Title: A physical picture for quantum contextuality

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Abstract:

A PHYSICAL PICTURE FOR QUANTUM CONTEXTUALITY

Giulio Chiribella
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CIFAR-Azrieli Global Scholars Program

Contextuality: Conceptual Issues, Operational Signatures, and Applications
PI, July 24-28 2017

CIFAR
CANADIAN INSTITUTE FOR ADVANCED RESEARCH

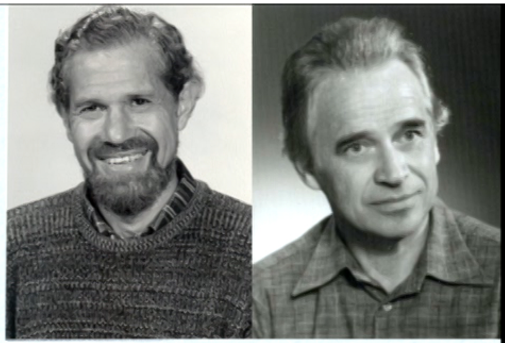
NSFC National Natural Science Foundation of China

FQXi FOUNDATIONAL QUESTIONS INSTITUTE

JTF

千人計劃
RECRUITMENT PROGRAM OF GLOBAL EXPERTS

CONTEXTUALITY



S. Kochen E. Specker

Quantum physics is strikingly different from classical physics.

One of the most fundamental non-classical features is contextuality *(Kochen and Specker, 1967)*

Also a resource for quantum information processing

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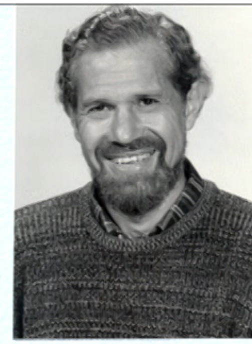
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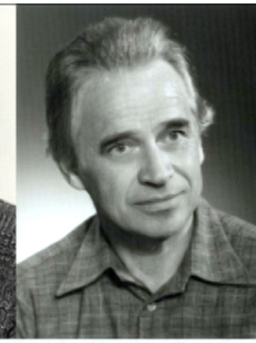
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Also a resource for quantum information processing

→ important to understand how contextuality works

A PHYSICAL PICTURE?

Quantum contextuality raises two fundamental questions:

1) Why is Nature contextual?
2) Why is Nature contextual *in the particular way* dictated by quantum theory?

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Quantum contextuality raises two fundamental questions:

1) Why is Nature contextual?
2) Why is Nature contextual *in the particular way* dictated by quantum theory?

Both questions cannot be addressed *within* quantum theory.

They require

- a framework, describing possible alternatives to QT
- a set of physical principles, determining the "amount of contextuality" seen in Nature

STATE OF THE ART

Framework: general probabilistic theories (GPTs)

Principles: QT *can* be derived from various sets of principles

e.g.

-Hardy 2001, Brukner-Dakic 2009, Masanes-Müller 2010

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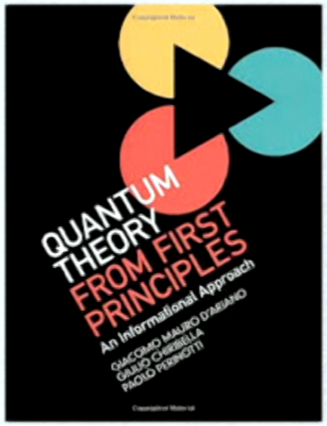

What is missing?

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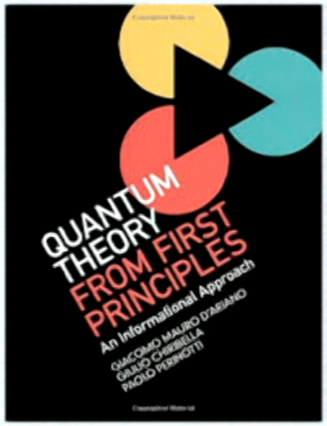

What is missing?

A **direct** and **compelling** explanation of contextuality

THIS TALK

In this talk, I will give:

1) **a definition** of contextuality in GPTs

2) **a principle** that bounds contextuality in every GPT

3) **a physical picture** about the origin of quantum contextuality

KEY IDEA:
THE "PURIFICATION PHILOSOPHY"

Non-ideal feature
observed in the lab

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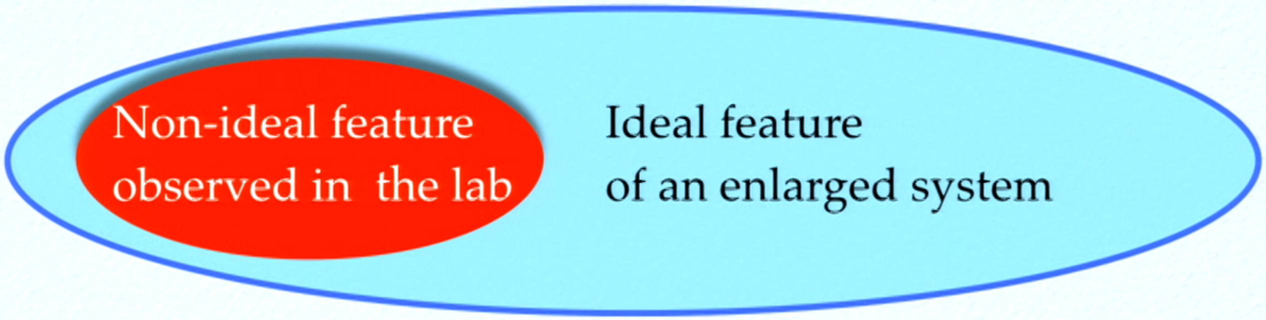

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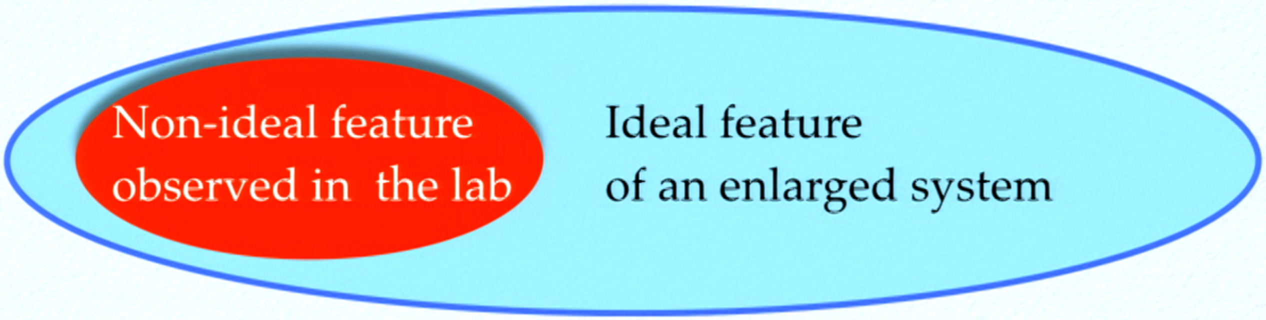

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States	Mixed	Pure
Evolutions	Irreversible	Reversible
Measurements	Unsharp	Sharp

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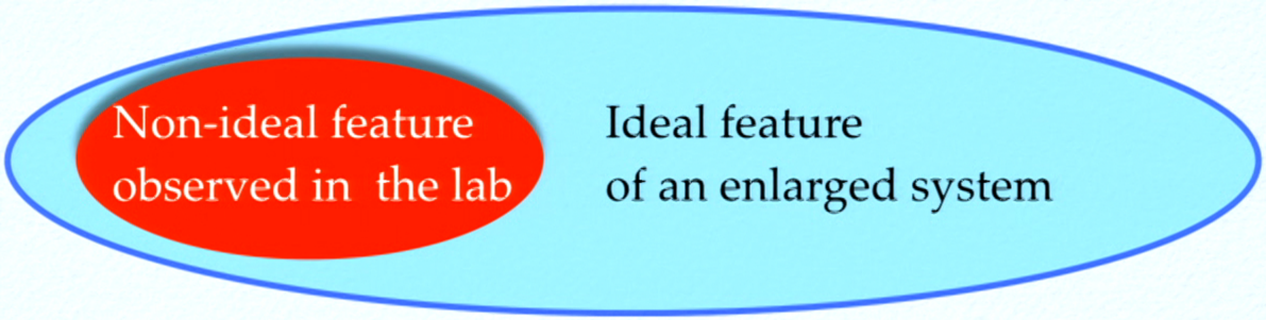

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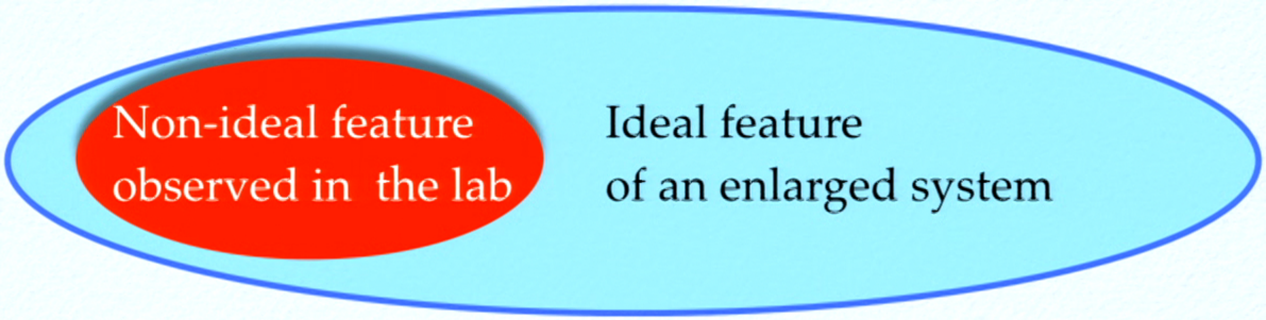

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States, Evolutions: Chiribella, D'Ariano, Perinotti, PRA 2010, PRA 2011

Measurements: Chiribella-Yuan 1404.3348

A PICTURE FOR CONTEXTUALITY

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"Purification brings [contextuality] in,
Sharpness cuts it down"
from Chiribella-Yuan, 1404.3348

HEURISTICS

Purification

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Purification ⟶ pure entangled states

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PRELIMINARIES

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PRELIMINARIES

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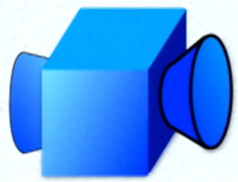
Question x →  → Answer y

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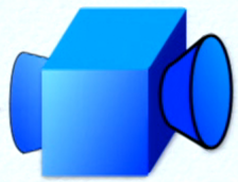
Question x →  → Answer y

Probability distribution p(y | x) *"Nature's response strategy"*

KS contextuality: Nature's response strategy p(y | x)
is incompatible with the existence of
"predetermined answers"

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Question x = set
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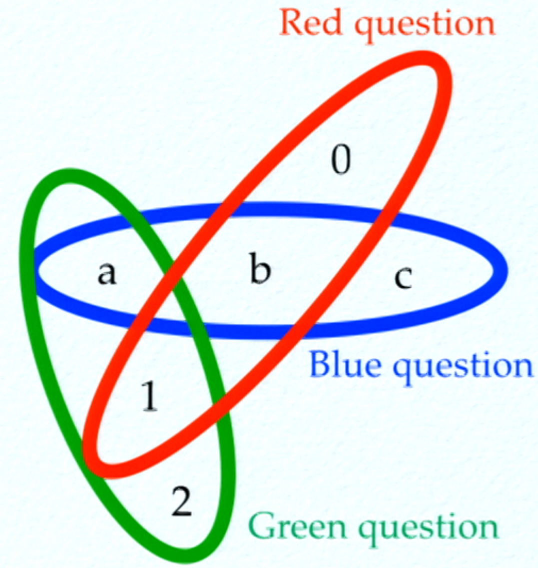

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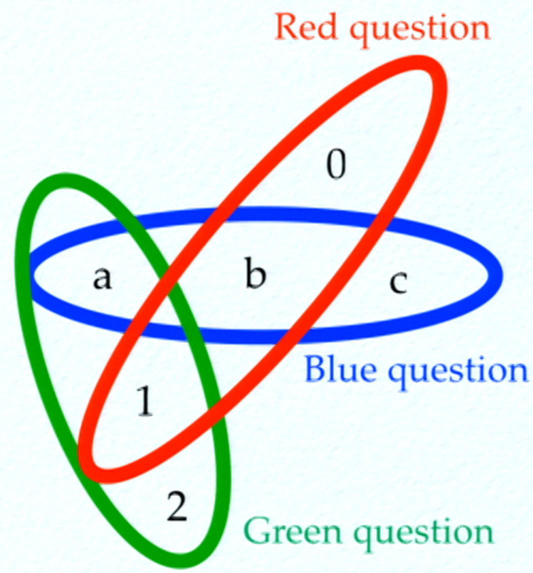

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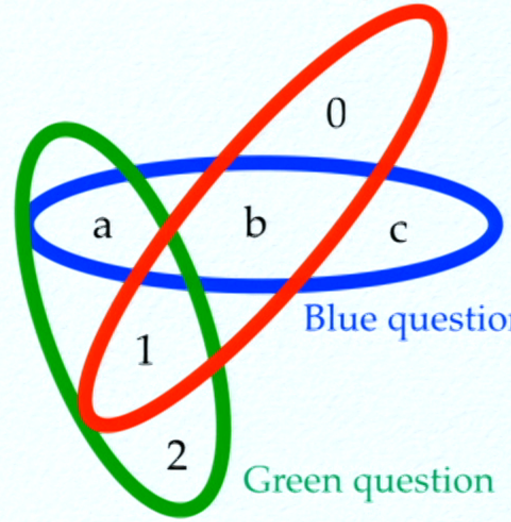

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Definition:
response is compatible with predetermined answers if

$$p(y|x) = \sum_{\lambda} p(\lambda)\, \delta_{y, f(x,\lambda)}$$

$$f(x, \lambda) \in x' \Longrightarrow f(x', \lambda) = f(x, \lambda)$$

QUANTIFYING CONTEXTUALITY

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$$\omega = \sum_{x,y} \omega(x,y)\, p(y|x)\, p(x)$$

Given a set of allowed strategies p(y | x)
the amount of contextuality of that set is quantified by
the maximum of the payoff over p(y | x)

THREE IMPORTANT VALUES

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ω_{Q} = maximum payoff if p(y | x) is of the form

$$p(y|x) = \left[P_y^{(x)} \rho \right]$$

ρ density matrix (of arbitrary dimension)

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Key observation: $\omega_{\mathrm{C}} \leq \omega_{\mathrm{Q}} \leq \omega_{\mathrm{G}}$

Problem: find physical principles that determine ω_{Q}

THE
BIG
CAVEAT

PROJECTIVE, *PROJECTIVE*, ***PROJECTIVE!***

The restriction to **projective measurements** is **essential** for the definition of ω_{Q}

Ana Belen Sainz, PhD thesis, 2013

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→ **it is the restriction to projective measurements that makes the problem non-trivial!**

Ana Belen Sainz, PhD thesis, 2013

THREE
RELATED
ISSUES

ISSUE 1: WHY SHOULD WE CARE ABOUT PROJECTIVE MEASUREMENTS?

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projectors represented *propositions*
and what was at stake was
the possibility to assign *truth-values* to those propositions.

But what about *us*?
Is there any *operational* reason to care
about projective measurements?

ISSUE 2: WHAT *IS* A PROJECTIVE MEASUREMENT OUTSIDE QUANTUM THEORY?

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"some special type of measurements",
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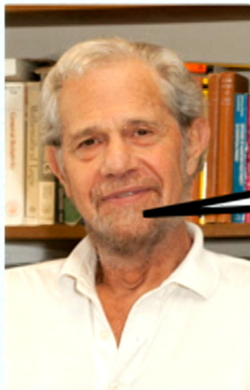
But *what type*?
What is the definition of
"projective measurement" in GPTs?

ISSUE 3: WHAT COUNTS AS A COMPELLING PHYSICAL PRINCIPLE?

A fundamental principle for KS contextuality is the Exclusivity principle (E-principle):

"if every two events in a set are mutually exclusive, then all events in the set are mutually exclusive"
(Specker 1960, "Orthocoherence", Cabello 2012, Henson 2012)



Ernst and I spent many hours discussing the principle.
[...]
The difficulty lays in trying to justify it
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without already assuming the Hilbert space formalism
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[...]. I have never found a general physical justification
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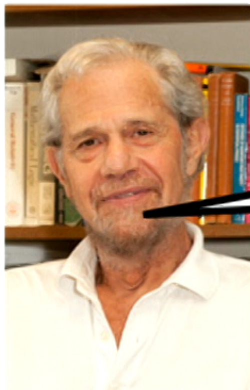

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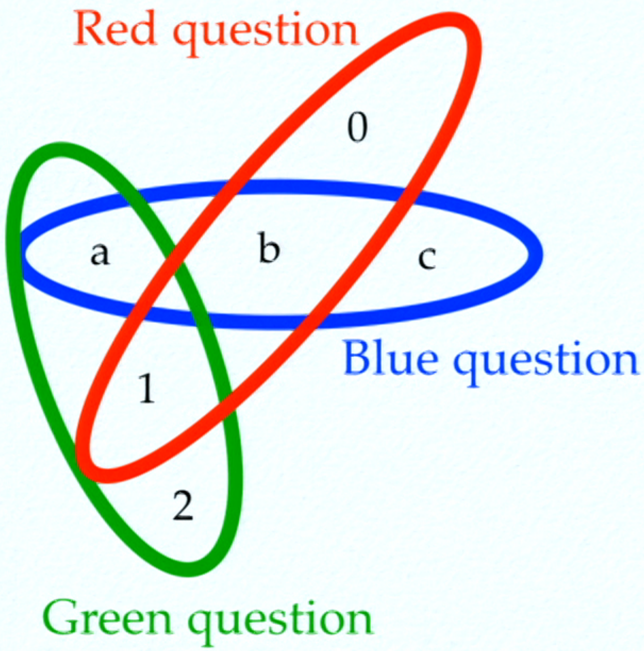
in A. Cabello,
arXiv:1212.1756

WHY SHOULD *THIS* BE A FUNDAMENTAL LAW OF NATURE?



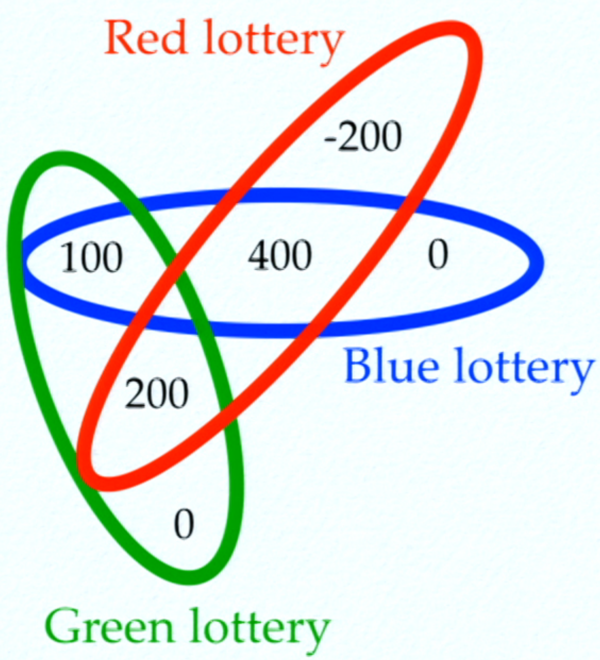
The pairs
{a,b} , {a,1} , and {b,1}
are mutually exclusive

The exclusivity principle demands

$p(a) + p(b) + p(1) \leq 1$

EXAMPLE, C'TD

Three lotteries, you can buy a ticket for one of them.



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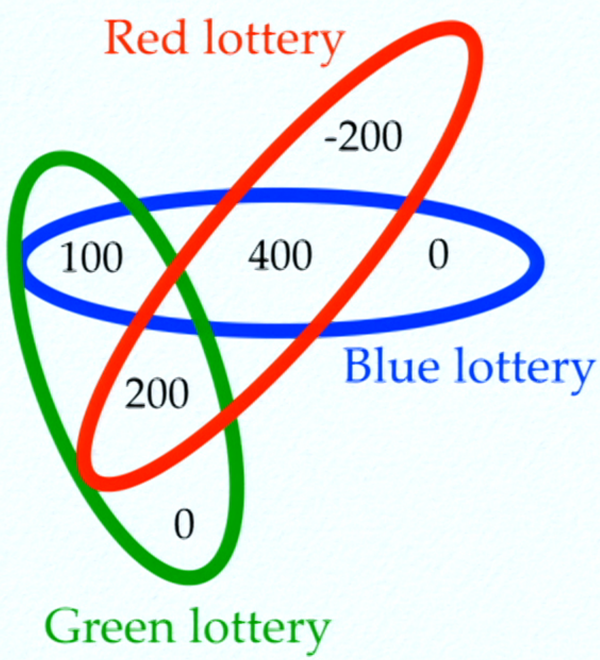

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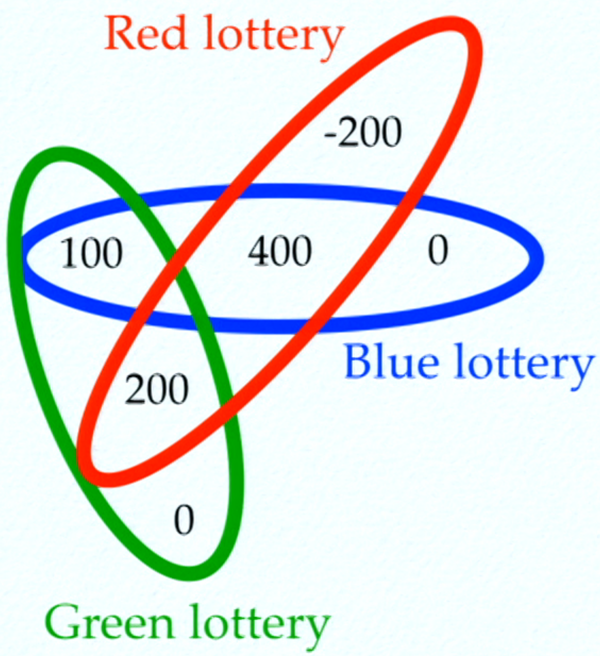

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To find a justification,
we need to remember that, in QT,
the E-principle is a property of **projective measurements.**

To justify the E-principle in general physical theories,
we must study **projective measurements in GPTs.**

DEFINITION OF PROJECTIVE MEASUREMENTS IN GPTS

Chiribella-Yuan, 1404.3348

INGREDIENT 1: REPEATABILITY

MEASUREMENTS IN GPTS

- **Demolition measurement** $\{m_i\}_{i \in \mathsf{X}}$

graphical representation: 

MEASUREMENTS IN GPTS

- **Demolition measurement** $\{m_i\}_{i \in \mathsf{X}}$

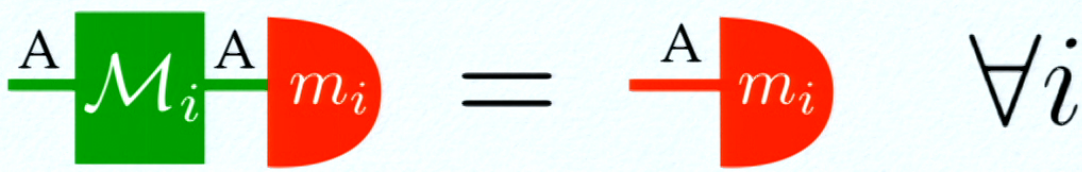
  graphical representation:

- **Non-demolition measurement** $\{\mathcal{M}_i\}_{i \in \mathsf{X}}$

  graphical representation:

REPEATABLE MEASUREMENTS

Measurement $\{m_i\}_{i\in\mathsf{X}}$ is repeatable if exists $\{\mathcal{M}_i\}_{i\in\mathsf{X}}$ such that



In short: same result when the measurement is performed multiple times.

INGREDIENT 2:
MINIMAL DISTURBANCE

NON-DISTURBANCE CONDITION

$\{m_i\}_{i \in \mathsf{X}}$ does not disturb $\{n_j\}_{j \in \mathsf{Y}}$ if exists $\{\mathcal{M}_i\}_{i \in \mathsf{X}}$

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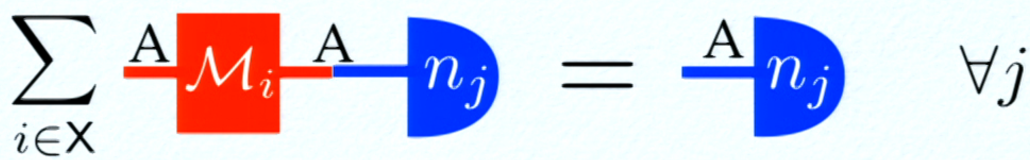

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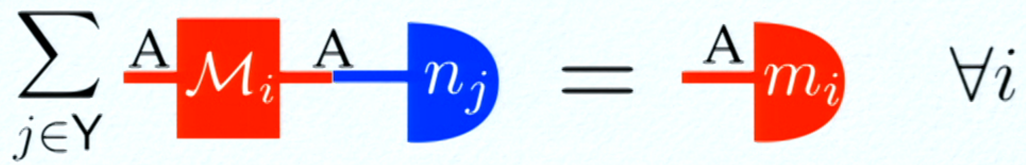

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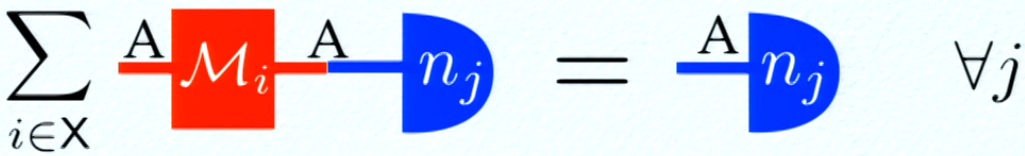

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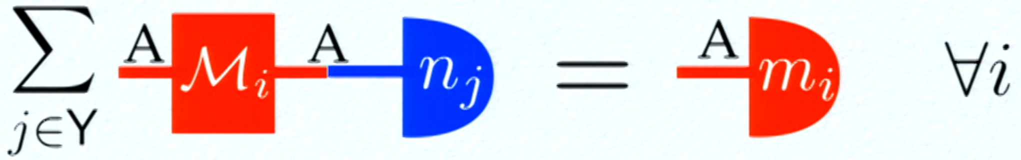

If a measurement does not disturb another measurement, then the two are *compatible* (i.e. *jointly measurable*)

MINIMALLY-DISTURBING MEASUREMENTS

A measurement is **minimally-disturbing**
if it **disturbs the smallest possible set of measurements,**
i.e.
the set of measurements with which it is incompatible.

In short: doing the measurement now does not
preclude the possibility
to extract the refined information later.

SHARP MEASUREMENTS

A measurement is sharp if it can be realized by a test that is repeatable and minimally disturbing.

(in quantum theory: sharp = projective)

DEFINING KS CONTEXTUALITY IN GPTS

A DEFINITION OF KS CONTEXTUALITY IN GPTS

Given a contextuality game,
define ω_{T}
as the maximum payoff achievable with strategies
of the form

$$p(y|x) =$$

where $\left\{ m_y^{(x)} \right\}_{y \in x}$ is a **sharp measurement**

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The theory T is **contextual** if $\omega_{\mathrm{T}} > \omega_{\mathrm{C}}$
for some contextuality game.

OTHER DEFINITIONS OF SHARP MEASUREMENTS

Other definitions of sharp measurement have been proposed in the literature:

- Measurements consisting of extremal effects (Holevo 1985, Cabello-Severini-Winter 2010)

- Measurements that distinguish maximal sets of distinguishable pure states (Hardy 2001)

- Coarse-graining of pure orthogonal measurements (Barnum-Masanes-Ududec 2015, Chiribella Yuan 2016)

A PHYSICAL REASON FOR THE EXCLUSIVITY PRINCIPLE

LESS INFORMATION, MORE SHARPNESS

> Axiom LIMS:
> Coarse-graining a sharp measurement yields another sharp measurement.

Let us put ourselves in the standard situation
where the physical theory is **causal***

meaning that the probabilities of outcomes at time t do not depend on the settings at time t'>t

**Chiribella-D'Ariano-Perinotti, PRA 2010.*

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LESS INFORMATION, MORE SHARPNESS

Axiom LIMS:
Coarse-graining a sharp measurement yields another sharp measurement.

Example:

$$\{m_1, m_2, m_3\} \text{ sharp} \quad \Longrightarrow \{m_1, m_2 + m_3\} \text{ sharp}$$

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In fact, LIMS could be even included in the *definition* of sharp measurement.

DERIVING THE E-PRINCIPLE

Theorem (Chiribella-Yuan 2014):
Every theory satisfying LIMS satisfies the E-principle.

THE E-PRINCIPLE HIERARCHY

The E-principle can be lifted to a hierarchy of more and more restrictive conditions

Define $\mathbf{x} := (x_1, x_2, \ldots, x_L)$

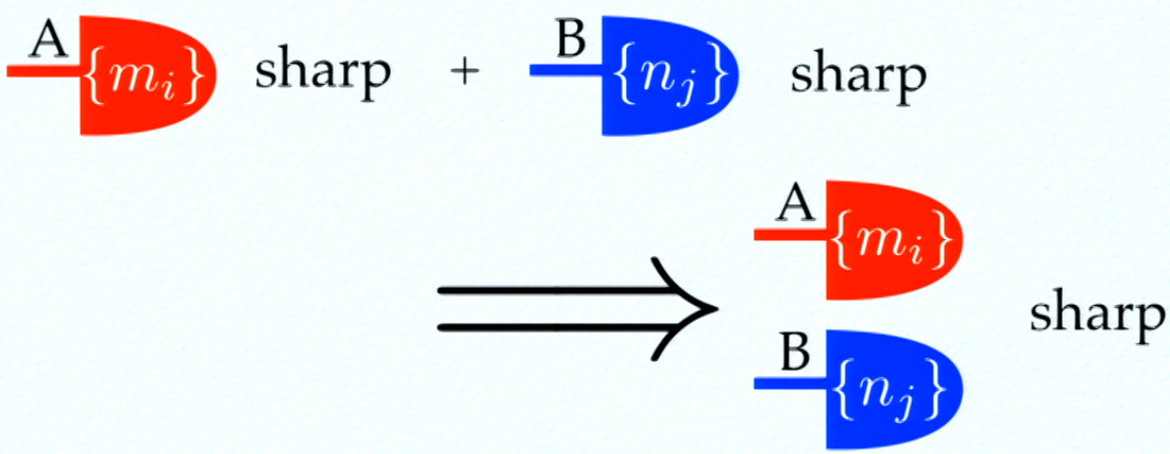
$$\mathbf{y} := (y_1, y_2, \ldots, y_L)$$

$$p_L(\mathbf{y}|\mathbf{x}) := p(y_1|x_1)\, p(y_2|x_2) \;\ldots\; p(y_L|x_L)$$

The L-th level of the hierarchy is defined by applying the E-principle to $p_L(\mathbf{y}|\mathbf{x})$
(with a suitable definition of exclusive events)

LOCALITY OF SHARP MEASUREMENTS

Axiom LSM
Two sharp measurements performed in parallel are a sharp measurement for the composite system



DERIVING THE E-PRINCIPLE HIERARCHY

Theorem (Chiribella-Yuan 2014):
Every theory satisfying LIMS and LSM satisfies all levels of the E-principle hierarchy.

DERIVING THE E-PRINCIPLE HIERARCHY

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The first levels of the hierarchy already determine famous quantum bounds like Klyachko's inequality (Cabello-Severini-Winter 2014) or the Tsirelson bound (Cabello 2015)

FROM
SHARP
MEASUREMENTS
TO
ARBITRARY MEASUREMENTS

LOCAL ORTHOGONALITY

Local Orthogonality (LO) is a multipartite principle introduced in the study of non-locality (Fritz *et al*, 2013).

LO is similar to the E-principle,
except that it applies to ***all measurements***
not only to sharp measurements.

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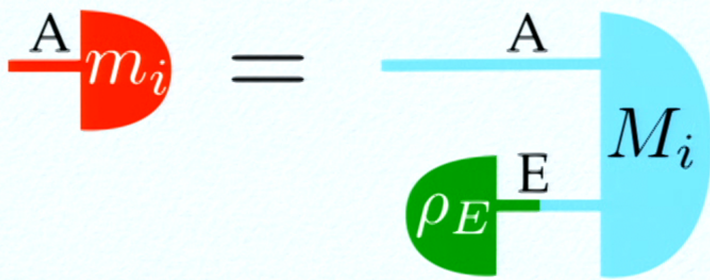
Still, also LO can also be reduced to the properties of sharp measurements.

FUNDAMENTAL SHARPNESS

Axiom FS:
Every unsharp measurement arises from a sharp measurement performed jointly on the system and an environment



$$\forall i \in \mathsf{X}$$

$$\{M_i\}_{i \in \mathsf{X}} \text{ sharp}$$

DERIVING LOCAL ORTHOGONALITY

Theorem (Chiribella Yuan 2014):
Every theory satisfying LIMS, LSM, and FS satisfies Local Orthogonality (at all levels of their hierarchy)

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BACK
TO
THE
"PURIFICATION PHILOSOPHY"

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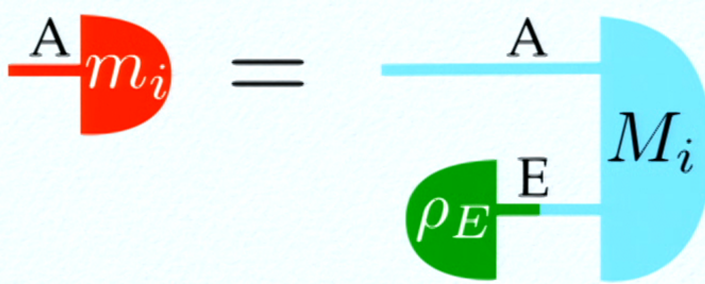

$$\forall i \in \mathsf{X}$$

$$\{M_i\}_{i \in \mathsf{X}} \text{ sharp}$$

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BACK
TO
THE
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THE MOST IDEAL MEASUREMENT

Suppose that there exists a sharp measurement
that is also *purity-preserving*
i.e.
a measurement that sends pure states to pure states
when performed locally on a composite system.

Then…

Input: DVI - 1920x1080p@60Hz
Output: SDI - 1920x1080i@60Hz

Theorem (Chiribella 2017):

Every theory satisfying
Purification and One Ideal Measurement satisfies

- Fundamental Sharpness
- Locality of Sharp Measurements
- Less information, More Sharpness
- All alternative definitions of sharp measurements coincide

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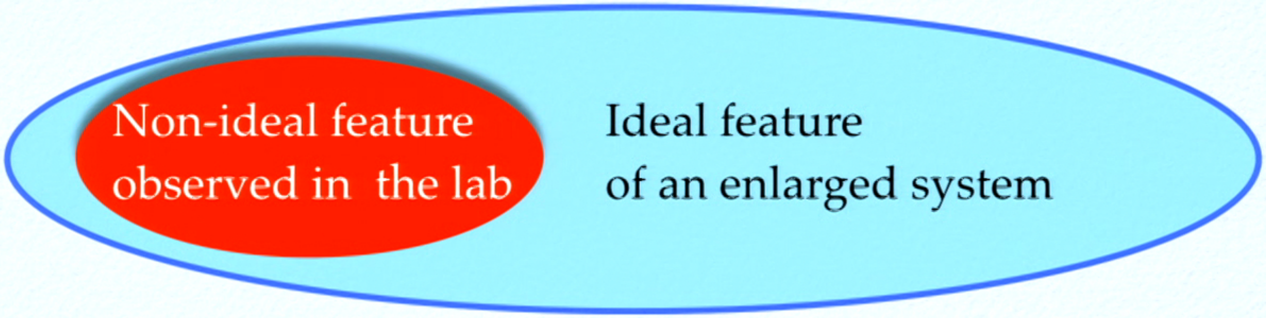
(Informed) Conjecture:
Purification and One Ideal Measurement determine exactly the quantum boundary of contextuality and non-locality.

A PICTURE FOR CONTEXTUALITY



Purification brings contextuality (and non-locality) in,
Sharpness cuts it down

TAKE-HOME MESSAGES

1) To talk about KS contextuality in GPTs
one has to define sharp measurements first

2) The E-principle and Local Orthogonality
arise from the properties of sharp measurements

3) Conjecture: Purification and One Ideal Measurement
define the quantum set.

Framework + one alternative derivation of the E-principle:
Chiribella and Yuan,
Bridging the gap between general probabilistic theories and the device-independent framework for nonlocality and contextuality,
Information and Computation, **250**, 15-49 (2016)

Sharp measurements in GPTs:
Chiribella and Yuan,
Measurement sharpness cuts nonlocality and contextuality in every physical theory,
arXiv:1404.3348