Title: Nonclassicality as the failure of noncontextuality

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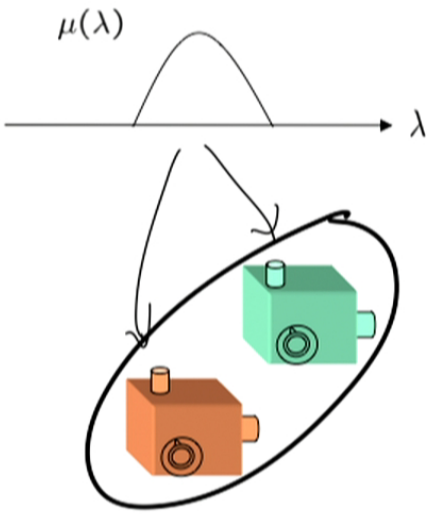
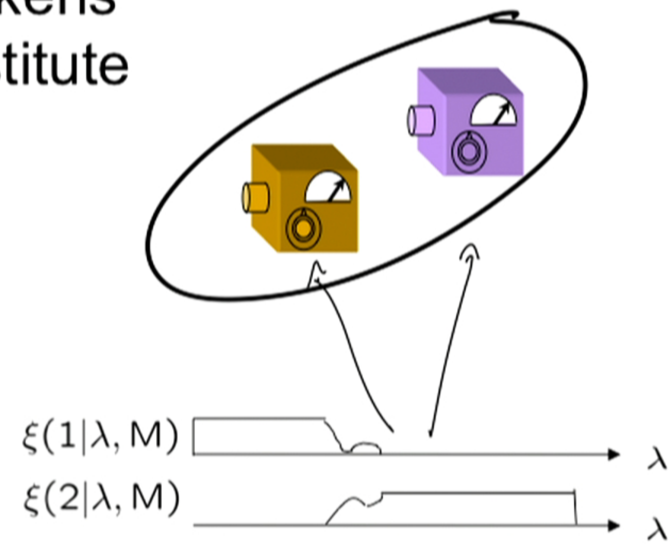
Abstract: To make precise the sense in which nature fails to respect classical physics, one requires a formal notion of "classicality". Ideally, such a notion should be defined operationally, so that it can be subjected to a direct experimental test, and it should be applicable in a wide variety of experimental scenarios, so that it can cover the breadth of phenomena that are thought to defy classical understanding. Bell's notion of local causality fulfills the first criterion but not the second, because it is restricted to scenarios with two or more systems that are space-like separated. The notion of noncontextuality fufills the second criterion, because it is applicable to any experiment (even those on a single system), but it is a long-standing question whether it can be made to fulfill the first. Previous attempts to experimentally test noncontextuality have all presumed certain idealizations that do not hold in real experiments, namely, noiseless measurements and exact operational equivalences. In this talk, I will describe how one can devise experimental tests that are free of these idealizations using an operational notion of noncontextuality that applies to both preparations and measurements. These new theoretical insights raise the bar significantly for any claim of an experimental demonstration of nonclassicality. They also provide the means of determining, for any phenomenon that is typically thought to defy classical explanation, which experimentally-testable features of that phenomenon, if any, conflict with the assumption of a noncontextual model.

Nonclassicality as the failure of noncontextuality



Robert Spekkens
Perimeter Institute



Information Theoretic Foundations of Quantum Theory
PI, May 12, 2015

What we want in a notion of nonclassicality

Subject to direct experimental test

Applicable to a broad range of physical scenarios

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	Subject to direct experimental test	Applicable to a broad range of physical scenarios
Failure of local causality	✓	✗

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Failure of local causality	✓	✗
Failure of noncontextuality	?	✓

What we want in a notion of nonclassicality

	Subject to direct experimental test	Applicable to a broad range of physical scenarios
Failure of local causality	✓	✗
Failure of noncontextuality	✓	✓

Operational theory

$$p(X|M,P)$$

Operational theory

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Ontological model of an operational theory

$\lambda \in \Lambda$ Ontic state space

λ causally mediates between P and M

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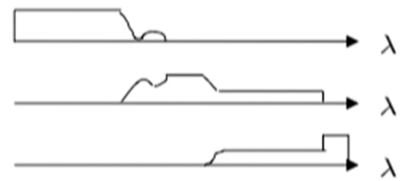
$\mathrm{P} \leftrightarrow \mu(\lambda|\mathrm{P})$

$\mathrm{M} \leftrightarrow \xi(X|\mathrm{M},\lambda)$



Operational theory

$$p(X|M,P)$$

Ontological model of an operational theory

$\lambda \in \Lambda$ Ontic state space

λ causally mediates between P and M

$\mathsf{P} \leftrightarrow \mu(\lambda|\mathsf{P})$

$\mathsf{M} \leftrightarrow \xi(X|\mathsf{M},\lambda)$

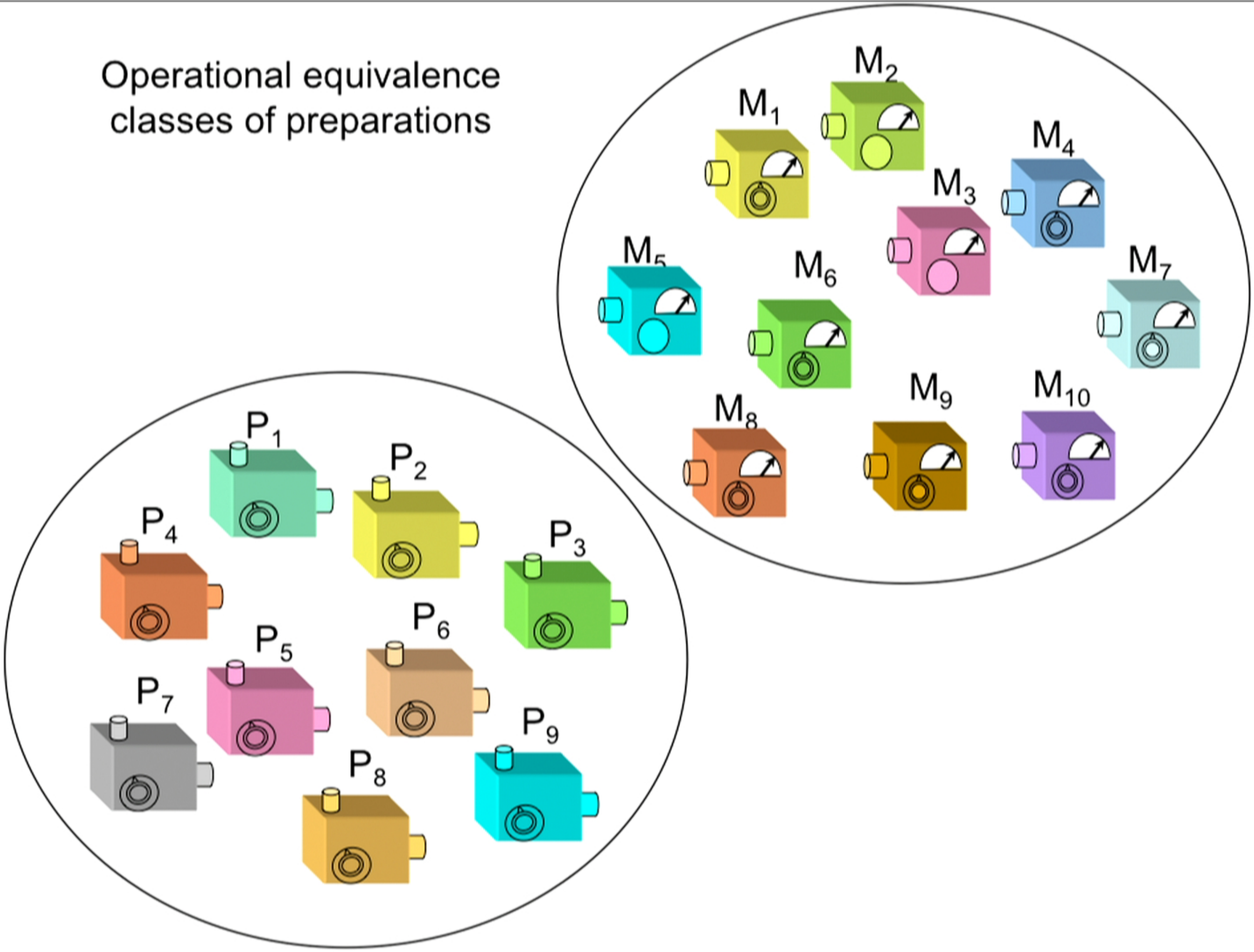
$$p(X|M,P) = \int \xi(X|M,\lambda)\, \mu(\lambda|P)\, \mathrm{d}\lambda$$

An ontological model of an operational theory is noncontextual if

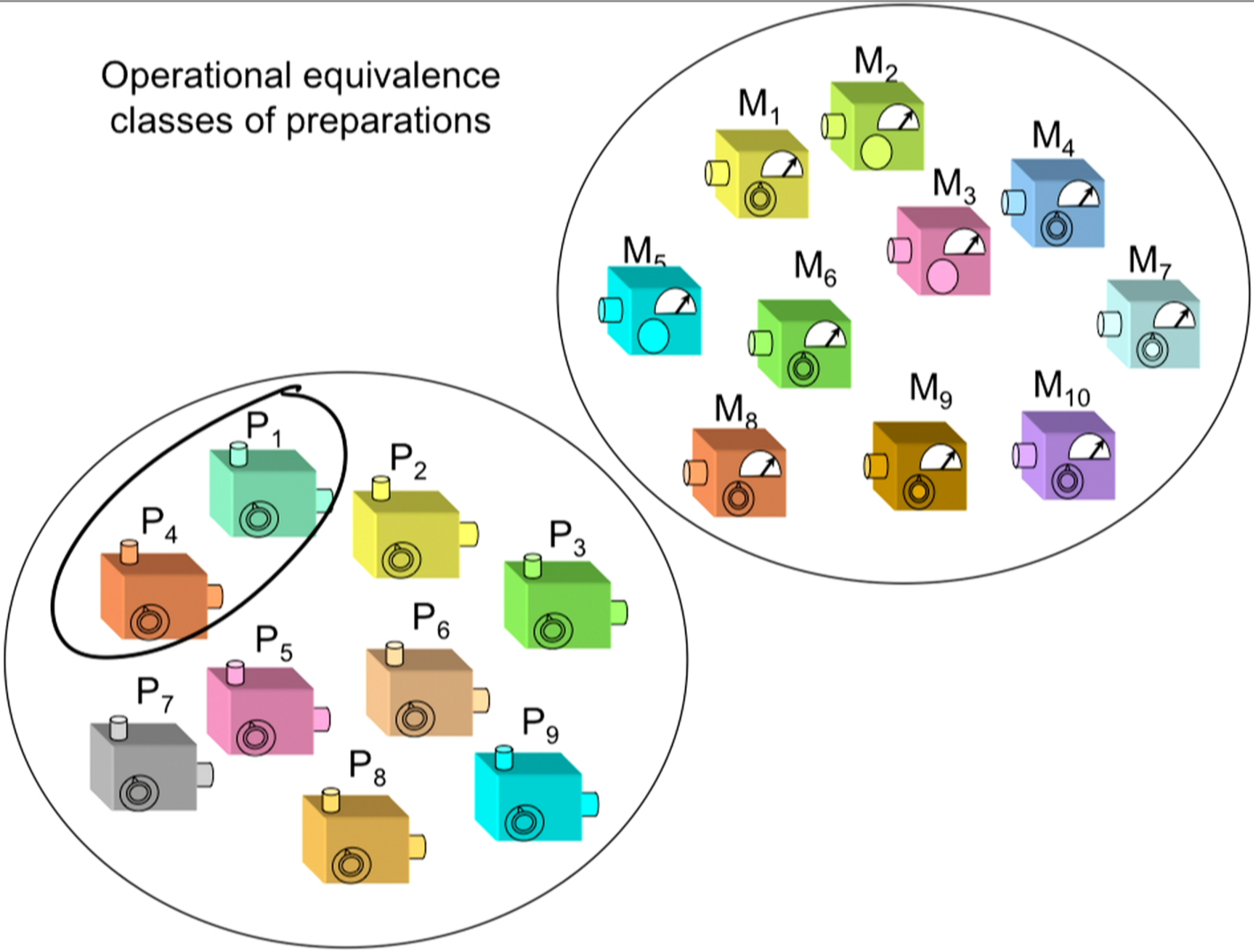
Operational equivalence of two experimental procedures → Equivalent representations in the ontological model

RWS, Phys. Rev. A 71, 052108 (2005)

Operational equivalence classes of preparations



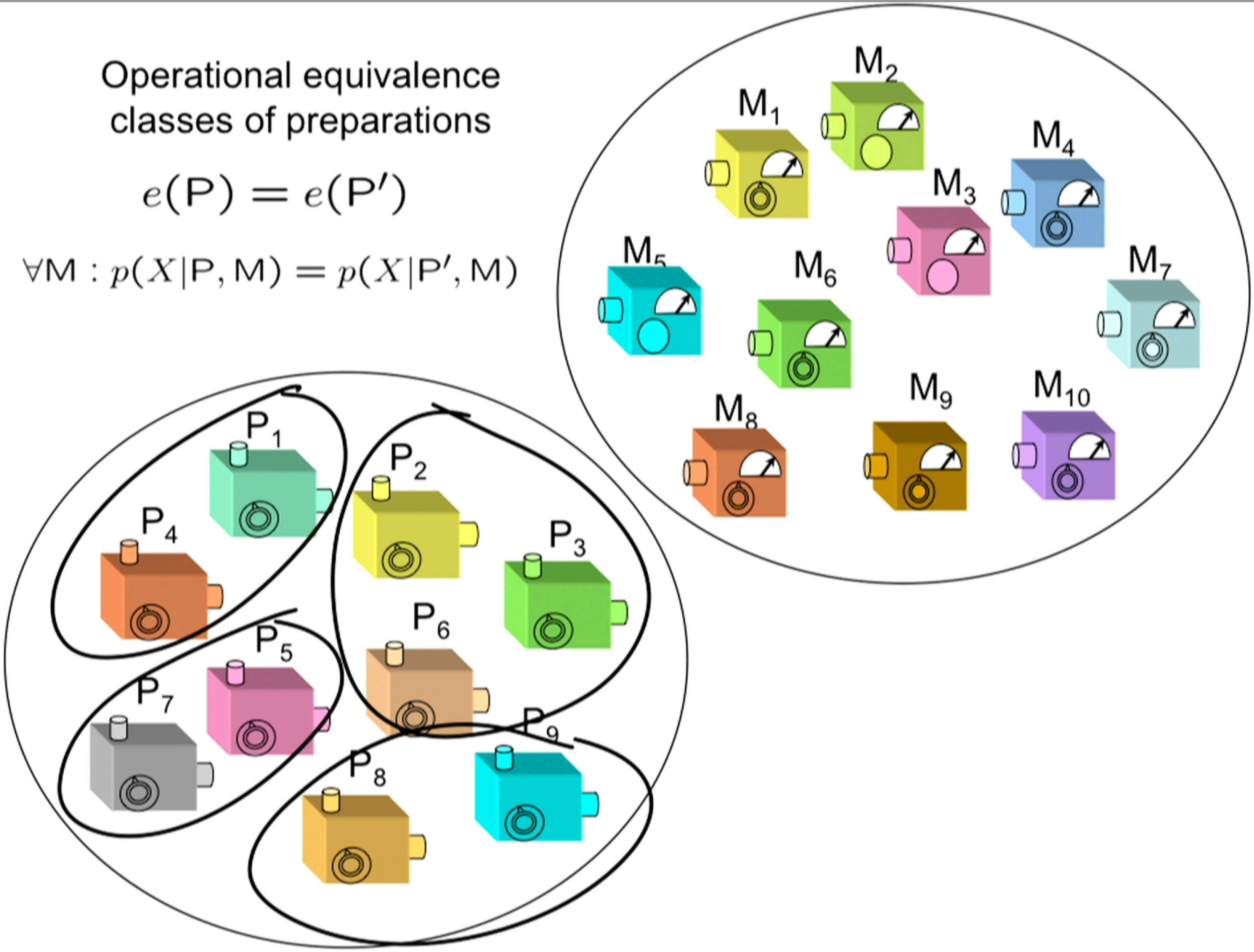
Operational equivalence classes of preparations

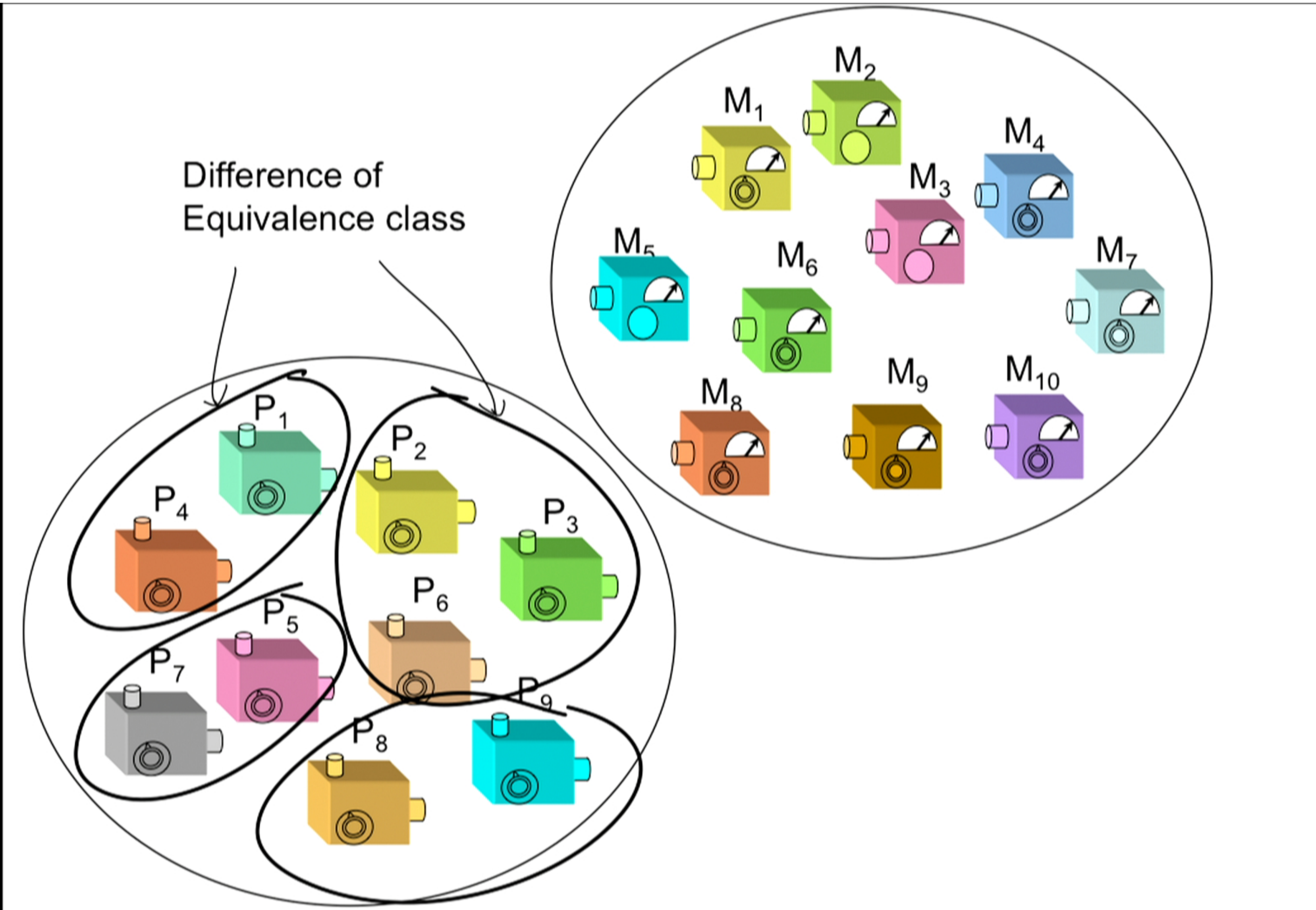


Operational equivalence
classes of preparations

$$e(\mathsf{P}) = e(\mathsf{P}')$$

$$\forall \mathsf{M} : p(X|\mathsf{P},\mathsf{M}) = p(X|\mathsf{P}',\mathsf{M})$$




Difference of
Equivalence class
P_1
P_2
P_3
P_4
P_5
P_6
P_7
P_8
P_9
M_1
M_2
M_3
M_4
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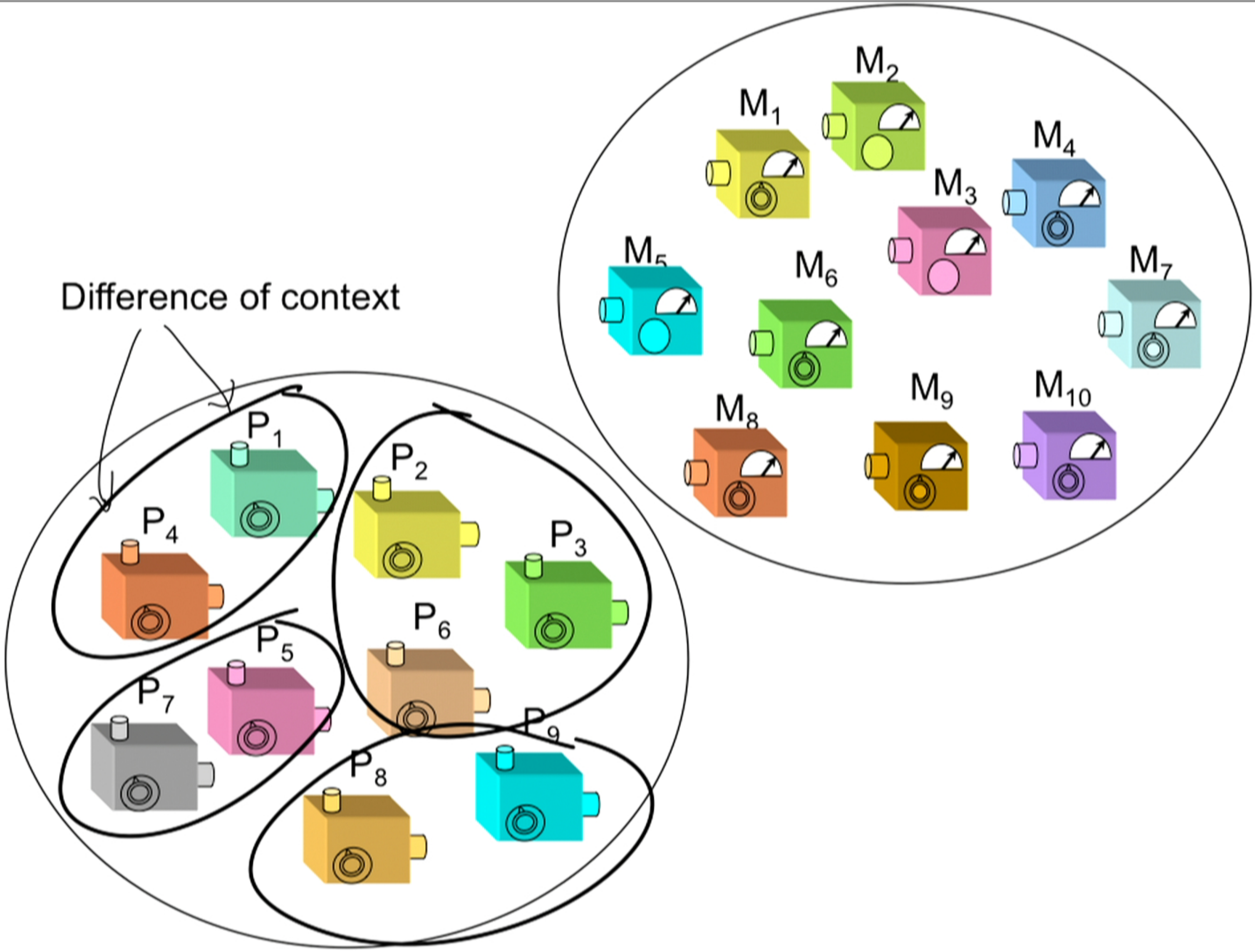
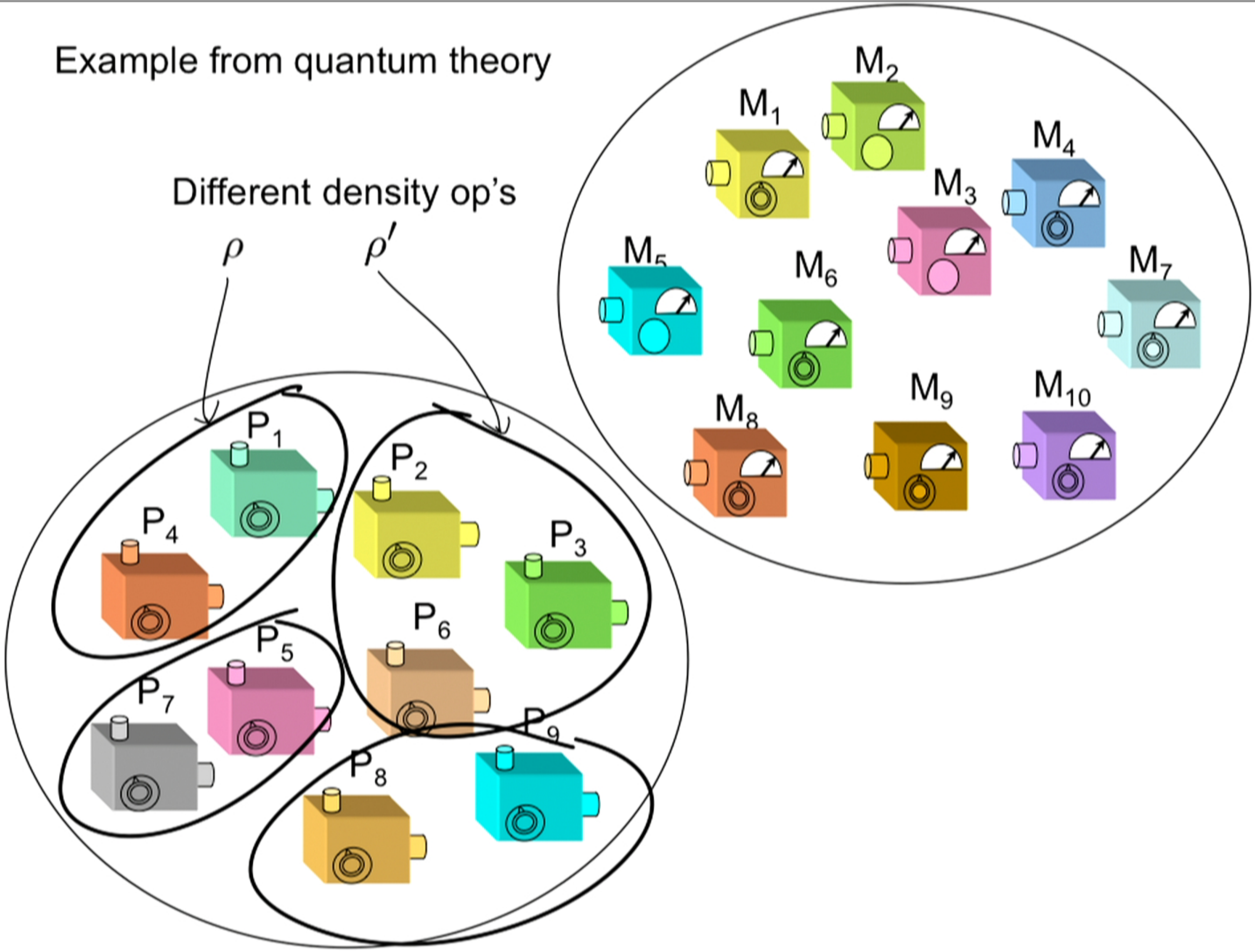
M_6
M_7
M_8
M_9
M_{10}


Difference of context
M_1
M_2
M_3
M_4
M_5
M_6
M_7
M_8
M_9
M_{10}
P_1
P_2
P_3
P_4
P_5
P_6
P_7
P_8
P_9

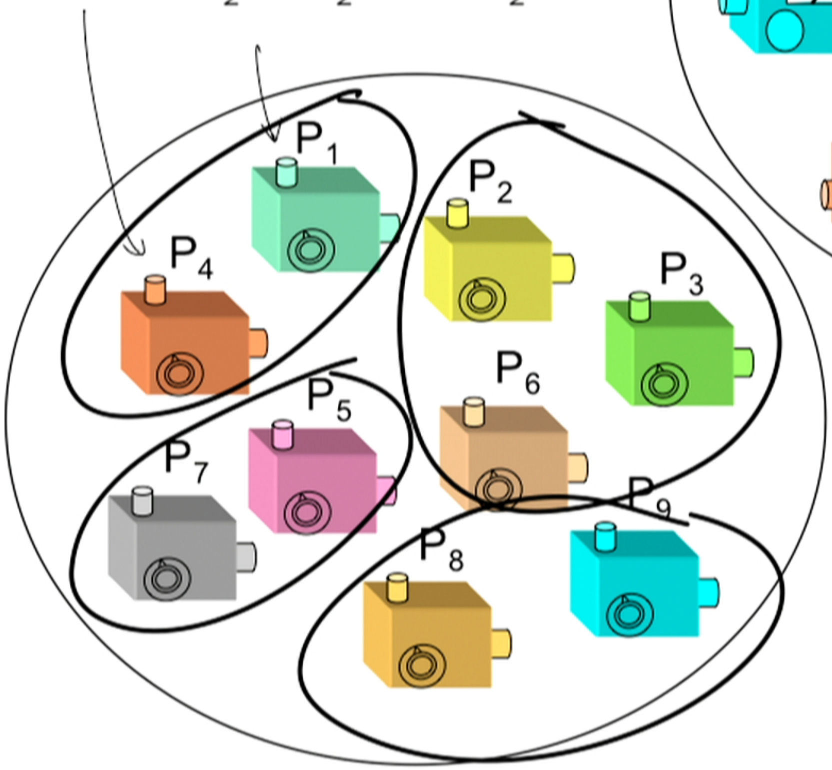
Example from quantum theory

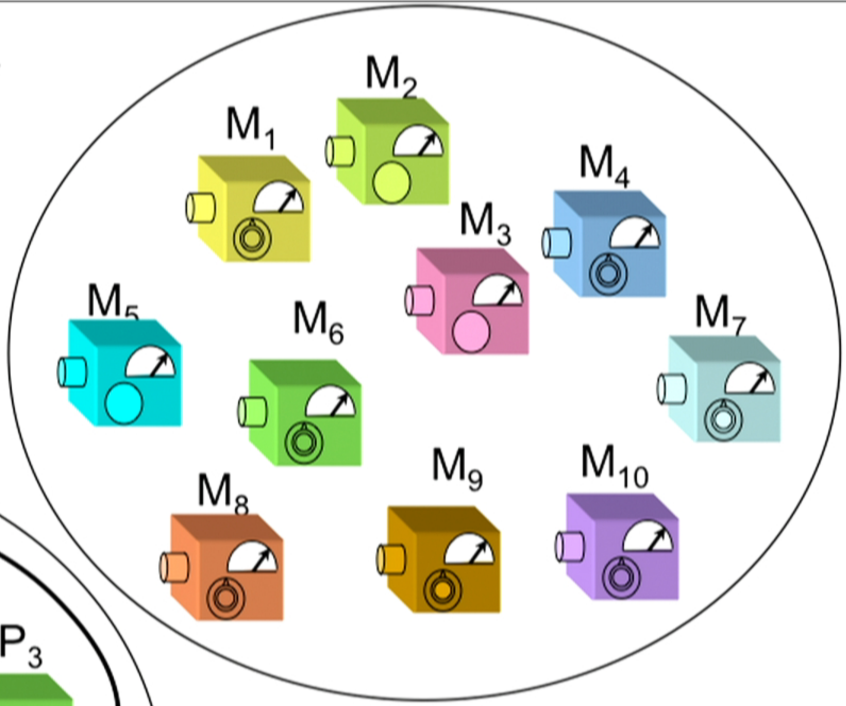


Example from quantum theory

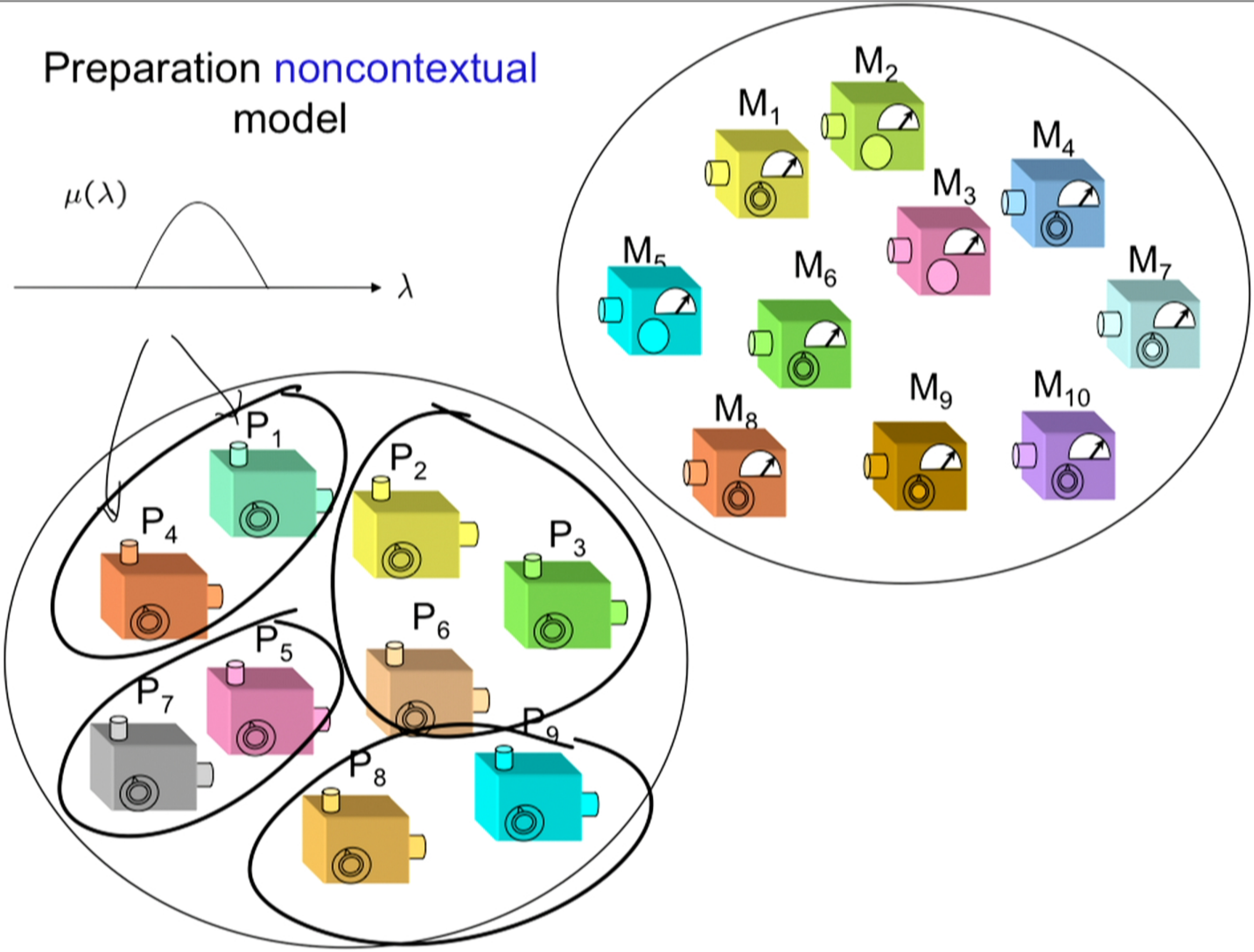
$$\frac{1}{2}I = \frac{1}{2}|0\rangle\langle 0| + \frac{1}{2}|1\rangle\langle 1|$$

$$\frac{1}{2}I = \frac{1}{2}|+\rangle\langle +| + \frac{1}{2}|-\rangle\langle -|$$

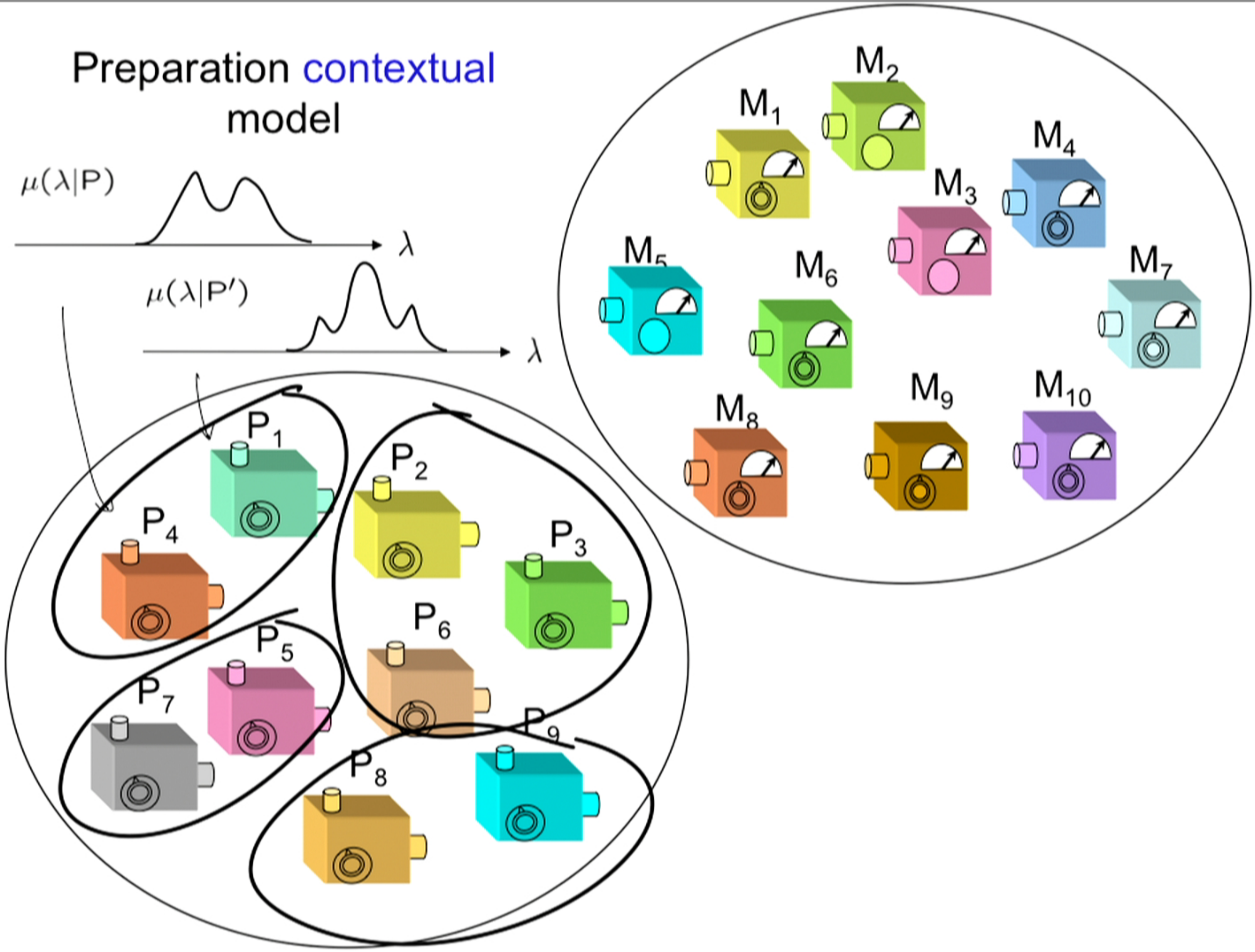


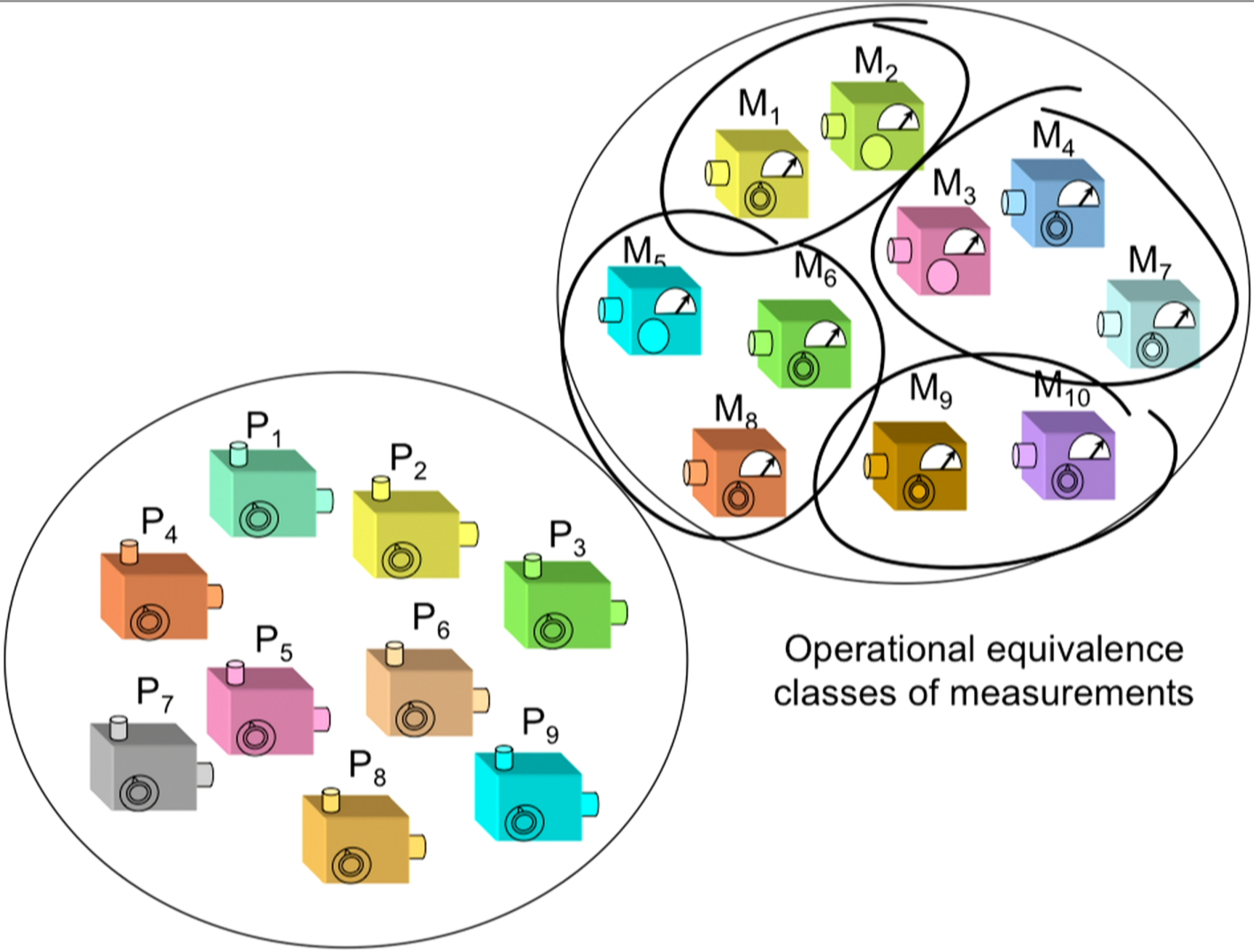


Preparation noncontextual model

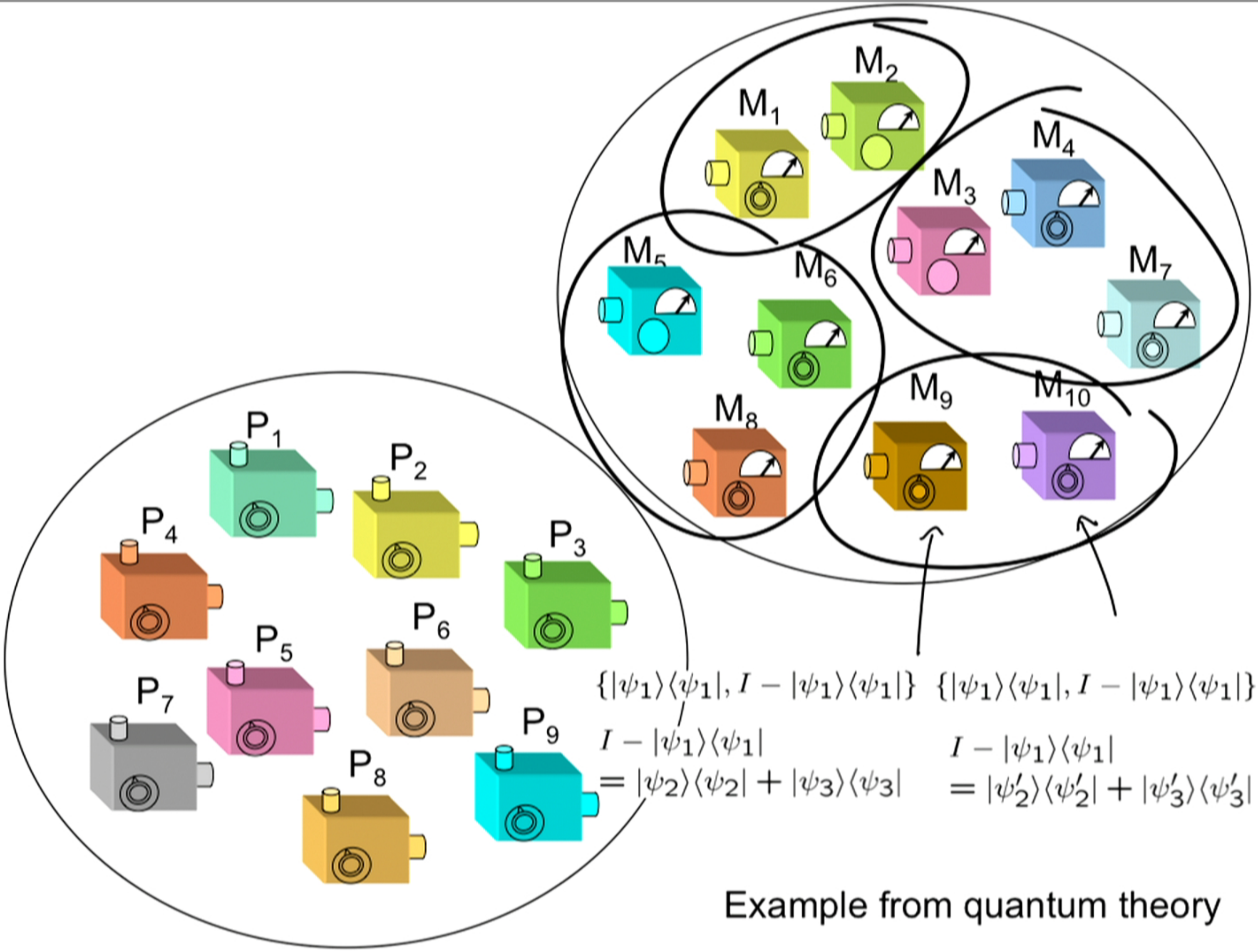


Preparation contextual model





Operational equivalence classes of measurements

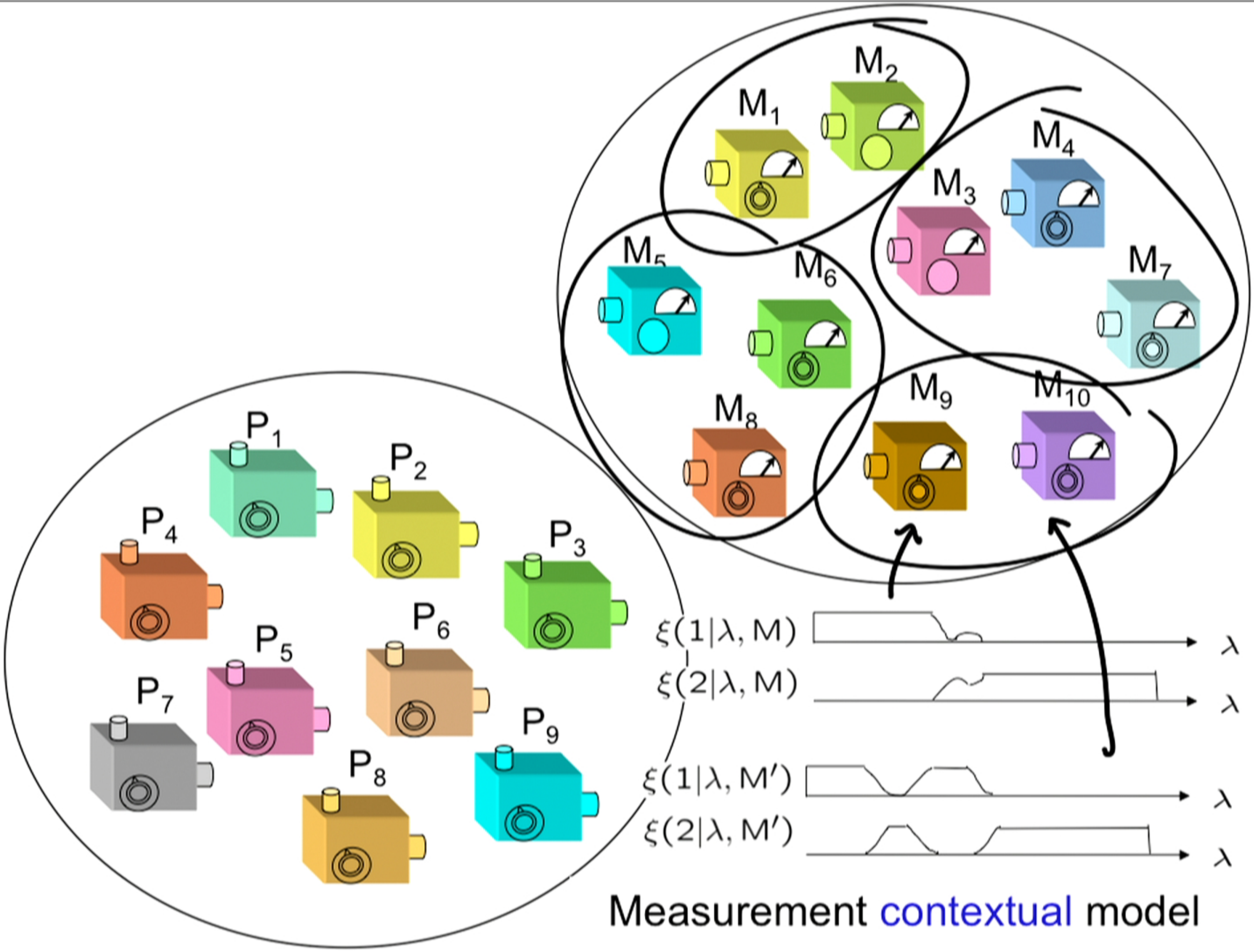


$$\{|\psi_1\rangle\langle\psi_1|, I - |\psi_1\rangle\langle\psi_1|\} \quad \{|\psi_1\rangle\langle\psi_1|, I - |\psi_1\rangle\langle\psi_1|\}$$

$$I - |\psi_1\rangle\langle\psi_1| = |\psi_2\rangle\langle\psi_2| + |\psi_3\rangle\langle\psi_3|$$

$$I - |\psi_1\rangle\langle\psi_1| = |\psi_2'\rangle\langle\psi_2'| + |\psi_3'\rangle\langle\psi_3'|$$

Example from quantum theory



Measurement contextual model

$$e(\mathsf{P}) = e(\mathsf{P}')$$

$$\forall \mathsf{M} : p(X|\mathsf{P},\mathsf{M}) = p(X|\mathsf{P}',\mathsf{M})$$

Preparation noncontextuality

$$\longrightarrow$$

$$\mu(\lambda|\mathsf{P}) = \mu(\lambda|\mathsf{P}')$$

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$$\forall \mathsf{P} : p(X|\mathsf{P},\mathsf{M}) = p(X|\mathsf{P},\mathsf{M}')$$

Measurement noncontextuality

$$\longrightarrow$$

$$\xi(X|\lambda,\mathsf{M}) = \xi(X|\lambda,\mathsf{M}')$$

Noncontextuality is an analogue of Leibniz's principle of the identity of indiscernables:

The ontological identity of operational indiscernables

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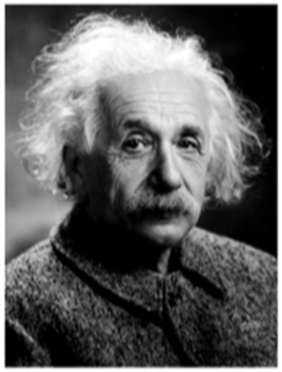
The ontological identity of operational indiscernables

Noncontextuality is an analogue of Einstein's strong equivalence principle



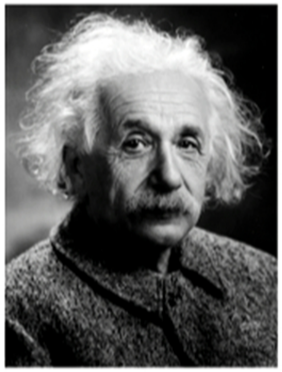
An information-theoretic equivalence principle

Noncontextuality is an analogue of Leibniz's principle of the identity of indiscernables:

The ontological identity of operational indiscernables

Noncontextuality is an analogue of Einstein's strong equivalence principle

An information-theoretic equivalence principle



Noncontextuality is an analogue of the principle of no fine-tuning used in causal inference

To achieve context-independence at the operational level while having context-dependence at the ontological level requires fine-tuning

Obstacles to a direct experimental test of noncontextuality

Obstacle #1: How to contend with noise?

Obstacle #2: How to contend with inexactness of operational equivalences?

Obstacles to a direct experimental test of noncontextuality

Obstacle #1: How to contend with noise?

Obstacle #2: How to contend with inexactness of operational equivalences?

Joint work with:
Ravi Kunjwal, Matt Pusey (theory)
Mike Mazurek, Kevin Resch (experiment)

Obstacle #1: How to contend with noise?

Previous no-go results

measurement noncontextuality

and

outcome determinism

for projective measurements

⟶ contradiction

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Previous no-go results

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→ contradiction

It turns out that

preparation noncontextuality

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Facts about projective measurements

→ outcome determinism for projective measurements

Obstacle #1: How to contend with noise?

Previous no-go results

measurement noncontextuality
and
outcome determinism
for projective measurements → contradiction

It turns out that

preparation noncontextuality
and
Facts about projective
measurements → outcome determinism for projective measurements

And therefore:

universal noncontextuality
and
Facts about projective
measurements → contradiction

Obstacle #1: How to contend with noise?

Recast as:

universal noncontextuality

and

Certain operational equivalences

Perfect correlations

⟶ contradiction

And then as:

universal noncontextuality

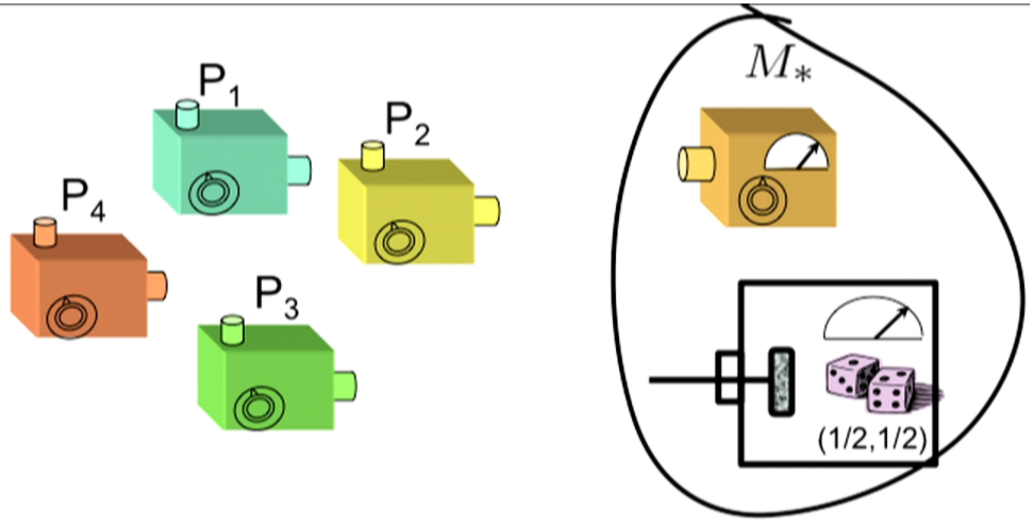
and

Certain operational equivalences

Degree of correlation above some bound

⟶ contradiction

A noncontextuality inequality robust to experimental noise

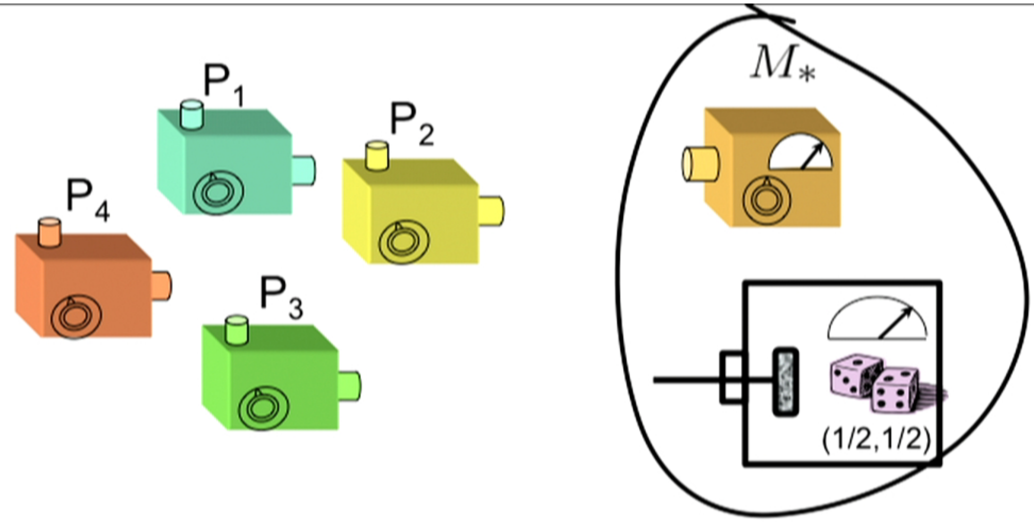


$$e(M_*) = e(\text{coin flip})$$

$$p(X = 0, 1 | M_*, P) = \frac{1}{2}, \ \forall P \in \mathcal{P}.$$

$\downarrow$ Measurement noncontextuality

$$\xi(X = 0, 1 | M_*, \lambda) = \frac{1}{2}, \ \forall \lambda \in \Lambda$$



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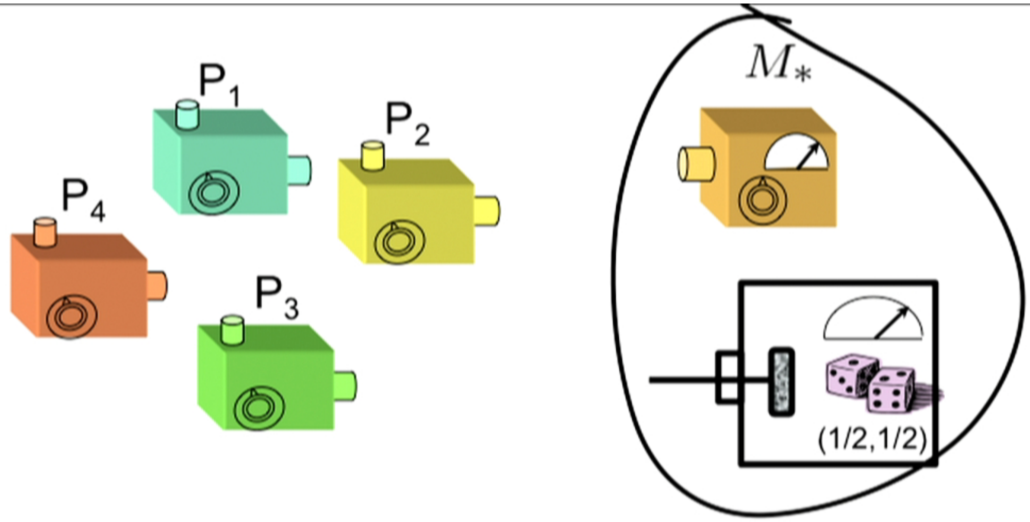

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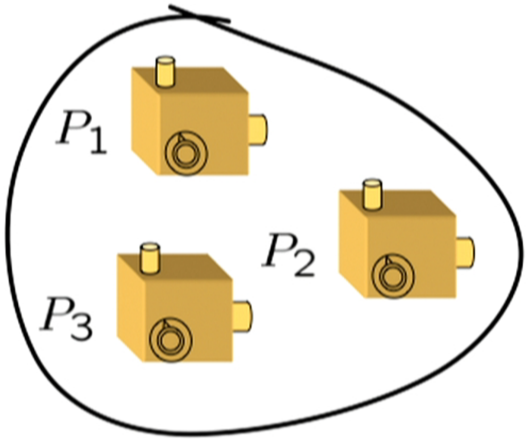
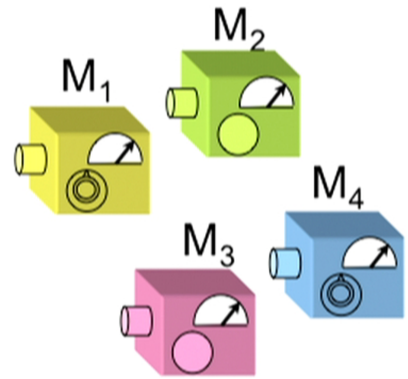


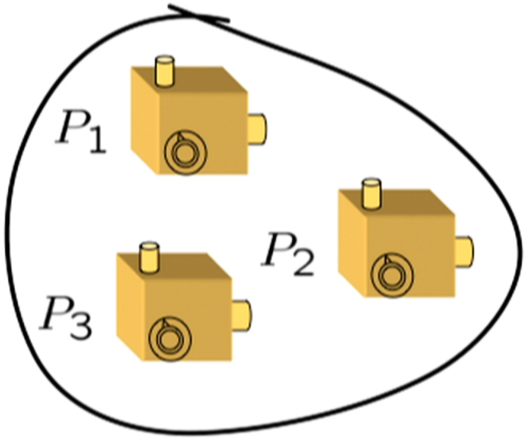


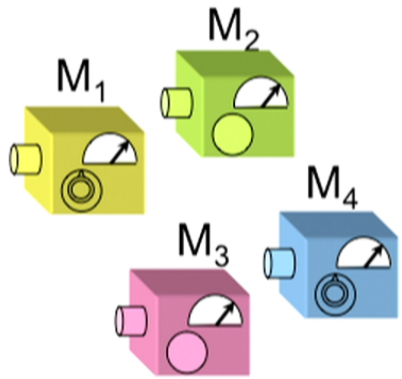
$$e(P_1) = e(P_2) = e(P_3)$$

$$p(X|M, P_1) = p(X|M, P_2) = p(X|M, P_3) \ \ \forall M \in \mathcal{M}$$

$\downarrow$ Preparation noncontextuality

$$\mu(\lambda|P_1) = \mu(\lambda|P_2) = \mu(\lambda|P_3) \ \ \forall \lambda \in \Lambda$$





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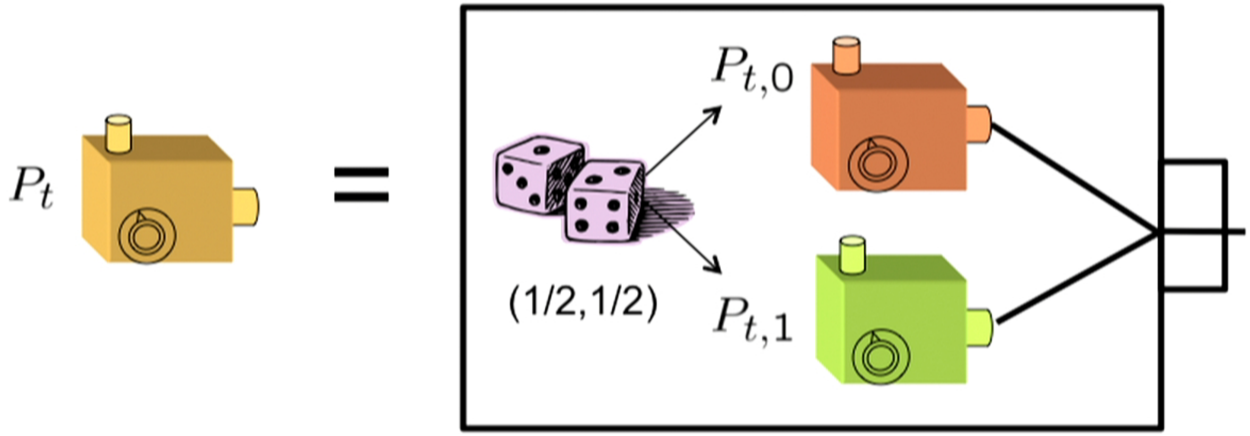
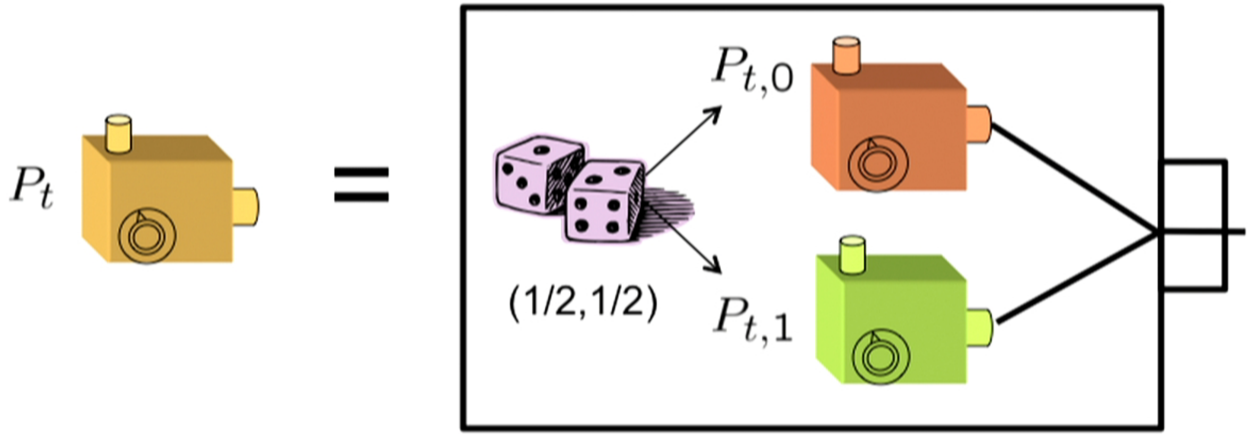
$$t \in \{1, 2, 3\}$$



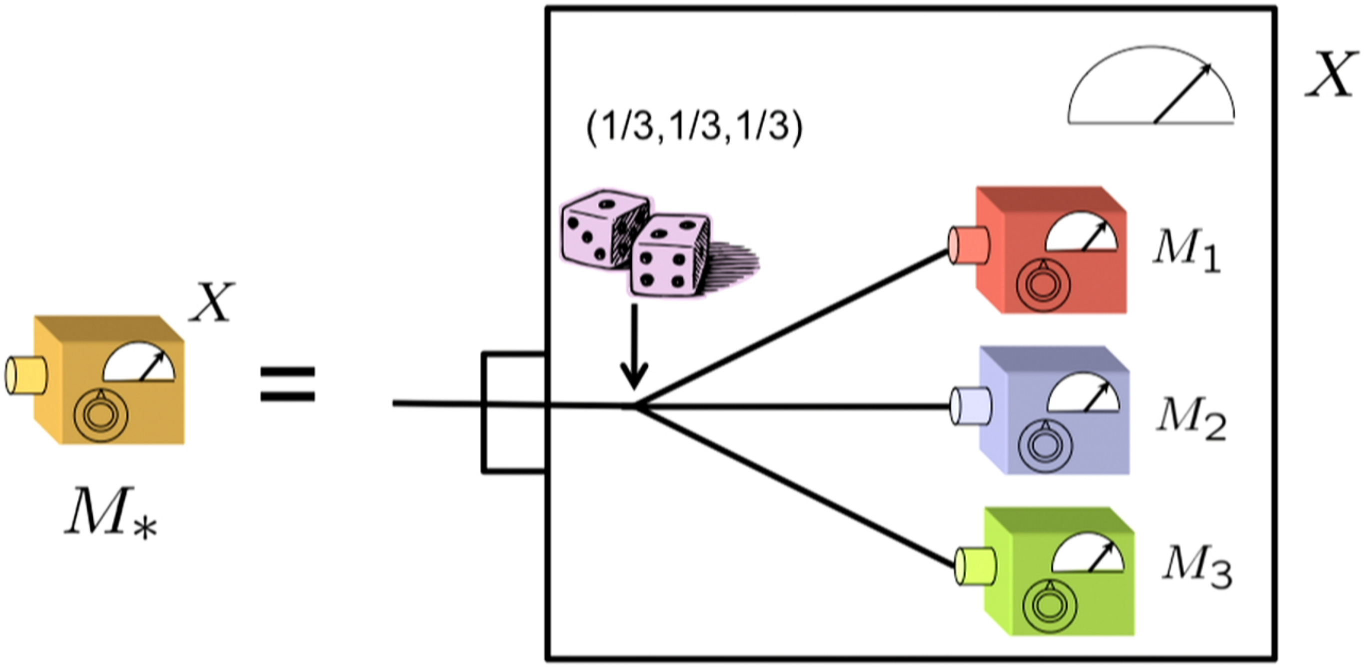
$$\mu(\lambda|P_t) = \frac{1}{2}\mu(\lambda|P_{t,0}) + \frac{1}{2}\mu(\lambda|P_{t,1})$$

$$t \in \{1, 2, 3\}$$

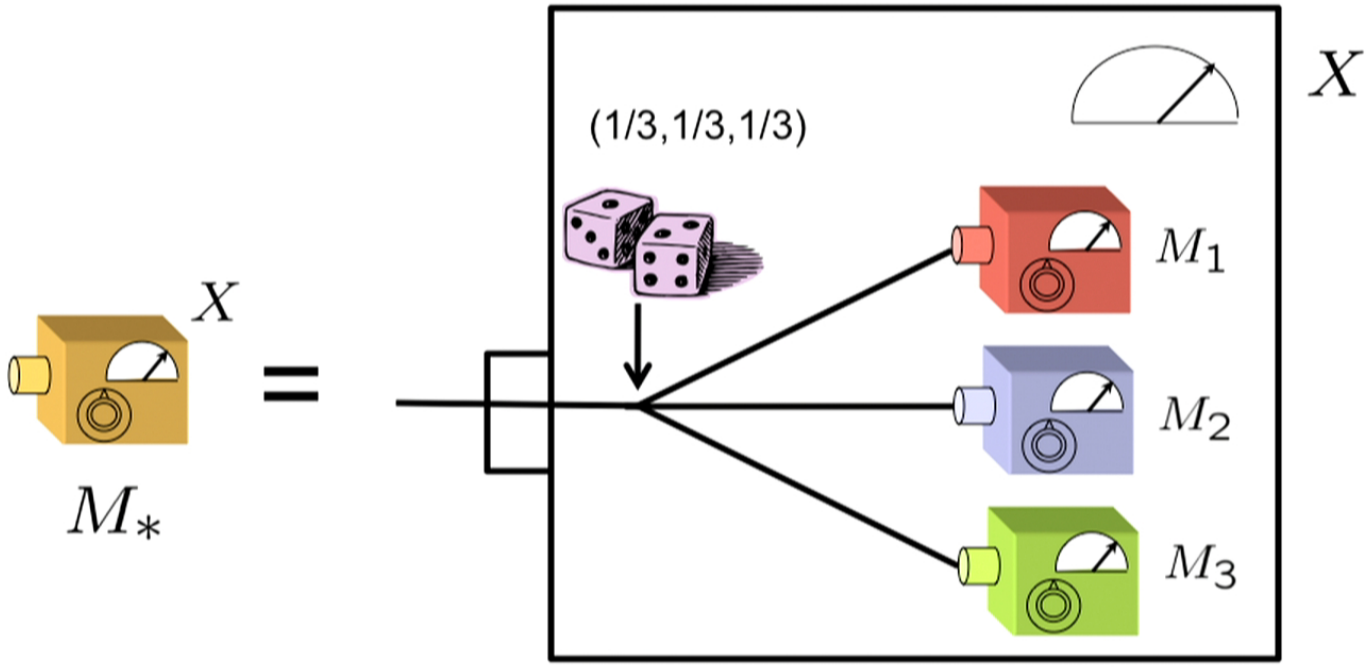


$$\mu(\lambda|P_t) = \tfrac{1}{2}\mu(\lambda|P_{t,0}) + \tfrac{1}{2}\mu(\lambda|P_{t,1})$$

$$\frac{1}{2}\sum_{b\in\{0,1\}} \mu(\lambda|P_{1,b}) = \frac{1}{2}\sum_{b\in\{0,1\}} \mu(\lambda|P_{2,b}) = \frac{1}{2}\sum_{b\in\{0,1\}} \mu(\lambda|P_{3,b})$$



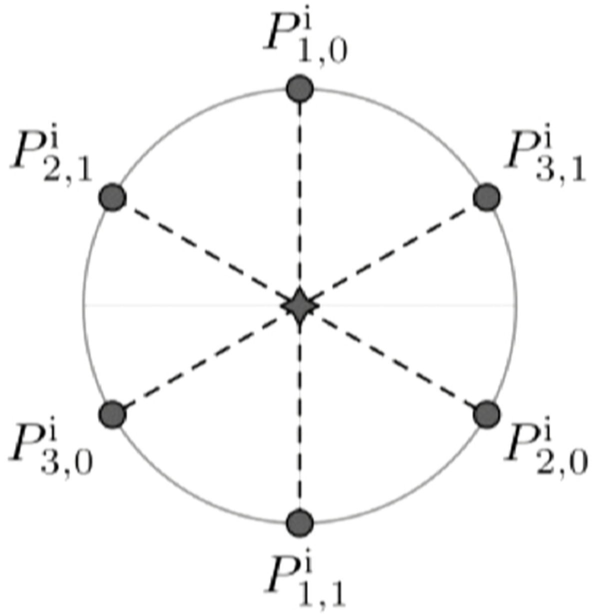
$$\xi(X=b|M_*,\lambda) = \frac{1}{3}\sum_{t\in\{1,2,3\}} \xi(X=b|M_t,\lambda)$$

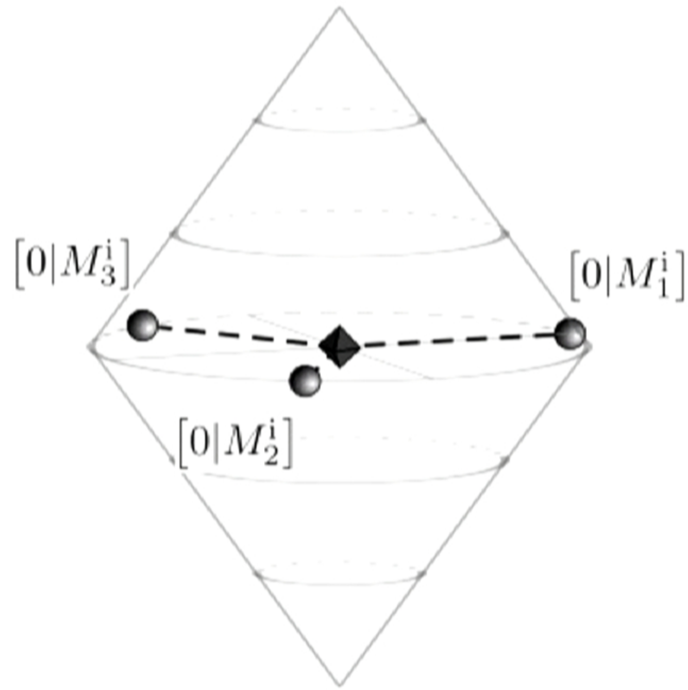


$$\xi(X = b|M_*, \lambda) = \frac{1}{3} \sum_{t \in \{1,2,3\}} \xi(X = b|M_t, \lambda)$$

$$\frac{1}{3} \sum_{t \in \{1,2,3\}} \xi(X = b|M_t, \lambda) = \frac{1}{2}$$

Quantum example





Def'n of average degree of correlation

$$A \equiv \frac{1}{6} \sum_{t \in \{1,2,3\}} \sum_{b \in \{0,1\}} p(X = b | M_t, P_{t,b})$$

Theorem: For any $P_{1,0}, P_{1,1}, P_{2,0}, P_{2,1}, P_{3,0}, P_{3,1}$

M_1, M_2, M_3

If $e(P_1) = e(P_2) = e(P_3)$

$e(M_*) = e(\text{coin flip})$

Then universal noncontextuality implies

$$A \leq \frac{5}{6}$$

A noncontextuality Inequality

Recall $A \equiv \frac{1}{6} \sum_{t \in \{1,2,3\}} \sum_{b \in \{0,1\}} p(X = b | M_t, P_{t,b})$

Recall $p(X = b | M_t, P_{t,b}) = \sum_\lambda \xi(X = b | M_t, \lambda) \mu(\lambda | P_{t,b})$

Recall $A \equiv \frac{1}{6} \sum_{t \in \{1,2,3\}} \sum_{b \in \{0,1\}} p(X = b | M_t, P_{t,b})$

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$$\xi(X = b | M_t, \lambda) \leq \eta(M_t, \lambda)$$

where $\eta(M_t, \lambda) \equiv \max_{b' \in \{0,1\}} \xi(X = b' | M_t, \lambda).$

$$A \leq \frac{1}{3} \sum_{t \in \{1,2,3\}} \sum_{\lambda \in \Lambda} \eta(M_t, \lambda) \left(\frac{1}{2} \sum_{b \in \{0,1\}} \mu(\lambda | P_{t,b}) \right)$$

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$$\frac{1}{2} \sum_{b \in \{0,1\}} \mu(\lambda | P_{1,b}) = \frac{1}{2} \sum_{b \in \{0,1\}} \mu(\lambda | P_{2,b}) = \frac{1}{2} \sum_{b \in \{0,1\}} \mu(\lambda | P_{3,b}) \equiv \nu(\lambda)$$

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$$A \leq \max_{\lambda \in \Lambda} \left(\frac{1}{3} \sum_{t \in \{1,2,3\}} \eta(M_t, \lambda) \right)$$

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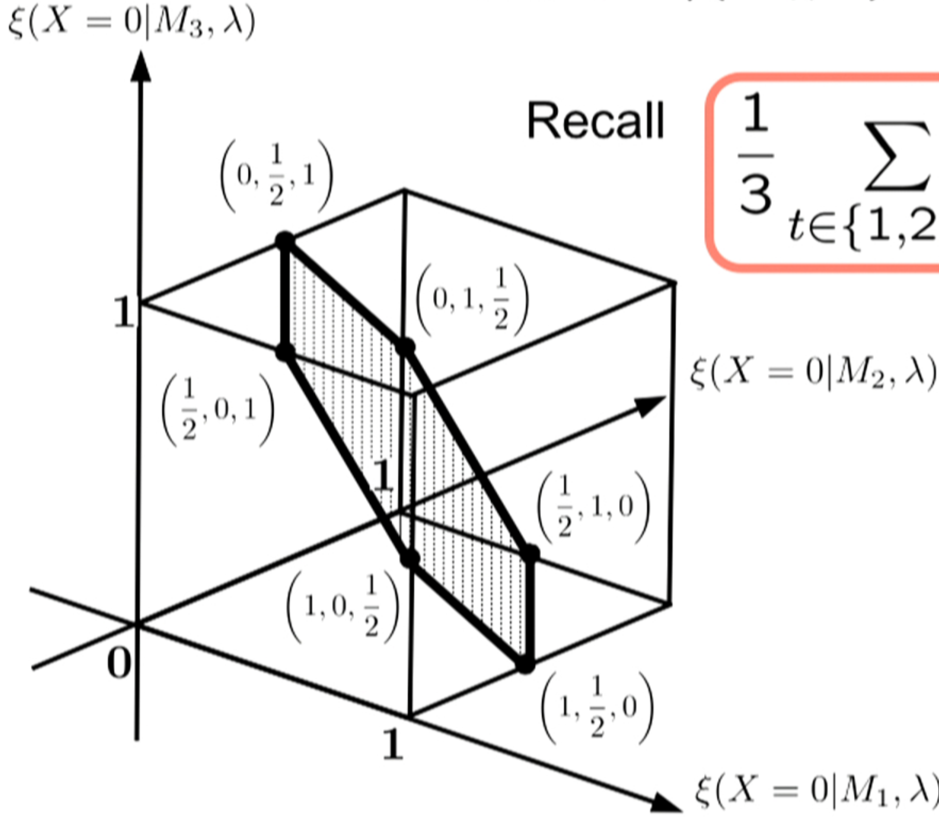
Recall $$\frac{1}{3} \sum_{t \in \{1,2,3\}} \xi(X = b | M_t, \lambda) = \frac{1}{2}$$

$$A \leq \max_{\lambda \in \Lambda} \left(\frac{1}{3} \sum_{t \in \{1,2,3\}} \eta(M_t, \lambda) \right)$$

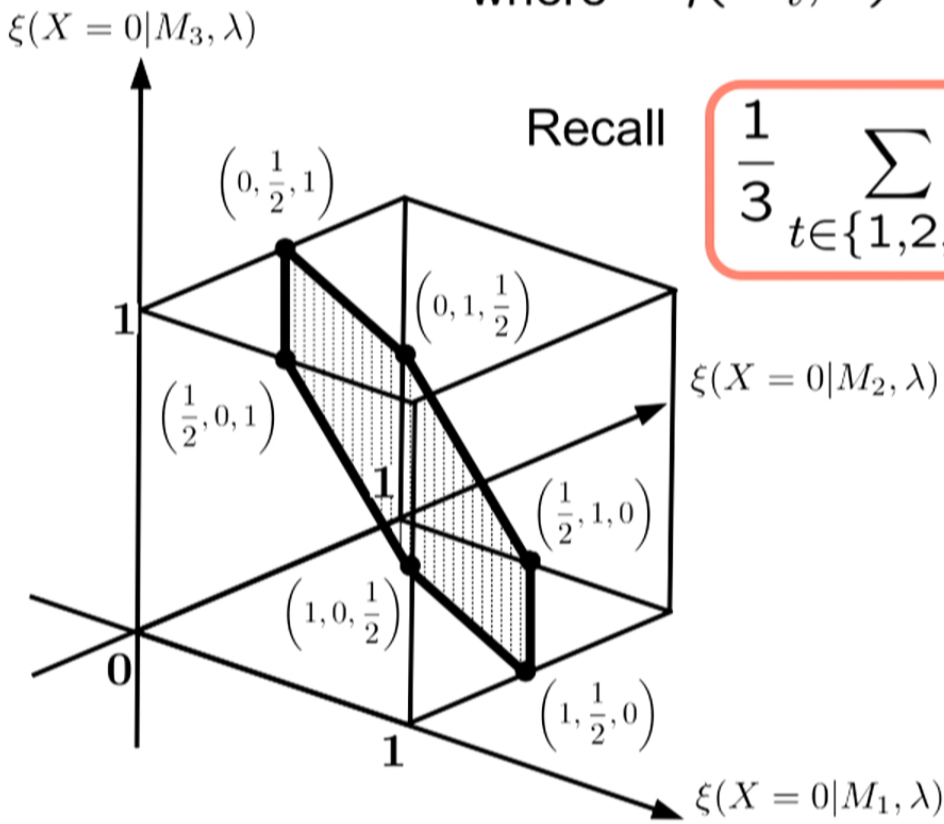
where $\eta(M_t, \lambda) \equiv \max_{b' \in \{0,1\}} \xi(X = b' | M_t, \lambda).$



Recall $$\frac{1}{3} \sum_{t \in \{1,2,3\}} \xi(X = b | M_t, \lambda) = \frac{1}{2}$$

$$A \leq \max_{\lambda \in \Lambda} \left(\frac{1}{3} \sum_{t \in \{1,2,3\}} \eta(M_t, \lambda) \right)$$

where $\eta(M_t, \lambda) \equiv \max_{b' \in \{0,1\}} \xi(X = b' | M_t, \lambda)$.

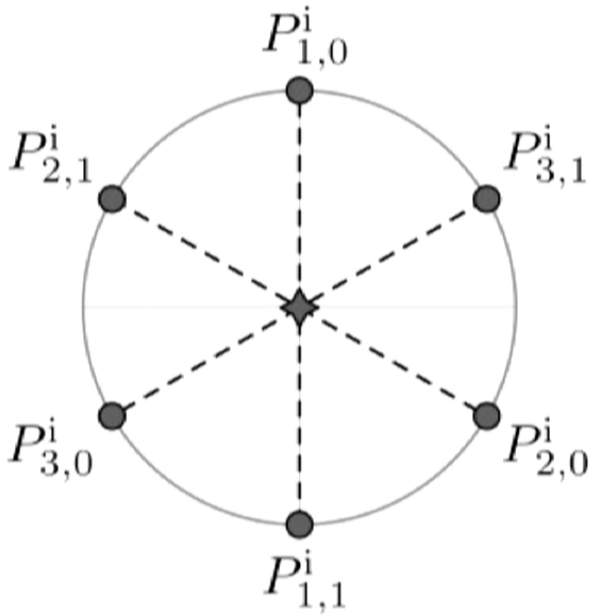


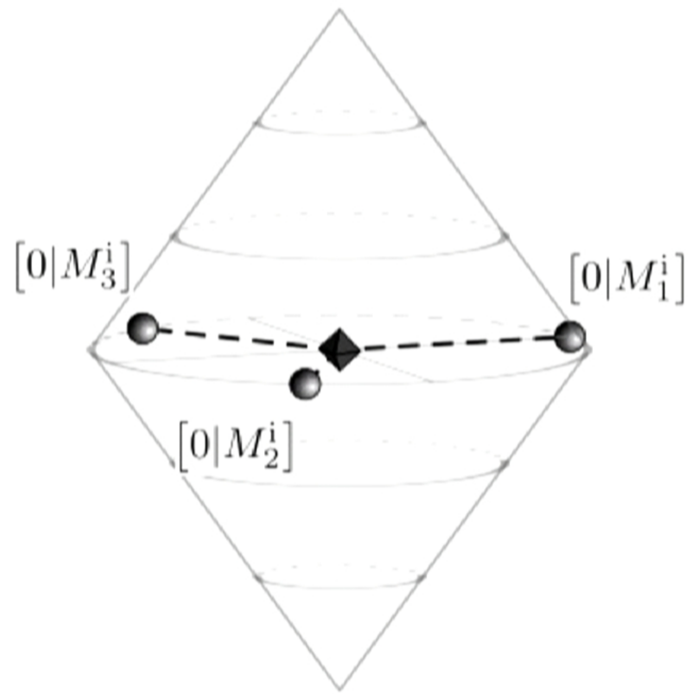
Recall
$$\frac{1}{3} \sum_{t \in \{1,2,3\}} \xi(X = b | M_t, \lambda) = \frac{1}{2}$$

$$A \leq \frac{1}{3}\left(1 + 1 + \frac{1}{2}\right) = \frac{5}{6}$$

Quantum violation

$$A = 1$$





Robust to noise

Obstacle #2: Lack of exact operational equivalence

$$e(\mathsf{P}) = e(\mathsf{P}')$$

$$\forall \mathsf{M} : p(X|\mathsf{P},\mathsf{M}) = p(X|\mathsf{P}',\mathsf{M})$$

Preparation noncontextuality $\longrightarrow$

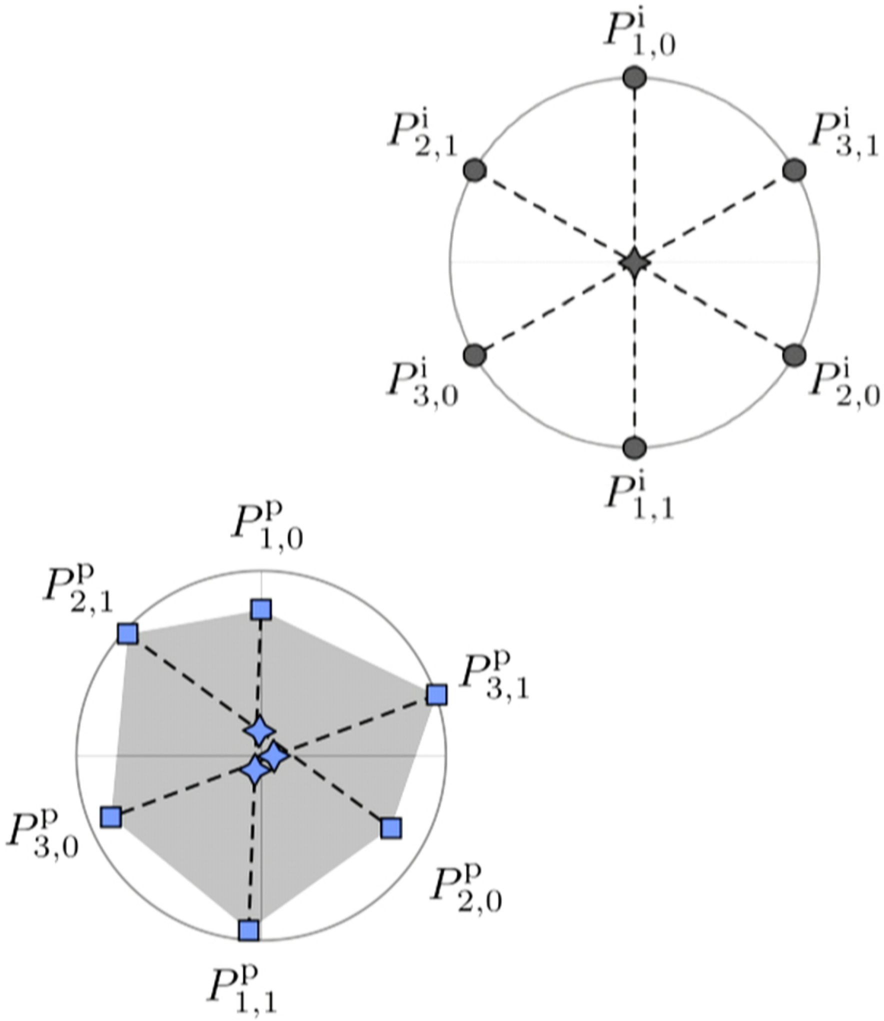
$$\mu(\lambda|\mathsf{P}) = \mu(\lambda|\mathsf{P}')$$

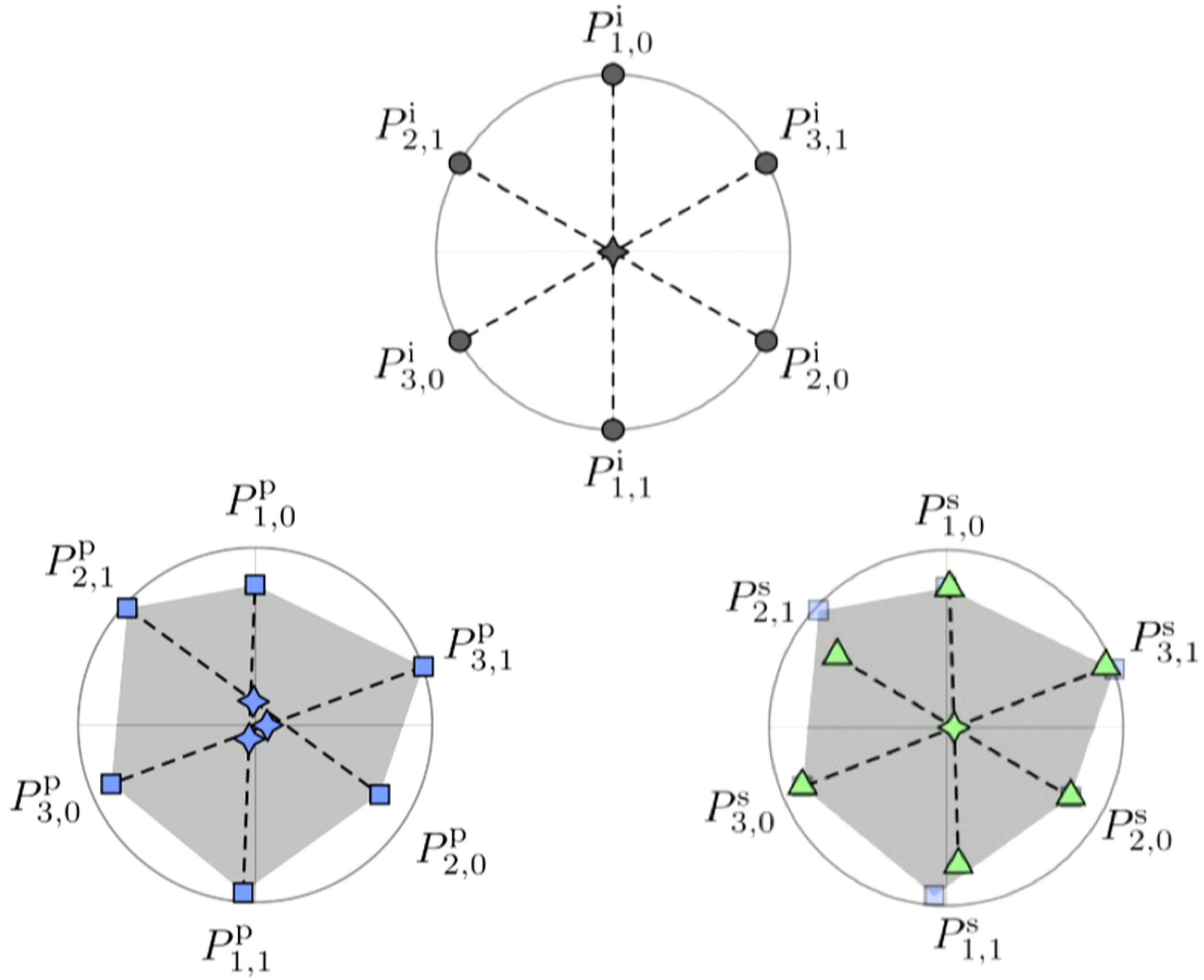
$$e(\mathsf{M}) = e(\mathsf{M}')$$

$$\forall \mathsf{P} : p(X|\mathsf{P},\mathsf{M}) = p(X|\mathsf{P},\mathsf{M}')$$

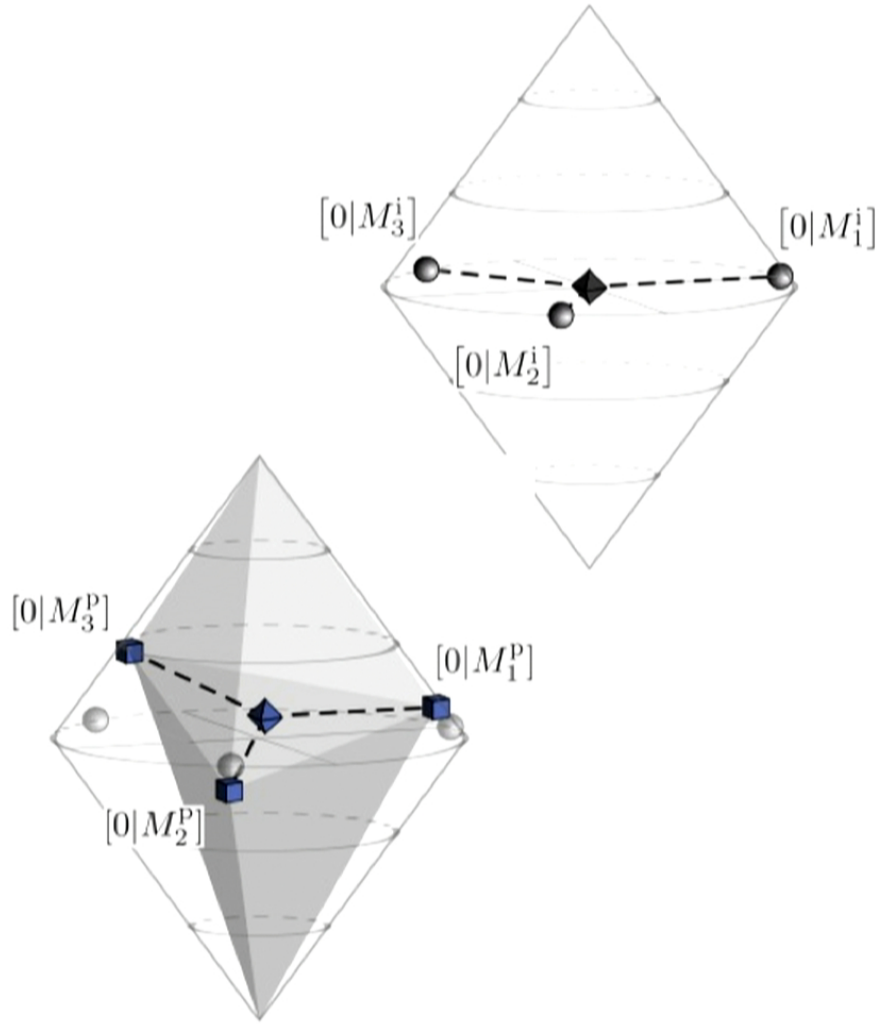
Measurement noncontextuality $\longrightarrow$

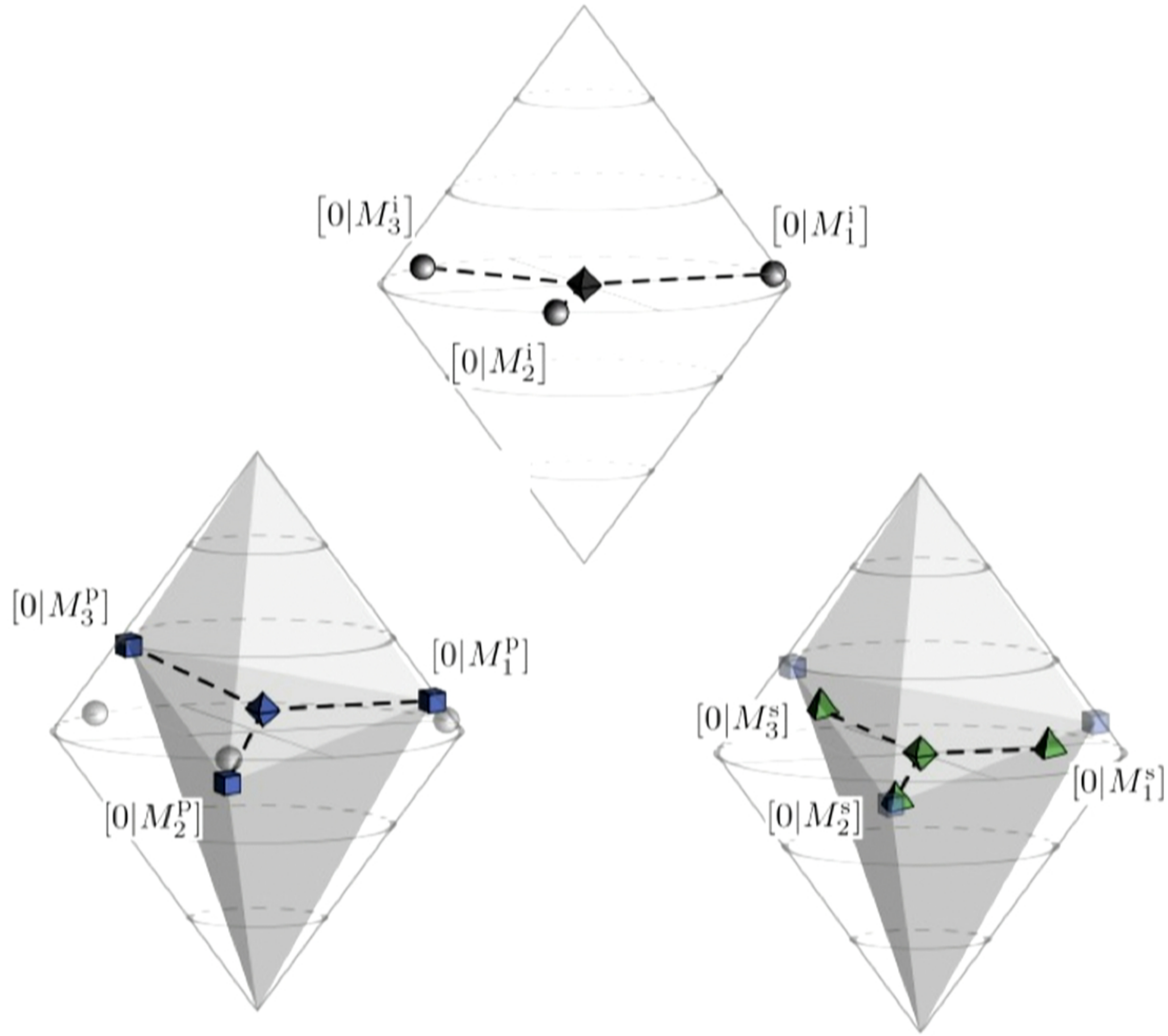
$$\xi(X|\lambda,\mathsf{M}) = \xi(X|\lambda,\mathsf{M}')$$


$P^{\mathrm{i}}_{1,0}$
$P^{\mathrm{i}}_{2,1}$
$P^{\mathrm{i}}_{3,1}$
$P^{\mathrm{i}}_{3,0}$
$P^{\mathrm{i}}_{2,0}$
$P^{\mathrm{i}}_{1,1}$
$P^{\mathrm{p}}_{1,0}$
$P^{\mathrm{p}}_{2,1}$
$P^{\mathrm{p}}_{3,1}$
$P^{\mathrm{p}}_{3,0}$
$P^{\mathrm{p}}_{2,0}$
$P^{\mathrm{p}}_{1,1}$



$P^{\mathrm{i}}_{1,0}$
$P^{\mathrm{i}}_{2,1}$
$P^{\mathrm{i}}_{3,1}$
$P^{\mathrm{i}}_{3,0}$
$P^{\mathrm{i}}_{2,0}$
$P^{\mathrm{i}}_{1,1}$
$P^{\mathrm{p}}_{1,0}$
$P^{\mathrm{p}}_{2,1}$
$P^{\mathrm{p}}_{3,1}$
$P^{\mathrm{p}}_{3,0}$
$P^{\mathrm{p}}_{2,0}$
$P^{\mathrm{p}}_{1,1}$
$P^{\mathrm{s}}_{1,0}$
$P^{\mathrm{s}}_{2,1}$
$P^{\mathrm{s}}_{3,1}$
$P^{\mathrm{s}}_{3,0}$
$P^{\mathrm{s}}_{2,0}$
$P^{\mathrm{s}}_{1,1}$


$[0|M^{\mathrm{i}}_3]$
$[0|M^{\mathrm{i}}_1]$
$[0|M^{\mathrm{i}}_2]$
$[0|M^{\mathrm{p}}_3]$
$[0|M^{\mathrm{p}}_1]$
$[0|M^{\mathrm{p}}_2]$



$[0|M_3^{\mathrm{i}}]$
$[0|M_1^{\mathrm{i}}]$
$[0|M_2^{\mathrm{i}}]$
$[0|M_3^{\mathrm{p}}]$
$[0|M_1^{\mathrm{p}}]$
$[0|M_2^{\mathrm{p}}]$
$[0|M_3^{\mathrm{s}}]$
$[0|M_1^{\mathrm{s}}]$
$[0|M_2^{\mathrm{s}}]$

A remaining issue:
How to verify that a given set of operations is tomographically complete?

$$e(\mathsf{P}) = e(\mathsf{P}')$$
$$\forall \mathsf{M} : p(X|\mathsf{P},\mathsf{M}) = p(X|\mathsf{P}',\mathsf{M})$$

Preparation noncontextuality $\longrightarrow$

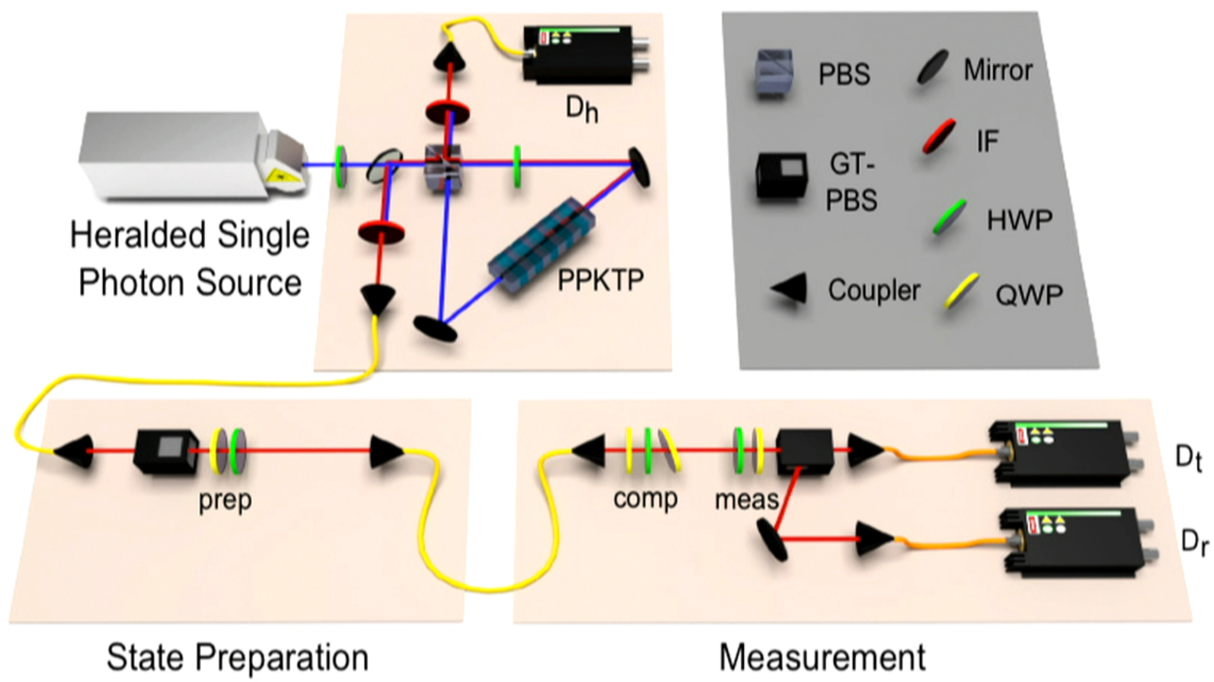
$$\mu(\lambda|\mathsf{P}) = \mu(\lambda|\mathsf{P}')$$

$$e(\mathsf{M}) = e(\mathsf{M}')$$
$$\forall \mathsf{P} : p(X|\mathsf{P},\mathsf{M}) = p(X|\mathsf{P},\mathsf{M}')$$

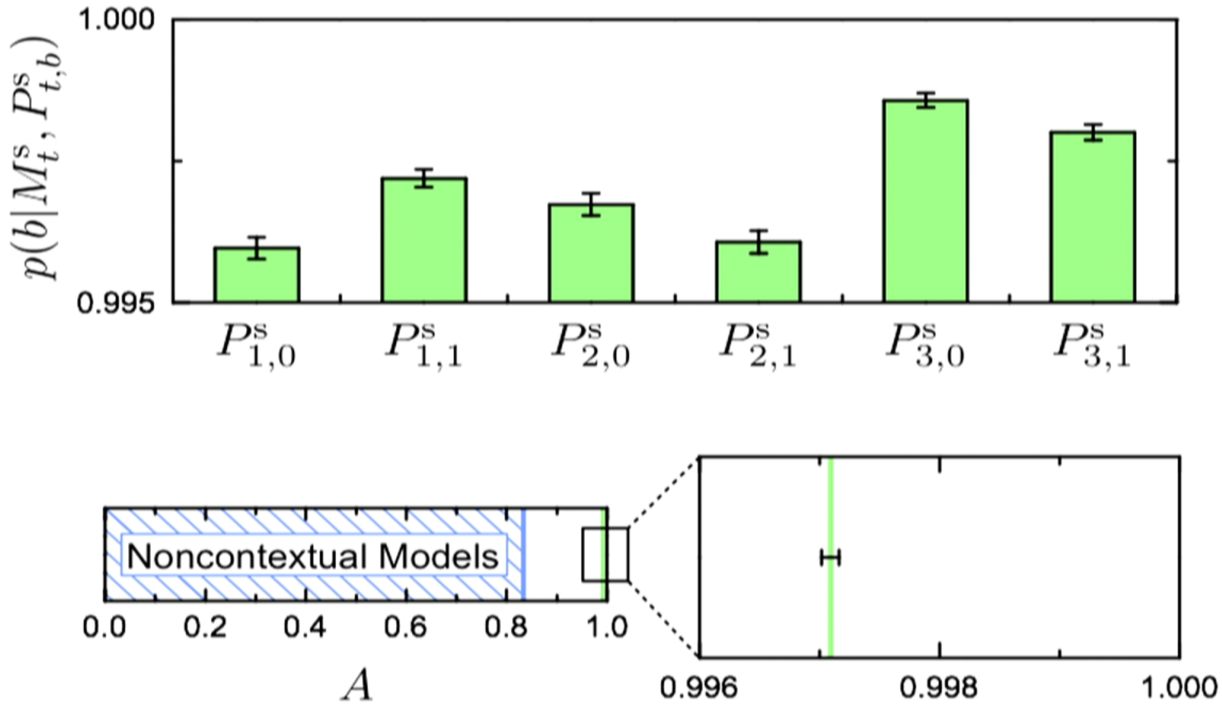
Measurement noncontextuality $\longrightarrow$

$$\xi(X|\lambda,\mathsf{M}) = \xi(X|\lambda,\mathsf{M}')$$

This is the new frontier for experimental tests of noncontextuality



Dh
Heralded Single Photon Source
PPKTP
PBS
Mirror
IF
GT-PBS
HWP
Coupler
QWP
prep
comp
meas
Dt
Dr
State Preparation
Measurement

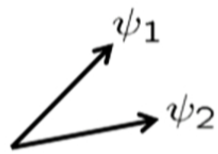


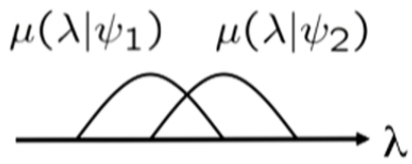
A = 0.99709 $\pm$ 0.00007

violating the noncontextual bound by 2300σ

Significance for characterizing nonclassicality

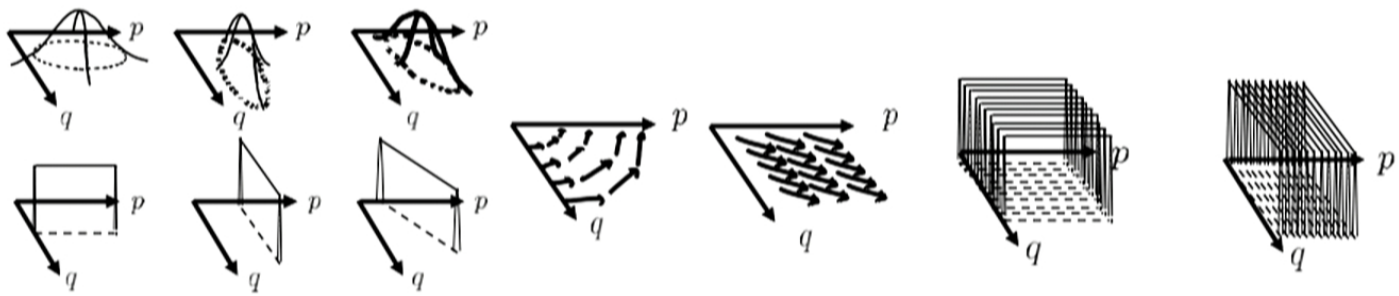
Epistemically restricted classical theories





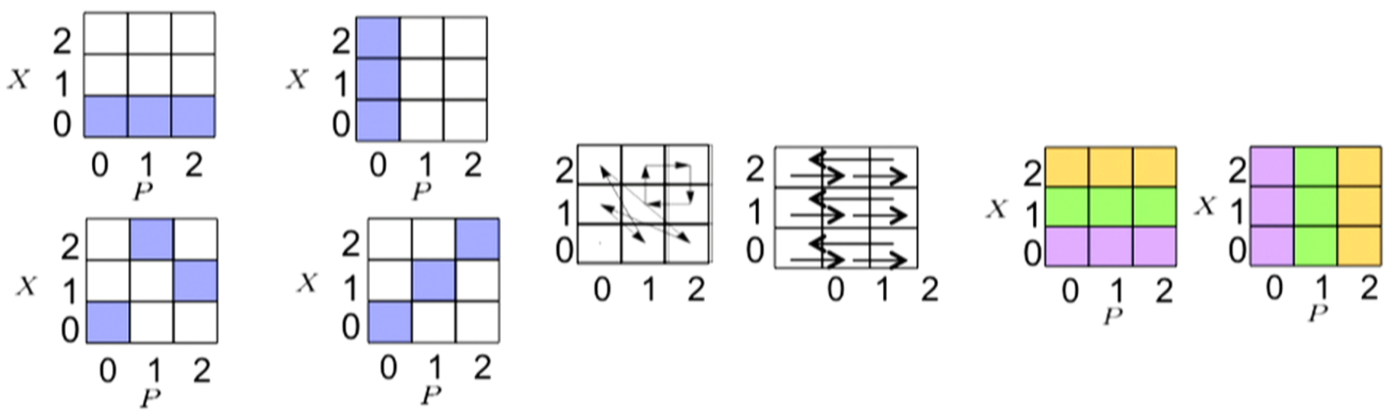
Can recover Gaussian quantum mechanics

Bartlett, Rudolph, RWS, 2011



Can recover the stabilizer theory of qutrits

RWS, arXiv:1409.5041



Categorizing nonclassical phenomena

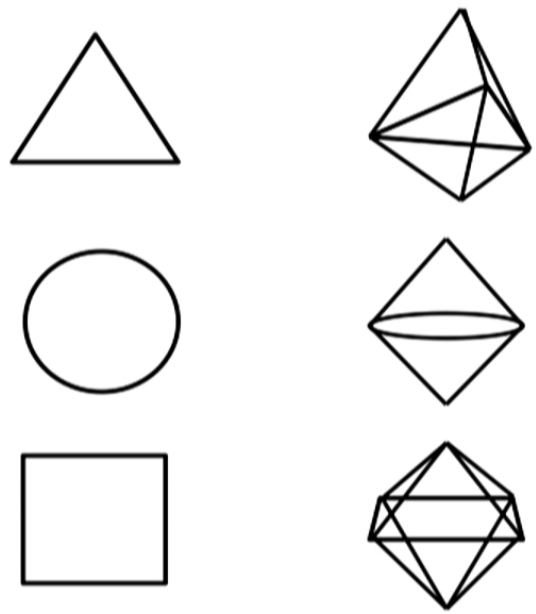
Those arising in epistemically restricted classical theories	Those not arising in epistemically restricted classical theories
Interference	Noncontextuality inequality violations
Noncommutativity	Bell inequality violations
Entanglement	Computational speed-up
Collapse	Certain aspects of items on the left
No perfect state discrimination	
No cloning	
Steering	
Teleportation	
Tunneling	
Improvements in metrology	
Pre and post-selection effects	
Key distribution	
Others…	
Weakly nonclassical	Strongly nonclassical

Operational theories

$$p(X|M,P)$$

Classical

Nonclassical



"Nonsimplicial"

Nonsimplicial but noncontextual

Remote steering
Einstein 1935; Caves-Fuchs-Schack 2000; Harrigan-RWS 2010

Three box paradox
Leifer-RWS 2004

Quantum multiplexing
RWS 2004

No error-free discrimination of nonorthogonal states
RWS 2004

Nonzero probability of wavepacket tunneling through a barrier
Bartlett-Rowe 1999

Failure of noncontextuality

Failure of preparation noncontextuality = BI violation
Bell 1964; Barrett 2006 unpublished; Liang-RWS-Wiseman 2010

Anomalous weak values
Pusey 2015

Probability of success in parity-oblivious multiplexing
RWS-Buzacott-Kheenn-Pryde-Toner 2008

Precise tradeoff of probability of discrimination with nonorthogonality
RWS-Wolfe (work in progress)

Precise dependence of tunneling probability on wavepacket width
RWS (work in progress)

Nonsimplicial but noncontextual	Failure of noncontextuality
Teleportation	???
No cloning	???
Various quantum information processing protocols	???
Interference phenomena Leifer-RWS unpublished	???
Quantum vacuum phenomena	???
Existence of path integral expression for unitary dynamics Koh-Penney-RWS (unpublished)	???
Thermodynamic phenomena	???