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quantum information theory group

SEEKING A PRINCIPLE OF QUANTUMNESS

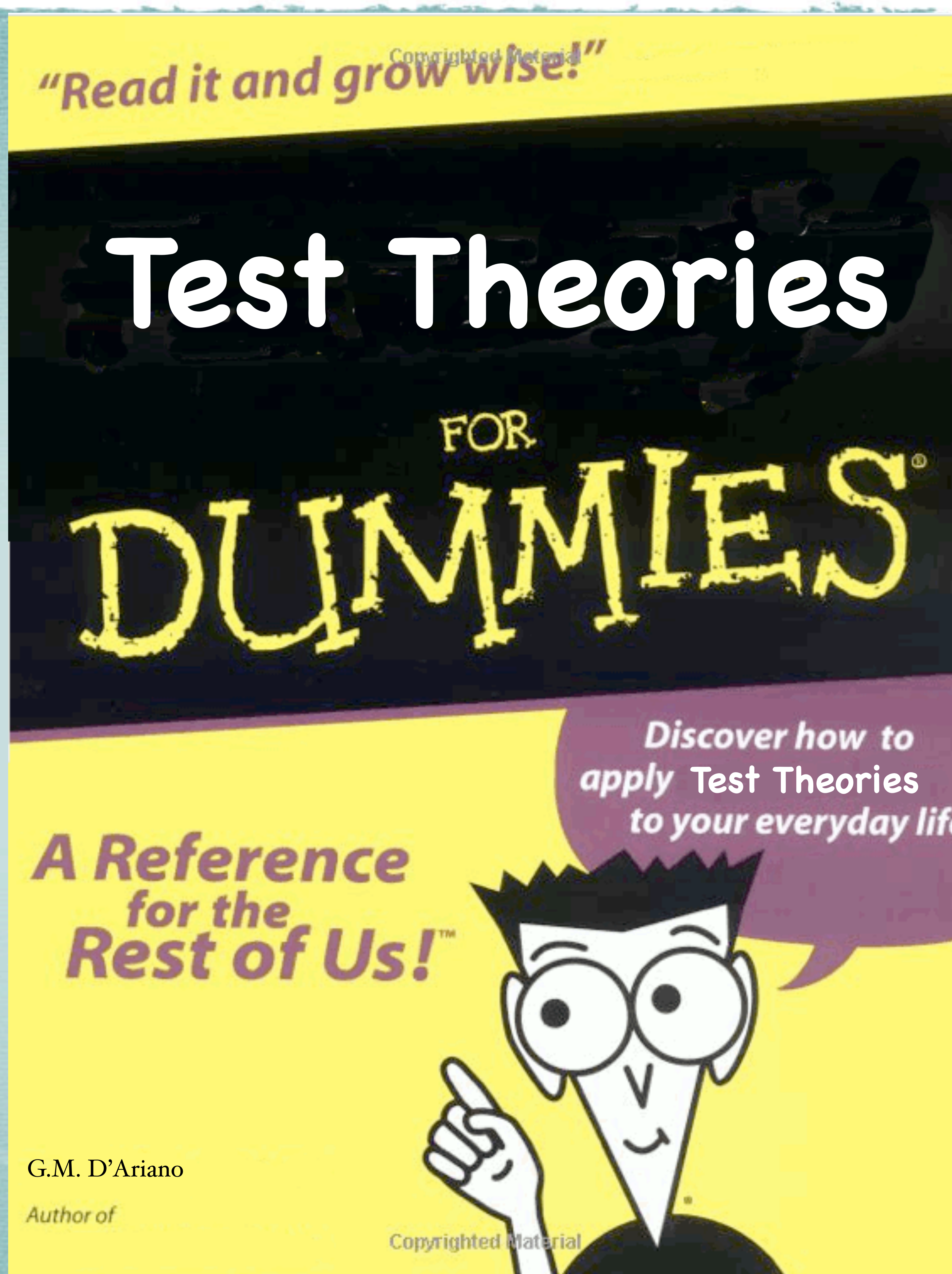
Giacomo Mauro D'Ariano

Pavia University

Quantum Theory: Reconsideration of Foundations, 5
June 17th, Växjö University

arXiv:0807.4383: in *Philosophy of Quantum Information and Entanglement*, Eds A. Bokulich and G. Jaeger (Cambridge University Press, Cambridge UK, in press)

Problem: to derive QM as a probabilistic theory from some operational principle: the principle of *Quantumness*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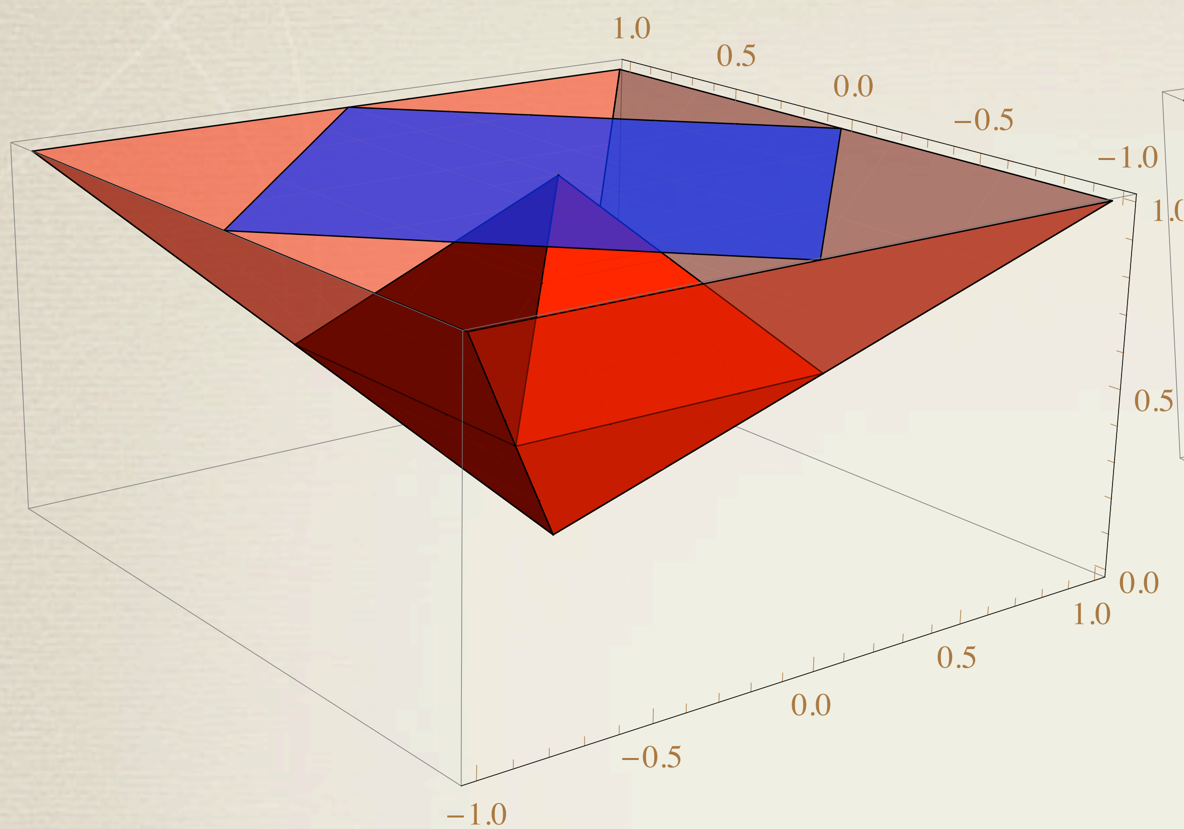
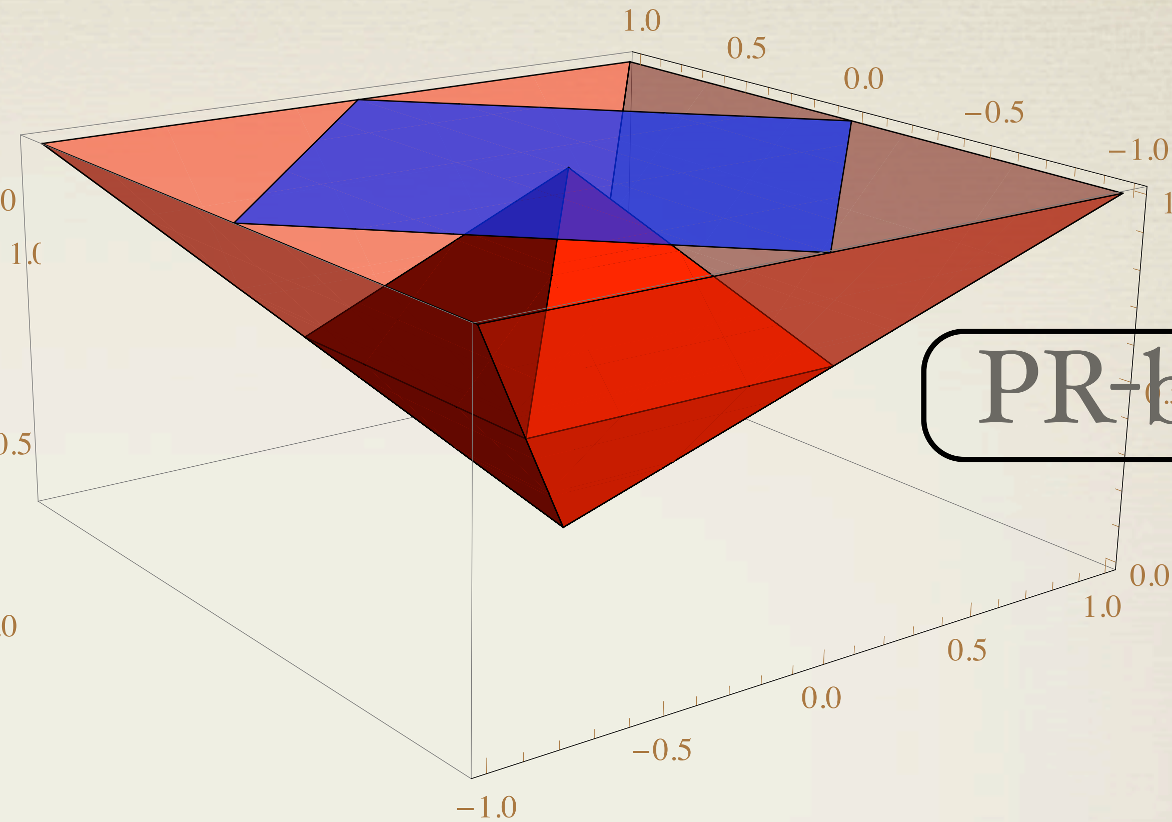
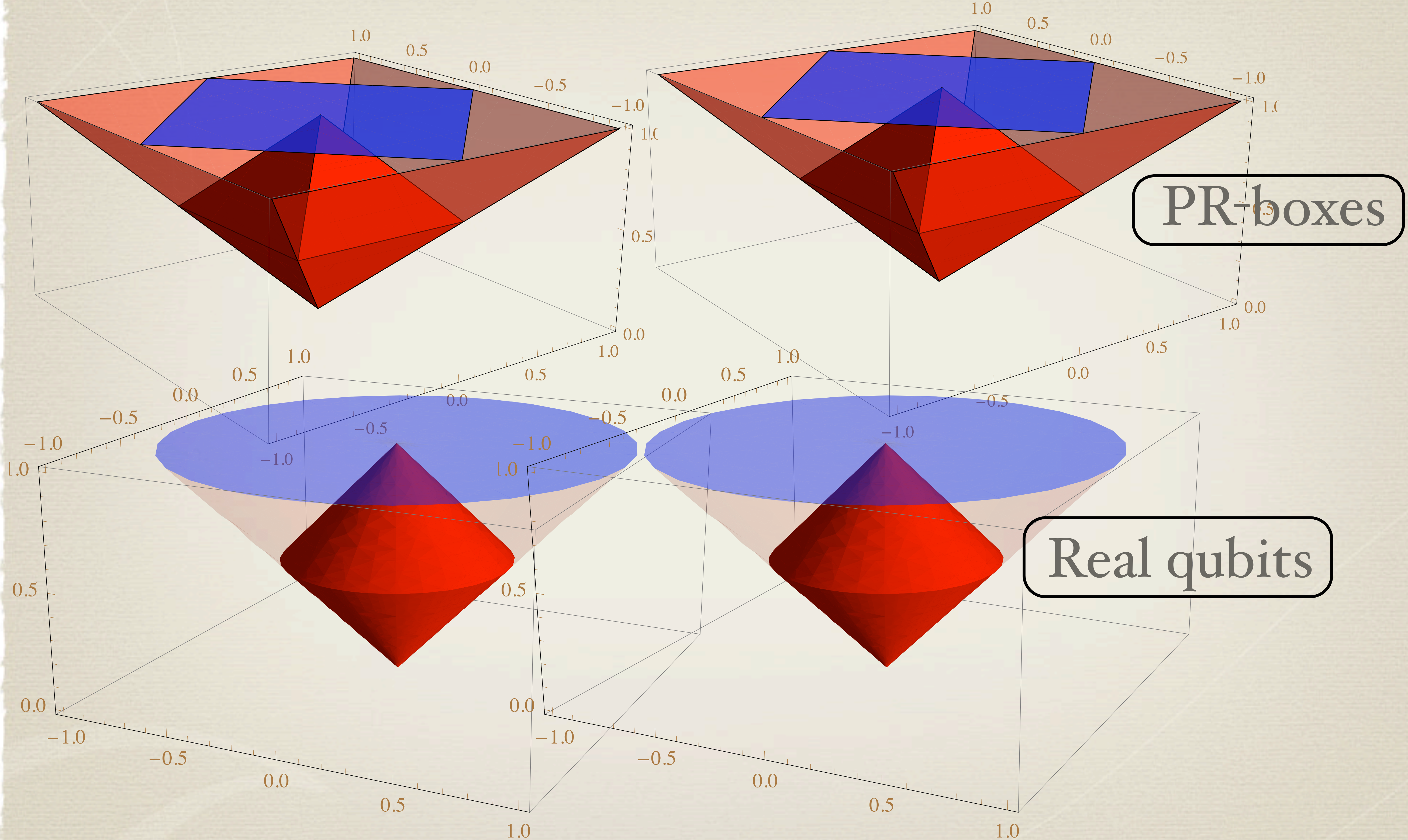
Toy theories





PR-boxes

Toy theories



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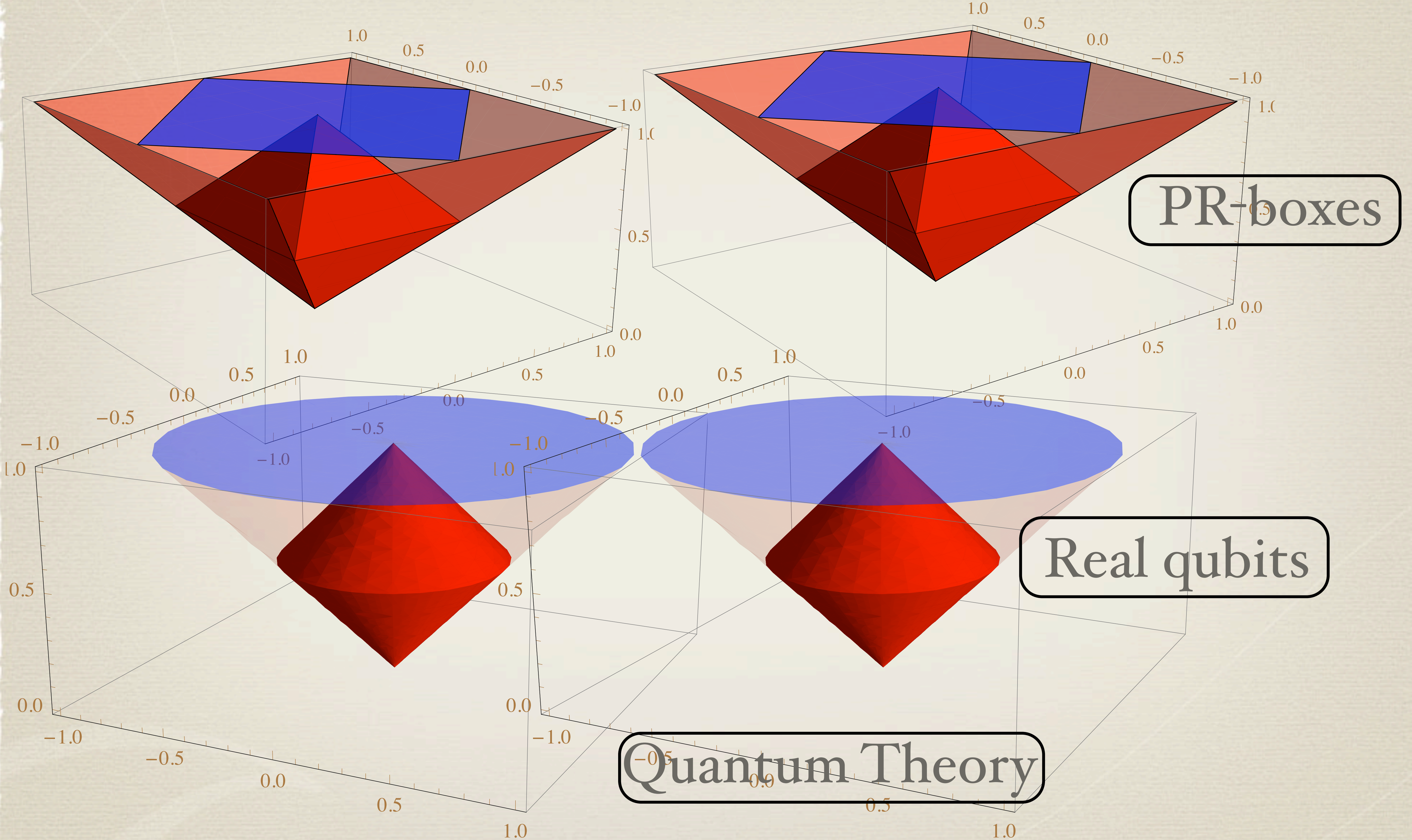

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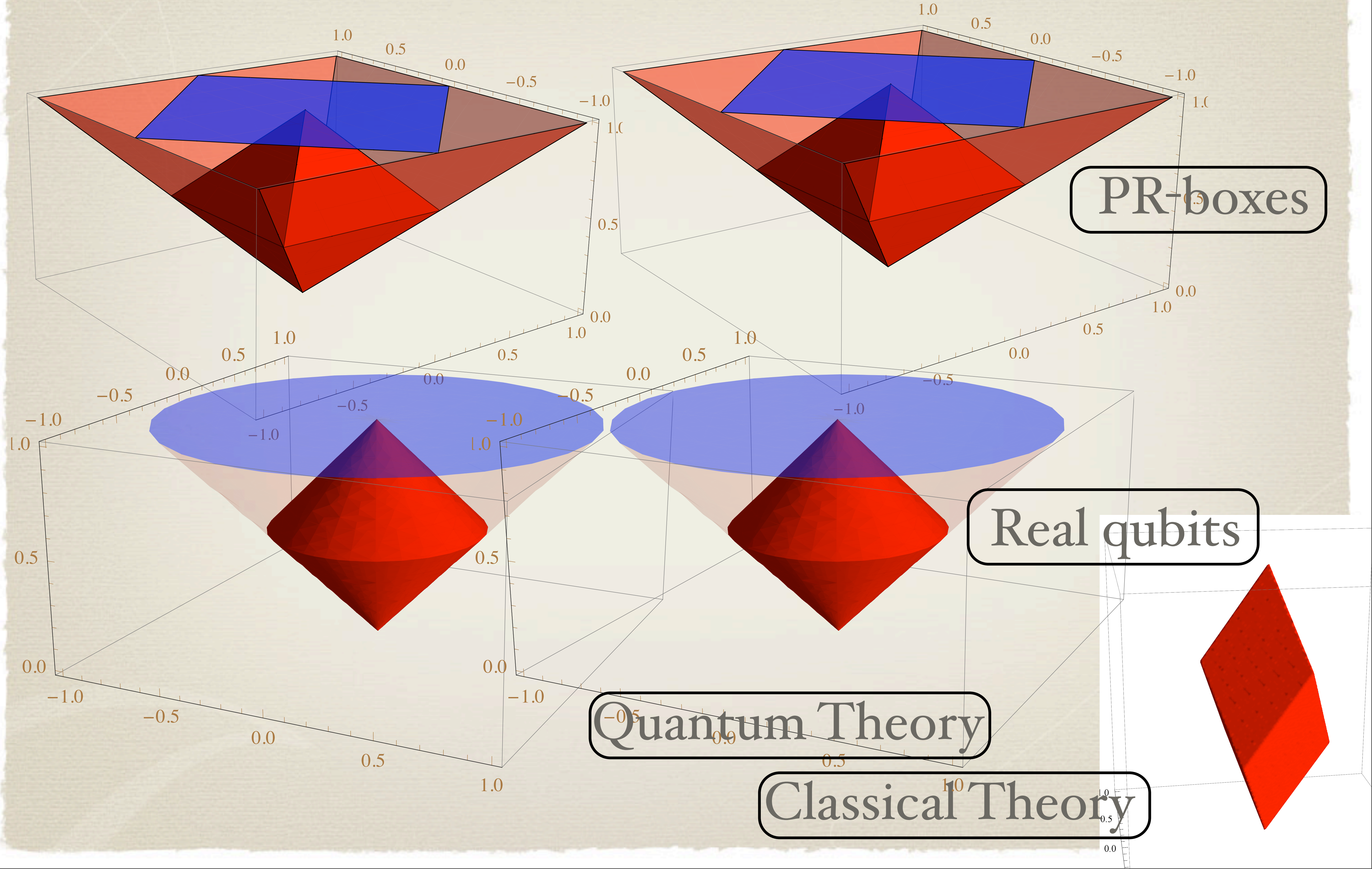
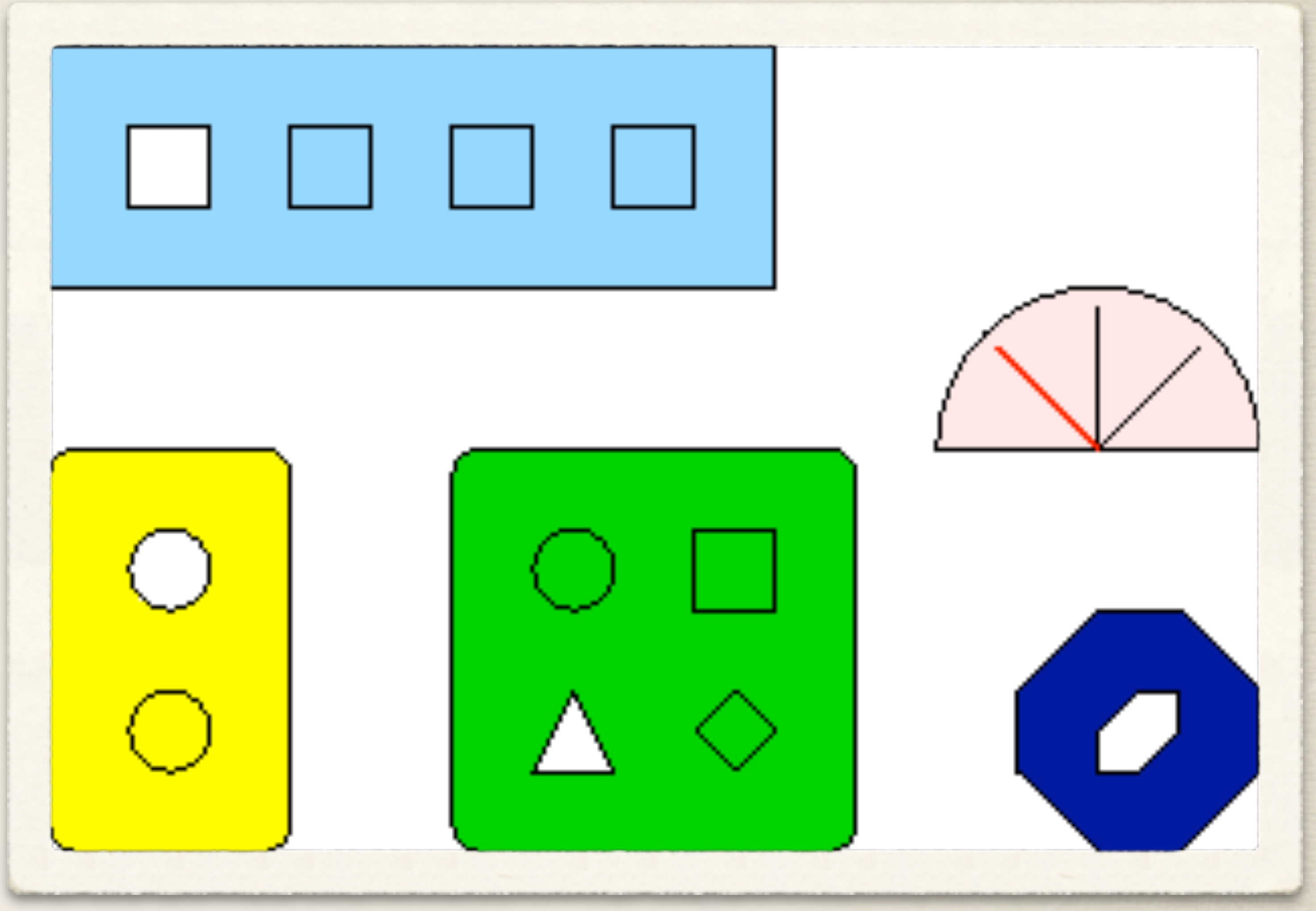


TESTS

Test: $\mathbb{A} \equiv \{\mathscr{A}_j\}$ set of possible events $\mathscr{A}_j$



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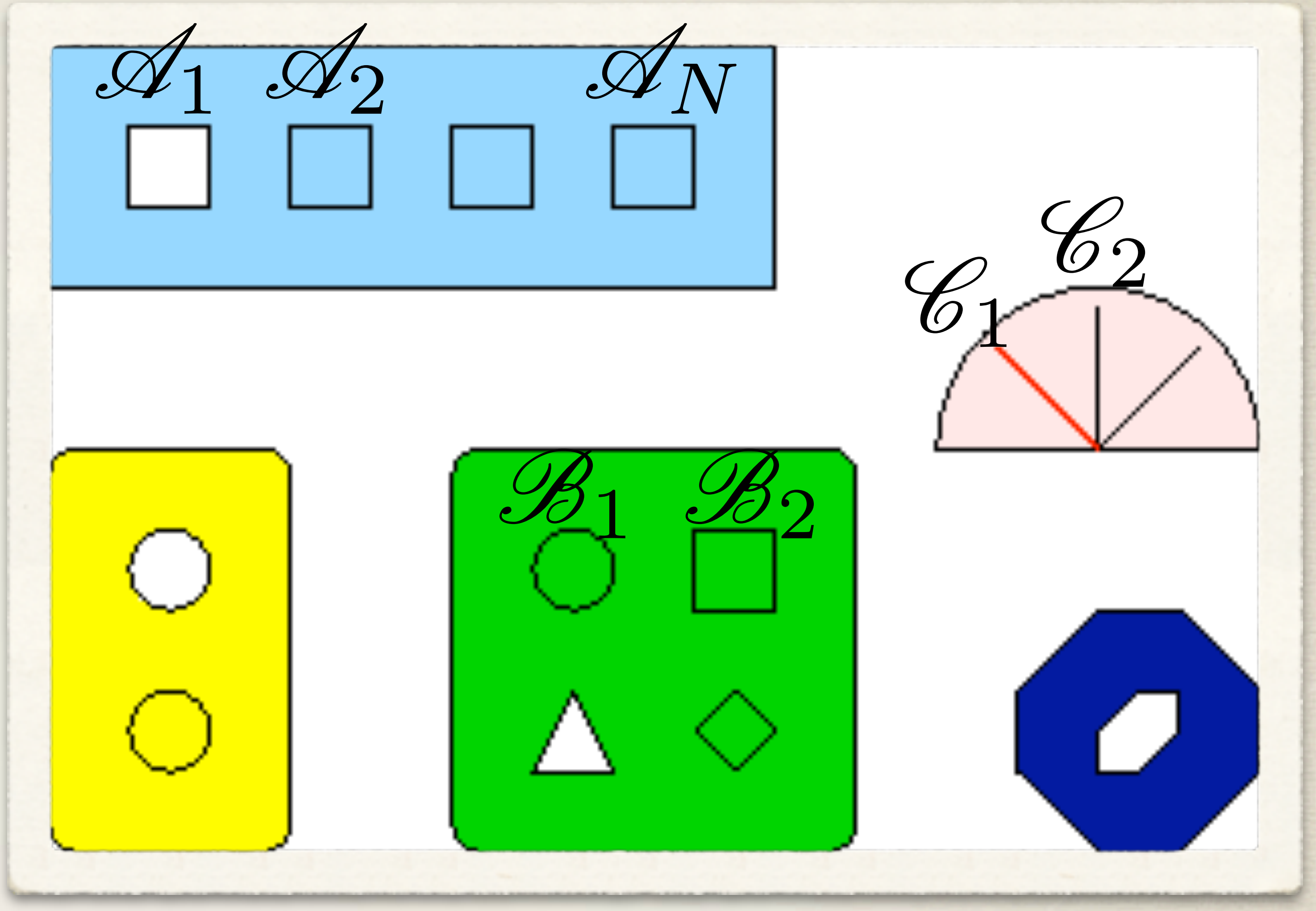

- The same event can occur in different tests
- Deterministic test = singleton

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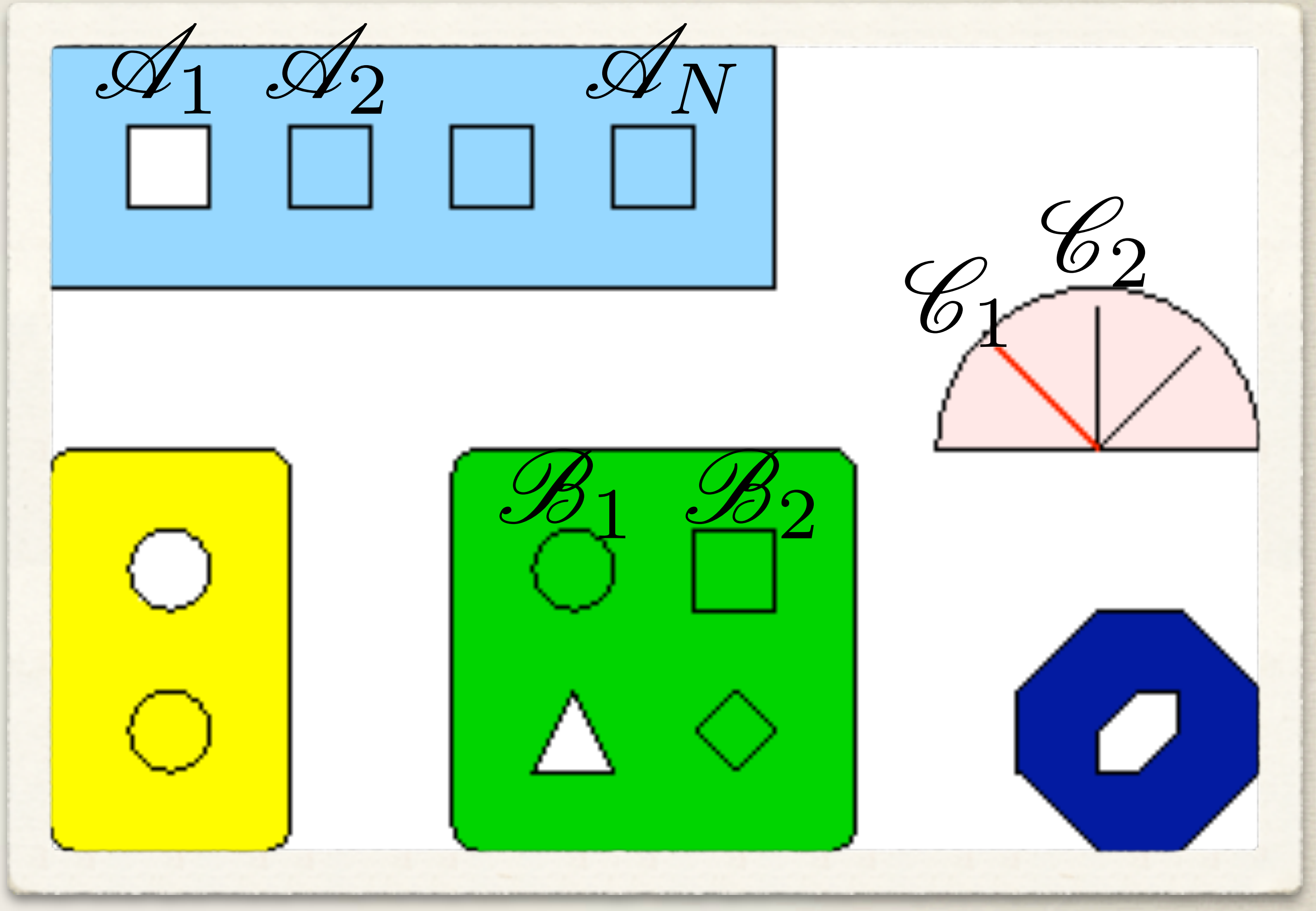

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Coarse-graining of events: $\mathscr{A} \cup \mathscr{B}$

$$\mathbb{A} = \{\mathscr{A}_1, \mathscr{A}_2, \mathscr{A}_3\} \xrightarrow{\text{Coarse-graining}} \mathbb{A}' = \{\mathscr{A}_1, \mathscr{A}_2 \cup \mathscr{A}_3\}$$

Refinement

STATES

State ω: probability rule $\omega(\mathscr{A})$ for any possible event $\mathscr{A}$ in any test

Normalization: $$\sum_{\mathscr{A}_j \in \mathbb{A}} \omega(\mathscr{A}_j) = 1$$

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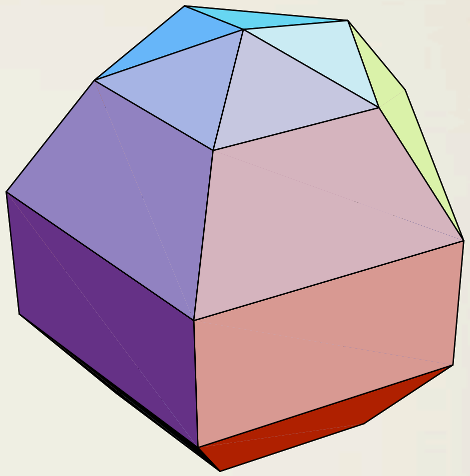
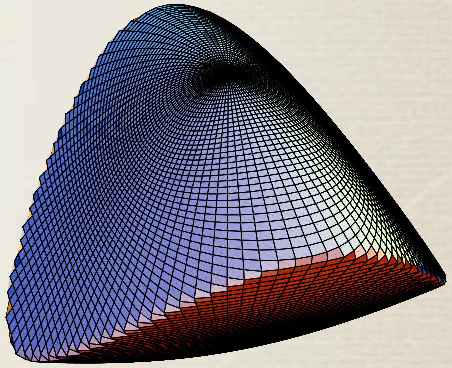


Convex set of states: $\mathfrak{S}$



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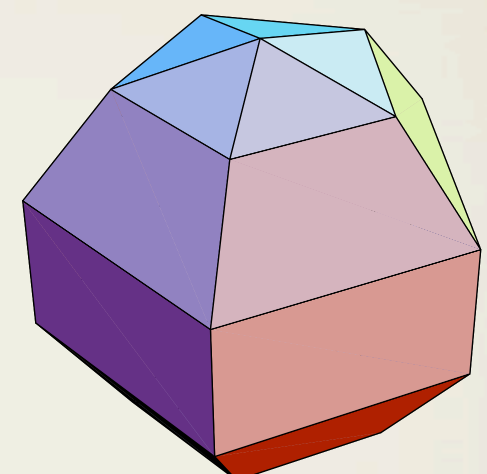
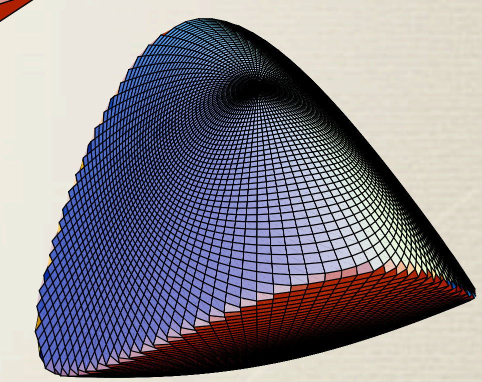


Normalization: $$\sum_{\mathscr{A}_j \in \mathbb{A}} \omega(\mathscr{A}_j) = 1$$



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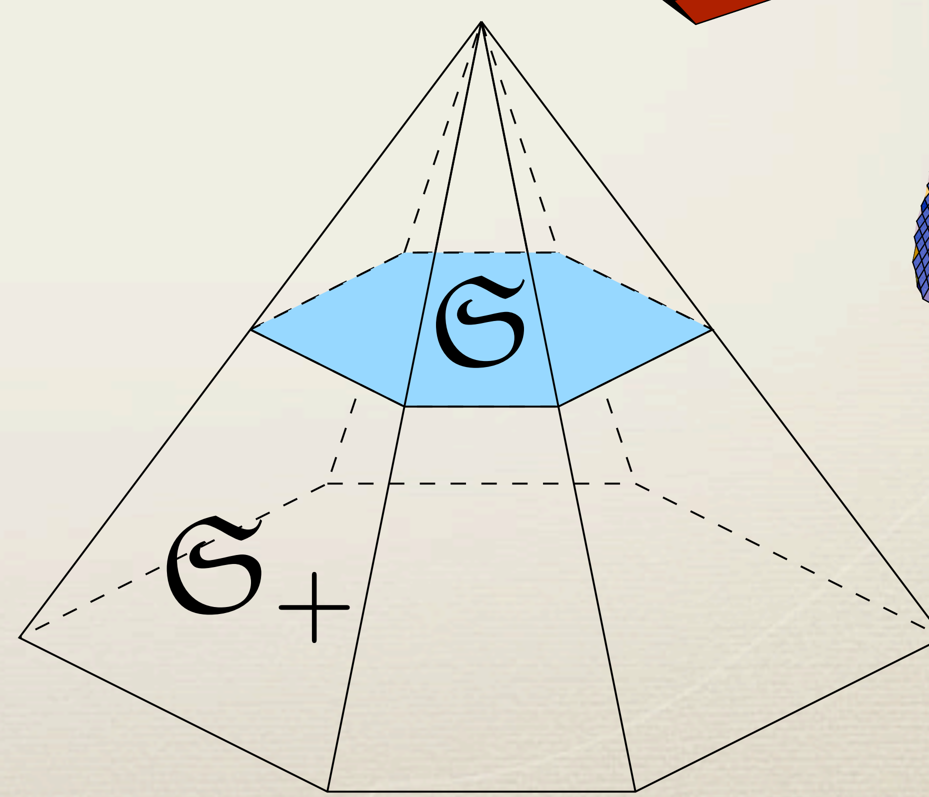
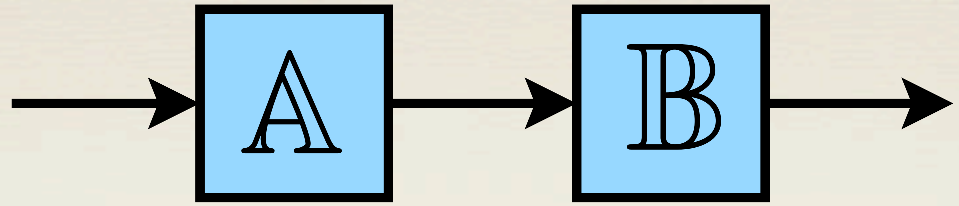


Convex cone of unnormalized states: $\mathfrak{S}_+$

CASCADES OF TESTS

Time-cascade: 

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CASCADES OF TESTS

Time-cascade: $\longrightarrow \boxed{\mathbb{A}} \longrightarrow \boxed{\mathbb{B}} \longrightarrow$

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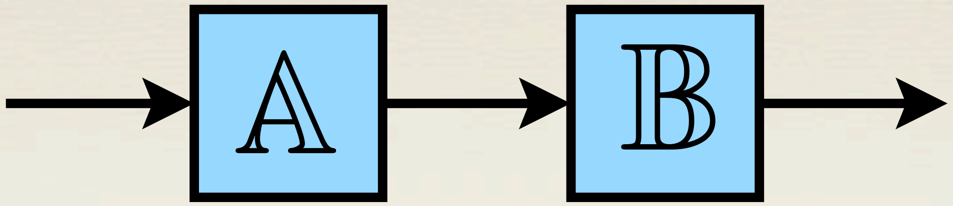
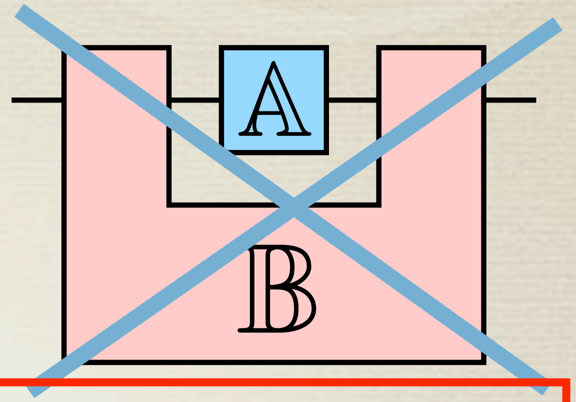
collection of joined events with the following rule for marginals:

$$\sum_{\mathscr{B}_j \in \mathbb{B}} \omega(\mathscr{B}_j \circ \mathscr{A}) =: f(\mathbb{B}, \mathscr{A}) \equiv \omega(\mathscr{A}), \quad \forall \mathbb{B}, \mathscr{A}, \omega$$

NSF (No signaling from the future)

CASCADES OF TESTS

Time-cascade: 



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composition of events $\mathscr{B} \circ \mathscr{A}$ + notion of conditional state

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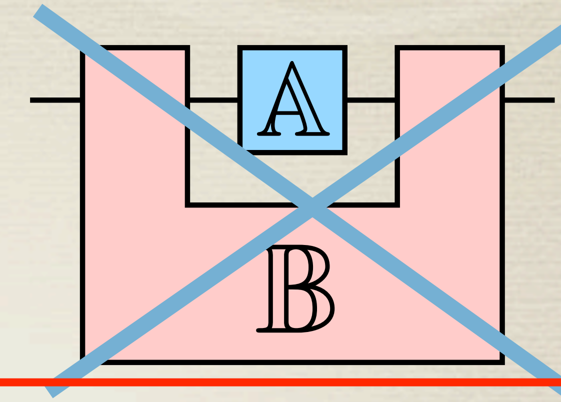

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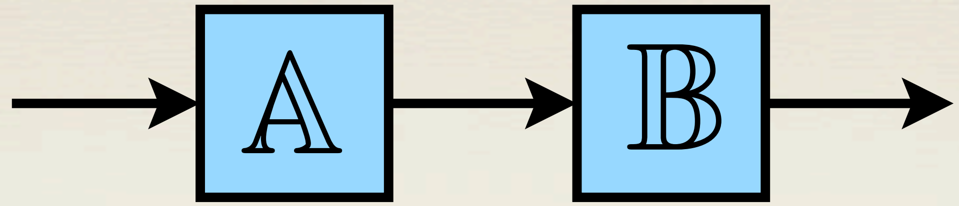

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$$\omega_{\mathscr{A}}(\mathscr{B}) = \frac{\omega(\mathscr{B} \circ \mathscr{A})}{\omega(\mathscr{A})}$$

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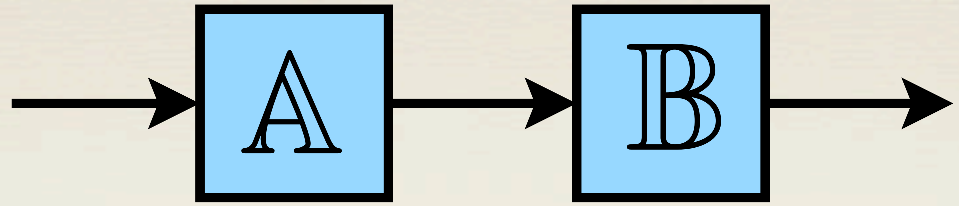
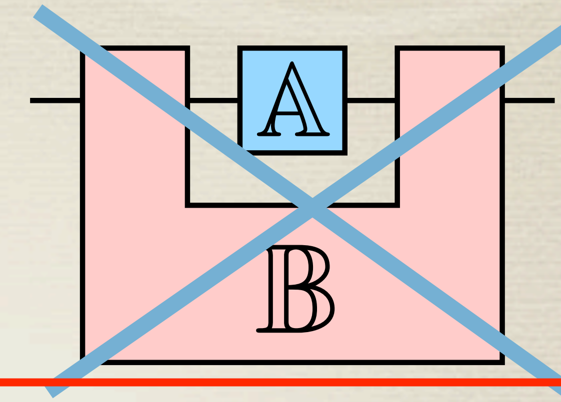
Time-cascade: 



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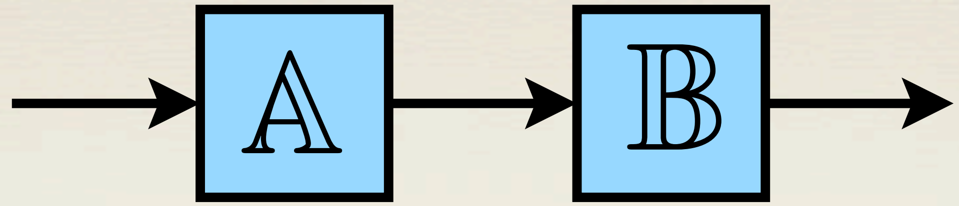

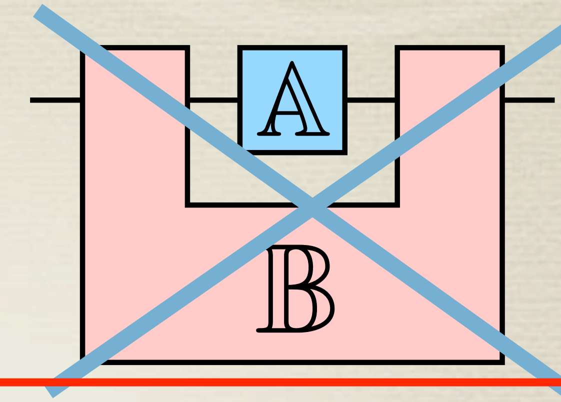

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composition of events $\mathscr{B}\circ\mathscr{A}$ + notion of conditional state

events $\equiv$ transformations + linearity of evolution

variable

$$\mathscr{A}\omega := \omega(\cdot \circ \mathscr{A})$$

Equivalence classes for transformations

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Two transformations $\mathscr{A}$ and $\mathscr{B}$ are conditioning equivalent if

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Probabilistic-equivalence class

A transformation is completely specified by the two classes:

$$\boxed{\mathscr{A}\omega = \omega(\mathscr{A})\omega_{\mathscr{A}}}$$

EFFECTS

Effect a: equivalence class of transformations occurring with the same probability as $\mathscr{A}$ for all states.

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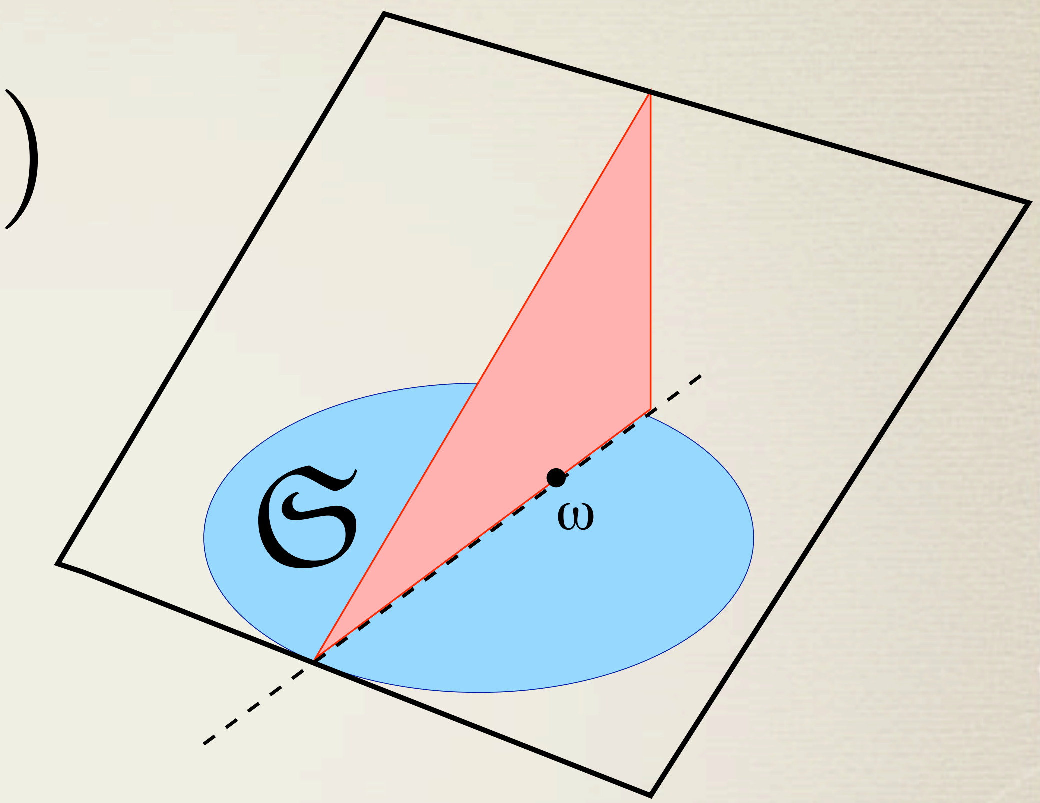

Duality: effects are positive linear functionals ≤ 1 over states.

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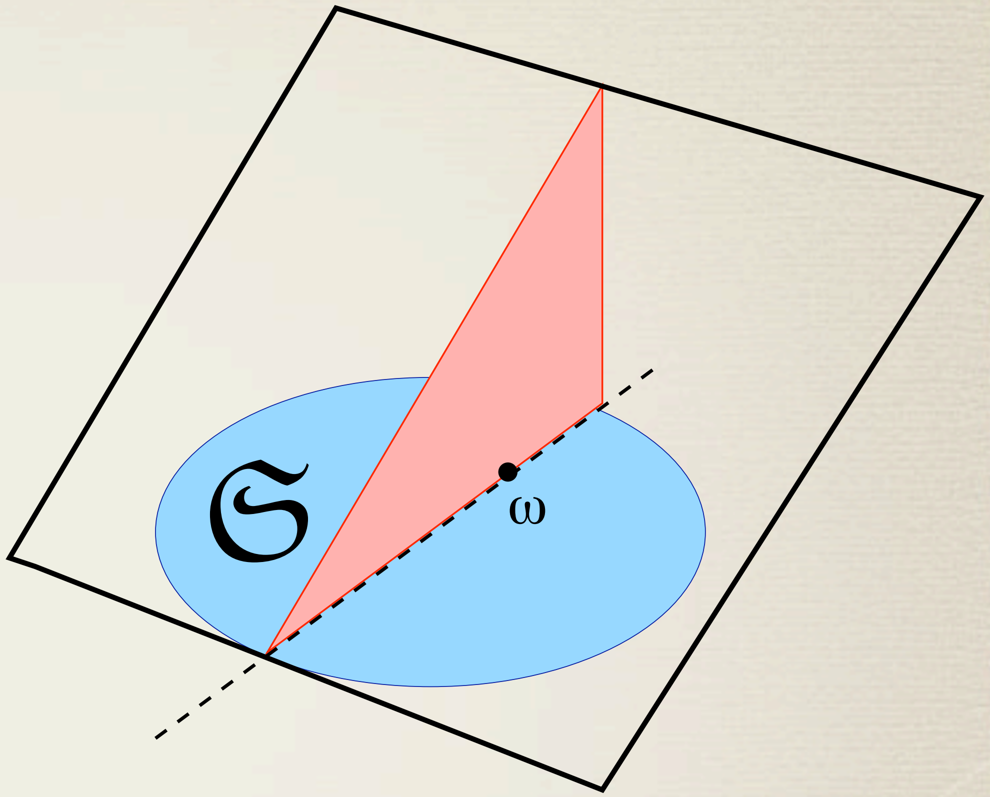

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Transformations act linearly on effects (Heisenberg Picture)

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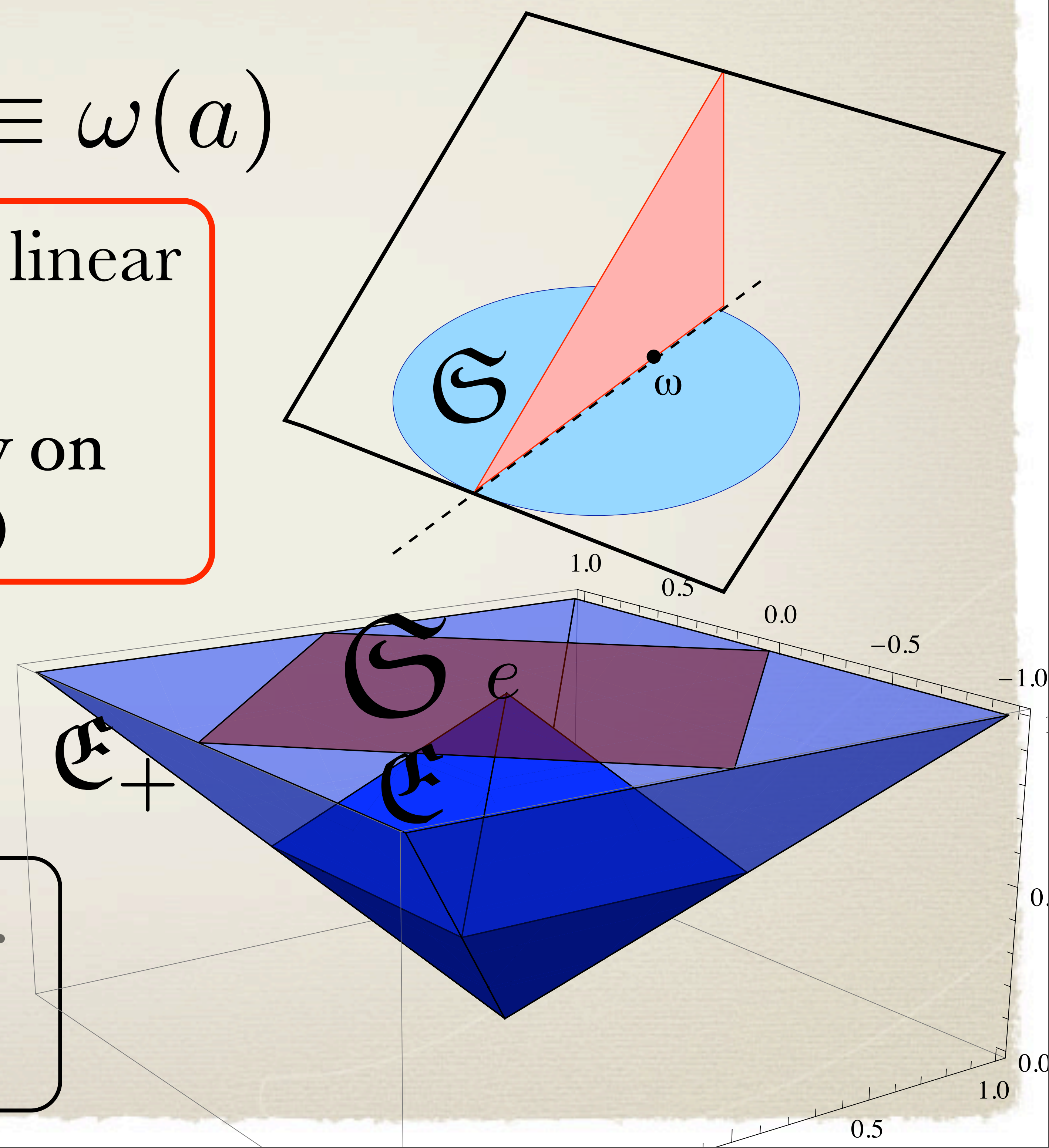
Transformations act linearly on effects (Heisenberg Picture)

Convex set of effects $\mathfrak{E}$

Convex cone $\mathfrak{E}_+$



e deterministic effect i.e.

$$\omega(e) = 1 \ \forall \omega \in \mathfrak{S}$$

Preparation-test and observation-tests

Preparation-test $\{\omega_i\}, \quad \sum_i \omega_i(e) = 1$

Observation-test $\{a_i\}, \quad \sum_i a_i = e$

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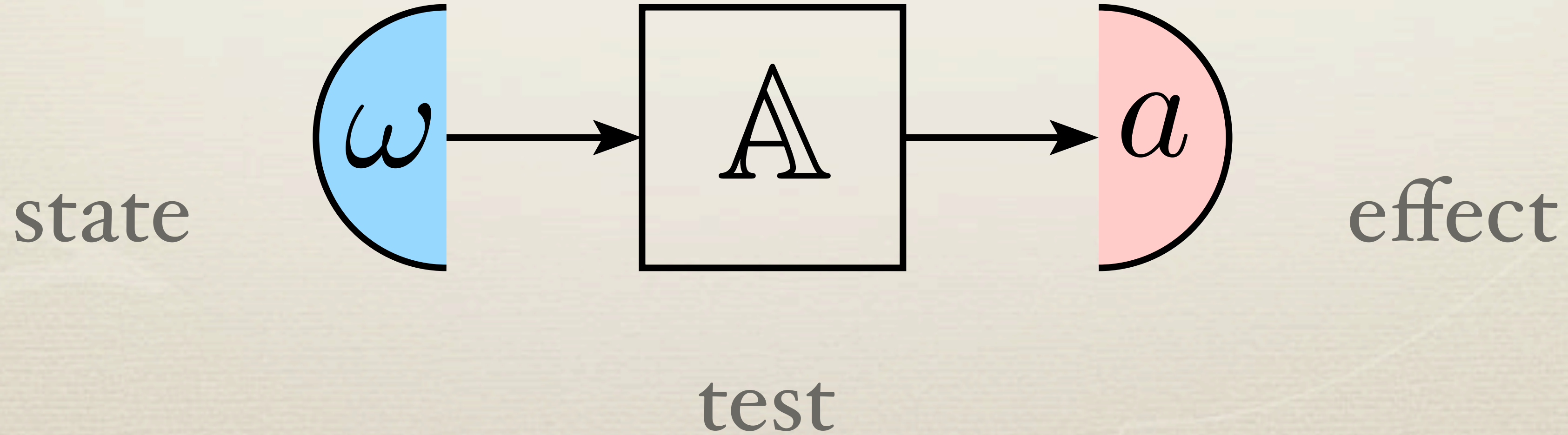
Dirac notation

$$(a|\omega) := \omega(a) \qquad (a|\,\mathscr{B}\,|\omega) := \omega(a \circ \mathscr{B})$$



Addition of transformations

Transformations $\mathscr{A}, \mathscr{B}$ (generally belonging to different tests)

Test-compatible if: $\omega(\mathscr{A}) + \omega(\mathscr{B}) \leqslant 1, \ \forall \omega \in \mathfrak{S}$

For test-compatible transformations $\mathscr{A}_1, \mathscr{A}_2$ define the transformation $\boxed{\mathscr{A}_1 + \mathscr{A}_2}$ as the coarse-graining $\mathscr{A}_1 \cup \mathscr{A}_2$ as if they belong to the same test

$$\boxed{(\mathscr{A}_1 + \mathscr{A}_2)\omega = \mathscr{A}_1\omega + \mathscr{A}_2\omega}$$

Rescaling of transformations

The rescaled transformation $\boxed{\lambda\mathscr{A}}$ of $\mathscr{A}$, $\lambda \in [0, 1]$ is the transformation giving the same conditioning but occurring with probability rescaled by λ for all states.

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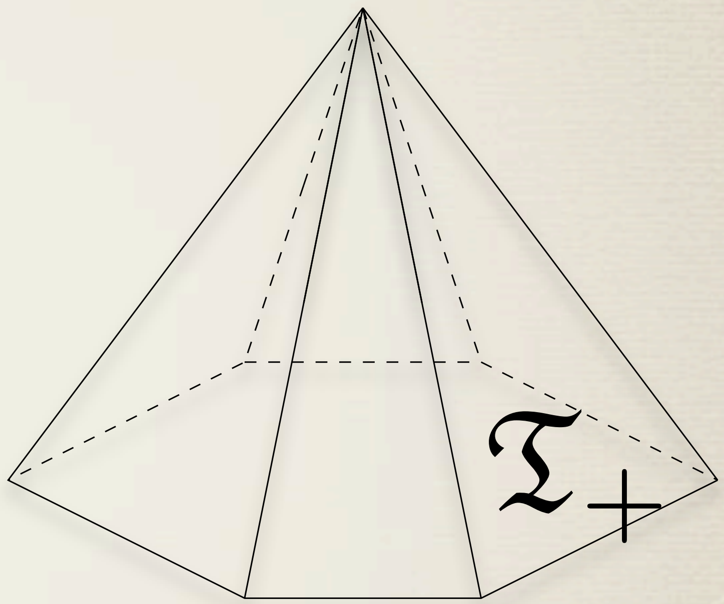

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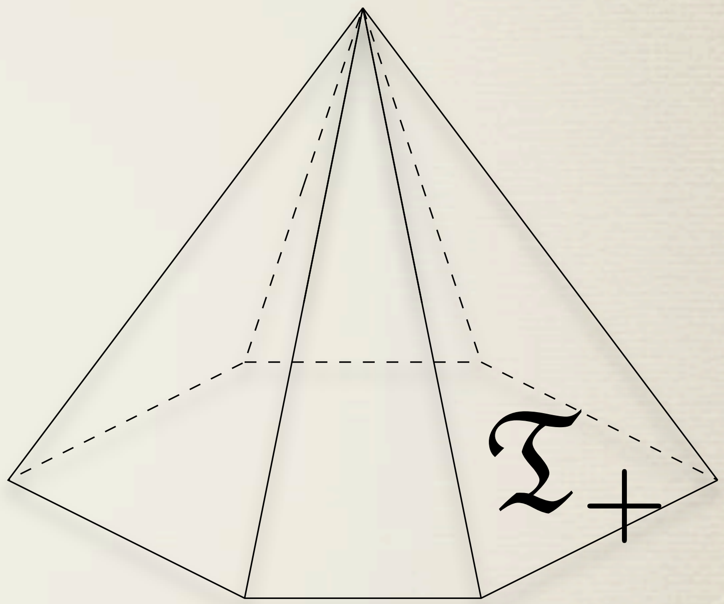
$\boxed{\text{Atomic:}}$ a transformation that cannot be refined in any test, i.e. it cannot be written as $\mathscr{A} = \sum_i \mathscr{A}_i$ with $\mathscr{A}_i \not\propto \mathscr{A} \ \forall i$



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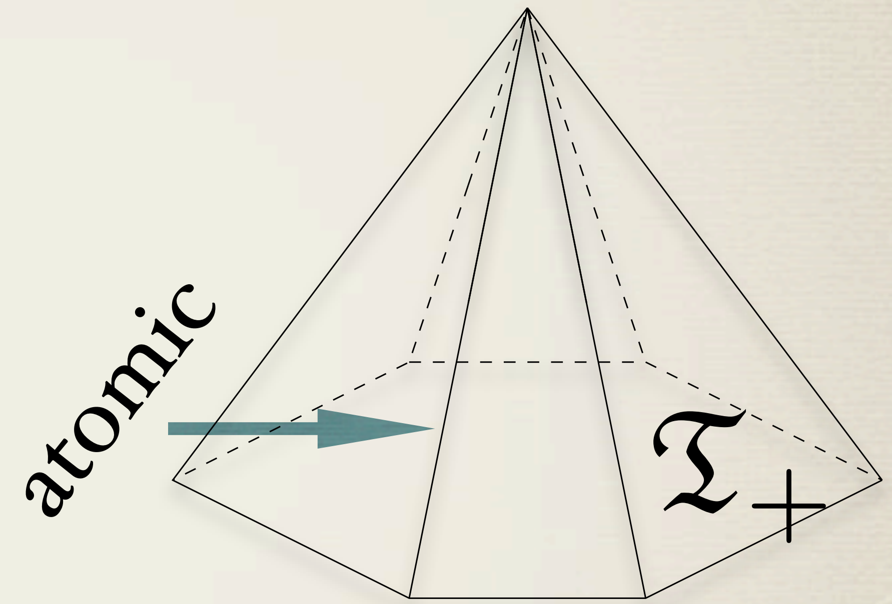

Convex set of transformations $\mathfrak{T}$
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Atomic transformations lie on extremal rays of $\mathfrak{T}_+$

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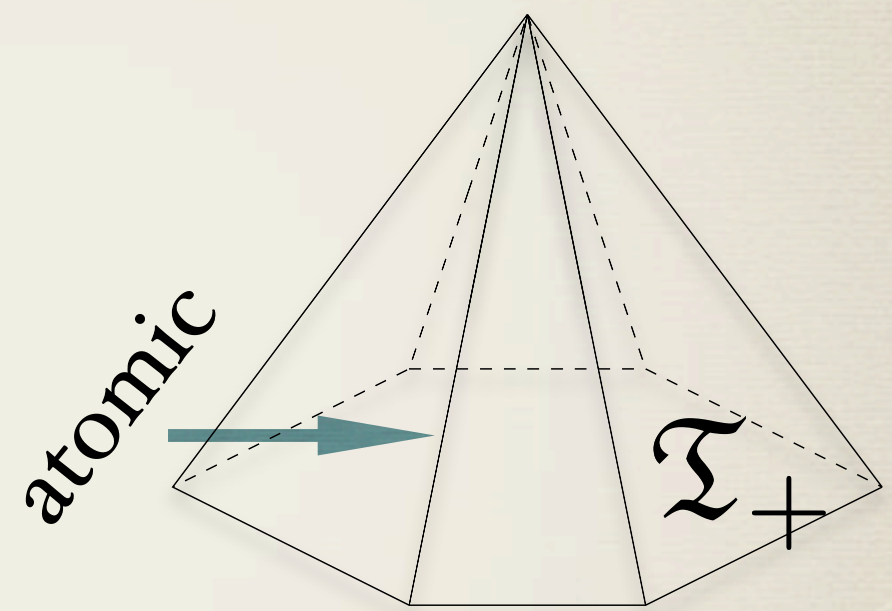

Convex set of transformations $\mathfrak{T}$

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Atomic transformations lie on extremal rays of $\mathfrak{T}_+$

- The identity transformation $\mathscr{I}$ is not necessarily atomic!

STANDARD REFERENCE-TEST

$$\mathbb{S} = \{\mathscr{S}_i\}, \qquad \mathscr{S}_i = |\lambda_i)(l_i|$$

$\{\lambda_i\}$ minimal effect-separating set of states

$\{l_i\}$ minimal state-separating set of effects (info-complete)

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- use biorthogonal real bases embedding states and effects in the same Euclidean space

$$(l_i|\lambda_j) = \delta_{ij}$$

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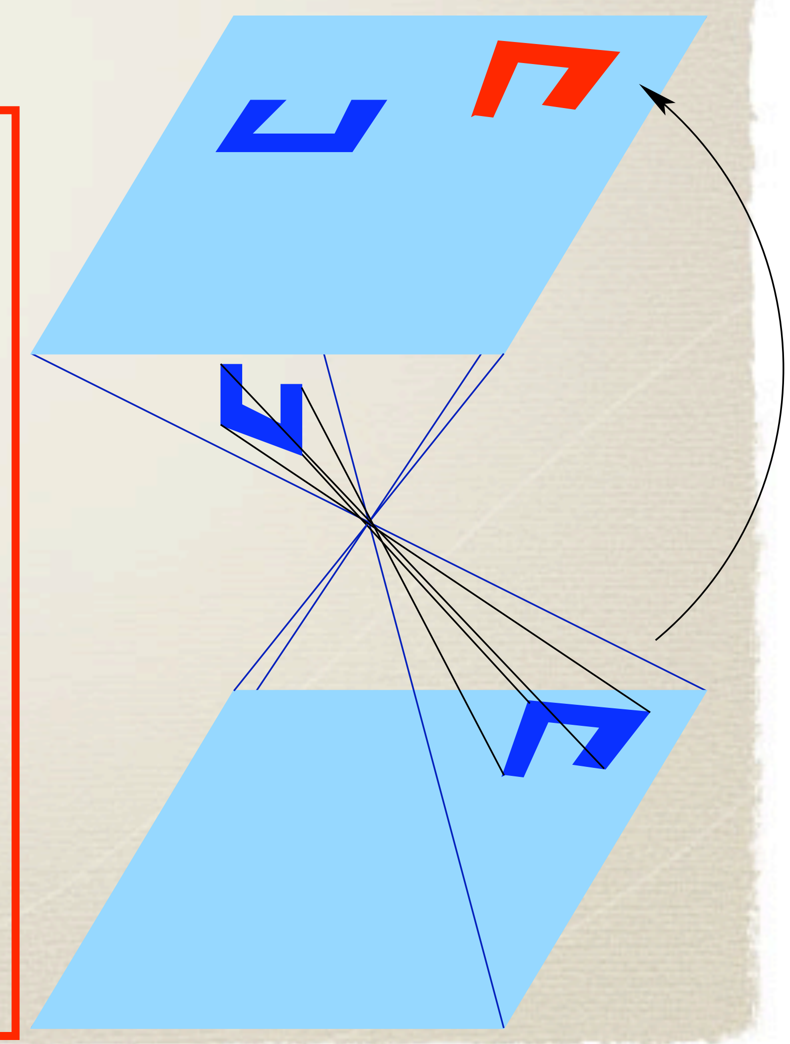
- take the last element $l_N \equiv e$ and correspondingly λ_N giving the direction of the cone axis of $\mathfrak{S}_+$

Matrix representation of the algebra of transformations

$$\boldsymbol{\omega} = \begin{bmatrix} (l_1|\omega) \\ (l_2|\omega) \\ \dots \\ (e|\omega) \end{bmatrix} = \begin{bmatrix} \hat{\boldsymbol{\omega}} \\ \hat{\omega} \end{bmatrix}, \quad \boldsymbol{a} = \begin{bmatrix} (a|\lambda_1) \\ (a|\lambda_2) \\ \dots \\ (a|\chi) \end{bmatrix} = \begin{bmatrix} \hat{\boldsymbol{a}} \\ \hat{a} \end{bmatrix}$$

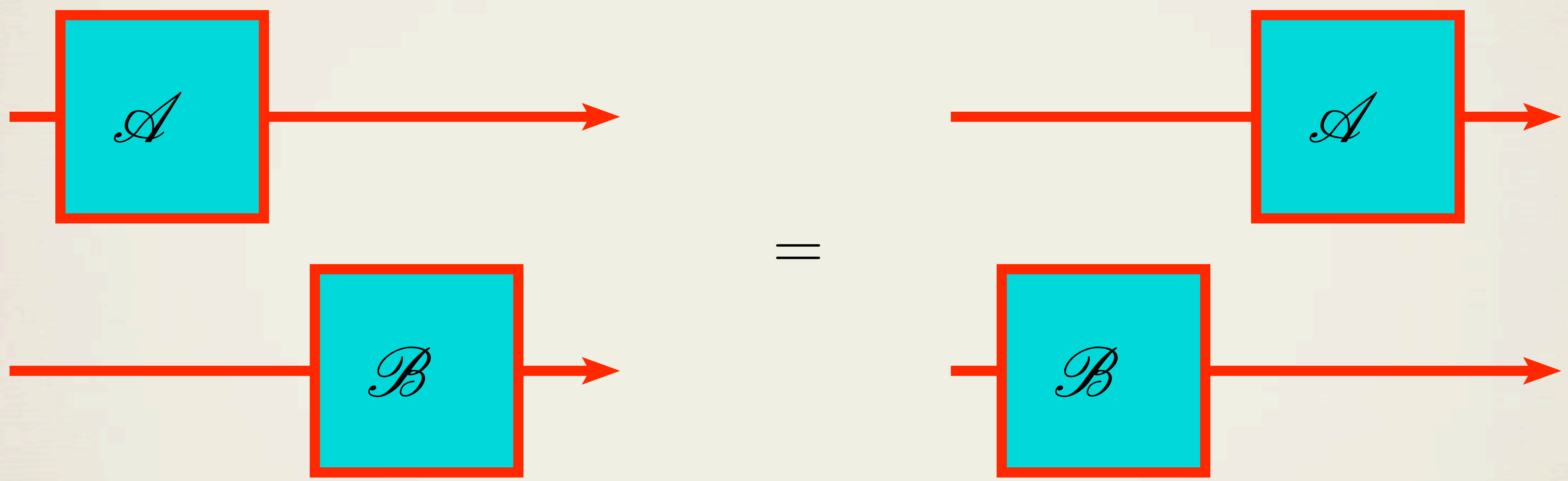
$$\boxed{\mathscr{A} = \sum_{ij} A_{ij} \, |\lambda_i)(l_j|}$$

$$\boxed{\boldsymbol{A} = \left(\begin{array}{c|c} \hat{\boldsymbol{A}} & \hat{\boldsymbol{\alpha}} \\ \hline \hat{\boldsymbol{a}}^T & \hat{a} \end{array} \right), \qquad \begin{aligned} \widehat{\boldsymbol{A}\boldsymbol{\omega}} &= \hat{\boldsymbol{A}}\hat{\boldsymbol{\omega}} + \hat{\boldsymbol{\alpha}}, \\ (a|\omega) &= \hat{\boldsymbol{a}}^T\hat{\boldsymbol{\omega}} + \hat{a}, \\ \hat{\boldsymbol{\omega}} \to \hat{\boldsymbol{\omega}}_{\mathscr{A}} &= \frac{\hat{\boldsymbol{A}}\hat{\boldsymbol{\omega}} + \hat{\boldsymbol{\alpha}}}{\hat{\boldsymbol{a}}^T\hat{\boldsymbol{\omega}} + \hat{a}}. \end{aligned}}$$



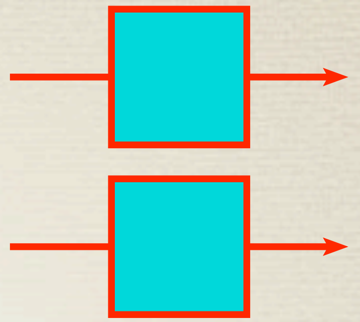
INDEPENDENT SYSTEMS

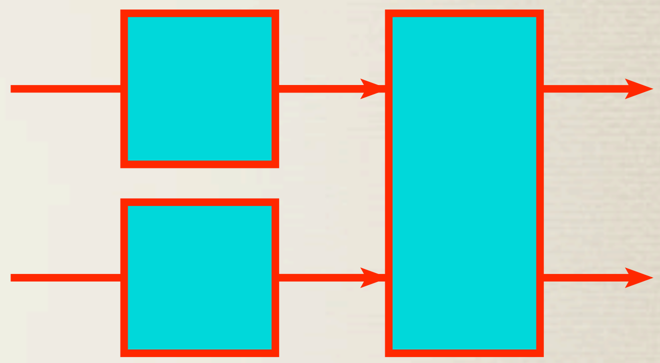
Two systems are independent if on each system it is possible to perform all their tests as local tests, i.e. such that on every joint state one has the commutativity of the transformations from different systems



$$\mathscr{A}^{(1)} \circ \mathscr{B}^{(2)} = \mathscr{B}^{(2)} \circ \mathscr{A}^{(1)}$$

MULTIPARTITE SYSTEMS





We compose the two systems A and B into the bipartite system AB considered as a new system containing all local tests $\mathsf{A} \times \mathsf{B}$ plus other tests, and closing w.r.t. coarse graining, convex combination and cascading:

$$\boxed{\mathsf{AB} \supseteq \mathsf{A} \times \mathsf{B}}$$

Nonlocal tests: $\mathsf{AB} \setminus \mathsf{A} \times \mathsf{B}$

MARGINAL STATE

For a multipartite system we define the marginal state $\Omega|_n$ of the n-th system the state that gives the probability of any local transformation $\mathscr{A}$ on the n-th system with all other systems untouched, namely

$$\Omega|_n(\mathscr{A}) := \Omega(\mathscr{I}, \ldots, \mathscr{I}, \underbrace{\mathscr{A}}_{n-th}, \mathscr{I}, \ldots)$$

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$$\Omega|_n(\mathscr{A}) := \Omega(\mathscr{I}, \dots, \mathscr{I}, \underbrace{\mathscr{A}}_{n-th}, \mathscr{I}, \dots)$$

$$\Omega|_n(a) \doteq \Omega(e, \dots, e, \underbrace{a}_{n\text{th}}, e, \dots)$$

MARGINAL STATE

For a multipartite system we define the marginal state $\Omega|_n$ of the n-th system the state that gives the probability of any local transformation $\mathscr{A}$ on the n-th system with all other systems untouched, namely

$$\Omega|_n(\mathscr{A}) := \Omega(\mathscr{I}, \ldots, \mathscr{I}, \underbrace{\mathscr{A}}_{n-th}, \mathscr{I}, \ldots)$$

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NS: (no-signaling) any local test on a system is equivalent to no-test on another independent system.

Bipartite states effects

No restriction on factorized states/effects

$$\Rightarrow \quad \mathfrak{S}_{\mathbb{R}}(\mathsf{AB}) \supseteq \mathfrak{S}_{\mathbb{R}}(\mathsf{A}) \otimes \mathfrak{S}_{\mathbb{R}}(\mathsf{B})$$

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$\supset \Longrightarrow$ **NO local discriminability:**

there are local effects are not separated by local states and/or viceversa.

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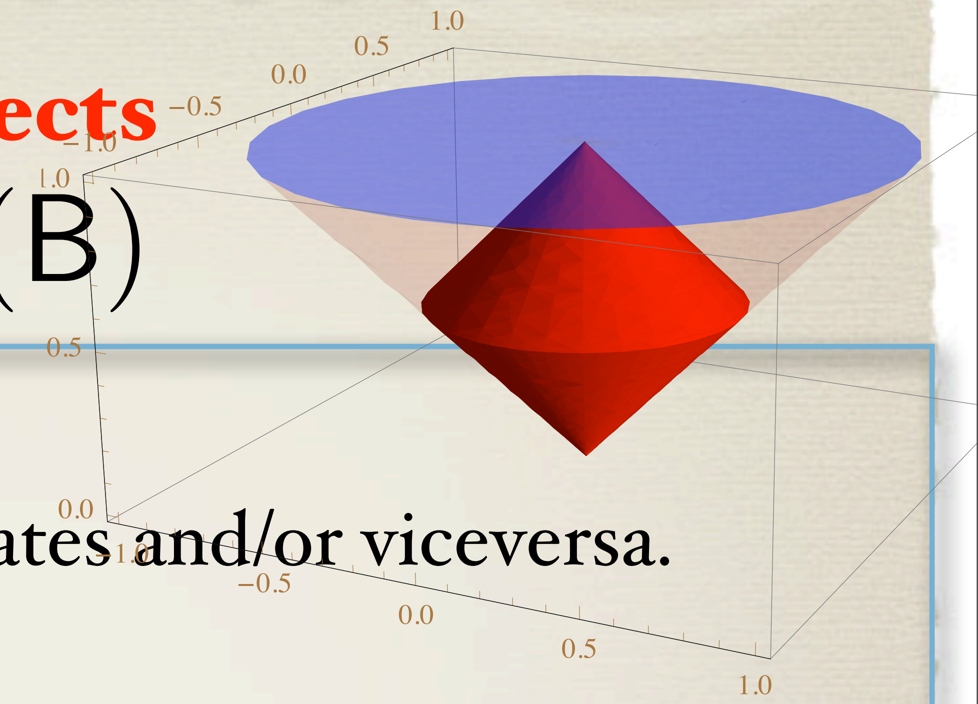

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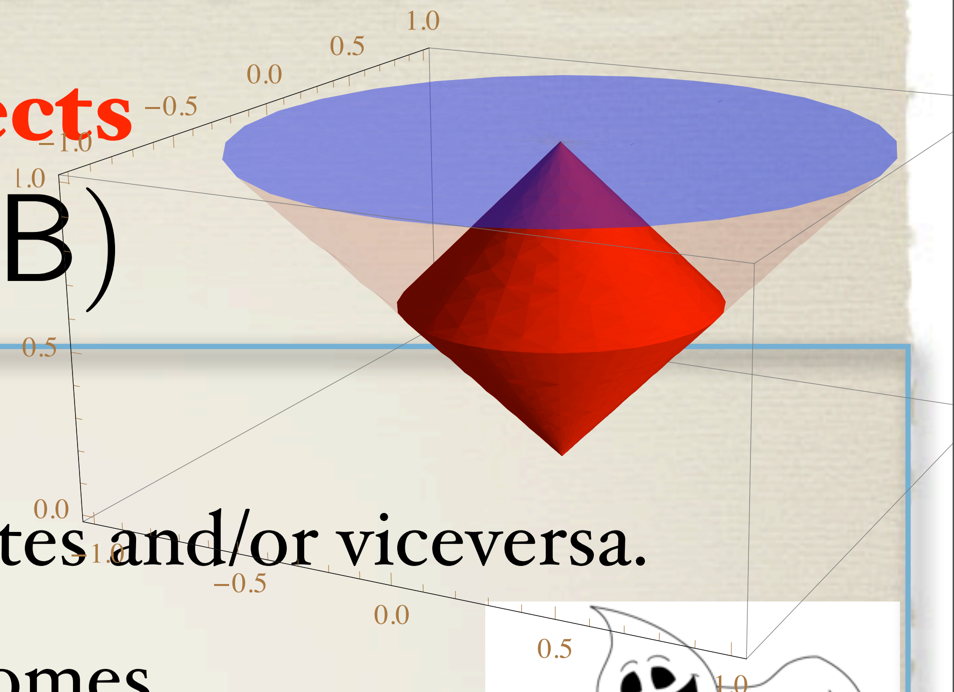

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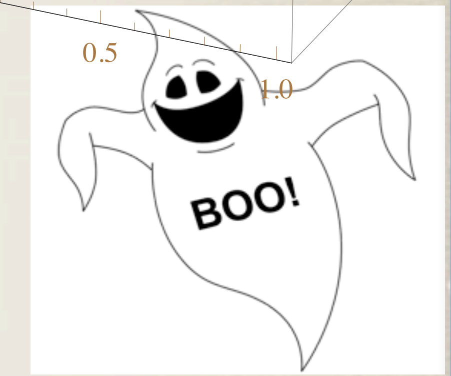
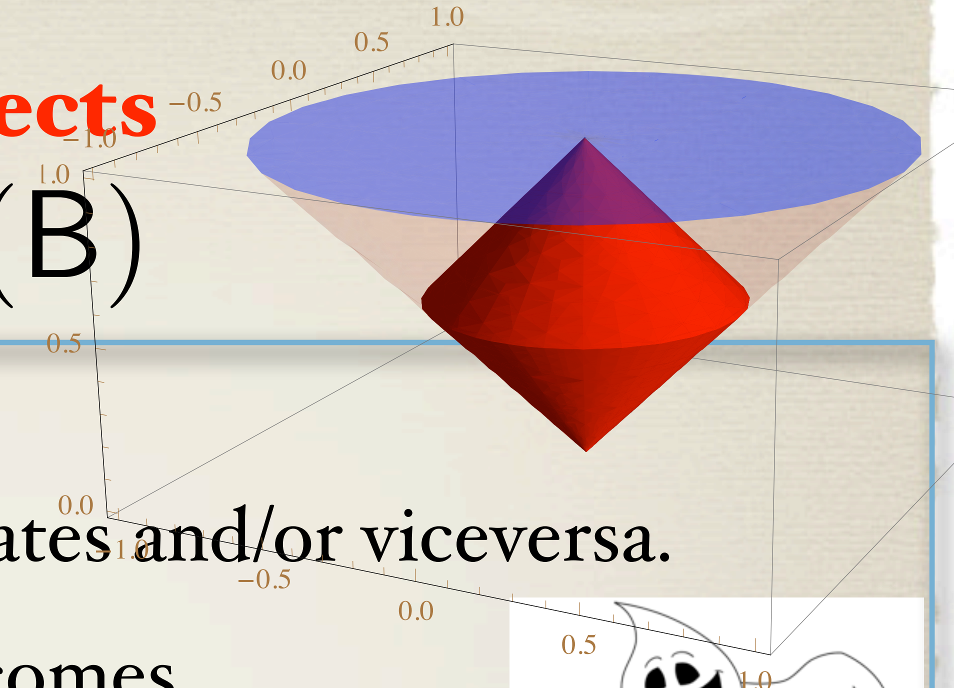
Effects/states that are locally indistinguishable becomes distinguishable using joint tests. Recipe: add local "ghost" states/effects to the reference-test to represent everything within the tensor product.



Bipartite states effects

No restriction on factorized states/effects



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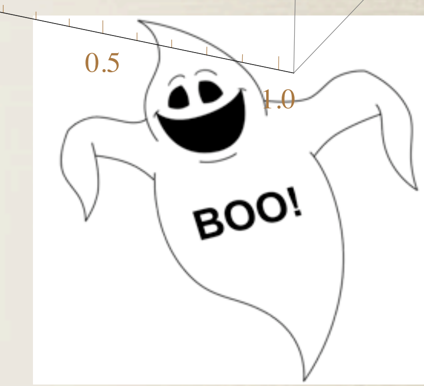
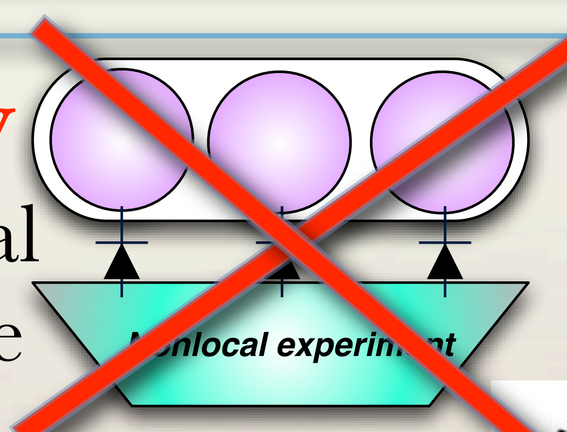
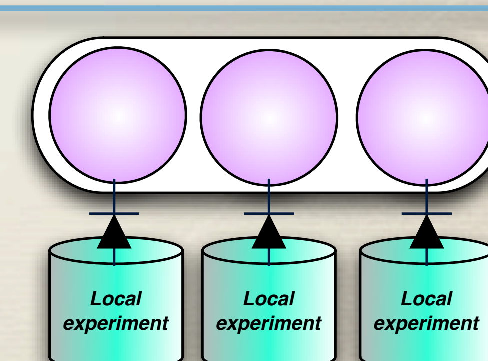


$= \Longrightarrow$ **Local discriminability**

$+$ **local observability:** global info-complete observables made of local info-complete



Holism



Reductionism

Matrix representation of bipartite states/effects

With respect to the standard test we can represent bipartite states and effects as follows

$$\boxed{|\Psi) = \sum_{ij} \Psi_{ij} \, |\lambda_i) \otimes |\lambda_j), \qquad (E| = \sum_{ij} E_{ij} \, (l_i| \otimes (l_j| \,,}$$

FAITHFUL STATES

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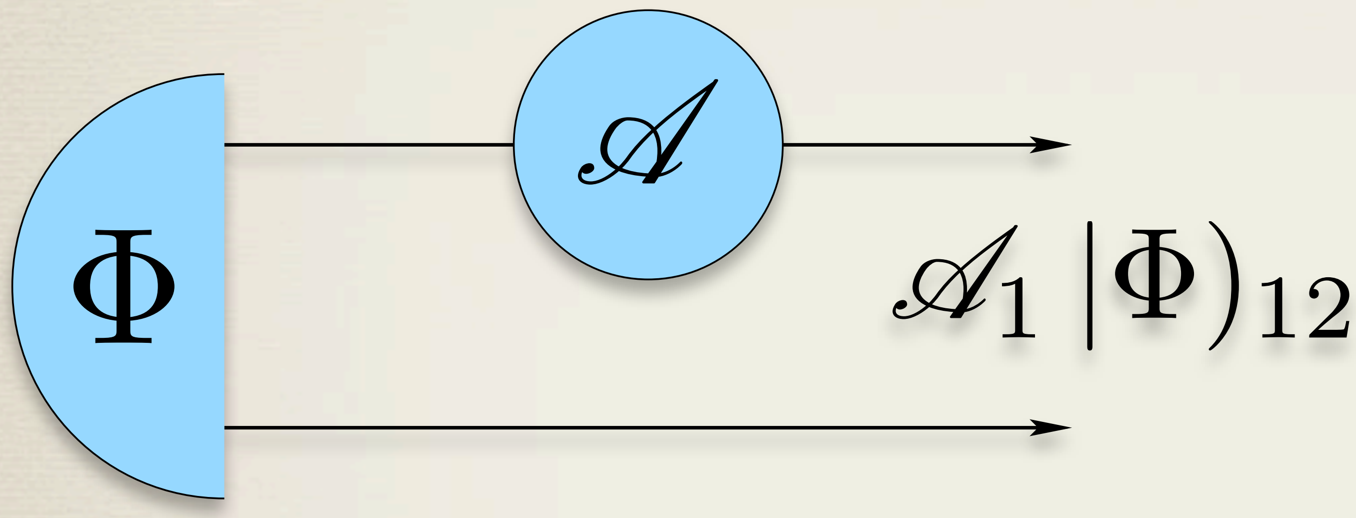
A state Φ of a bipartite system is dynamically faithful when the output state $\mathscr{A}_1 |\Phi)_{12}$ from a local transformation $\mathscr{A}$ on one system is in 1-to-1 correspondence with the transformation $\mathscr{A}$



calibrability of tests

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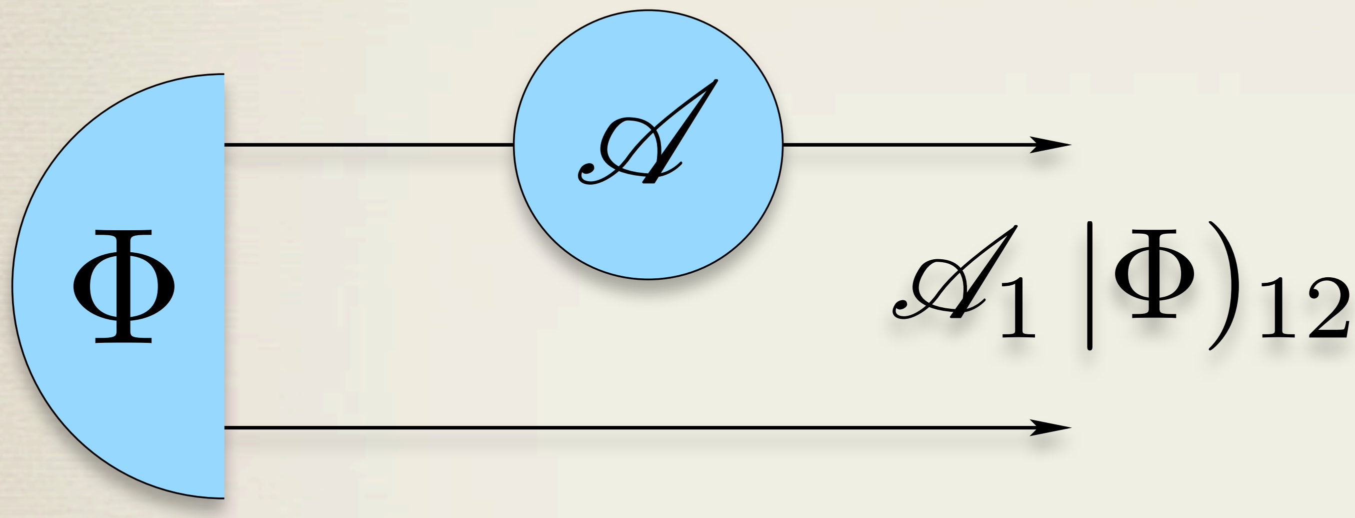
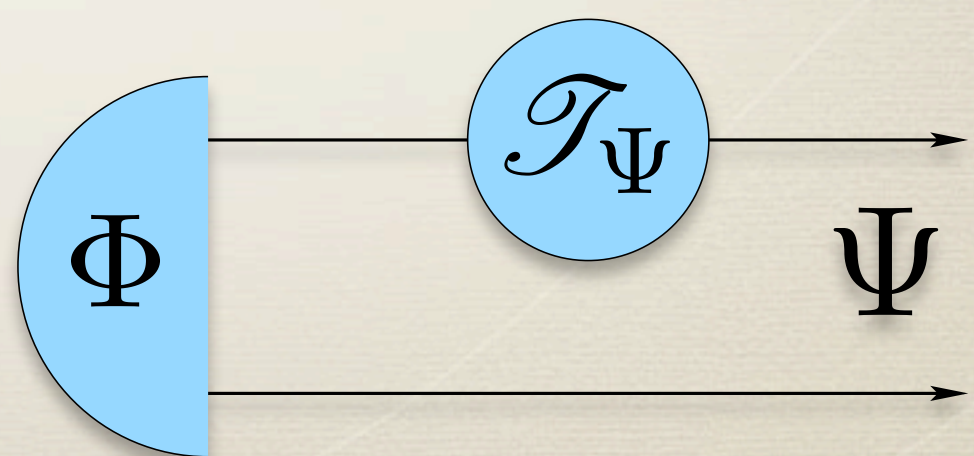


calibrability of tests

local state-preparability

A state Φ of a bipartite system is preparationally faithful if every joint state Ψ can be achieved by a suitable local transformation $\mathscr{T}_\Psi$ on one system occurring with nonzero probability



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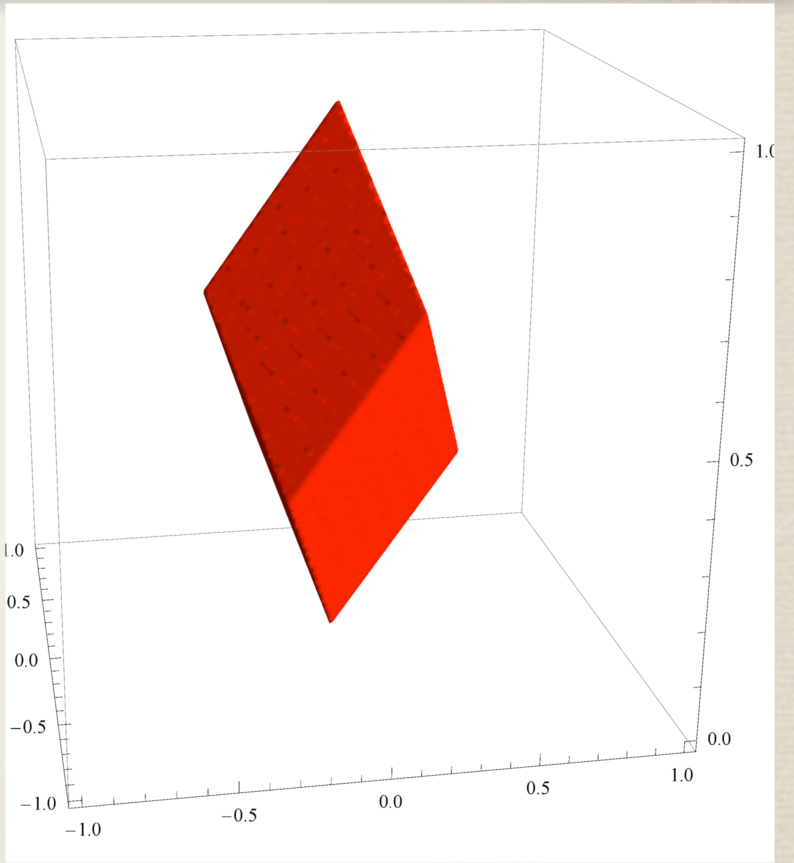
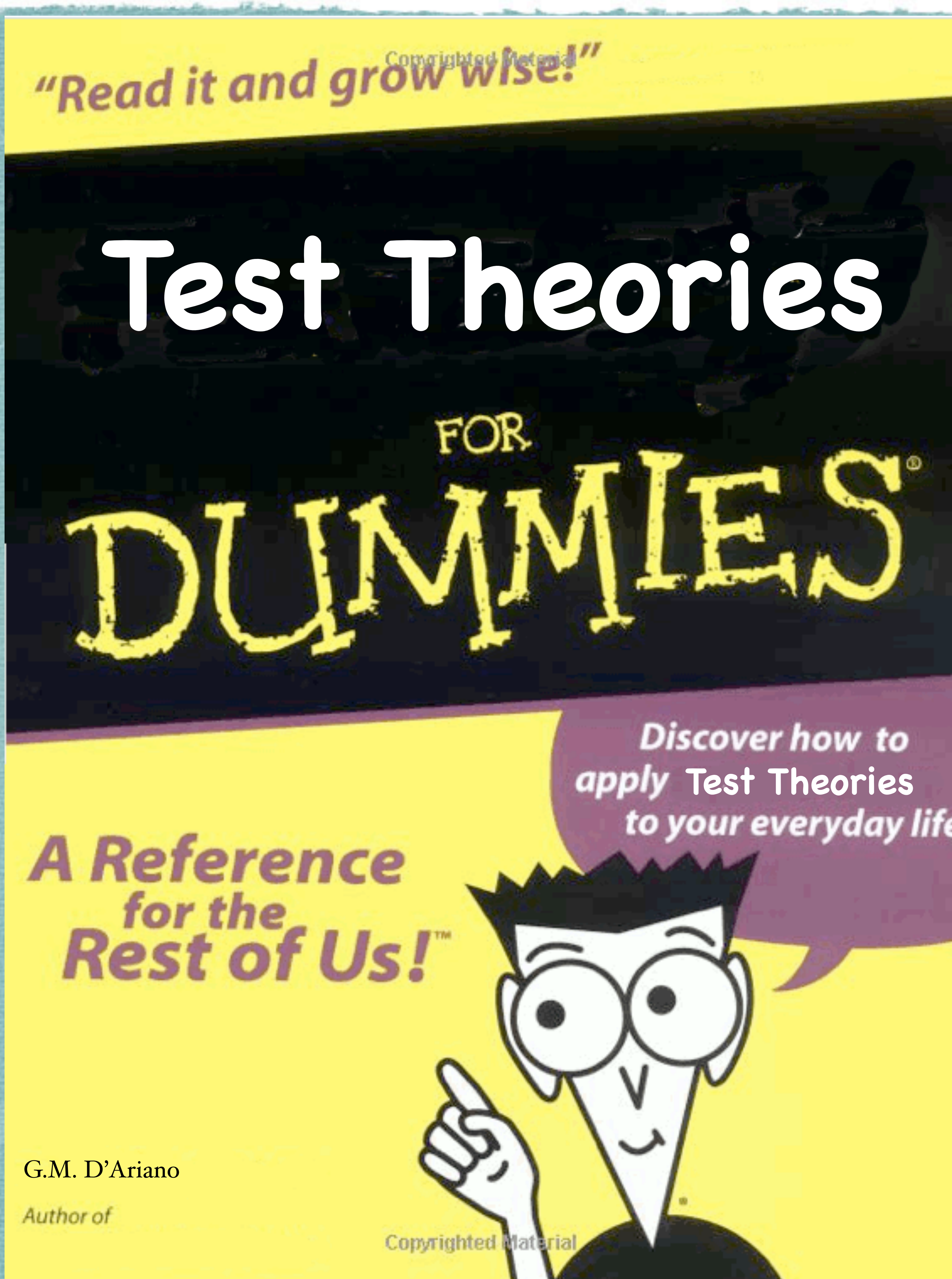
- Faithful states are pure iff $\mathscr{I}$ is atomic (joint property from local geometry!)

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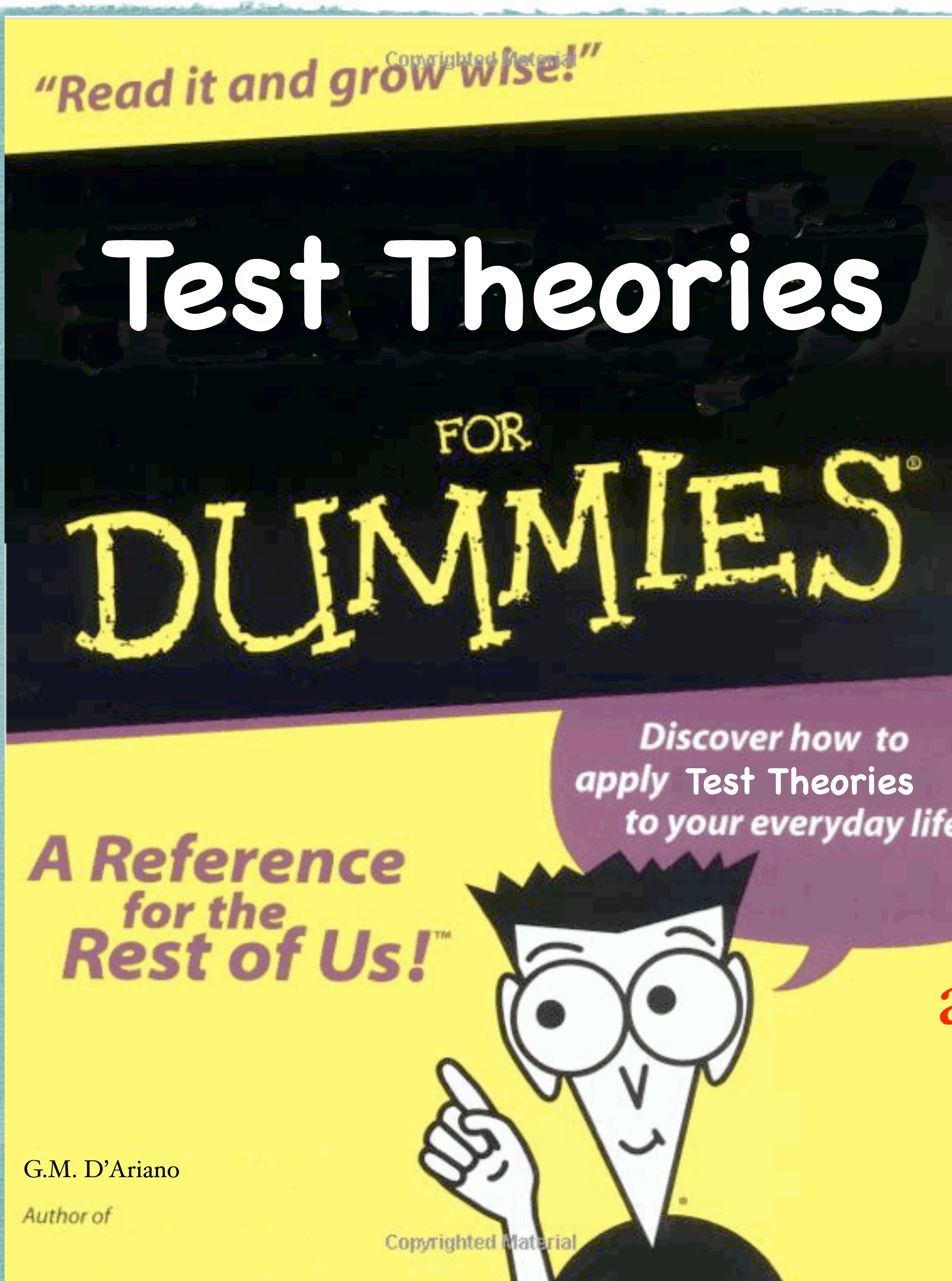
THE END



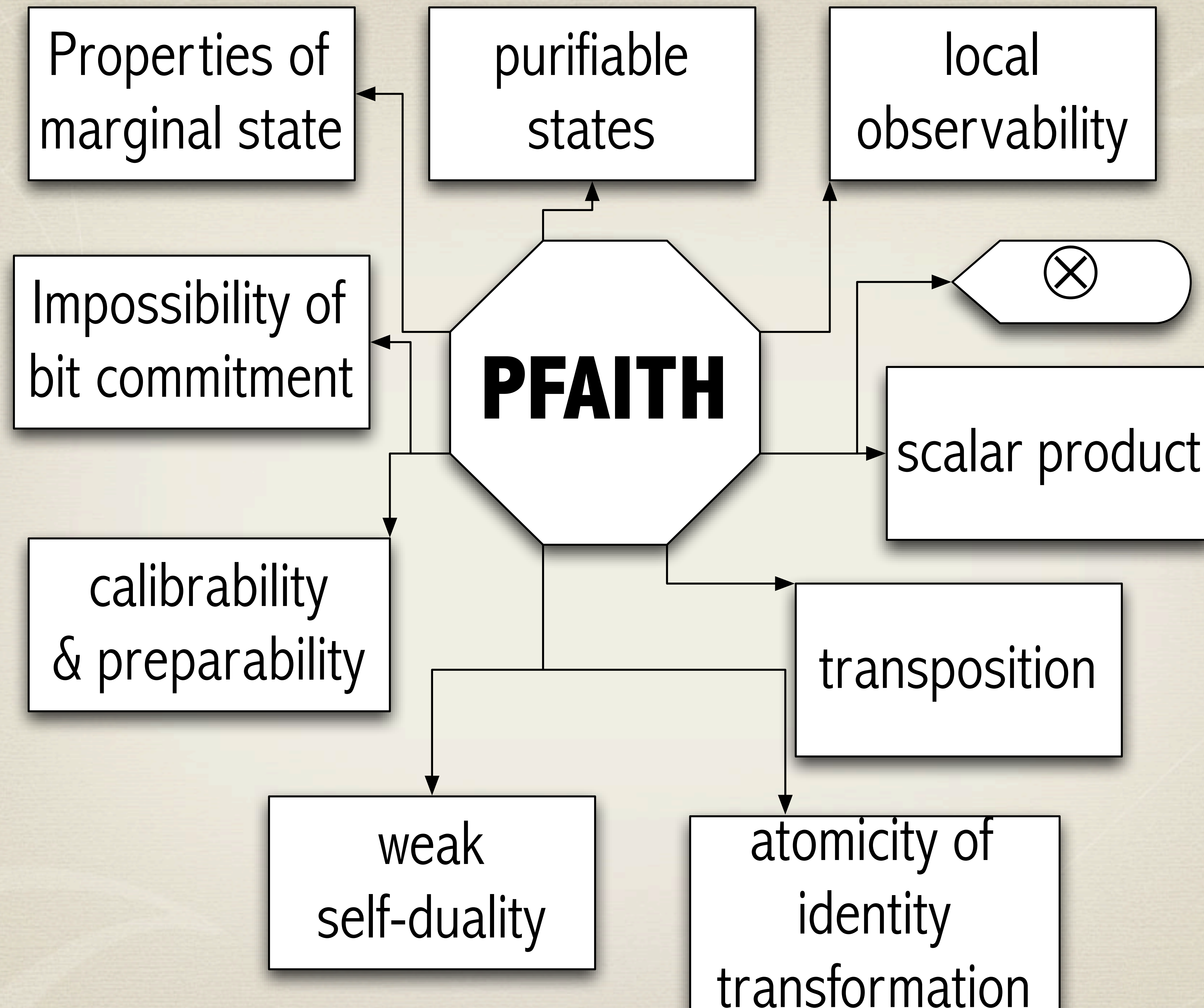
THE END

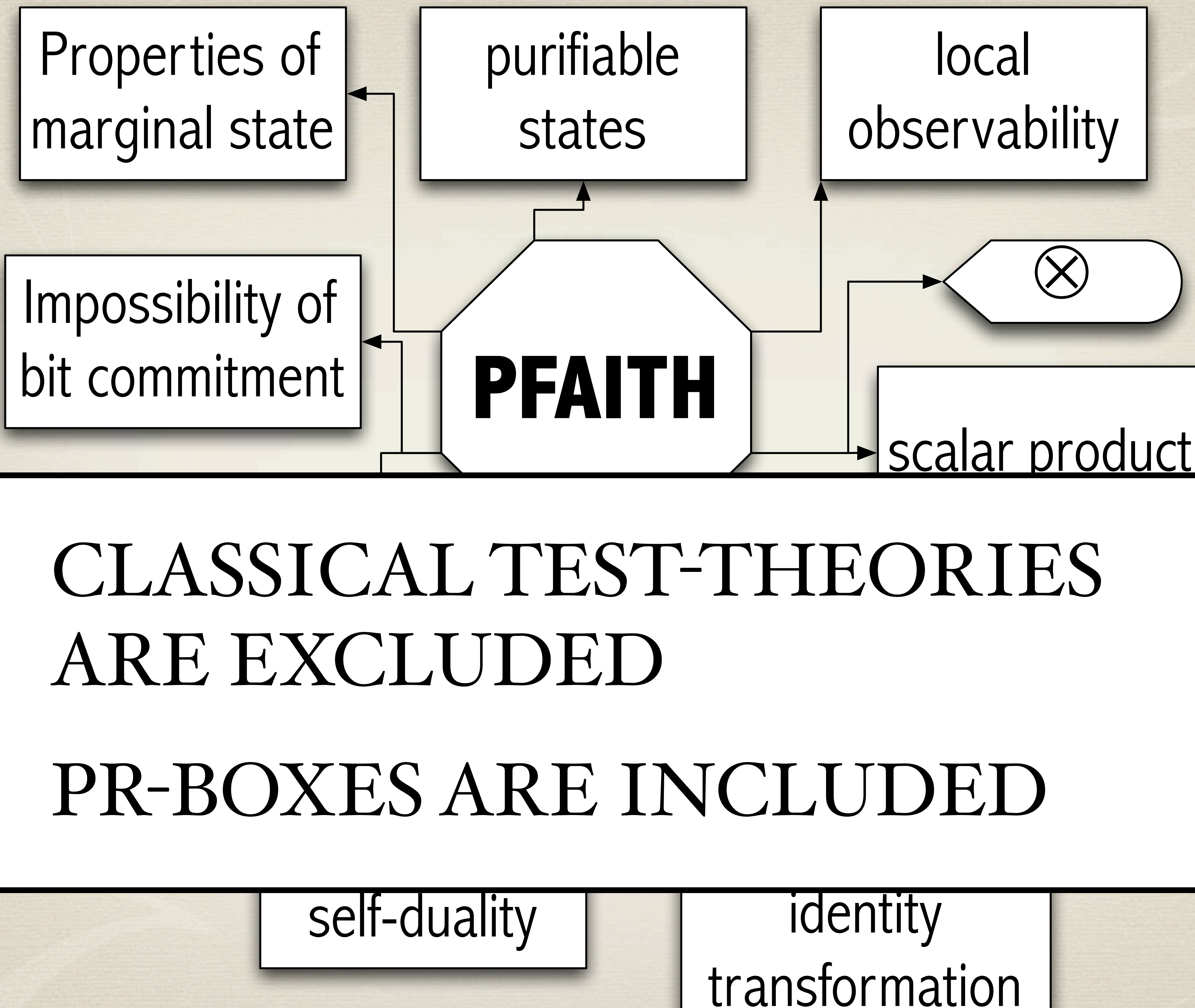
Lesson learnt:
all test-theories have
a nice matrix
representation

EXPLORING POSSIBLE PRINCIPLES OF THE QUANTUMNESS

Postulate PFAITH

PFAITH: For any couple of identical systems, there exist a symmetric pure state Φ that is preparationally faithful.


Properties of marginal state
purifiable states
local observability
Impossibility of bit commitment
PFAITH
$\otimes$
scalar product
calibrability & preparability
transposition
weak self-duality
atomicity of identity transformation



CLASSICAL TEST-THEORIES ARE EXCLUDED

PR-BOXES ARE INCLUDED

Postulate: FAITHE

$\boxed{\textbf{Postulate FAITHE:}}$ (faithful effect)

$$F := \alpha \left(\Phi^{-1}\right| \in \mathfrak{E}(\mathsf{SS}),\ 0 < \alpha \leqslant 1$$

proportional to a joint effect.

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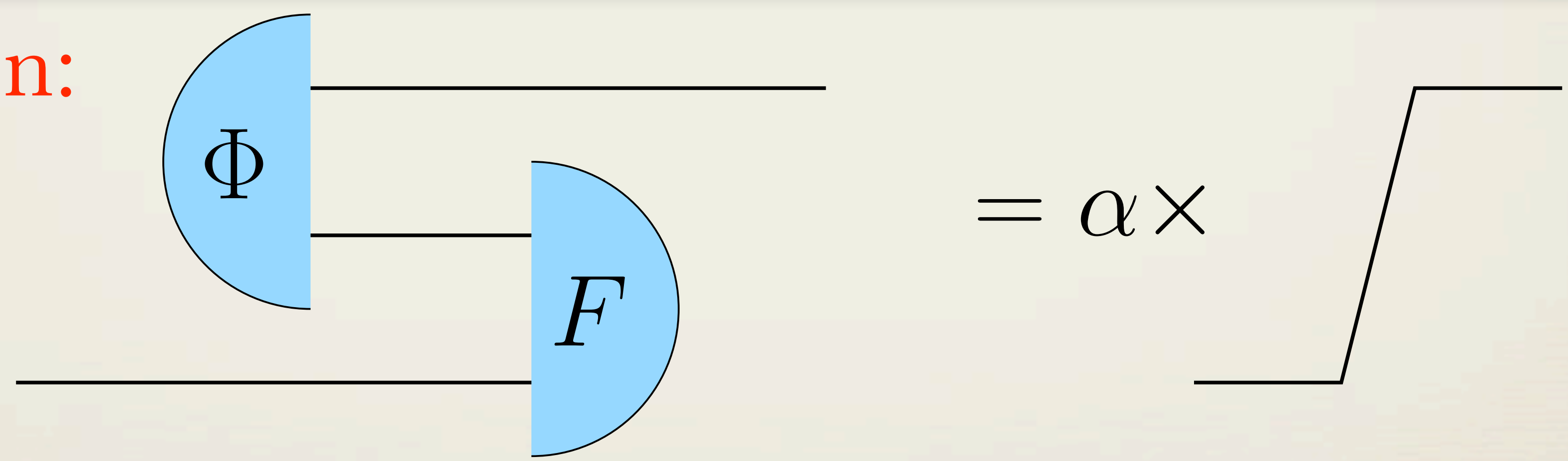
- Teleportation:



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Postulate FAITHE: (faithful effect)

BOTH CLASSICAL TEST-THEORIES AND P-BOXES ARE EXCLUDED

Postulate: Purification

Postulate PURIFY: Every state has a purification on two identical systems.

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- A symmetric preparationally faithful state is necessarily pure and $\mathscr{I}$ is atomic.
- The sets of (bipartite) states/effects are strongly convex
- Each state can be obtained by applying an atomic transformation to the marginal state $\chi = \Phi(e, \cdot)$
- Each effect contains an atomic transformation.

DO WE GET QUANTUM THEORY FROM OUR POSTULATES?

DO WE GET QUANTUM THEORY FROM OUR POSTULATES?

HOW TO PROVE THAT WE HAVE QUANTUM MECHANICS?

THANK YOU FOR YOUR ATTENTION