Title: PSI 17/18 - Foundations of Quantum Mechanics - Lecture 5

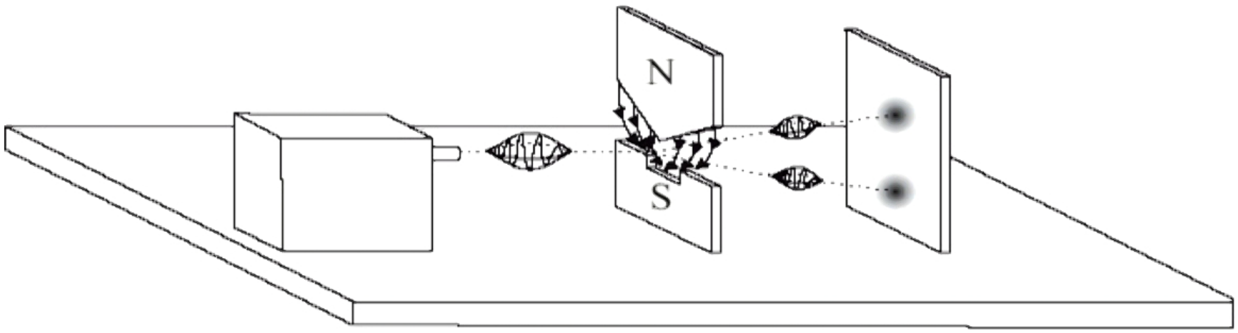
Date: Feb 02, 2018 10:15 AM

URL: http://pirsa.org/18020064

Abstract:

Dynamical Collapse Theories

The quantum measurement problem



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

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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Posit a new nonunitary dynamical evolution law
(either nonlinear or indeterministic or both)

Macroscopic systems obey collapse postulate dynamics to good approximation

Microscopic systems obey unitary dynamics to good approximation

Responses to the measurement problem

1. Deny realism
   - Purely operational account of quantum theory
2. Deny the universality of unitary dynamics
   - Dynamical collapse theories
3. Deny that ψ is a complete representation of reality
   - Hidden variable models
   - Models of reality beyond hidden variables?
4. Deny indeterminism and discontinuity, except as subjective illusions
   - Everett's relative state interpretation, or "many worlds"

Linear indeterministic models

The goal:

$$(a|\uparrow\rangle + b|\downarrow\rangle)|\text{“ready”}\rangle \;\rightarrow\; |\uparrow\rangle|\text{“up”}\rangle \quad \text{with probability} \quad |a|^2$$

$$\rightarrow\; |\downarrow\rangle|\text{“down”}\rangle \quad \text{with probability} \quad |b|^2$$

The preferred decomposition issue

Into what states do collapses occur?

Linear indeterministic models

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The preferred decomposition issue

Into what states do collapses occur?

$$\left(a|+\rangle + b|-\rangle\right)|O_0\rangle \rightarrow a|+\rangle|O_+\rangle + b|-\rangle|O_-\rangle$$

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

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

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Into what states do collapses occur?

A: Choose a collapse mechanism that tends to localize in space

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When and how do collapses occur?

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The preferred decomposition issue

Into what states do collapses occur?

A: Choose a collapse mechanism that tends to localize in space

The trigger issue

When and how do collapses occur?

A: Postulate collapse as a new primitive physical mechanism

The Ghirardi-Rimini-Weber model

At most times:

$$i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle = H|\psi(t)\rangle$$ Schrödinger's equation

Every τ/N time interval on average

$$|\psi(t+dt)\rangle = \frac{1}{\sqrt{p(\mathbf{q}_k)}}\sqrt{E^{(k)}(\mathbf{q}_k)}|\psi(t)\rangle$$ "Collapse"

where $$E^{(k)}(\mathbf{q}_k) = \int d\mathbf{r}_k\ K\exp\left(-\frac{(\mathbf{r}_k-\mathbf{q}_k)^2}{\sigma^2}\right)|\mathbf{r}_k\rangle\langle\mathbf{r}_k|$$

$$p(\mathbf{q}_k) = \langle\psi(t)|E^{(k)}(\mathbf{q}_k)|\psi(t)\rangle$$

k is chosen uniformly at random

$\mathbf{q}_k$ is chosen by sampling from $p(\mathbf{q}_k)$

Two new fundamental constants:

$\tau \approx 10^{15}\mathrm{s} \approx 100\ \text{million years}$ mean time between collapses for one particle

$\sigma \approx 10^{-7}\mathrm{m} \approx \text{size of large molecule}$ Localization width

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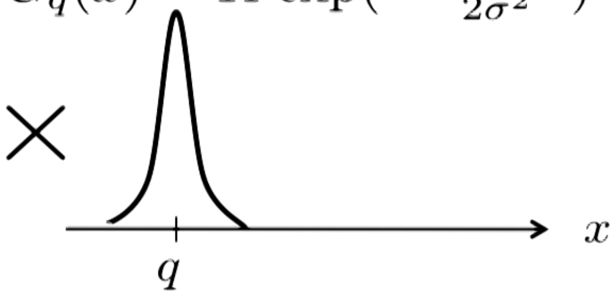
Single particle in 1D

$$\psi(x) = \frac{\sqrt{3}}{2}\phi_a(x) + \frac{1}{2}\phi_b(x)$$

$$G_q(x) = K\exp(-\tfrac{(x-q)^2}{2\sigma^2})$$



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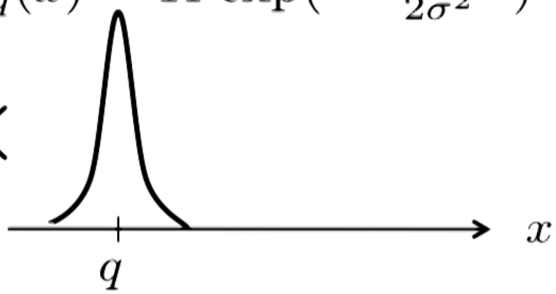

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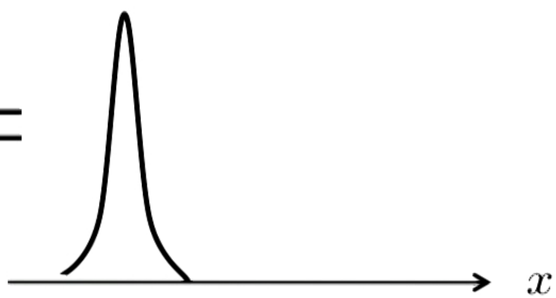

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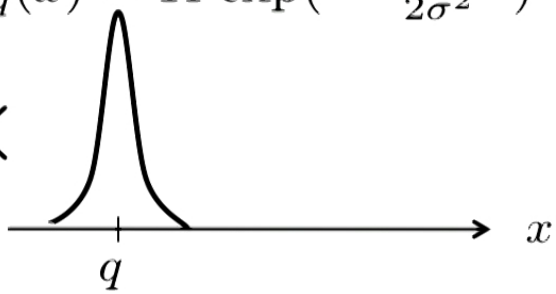

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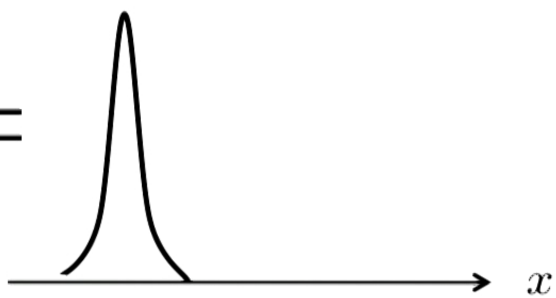

Two particles in 1D

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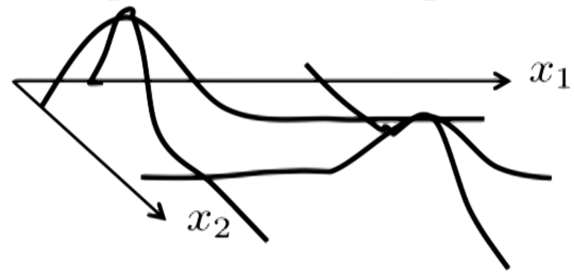

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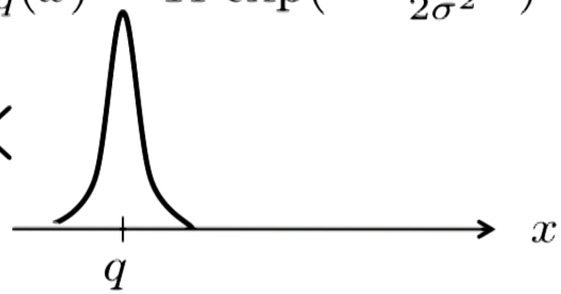

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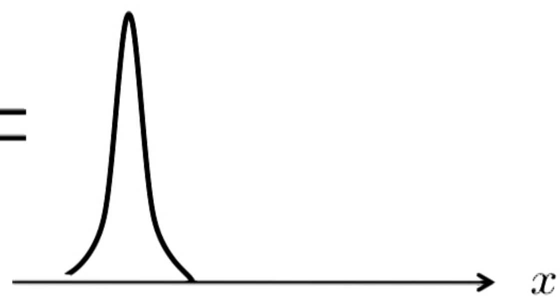

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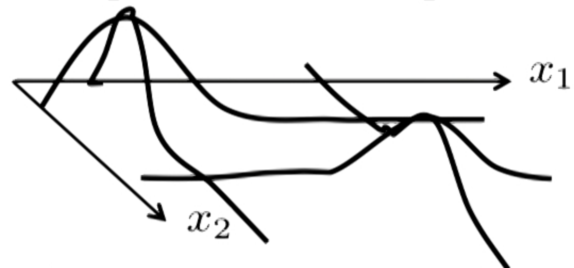

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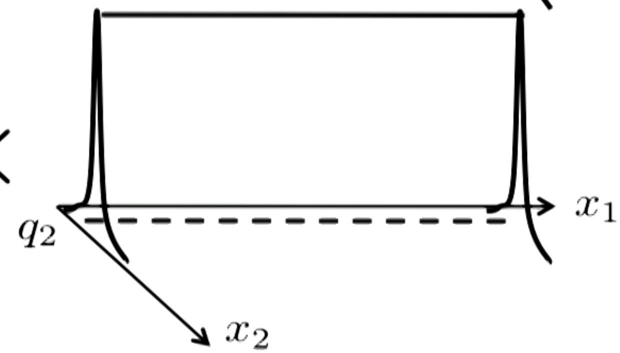

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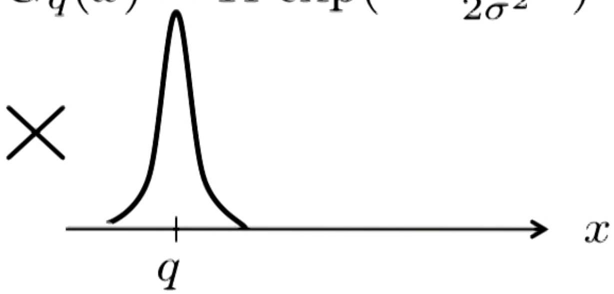

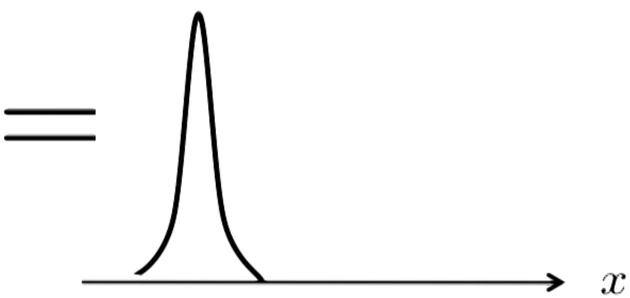

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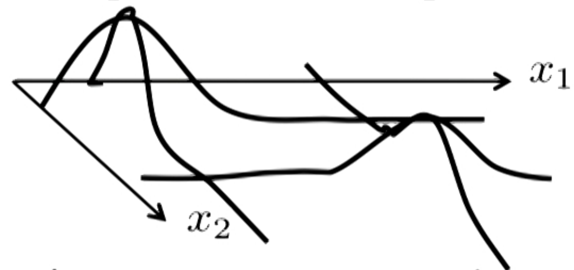

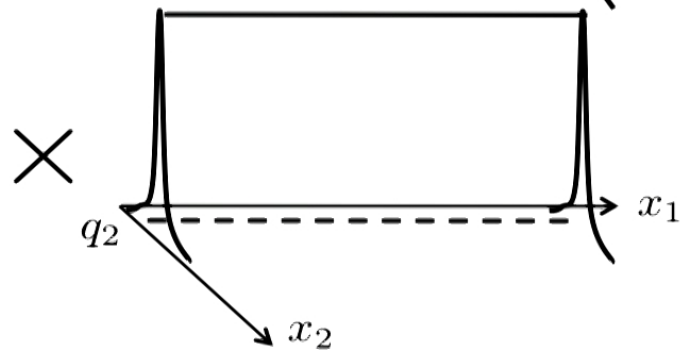

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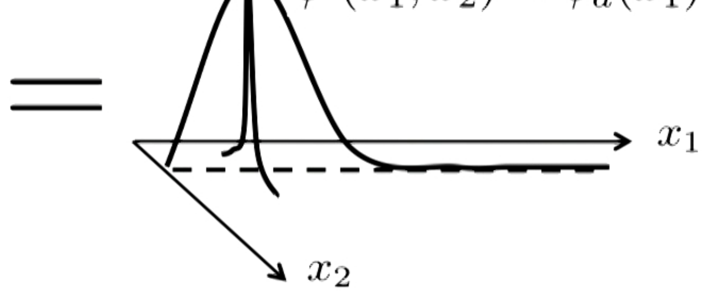

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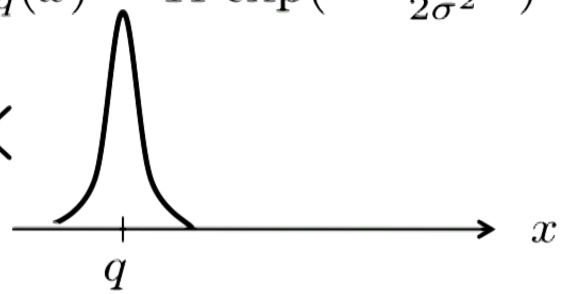

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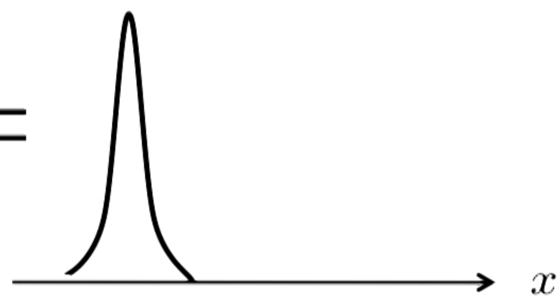

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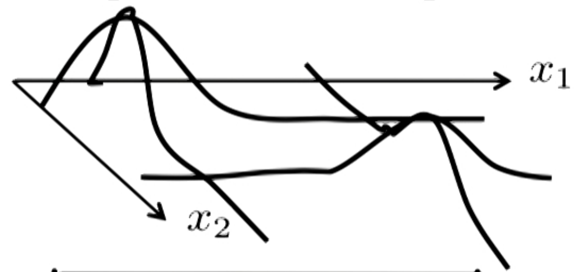

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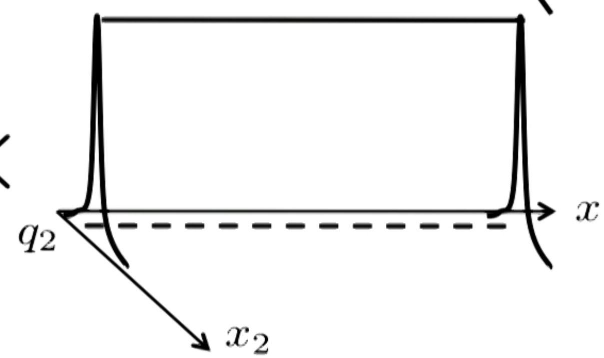

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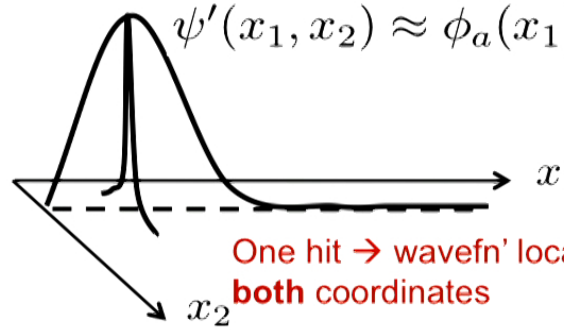
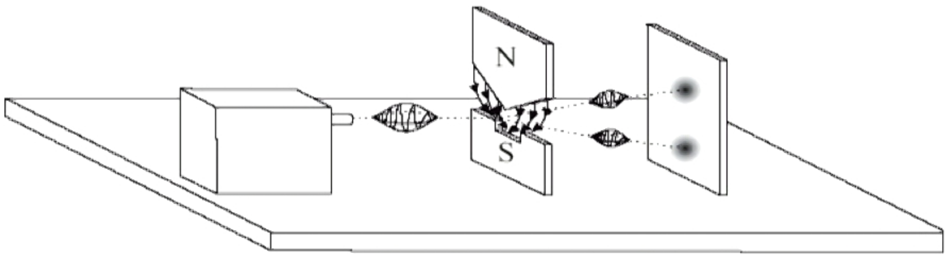
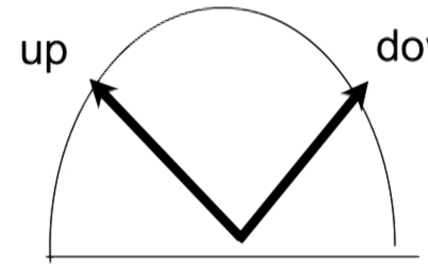


One hit → wavefn' localized in **both** coordinates



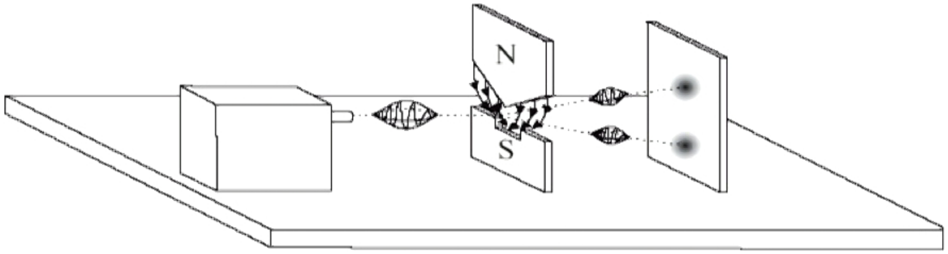


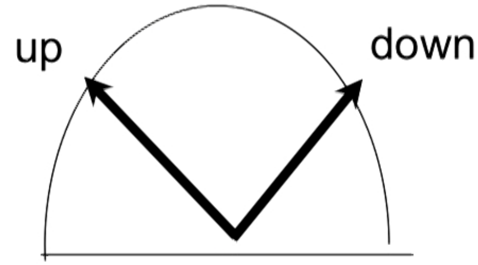
$$(a|\uparrow\rangle + b|\downarrow\rangle)|\text{“ready”}\rangle \;\rightarrow a|\uparrow\rangle|\text{“up”}\rangle + b|\downarrow\rangle|\text{“down”}\rangle$$

$$|\psi\rangle = a\,|+\rangle|O_+\rangle + b\,|-\rangle|O_-\rangle$$

Suppose that for macroscopic # of components k, $|\langle O_+|\mathbf{r}_k\rangle|^2|\langle O_-|\mathbf{r}_k\rangle|^2 \approx 0$

One particle is hit → wavefn' is localized in all coordinates





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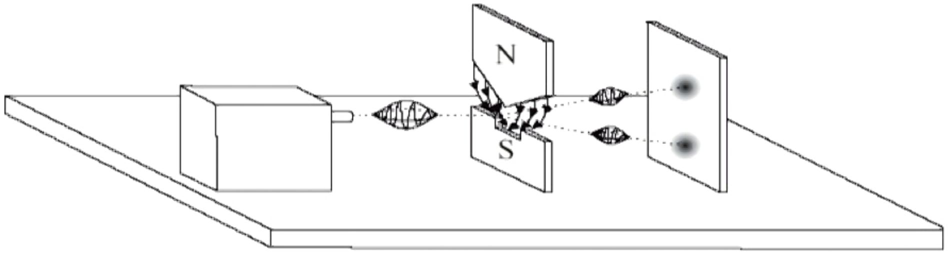

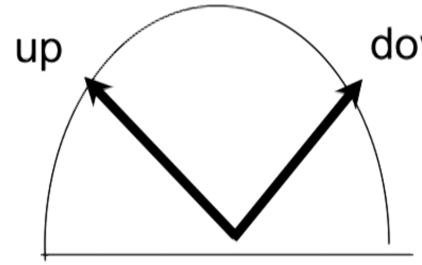

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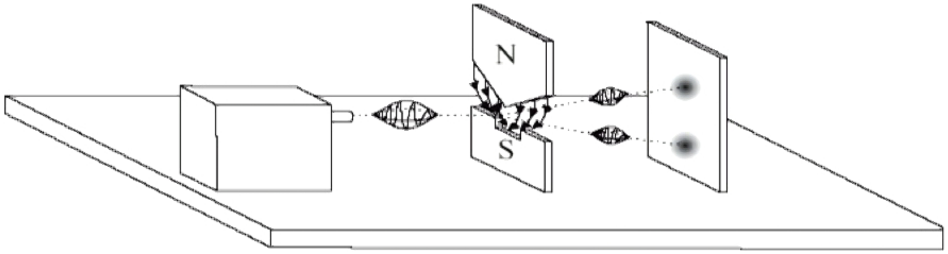
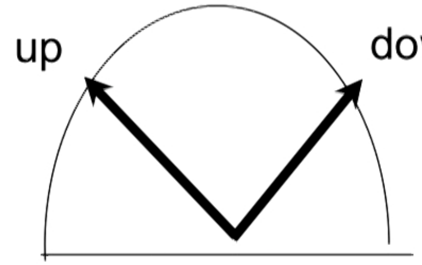
If apparatus contains $\approx 10^{20}$ particles

This happens every $\dfrac{10^{15}\mathrm{s}}{10^{20}} \approx 10^{-5}\mathrm{s}$





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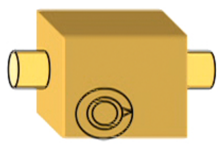
The apparatus gets determinate properties
And we recover the collapse postulate

Criticisms

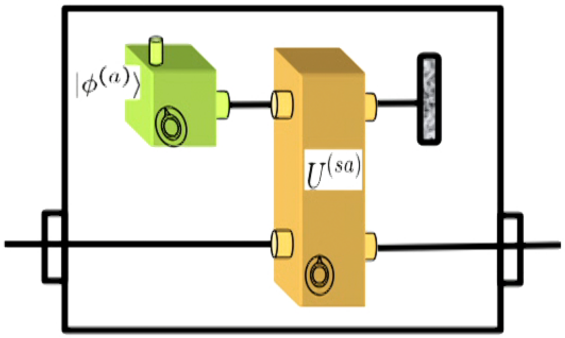
Any anomolous decoherence is also consistent with unitary coupling to novel degrees of freedom

$$\rho \to \sum_k \int \mathrm{d}q_k \sqrt{E^{(k)}(\mathbf{q}_k)}\, \rho \sqrt{E^{(k)}(\mathbf{q}_k)}$$



Trace-preserving completely positive linear map (CP map)

$\mathcal{T}$



Stinespring dilation

$|\phi^{(a)}\rangle, U^{(sa)}$

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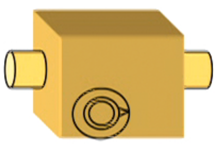

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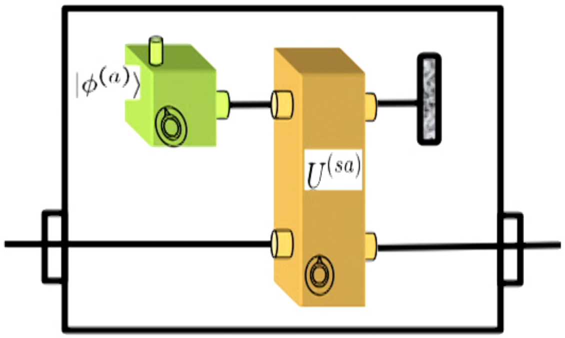


Stinespring dilation

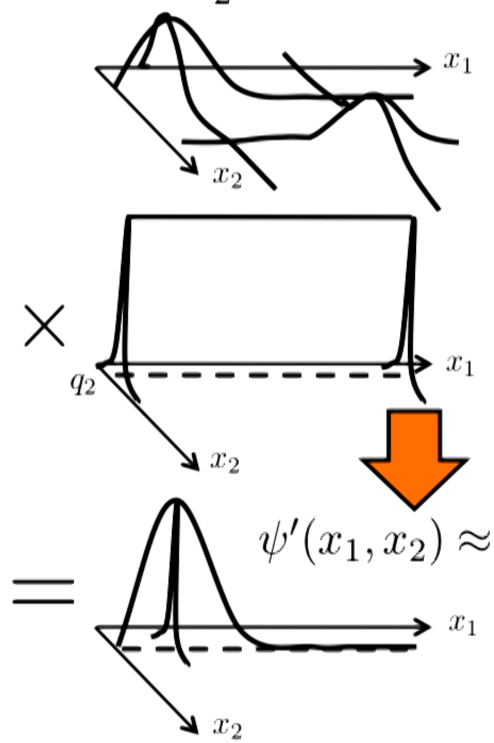
$|\phi^{(a)}\rangle, U^{(sa)}$

The "smoking gun" experimental signature of dynamical collapse does not rule decisively in its favour

Criticisms

How localized is localized enough? The “tails” problem.

$$\psi(x_1, x_2) = \frac{\sqrt{3}}{2}\phi_a(x_1)\chi_a(x_2) + \frac{1}{2}\phi_b(x_1)\chi_b(x_2)$$



$$\psi'(x_1, x_2) \approx \phi_a(x_1)\chi'_a(x_2)$$

Criticisms

Failure of energy conservation

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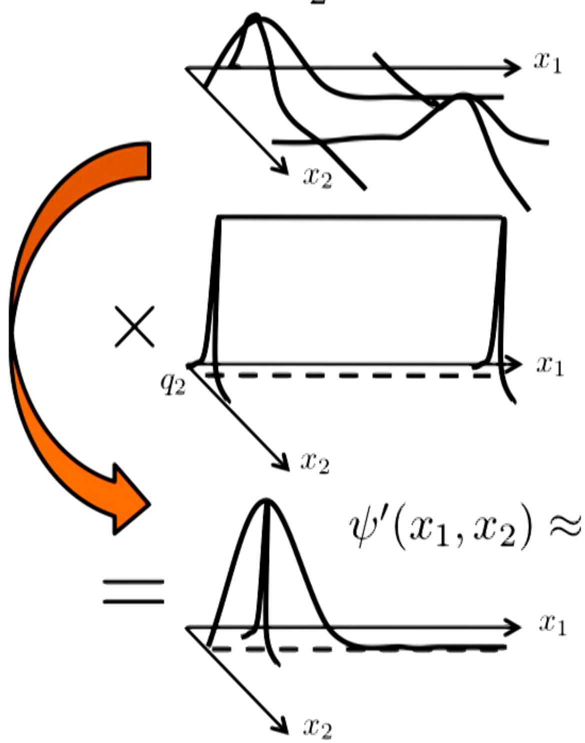

$$\psi'(x_1, x_2) \approx \phi_a(x_1)\chi'_a(x_2)$$

Criticisms

The fact that a hit on one system leads to an approximate localization of a distant system is a failure of local causality and of Lorentz invariance

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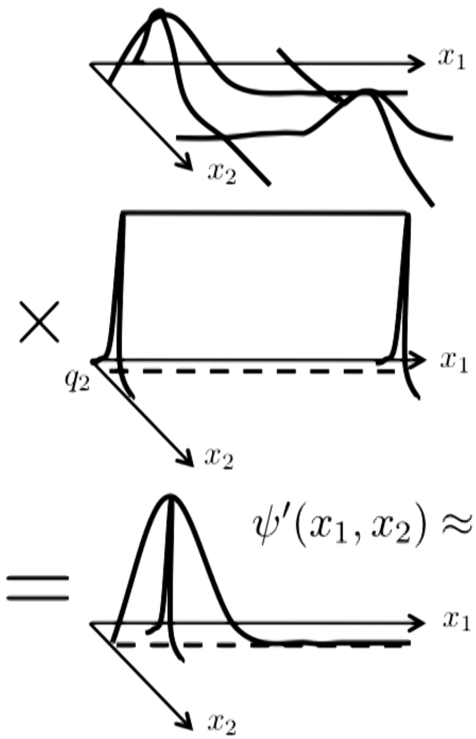

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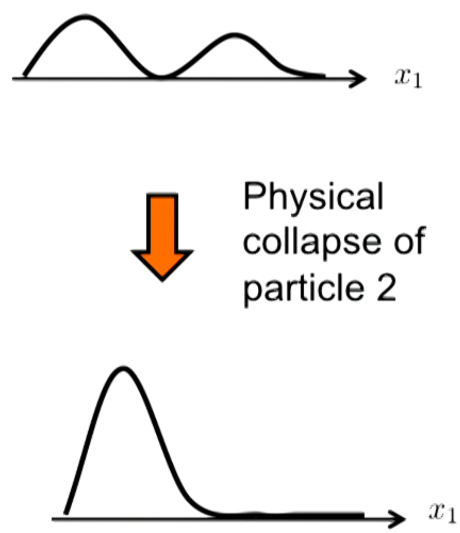
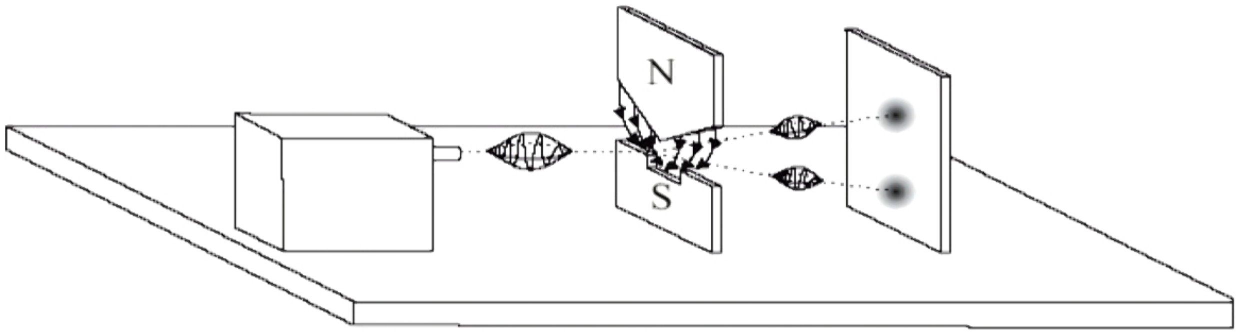


The Everett interpretation
“Many Worlds”

Hugh Everett, III
(1930-1982)

The quantum measurement problem



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

Inconsistencies of the orthodox interpretation

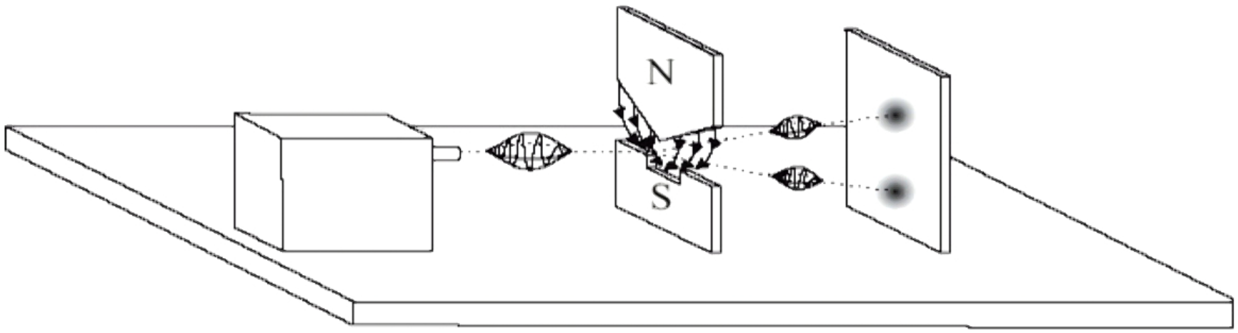
By the collapse postulate (applied to the system)	By unitary evolution postulate (applied to isolated system that includes the apparatus)
Indeterministic and discontinuous evolution	Deterministic and continuous evolution
Determinate properties	Indeterminate properties

Subjective illusion

Responses to the measurement problem

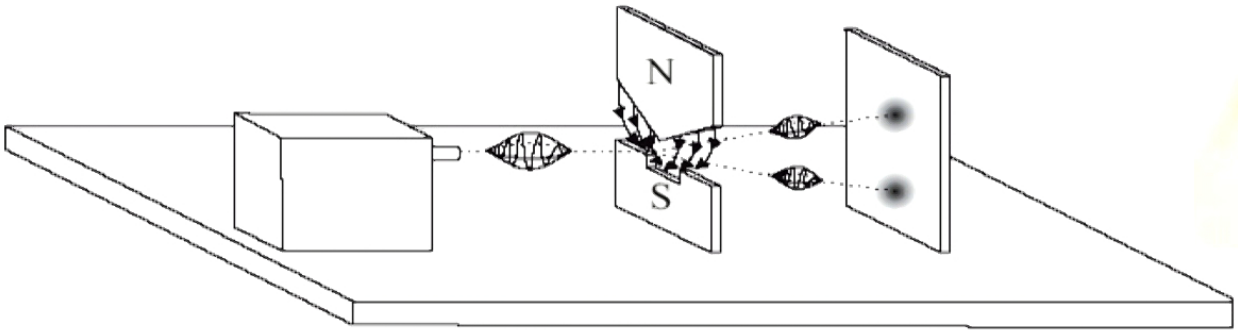
1. Deny realism
   - Purely operational account of quantum theory
2. Deny the universality of unitary dynamics
   - Dynamical collapse theories
3. Deny that ψ is a complete representation of reality
   - Hidden variable models
   - Models of reality beyond hidden variables?
4. Deny indeterminism and discontinuity, except as subjective illusions
   - Everett's relative state interpretation, or "many worlds"

Quantum measurement



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

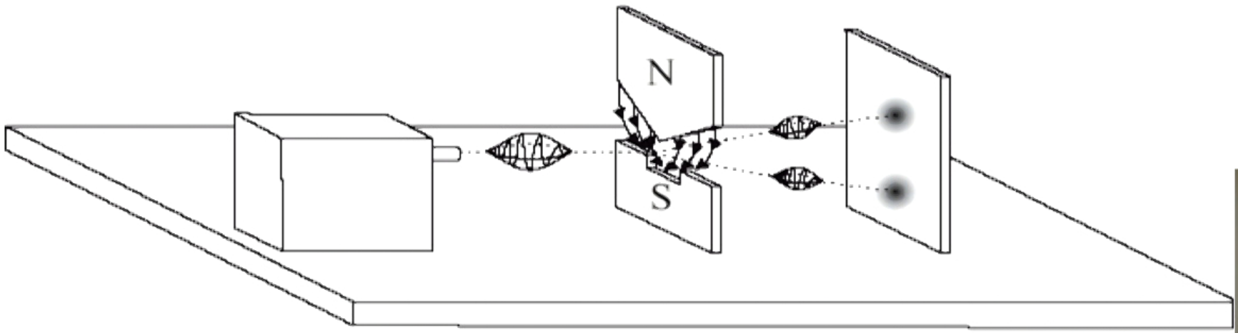
Quantum measurement with observer

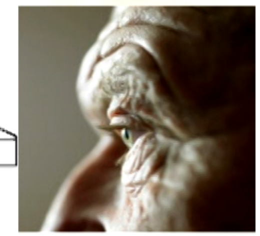


$$(a|\uparrow\rangle + b|\downarrow\rangle)|\text{“ready”}\rangle|\text{“ready to observe”}\rangle$$

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

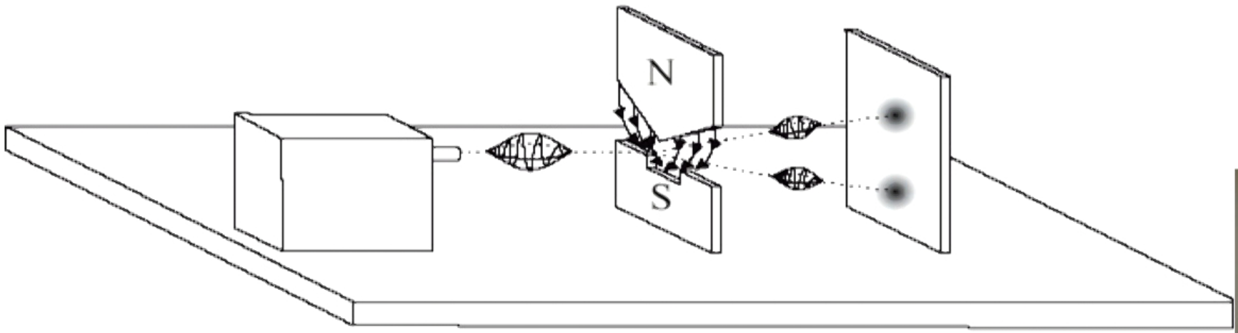
Quantum measurement with many observers

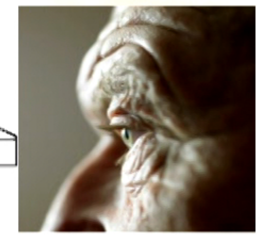




$$(a|\uparrow\rangle+b|\downarrow\rangle)|\text{“ready”}\rangle|\text{“ready to observe”}\rangle|\text{“ready to observe”}\rangle$$

Quantum measurement with many observers

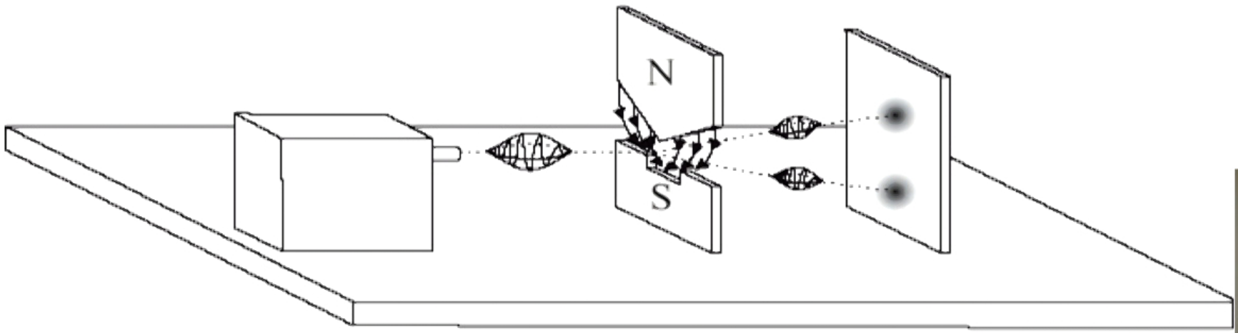


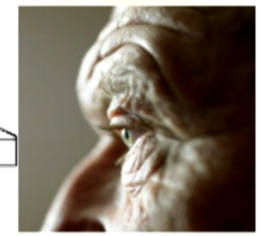


$$(a|\uparrow\rangle + b|\downarrow\rangle)|\text{“ready”}\rangle|\text{“ready to observe”}\rangle|\text{“ready to observe”}\rangle$$

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

Quantum measurement with many observers



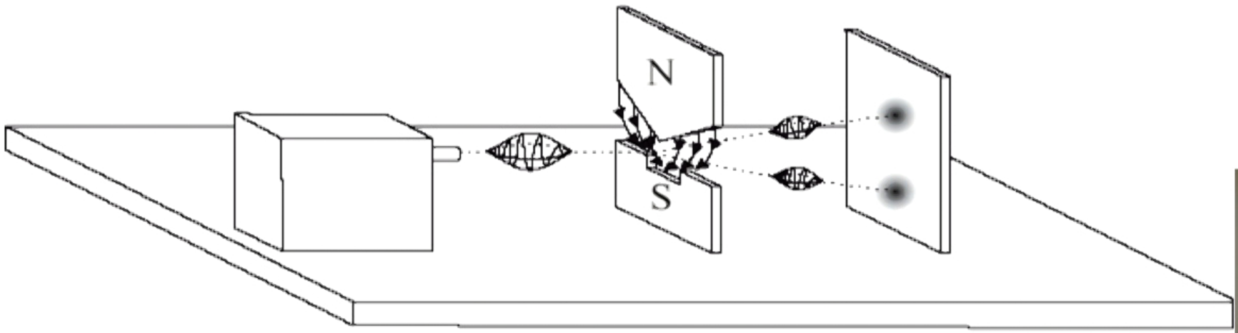


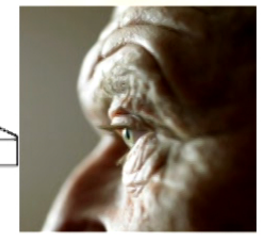
$$(a|\uparrow\rangle + b|\downarrow\rangle)|\text{“ready”}\rangle|\text{“ready to observe”}\rangle|\text{“ready to observe”}\rangle$$

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

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

Quantum measurement with many observers





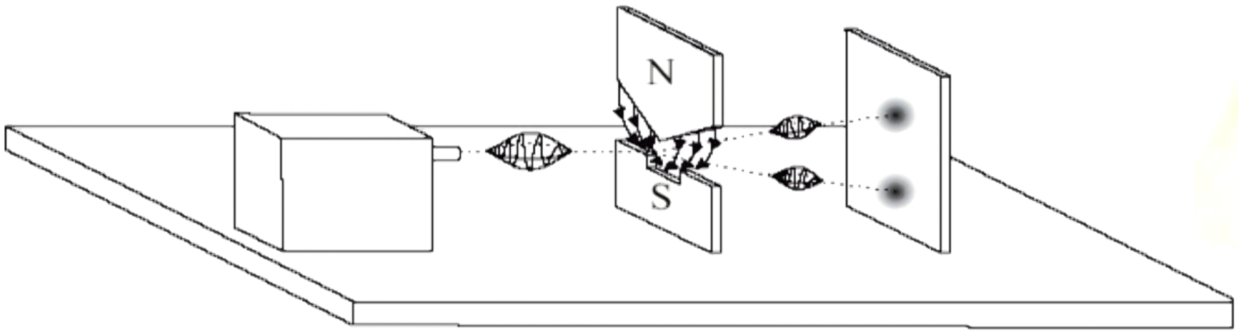
$$(a|\uparrow\rangle + b|\downarrow\rangle)|\text{“ready”}\rangle|\text{“ready to observe”}\rangle|\text{“ready to observe”}\rangle$$

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

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

There is intersubjective agreement about the outcome

Quantum measurement with observer



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

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

again rewrite as

$$\big(a|+\rangle + b|-\rangle\big)|O_0\rangle \;\rightarrow\; a|+\rangle|O_+\rangle + b|-\rangle|O_-\rangle$$

Preferred basis problem

$$\left(a\left|+\right\rangle + b\left|-\right\rangle\right)\left|O_0\right\rangle \quad \rightarrow \quad a\left|+\right\rangle\left|O_+\right\rangle + b\left|-\right\rangle\left|O_-\right\rangle$$

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

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

Adrian Kent: Everett needs a basis selection rule

Preferred basis problem

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

Preferred basis problem

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

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

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

Preferred basis problem

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

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

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

$$\left|O_{+}\right\rangle\left|E_{0}^{(2)}\right\rangle\rightarrow\left|O_{+}\right\rangle\left|E_{+}^{(2)}\right\rangle$$

Preferred basis problem

$$\big(a|+\rangle|O_+\rangle+b|-\rangle|O_-\rangle\big)|E_0\rangle \quad\rightarrow\quad a|+\rangle|O_+\rangle|E_+\rangle+b|-\rangle|O_-\rangle|E_-\rangle$$

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

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

$$|O_+\rangle|E_0^{(2)}\rangle\rightarrow|O_+\rangle|E_+^{(2)}\rangle$$

$$\left(\frac{|O_+\rangle+|O_-\rangle}{\sqrt{2}}\right)|E_0^{(2)}\rangle\rightarrow\left(\frac{|O_+\rangle|E_+^{(2)}\rangle+|O_-\rangle|E_-^{(2)}\rangle}{\sqrt{2}}\right)$$

$$=\frac{1}{\sqrt{2}}\left(\frac{|O_+\rangle+|O_-\rangle}{\sqrt{2}}\right)\left(\frac{|E_+^{(2)}\rangle+|E_-^{(2)}\rangle}{\sqrt{2}}\right)+\frac{1}{\sqrt{2}}\left(\frac{|O_+\rangle-|O_-\rangle}{\sqrt{2}}\right)\left(\frac{|E_+^{(2)}\rangle-|E_-^{(2)}\rangle}{\sqrt{2}}\right)$$

Preferred basis problem

$$\big(a|+\rangle|O_+\rangle + b|-\rangle|O_-\rangle\big)|E_0\rangle \;\rightarrow\; a|+\rangle|O_+\rangle|E_+\rangle + b|-\rangle|O_-\rangle|E_-\rangle$$

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

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

$$|O_+\rangle|E_0^{(2)}\rangle \rightarrow |O_+\rangle|E_+^{(2)}\rangle$$

Evolution in this basis is predictable

$$\left(\frac{|O_+\rangle + |O_-\rangle}{\sqrt{2}}\right)|E_0^{(2)}\rangle \rightarrow \left(\frac{|O_+\rangle|E_+^{(2)}\rangle + |O_-\rangle|E_-^{(2)}\rangle}{\sqrt{2}}\right)$$

$$= \frac{1}{\sqrt{2}}\left(\frac{|O_+\rangle + |O_-\rangle}{\sqrt{2}}\right)\left(\frac{|E_+^{(2)}\rangle + |E_-^{(2)}\rangle}{\sqrt{2}}\right) + \frac{1}{\sqrt{2}}\left(\frac{|O_+\rangle - |O_-\rangle}{\sqrt{2}}\right)\left(\frac{|E_+^{(2)}\rangle - |E_-^{(2)}\rangle}{\sqrt{2}}\right)$$

Evolution in this basis is unpredictable

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.

real, but not directly represented in the axioms

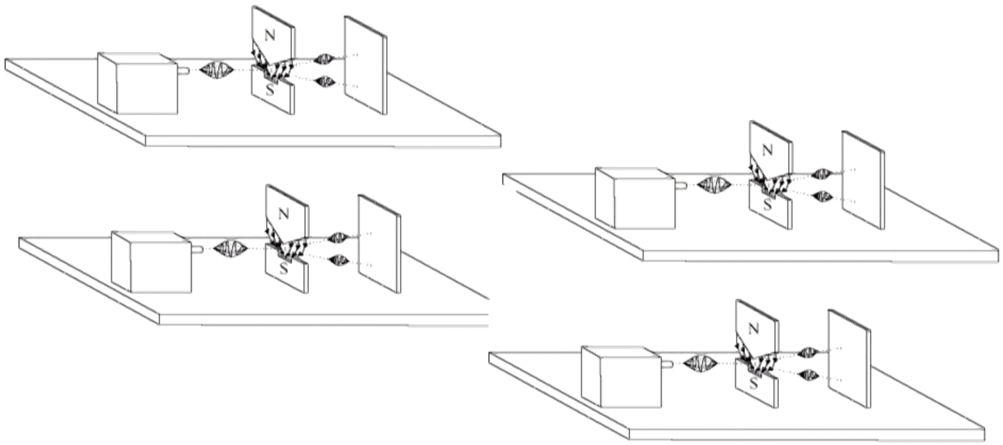
The basis picked out by decoherence admits of patterns that have explanatory and predictive power, such as tigers. Such patterns define the ontology.

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

The problem with probabilities

How can anything “be probability” in a deterministic theory where all possible outcomes occur? There are no propensities and there is nothing to be ignorant about.

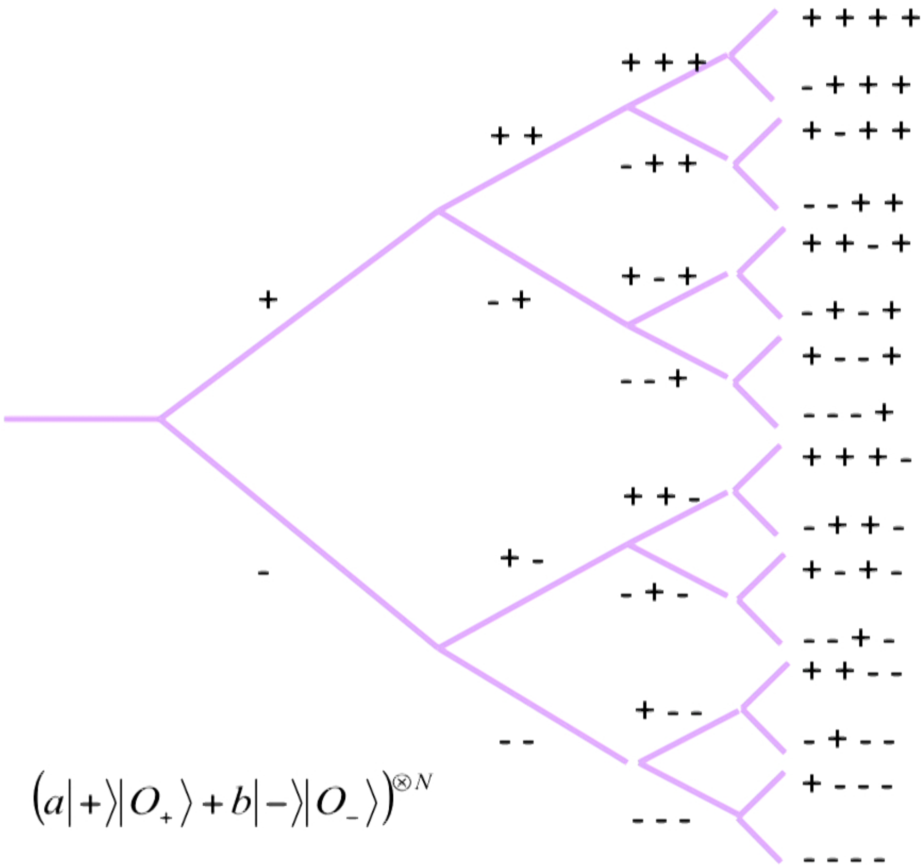
Sequence of measurements:



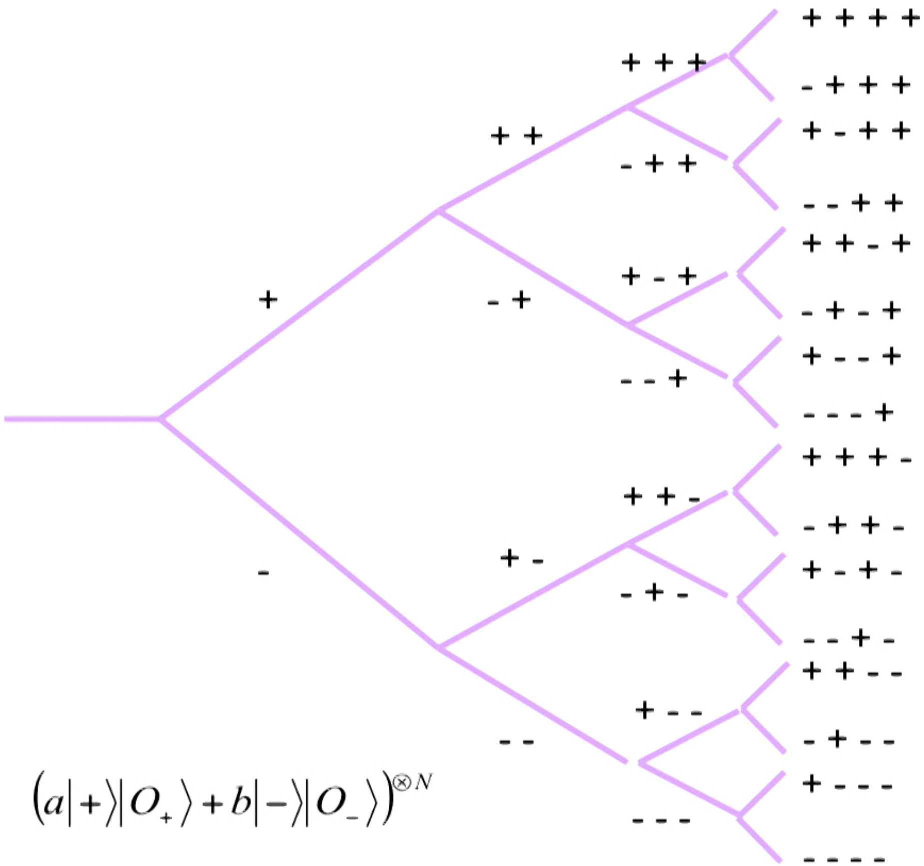
$$\left(a|+\rangle + b|-\rangle\right)^{IV}\left(a|+\rangle + b|-\rangle\right)^{III}\left(a|+\rangle + b|-\rangle\right)^{II}\left(a|+\rangle + b|-\rangle\right)^{I}\quad |O_0\rangle^{I}|O_0\rangle^{II}|O_0\rangle^{III}|O_0\rangle^{IV} \rightarrow$$

$$\left(a|+\rangle + b|-\rangle\right)^{IV}\left(a|+\rangle + b|-\rangle\right)^{III}\left(a|+\rangle + b|-\rangle\right)^{II}\left(a|+\rangle^{I}|O_+\rangle^{I} + b|-\rangle^{I}|O_-\rangle^{I}\right)\quad |O_0\rangle^{II}|O_0\rangle^{III}|O_0\rangle^{IV} \rightarrow$$

$$\ldots \qquad \left(a|+\rangle|0_+\rangle + b|-\rangle|O_-\rangle\right)^{\otimes 4}$$



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

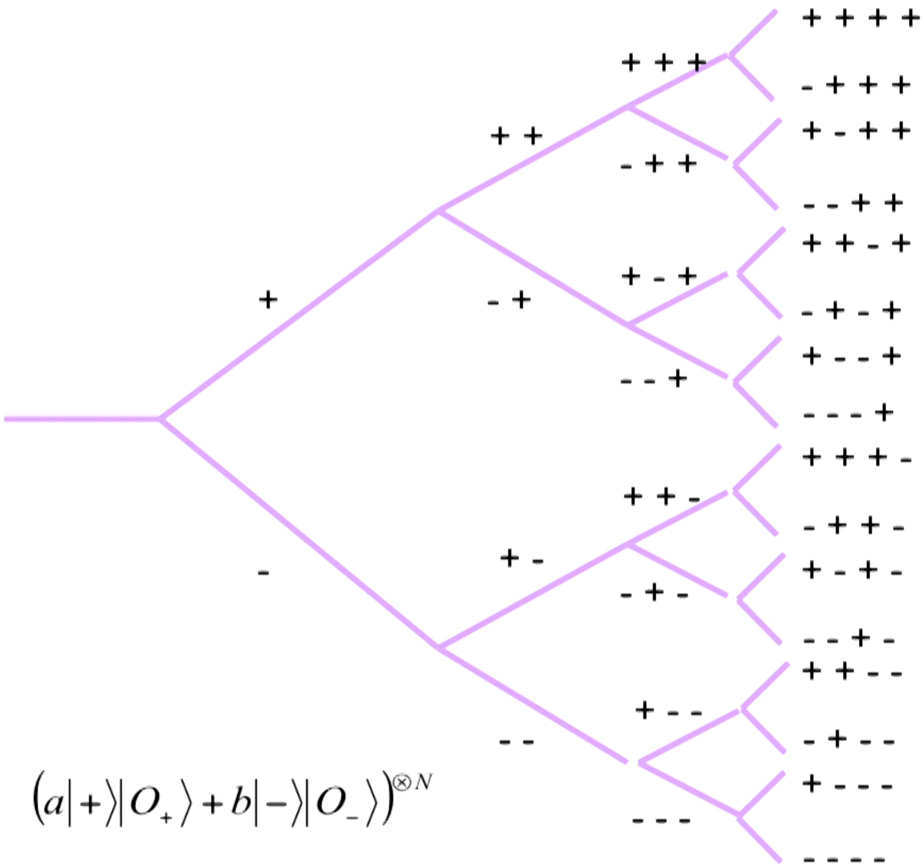


$$\left(a|+\rangle|O_+\rangle+b|-\rangle|O_-\rangle\right)^{\otimes N}$$

Different branches correspond to different subjective experiences

All branches are actual → all experiences occur

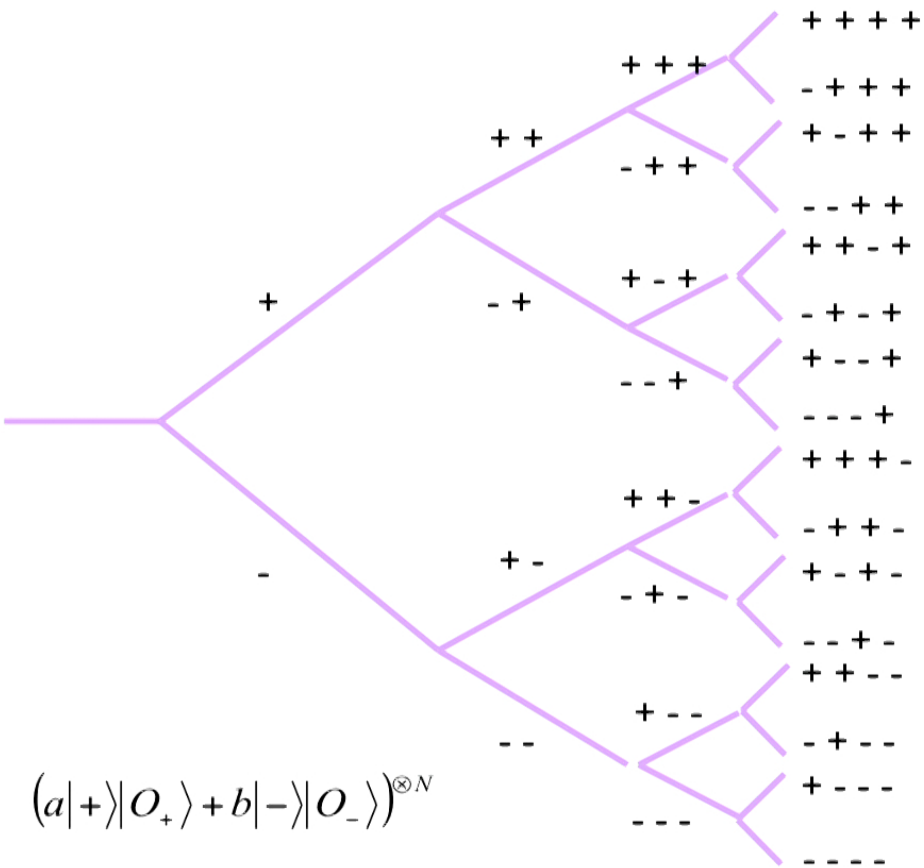
Therefore, cannot understand probability in terms of where the "real" me ends up



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

In the limit N→ ∞, in all branches except a set of measure zero, the frequency of + results is the same.

What is this "typical" frequency?

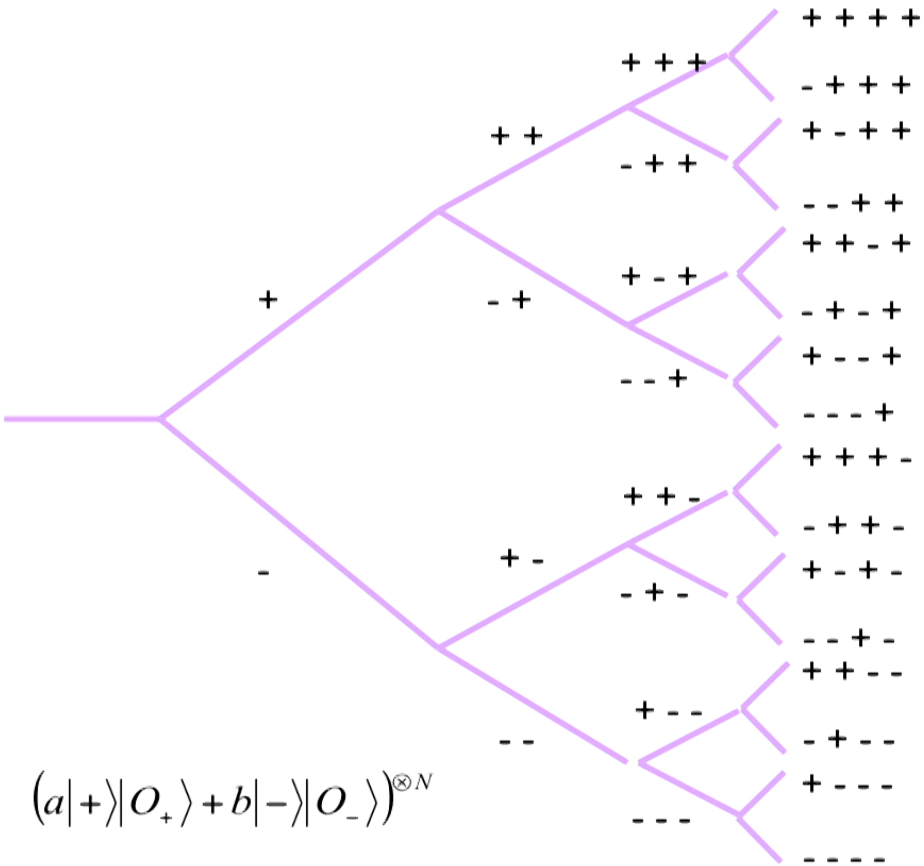


$$\left(a|+\rangle|O_+\rangle+b|-\rangle|O_-\rangle\right)^{\otimes N}$$

In the limit N→ ∞, in all branches except a set of measure zero, the frequency of + results is the same.

What is this “typical” frequency?

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



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

In the limit N→ ∞, in all branches except a set of measure zero, the frequency of + results is the same.

What is this "typical" frequency?

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

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

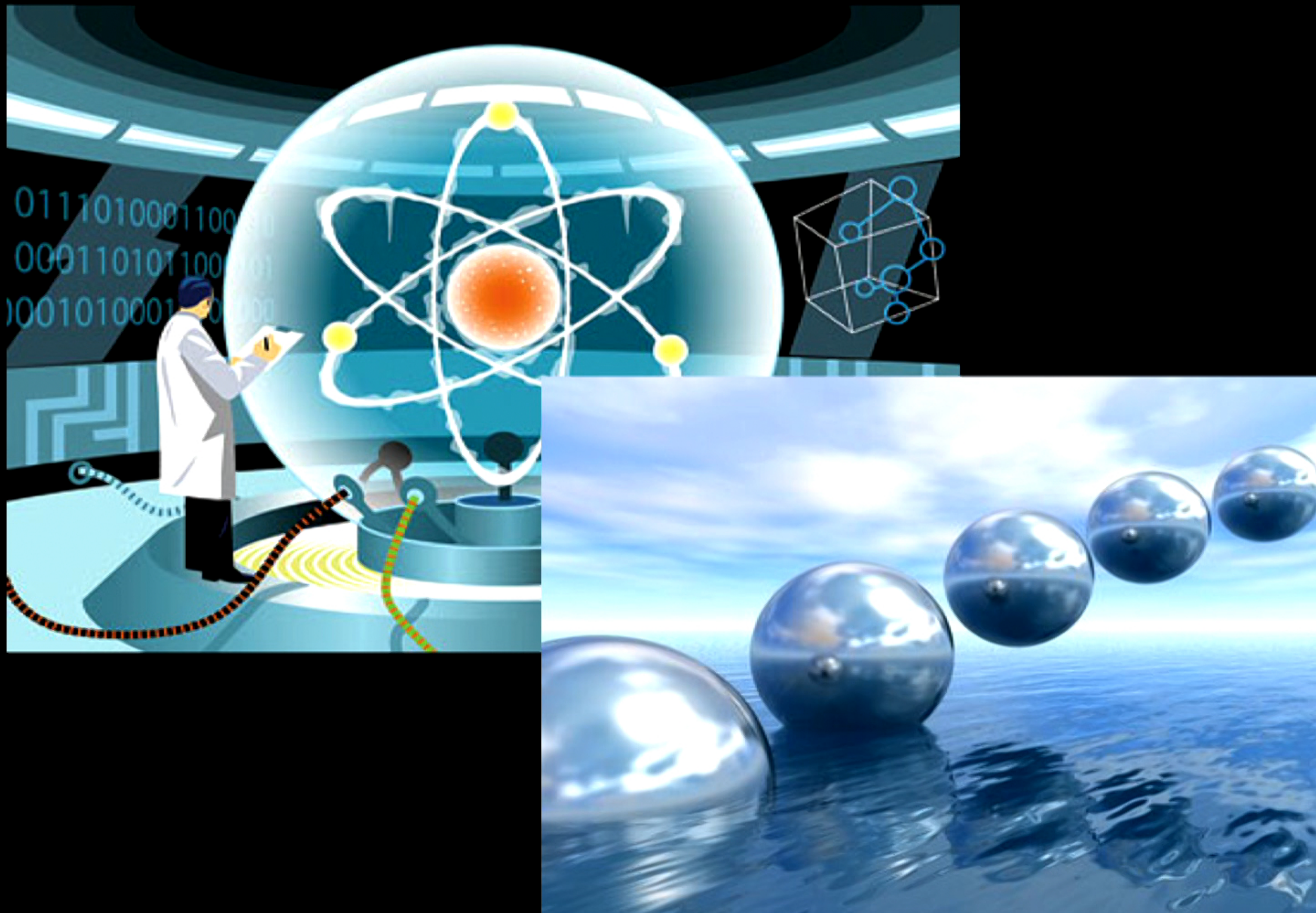
Deutsch's decision-theoretic strategy: Probability gets its meaning through the rational preferences of agents who consider the utility of all future versions of themselves.

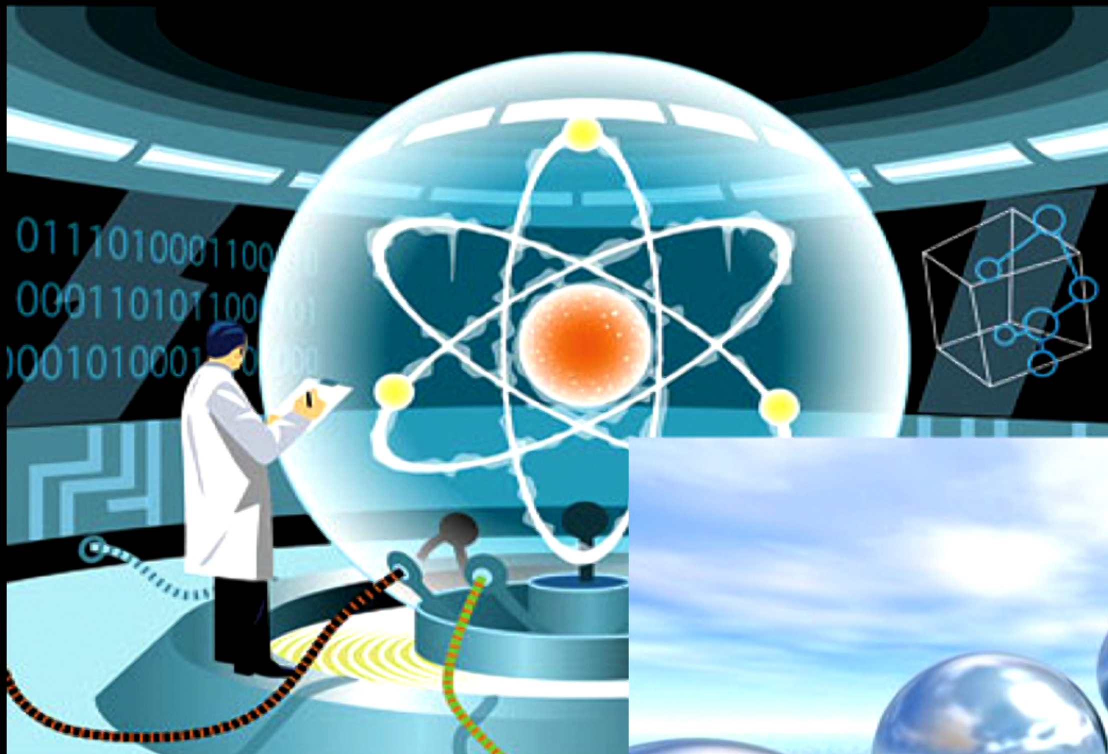
Purports to show that a rational agent who knows that the Born-rule weight of an outcome is p is rationally compelled to act as if that outcome had probability p.

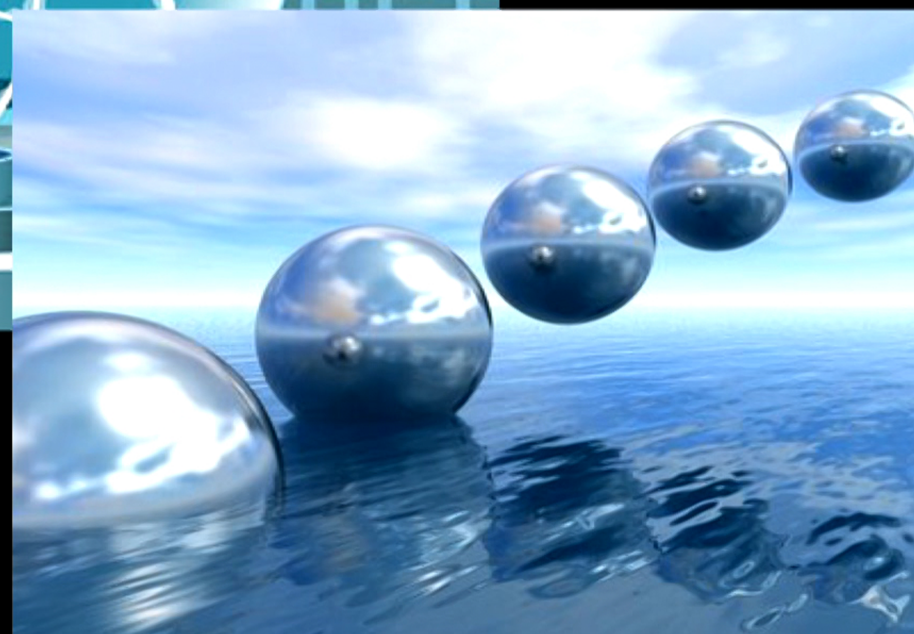
Deutsch's decision-theoretic strategy: Probability gets its meaning through the rational preferences of agents who consider the utility of all future versions of themselves.

> Purports to show that 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.

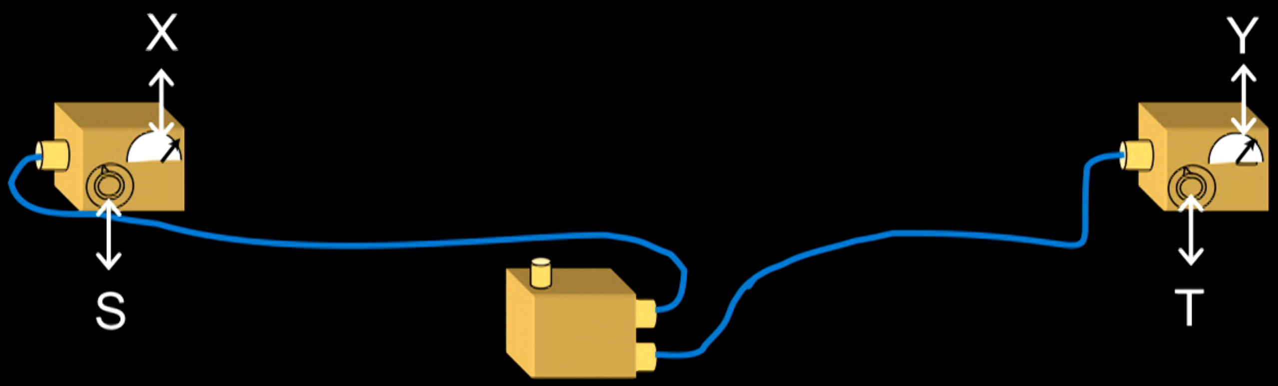
Barnum et al.: Deutsch's proof has a hidden assumption which is akin to applying Laplace's Principle of Insufficient Reason to a set of equal-amplitude alternatives, an application that requires assuming, rather than deriving, how amplitudes are related to probabilities.





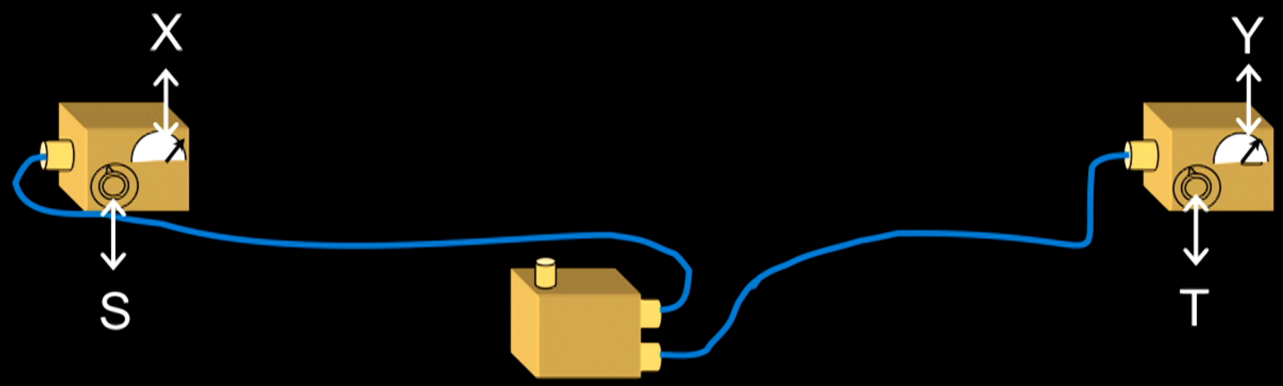


The intuition about
computation in parallel worlds
does not explain the precise
computational power of
quantum computers



	X=0, Y=0	X=0, Y=1	X=1, Y=0	X=1, Y=1
S=0, T=0	0.427	0.073	0.073	0.427
S=0, T=1	0.427	0.073	0.073	0.427
S=1, T=0	0.427	0.073	0.073	0.427
S=1, T=1	0.073	0.427	0.427	0.073

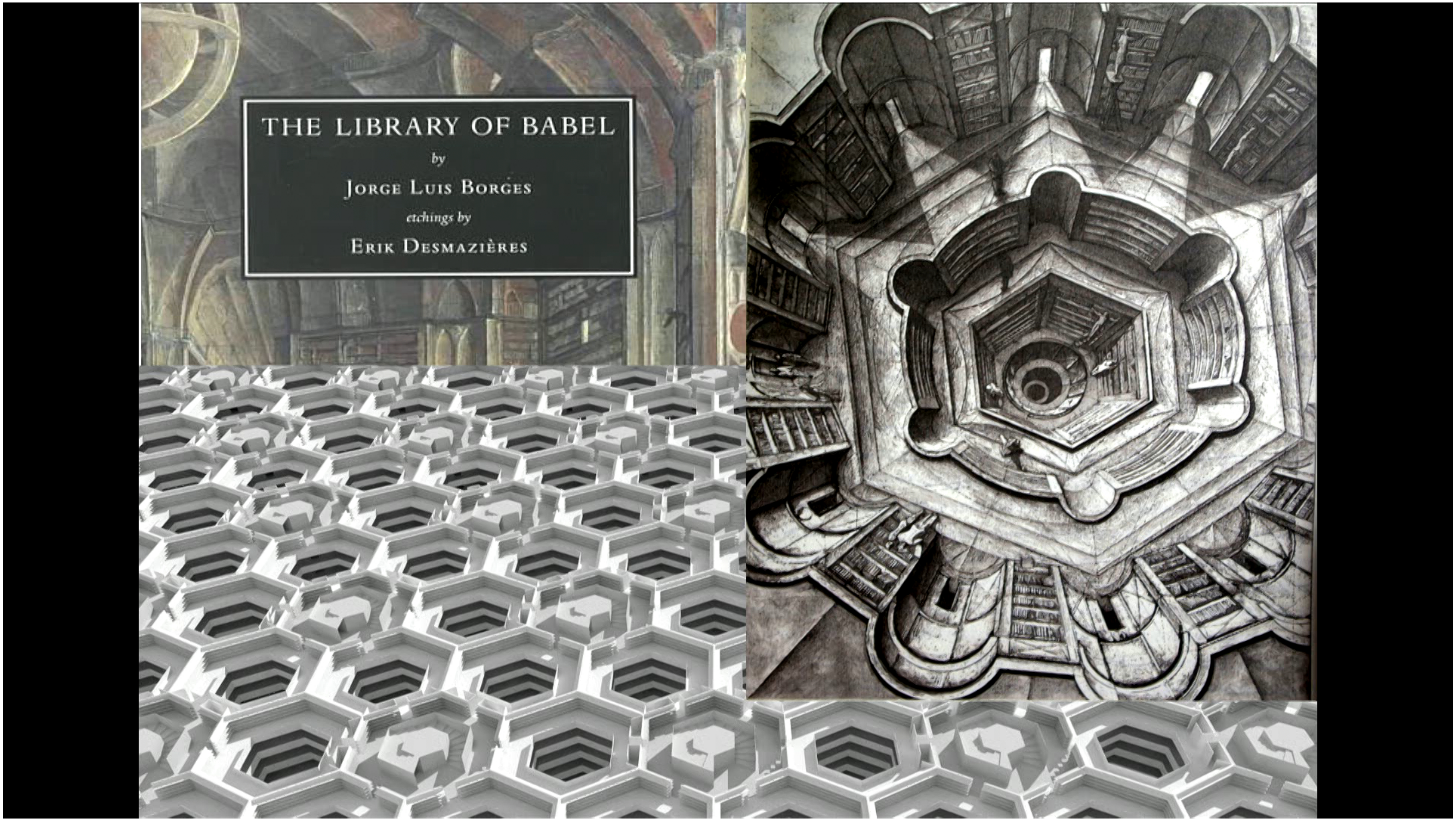
	X=0, Y=0	X=0, Y=1	X=1, Y=0	X=1, Y=1
S=0, T=0	1/2	0	0	1/2
S=0, T=1	1/2	0	0	1/2
S=1, T=0	1/2	0	0	1/2
S=1, T=1	0	1/2	1/2	0



	X=0, Y=0	X=0, Y=1	X=1, Y=0	X=1, Y=1
S=0, T=0	0.427	0.073	0.073	0.427
S=0, T=1	0.427	0.073	0.073	0.427
S=1, T=0	0.427	0.073	0.073	0.427
S=1, T=1	0.073	0.427	0.427	0.073

	X=0, Y=0	X=0, Y=1	X=1, Y=0	X=1, Y=1
S=0, T=0	1/2	0	0	1/2
S=0, T=1	1/2	0	0	1/2
S=1, T=0	1/2	0	0	1/2
S=1, T=1	0	1/2	1/2	0

Any generalized probabilistic theory can be given a many worlds interpretation. The interpretation does not explain the precise degree of violation of Bell inequalities seen in quantum theory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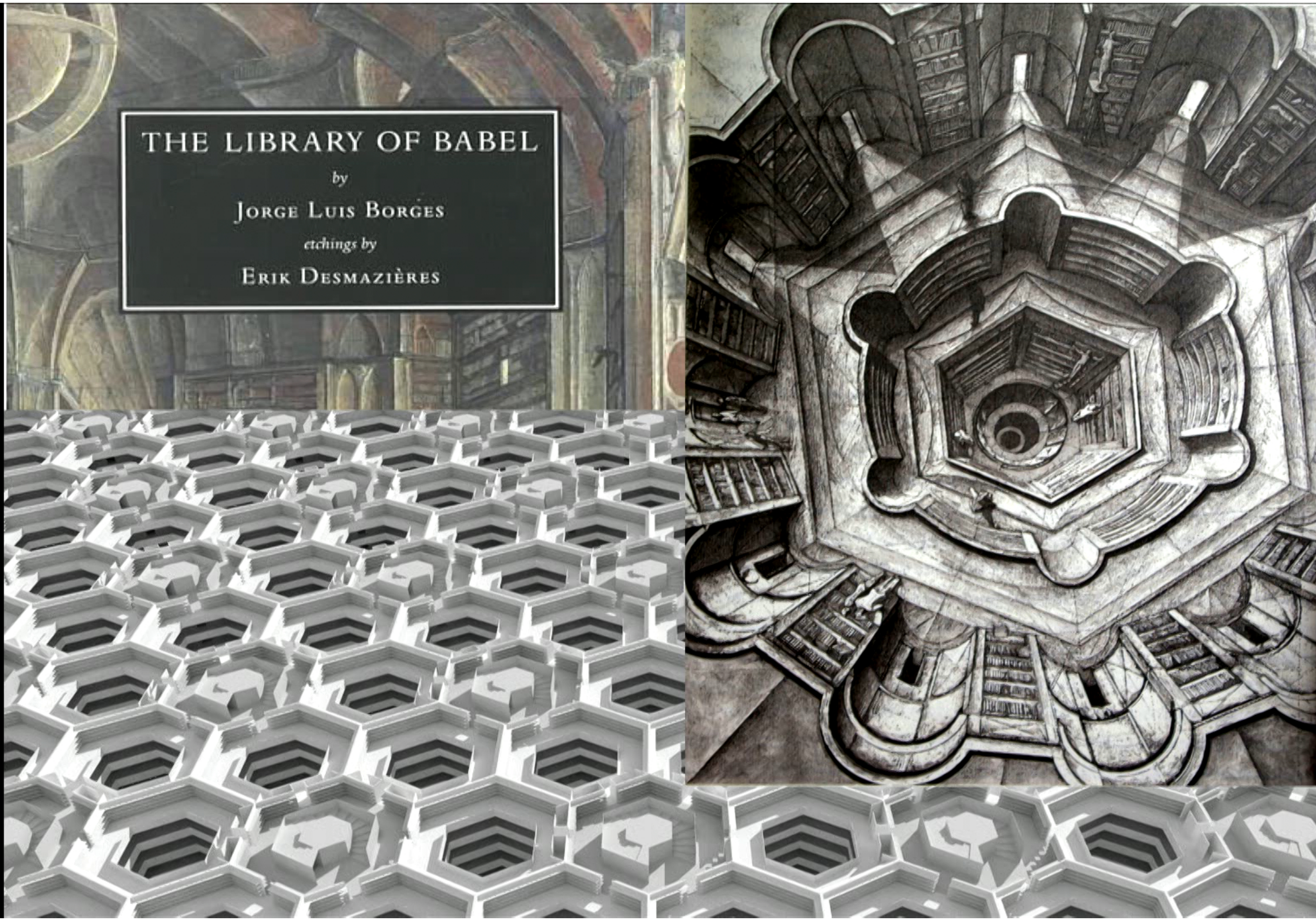
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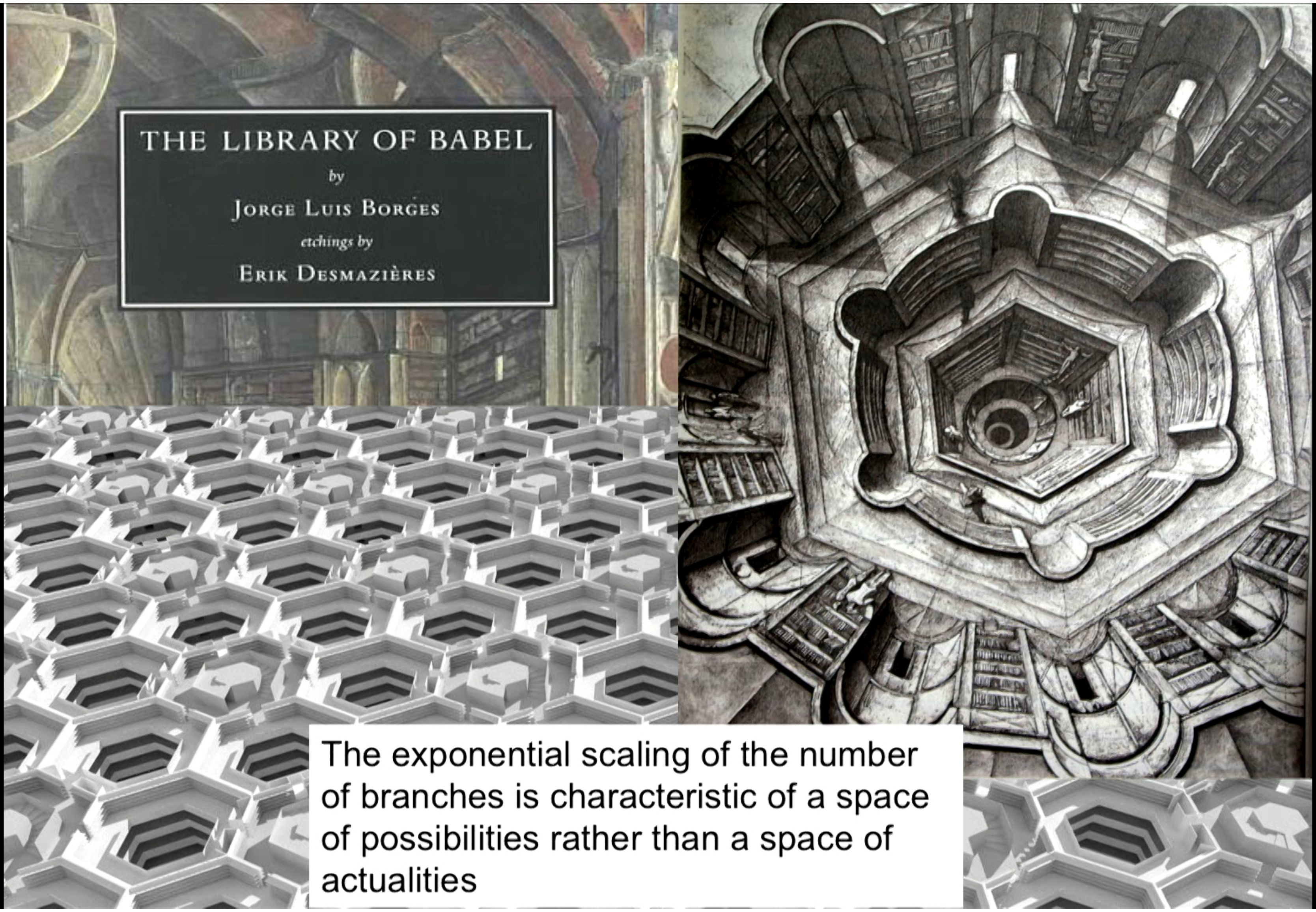

The exponential scaling of the number of branches is characteristic of a space of possibilities rather than a space of actualities