^2$$

The quantum measurement problem



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If the measurement apparatus is treated internally

$$|\uparrow\rangle \otimes |\text{“ready”}\rangle \quad \rightarrow U(|\uparrow\rangle \otimes |\text{“ready”}\rangle) = |\uparrow\rangle \otimes |\text{“up”}\rangle$$
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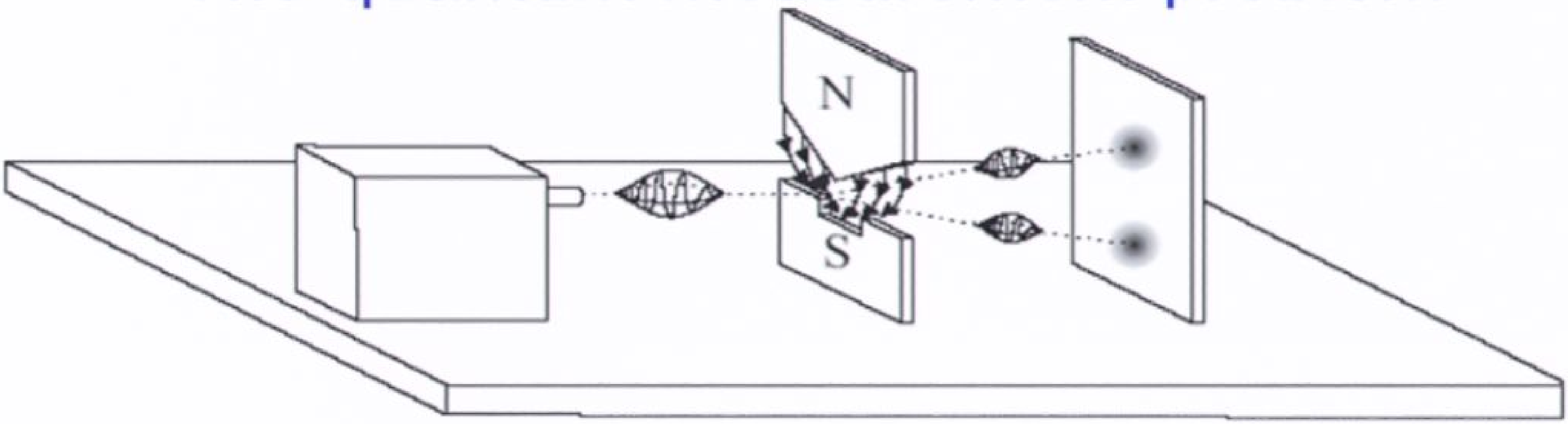
The quantum measurement problem



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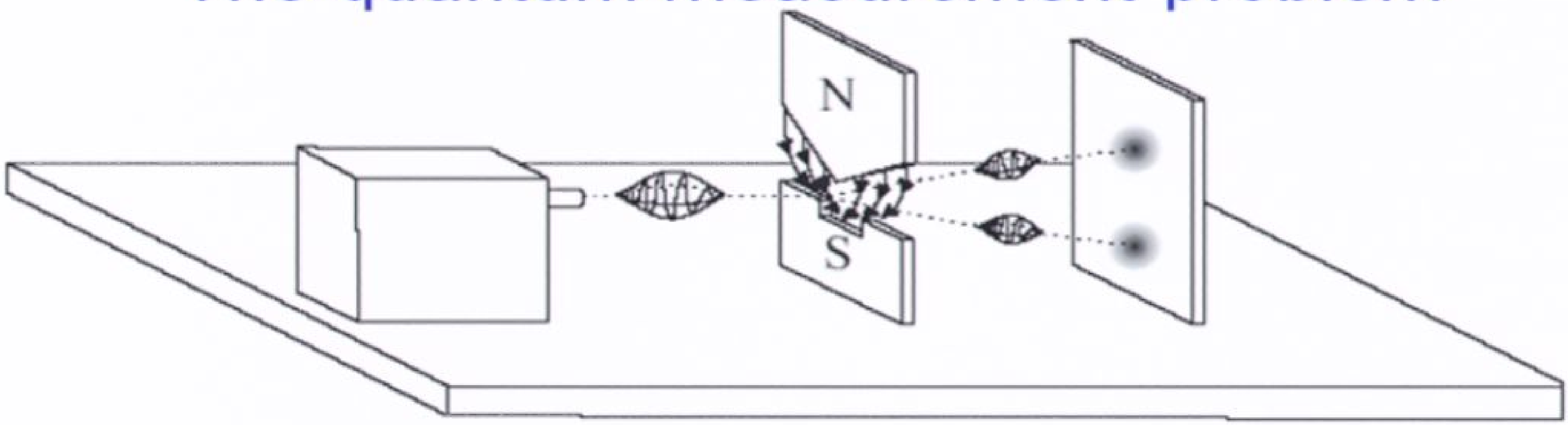

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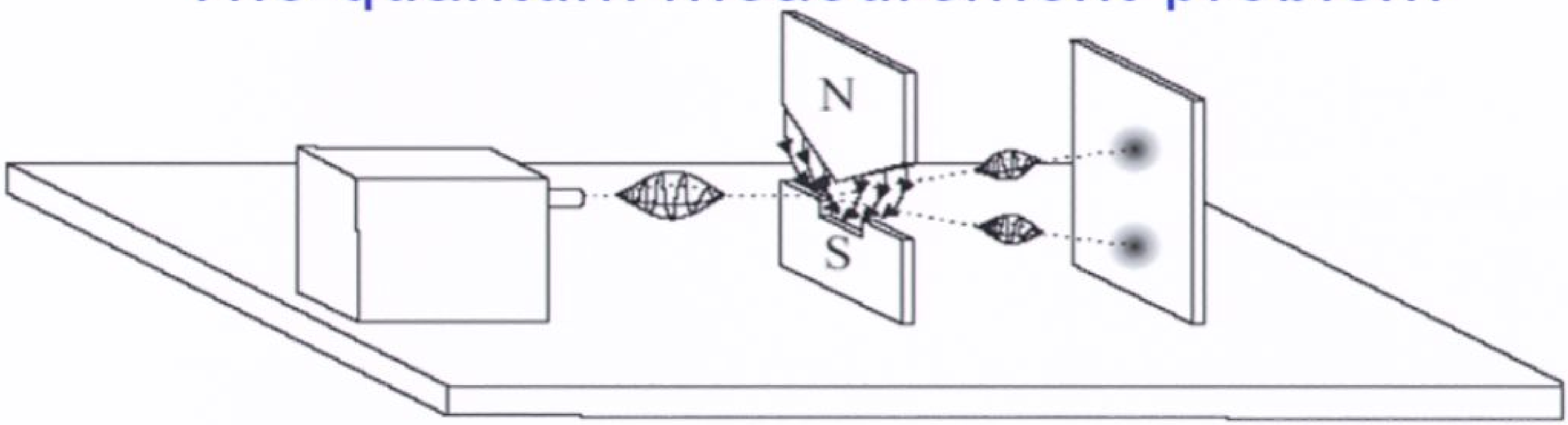
U is a linear operator $\quad U(a|\psi\rangle + b|\phi\rangle) = aU|\psi\rangle + bU|\phi\rangle$

The quantum measurement problem



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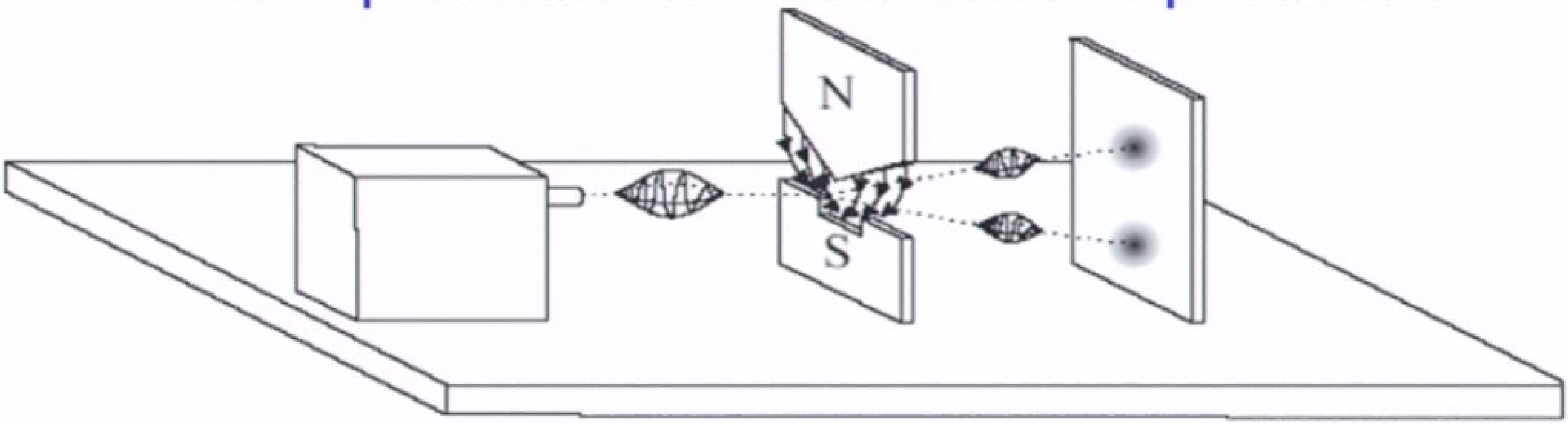

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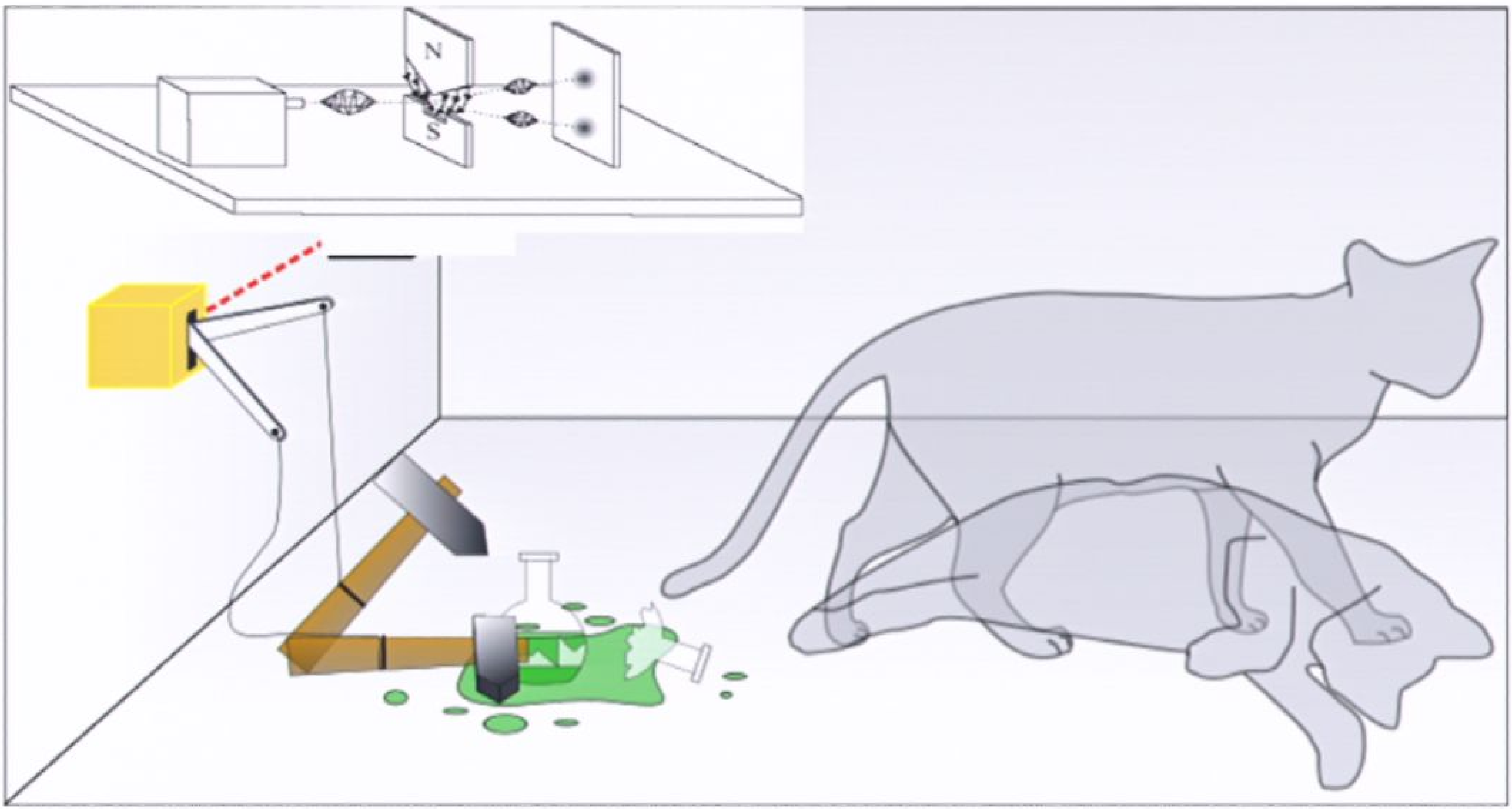
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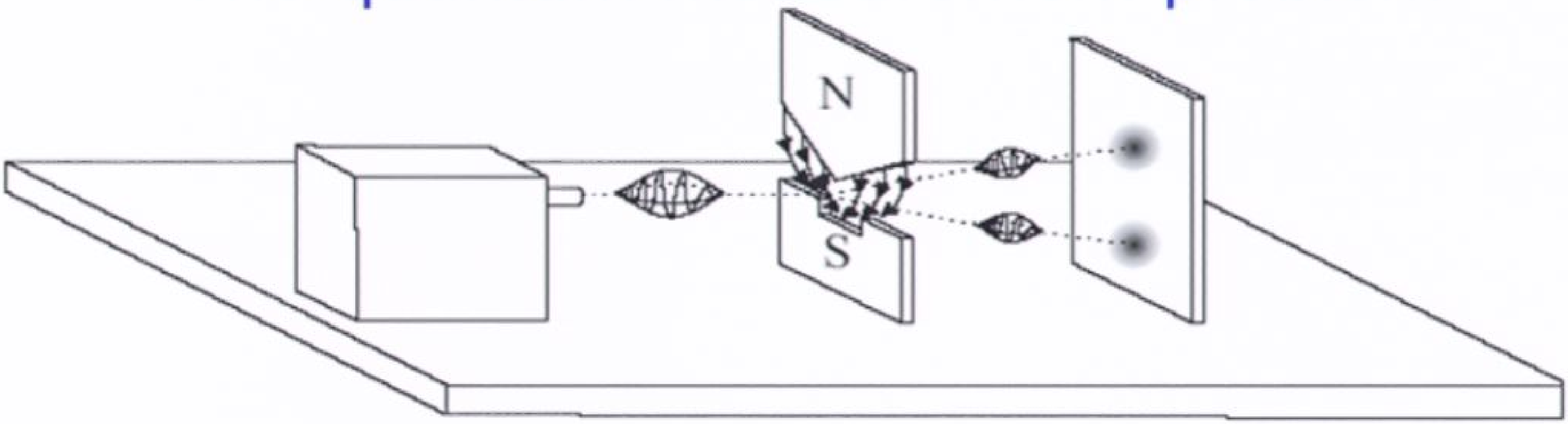

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False starts on the measurement problem

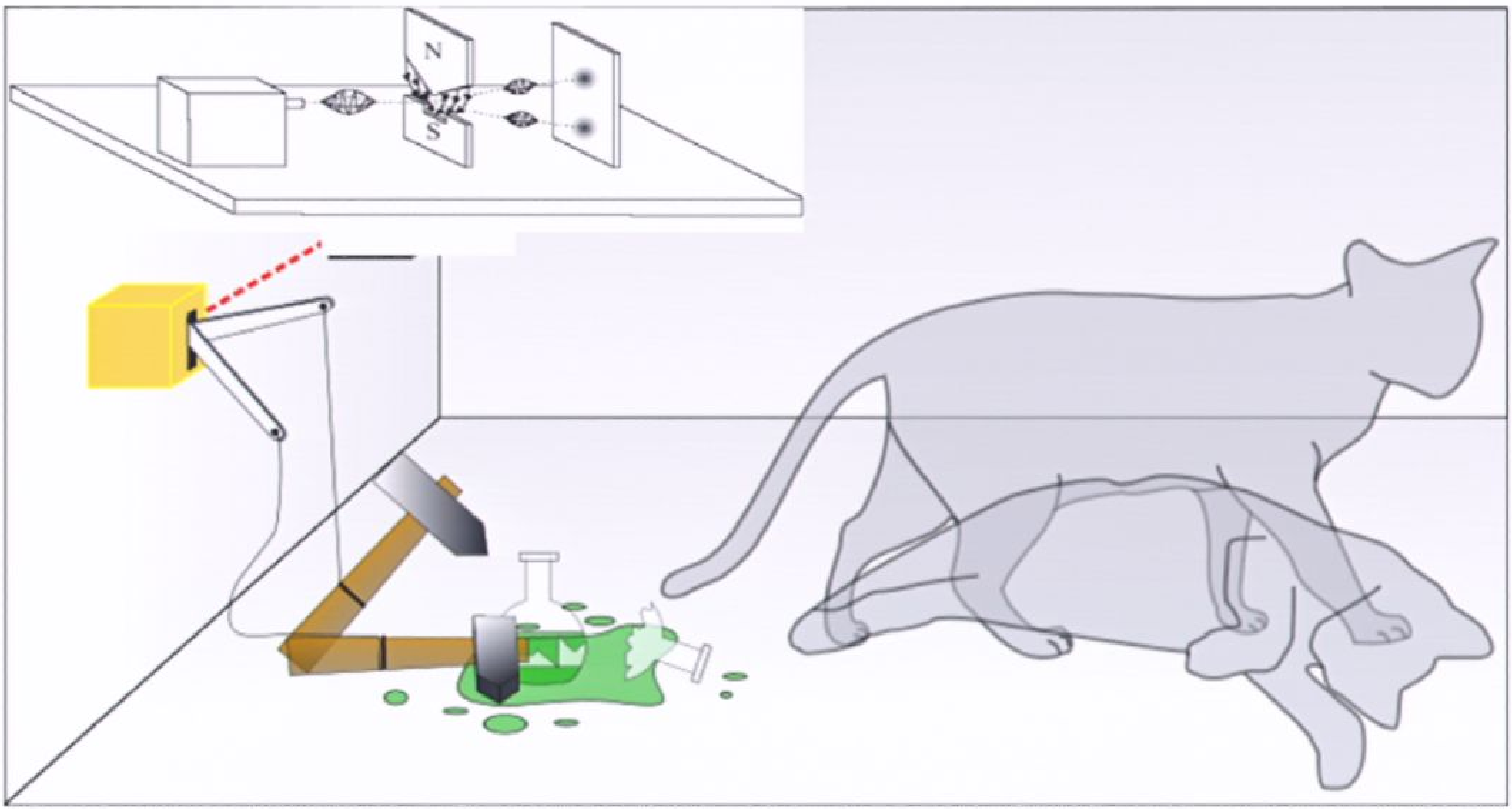
- Interpret coherent superposition as disjunction

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

Means either $|\uparrow\rangle \otimes |\text{“up”}\rangle$

or $|\downarrow\rangle \otimes |\text{“down”}\rangle$

with probabilities $|a|^2$ and $|b|^2$ respectively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This is a denial of the representational completeness of ψ

False starts on the measurement problem

- Interpret the reduced density operator as a proper mixture

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

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

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And by linearity

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The postulated evolution does not correspond to a proper measurement

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5. Deny some other feature of the realist framework?