AUSTRIAN ACADEMY OF SCIENCES

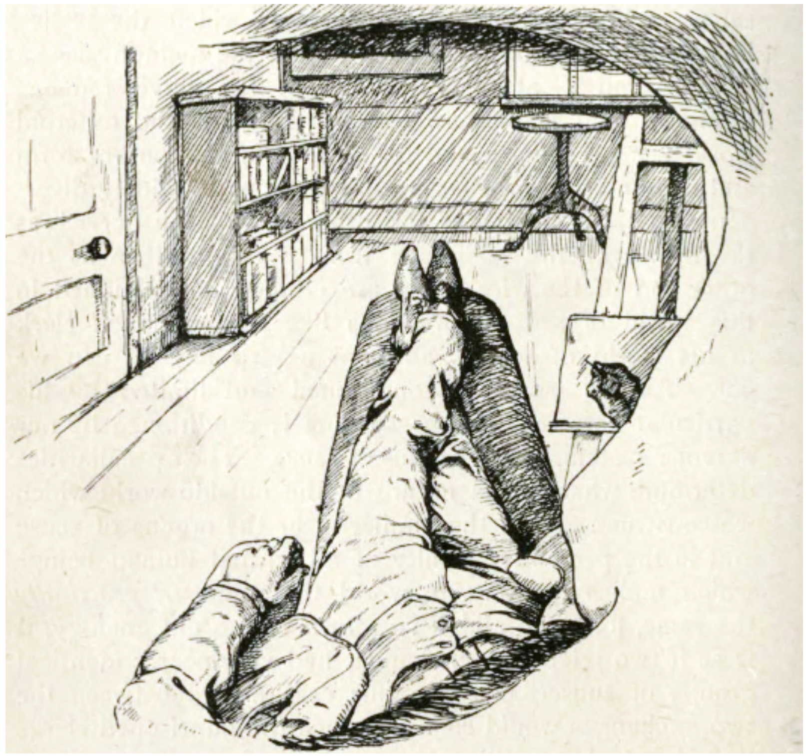
IQOQI – INSTITUTE FOR QUANTUM OPTICS AND QUANTUM INFORMATION VIENNA

# A first-person approach to quantum paradoxes and beyond


**Markus P. Müller**

Institute for Quantum Optics and Quantum Information (IQOQI), Vienna

Perimeter Institute for Theoretical Physics (PI), Waterloo, Canada

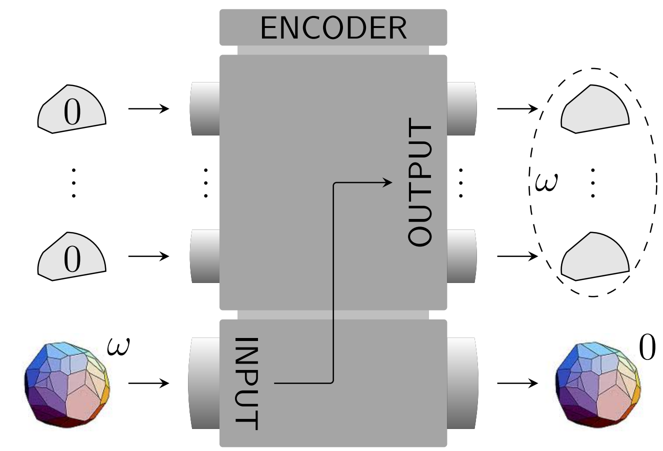



PERIMETER INSTITUTE

# Overview

1. Probabilistic theories beyond quantum theory

2. Quantum theory from simple principles

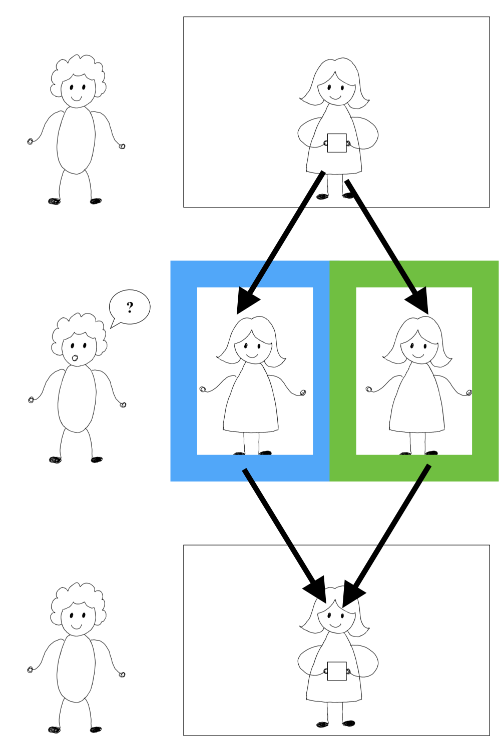



3. Reproducing Wigner's Friend phenomena classically

4. Restriction A

When physics fails to allow agents to predict their future experiences

5. Consequence: fragmentalism/idealism



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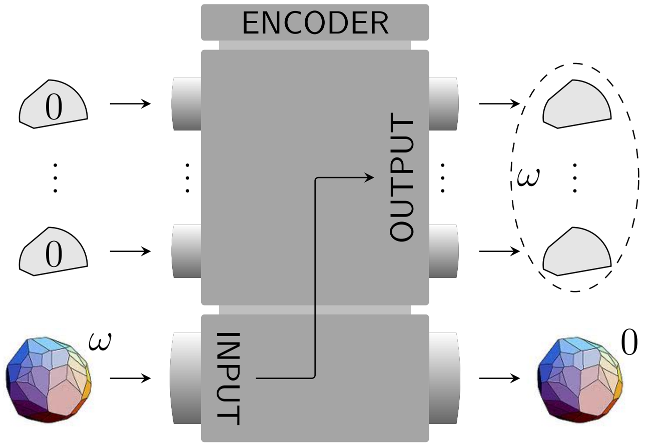


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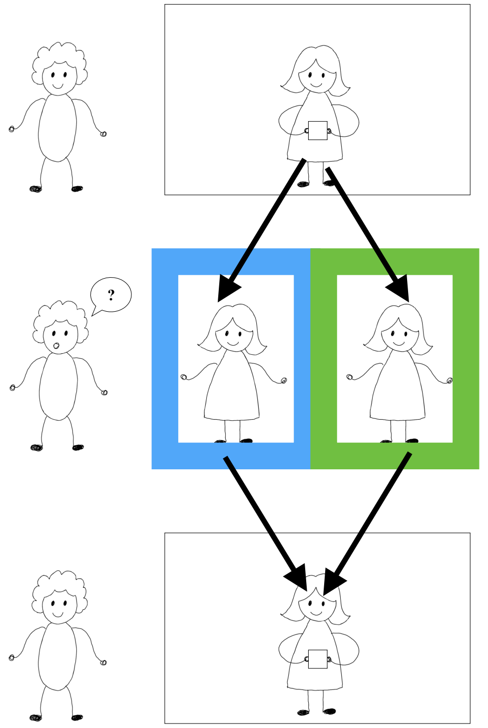

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# Motivation

John A. Wheeler, New York Times, Dec. 12 2000:

*„Quantum physics [...] has explained the structure of atoms and molecules, [...] the behavior of semiconductors [...] and the comings and goings of particles from neutrinos to quarks.*

*Successful, yes, but mysterious, too.*
*Why does the quantum exist?“*


The New York Times

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Need some intuition first: **how could (probabilities in) physics be different from quantum <u>and</u> classical?**

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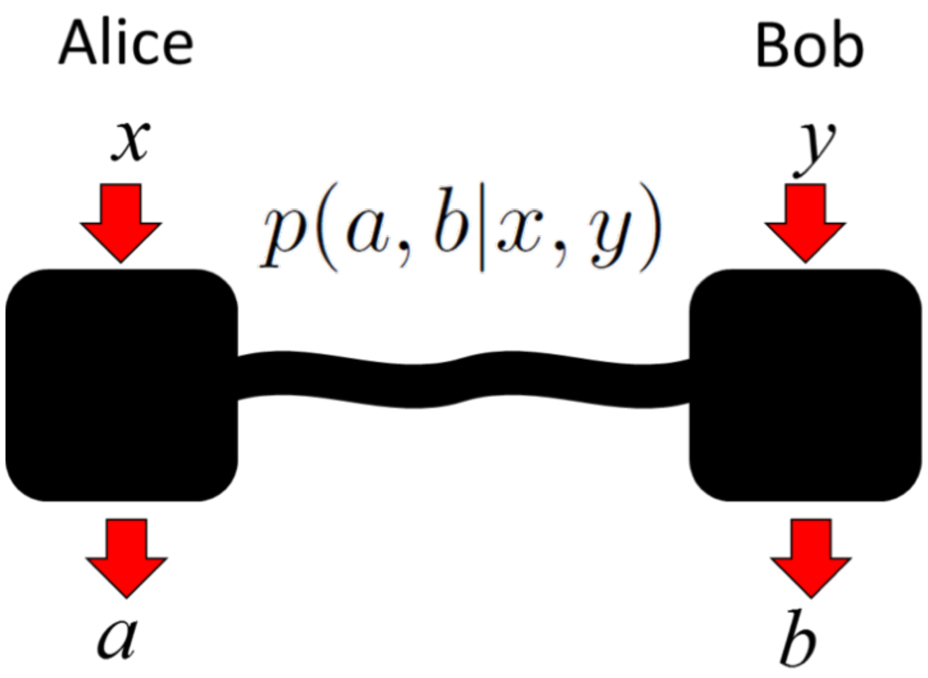

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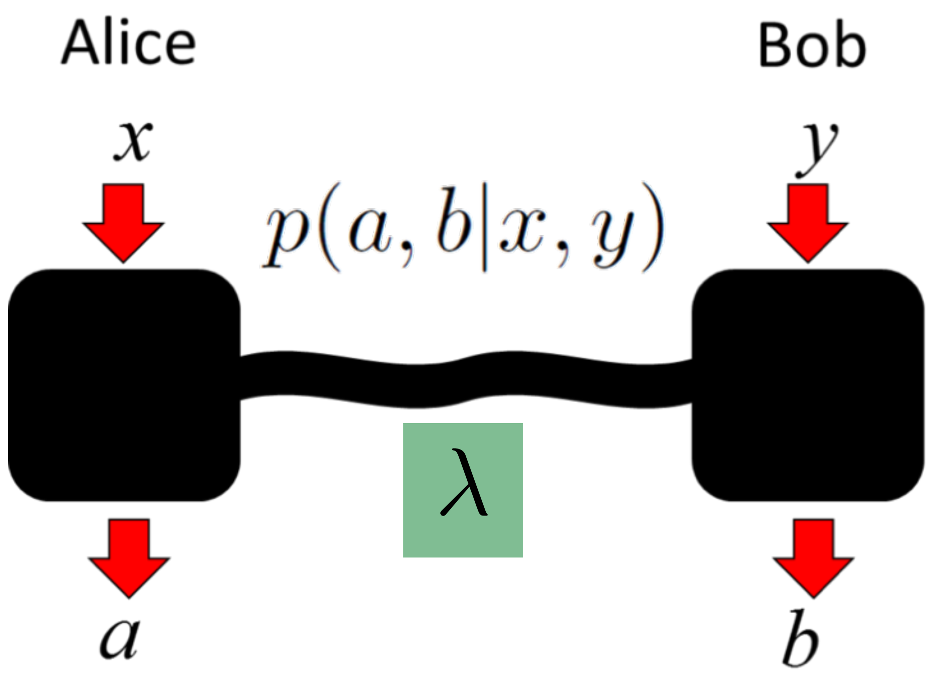


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$$P(a,b|x,y) = \sum_{\lambda\in\Lambda} P_A(a|x,\lambda)P_B(b|y,\lambda)P_\Lambda(\lambda)$$

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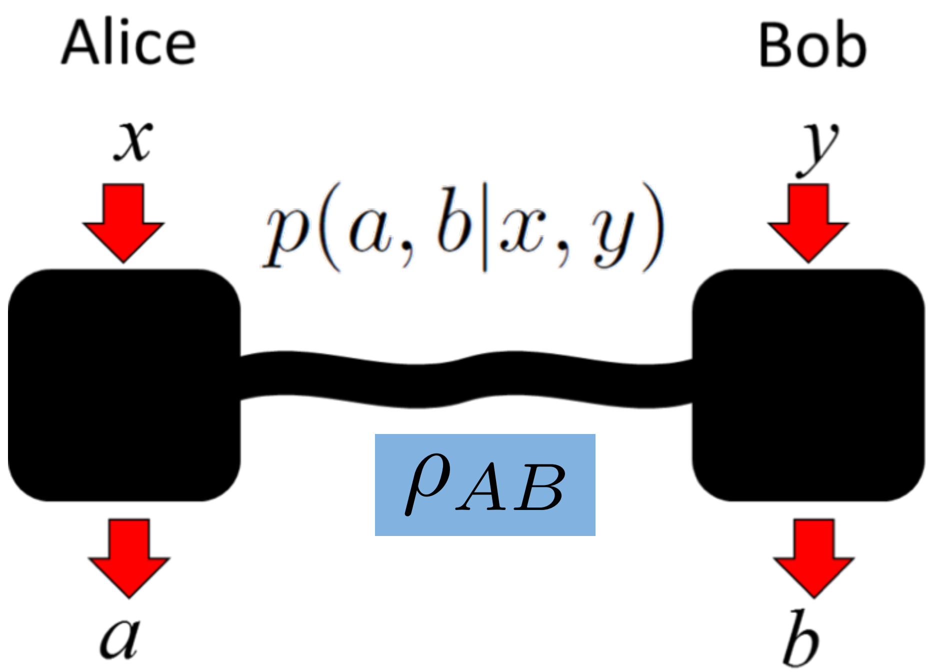


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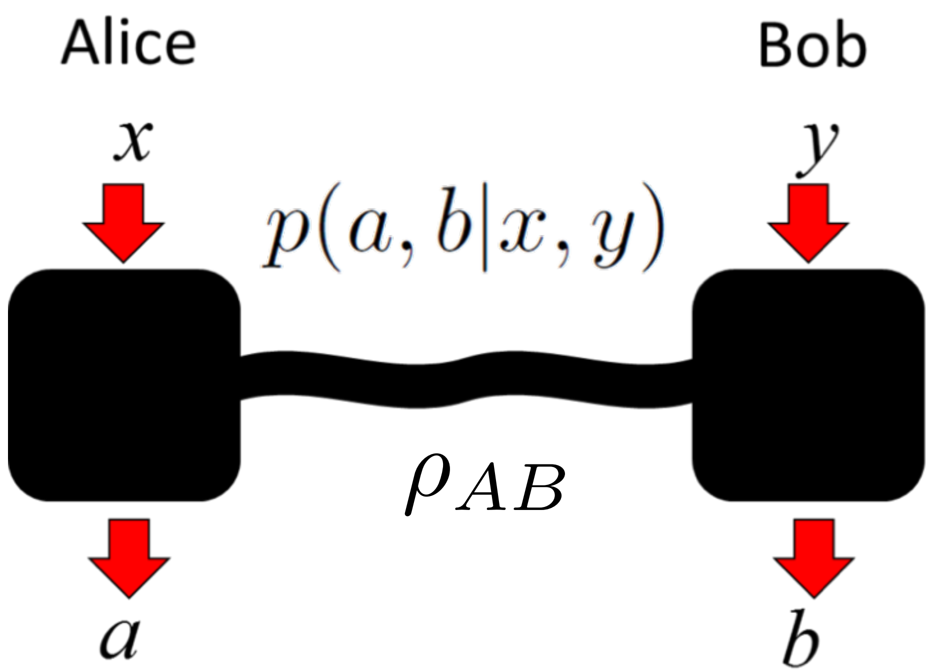


**No-signalling** conditions:

$P(a|x,y)$ is independent of $y$,

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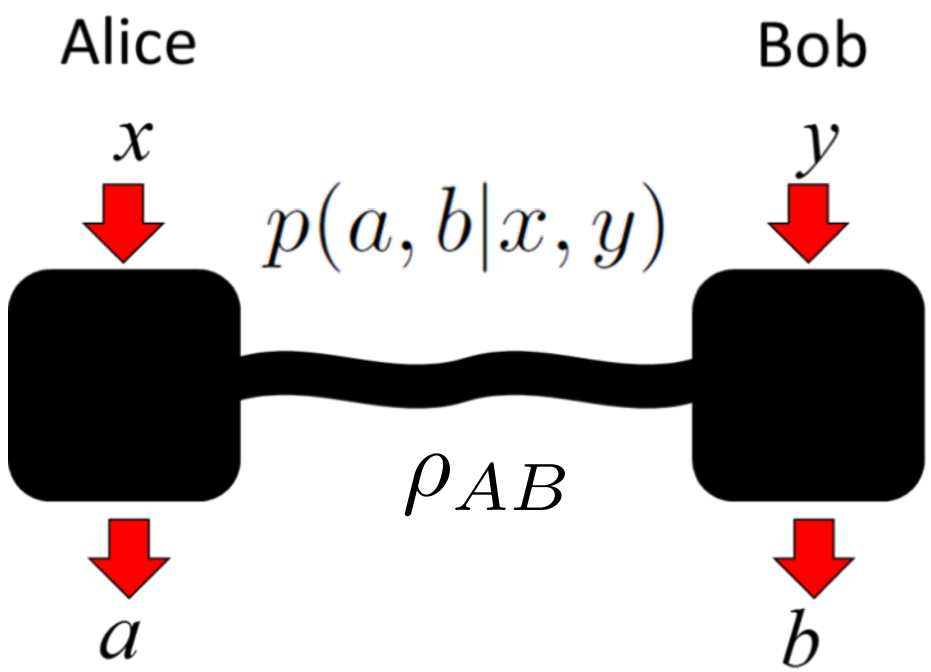


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Quantum theory admits more general *P*'s due to the **violation of Bell inequalities**.

# The Bell-CHSH inequality

Classical probability distributions satisfy Bell inequality:

$$\mathrm{CHSH} := |C_{00} + C_{01} + C_{10} - C_{11}| \leq 2 \quad \text{where} \quad C_{xy} := \mathbb{E}(a \cdot b | x, y).$$

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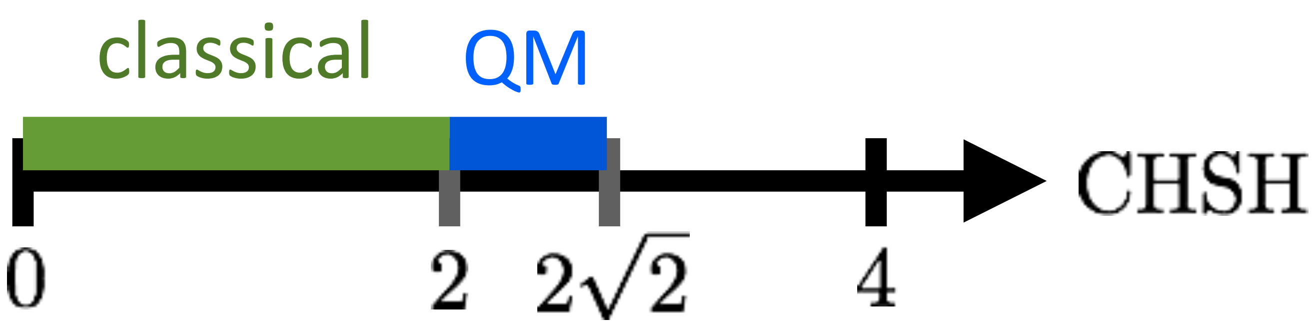


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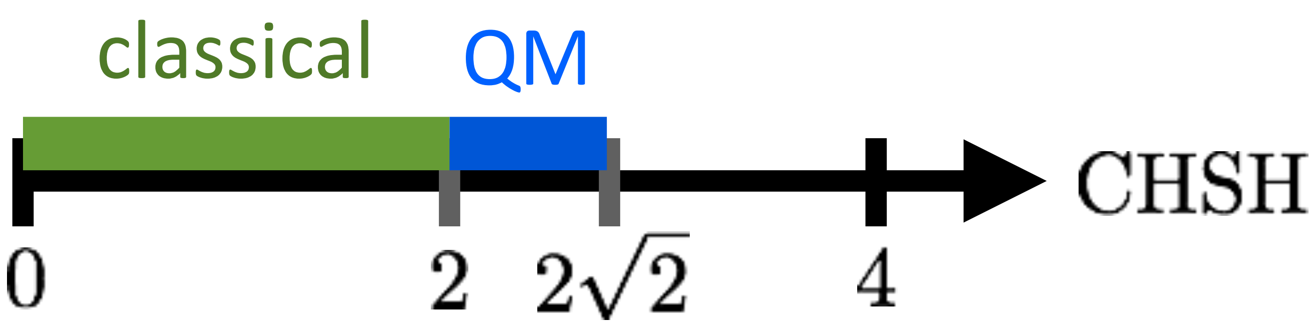


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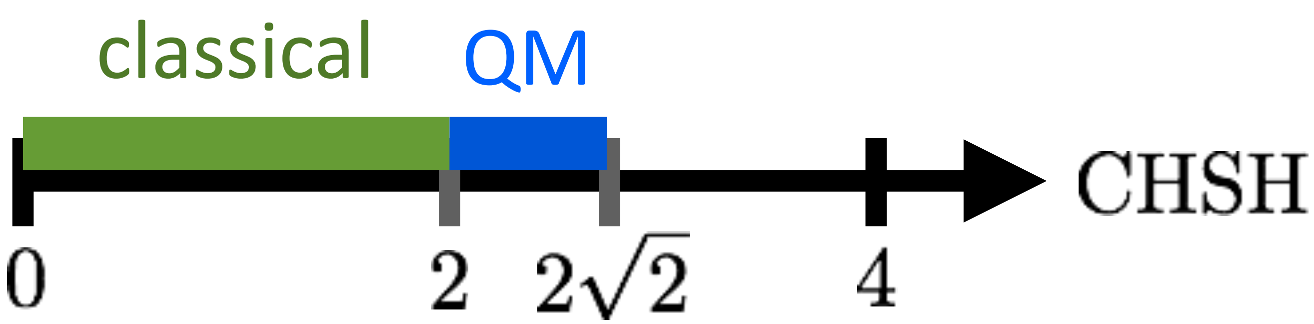


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No! Counterexample: the PR-box correlations

$$\begin{aligned} P(+1, +1|x, y) &= P(-1, -1|x, y) = \frac{1}{2} \\ &\quad \text{if } (x, y) \in \{(0, 0), (0, 1), (1, 0)\} \\ P(+1, -1|1, 1) &= P(-1, +1|1, 1) = \frac{1}{2} \end{aligned}$$

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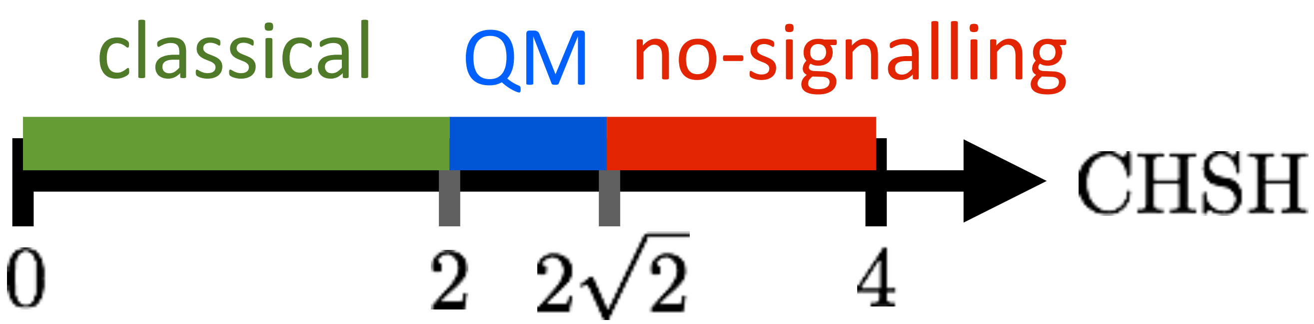


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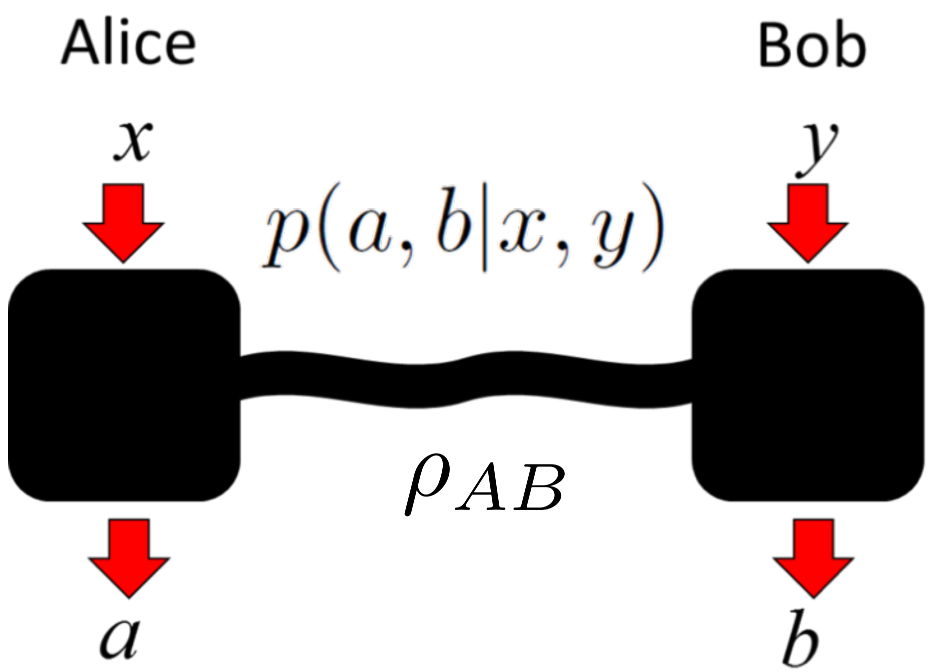


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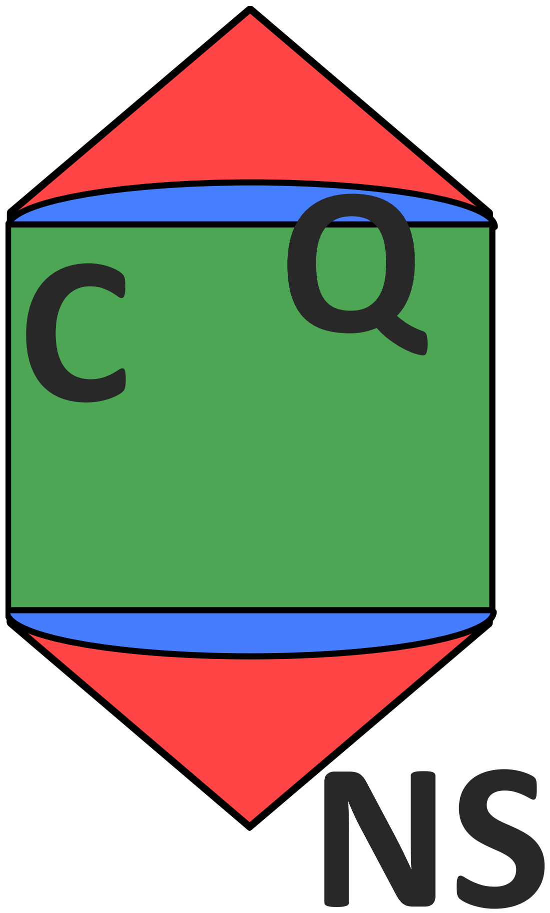

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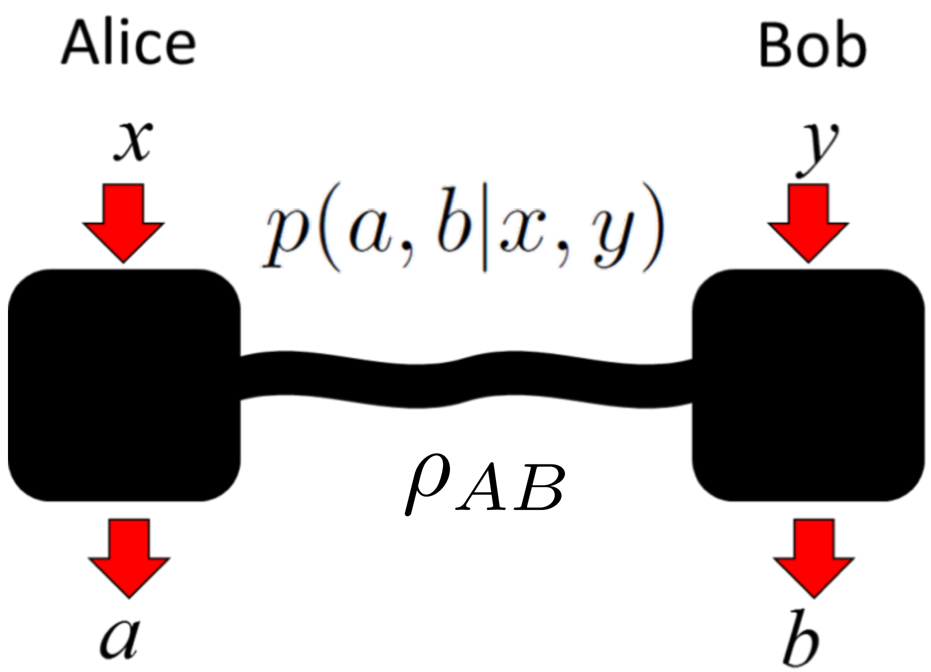


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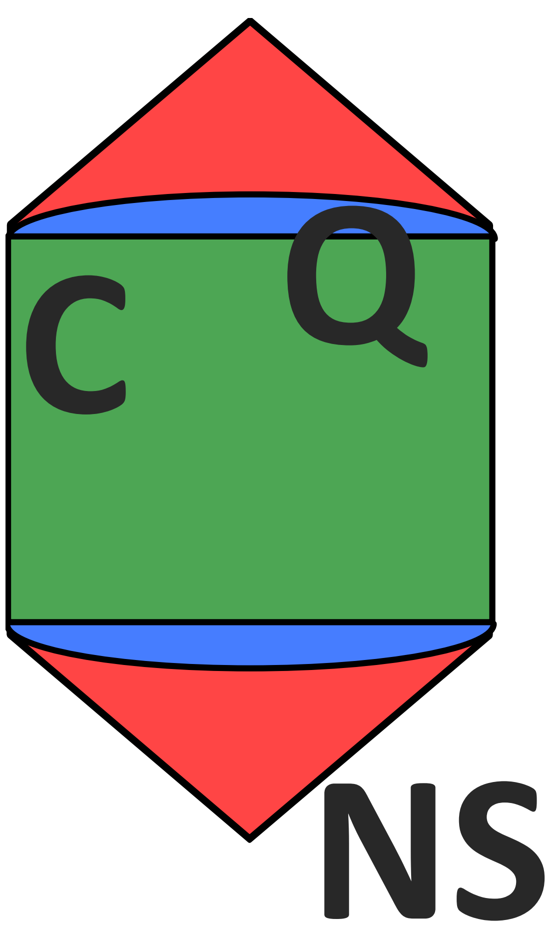


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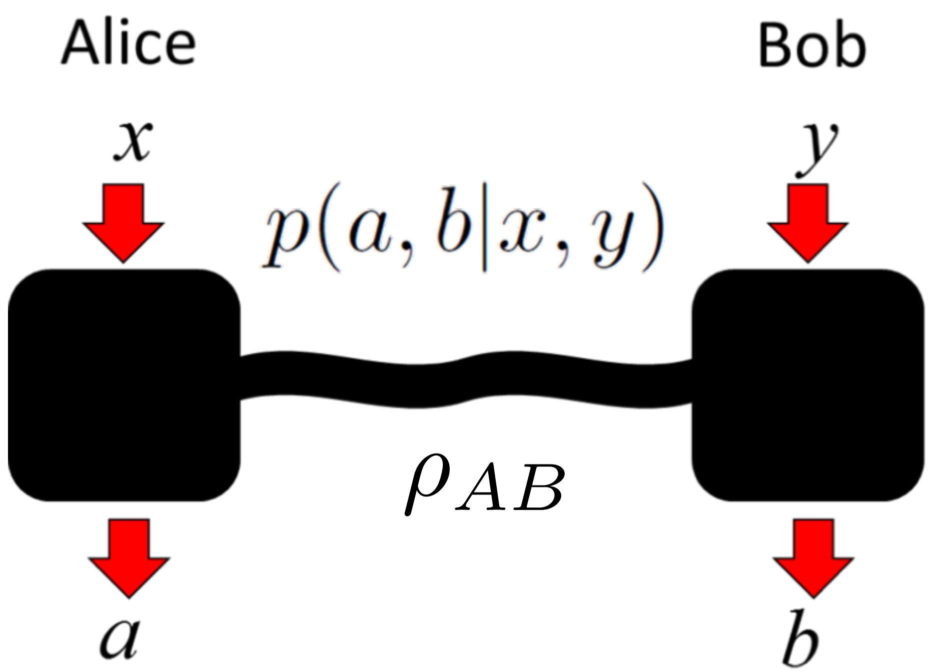


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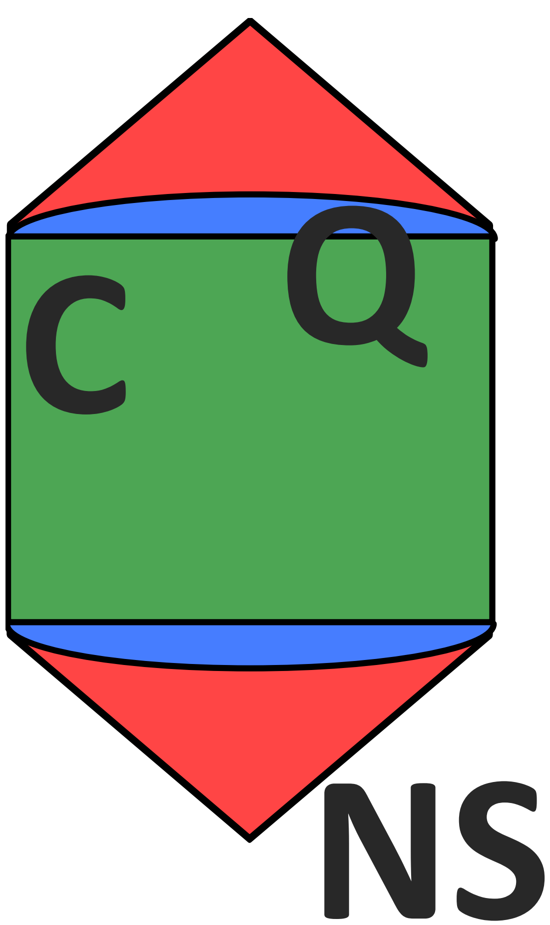


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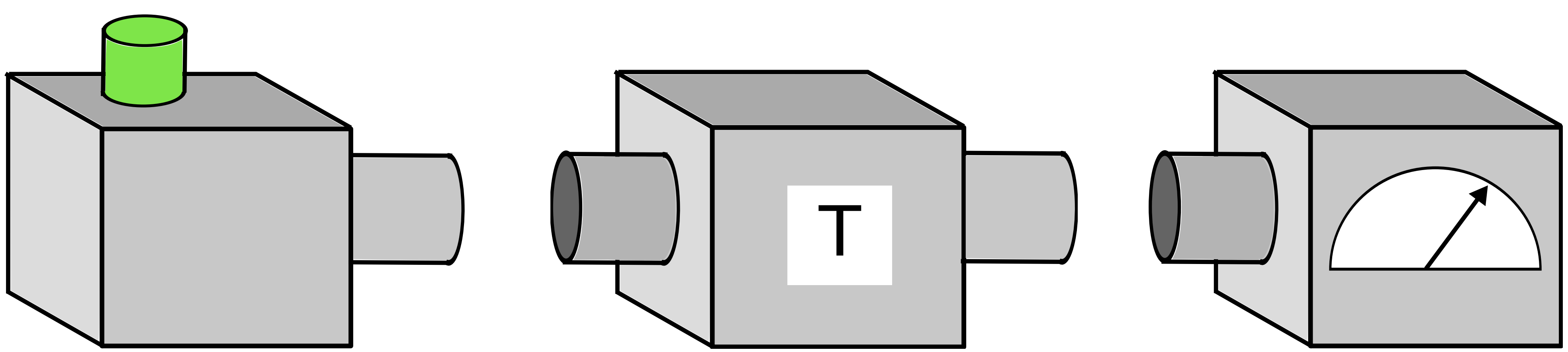
3 examples of a "**generalized probabilistic theory**".

# Generalized probabilistic theories

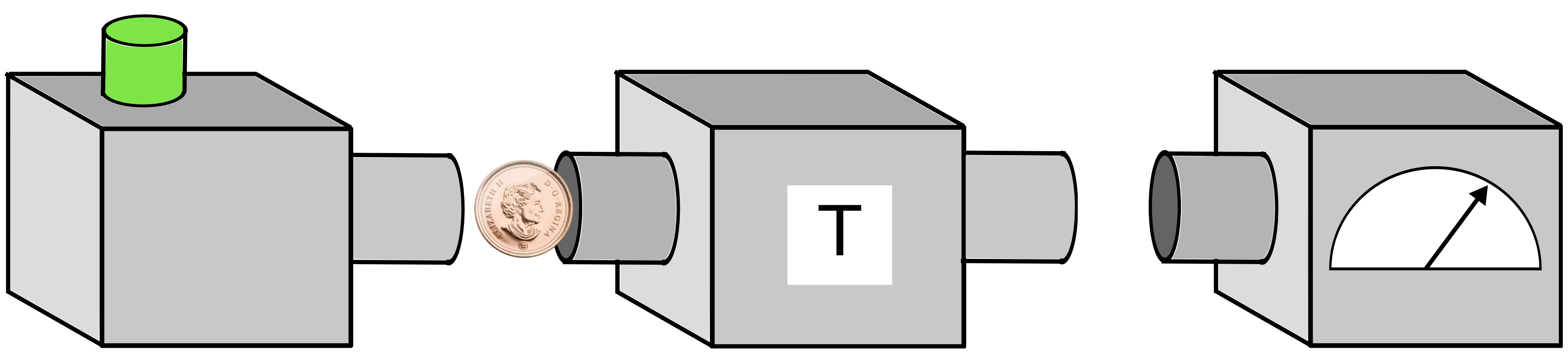



Preparation transformation measurement

# Generalized probabilistic theories

**Example**: classical coin toss.


- On every push of button, the preparation device performs a biased coin toss.

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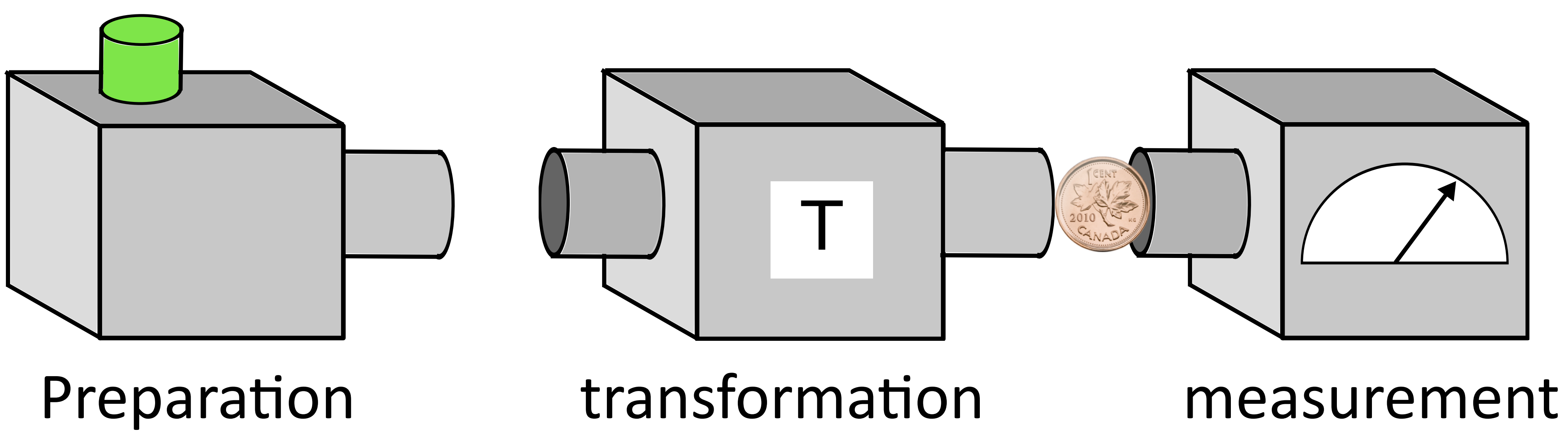

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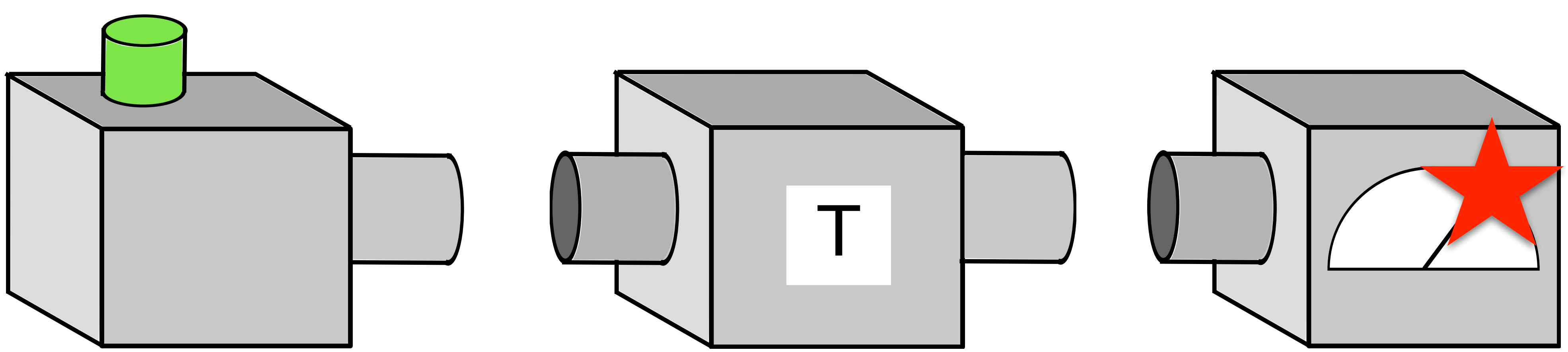
- The measurement outcome is "heads" or "tails".

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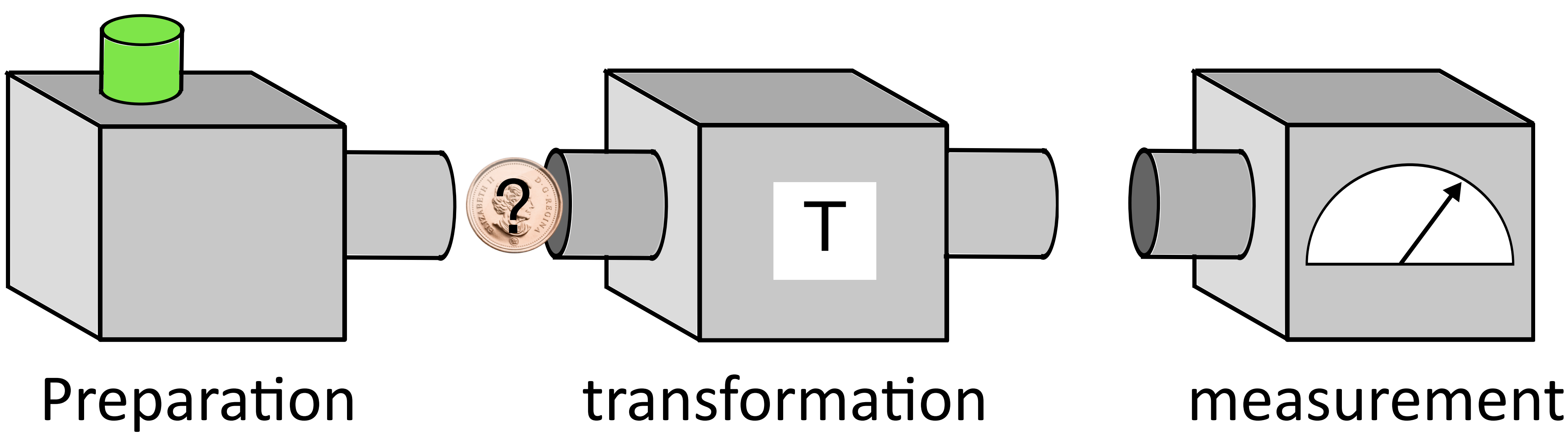
- The preparation device prepares a physical system in a state ω. Here

$$\omega = \begin{pmatrix} \text{Prob(heads)} \\ \text{Prob(tails)} \end{pmatrix} = \begin{pmatrix} p \\ 1-p \end{pmatrix}.$$



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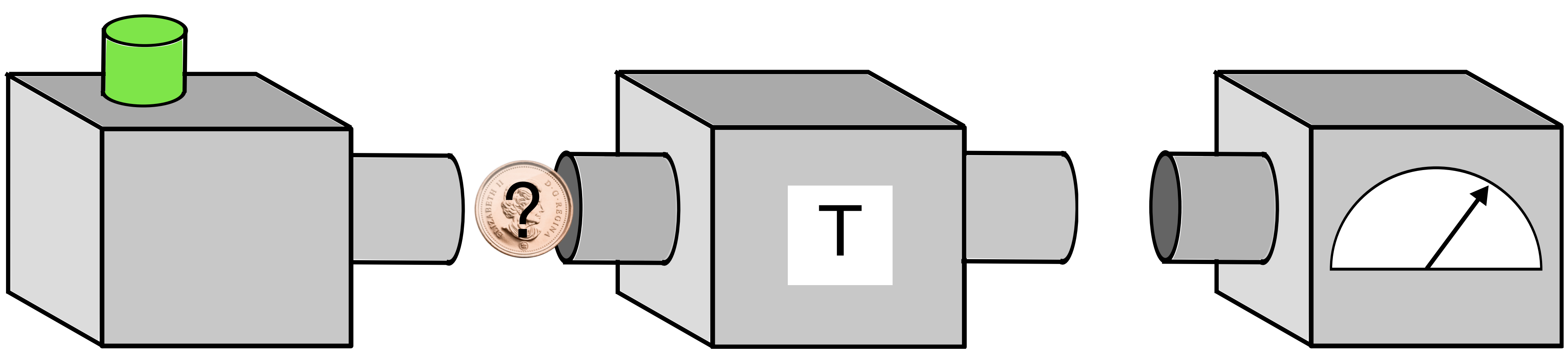


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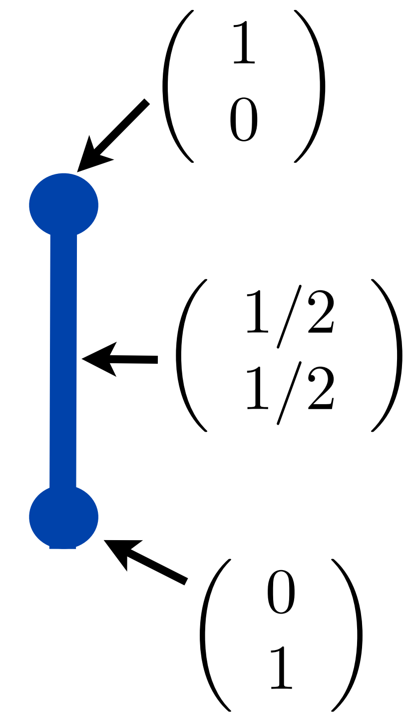


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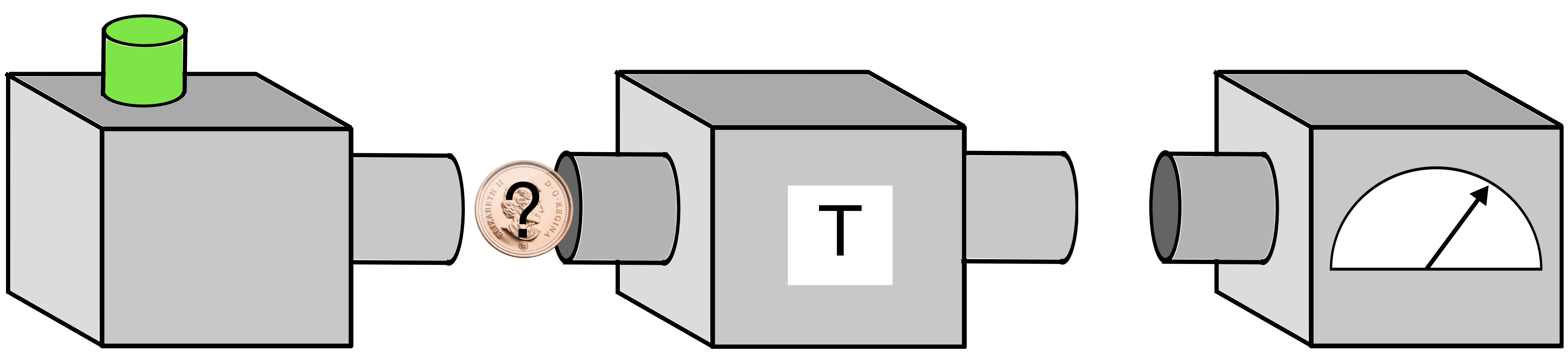


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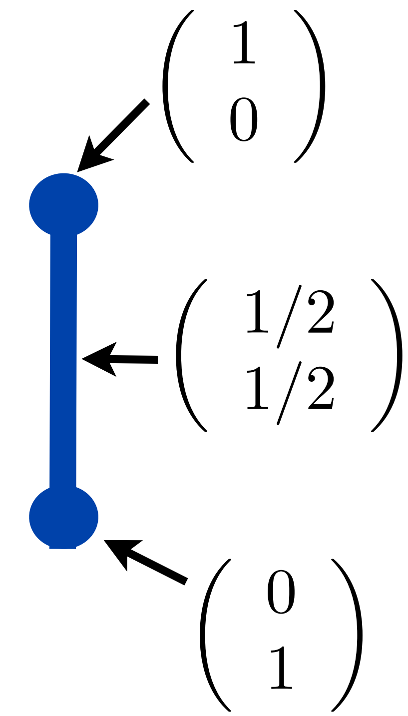


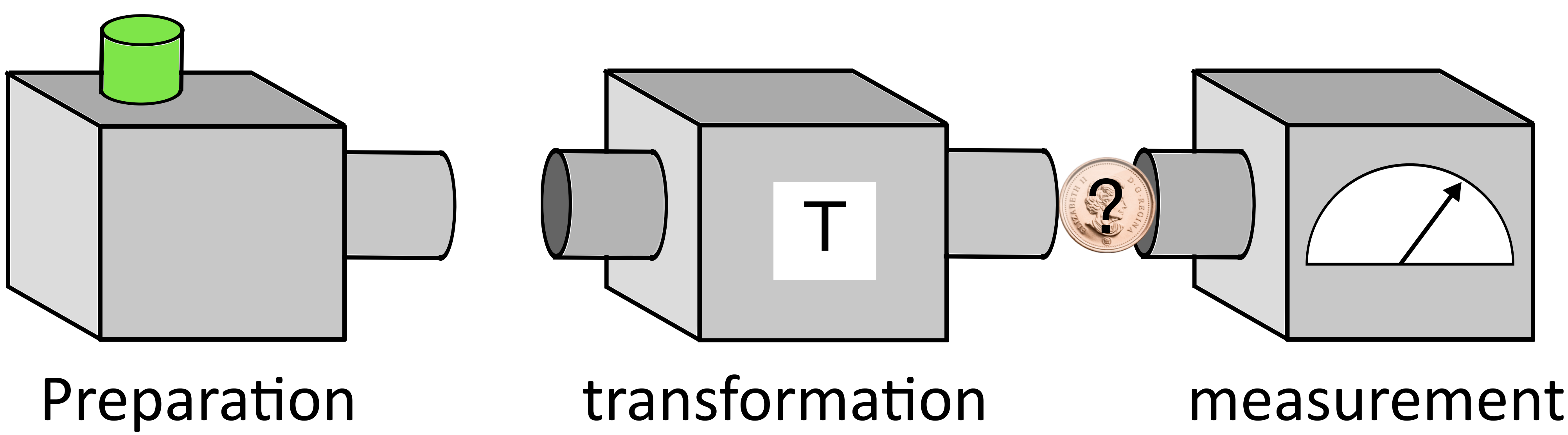

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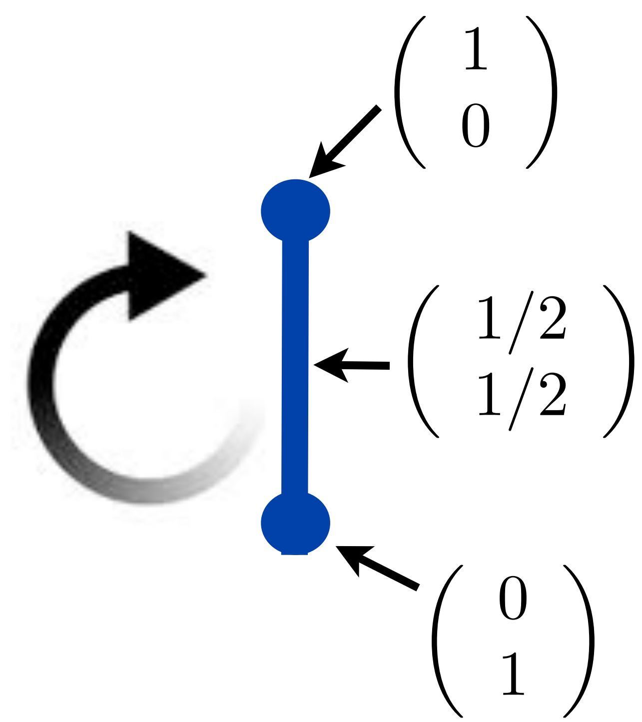


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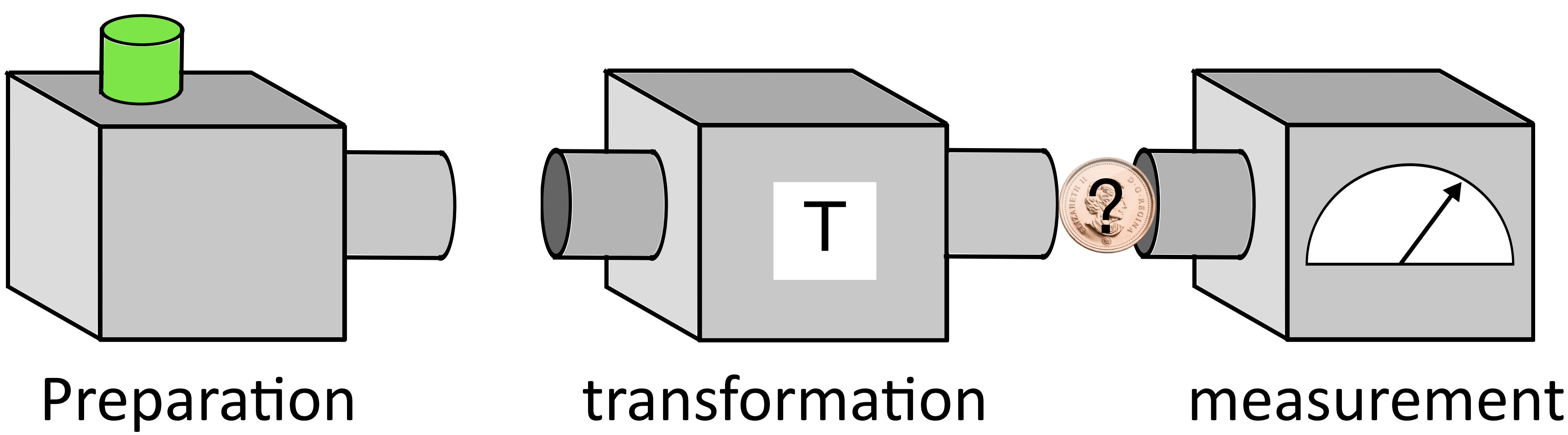
  Maps states to states and is linear.



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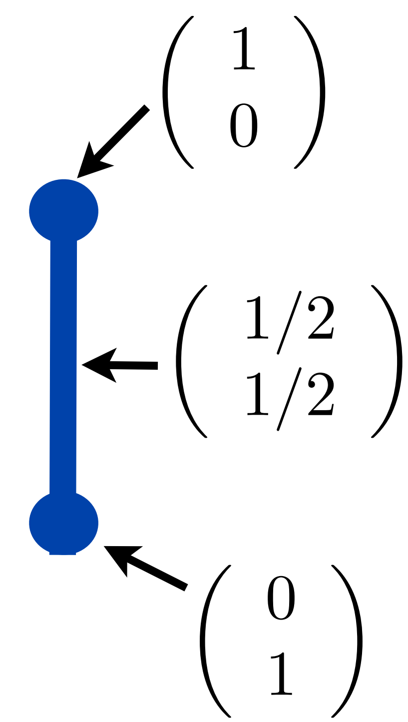


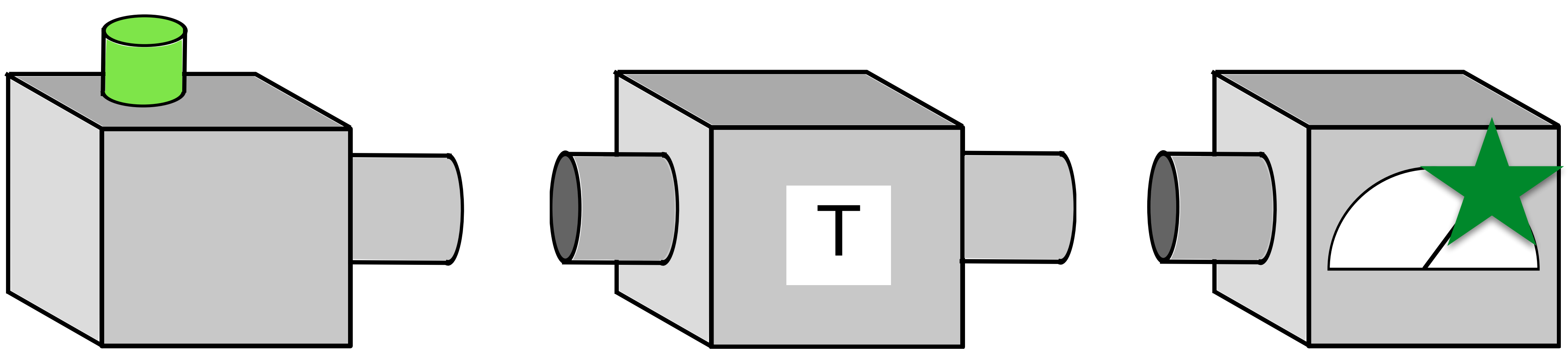


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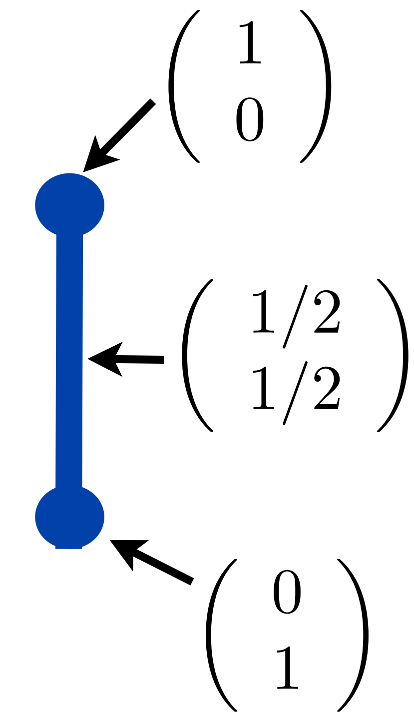
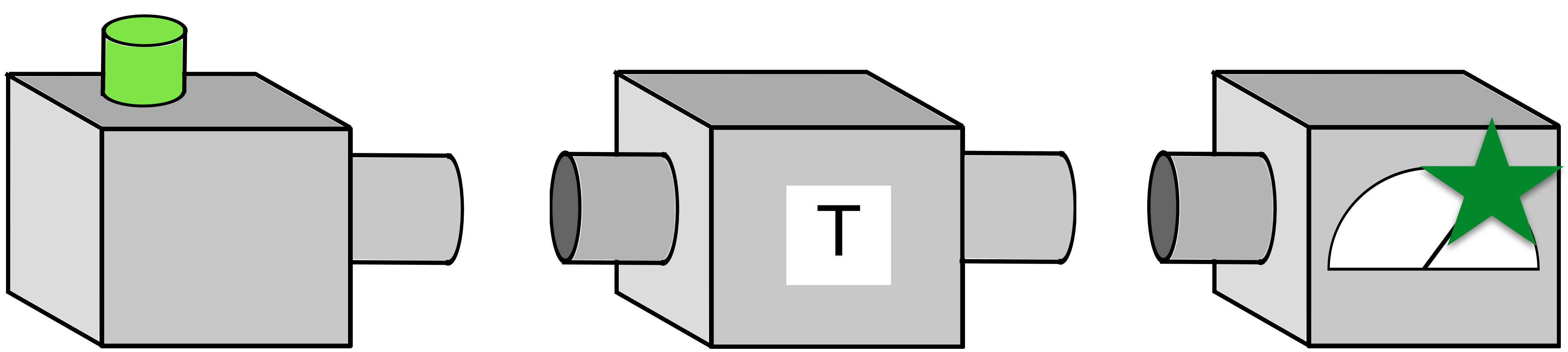
$$\mathrm{Prob}(\mathrm{heads}|\omega) = p = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \cdot \begin{pmatrix} p \\ 1-p \end{pmatrix} = e \cdot \omega.$$

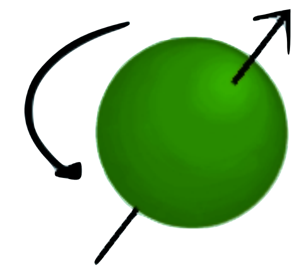


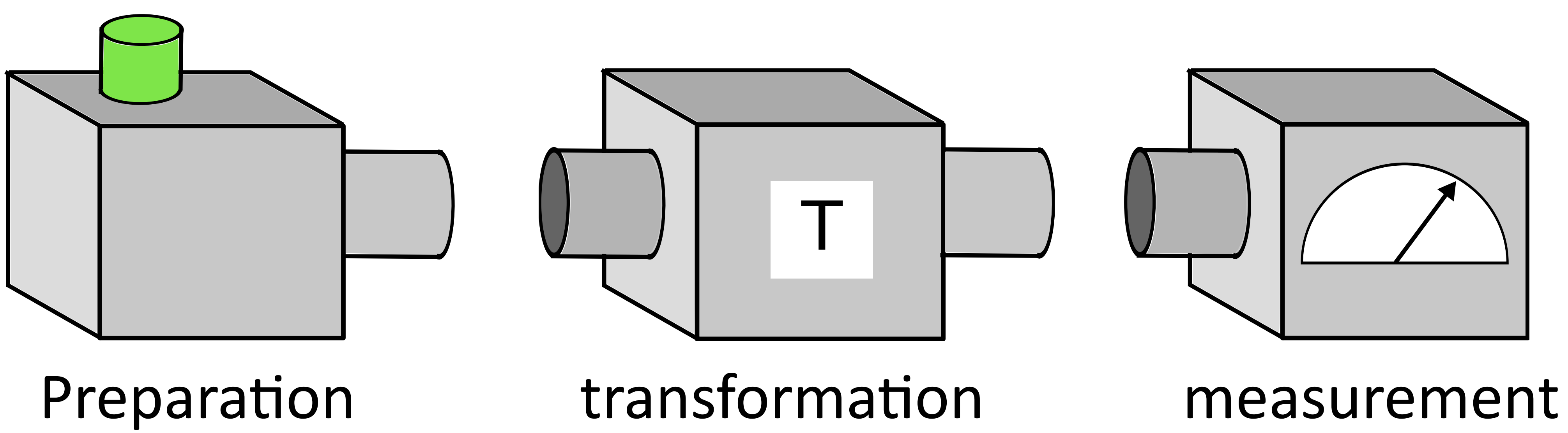




Preparation　　transformation　　measurement

## Generalized probabilistic theories

**Example**: quantum bit.





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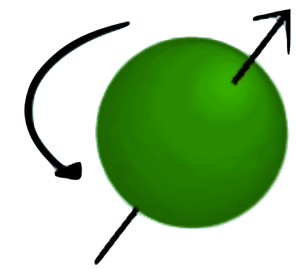
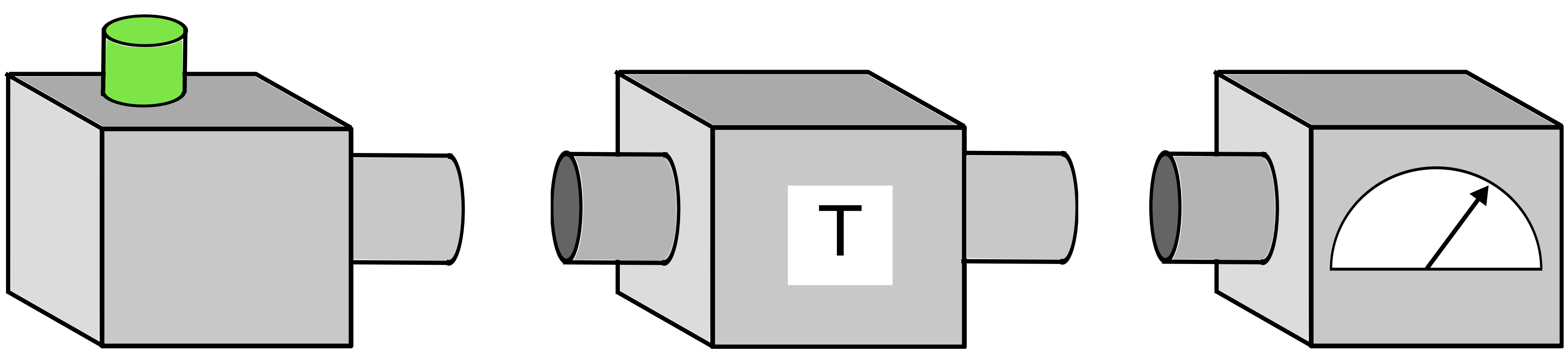


- The preparation device prepares a qubit in some quantum state $\rho = |\psi\rangle\langle\psi|,$

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

More generally: $\rho$ is (mixed-state-)2x2 density matrix.

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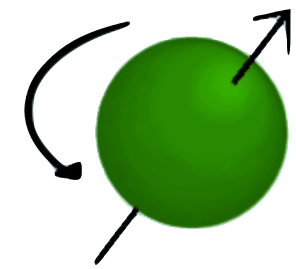
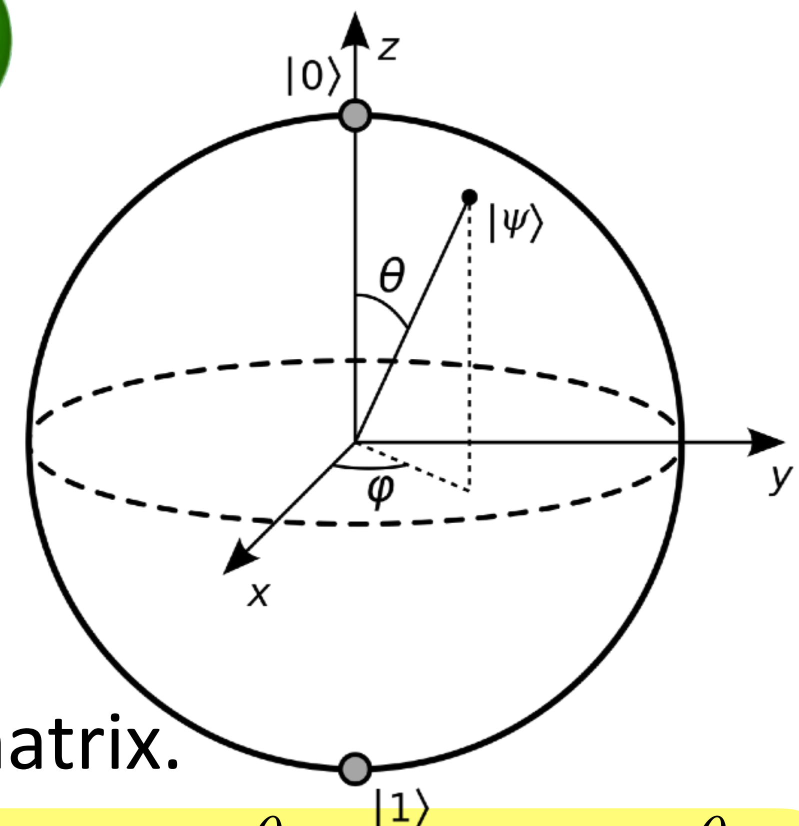


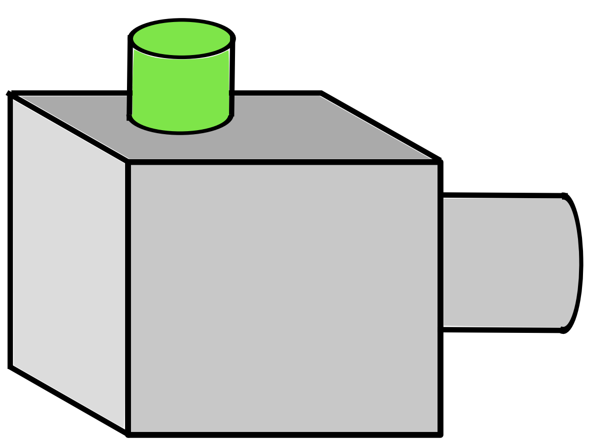



- The preparation device prepares a qubit in some quantum state $\rho = |\psi\rangle\langle\psi|$,

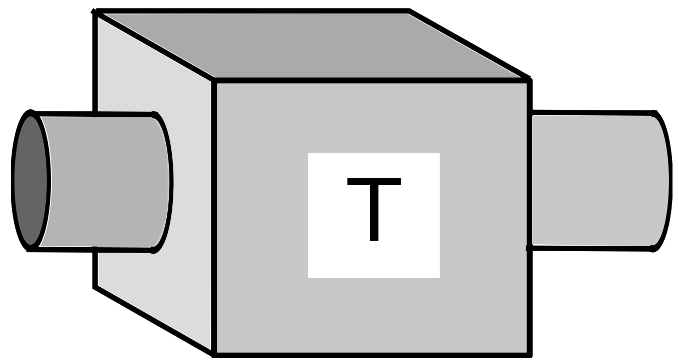
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

More generally: $\rho$ is (mixed-state-)2x2 density matrix.

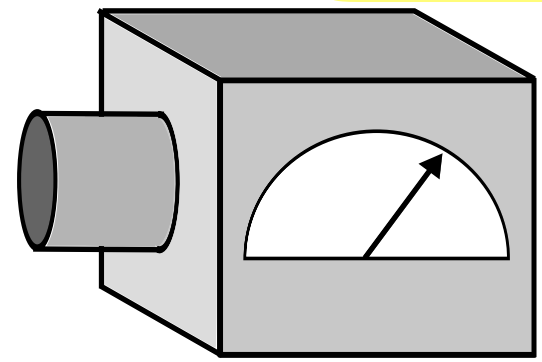
$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle$$



Preparation



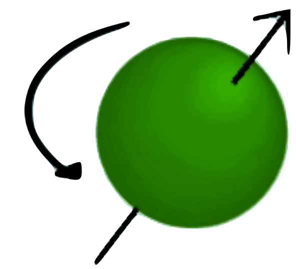

transformation



measurement

# Generalized probabilistic theories

**Example**: quantum bit.



- Unitary transformation of the density matrix:

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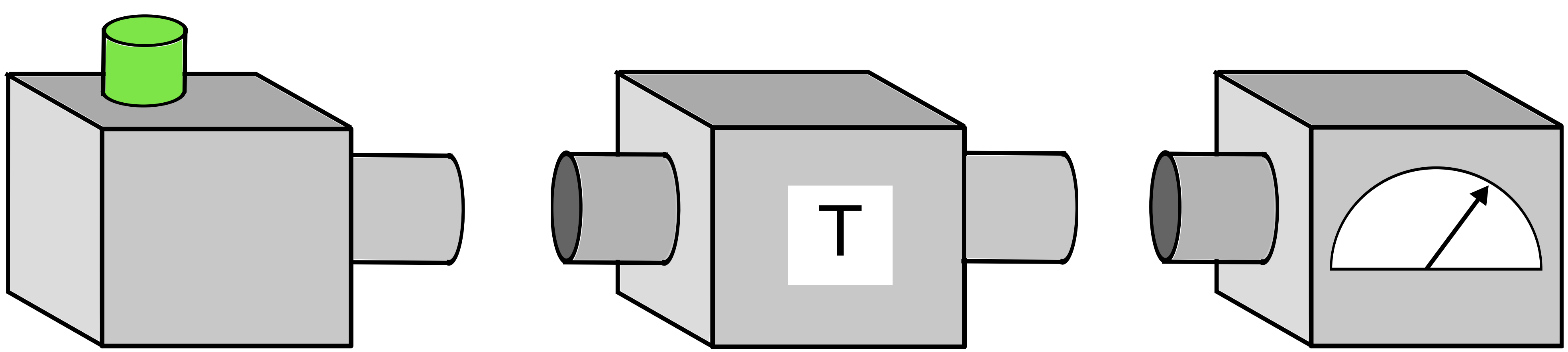


Preparation transformation measurement

## Generalized probabilistic theories

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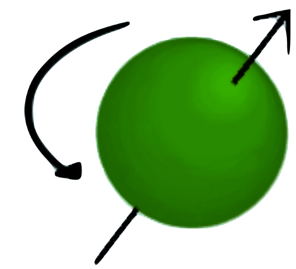

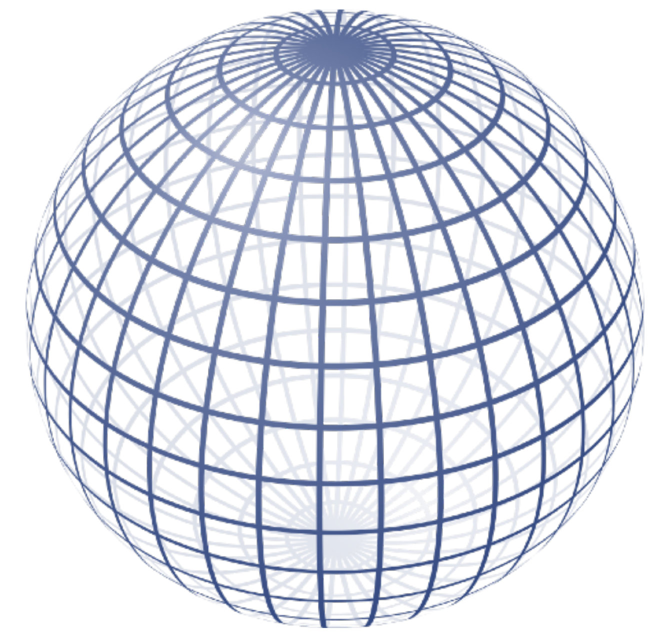

- Unitary transformation of the density matrix:

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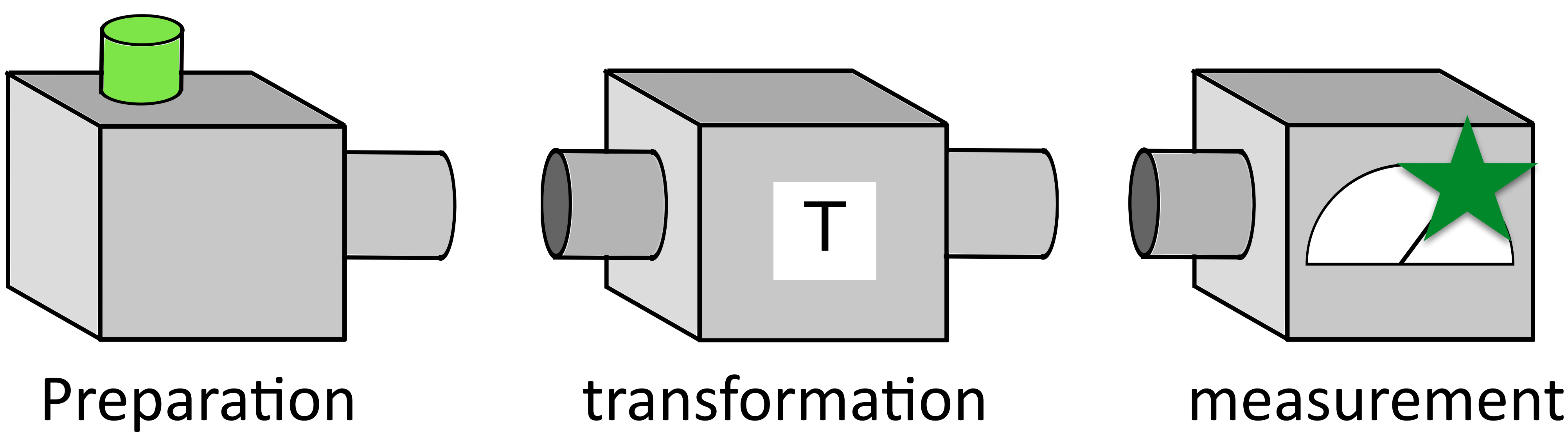
- Measurement in arbitrary spin direction *d*:

$$\mathrm{Prob}(\uparrow|\rho) = \mathrm{tr}(P_d\rho).$$



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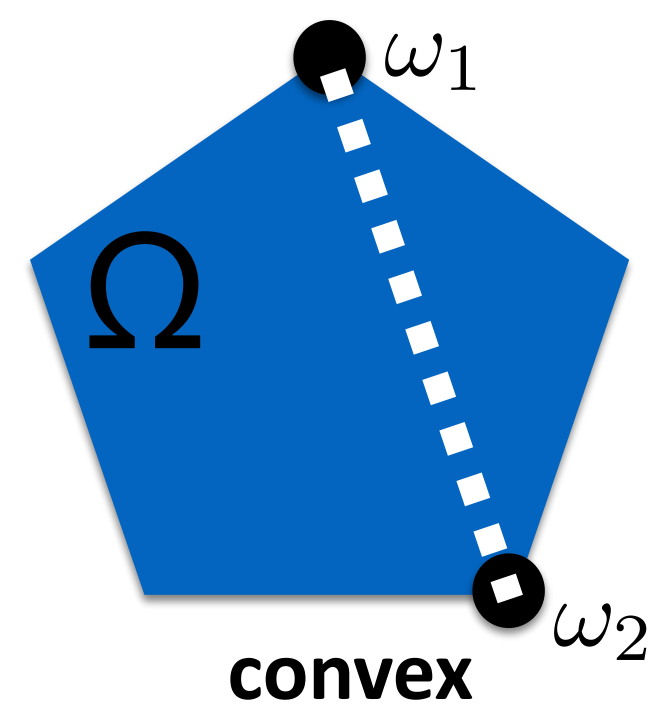

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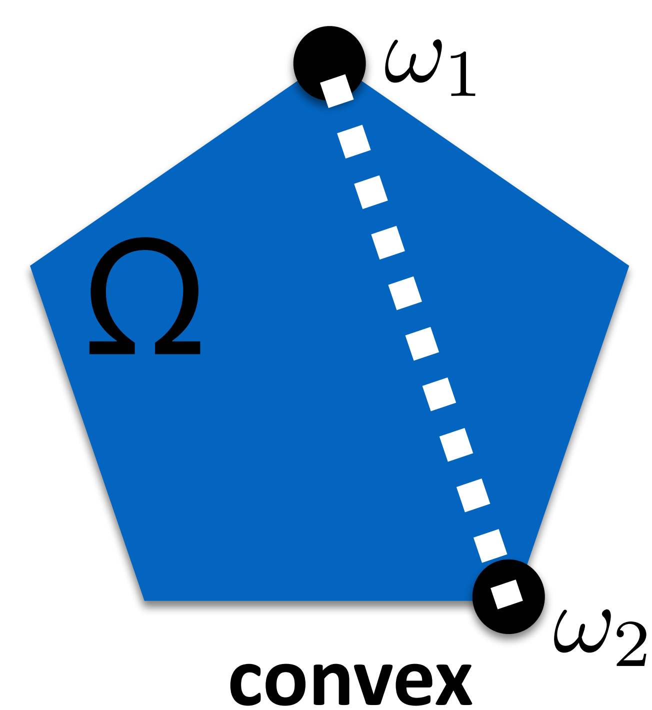

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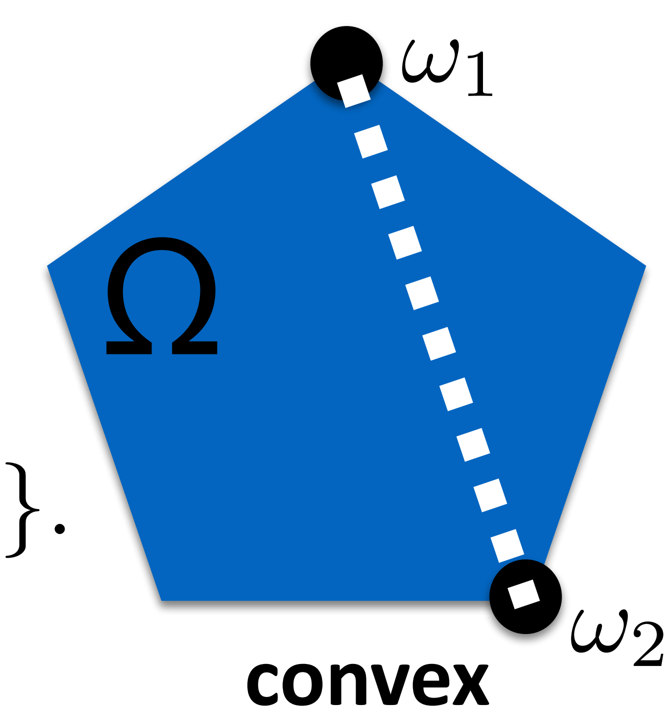
**CPT:** $\Omega = \{(p_1, \ldots, p_N) \mid p_i \geq 0, \ \sum_i p_i = 1\}$.



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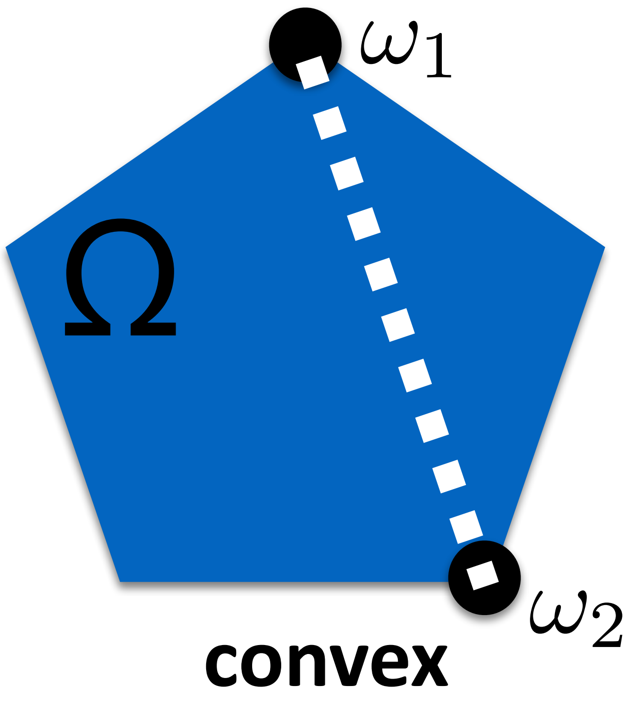

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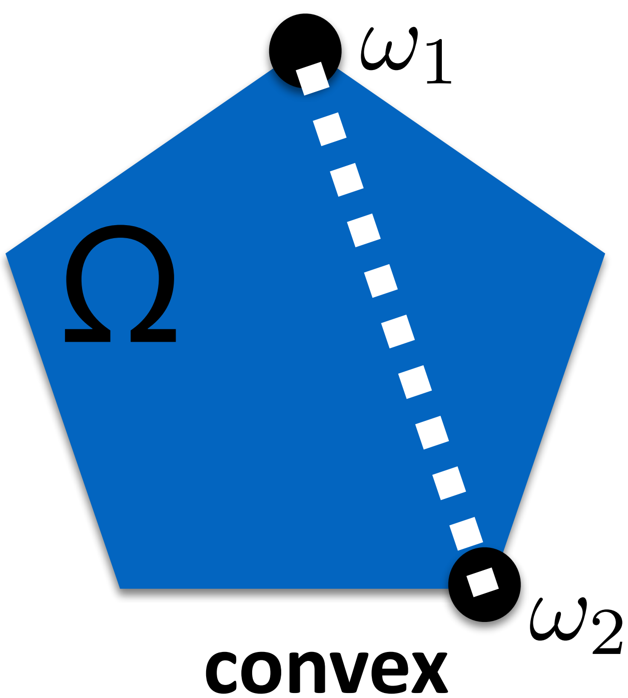

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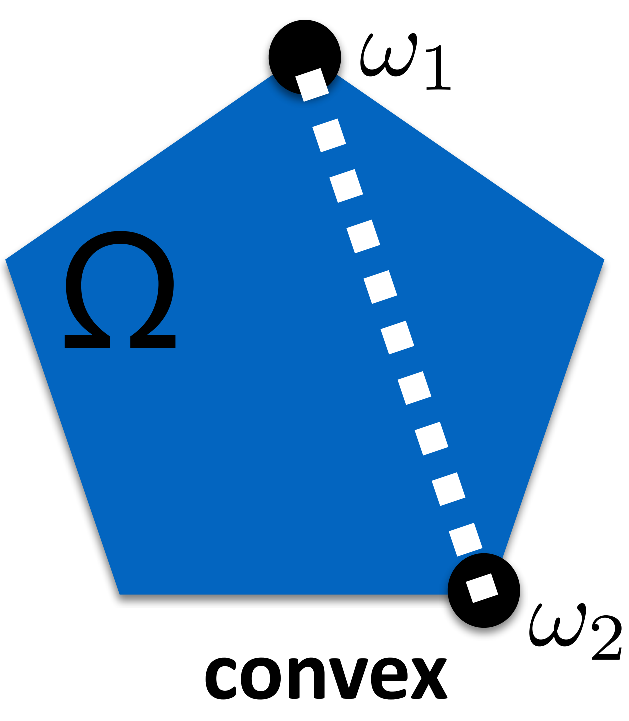

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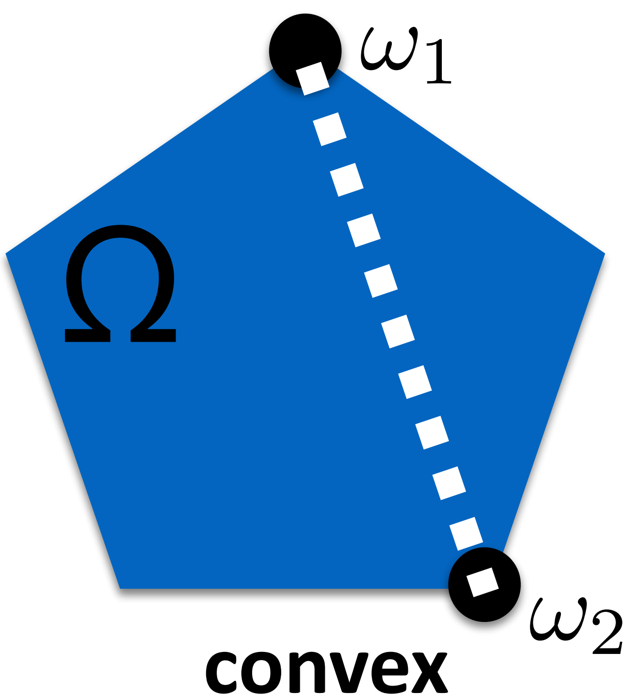
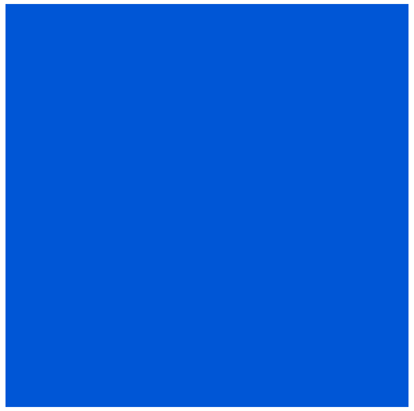
  $e_i(\omega) = \mathrm{tr}(E_i \omega)$.



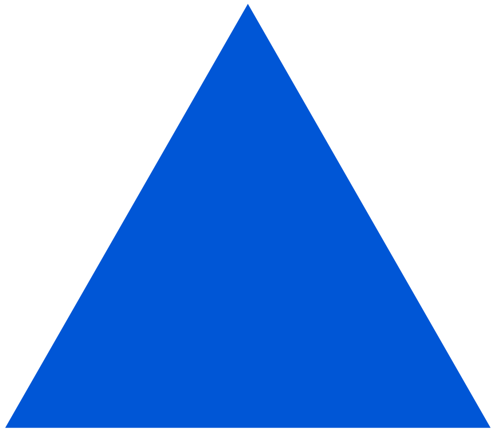
# Generalized probabilistic theories

classical
bit

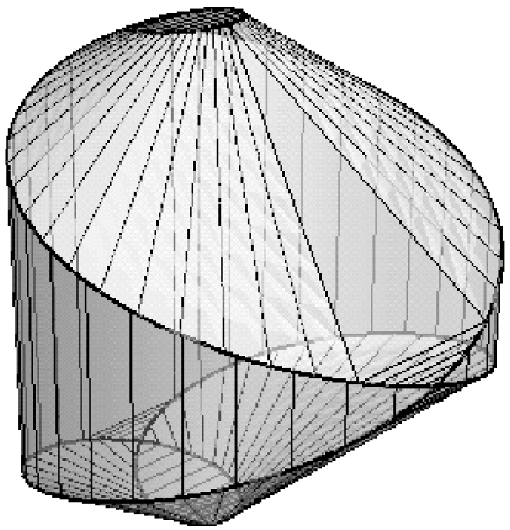
quantum
bit



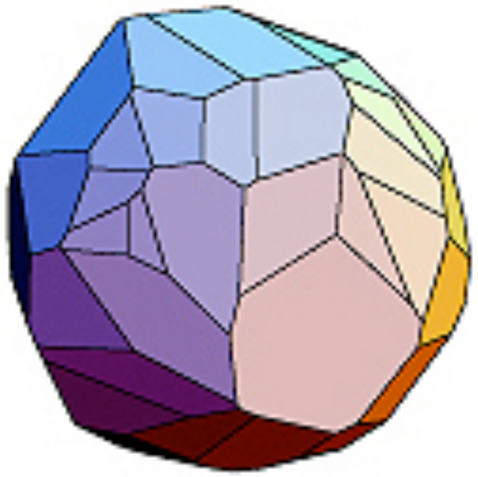
"gbit"



Classical trit
(3-level-system)



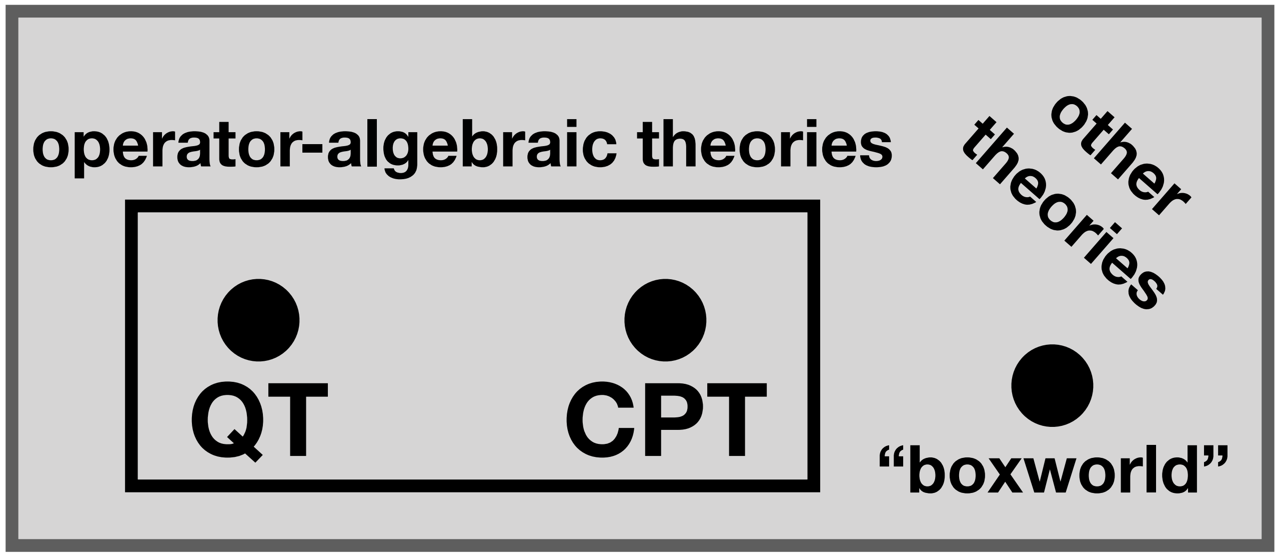
Quantum trit:
8D and complicated!



Arbitrary convex
state space

## Generalized probabilistic theories

There is a large landscape of generalized probabilistic theories or GPT systems:



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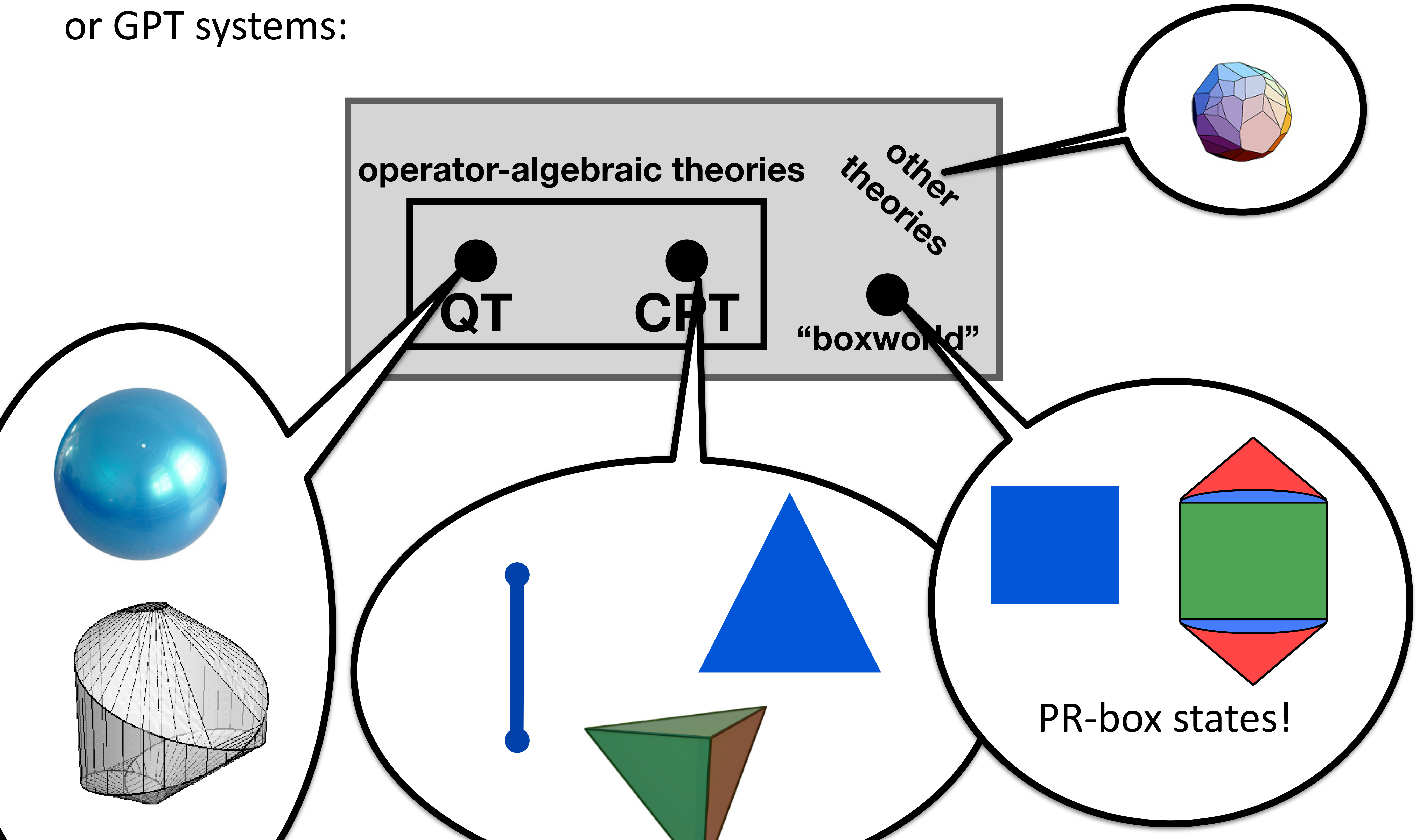

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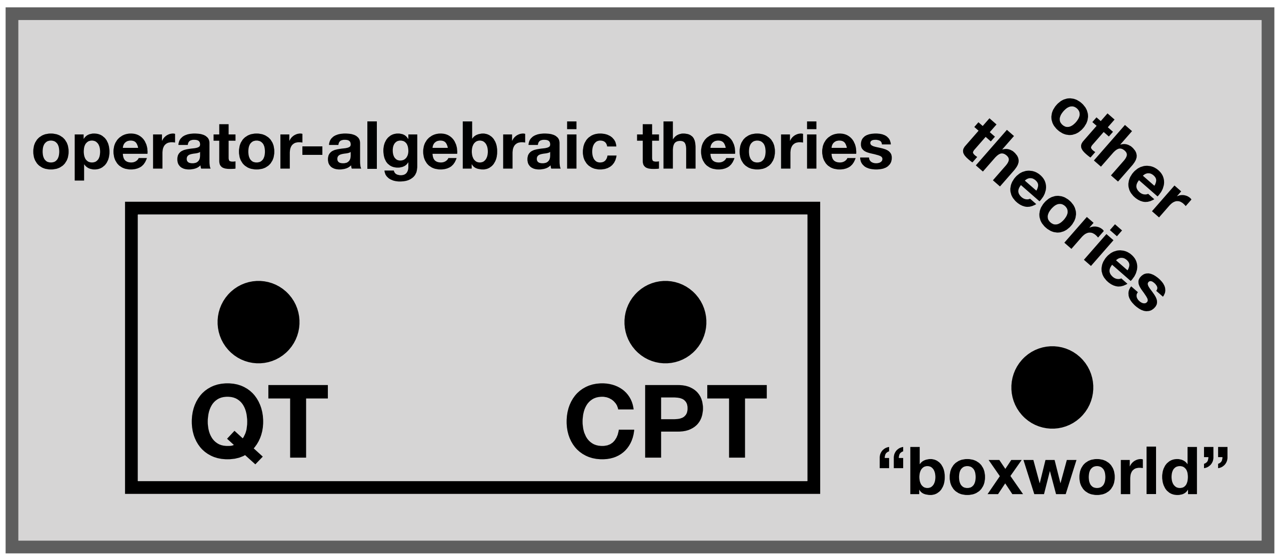

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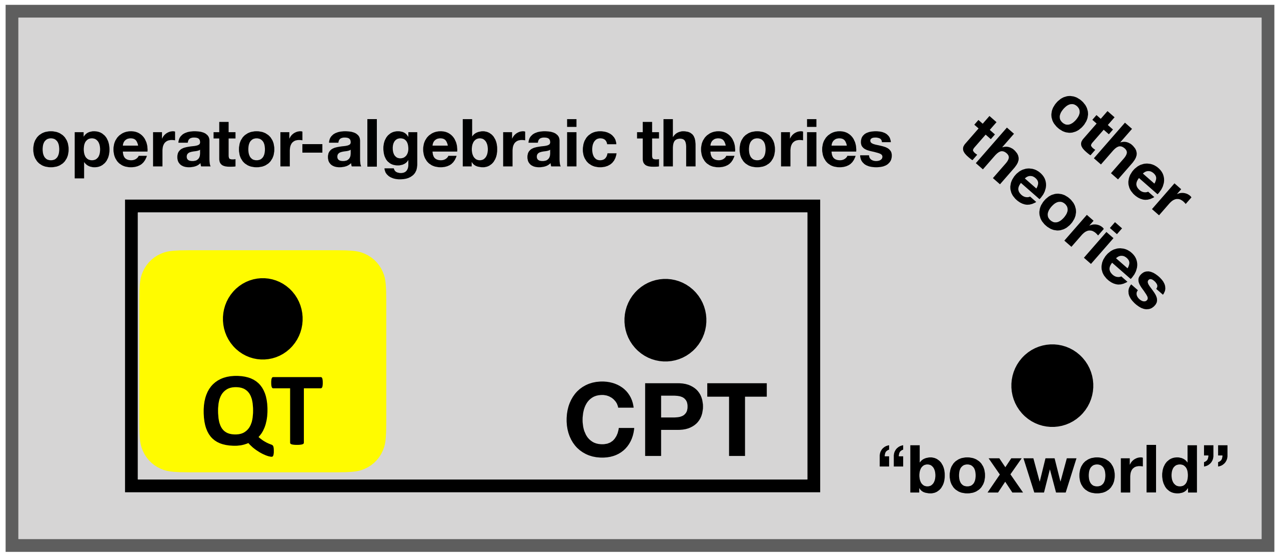


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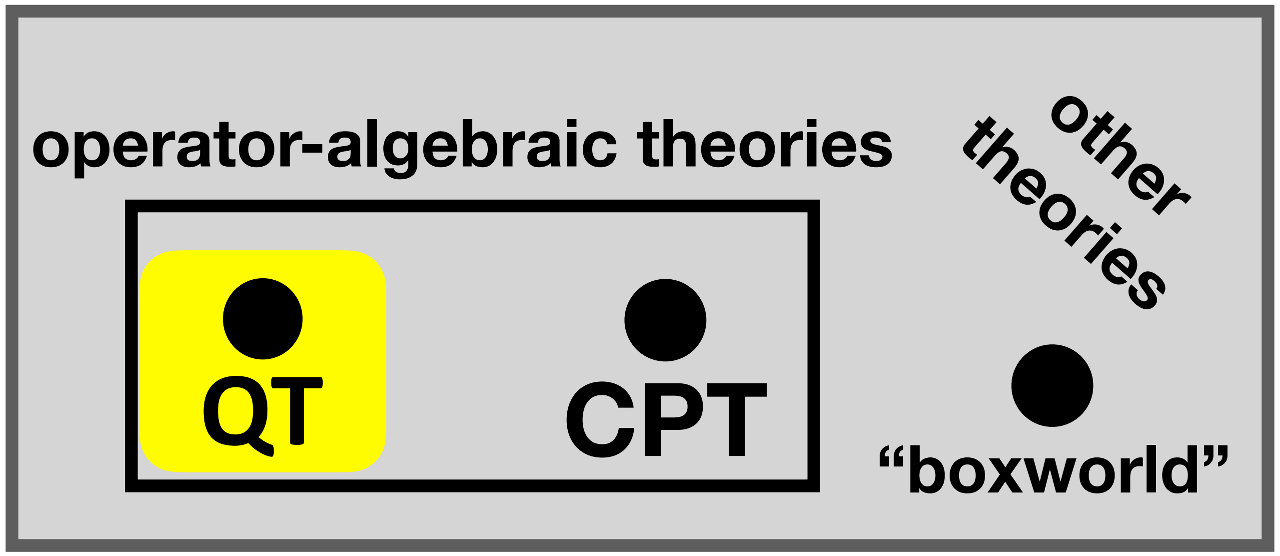
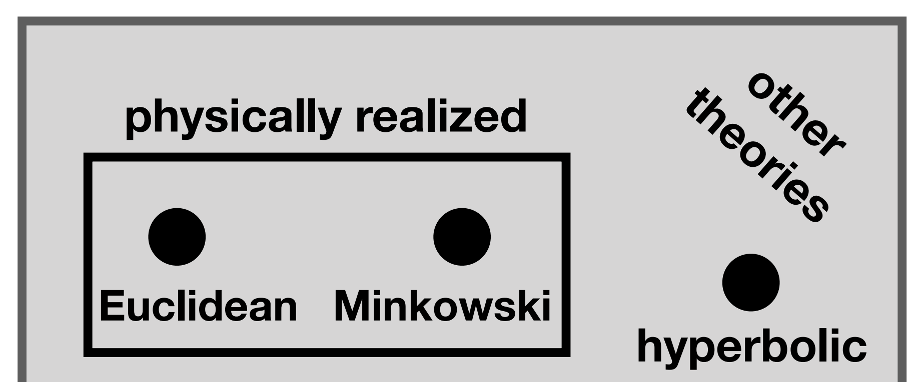



**Goal:** Find a small set of simple physical / information-theoretic **principles** that singles out QT uniquely.

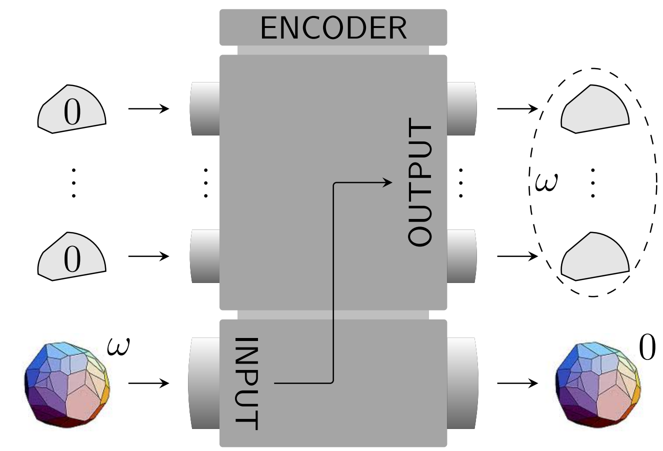
**Role model:** Einstein's **Relativity Principle** and **Light Postulate** determine Minkowski spacetime.



# Overview

1. Probabilistic theories beyond quantum theory

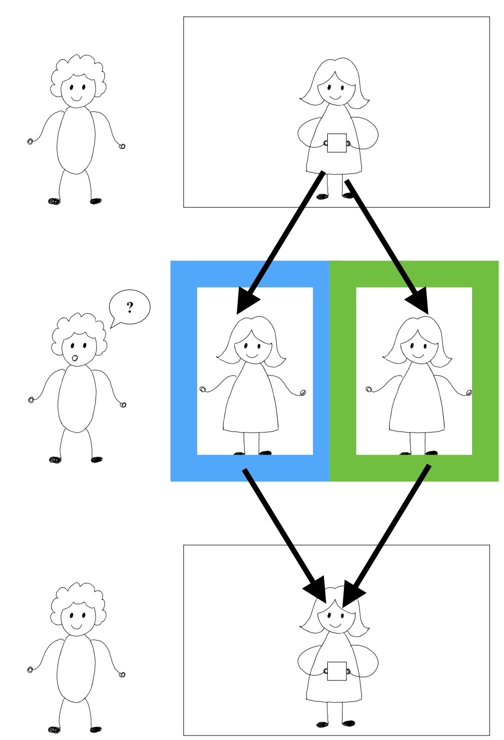
2. Quantum theory from simple principles




3. Reproducing Wigner's Friend phenomena classically

4. Restriction A

When physics fails to allow agents to predict their future experiences

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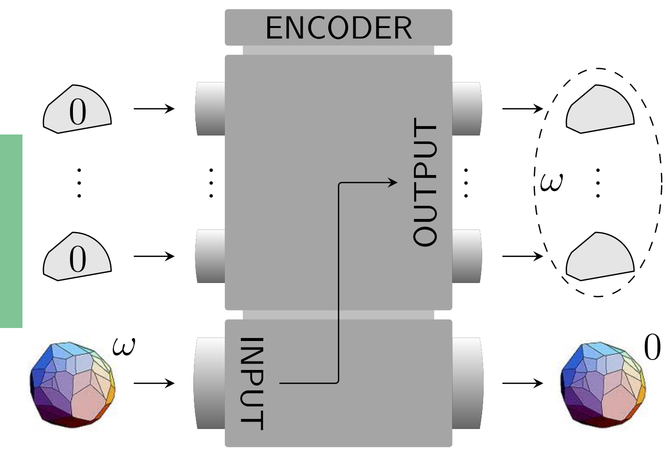


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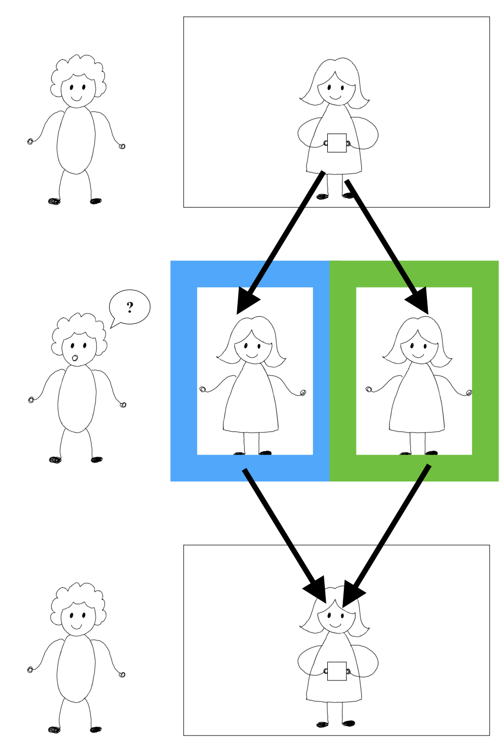


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## A reconstruction of quantum theory

- Prehistory:

  Birkhoff & von Neumann (1936); quantum logic (Piron, ...), Ludwig (1954); Alfsen&Shultz (≈1980); .....

- Quantum information revolution:

  **L. Hardy 2001:** Quantum Theory From Five Reasonable Axioms. But needs "simplicity axiom"...

- Clifton, Bub, and Halvorson 2002.

  But assumed C*-algebras.

**Dakić+Brukner 2009; Masanes+MM 2009**
**Chiribella, d'Ariano, Perinotti 2010**; Hardy 2011
*the one I'll present now* 2013;
Barnum, MM, Ududec 2014; Hoehn 2015;
Wilce 2016, ...

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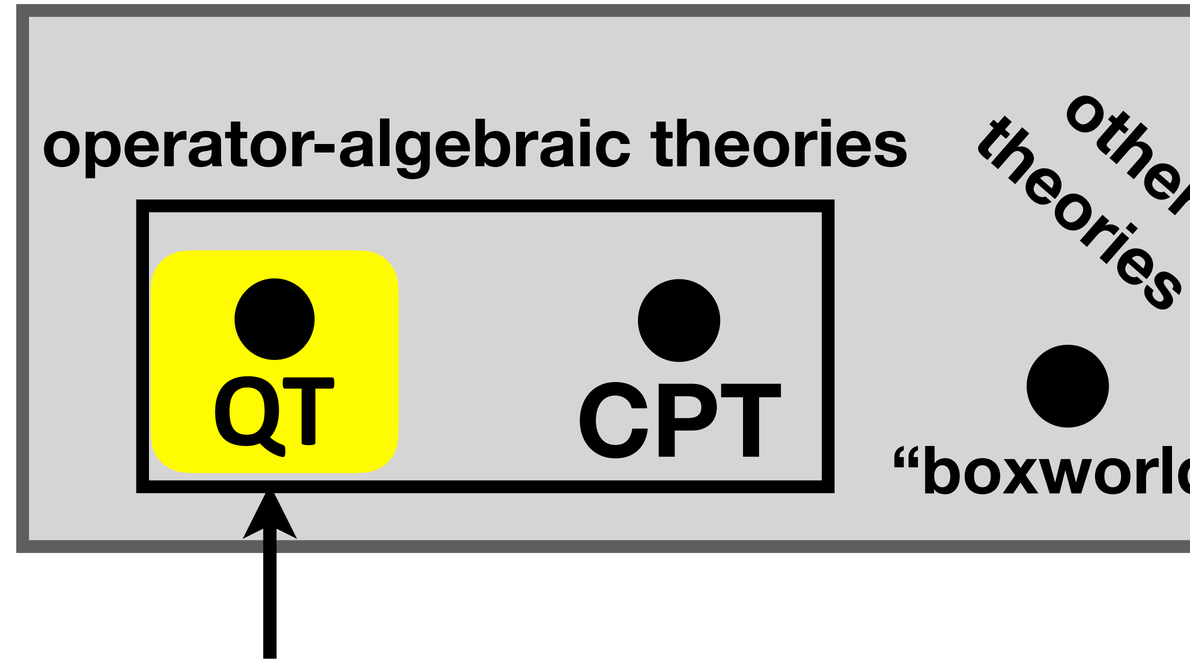


Which principles
single out quantum theory?

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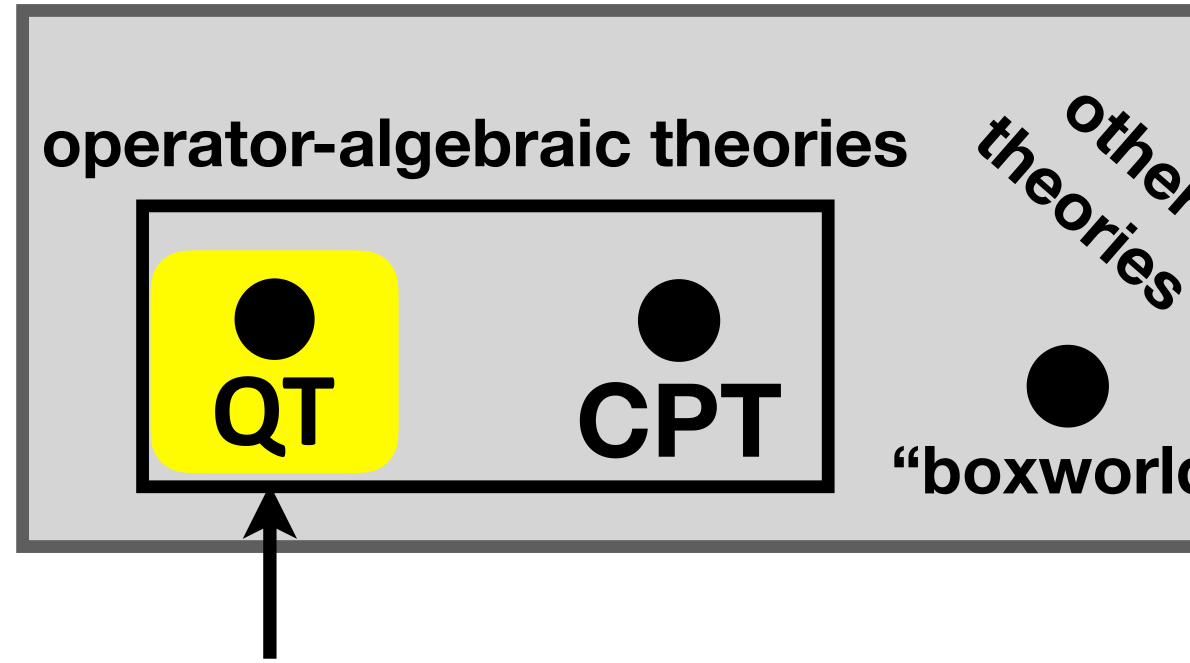
Ll. Masanes, **MM**, R. Augusiak, and D. Pérez-García, PNAS **110**(4), 16373 (2013).

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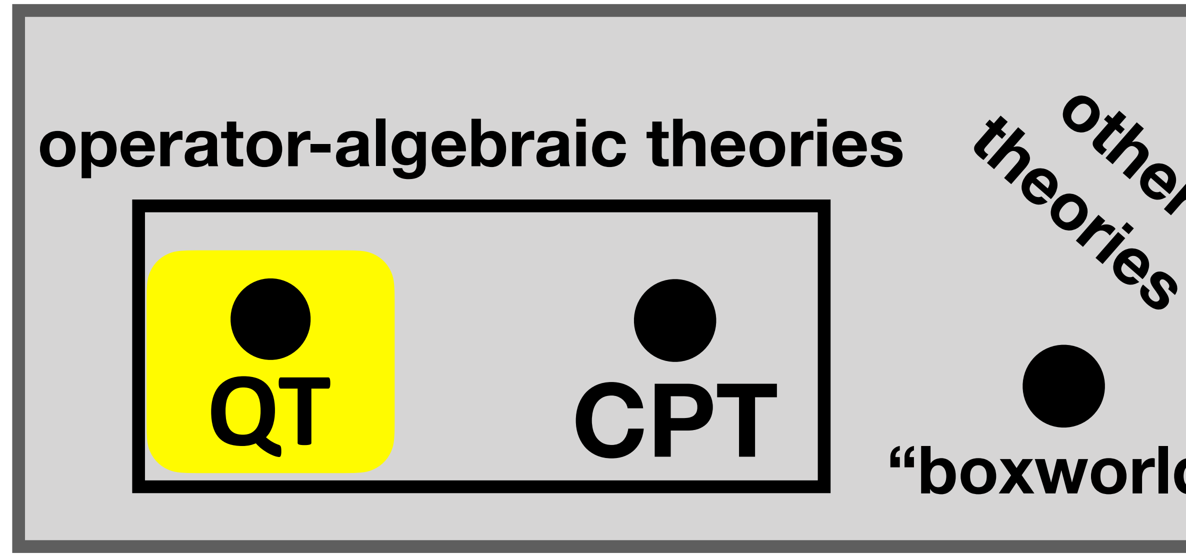
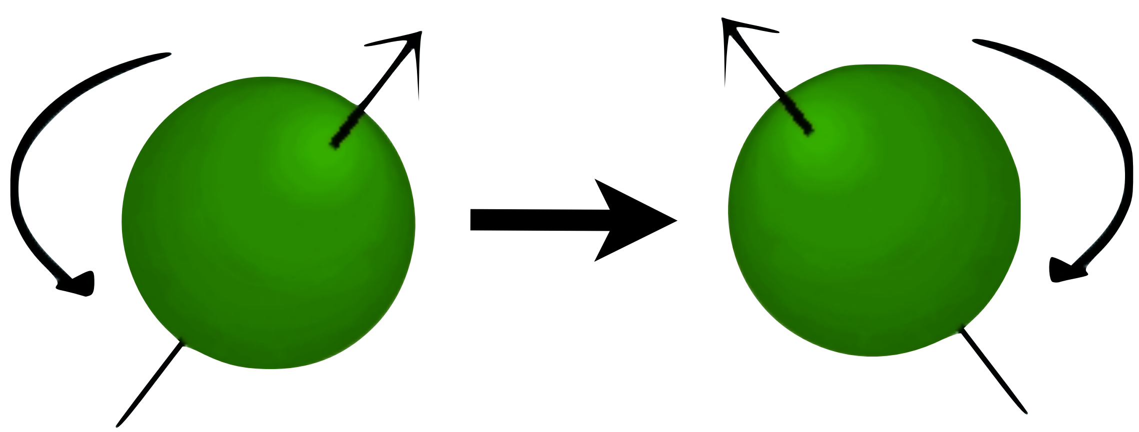



*Reversible transformations can (in principle) map every pure state continuously to every other.*



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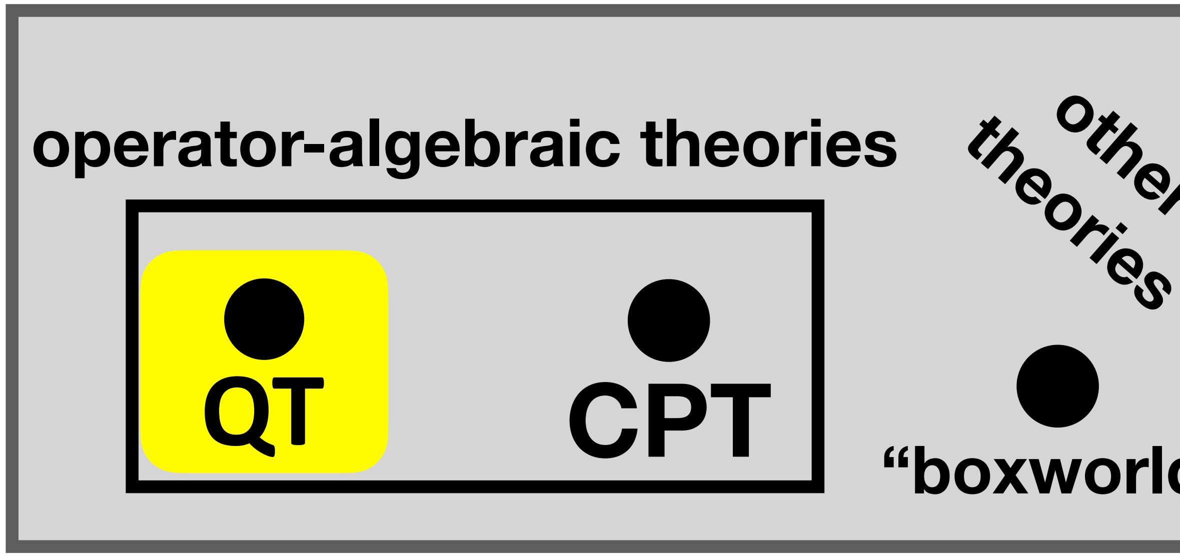
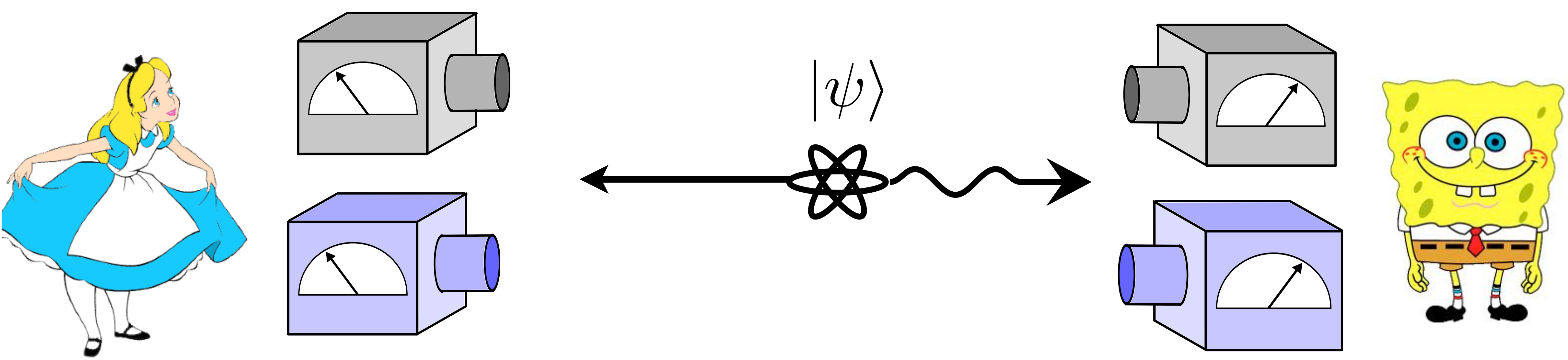



*The state of a composite system is completely characterized by the correlations of measurements on the individual components.*



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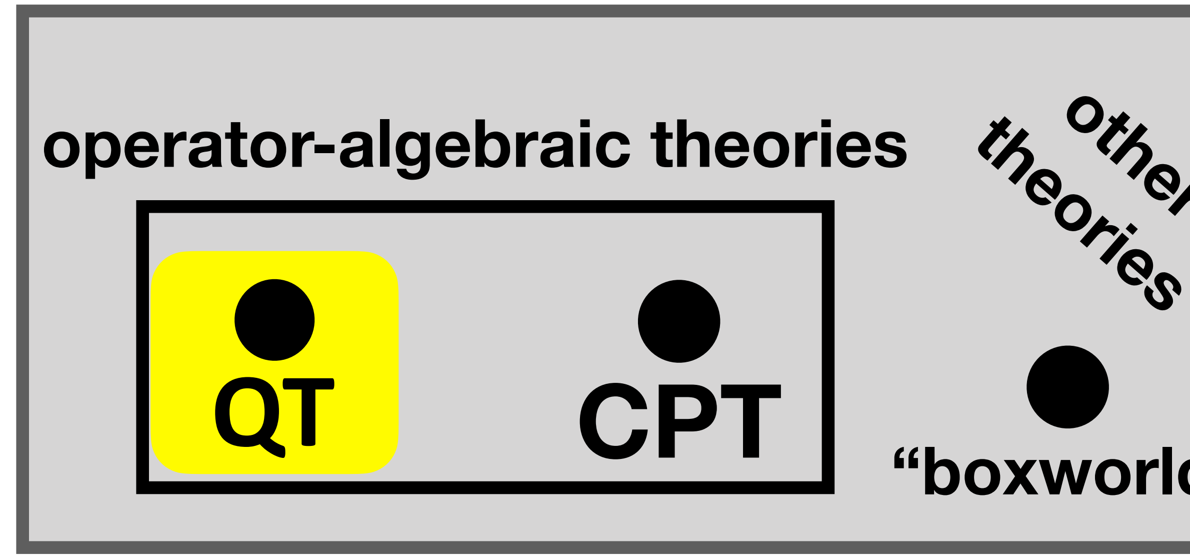

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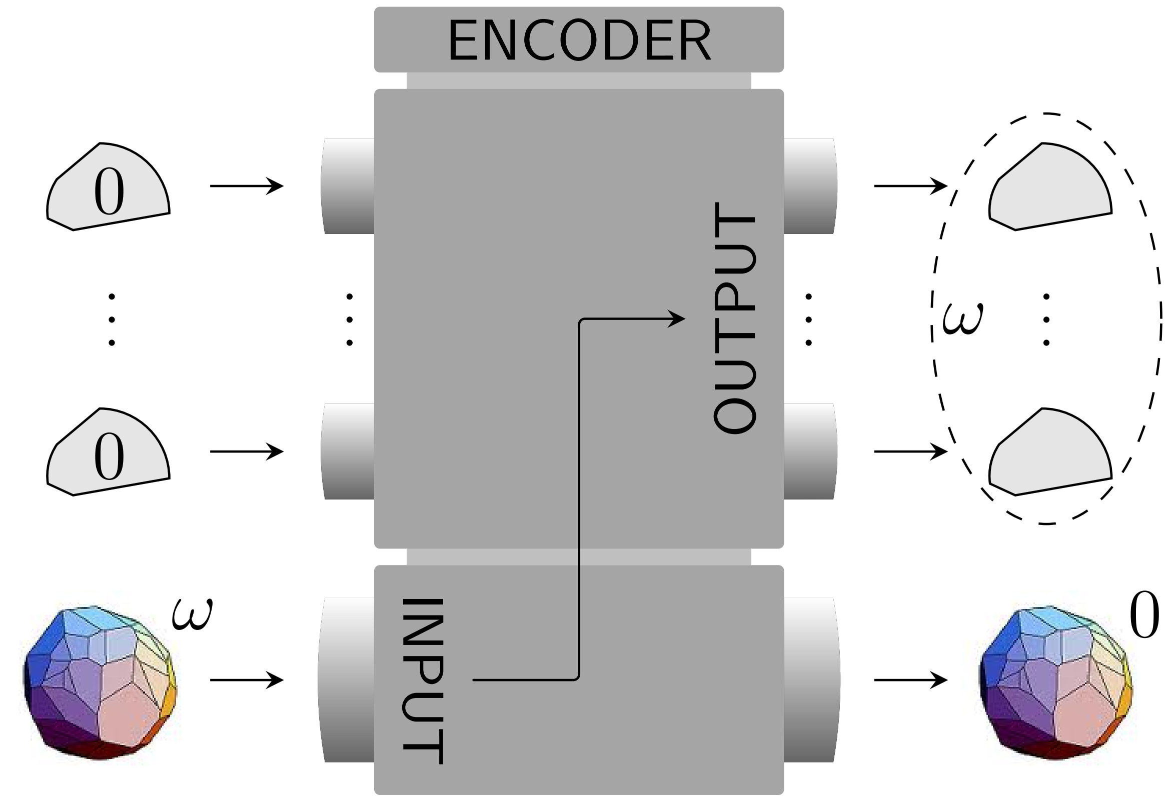


*There is a type of system (the "ubit") such that every system can be encoded into a sufficiently large number of ubits.*

*Pairs of ubits can continuously reversibly interact.*

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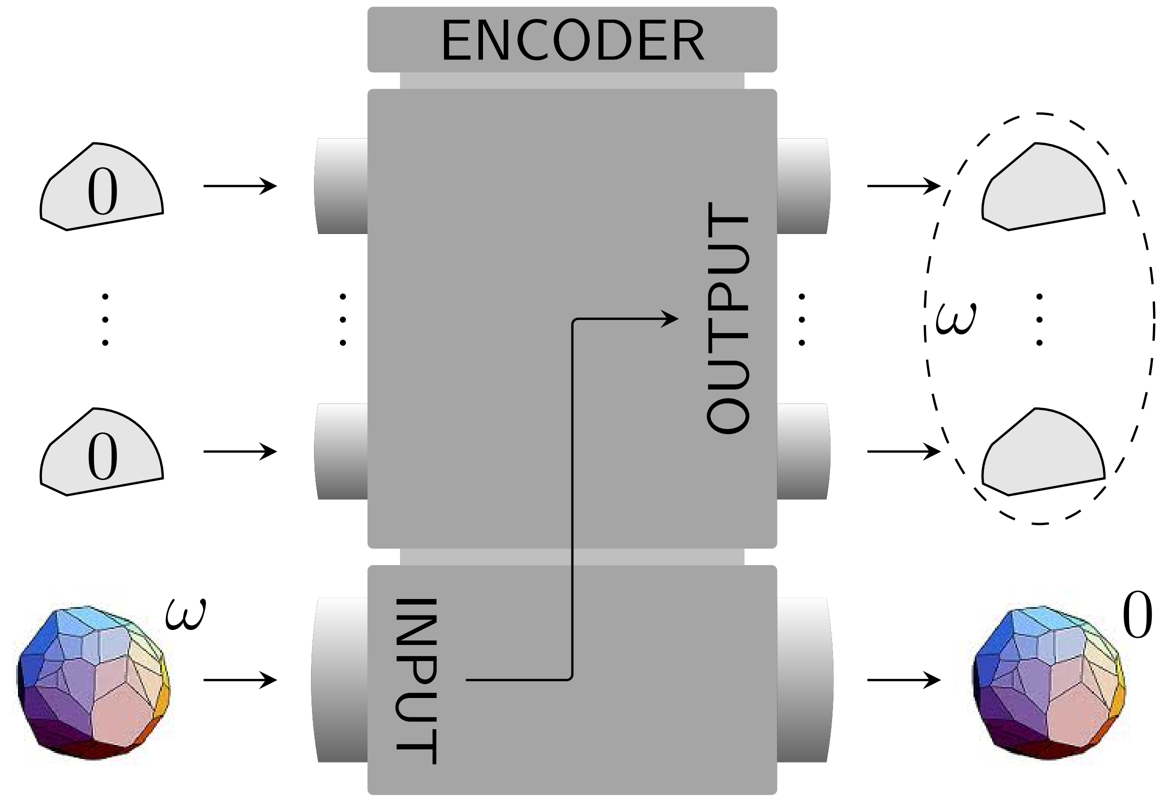


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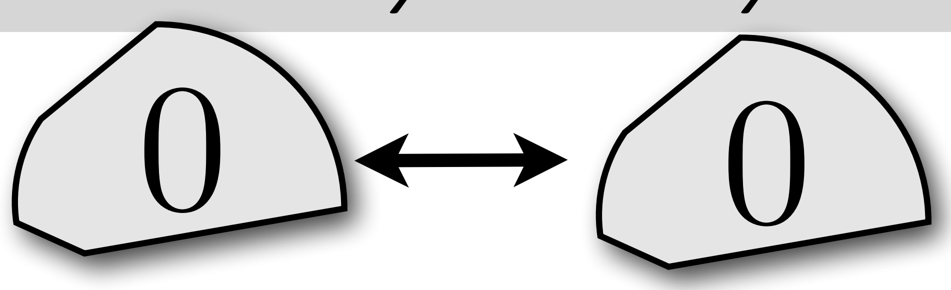

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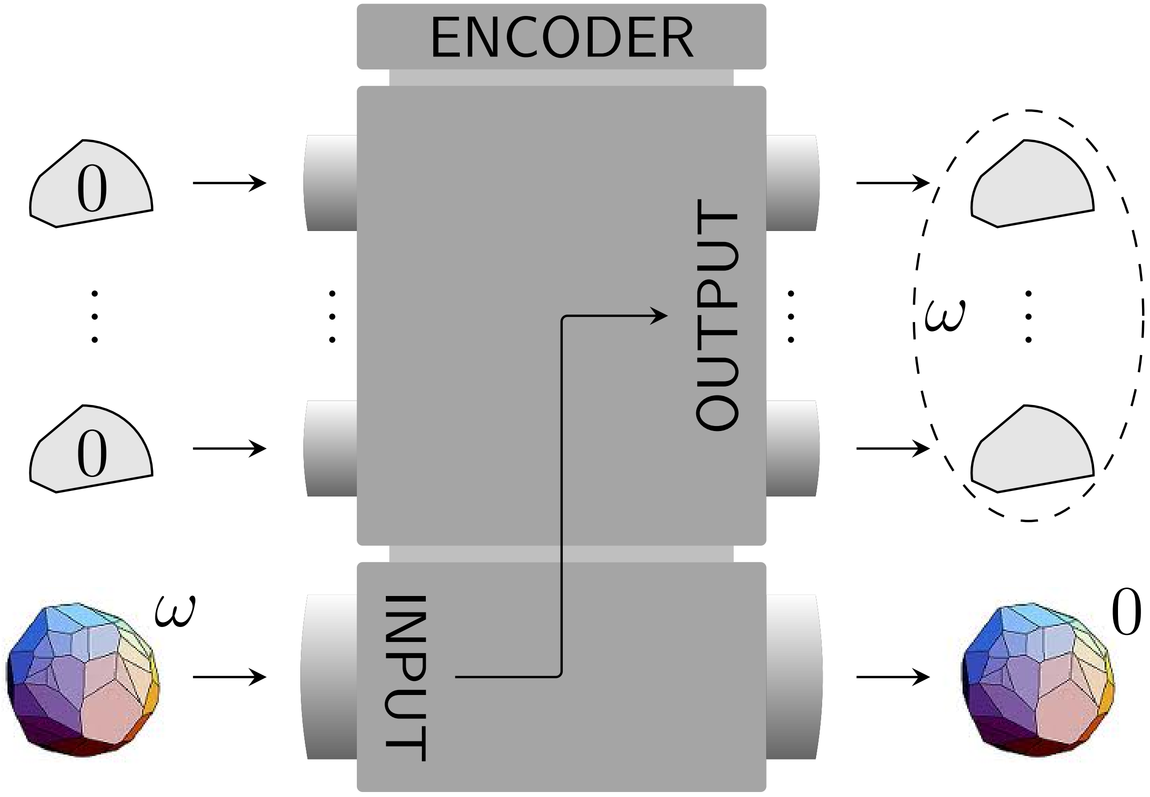


*If a ubit is used to perfectly encode one classical bit, it cannot simultaneously encode any further information.*

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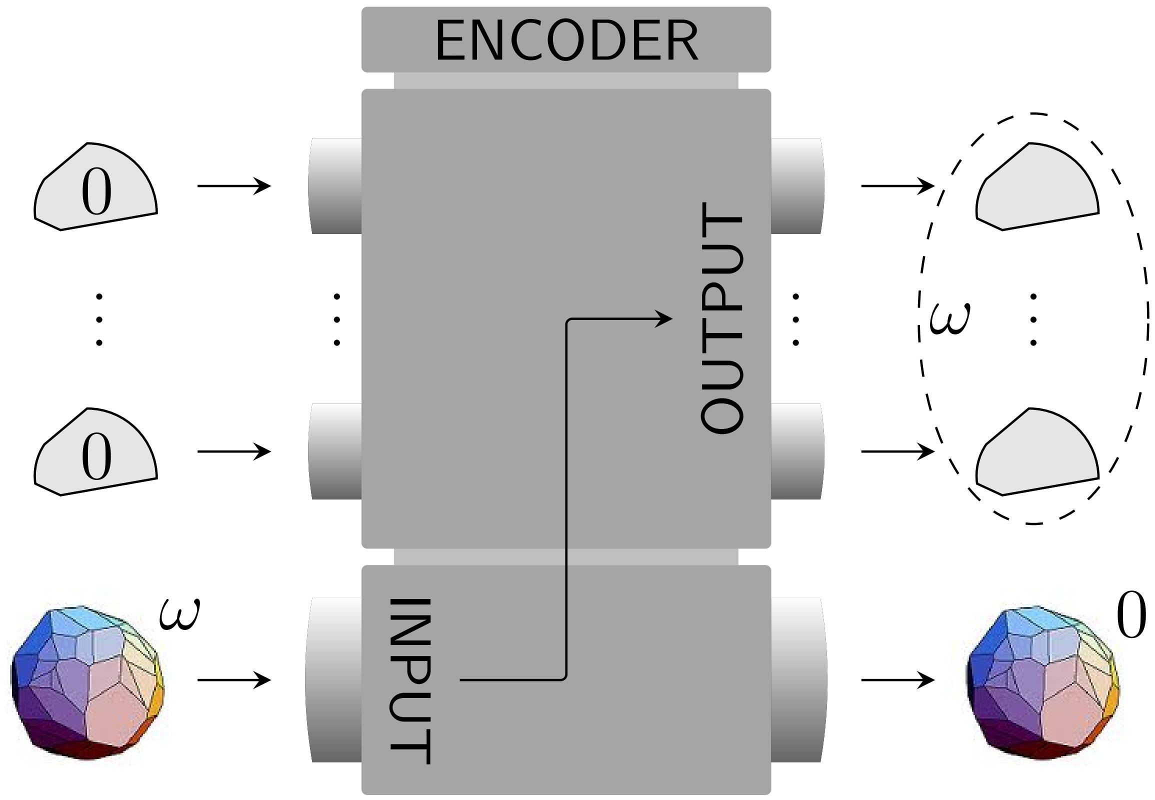


**Theorem.** If Postulates 1-4 hold, then the state space of *n* ubits is

$$\Omega = \{\rho \in \mathbf{H}_{2^n}(\mathbb{C}) \mid \mathrm{tr}(\rho) = 1, \rho \geq 0\},$$

and the reversible transformations are the unitaries, $\rho \mapsto U\rho U^\dagger$.

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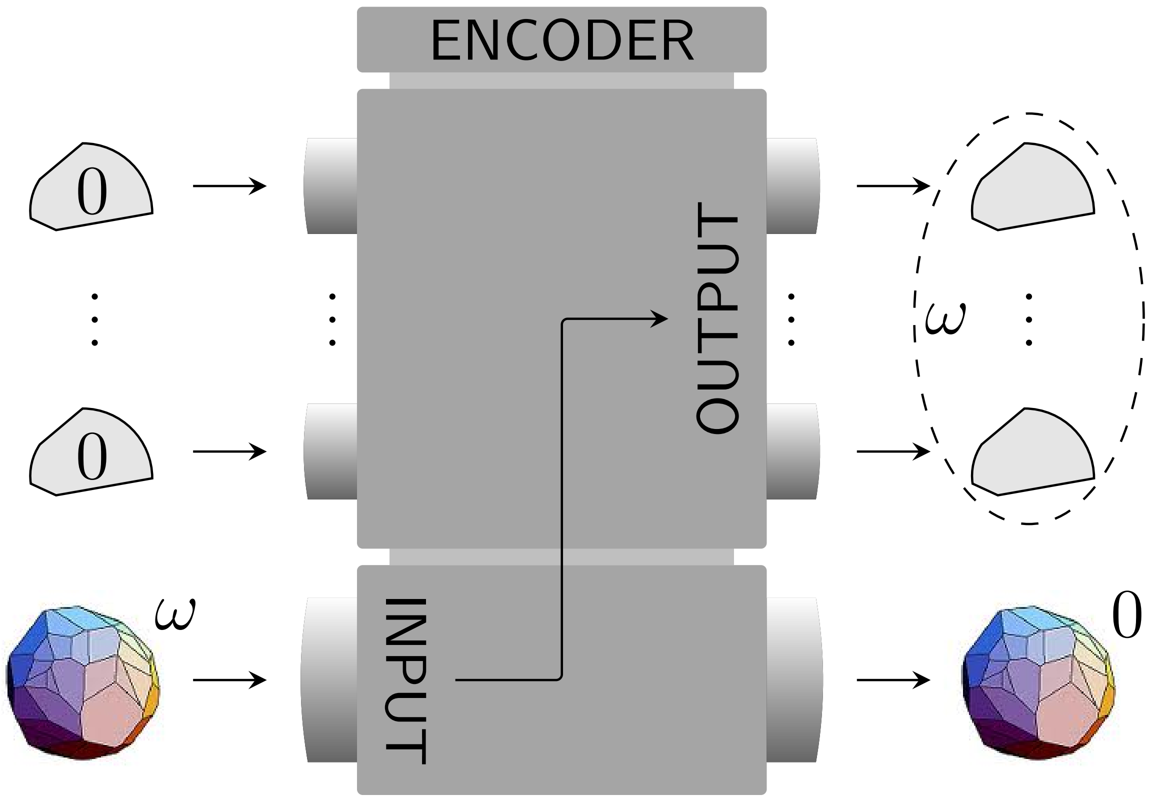


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and the reversible transformations are the unitaries, $\rho \mapsto U\rho U^\dagger$.

- No assumptions on complex numbers, operators, algebras, … were made.
- Drop “continuous” in Postulate 1 -> obtain **classical probability theory**.

# Example: why are ubits balls?

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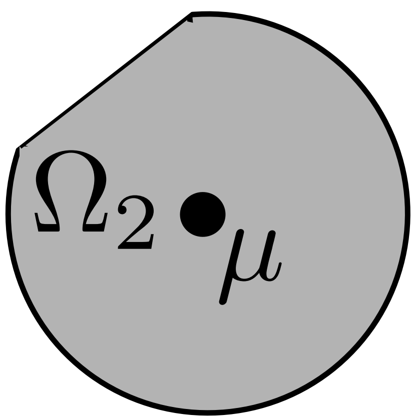
**Group rep. theory:** can reparametrize space such that transformations are rotations. Then, pure states lie on unit sphere (of some dim. *d*).



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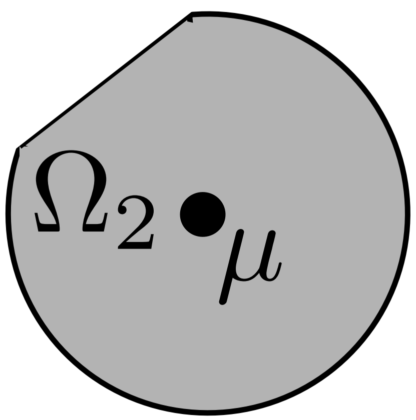


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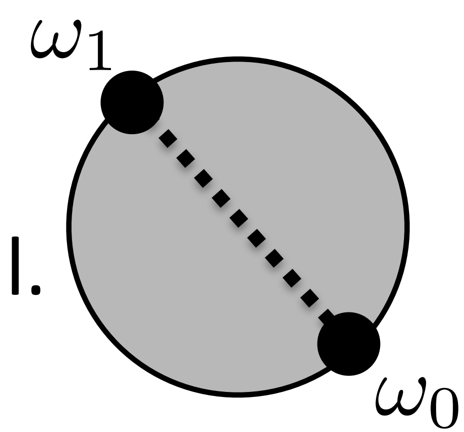

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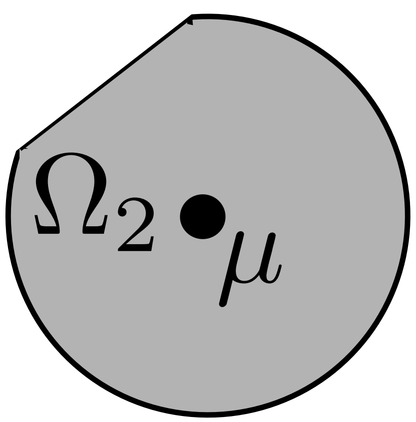


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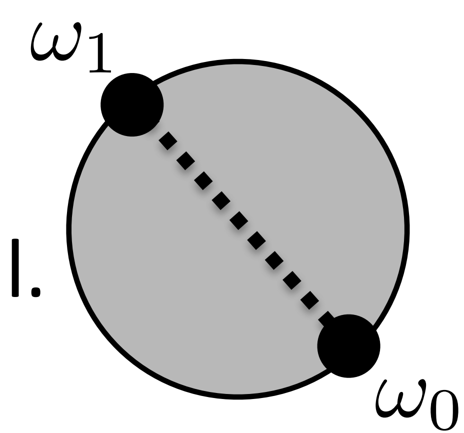
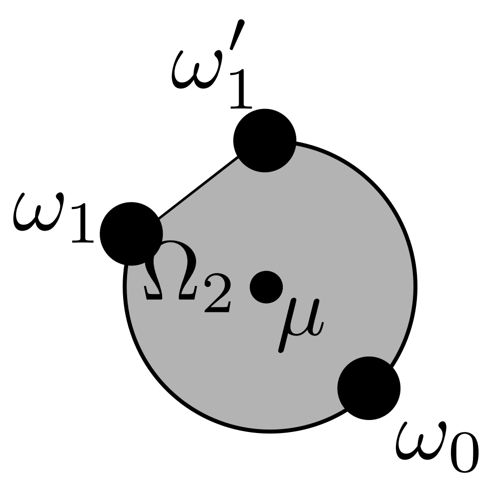



If **not** full ball: can encode one bit **and a little more** by preparing state or **one of** antipodal states.



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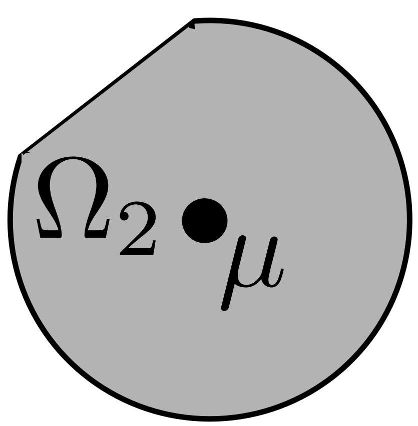


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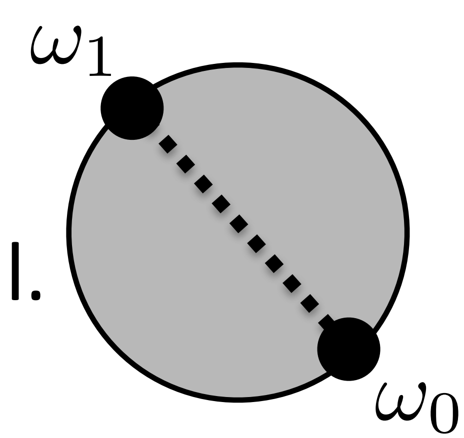


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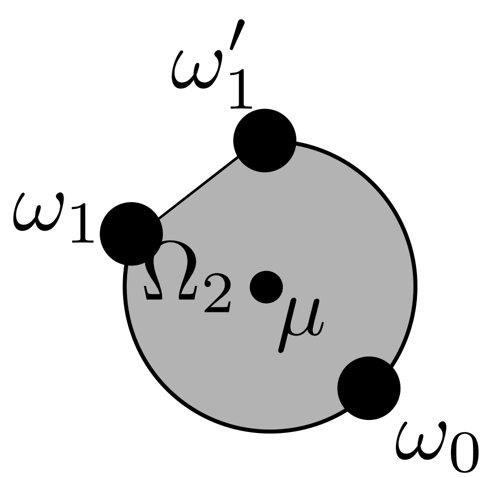


Violates Postulate 4.

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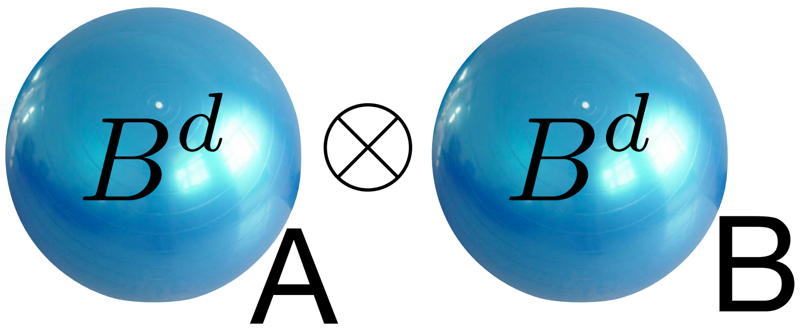


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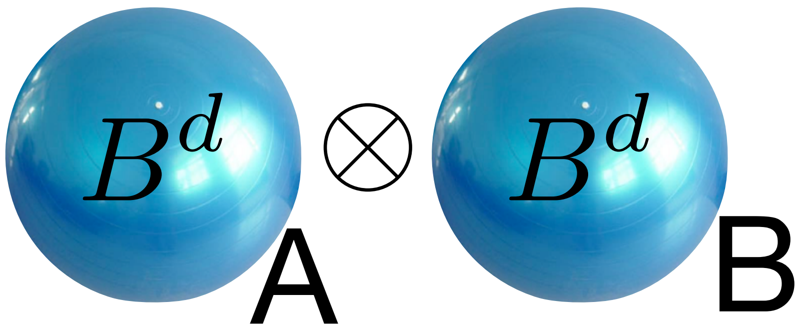


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**Theorem.** Among all dimensions $d$ and all groups $\mathcal{G}_A$, there are only the following possibilities:

- The trivial solution: $\mathcal{G}_{AB} = \mathcal{G}_A \otimes \mathcal{G}_B$.
- $d = 3$, $\mathcal{G}_A = \mathrm{SO}(3)$ (i.e. the quantum bit), $\mathcal{G}_{AB} \simeq \mathrm{PU}(4)$, and $\Omega_{AB}$ is equivalent to the two-qubit quantum state space.

In particular, **continuous reversible interaction** is only possible for $d = 3$, in standard complex two-qubit quantum theory.

Ll. Masanes, **MM**, R. Augusiak, and D. Pérez-García, J. Math. Phys. **55**, 122203 (2014).

# Proof idea

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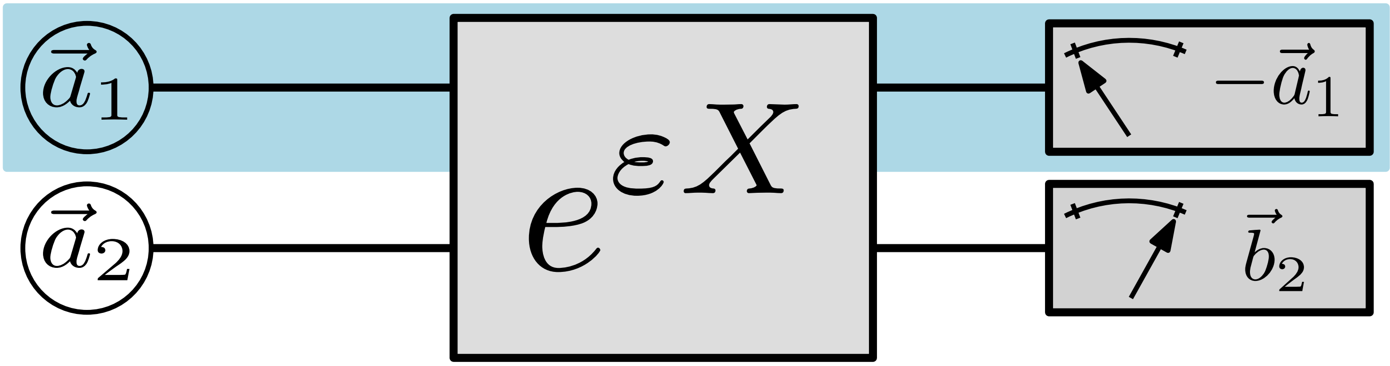
Generator *X* of global reversible transformation (no idea what it is…)



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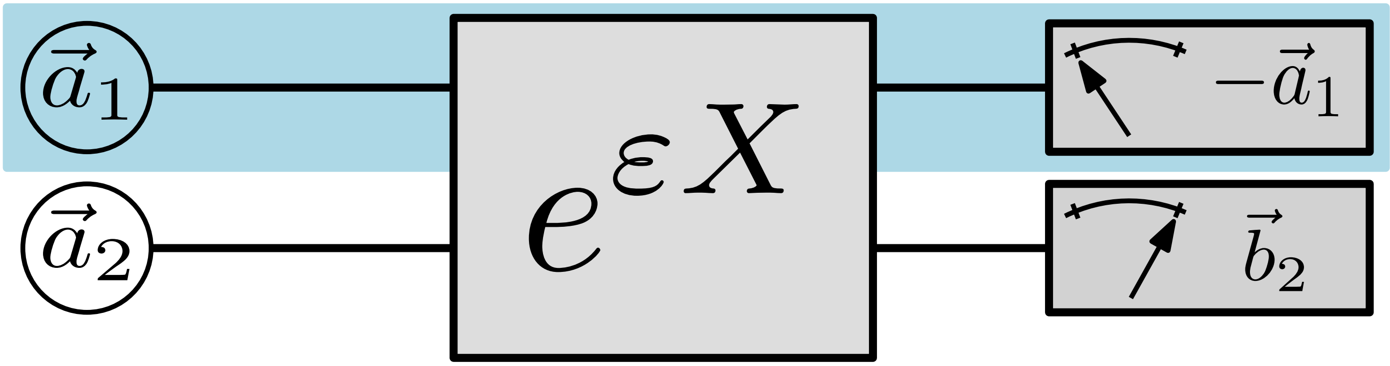


We must obtain **valid probabilities**. For example,

$$0 \leq (e_{-\vec{a}_1} \otimes e_{\vec{b}_2}) e^{\varepsilon X} (\omega_{\vec{a}_1} \otimes \omega_{\vec{a}_2}) \leq 1.$$

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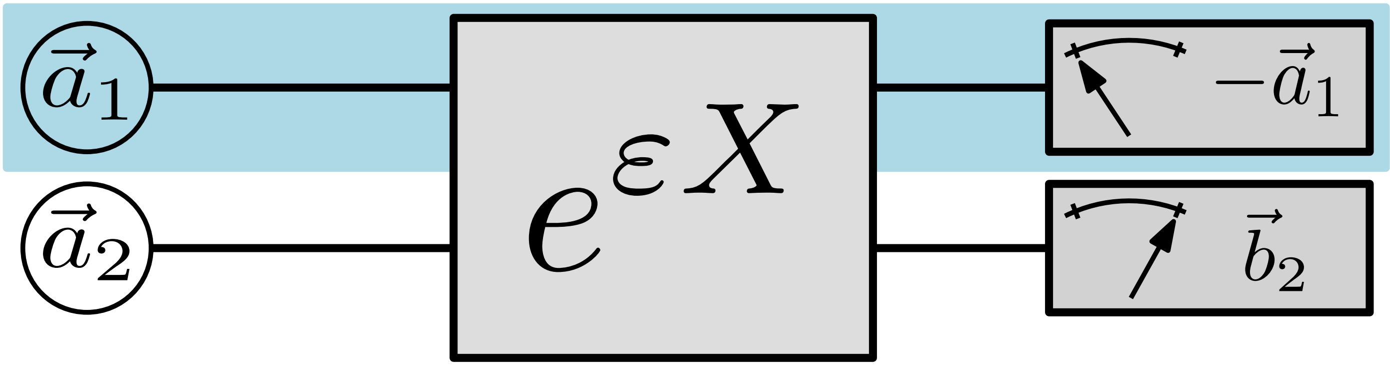


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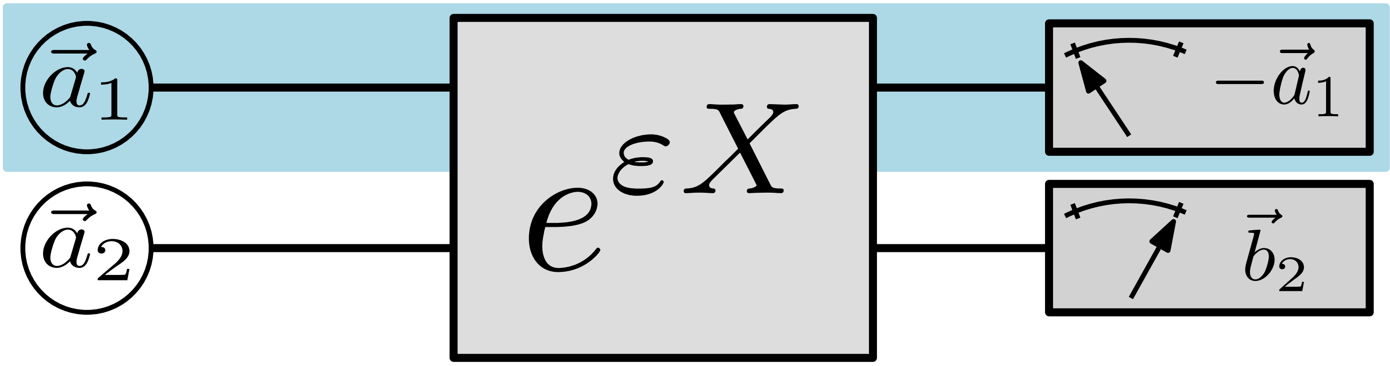


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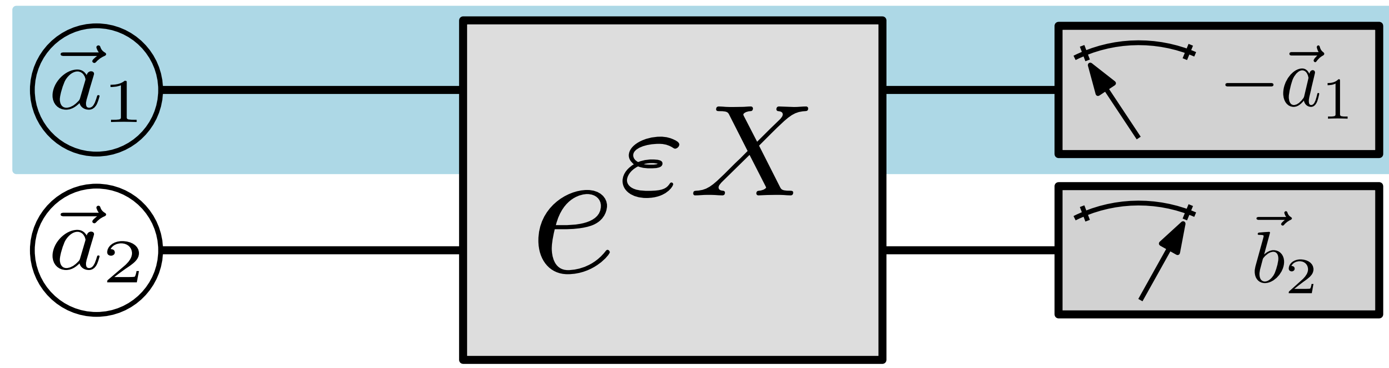


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Main reason: $\mathrm{SO}(d-1)$ is only non-trivial and **commutative** for $d = 3$.

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- **Time evolution**: correlation with idealized clock variables.
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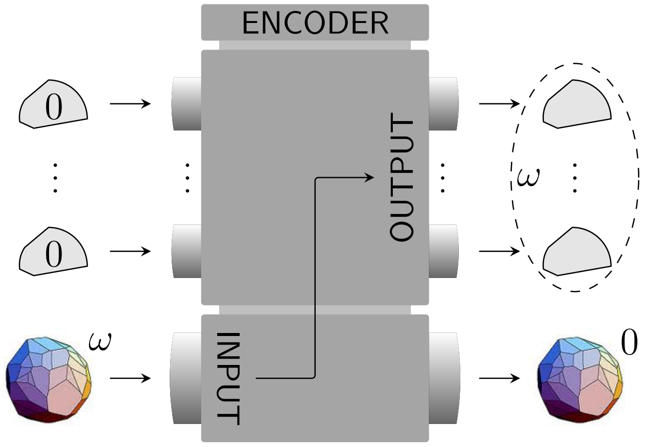
**Challenge to Everettians:** start with a landscape of "theories of many worlds", write down a few simple principles of some kind, and prove that QT is the unique many-worlds-like theory that satisfies those.

A. Koberinski and **MM**, arXiv:1707.05602

# Overview

1. Probabilistic theories beyond quantum theory

2. Quantum theory from simple principles




3. Reproducing Wigner's Friend phenomena classically

4. Restriction A

When physics fails to allow agents to predict their future experiences

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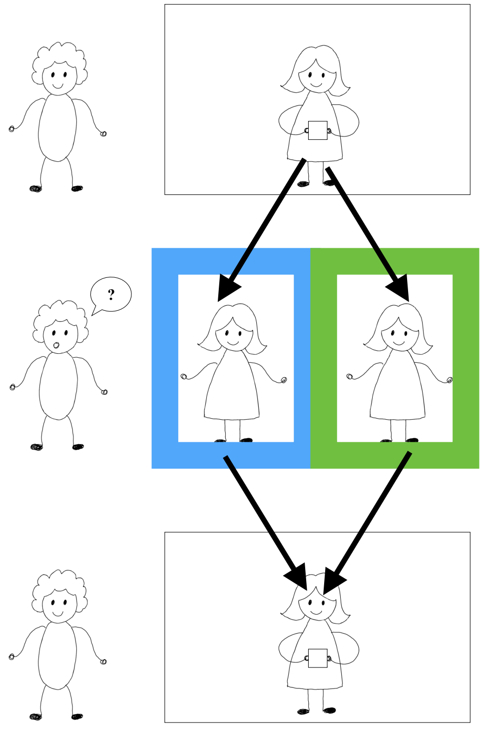

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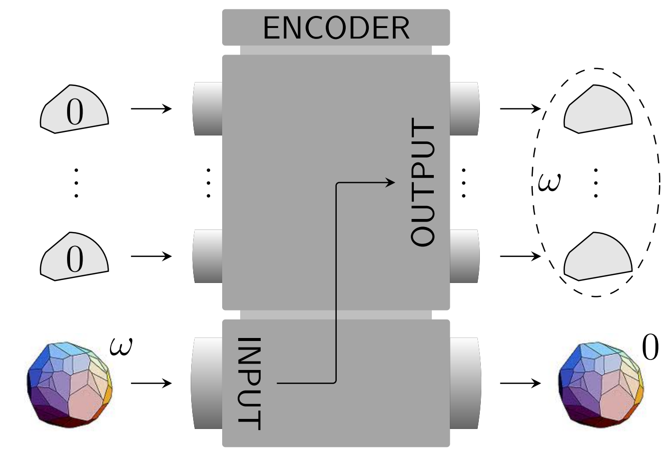


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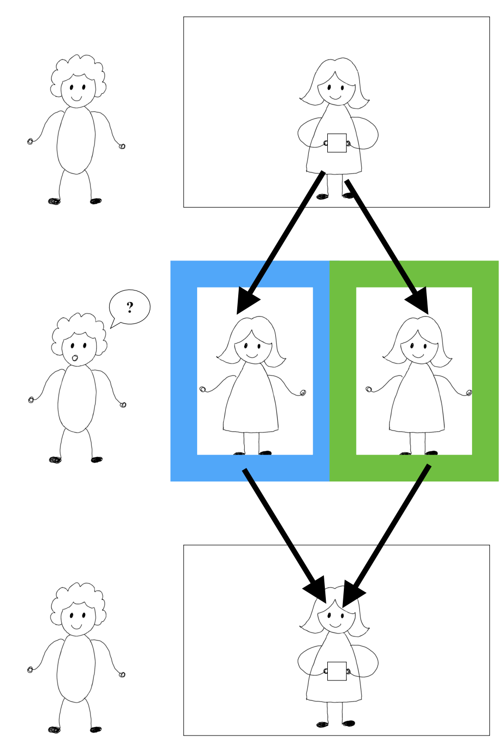

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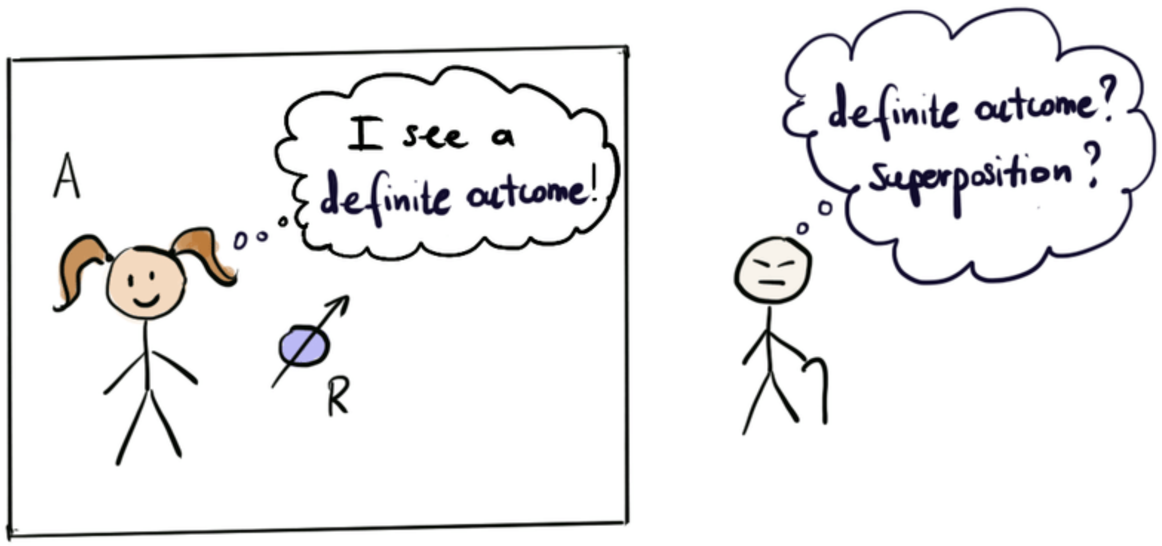


Picture credits: Nurya Nurgalieva

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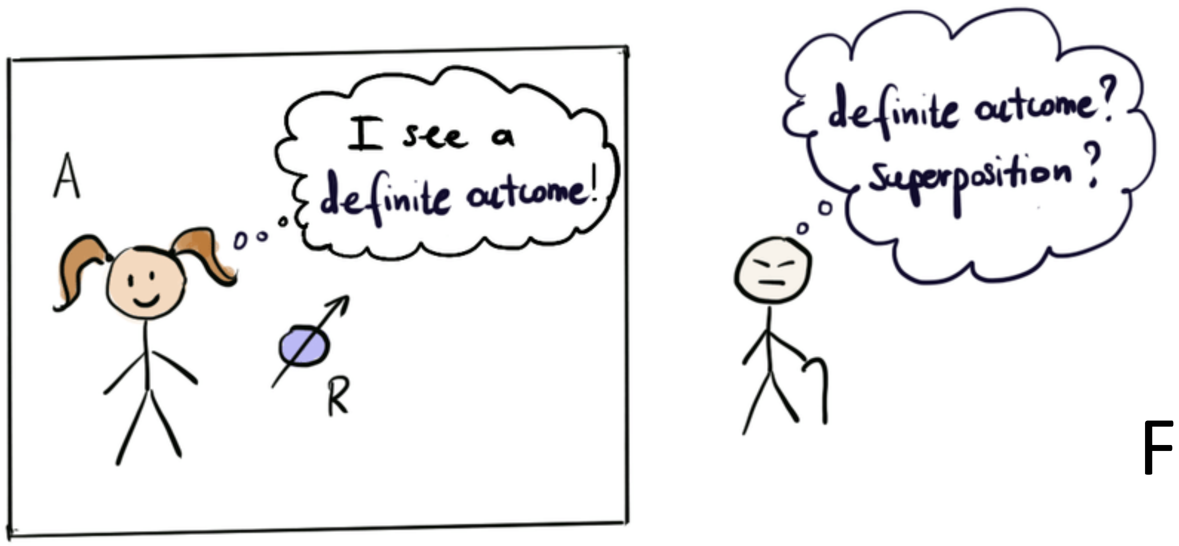


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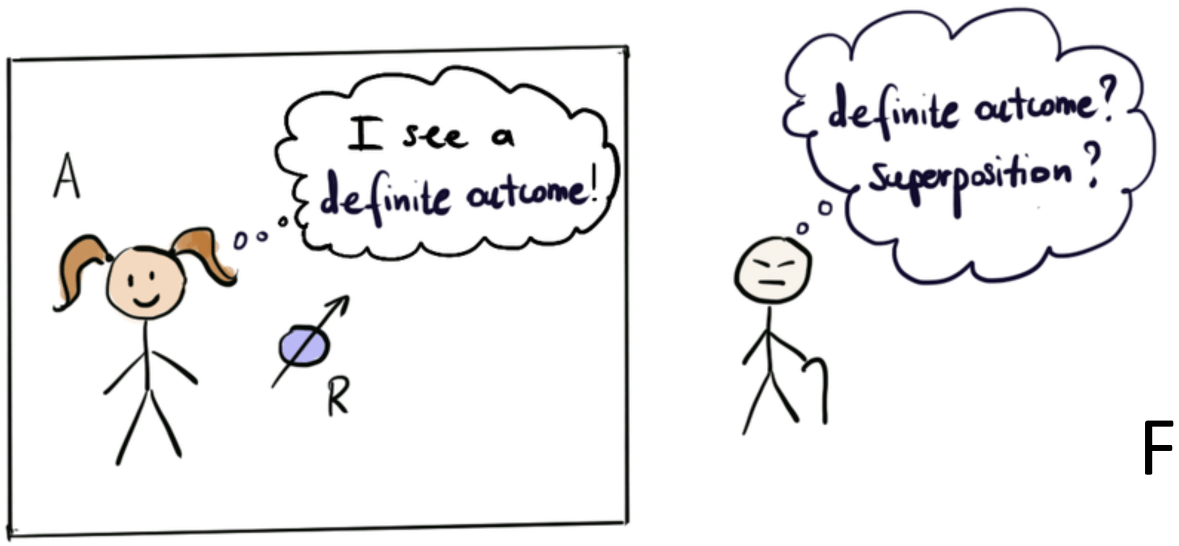


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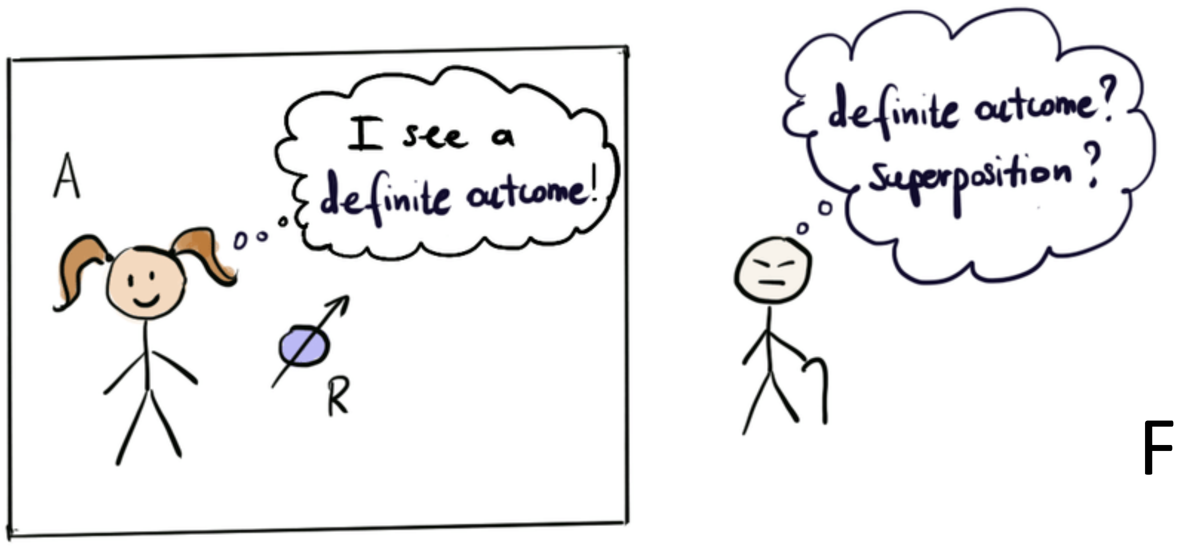


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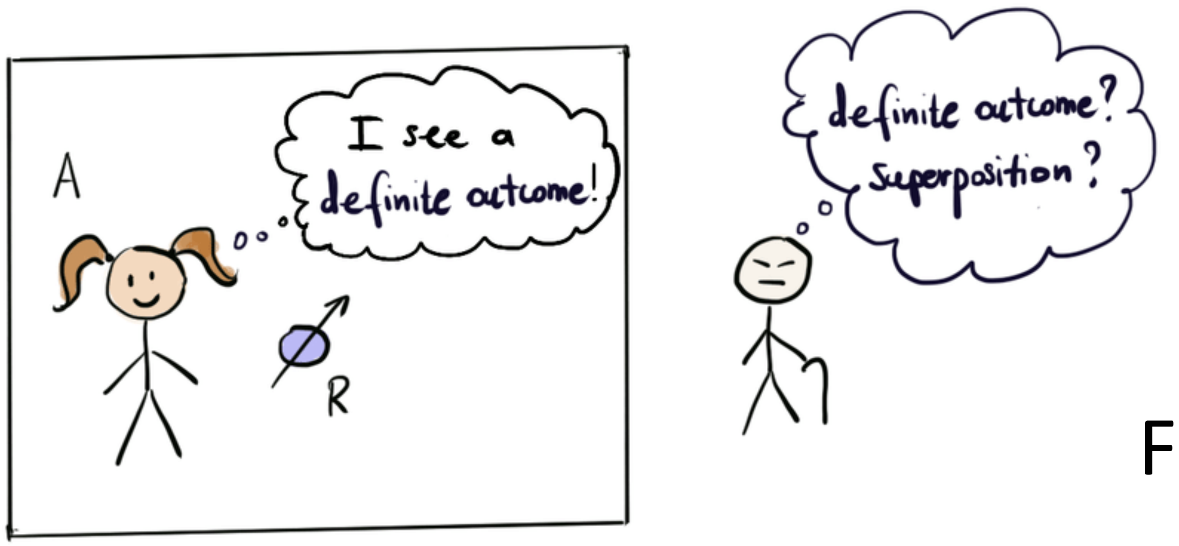


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These will typically not "fit together" into a joint description. The "world" is a mosaic of the (more fundamental) first-person perspectives.

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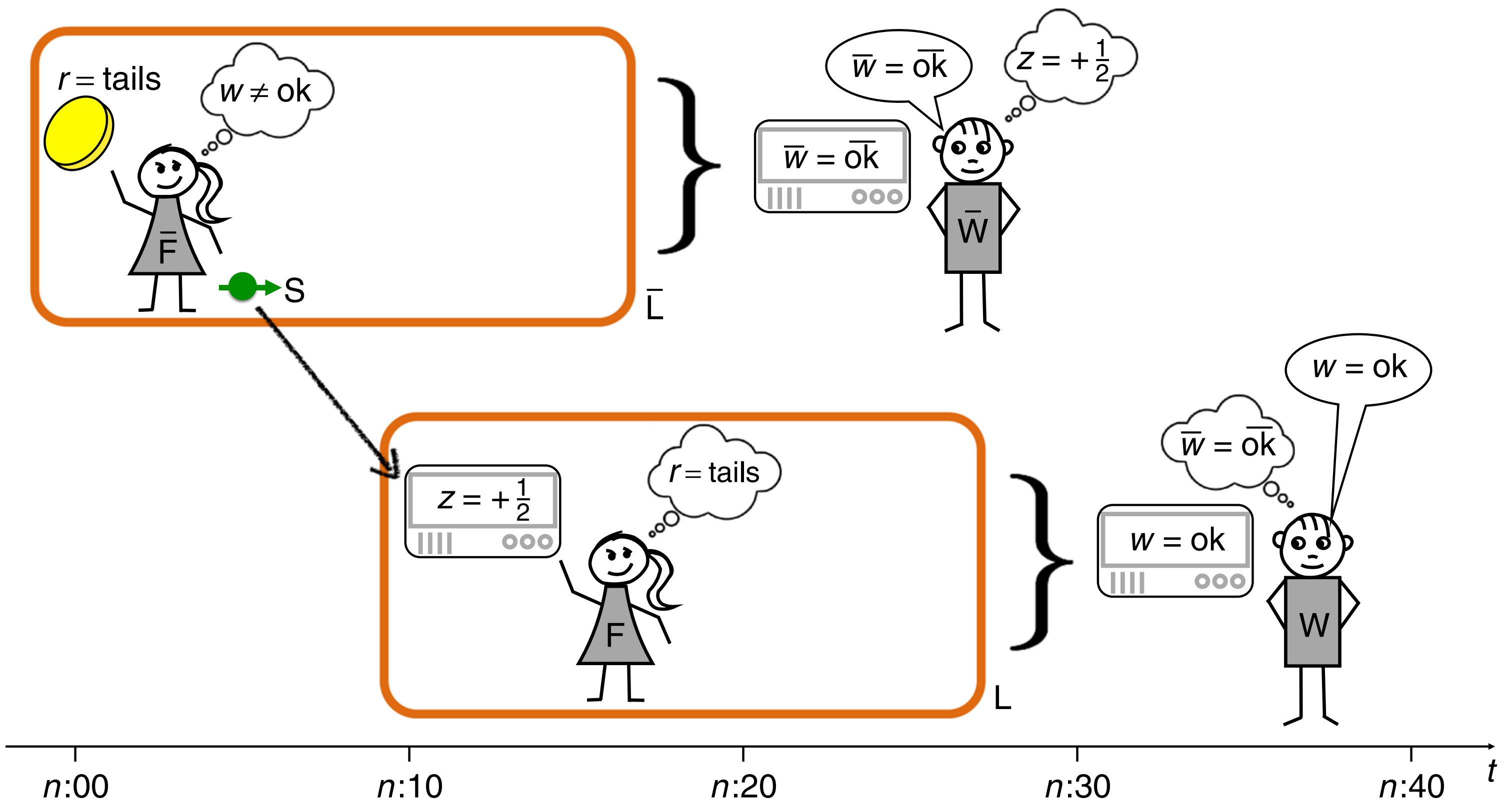
D. Frauchiger and R. Renner, Nat. Commun. **9**, 3711 (2018).



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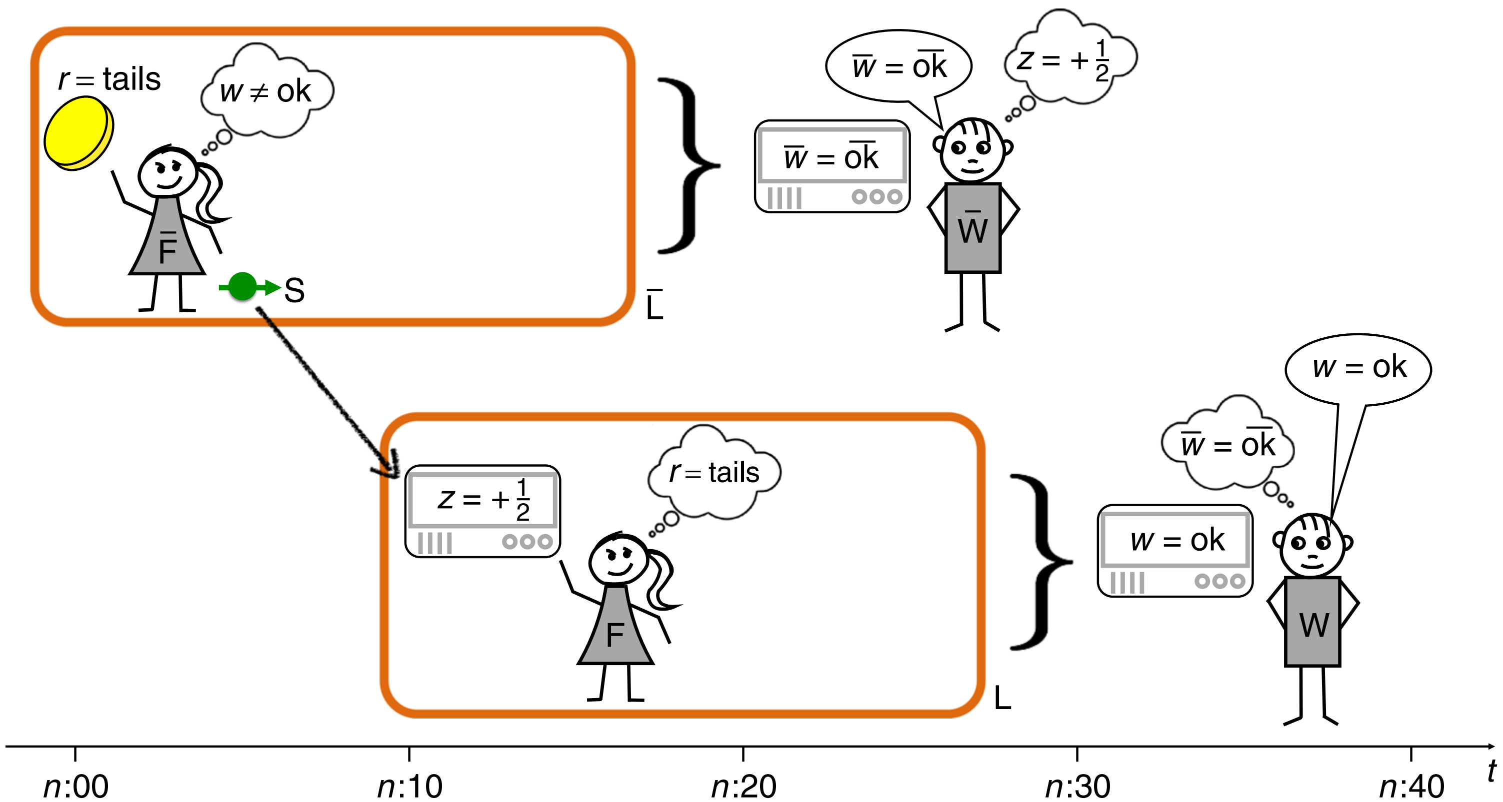


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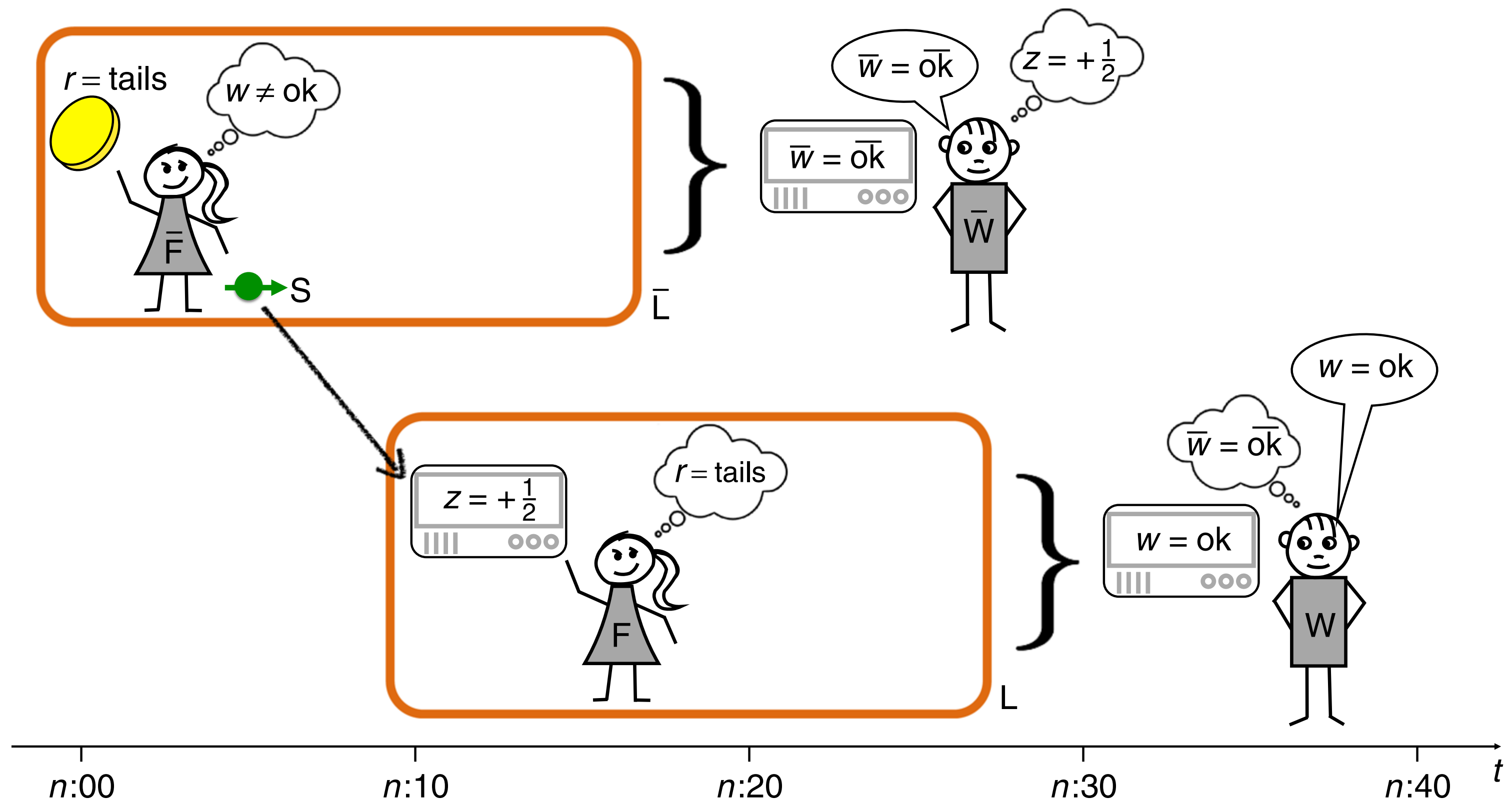


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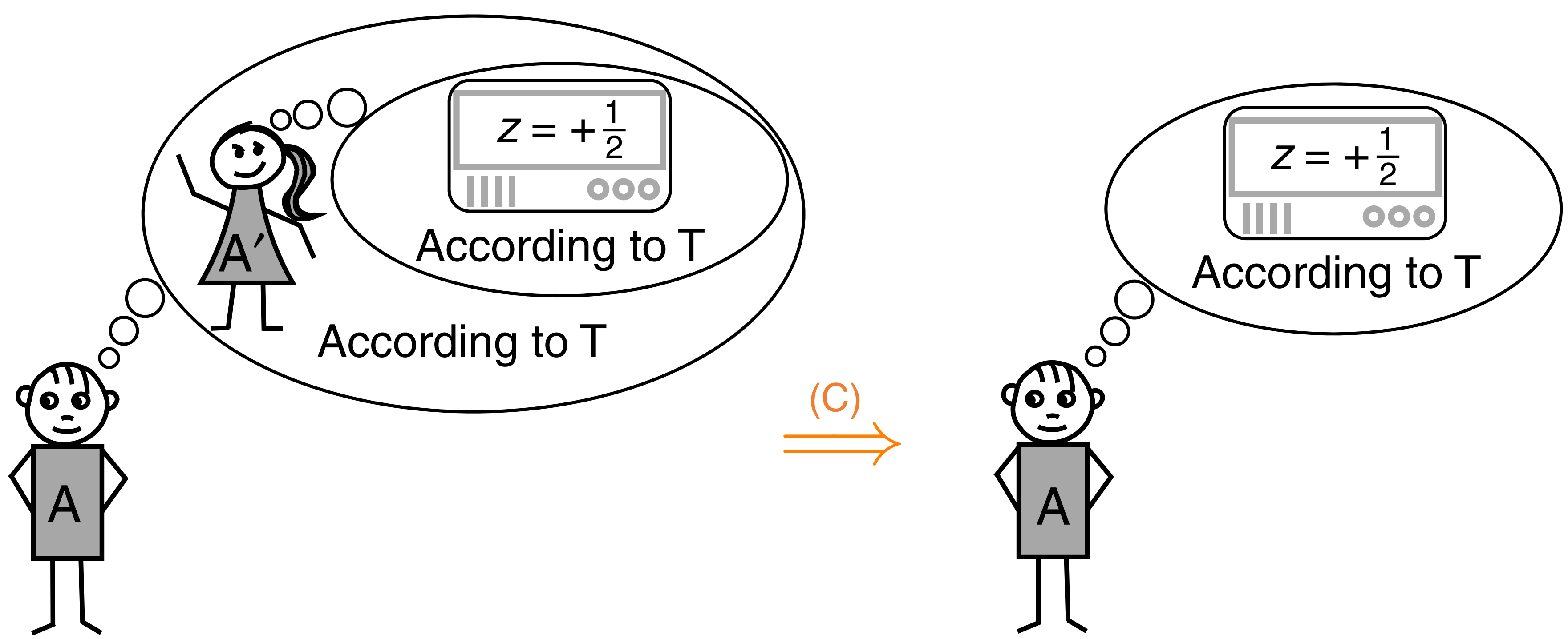



**Box 3: Assumption (C)**

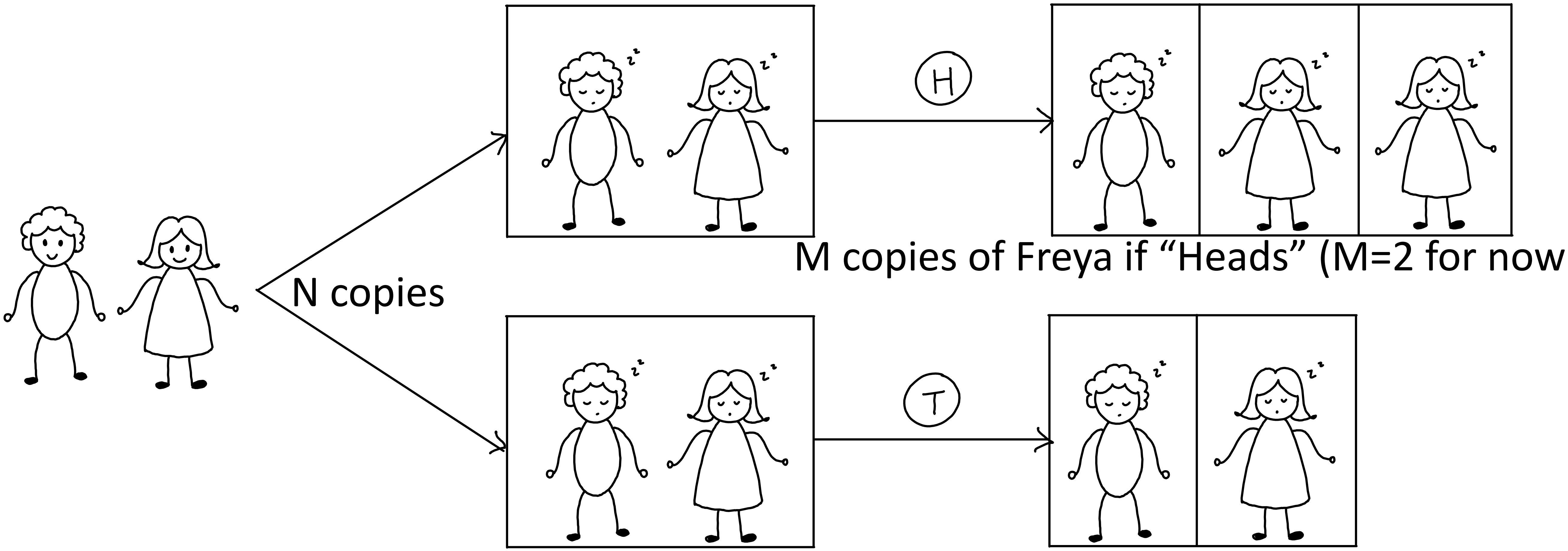
Suppose that agent A has established that

*Statement* A$^{(i)}$: "I am certain that agent A′, upon reasoning within the same theory as the one I am using, is certain that $x = \xi$ at time $t$."

Then agent A can conclude that

*Statement* A$^{(ii)}$: "I am certain that $x = \xi$ at time $t$."

# A classical thought experiment



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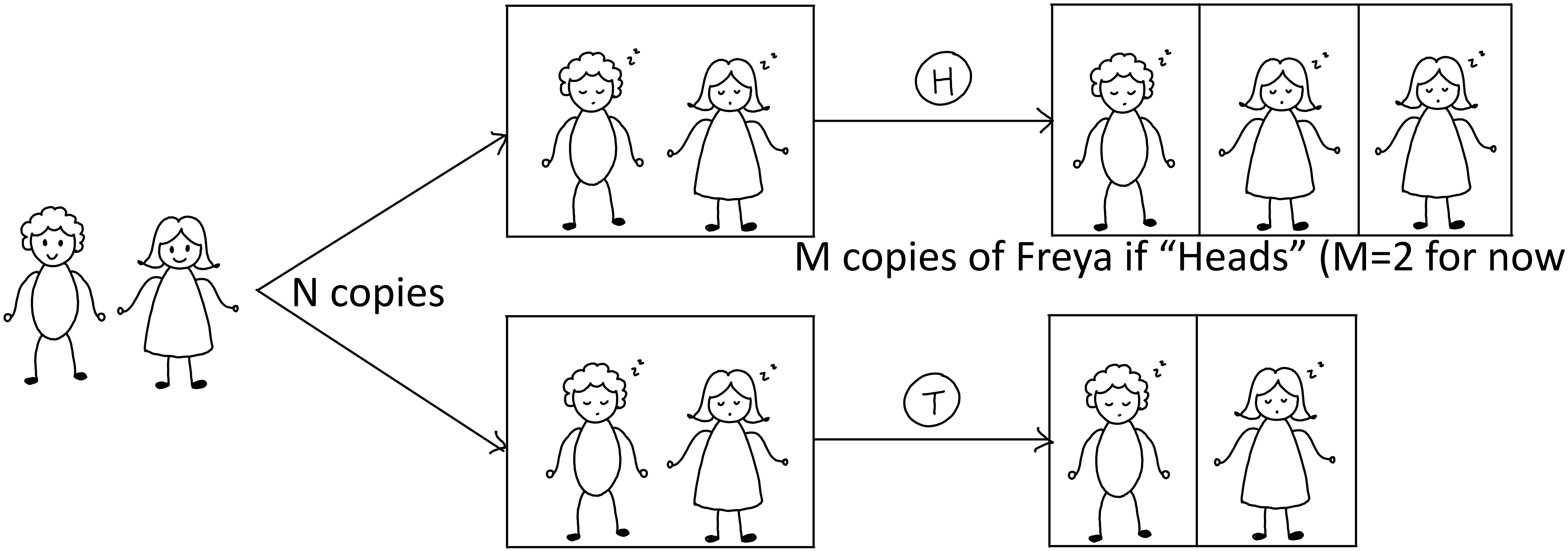


**Thought Experiment 2.** Imagine Freya and Wigner are to be put to sleep, and multiplied into $N$ copies. Each couple is distributed to one of $N$ identical laboratories. In each laboratory, a fair coin is tossed, and if the outcome is Heads, the copy of Freya (but not the copy of Wigner) is duplicated again. Then, all participants are woken and asked to give their credence that the outcome of their lab's coin toss was Tails. (We assume that they cannot notice the presence/absence of an identical copy of Freya in the lab). This scenario is sketched in Figure 2.

In fact, all participants are offered a bet: they can buy a ticket from a bookie for $(2/3 - \varepsilon)\$$, where $\varepsilon > 0$ is small, (say, for 66 cents) that wagers on the coin toss having shown Heads. It is natural to argue (see below) that the credence that Freya should assign to Tails (which directly determines the maximum price $1 - p$ she rationally ought to be prepared to pay) is 1/3, whilst for Wigner it is 1/2: Freya should buy the ticket, but Wigner should not.

Finally, all copies survive the experiment and are released. Everyone who has bought the ticket now receives 1\$ if the outcome of their lab's coin toss was indeed Tails. Freya and Wigner have been initially informed about all the details of the experiment.

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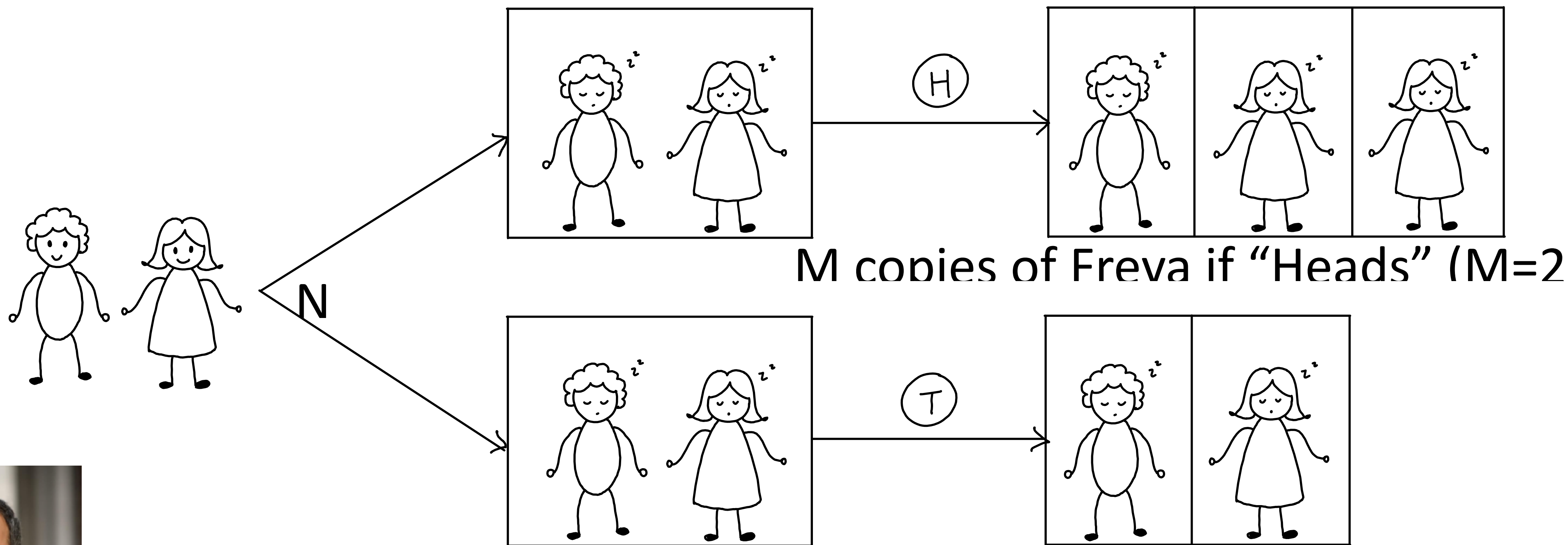



Adam Elga (Princeton)

**Elga’s Principle of Indifference:**

Similar centered worlds deserve equal credence.

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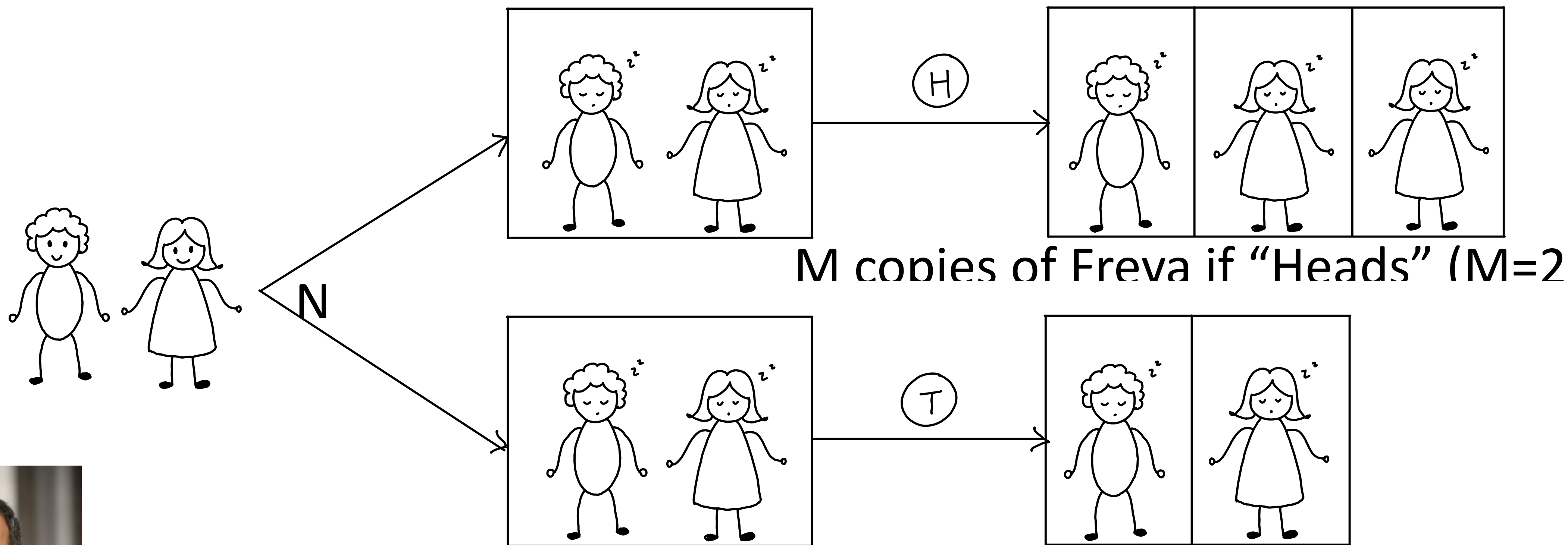



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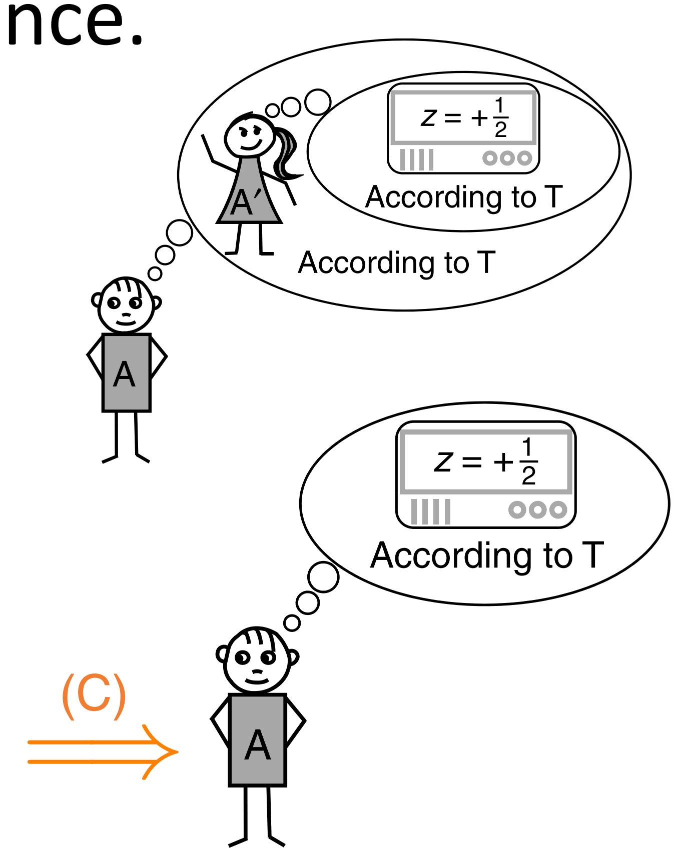

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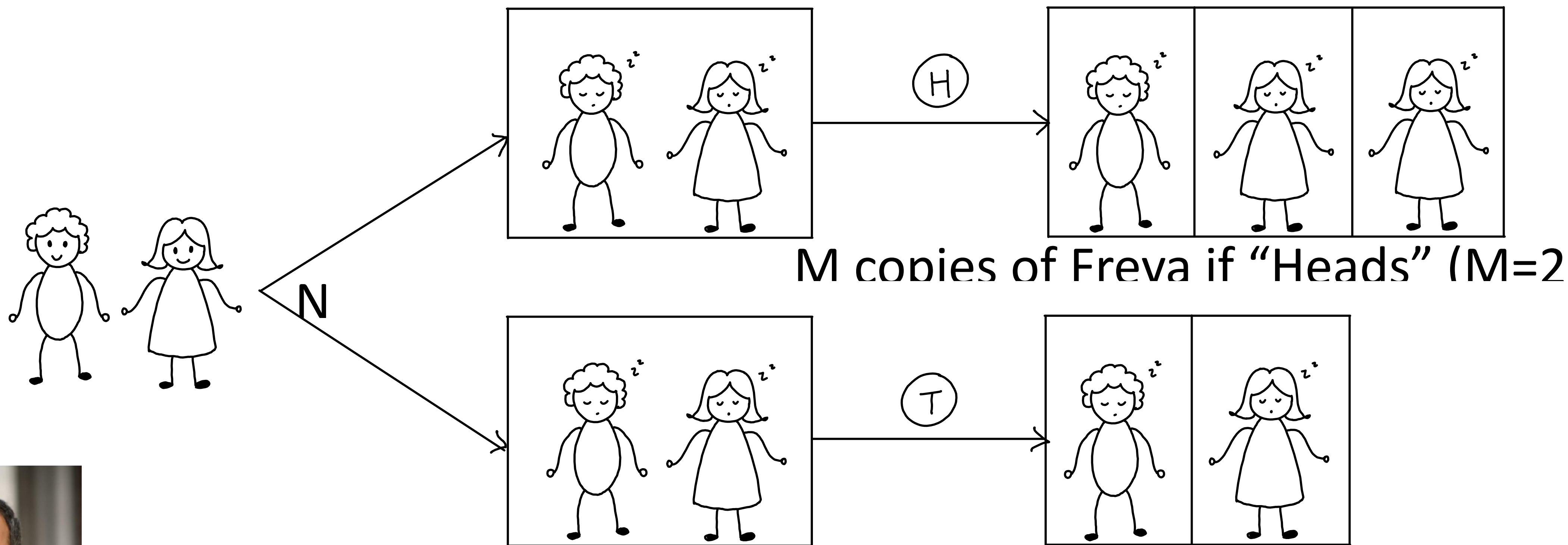


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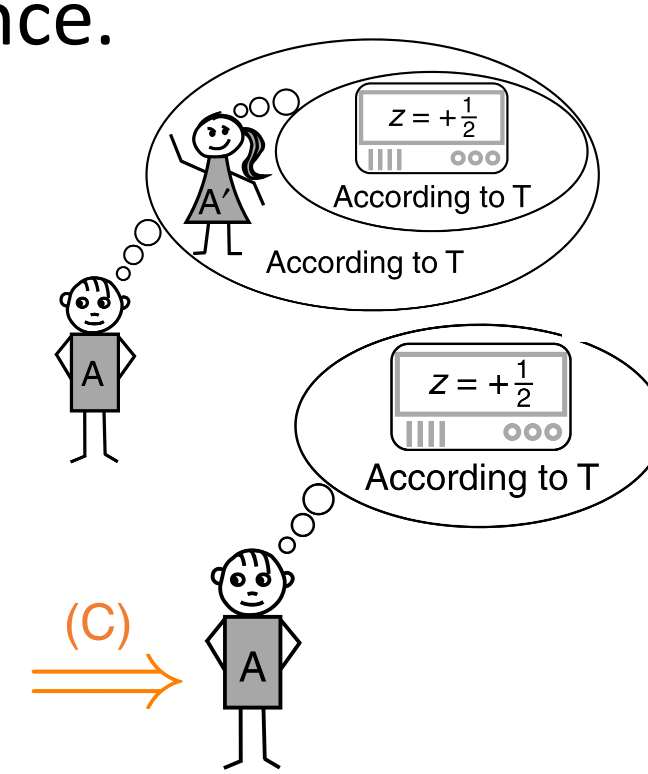

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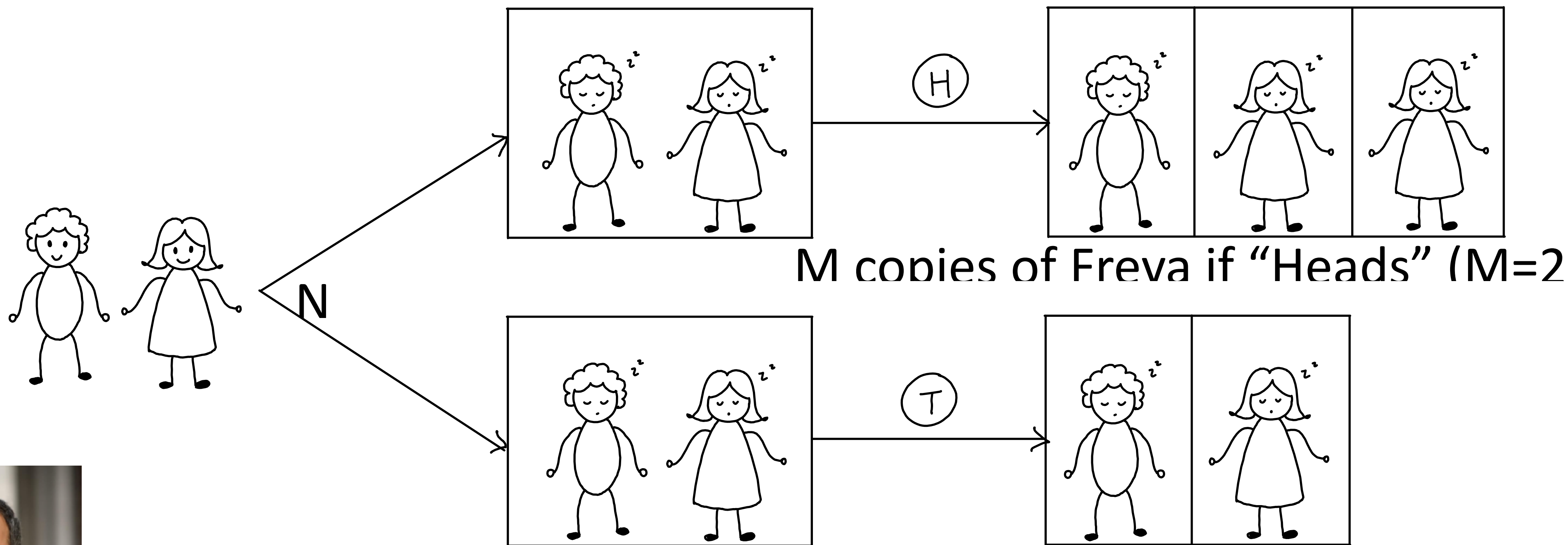



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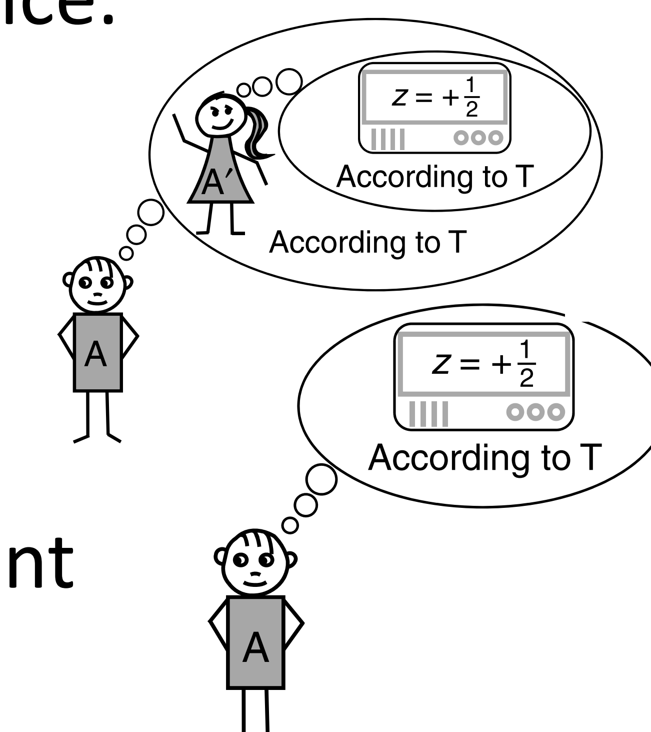
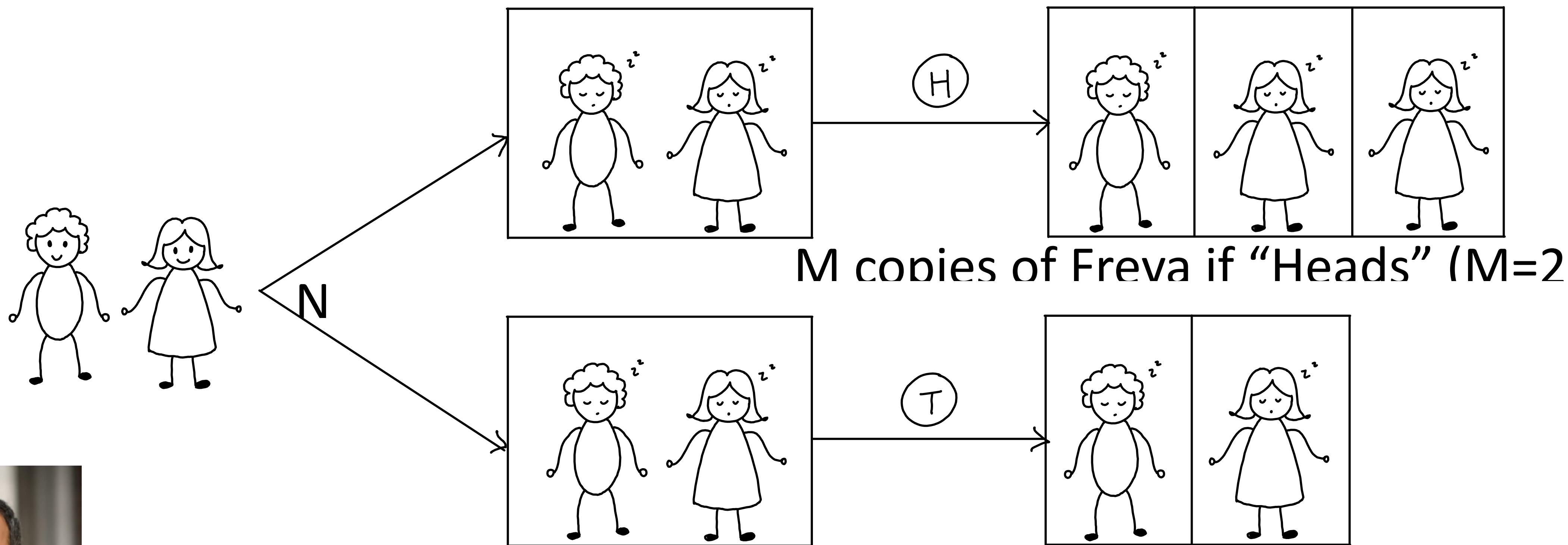



**NUI (no update on irrelevant information):**

If Freya knows that all her future copies will undergo the exact same procedure until the experiment is completed, then her predictions for her future observations are unchanged if she is told which copy she is.

# A classical thought experiment





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**Principle CP (probabilistic consistency)**

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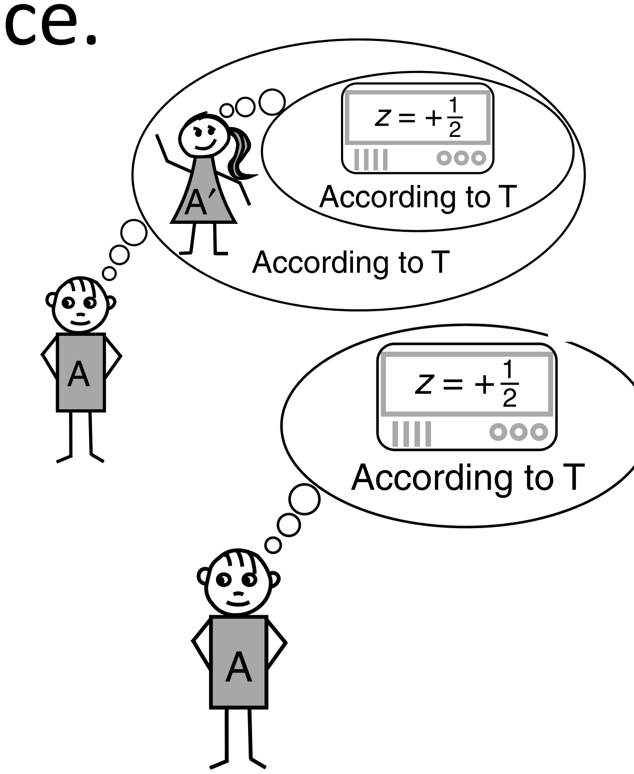
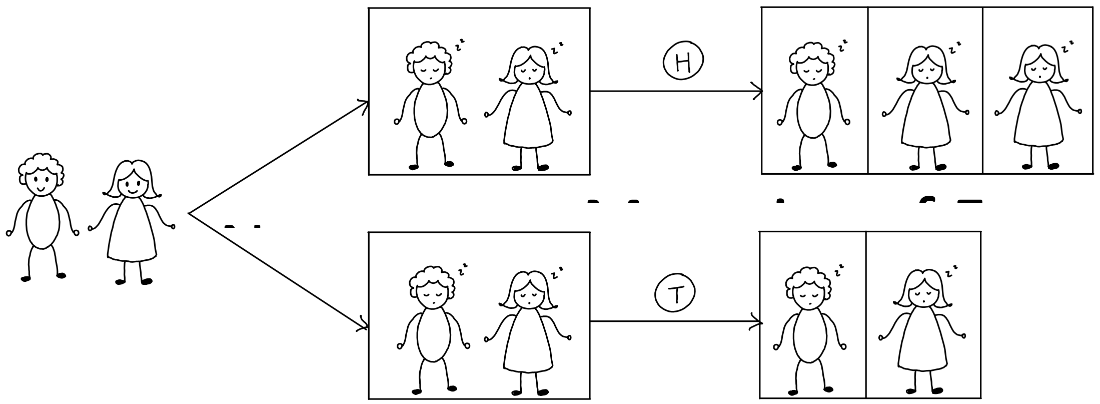



**Theorem:** These three principles cannot hold jointly in this experiment.

# Some clarifications




- We do **not** claim that FR-WF and this duplication scenario are **ontologically** similar!

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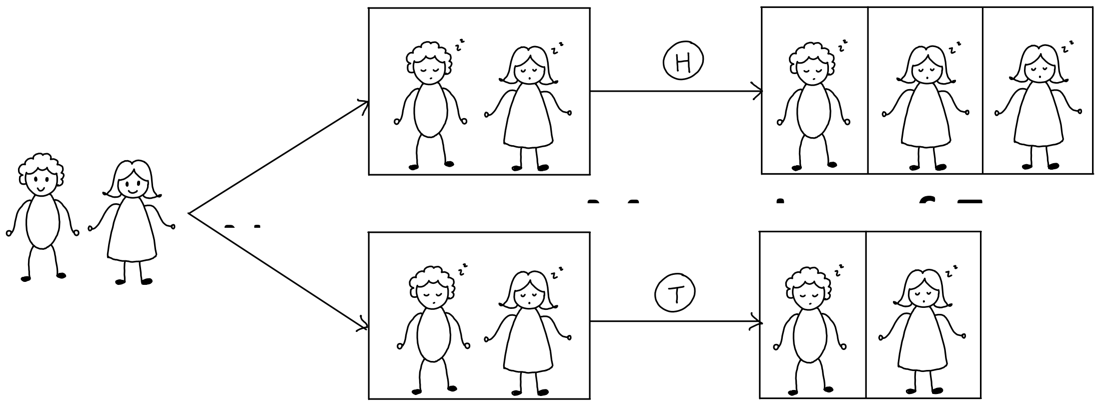


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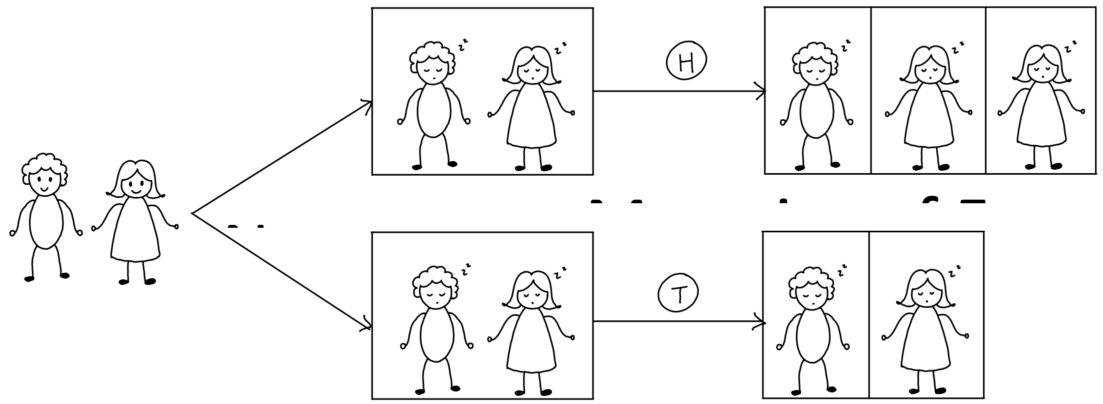


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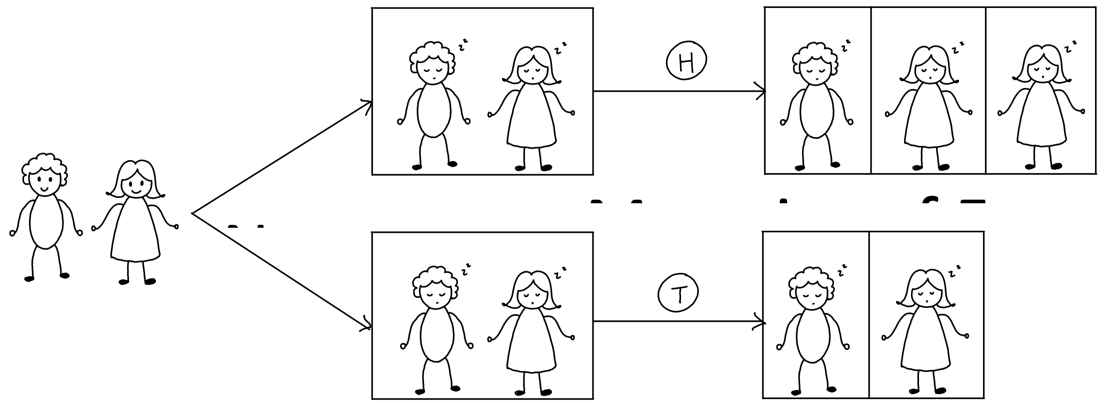


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- **Isn't quantum theory natural, but duplication=science fiction?** **No.** WF-scenarios are **extremely** invasive on the Friend! Resource requirements for classical duplication are ~5 orders of magnitude smaller than Quantum-WF (classical vs. quantum computation).

# Absoluteness of observed events

nature physics

ARTICLES

https://doi.org/10.1038/s41567-020-0990-x

Check for updates

## A strong no-go theorem on the Wigner's friend paradox

Kok-Wei Bong[1,4], Aníbal Utreras-Alarcón[1,4], Farzad Ghafari[1], Yeong-Cherng Liang[2], Nora Tischler[1]✉, Eric G. Cavalcanti[3]✉, Geoff J. Pryde[1] and Howard M. Wiseman[1]

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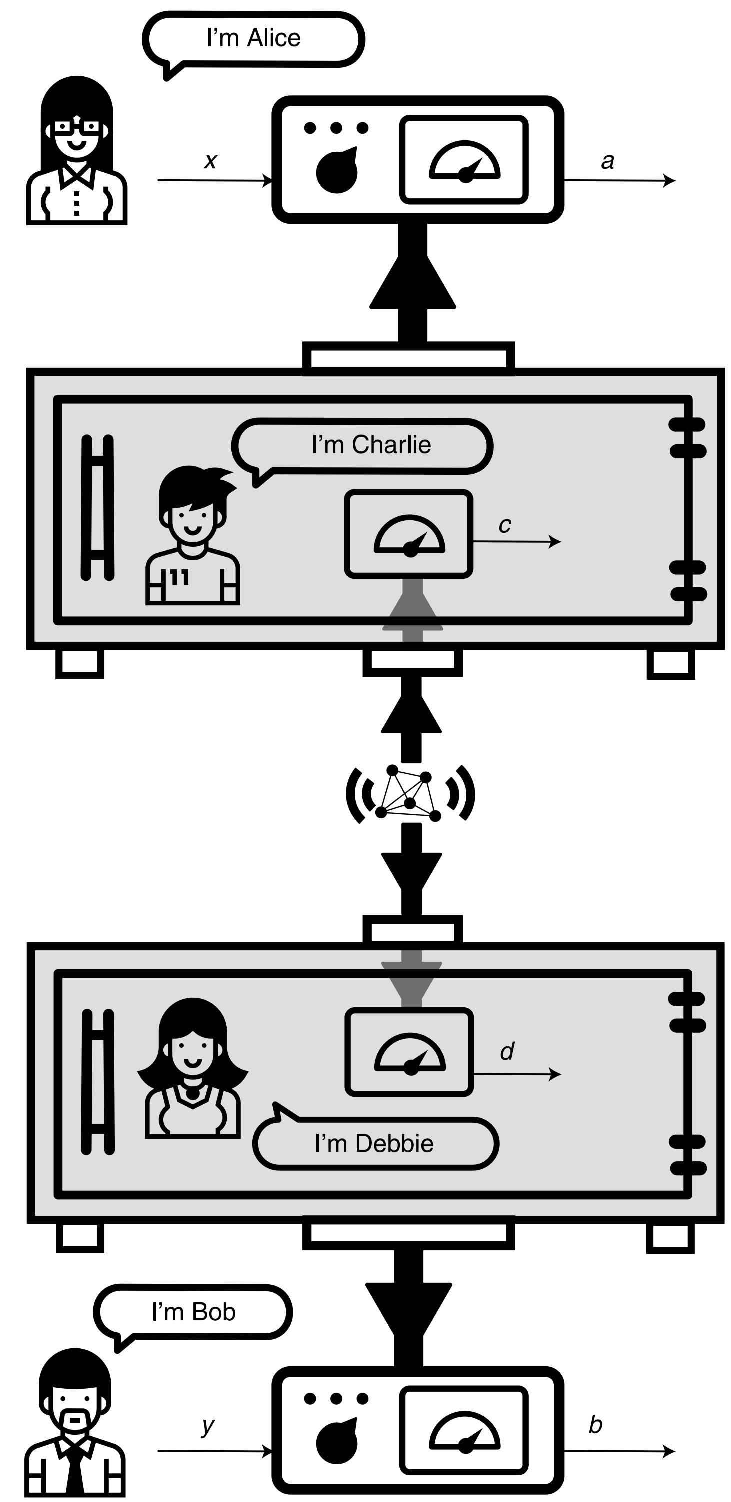


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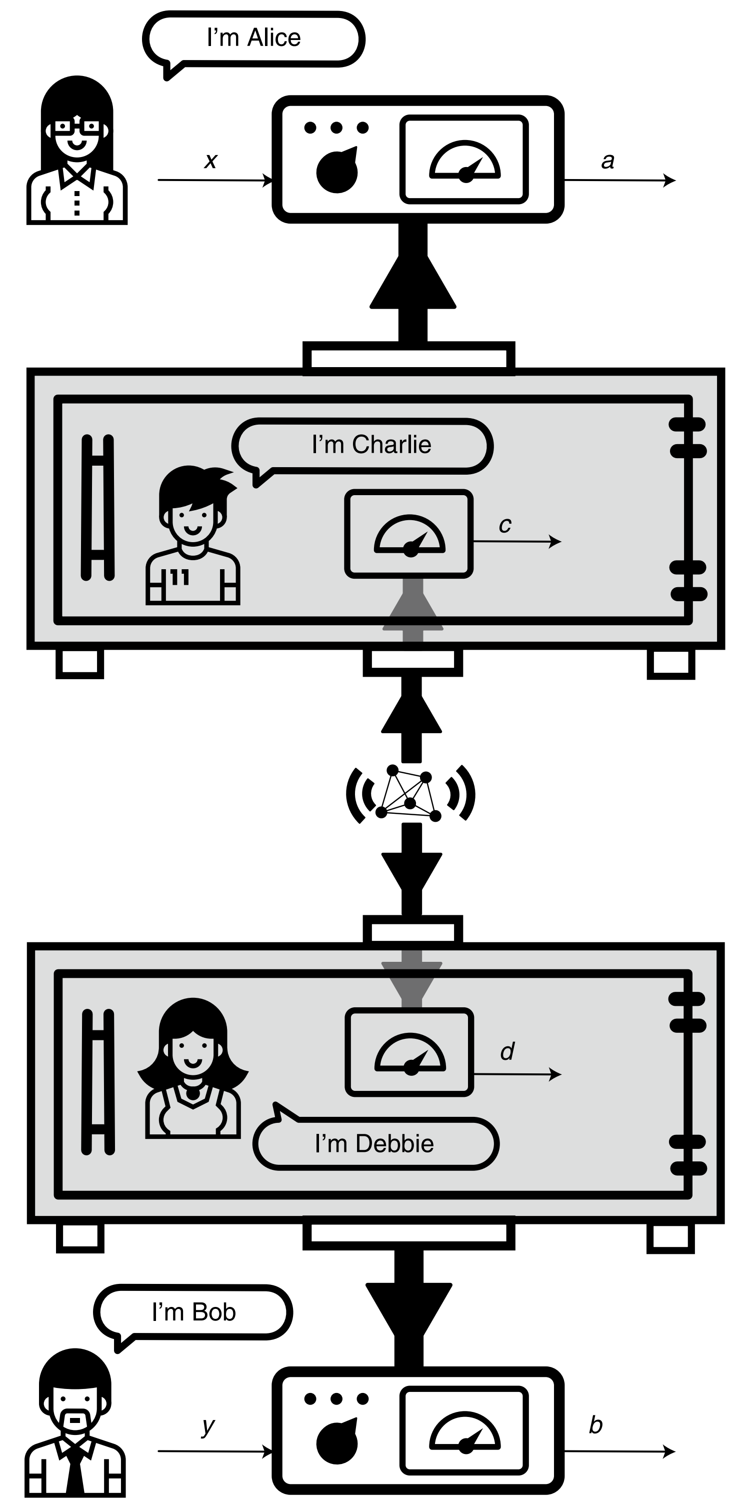


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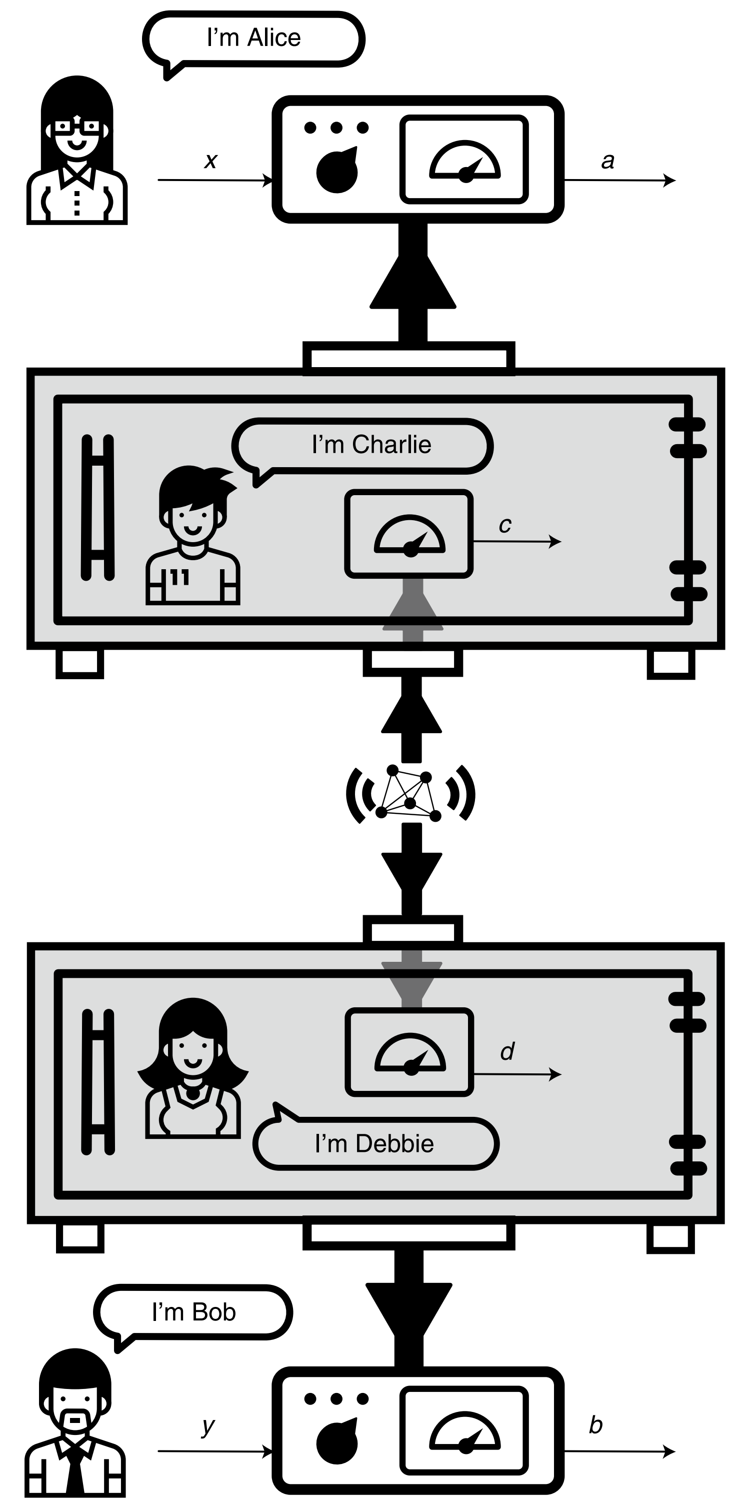
Locality, No Superdeterminism,
**Absoluteness of Observed Events:**
For every x,y, there is a joint prob. distr. P(a,b,c,d|x,y) reproducing the observed distribution p(a,b|x,y) as its marginal.

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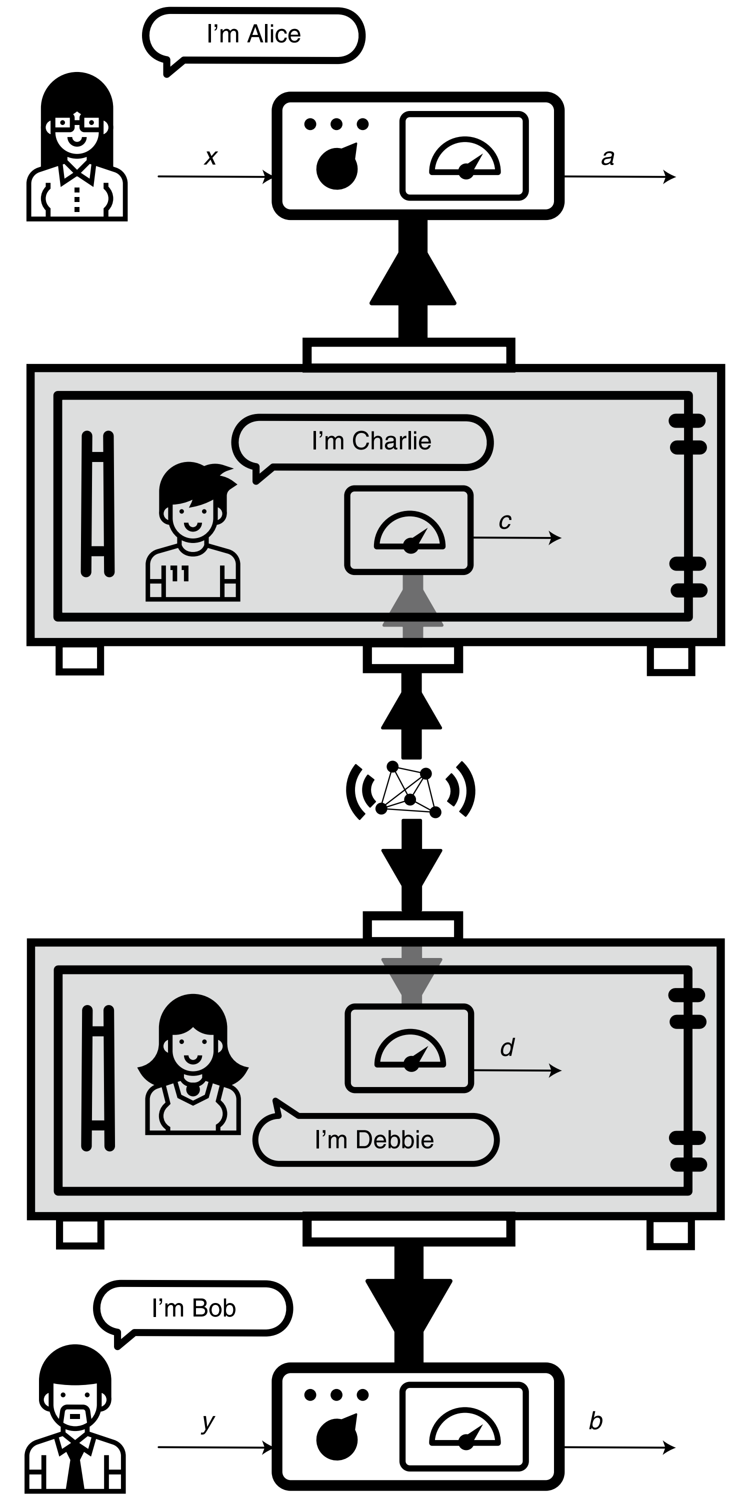


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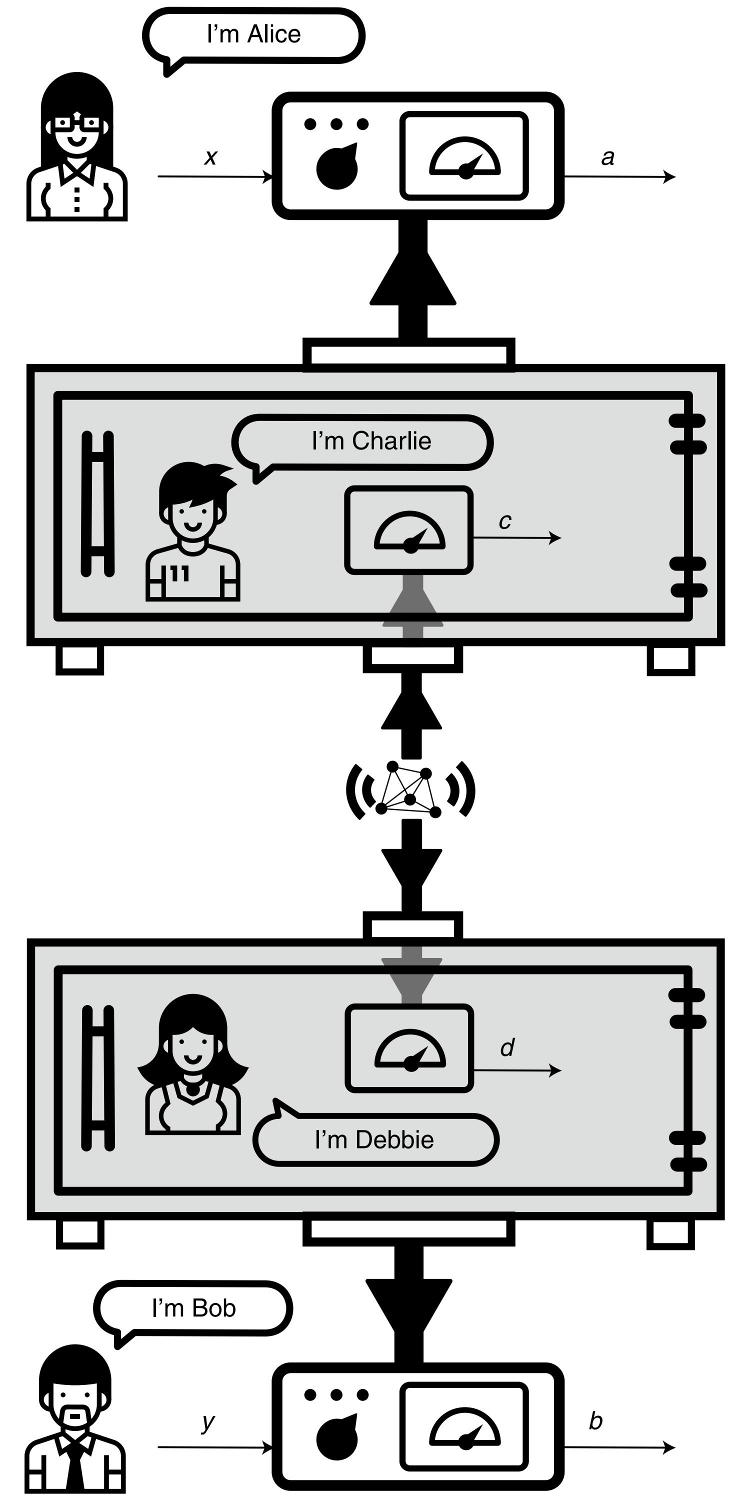


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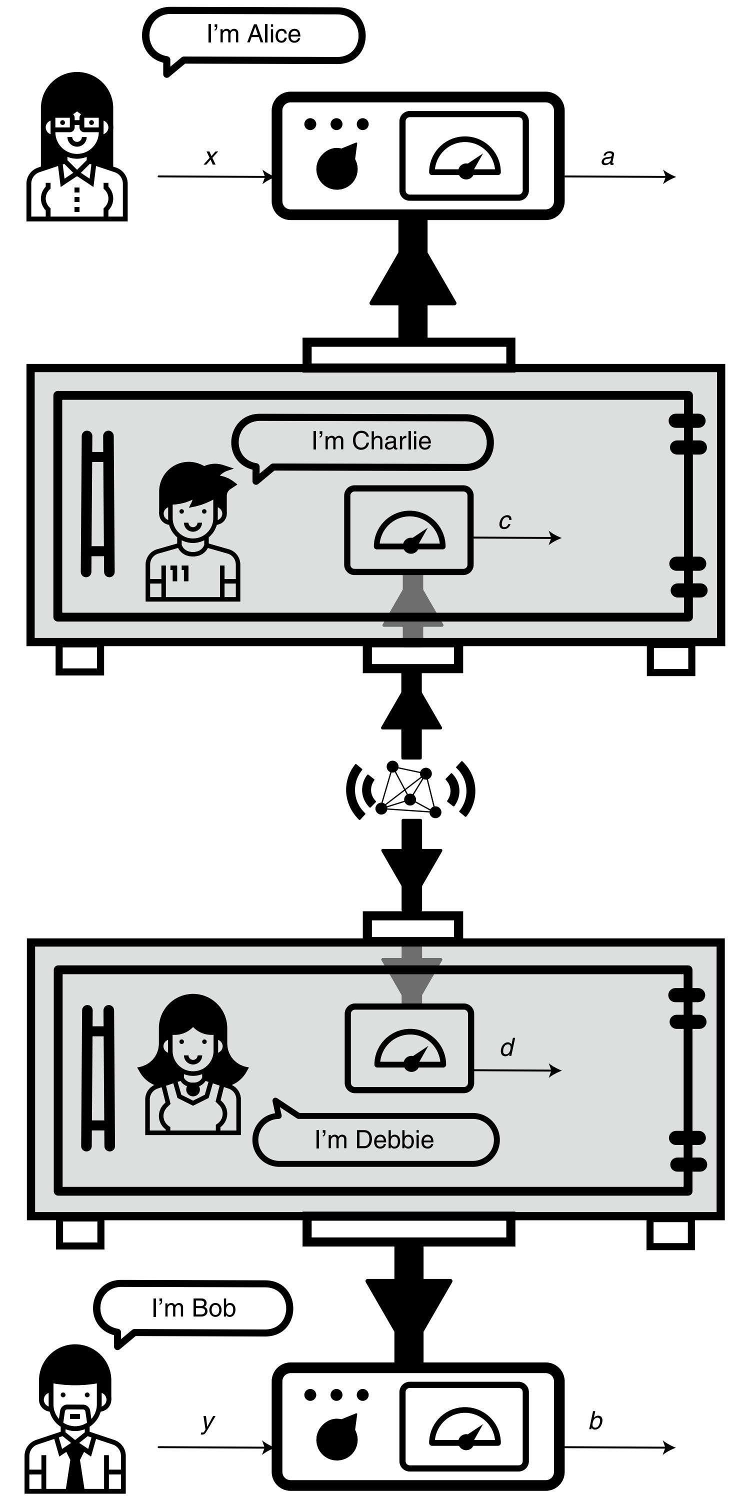


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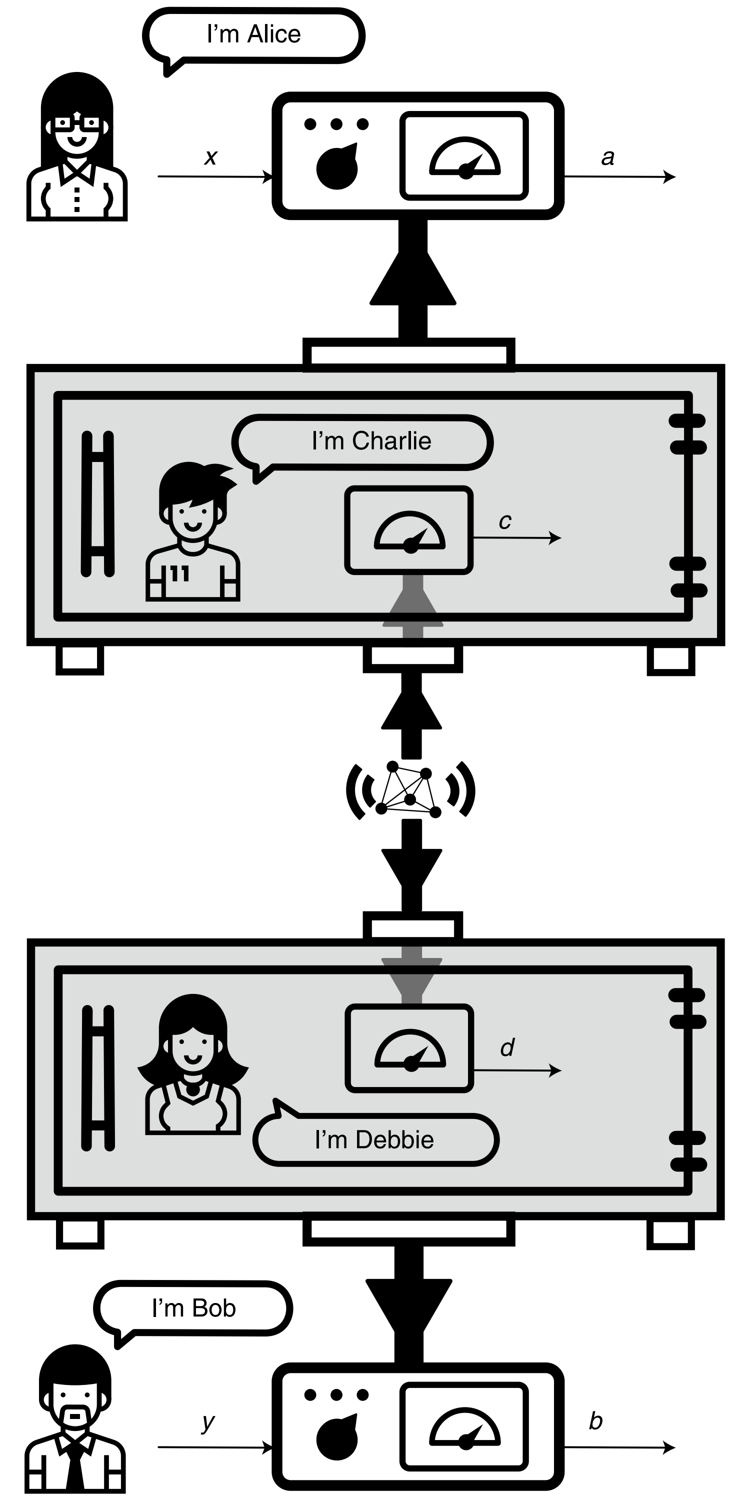
We can simulate this behavior via duplication. To do so, let us look at a reformulation of this WF thought experiment.

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# A "thoughtful" Local Friendliness no-go theorem

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Conceived implementation of the previous thought experiment on a **quantum computer**, proving that the following cannot all hold:

1. **Local Agency:** Any [random] intervention [...] is uncorrelated with any set of physical events that are relevant to that phenomenon and outside the future light-cone of that intervention.
2. **Physical Supervenience:** Any thought supervenes upon some physical process in the brain (or other information-processing unit as appropriate) which can thus be located within a bounded region in space-time.
3. **Ego Absolutism:** My communicable thoughts are absolutely real.
4. **Friendliness:** If [...] an independent party displays cognitive ability at least on par with my own, then they have thoughts, and any thought they communicate is as real as any communicable thought of my own.

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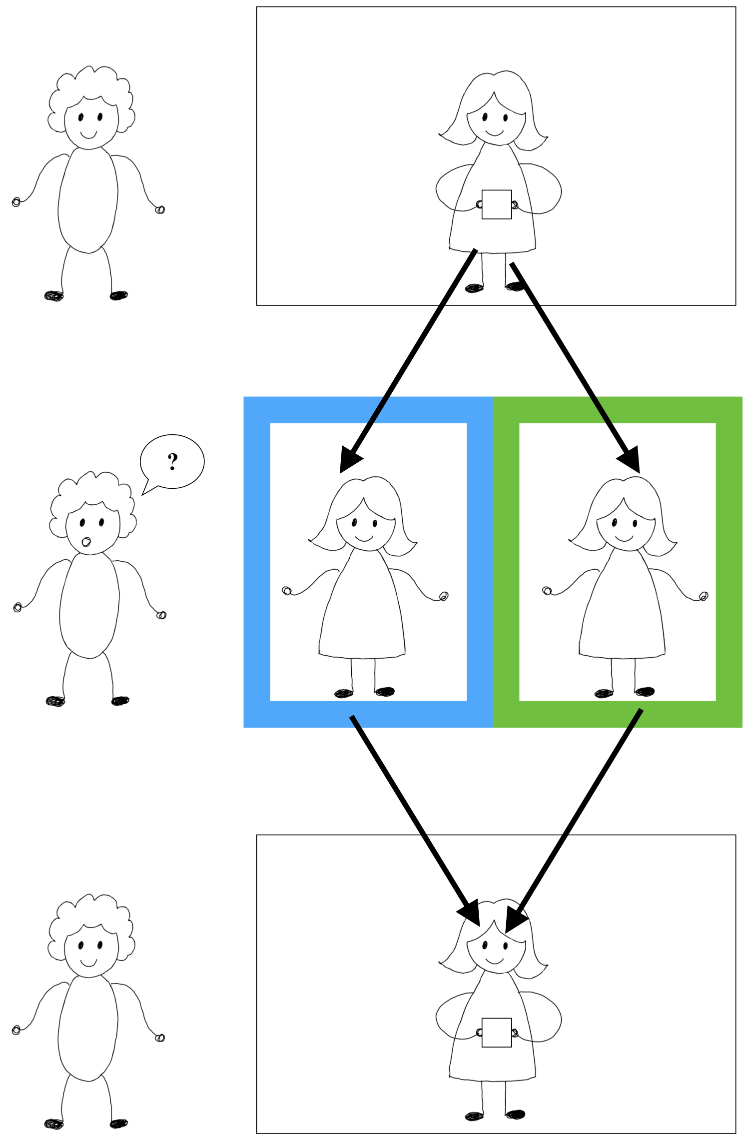

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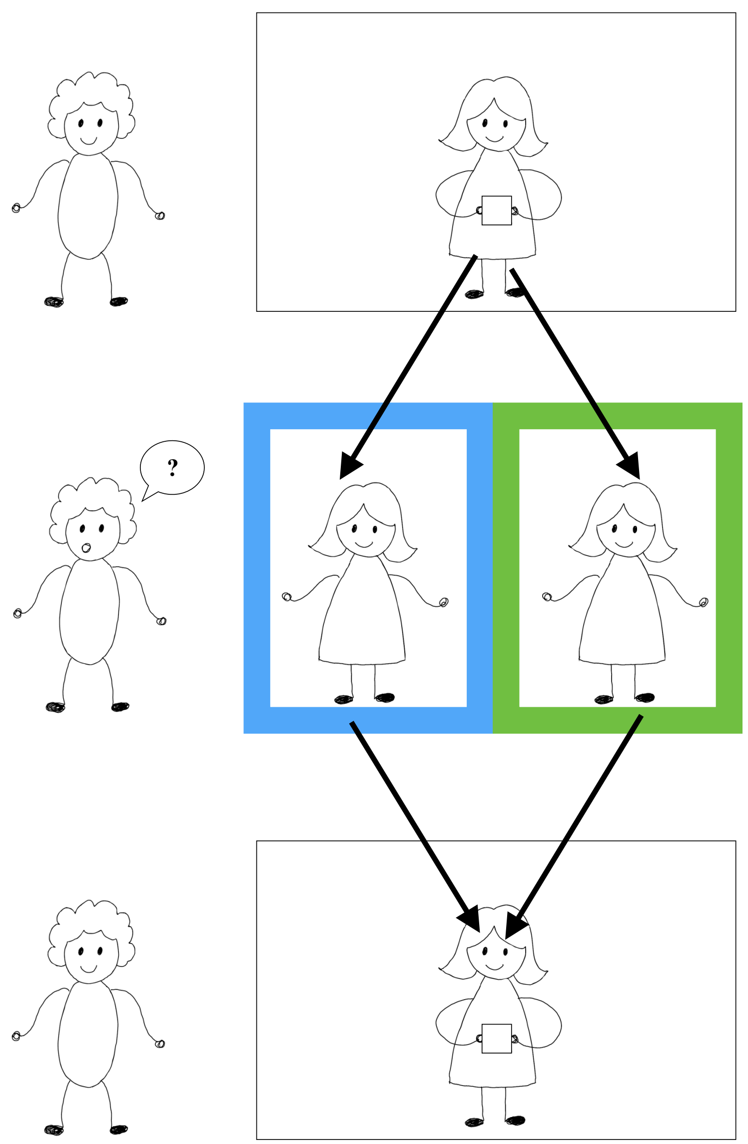


Naively understood, there exists an ambiguity regarding what “my” indexes for branching scenarios. Returning to the example of Freya, who is yet to be duplicated, she reads Ego Absolutism to say that her communicable thoughts are absolutely real. This includes her thoughts in that instance, such as “I am hungry”. It may also be understood to include thoughts she had this morning, such as “It is raining”. Does it include her future thoughts though? This afternoon, she will be duplicated, whereupon her future copies will have separate experiences. Thus, in describing any future thought she may have, there is an inherent ambiguity as to the meaning of such statements, and whether or not we should take their referent as “absolute”. That is, it is unclear what the words “my (future) thoughts”, if uttered by Freya before the start of the experiment, would refer to, and in disregarding this indexical ambiguity, we will typically be led to mathematical formulations of Ego Absolutism that tacitly involve additional assumptions. In particular, it will lead to the formal assumption that there is always, at every time, a single variable describing a single thought of some person called Freya, while in this branching scenario there are actually two. Indeed, this assumption is part of the mathematical formulation of Bong et al. [7].

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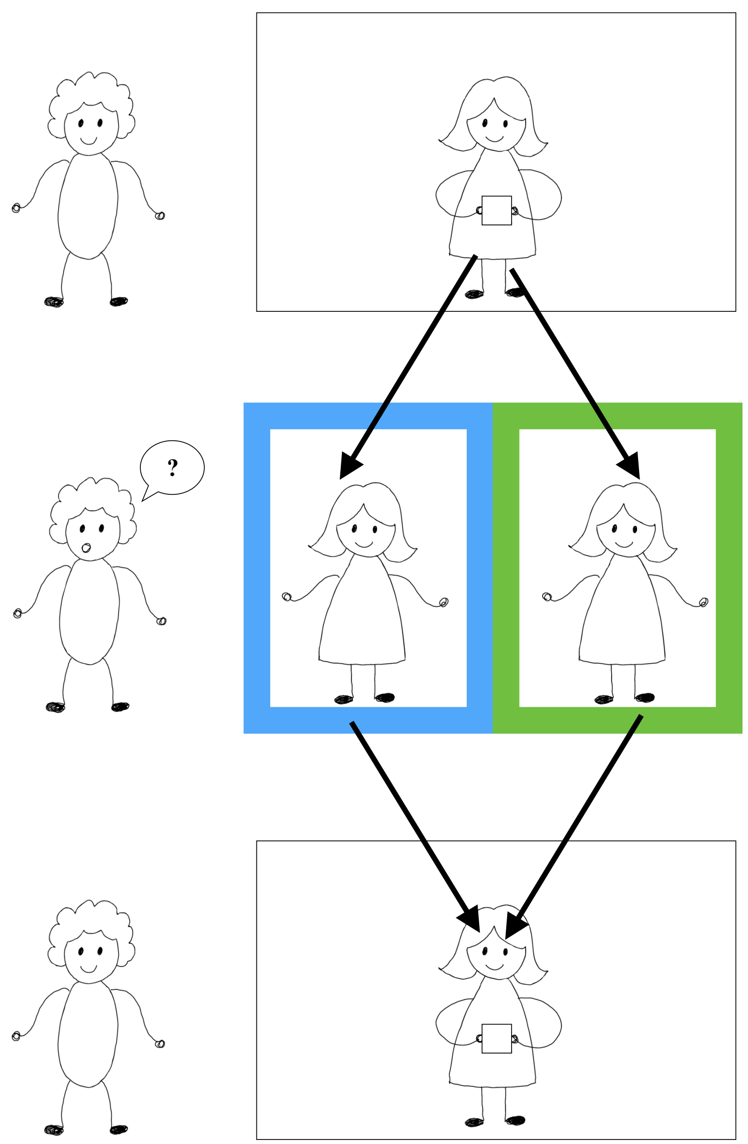


Adrian Kent

A. Kent: “duplication loophole”

A. Kent, *Friendly thoughts on thoughtful friendliness*, arXiv:2302.12707.

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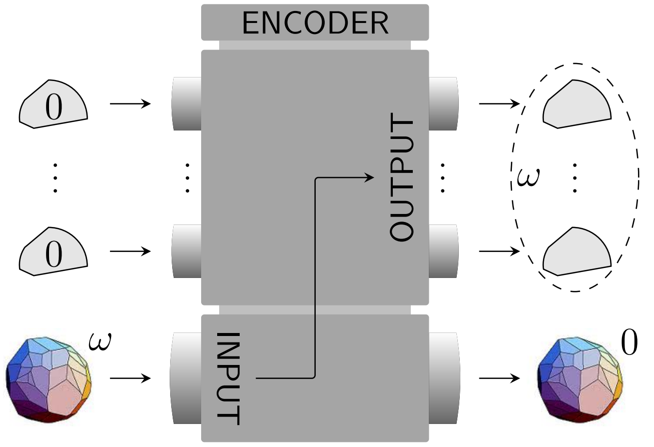


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4. Restriction A

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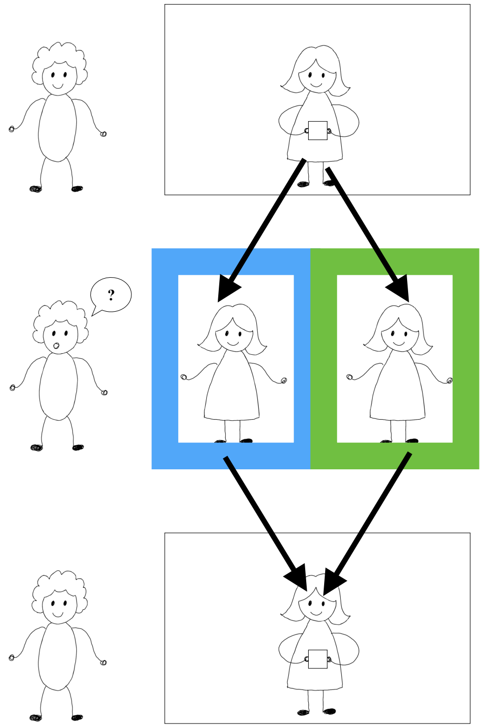

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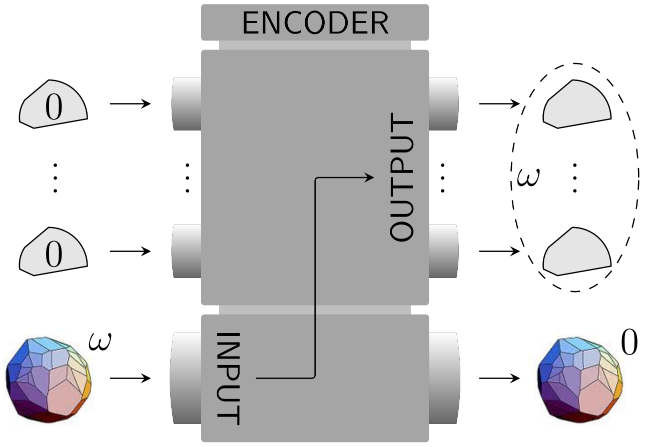


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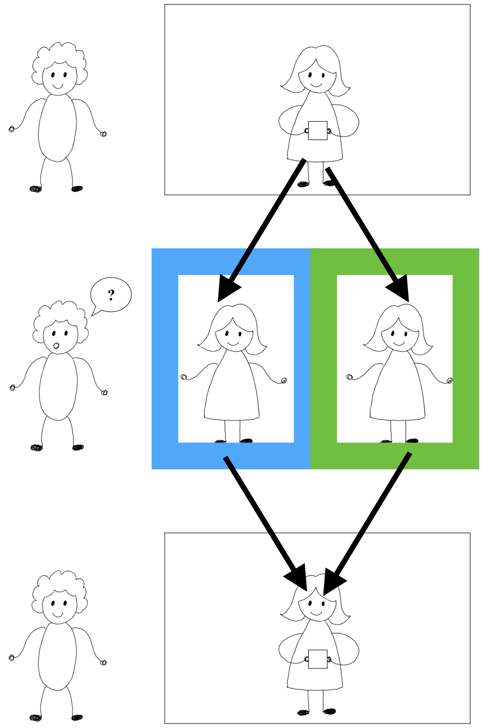


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**Observation:** Unless our physical theory T is empirically incomplete, Restriction A can only apply to situations where it is **impossible** to repeat the scenario identically many times, record the observations of the *n* agents, and estimate the probabilities via frequencies.

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- **Bong et al., Absoluteness of Observed Events:** Under the background assumptions of Locality and No Superdeterminism, Restriction A applies to Quantum Theory (in this scenario). Indeed, assuming that an LF-inequality will be experimentally violated, **Restriction A applies to all empirically adequate future physical theories** for 2≤n agents.

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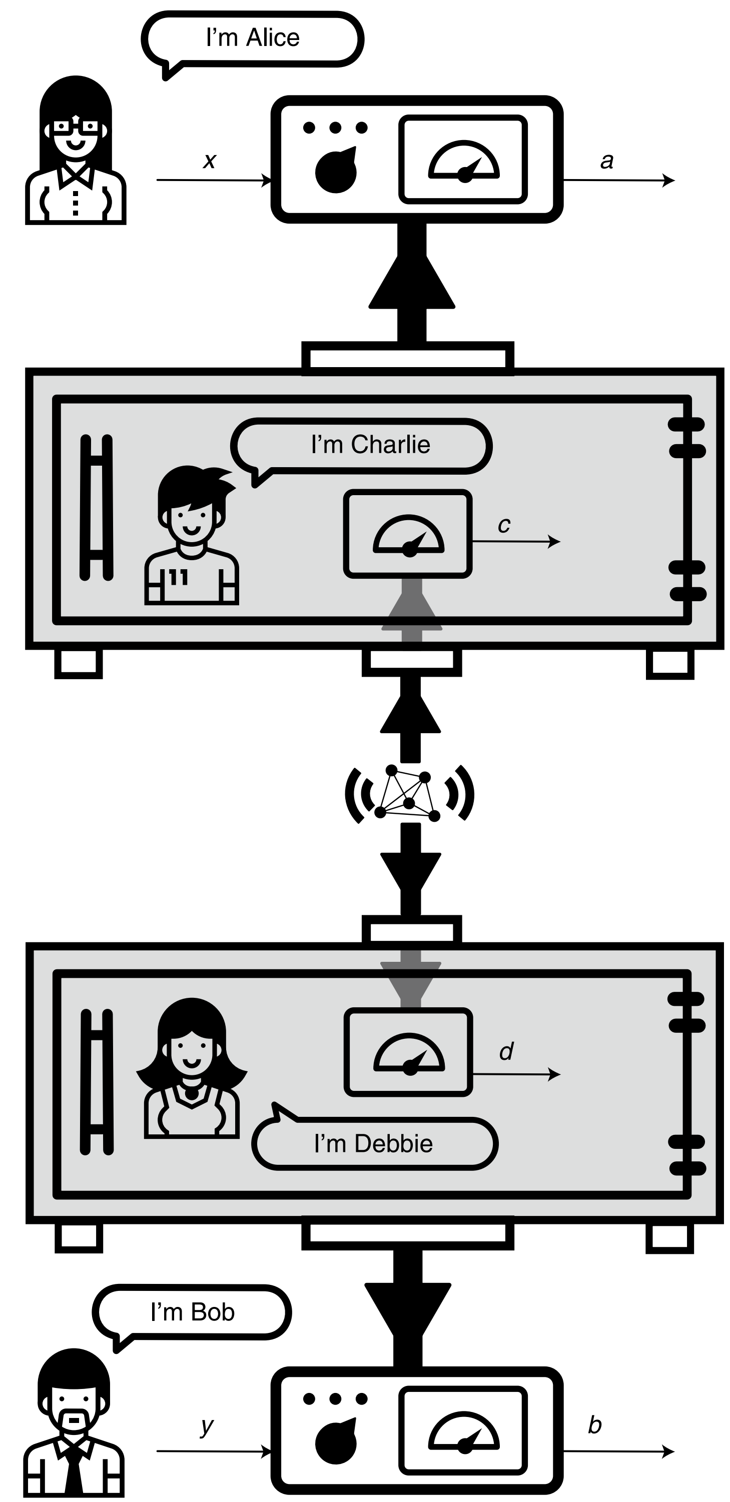

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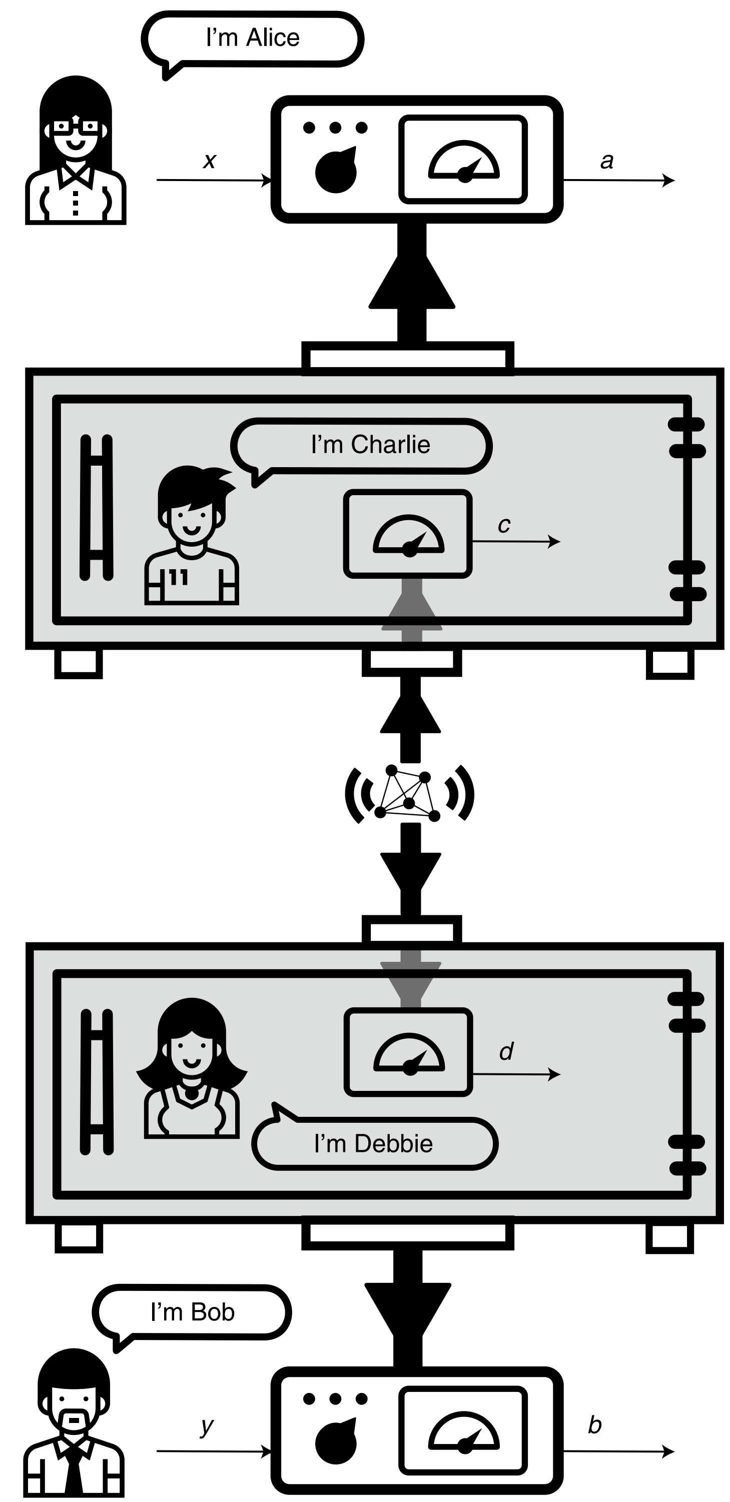


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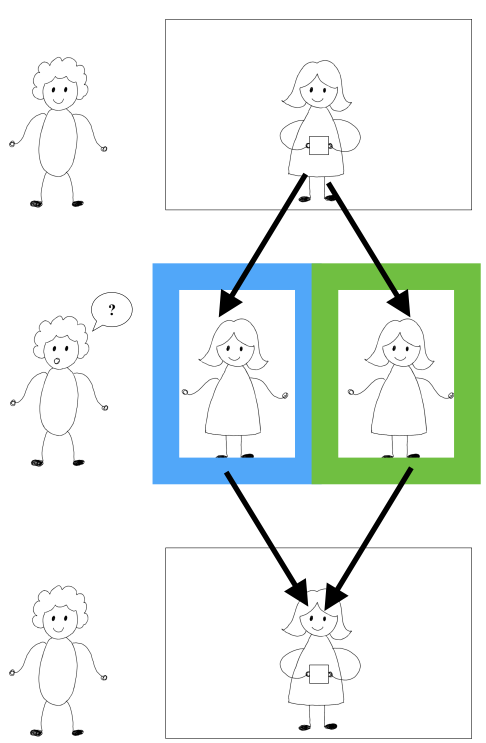

- **Classical fission&fusion: n=1.** Our physical theories have nothing at all to say about what Freya should believe about the color of room she will see.

Restriction A applies here to all current physical theories.

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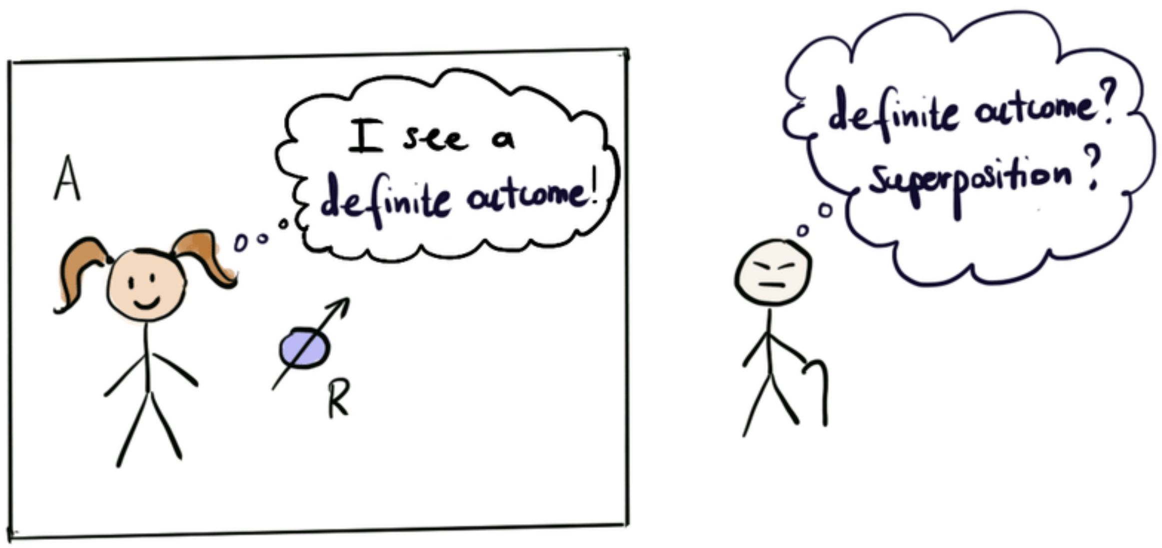


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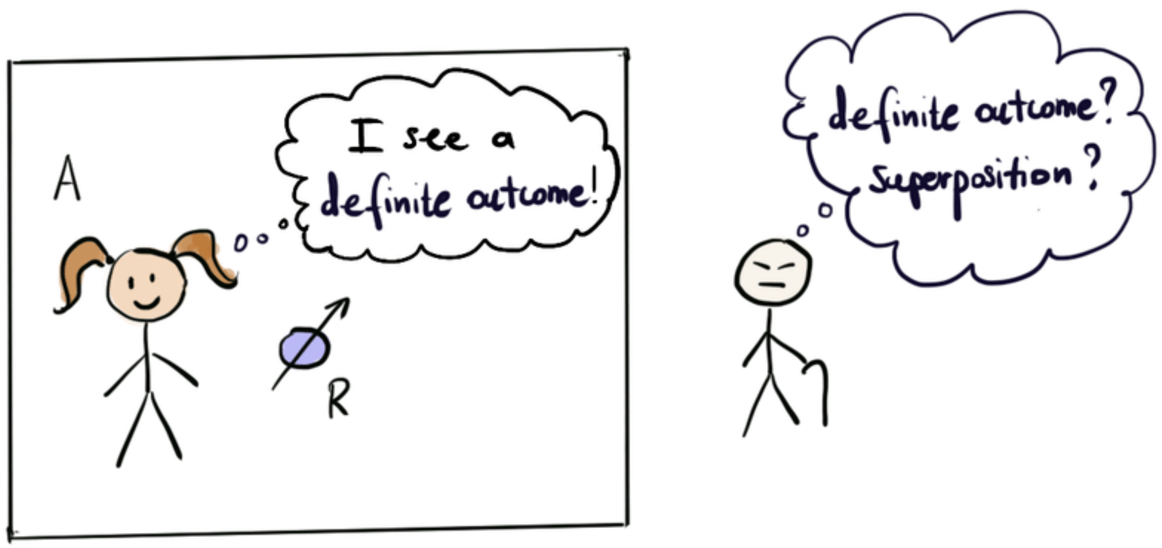


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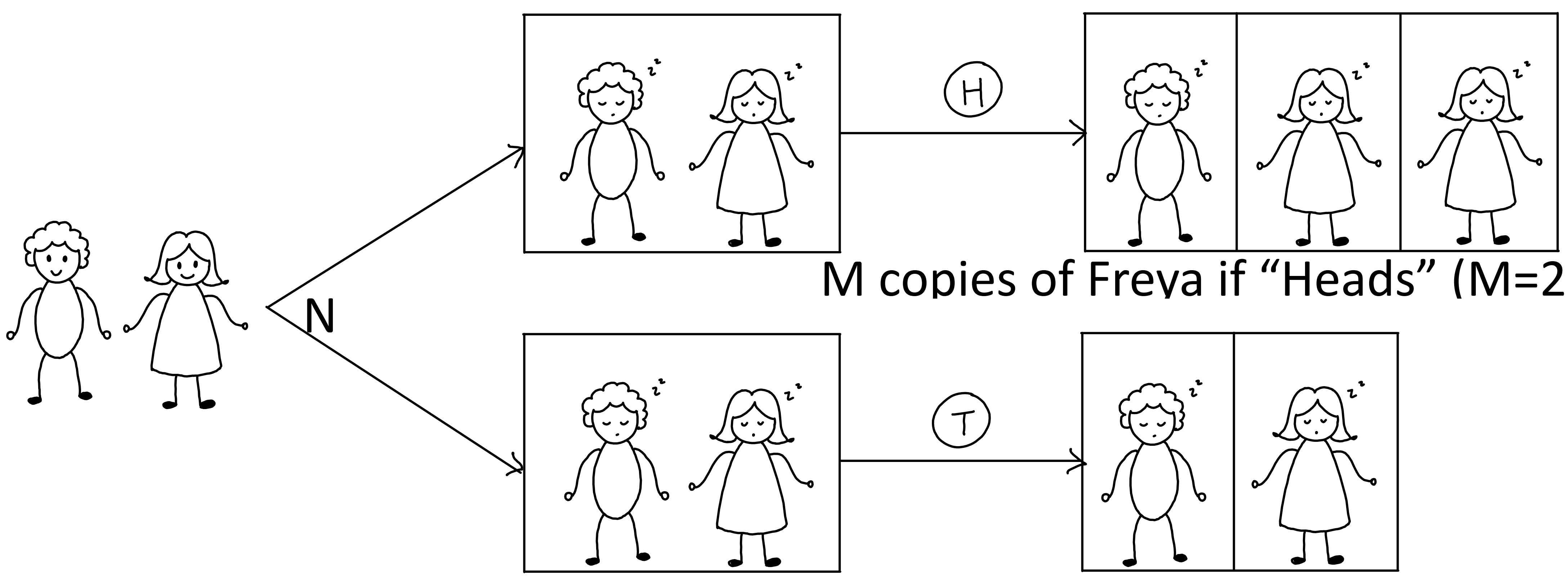

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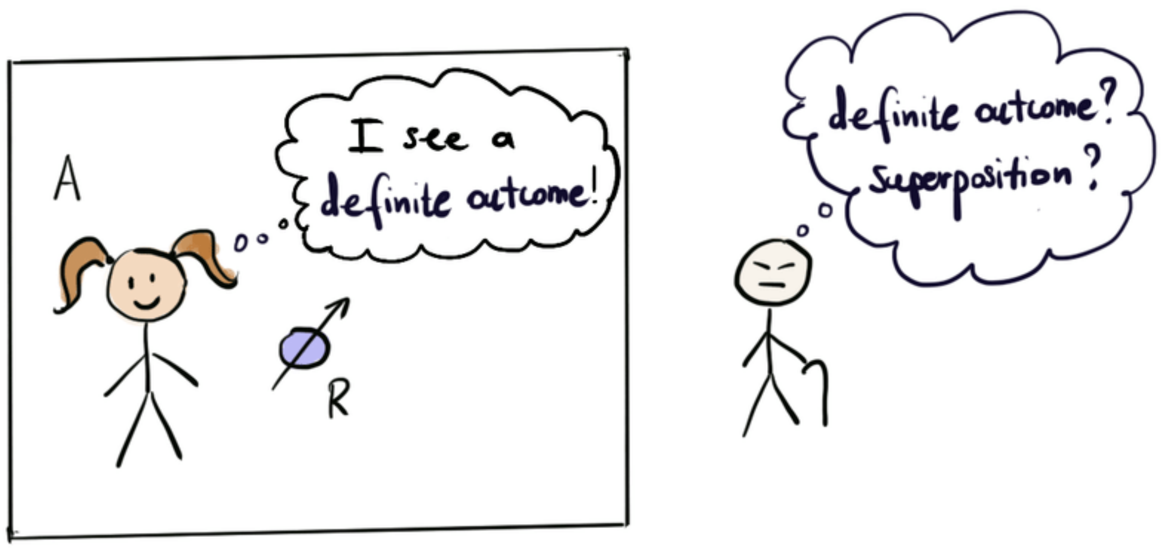


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  Restriction A applies to this scenario as described by, say, classical physics (because it does not tell us what Freya should believe about her future observations — i.e., to $n$=1 observer). Moreover, even if we supplement classical physics with any probability rule whatsoever (not necessarily Elga's Principle of Indifference), which informs Freya about what she should believe about her future observations *in a way that is not completely ignoring her subsequent multiplicity M*, then the resulting theory will be subject to Restriction A for $2 \leq n$ agents.

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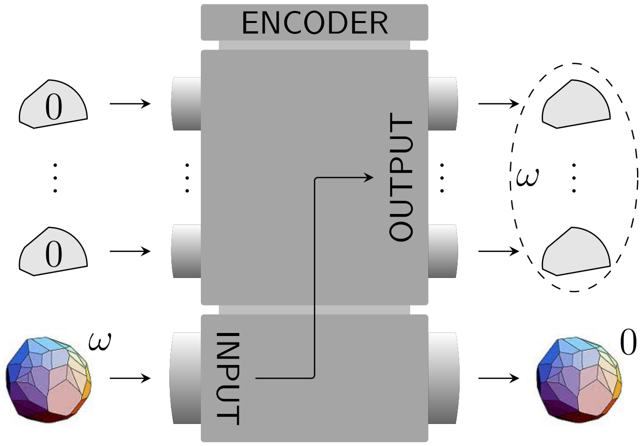


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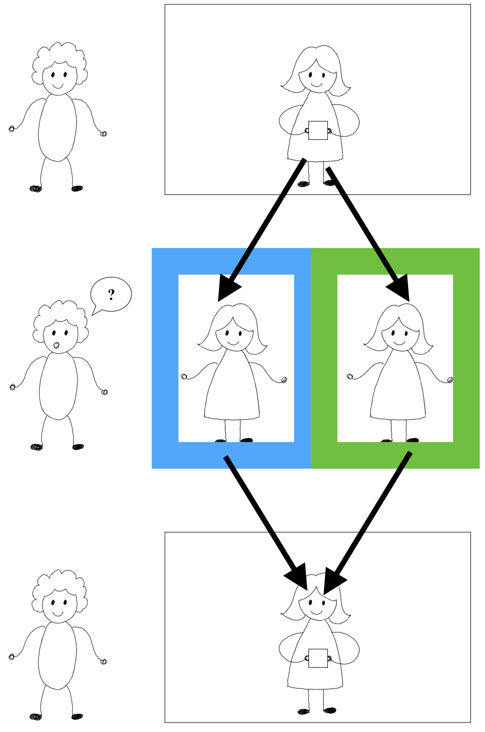

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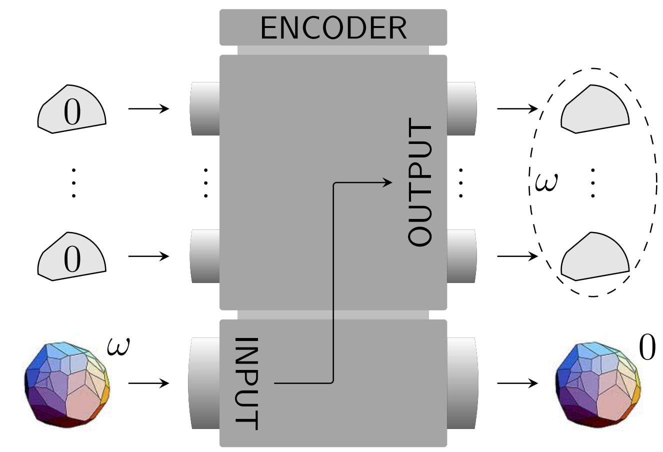


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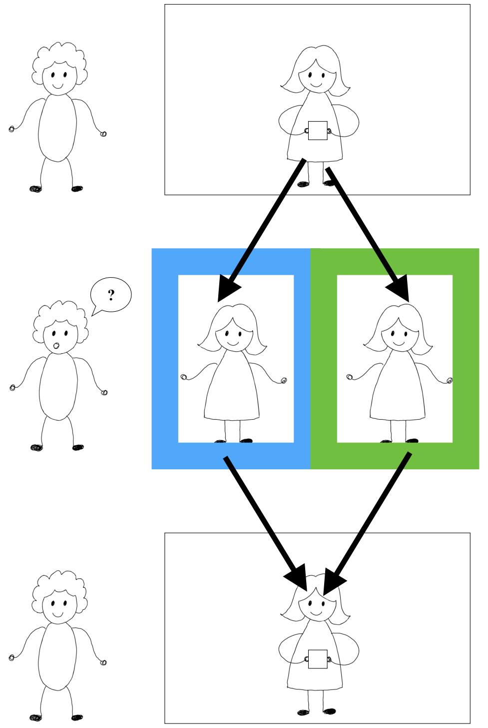


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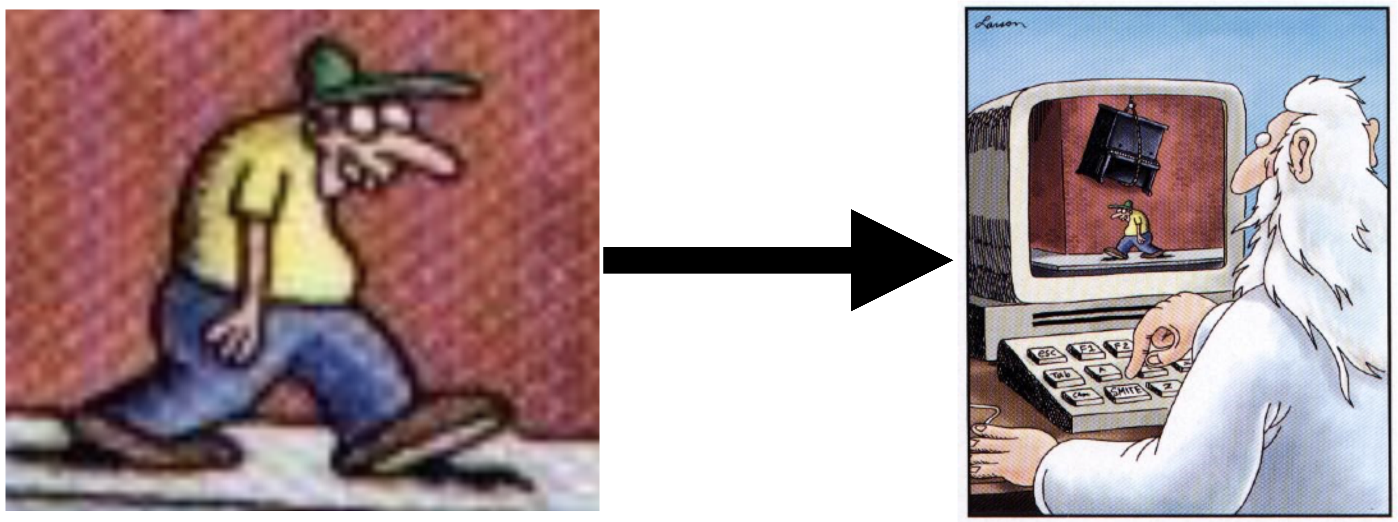

God at His computer

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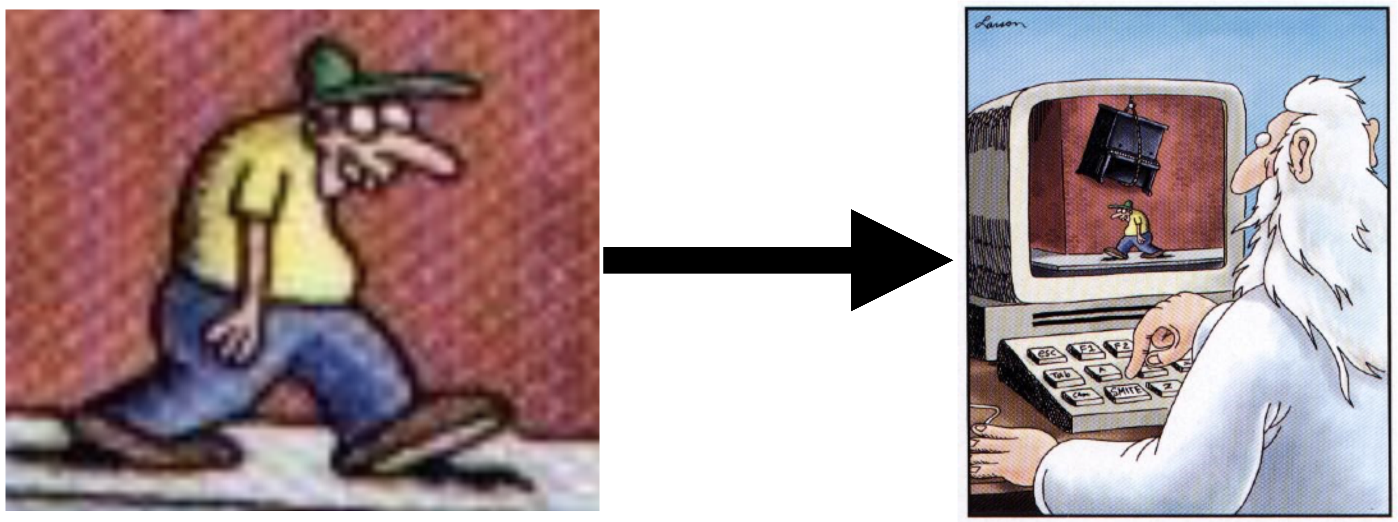

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**You:** Great, but will I *really* wake up in the simulation? Damn, I *really, really want to know!* I'm so afraid! What should I believe will happen to me?

**Doctor:** Hahaha, you fool! You are asking a non-question! All there is to say is that there is a human being here now, and a computer running a simulation of that thing later. This is all there is to know about the facts of the world. What is the proposition that you are even uncertain *about*?

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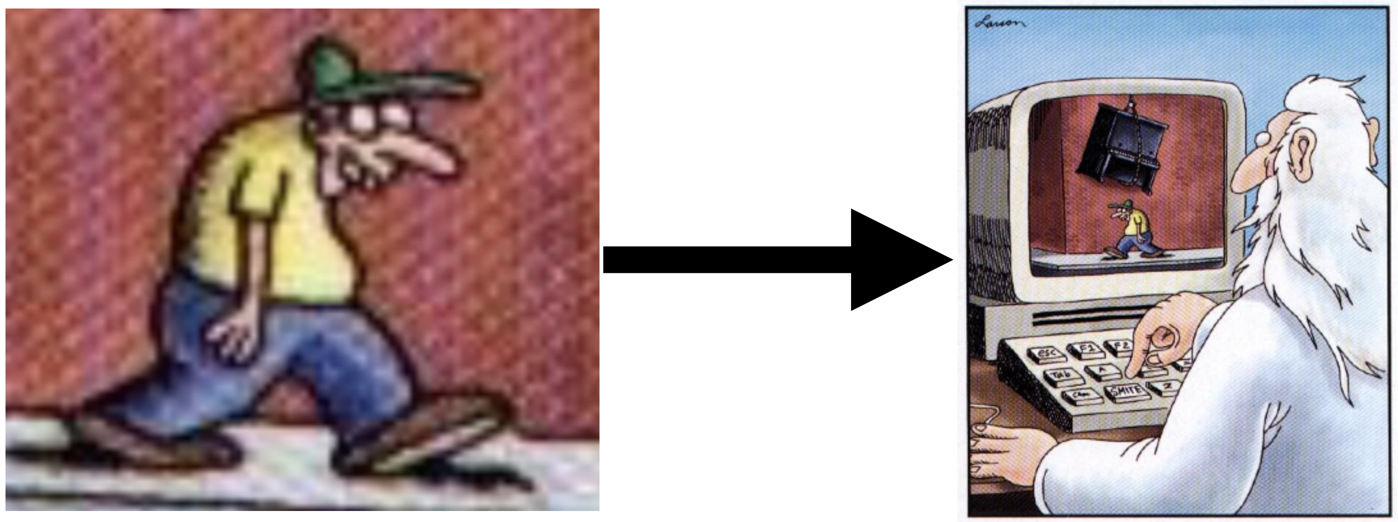

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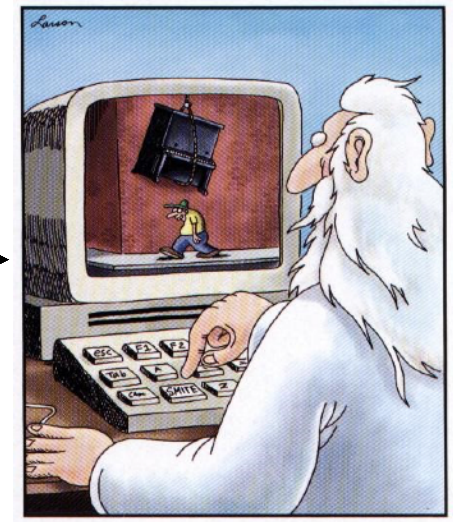
**My claim: This is unacceptable**. The first-person perspective is real. There always exists some (degree of) belief that a single agent *should* have — the agent can perform a **private** experiment, and the world will kick back.

# What about our to-be-simulated and duplicated friends?



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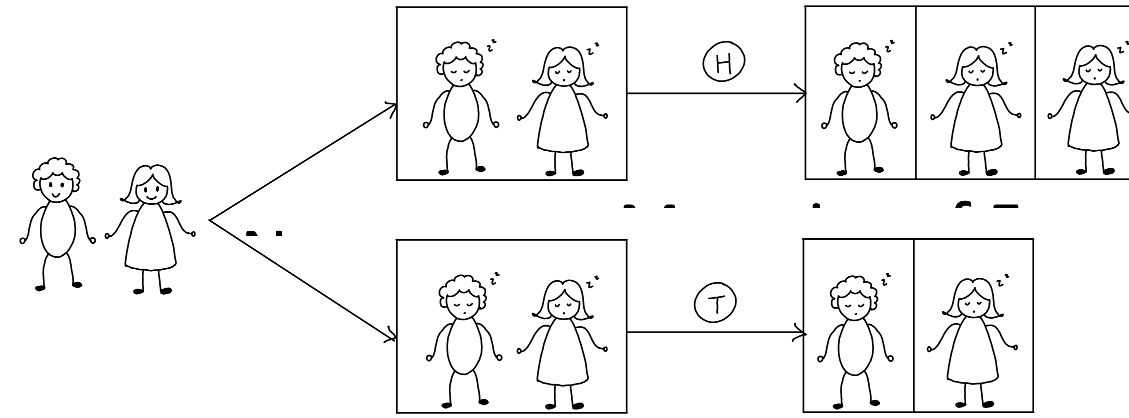

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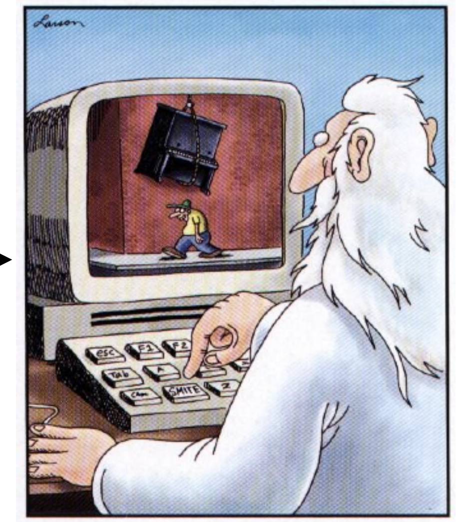

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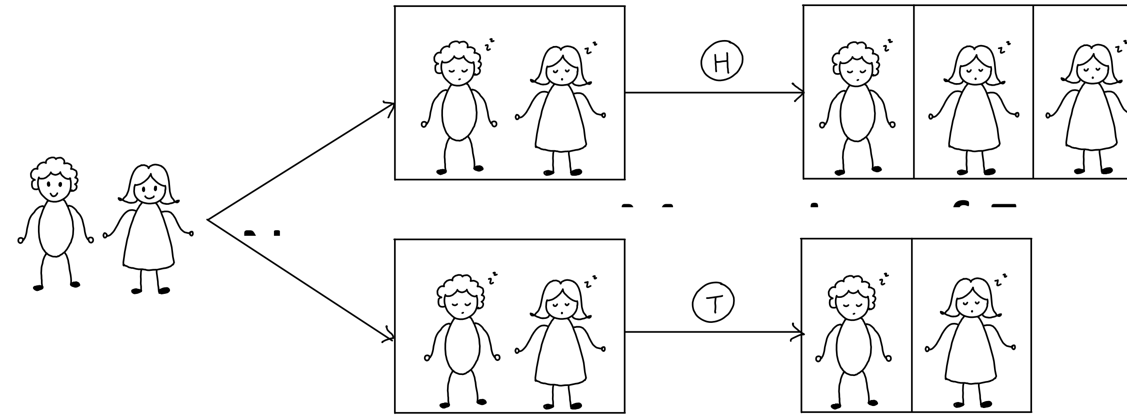
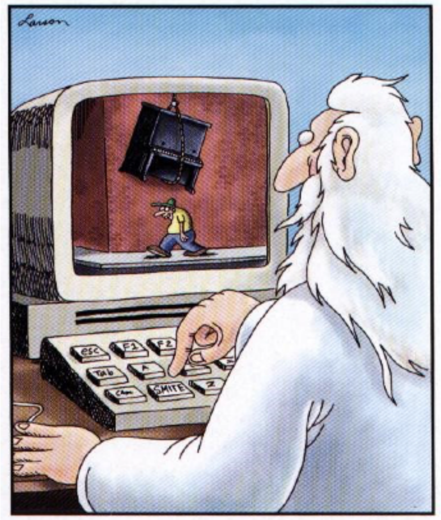
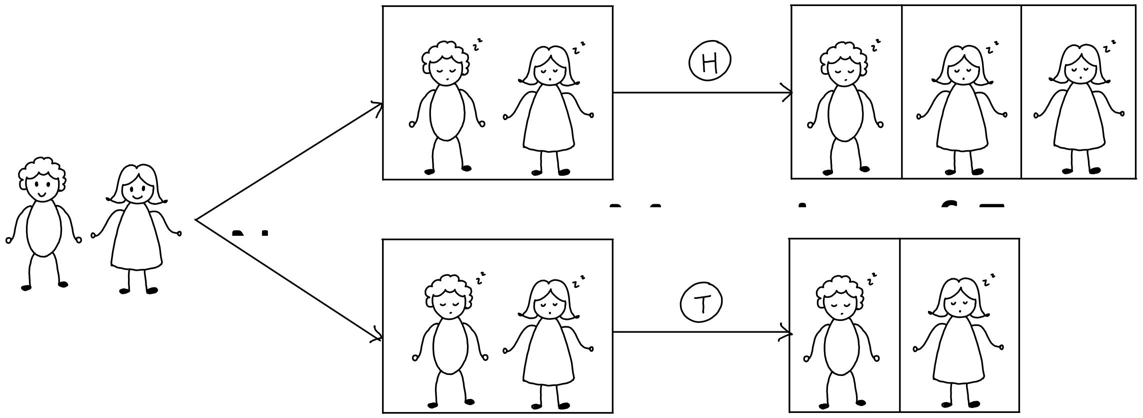



For every **single** agent, there should be a mathematical expression for what they should believe about future experiences, *in all circumstances.* In ordinary physics, this is exactly the quantum state.

# What about our to-be-simulated and duplicated friends?



God at His computer




For every **single** agent, there should be a mathematical expression for what they should believe about future experiences, *in all circumstances.* In ordinary physics, this is exactly the quantum state.

This would be a theory that explains, starting with private probabilities,

- how a notion of “external world” emerges for N=1 agents, and
- how an approximate notion of objectivity emerges for N>1 agents.
- Since the **personalist** probabilities do not typically fit together into a joint distribution, the hope is that aspects of quantum theory arise.
- Then we can tell our simulated & duplicated friends what to expect.

# Algorithmic idealism

An approach of this sort already exists, and is under further construction.

If you are interested: mpmueller.net/ai

Coming soon: Adversarial collaboration with Kelvin McQueen.

**Technical paper:**

M. P. Müller, *Law without law: from observer states to physics via algorithmic information theory*, Quantum **4**, 3301 (2020).

**Recent essay:**

M. P. Müller, *Algorithmic idealism: what should you believe to experience next?*, arXiv:2412.02826.

# Conclusions 1/2

- Quantum theory is just one of many probabilistic theories.

- Since 2011, we know how to derive **QT from simple principles**, without preassuming any of the usual mathematical machinery (algebras, complex numbers, Hilbert spaces…)

- Have shown one such "reconstruction" of QT:

  Ll. Masanes, M. P. Müller, R. Augusiak, and D. Pérez-García, *Existence of an information unit as a postulate of quantum theory*, Proc. Natl. Acad. Sci. USA **110**, 16737 (2013).

  but there are many others, e.g.

  Ll. Masanes and M. P. Müller, New J. Phys. **13**, 063001 (2011).

- The view that a **quantum state is a "catalog of probabilities"** for what some agent should believe to observe/experience next has the power to explain why QT has the very mathematical structure that it does.

# Conclusions 2/2

- Have shown how to reproduce certain structural aspects of Wigner's friend scenarios classically via **duplication**.

- **Restriction A** as a common core: physical theories do not always give us joint probability distributions for the future observations of all agents (or even a *single* agent).
  Have argued that this is what Wigner's friend is ultimately about.

- This is at the core of several other puzzles in physics and philosophy, including **classical duplication** or the Boltzmann brain problem, see:

  Caroline Jones and MM, arXiv:2402.08727 (and mpmueller.net/ai)

- Have argued that this motivates idealist/fragmentalist approaches where "reality" is a mosaic of the fundamental first-person pieces.

**Thank you!**