The informational approach to quantum theory: probabilistic theories, quantum principles, and hidden variable models

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Open Problems in Quantum Mechanics, Frascati,
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In collaboration with

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- G. Chiribella

- F. Manessi

Outline

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- Operational-probabilistic framework

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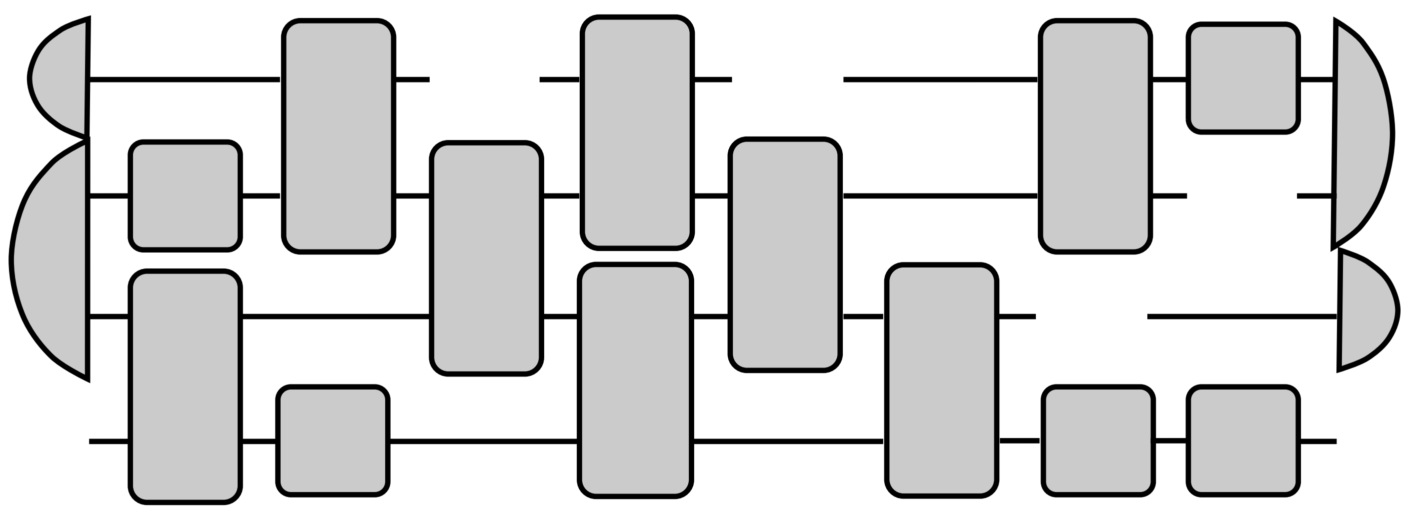
- Hidden variable theories and their properties
    - Spooky action at a distance and outcome independence
    - Completeness
    - Steering, Complementarity and Schrödinger's cat

The operational language

- Operational theory: tests with composition rules



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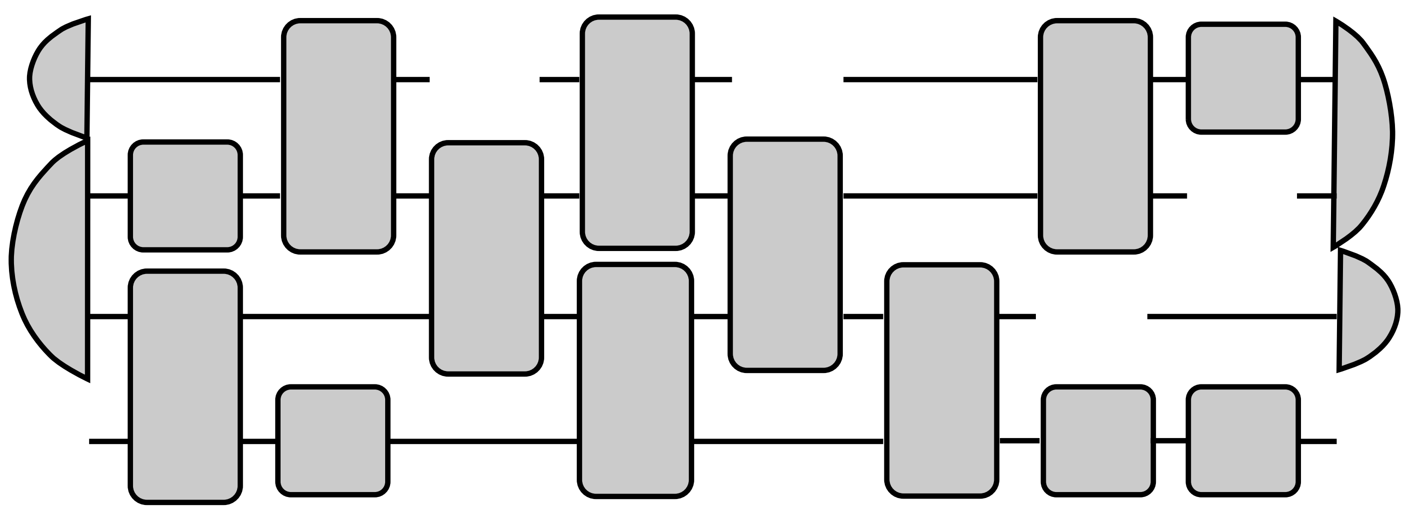

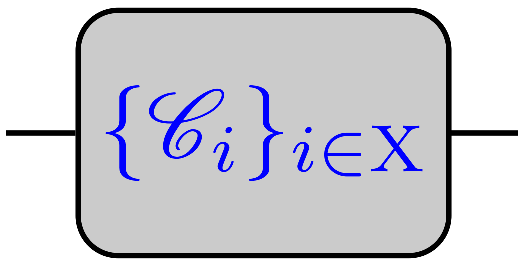

i∈X: outcome

$\mathscr{C}_i$: event of the test

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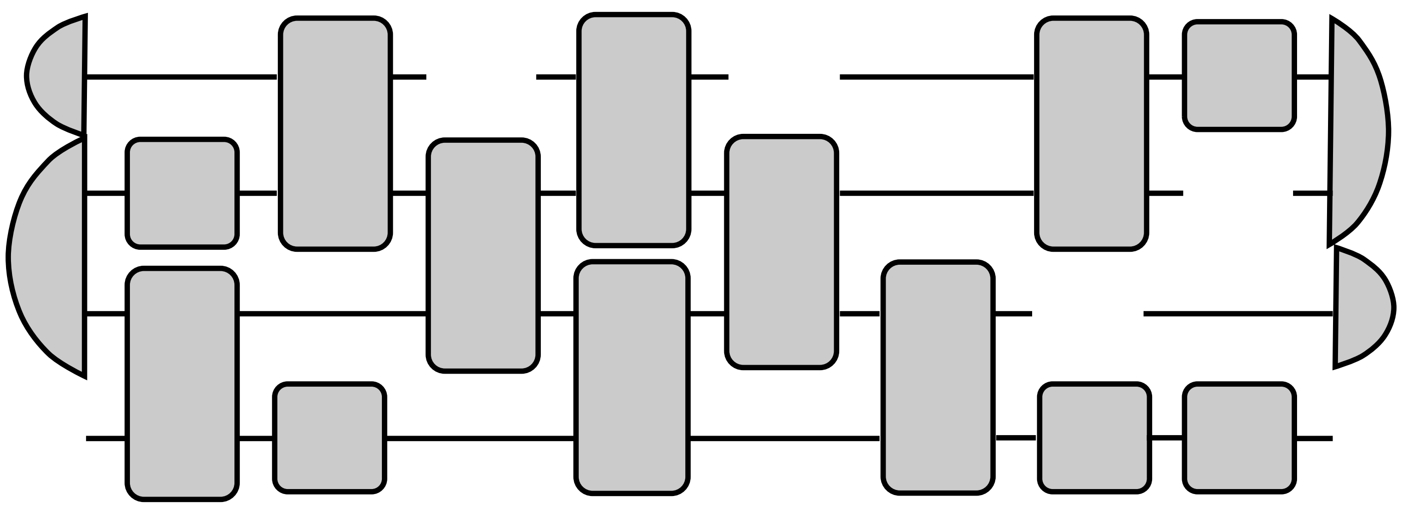

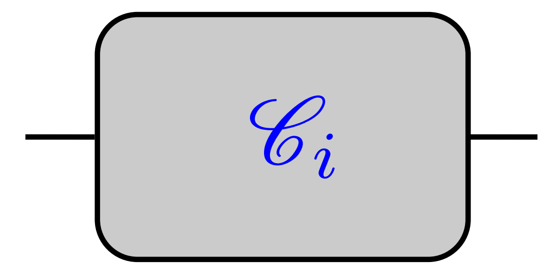

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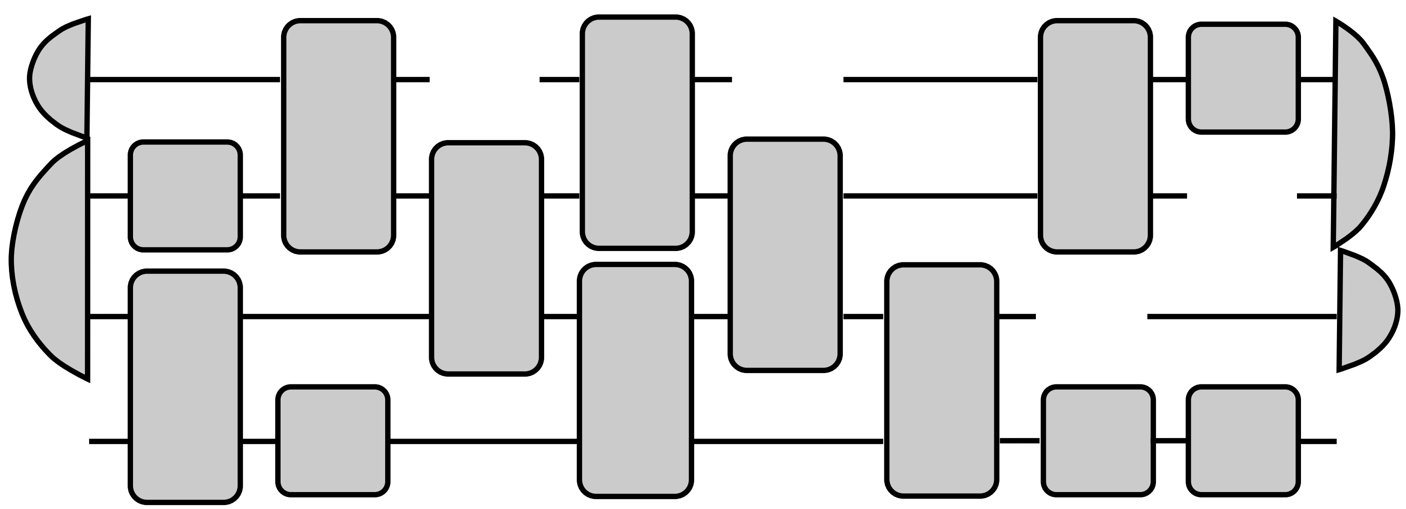

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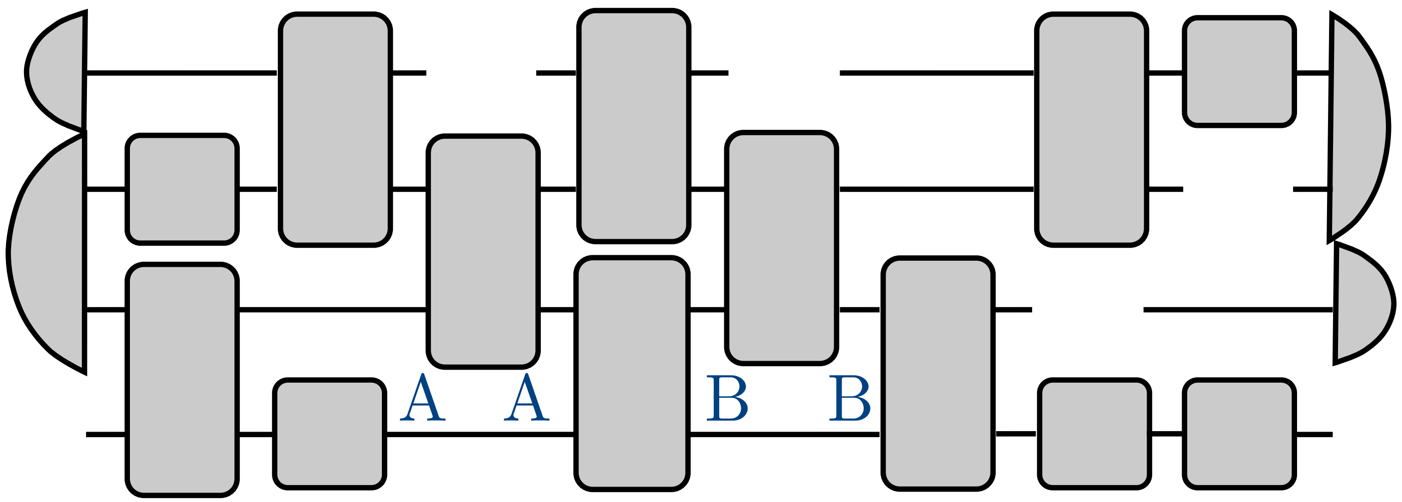

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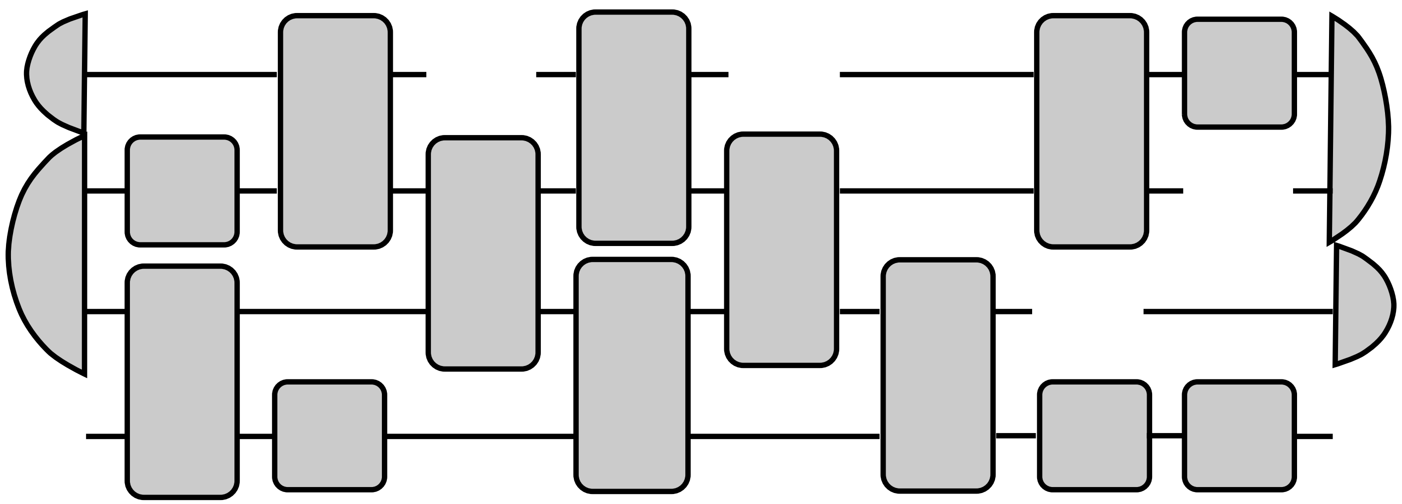

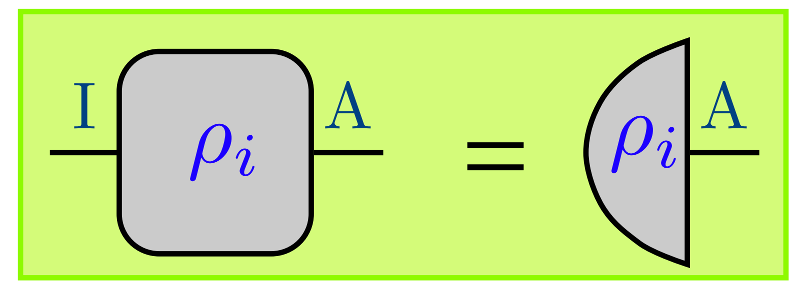

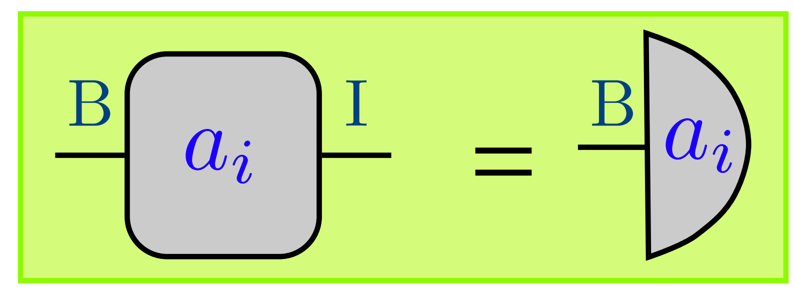

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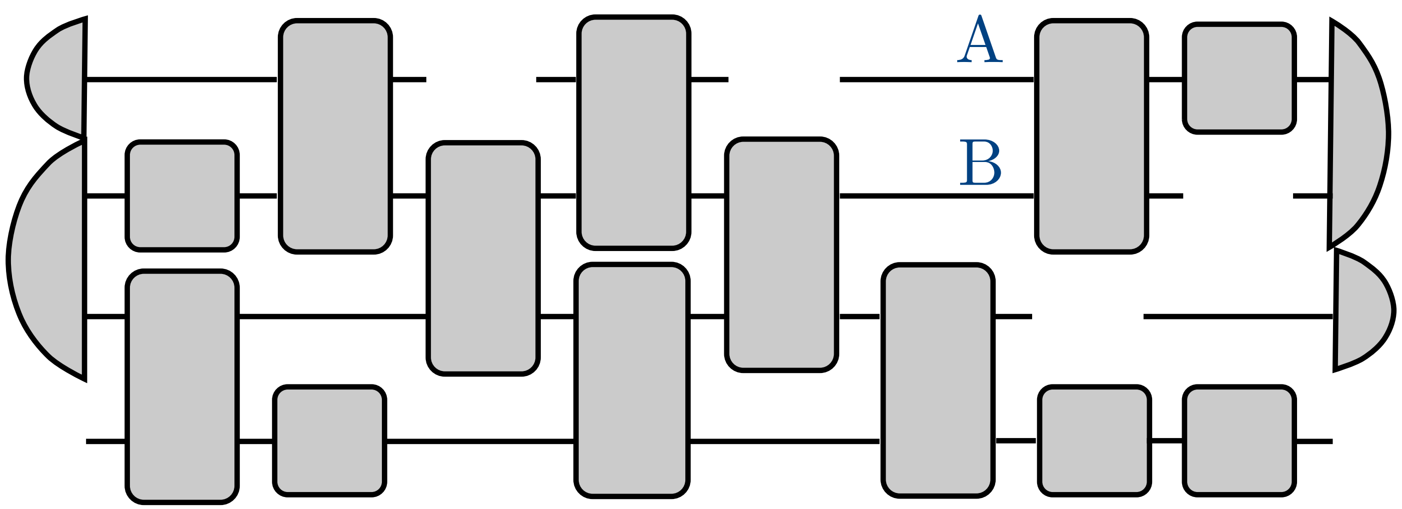

- •C:=AB=BA
- •(AB)C=A(BC)
- •AI=IA=A

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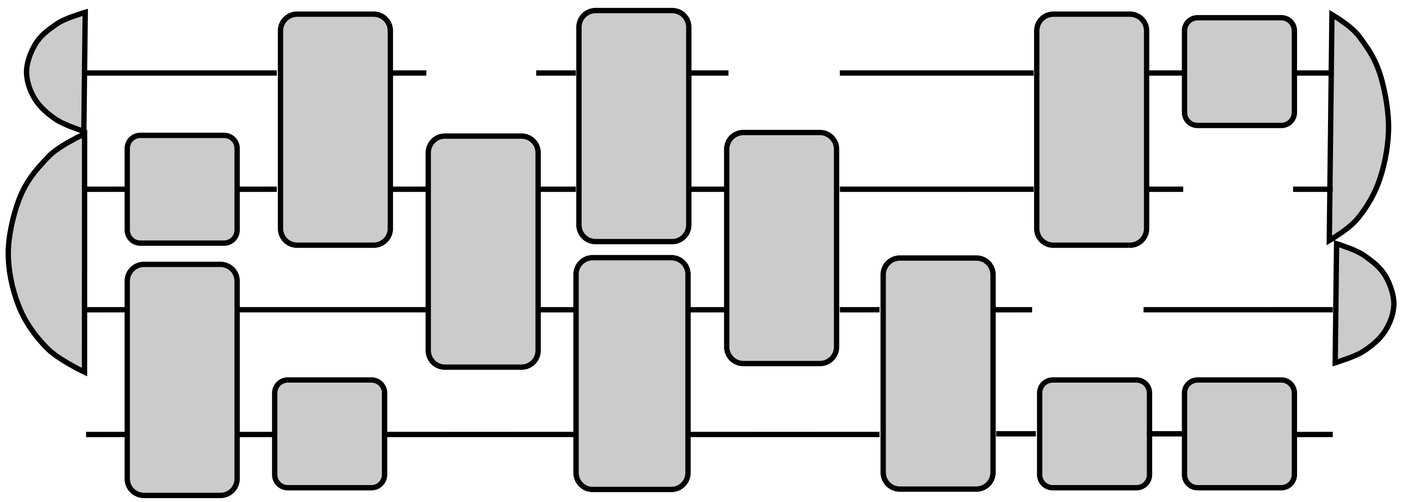
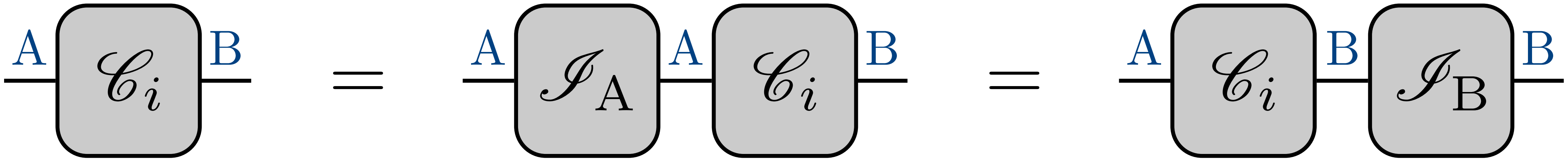


- For any system A there exists a unique test $\mathscr{I}_{\mathrm{A}}$ such that



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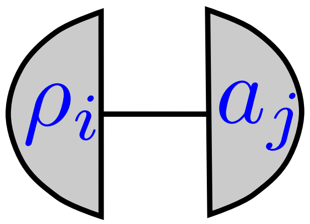
Operational probabilistic theories

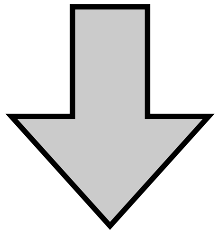
- Probabilistic theory

Every test of type I→I is a probability distribution



$= \mathrm{Pr}(a_j, \rho_i)$

States are functionals on effects and viceversa



Real vector spaces $\mathsf{St}_{\mathbb{R}}(\mathrm{A}), \mathsf{Eff}_{\mathbb{R}}(\mathrm{A})$

Events are linear transformations

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Coarse graining and Atomicity

- Coarse graining of the test $\{\mathscr{A}_i\}_{i\in\mathrm{X}} \Rightarrow \{\mathscr{B}_j\}_{j\in\mathrm{Y}}$

$$\mathscr{B}_j = \sum_{i\in\mathrm{X}_j} \mathscr{A}_i \qquad \bigcup_{j\in\mathrm{Y}} \mathrm{X}_j = \mathrm{X} \qquad \mathrm{X}_j \cap \mathrm{X}_k = \emptyset$$

- Atomic is an event which does not represent a coarse graining

- The refinement set of an event contains all refining events

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Axioms for Quantum Theory

- Causality
- Local discriminability
- Atomic composition
- Perfect discriminability
- Ideal compression
- Purification

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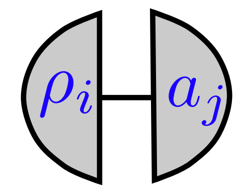
$p_a(\rho_i) := \sum_j$  $= p(\rho_i)$

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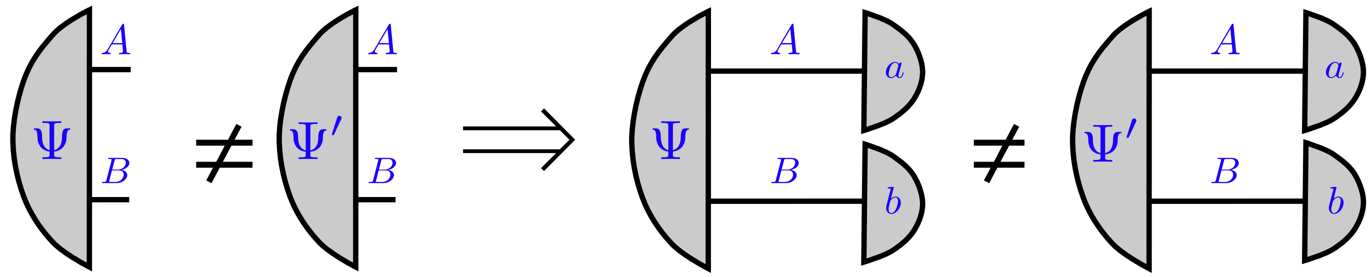

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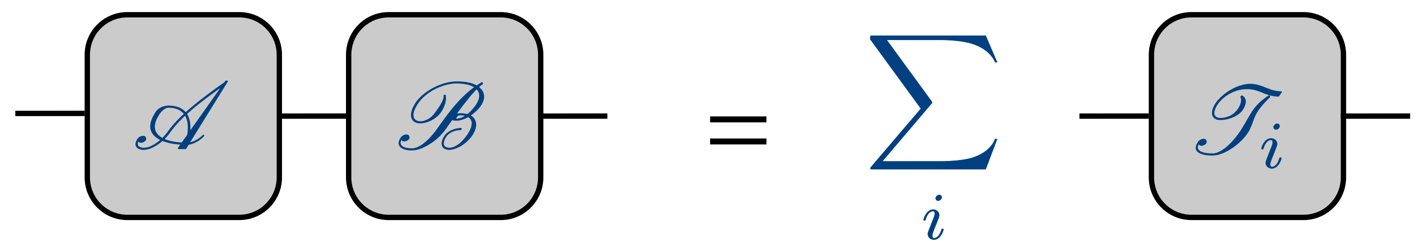

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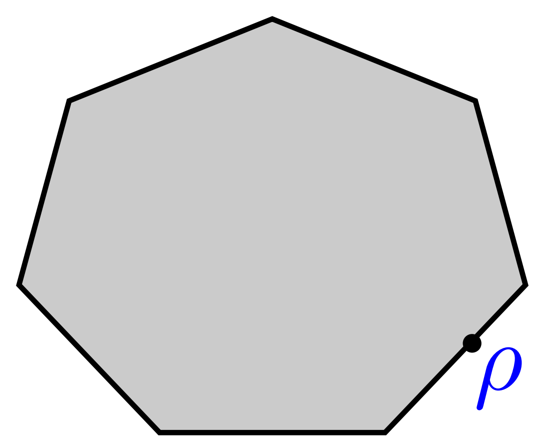

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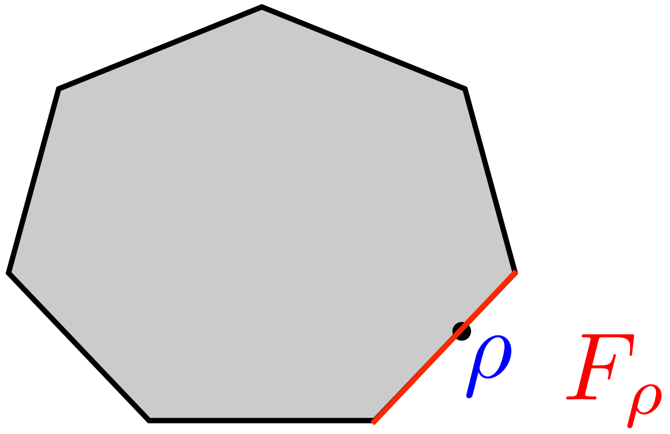

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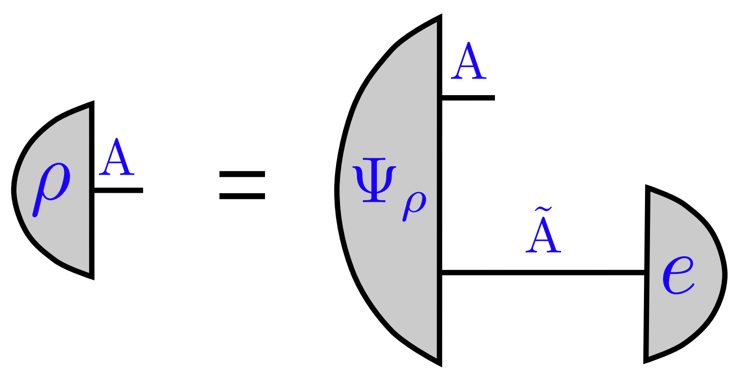

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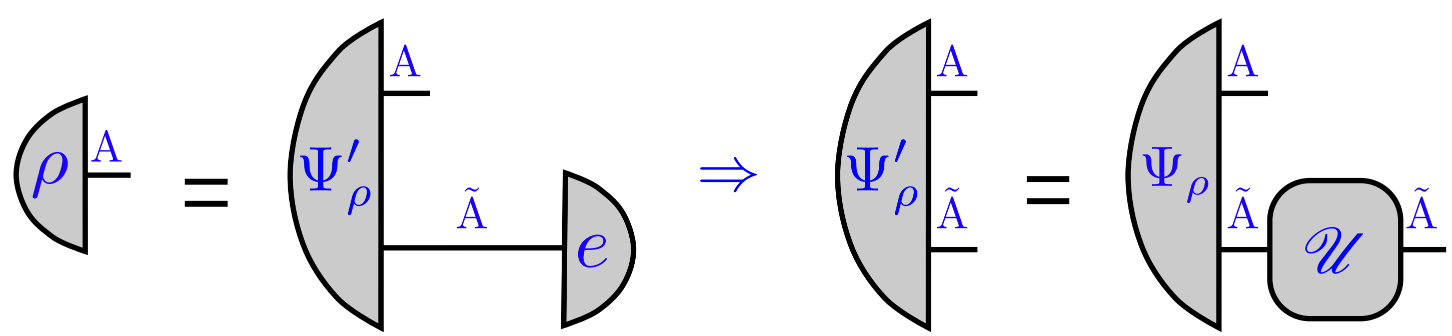

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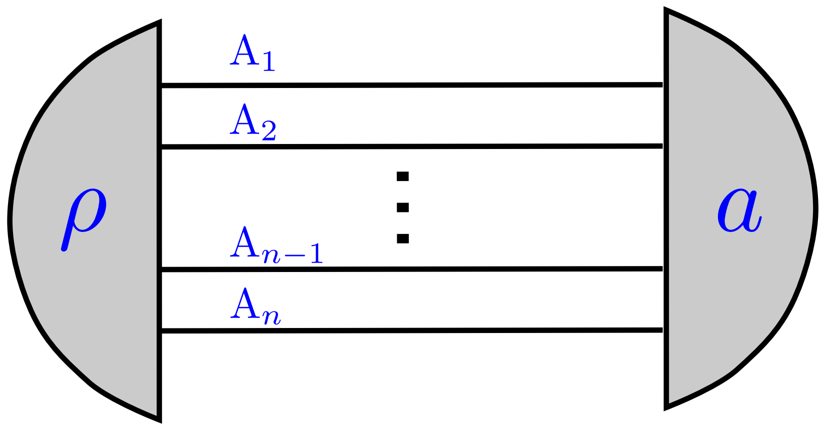
Hidden Variable Theories for OPTs

- Given an OPT for every circuit of type



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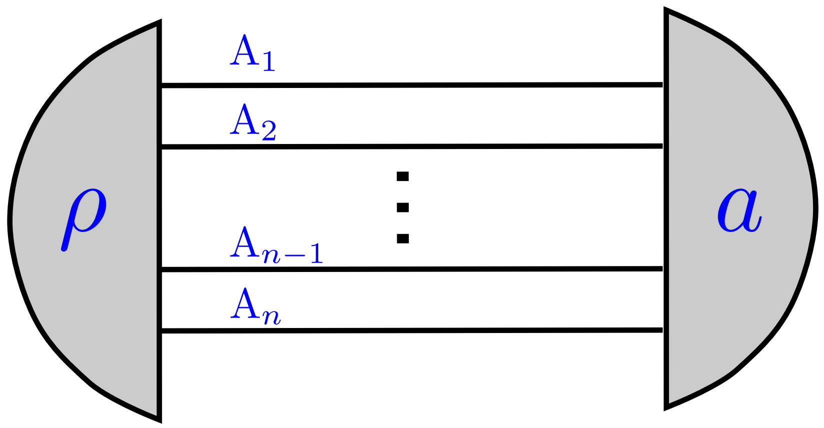

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- Define the sample space $\Psi^{\mathrm{A}_1 \otimes \cdots \otimes \mathrm{A}_n} := \mathrm{Y} \times \{a^{(1)}, \ldots, a^{(n)}\}$

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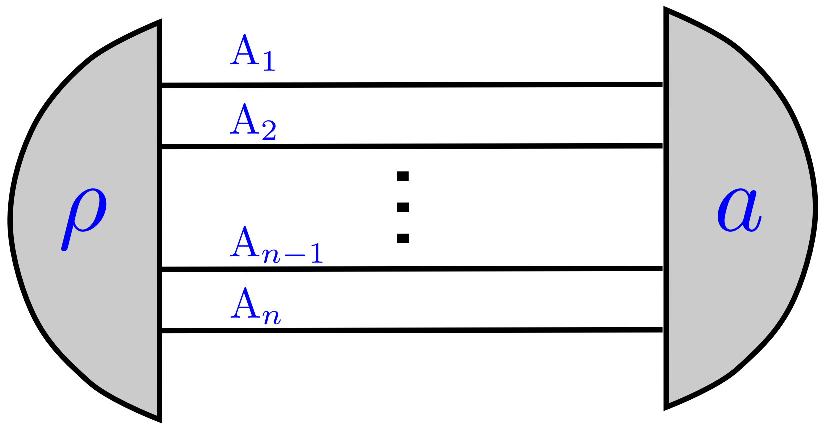

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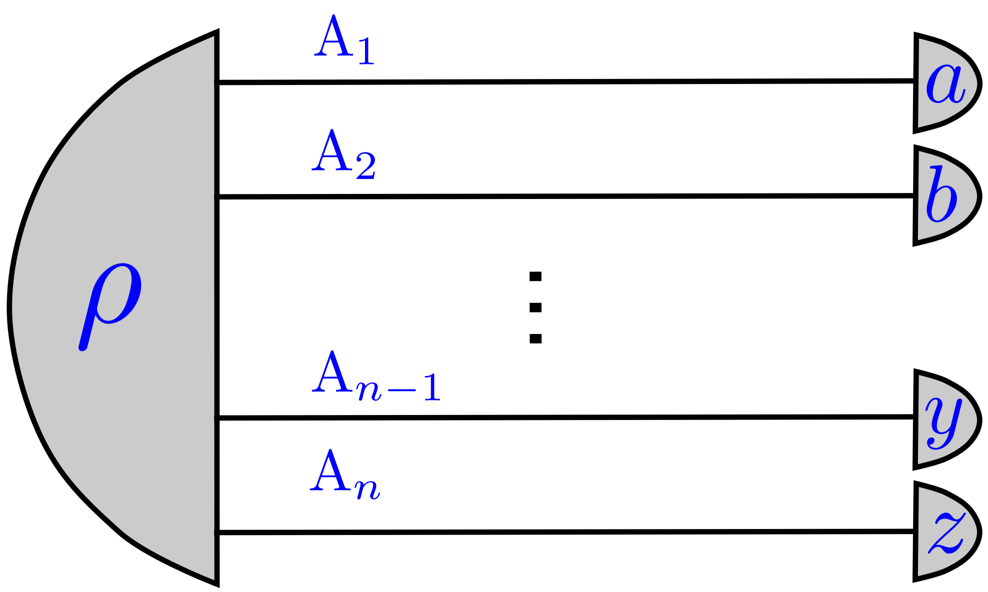
- Equivalent HVT: $\Lambda^{\mathrm{A}_1 \otimes \cdots \otimes \mathrm{A}_n}, \mathrm{Pr}^{\rho}_{\lambda} : \Psi \times \Lambda$

$$\mathrm{Pr}(a_j|a) = \sum_{\lambda \in \Lambda} \mathrm{Pr}_{\lambda}(a_j|a, \lambda) \mathrm{Pr}_{\lambda}(\lambda|a)$$

Hidden variable theories and locality

- Typical setting: local measurements



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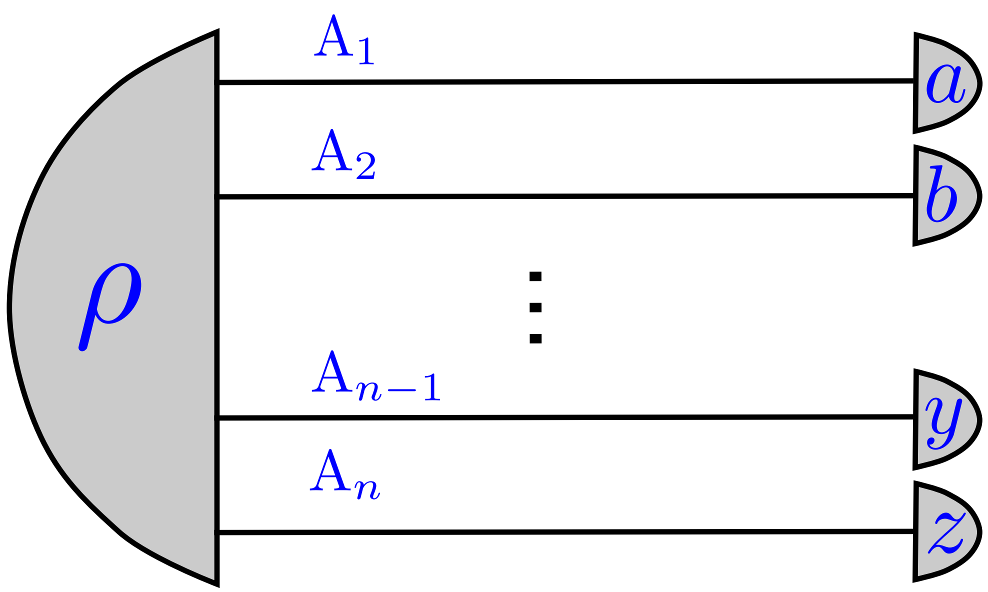

- This setting is used to prove non-locality of quantum theory

$$\Pr(a_i, b_j | a, b) \neq \sum_{\lambda \in \Lambda} \Pr_\lambda(a_i | a, \lambda) \Pr_\lambda(b_j | b, \lambda) \Pr_\lambda(\lambda)$$

Basic properties of HVTs

- λ-Independence $$\Pr_\lambda(\lambda|a,b,\ldots) = \Pr_\lambda(\lambda|a',b',\ldots)$$

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- Parameter Independence $$\Pr_\lambda(a_i|a,b,\dots,\lambda) = \Pr_\lambda(a_i|a,\lambda)$$

- Free Choice* $$\Pr_\lambda(a|b_i,b,\lambda) = \Pr_\lambda(a|b_i',b',\lambda')$$ $$\Pr_\lambda(a) > 0, \quad \forall a$$

* R. Colbeck and R. Renner, arXiv:1111.6597 (2011)

Determinism

- Strong determinism:

$$\forall a, \lambda \quad \exists! \; a_i \text{ s.t. } \quad \Pr_\lambda(a_i|a, \lambda) = 1$$

- Weak determinism:

$$\forall a, b, \ldots, \lambda \quad \exists! \; (a_i, b_j, \ldots) \text{ s.t. } \quad \Pr_\lambda(a_i, b_j, \ldots |a, b, \ldots, \lambda) = 1$$

Existence theorems

- T1: Given any empirical model, there is an equivalent hidden-variable model which satisfies Strong Determinism*.

- T2: Given any empirical model, there is an equivalent hidden-variable model which satisfies Weak Determinism and λ-Independence*.

T1 does not grant λ-independence and parameter independence

T2 does not grant parameter independence

* A. Brandenburger and N. Yanofsky, J. Phys. A: Math. Theor. **41**, 425302 (2008)

Assumption

- We will consider only HVTs with both

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Properties of HVTs

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- Locality

Properties of HVTs

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- Locality $\Pr_\lambda(a_i, b_j, \ldots|a, b, \ldots, \lambda) = \Pr_\lambda(a_i|a, \lambda)\Pr_\lambda(b_j|b, \lambda)\ldots$
- Completeness

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- Completeness $\mathrm{Pr}_{\lambda\mu}(a_i|a,\lambda,\mu) = \mathrm{Pr}_\lambda(a_i|a,\lambda), \quad \forall\lambda,\mu\ \mathrm{Pr}_{\lambda,\mu}(\lambda,\mu) > 0$

Locality ⇔ Parameter Independence + Outcome Independence

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Locality ⇔ Parameter Independence + Outcome Independence

- Notice: violation of locality ⇔ violation of Outcome Independence

Spooky action at a distance

- A theory is spooky* if any equivalent HVT violates Outcome Independence

* G. M. D'Ariano, F. Manessi, and PP arXiv:1108.3681 (2011).

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    ➡ It necessarily violates outcome independence

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Complete operational probabilistic theories

- HVT for an OPT: descriptively non significant* if for every pure state

$$\mathrm{Pr}_\lambda[a_i, b_j, \ldots | a, b, \ldots, |\Psi, \lambda] = \mathrm{Pr}_\lambda[a_i, b_j, \ldots | a, b, \ldots, |\Psi, \lambda']$$

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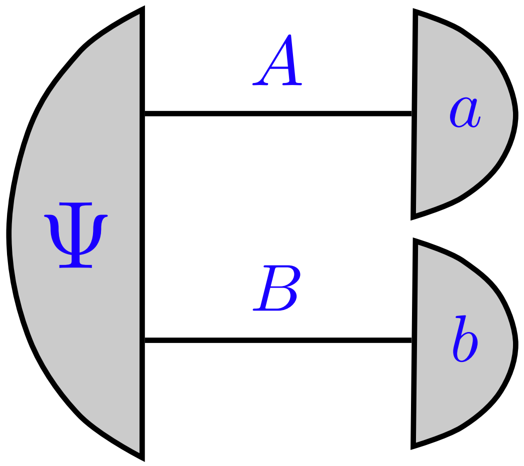
- OPT: complete if any HVT is descriptively non significant
  - Quantum Theory is complete**

* G. M. D'Ariano, F. Manessi, and PP arXiv:1108.3681 (2011).

** R. Colbeck and R. Renner, Nature Communications **2**, 411 (2011)

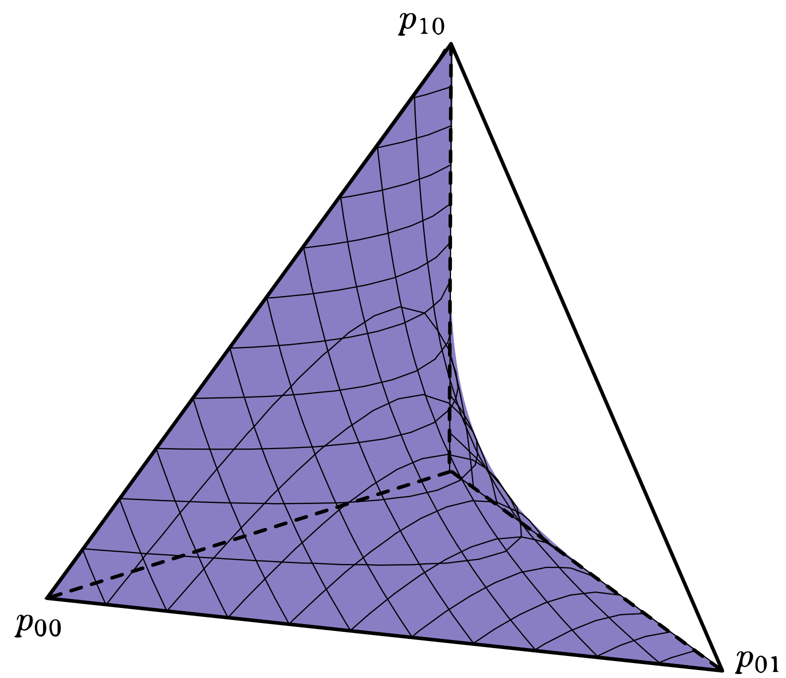
Complete spooky theories

- Theorem*: a complete theory is spooky if and only if there exists a pure state Ψ and tests $a:=(a_0,a_1)$ and $b:=(b_0,b_1)$ such that



$$p_{00}p_{11} \neq p_{01}p_{10}$$

$$p_{ij} := \Pr(a_i, b_j|\Psi)$$



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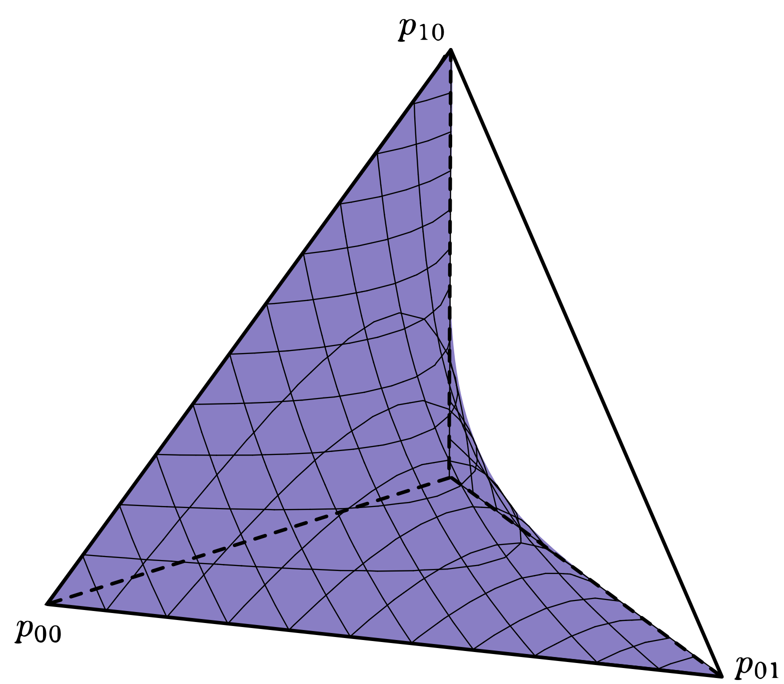
- It seems very likely to have theories violating outcome independence



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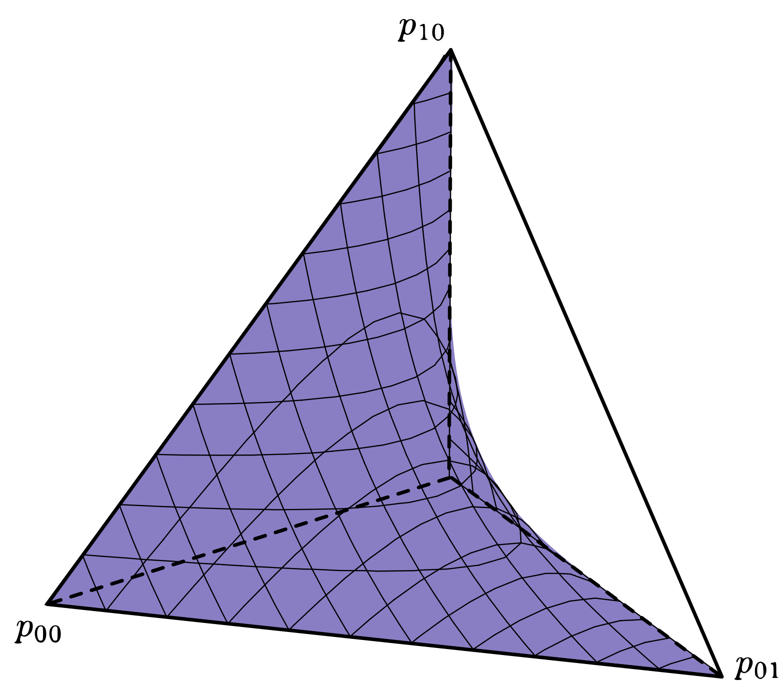

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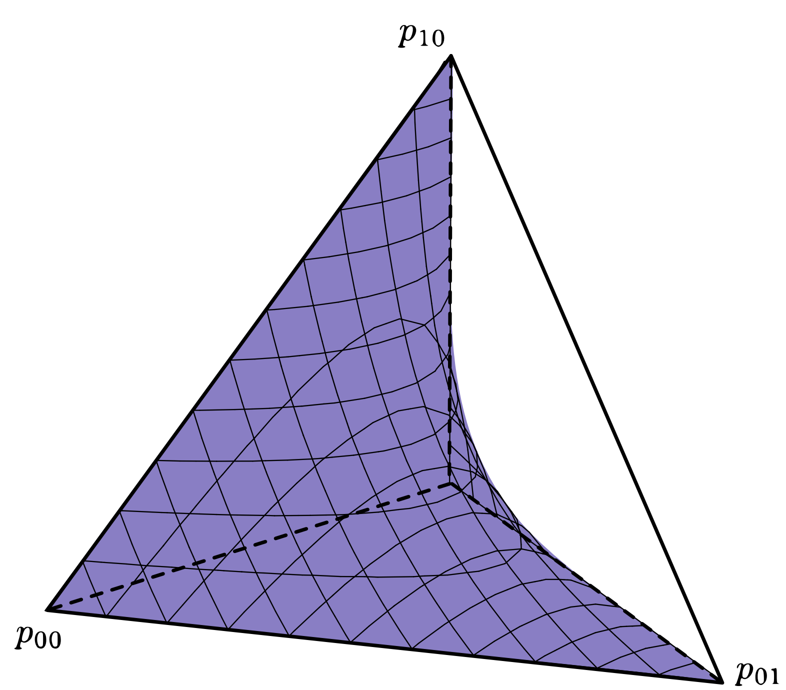
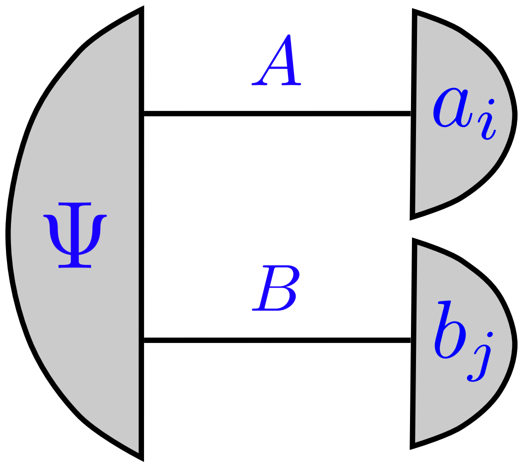
  - Question: how can one characterise complete theories?
  - Is completeness sufficient to single out Classical and Quantum statistics?

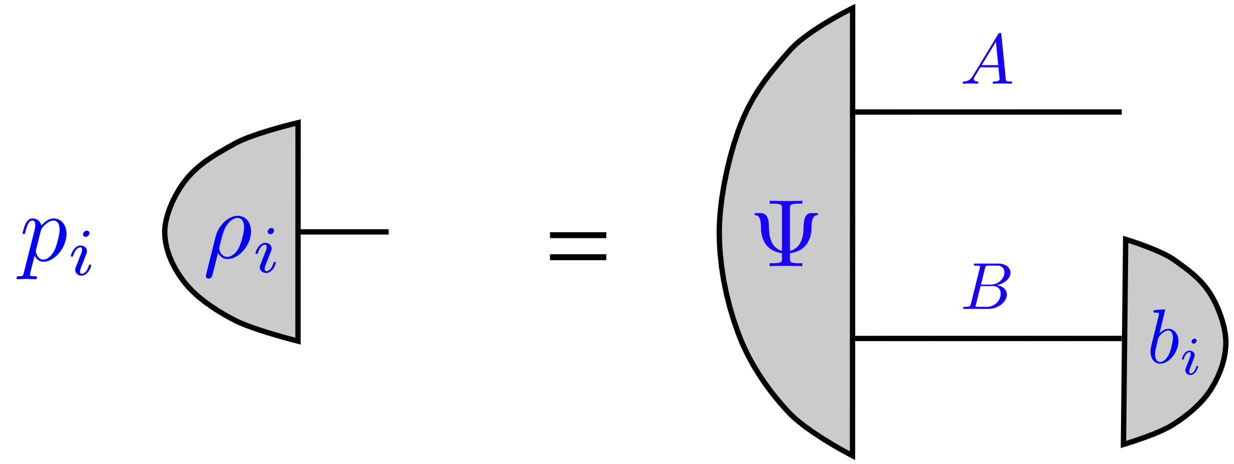


Steering and outcome independence

- Theorem*: An OPT admits a steering state for a non trivial ensemble of two different states if and only if its probabilities satisfy



$$p_{00}p_{11} \neq p_{01}p_{10}$$



* G. M. D'Ariano, F. Manessi, and PP arXiv:1108.3681 (2011).

Steering and spookiness

- Corollary*: For a complete OPT the following are equivalent

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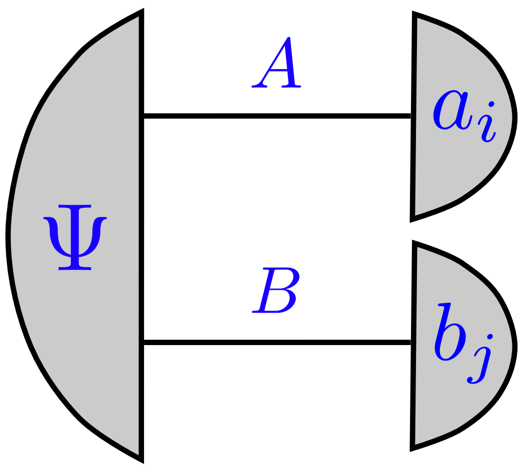
1. 

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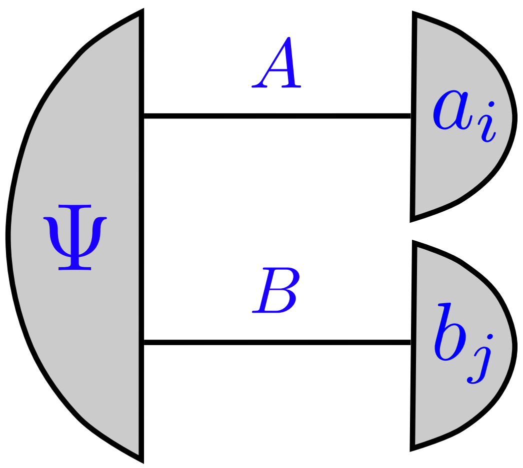
1. 

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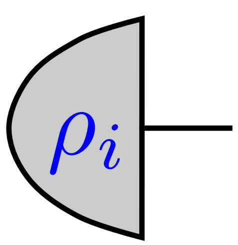
2. p_i 

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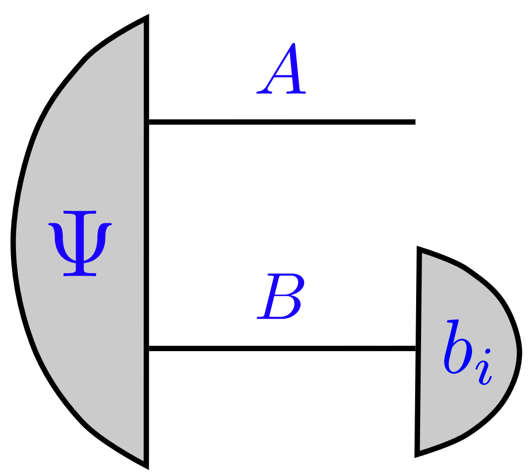

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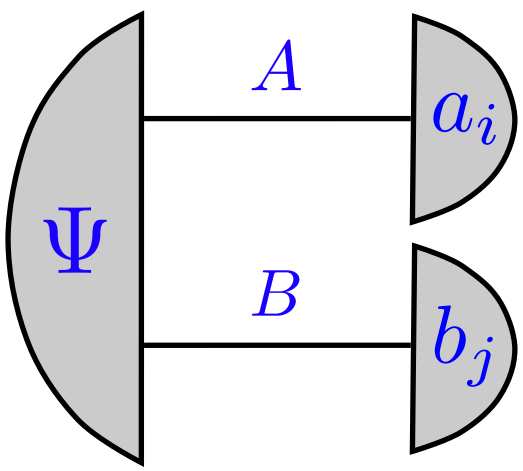

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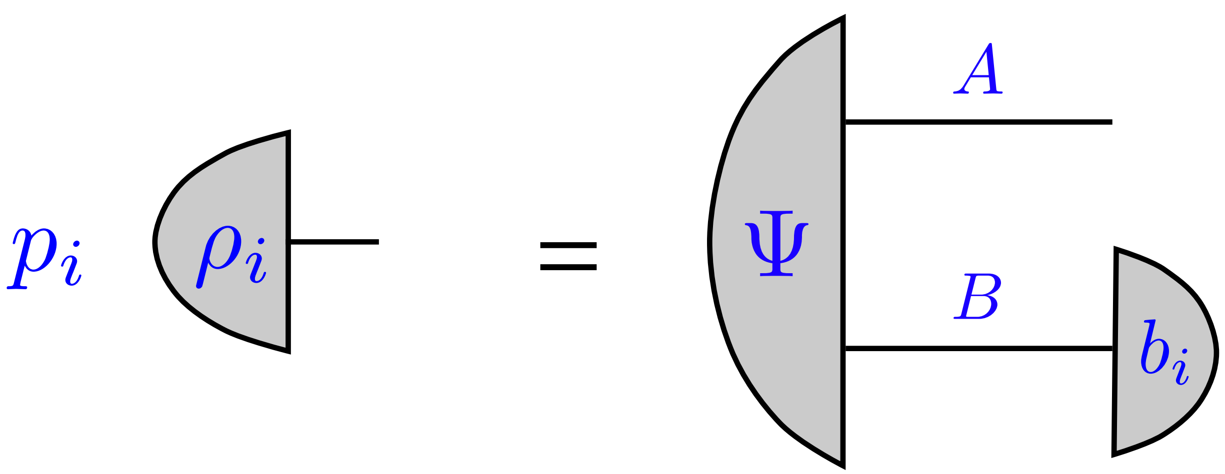

3. Spookiness

* G. M. D'Ariano, F. Manessi, and PP arXiv:1108.3681 (2011).

Propositions

- Proposition*: a test a=(a_0, a_1) such that there exist two states ρ_0, ρ_1 s.t.

$$\Pr(a_i|\rho_j) = \delta_{ij}$$

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- The proposition can have definite truth values, corresponding to preparations ρ_0 (false), and ρ_1 (true).

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- In Quantum Theory propositions correspond to orthogonal projections

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- In Quantum Theory propositions correspond to orthogonal projections
    - Their existence in Quantum Theory is granted by the axiom of discriminability of non fully mixed states**:

      Every state that is not fully mixed can be perfectly discriminated from another state

* G. M. D'Ariano, F. Manessi, and PP arXiv:1108.3681 (2011).
** G. Chiribella, G. M. D'Ariano, and PP, Phys. Rev. A **84**, 012311 (2011).

Complementarity

- An OPT entails complementarity if there are two propositions $a^{(i)}=(a^{(i)}_0, a^{(i)}_1)$ s.t.

$$\Pr(a_i^{(0)}|\rho) = 1 \quad \Rightarrow \quad 0 < \Pr(a_j^{(1)}|\rho) < 1$$

- An OPT entails complementarity if and only if there is a set of propositions $a^{(i)}=(a^{(i)}_0, a^{(i)}_1)$ s.t.

$$\Pr(a_j^{(i)}|\rho) = 1 \quad \Rightarrow \quad \exists\, k, l \quad 0 < \Pr(a_l^{(k)}|\rho) < 1$$

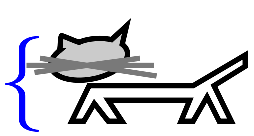
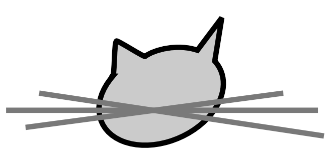
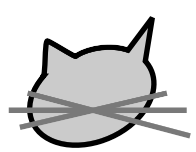
G. M. D'Ariano, F. Manessi, and PP arXiv:1108.3681 (2011).

Schrödinger's cat I

G. M. D'Ariano, F. Manessi, and PP arXiv:1108.3681 (2011).

Schrödinger's cat I

- An OPT with complementarity exhibits Schrödinger's cat-like paradox

$a^{(0)} = \{$  ,  $\}$ $a^{(1)} = \{$  ,  $\}$

G. M. D'Ariano, F. Manessi, and PP arXiv:1108.3681 (2011).

Schrödinger's cat II

- Given a complete OPT with complementarity and a pure steering state for the ensemble $\{p_0\rho^{(0)}, p_1\rho^{(1)}\}$ where $\Pr(a_0^{(0)}|\rho^{(0)}) = 1$ $\Pr(a_0^{(0)}|\rho^{(1)}) = 0$

the states verifying "alive" or "dead" are remotely prepared

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- The paradox stems from both violation of locality (outcome independence) and complementarity

G. M. D'Ariano, F. Manessi, and PP arXiv:1108.3681 (2011).

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- Given a complete OPT with complementarity and a pure steering state for the ensemble $\{p_0\rho^{(0)}, p_1\rho^{(1)}\}$ where $\Pr(a_0^{(0)}|\rho^{(0)}) = 1 \quad 0 < \Pr(a_0^{(0)}|\rho^{(1)}) < 1$

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Concluding remarks

- Quantum Theory as an OPT
    - five standard axioms for information theories
    - purification postulate
- Can completeness be an alternate postulate?
    - Completeness, spookiness and pure state steering
- Steering, complementarity and Schrödinger's cat
    - HVTs can provide useful classification of OPTs