Title: Communication Genuine Multipartite Nonlocality as a benchmark for large nonclassicality

Speakers: Marc-Olivier Renou

Collection: Causal Inference & Quantum Foundations Workshop

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Abstract: "Quantum computing requires the ability to manipulate large nonclassical quantum systems. As we are far from any useful quantum computing advantage, certifying this ability is an important benchmark to assess progress toward this goal. This can be done using the nonlocal nature of quantum correlations, which allows to certify a non-trusted experimental apparatus from its input/output behaviour in a device independent way. It first requires to introduce the concept of Genuine Multipartite Nonlocality (GMNL) of size n, which designate systems which nonlocality cannot be understood an obtained from many states composed of n - 1 (or less) constituents.

The first historical definition of GMNL, proposed by Svetlichny, is ill-defined when used to assess the large nonclassical nature of quantum systems, as it predicts that maximal GMNL states can be obtain from bipartite sources only. A more appropriate re-definition of that concept, called LOSR-GMNL, was proposed recently [arXiv:2105.09381]. However, it is not satisfactory in all experimental situations, as it cannot (by design) capture potential communications between the systems which could occur in some realistic experimental systems (e.g., many-body systems) - which Svetlichny definition captures in a naïve way.

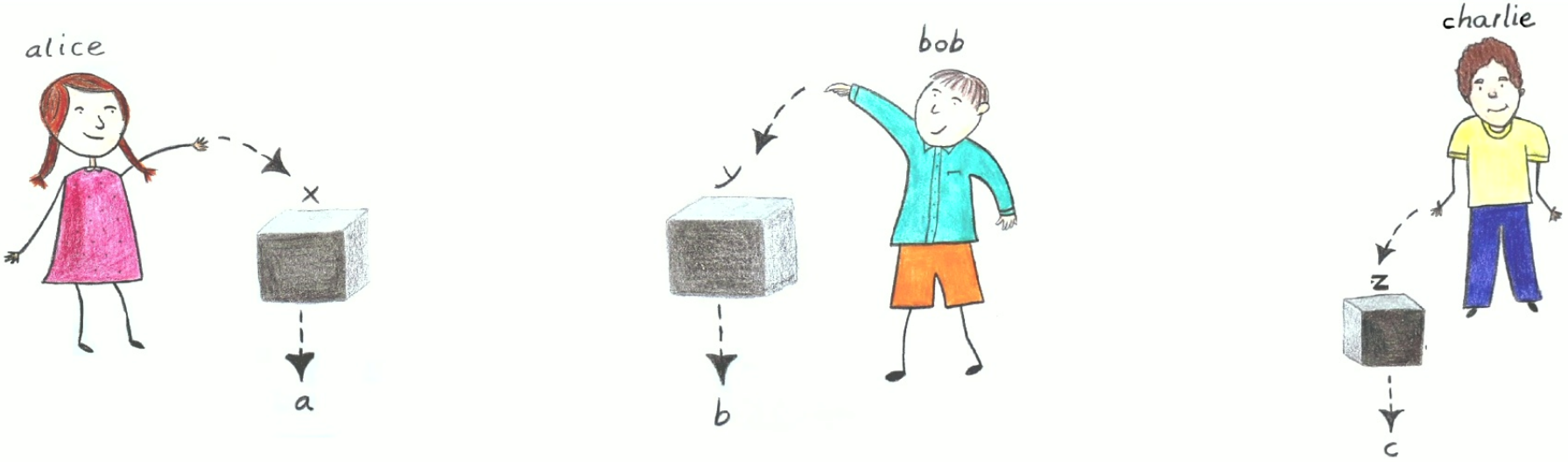
In this talk, I will propose a new alternative re-definition solving this issue, called Communication-Genuine Multipartite Nonlocality of length t (C-GMNL). It is based on a model inspired from synchronous distributed computing, that involves t communications steps along a graph.

I will show that (i) the GHZ state is maximally nonlocal according to this C-GMNL definition, (ii) the cluster state is trivial in this C-GMNL definition but that (iii) the cluster state is maximally difficult in the LOSR-GMNL definition. Hence, some complicated LOSR-GMNL states become trivial when a small amount of communication is allowed.

Based on a joint work in preparation with Xavier Coiteux-Roy, Owidiusz Makuta, Fionnuala Curran, Remigiusz Augusiak."

Communication Genuine Multipartite Nonlocality

A benchmark for large nonclassicality



ÉCOLE POLYTECHNIQUE

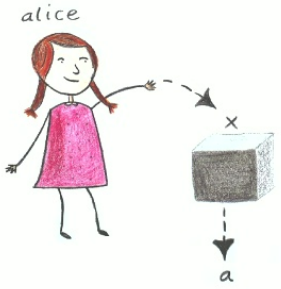
Inria

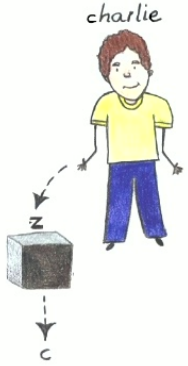
Perimeter Institute
Causal Inference Workshop

Xavier Coiteux-Roy, Owidiusz Makuta, Fionnuala Curran,
Remigiusz Augusiak, Marc-Olivier Renou
In preparation

Marc-Olivier Renou
Junior Professor Chair INRIA Paris Saclay
Computer Science Laboratory / Center for Theoretical Physics
Ecole Polytechnique

Nature Correlations are Genuinely Multipartite Nonlocal



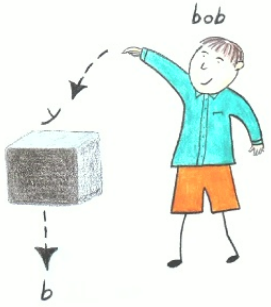


I. **Quantum theory: 'Nice states', but also 'very nice states'?**

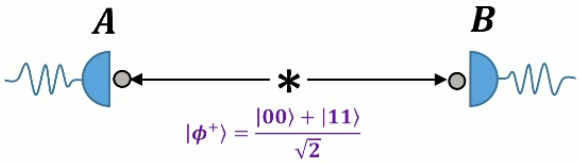
II. 'Very nice states': existing definitions

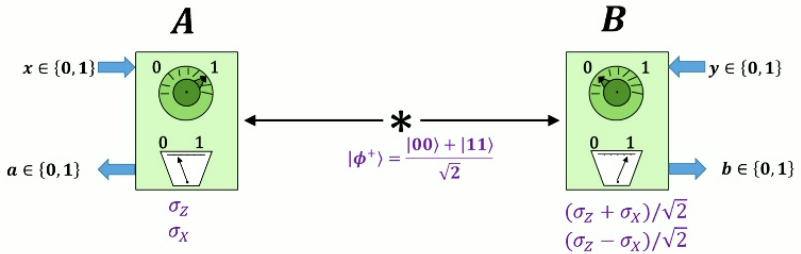
III. A new concept: 'Communication-very nice state'

IV. Some results



Nonclassicality ≡ Entanglement / Nonlocality





Quantum Theory is nonlocal, with entanglement

- ∃ bipartite quantum systems with 'no classical physics' interpretation, e.g. $|\phi^+\rangle_{AB}$
- Formalisation (mathematical definition):
  - Device Dependent property: entanglement

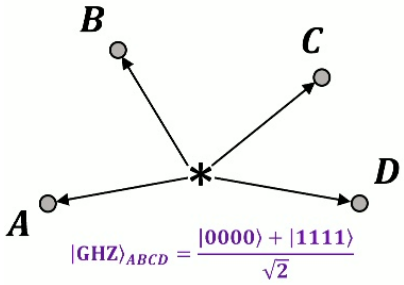
$$\rho_{AB} \neq \sum_{\lambda} \sigma_A^{\lambda} \otimes \sigma_B^{\lambda}$$

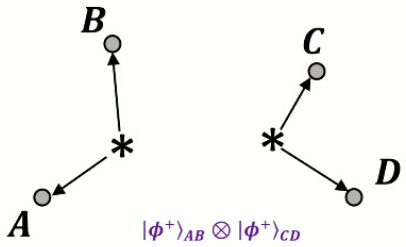
  - Device Independent property: nonlocality

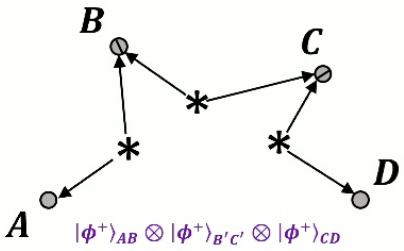
$$\rho_{AB} \rightarrow P(ab|xy) \neq \int d\lambda P(a|x\lambda) P(b|y\lambda)$$

- ρ_{AB} is entangled / nonlocal ≡ it is a 'nice state'
  - Resource for randomness, cryptography, …

Large nonclassicality







Beyond nonlocality/entanglement

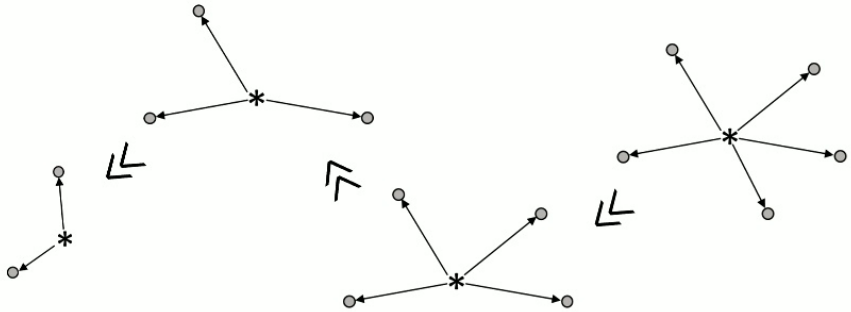
- Intuitively, $|\phi^+\rangle_{AB}$ does not contain "all QT nonclassicality":

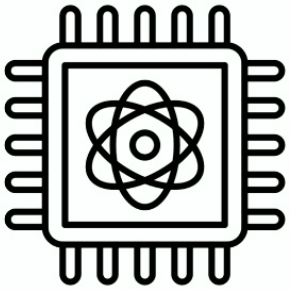
$$|\mathrm{GHZ}\rangle_{ABCD} \gg |\phi^+\rangle_{AB} \otimes |\phi^+\rangle_{CD}$$

$$|\mathrm{GHZ}\rangle_{ABCD} \gg |\phi^+\rangle_{AB} \otimes |\phi^+\rangle_{B'C} \otimes |\phi^+\rangle_{C'D}$$

- Definition?
  - When is ρ_{ABCD} a 'very nice state'?
    - Device Dependent 4-Genuine Multipartite Entangled (4-GME)
    - Device Independent 4-Genuine Multipartite Nonlocal (4-GMNL)

Why considering ‘large nonclassicality’?





Fundamental physics

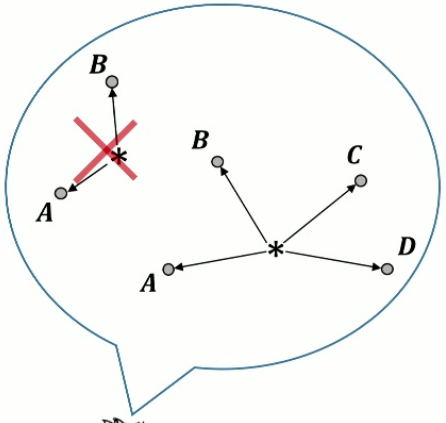
- ∀N: QT introduces “nonclassical N-partite systems”
  - DD: mathematical definition within QT ?
  - DI: Is it necessary? ∃ alternative theory without it

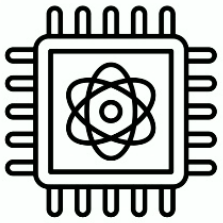
Applied goal

- Concrete experiments: Is my system nonclassicality “large”?
- Benchmark towards quantum advantages

O. Gühne and G. Tóth, Phys. Rep. 474, 1 (2009)
L. Pezzè, A. Smerzi, M. Oberthaler, R. Schmied, P. Treutlein, Rev. Mod. Phys. 90, 035005 (2018)
M. Pont, G. Corrielli, A. Fyrillas, I. Agresti, G. Carvacho, N. Maring, P-E. Emeriau, F. Ceccarelli, R. Albiero, P. Ferreira, N. Somaschi, J. Senellart, I. Sagnes, M. Morassi, A. Lemaitre, P. Senellart, F. Sciarrino, M. Liscidini, N. Belabas, R. Osellame., arXiv:2211.15626 (2022)
G. Bornet, G. Emperauger, C. Chen, B. Ye, M. Block, M. Bintz, J. Boyd, D. Barredo, T. Comparin, F. Mezzacapo, T. Roscilde, T. Lahaye, N. Yao, A. Browaeys, arXiv:2303.08053 (2023)

Experimentalist vs referee contest





Experimentalist vs referee contest

- Day 1:
  - Experimentalist creates a ‘nice state’
  - Convince the referee of it?
  - ➢ entanglement witness / Bell inequality violation
- Day 2:
  - Experimentalist believes he creates a ‘very nice state’

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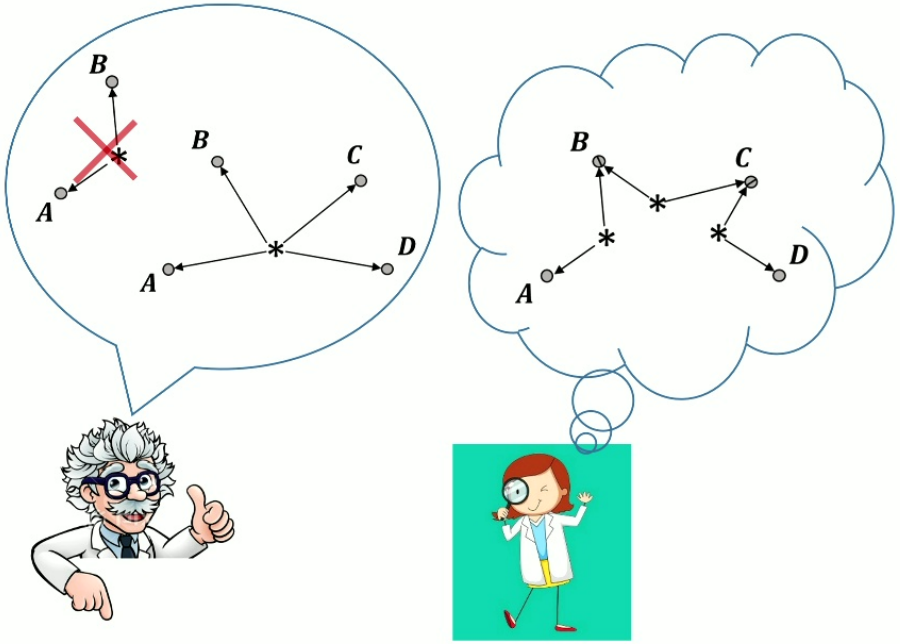

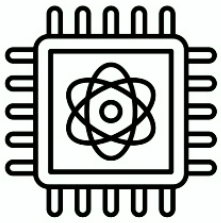

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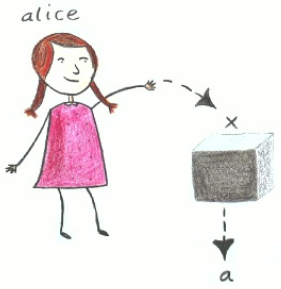
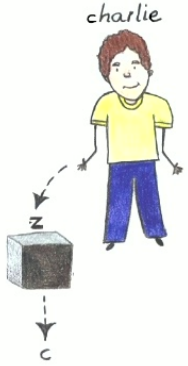
- Day 2:
  - Experimentalist believes he creates a ‘very nice state’
  - How to convince the referee?
  - ➢ Referee first needs to define the alternative model

Nature Correlations are Genuinely Multipartite Nonlocal





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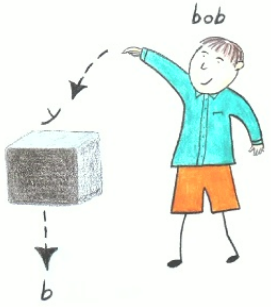
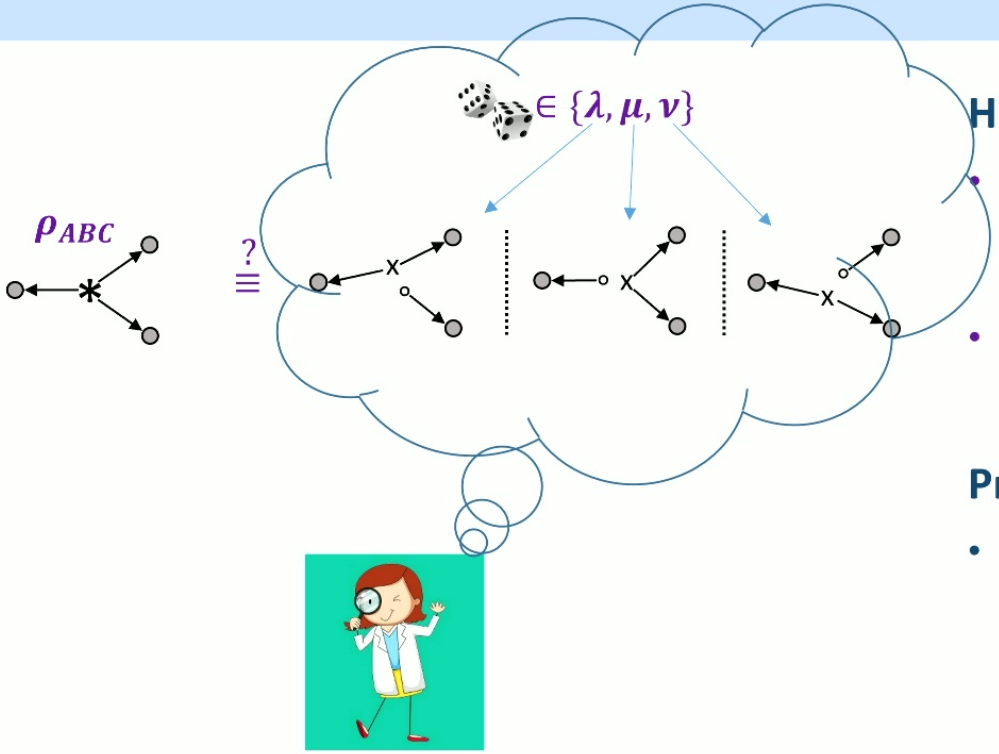


Historical definitions from Seevinck, Uffink, Svetlichny



Historical definitions of 'very nice state'

- ρ_{ABC} is **Seevinck, Uffink 3-GME** iff

$$\rho_{ABC} \neq \sum_{\lambda} \sigma_{AB}^{\lambda} \otimes \sigma_{C}^{\lambda} + \sum_{\mu} \tau_{BC}^{\mu} \otimes \tau_{A}^{\mu} + \sum_{\nu} \chi_{CA}^{\nu} \otimes \chi_{B}^{\nu}$$

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Problems with the definition

- Based on a non motivated underlying explanatory model
  - Experiment: the referee wants to exclude this?

M. Seevinck and J. Uffink, Phys. Rev. A 65, 012107 (2001)
G. Svetlichny, Phys. Rev. D 35, 3066 (1987)

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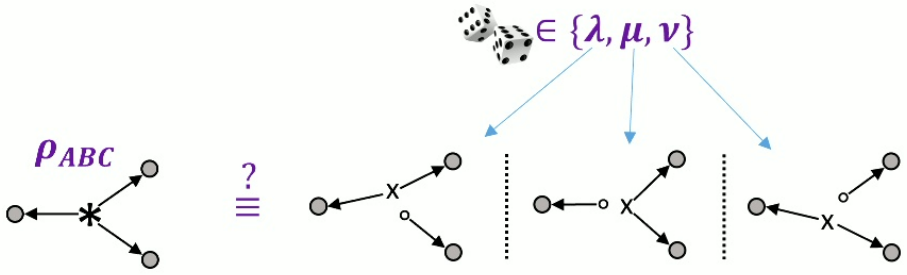

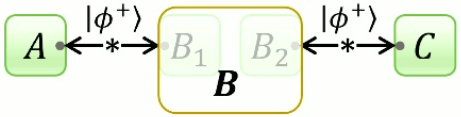

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- $|\phi^+\rangle_{AB_1} \otimes |\phi^+\rangle_{B_2C}$ **is** 'very nice'
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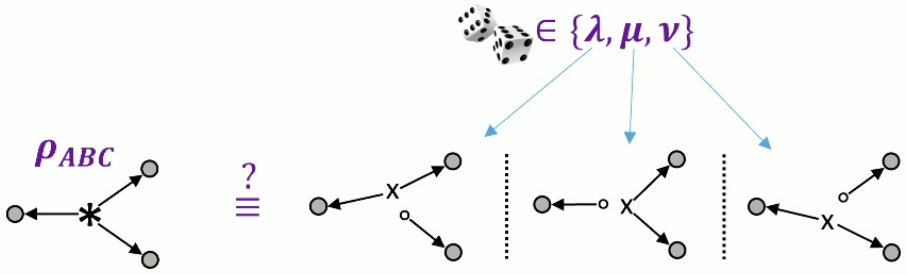

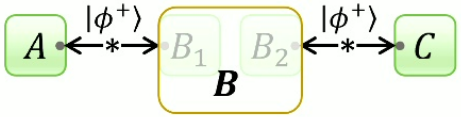

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- Fine tuning for no-signalling
  - The underlying model contains signalling washed out by the average

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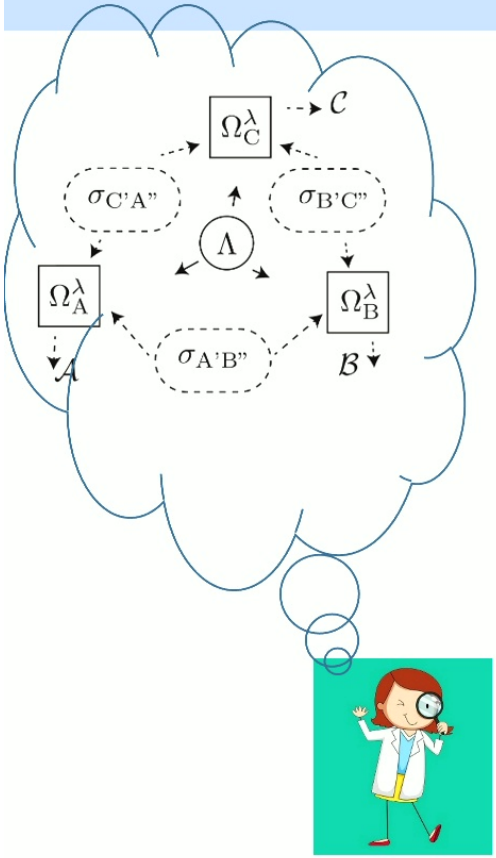
Recent redefinition



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Miguel Navascués, Elie Wolfe, Denis Rosset, Alejandro Pozas-Kerstjens, Phys. Rev. Lett. 125, 240505 (2020)

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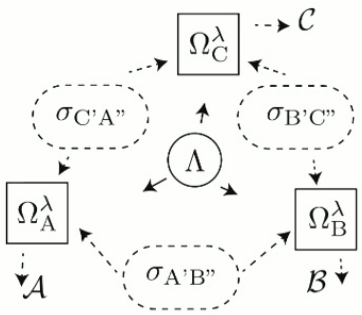

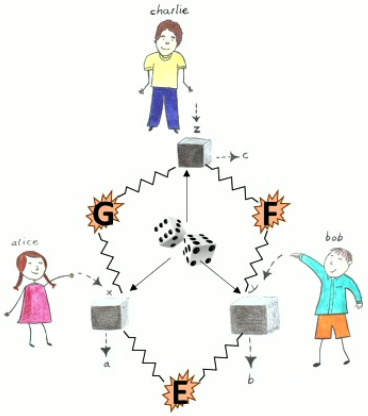

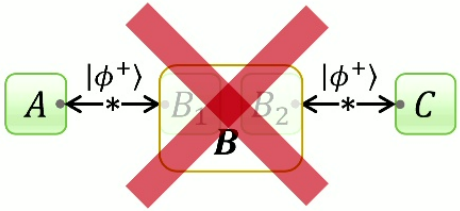

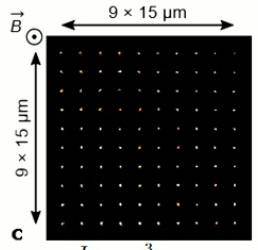

$$H_{XY} = -\frac{J}{2}\sum_{i<j}\frac{a^3}{r_{ij}^3}(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y),$$

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cannot be obtained with bipartite causal sources + shared randomness

Solve Svetlichny's definition problems

- $|\phi^+\rangle_{AB_1} \otimes |\phi^+\rangle_{B_2C}$ is not **'very nice'**
- Well motivated underlying explanatory model
- No Fine-Tuning

Cannot model communication

- No communication in underlying model
  - ➢ Some experiment: Should be included? e.g. 1D/2D spin chains

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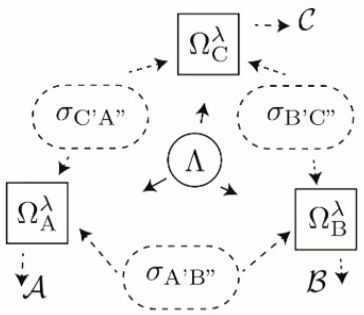

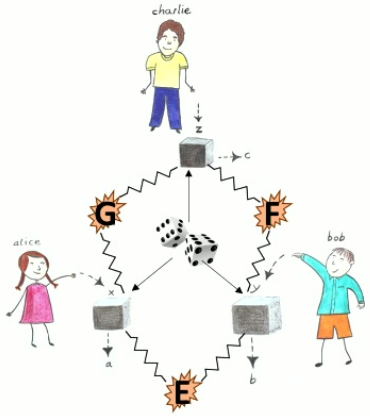

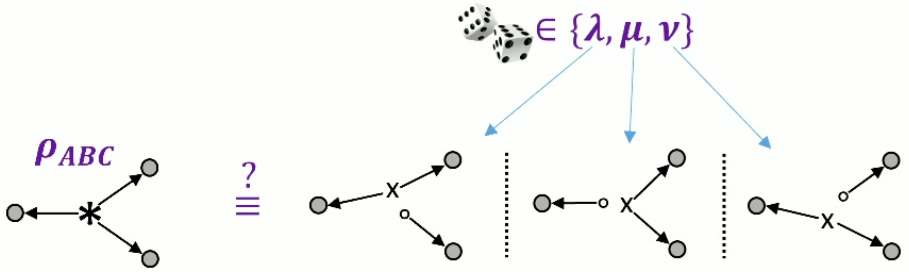

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  - Some experiment: Should be included? e.g. 1D/2D spin chains
  - Svetlichny's definition included it in a naïve way

G. Bornet, G. Emperauger, C. Chen, B. Ye, M. Block, M. Bintz, J. Boyd, D. Barredo, T. Comparin, F. Mezzacapo, T. Roscilde, T. Lahaye, N. Yao, A. Browaeys, arXiv:2303.08053 (2023)

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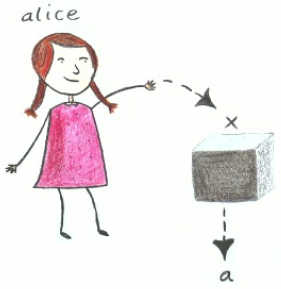

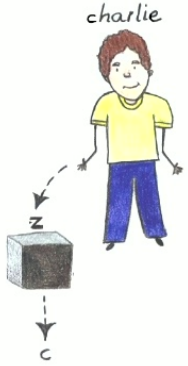

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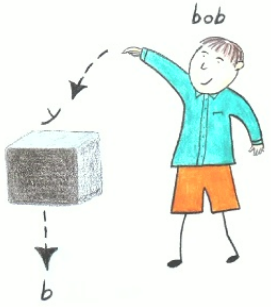

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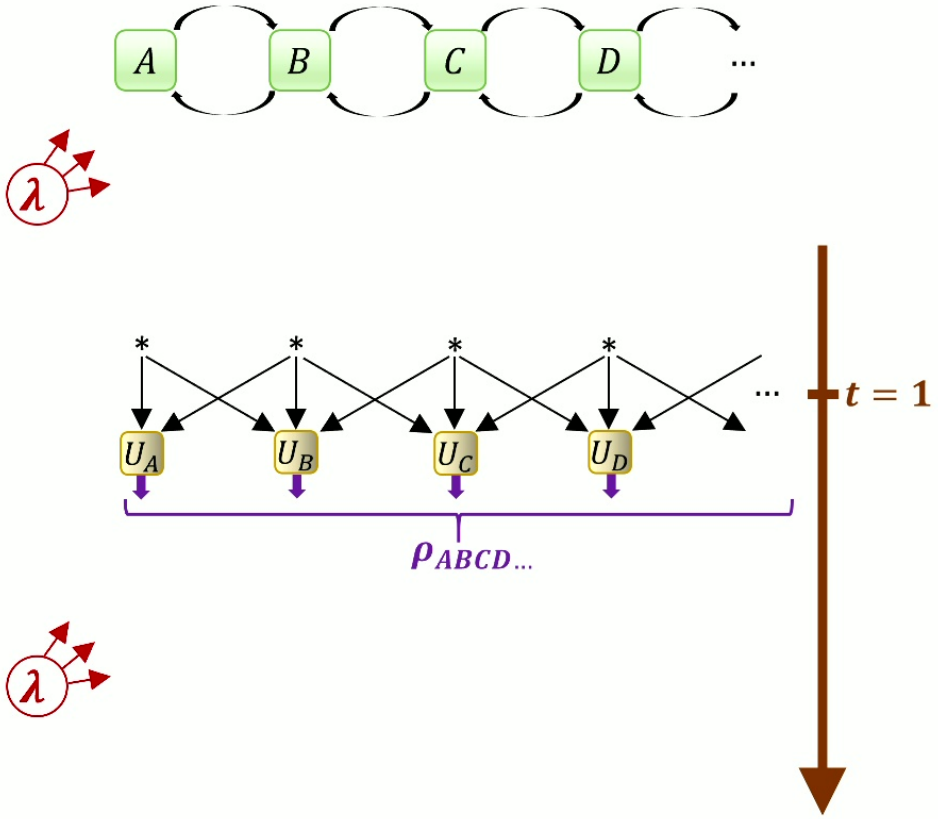

Definition of ‘Communication-very nice state’

- Given a communication graph G (e.g., line)
- Given a number of communication steps t

- $\rho_{ABCD...}$ is G, t **Communication-GME** iff cannot be obtained with
  - shared randomness λ
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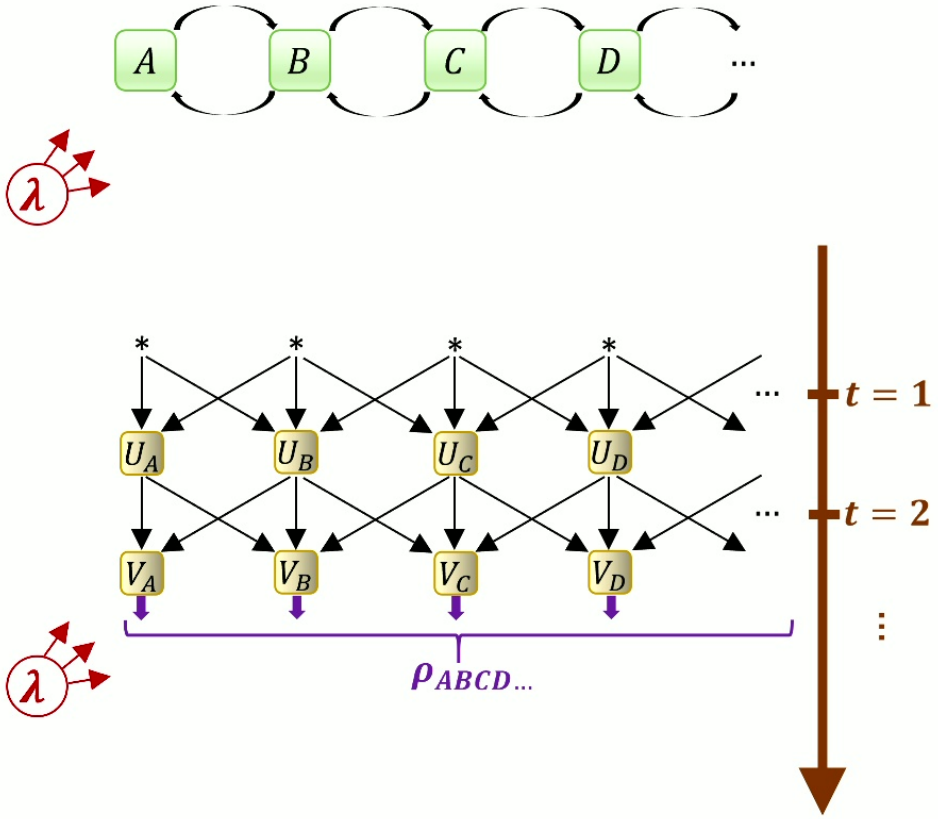
Xavier Coiteux-Roy, Owidiusz Makuta, Fionnuala Curran, Remigiusz Augusiak, Marc-Olivier Renou In preparation

A new concept: ‘Communication-very nice state’



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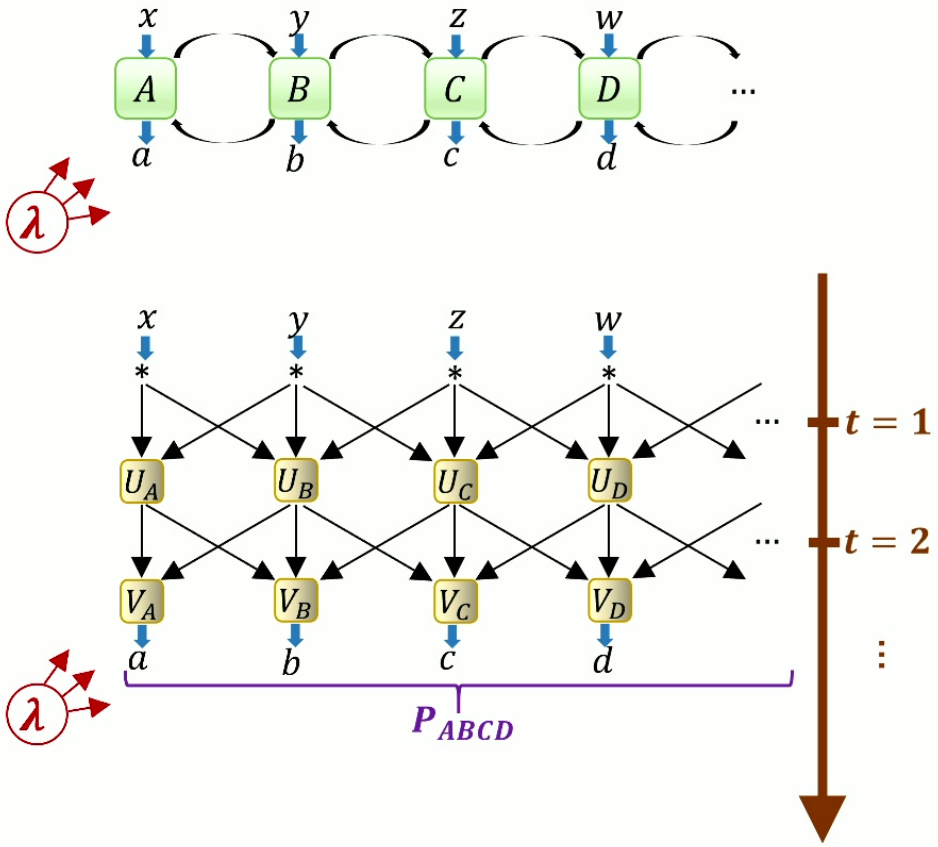

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Experimental benchmark

- Experiment device ⇒ communication graph G
- t^*: smaller t required to reproduce ρ, P

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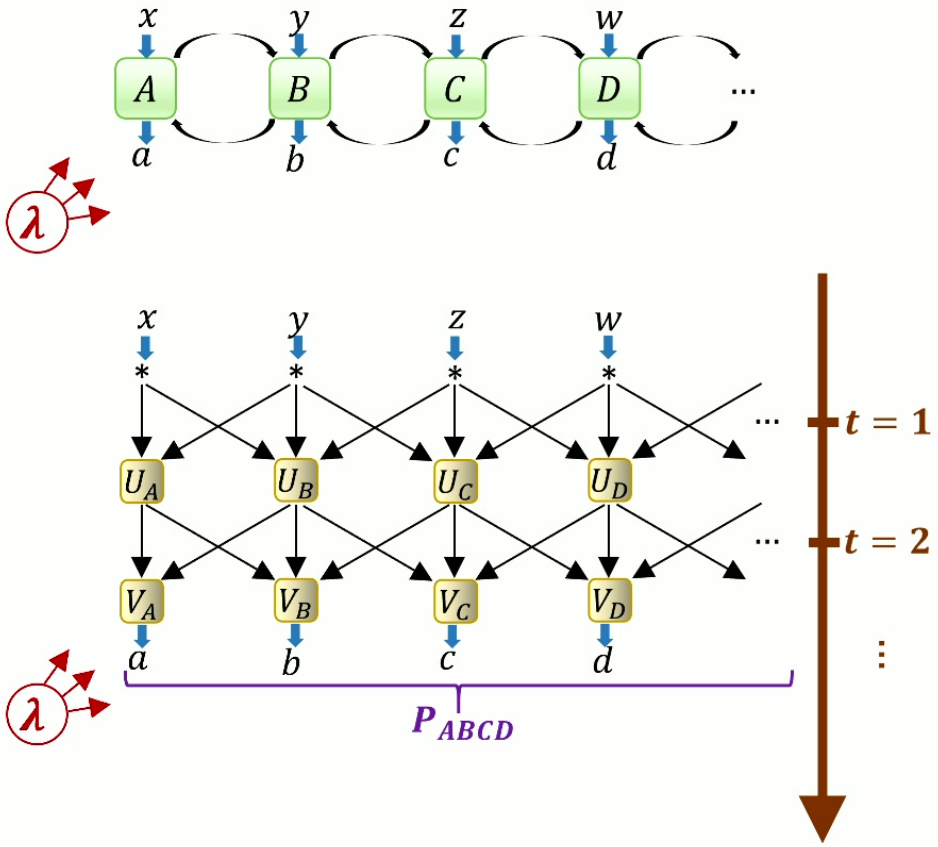

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Inspired from distributed computing

- LOCAL synchronous distributed computing model

Xavier Coiteux-Roy, Owidiusz Makuta, Fionnuala Curran, Remigiusz Augusiak, Marc-Olivier Renou In preparation

Nathan Linial. Locality in distributed graph algorithms. SIAM Journal on Computing, 21(1) :193–201, 1992.

Some results

	Seevinck, Uffink, Svetlichny historical definition	LOSR redefinition	Communication redefinition **1D line graph**
$\|\mathbf{GHZ}\rangle_{A_1\ldots A_N}$	N partite GME / GMNL ➢ 'maximally nice state'	N partite GME / GMNL ➢ 'maximally nice state'	Requires $t^* \sim N/2$ ➢ 'maximally nice state'
$\|\phi^+\rangle_{A_1A_2} \otimes \|\phi^+\rangle_{A_2'A_3} \otimes \cdots \otimes \|\phi^+\rangle_{A_{N-1}'A_N}$	N partite GME / GMNL ➢ 'maximally nice state'	2 partite GME / GMNL ➢ 'not a nice state'	Requires $t^* = 2$ ➢ 'not a nice state'
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Graph state $\|G\rangle_{A_1\ldots A_N}$	N partite GME / GMNL ➢ 'maximally nice state'	Corollary: If G contains a path of length M : M partite GME / GMNL ➢ Previously known to be 3-partite GME	

Miguel Navascués, Elie Wolfe, Denis Rosset, Alejandro Pozas-Kerstjens, PRL 125, 240505 (2020) Xavier Coiteux-Roy, Elie Wolfe, Marc-Olivier Renou PRL 127.200401 PRA 104.052207 (2021)
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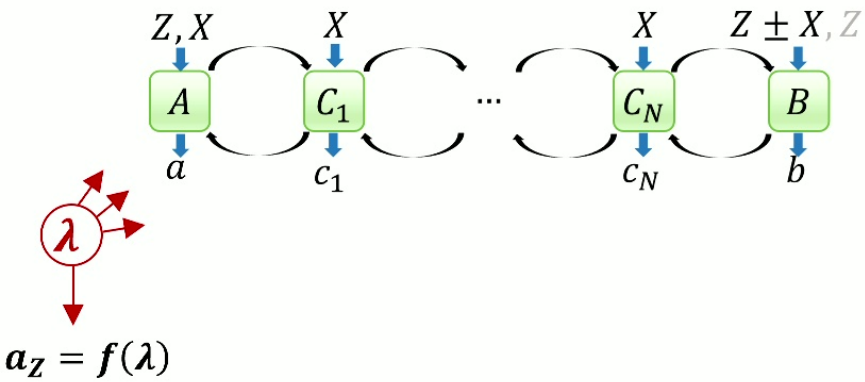
$|\mathbf{GHZ}\rangle_{AC_1\ldots C_NB}$ requires $t^* \sim N/2$



$|GHZ\rangle$ is 'maximally nice' in the line graph:

- If $A, C_1 \ldots C_N, B$ share a $|GHZ\rangle$ state
- We consider P obtained as :
  - $C_1 \ldots C_N$ do entanglement swapping (Pauli X measurement)
  - A/B perform a CHSH test (measure $Z, X/\ Z \pm X$)
  - A/B perform a shared random bit test (measure $Z/\ Z$)
- Then P cannot be obtain for $t < t^* \sim \frac{N}{2}$. By contradiction:
  - $\forall \lambda, P_\lambda(AB) = P_\lambda(A)P_\lambda(B)$: as t small, correlations only from λ
    - ➢ hence $a_Z = f(\lambda)$
  - a_Z is also part of a steered CHSH game
  - ➢ **Contradicts monogamy of entanglement**

Some results

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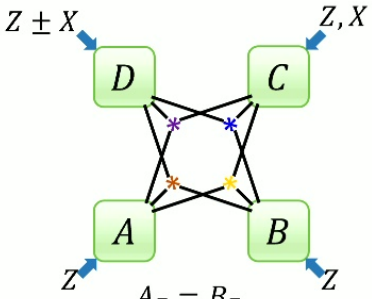
$|\mathbf{C}\rangle_{ABCD}$ is ‘LOSR very nice’



$A_Z = B_Z$

$\mathrm{CHSH}_{\mathrm{CD}}^{A_Z=0} = 2\sqrt{2}$

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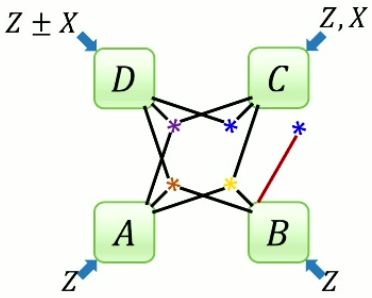

$$|\mathbf{C}\rangle_{ABCD} = |\mathbf{00}\rangle \otimes |\boldsymbol{\phi}^+\rangle + |\mathbf{11}\rangle \otimes |\boldsymbol{\phi}^-\rangle$$
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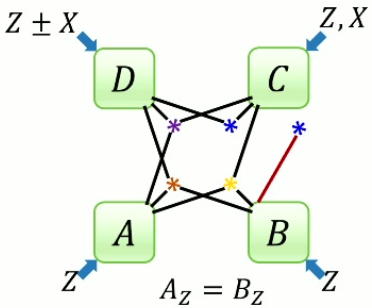

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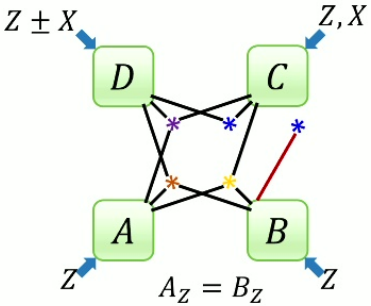

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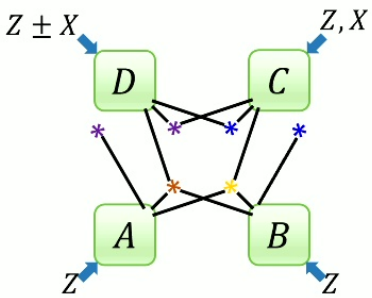

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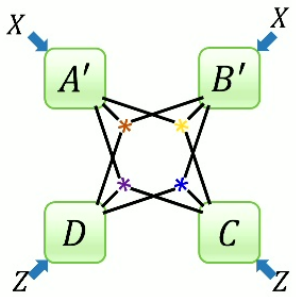

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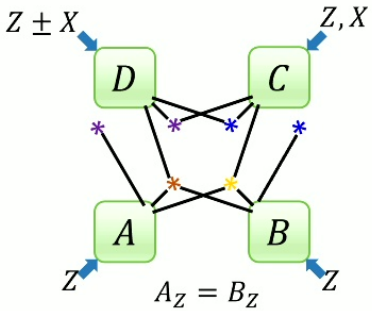

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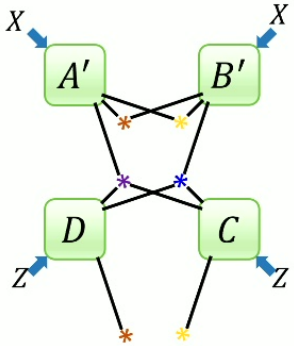

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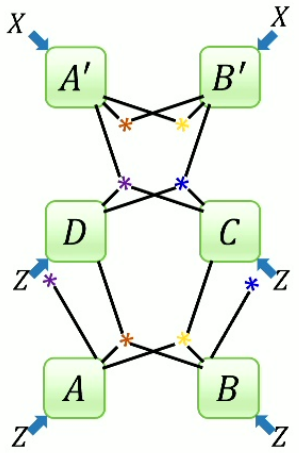

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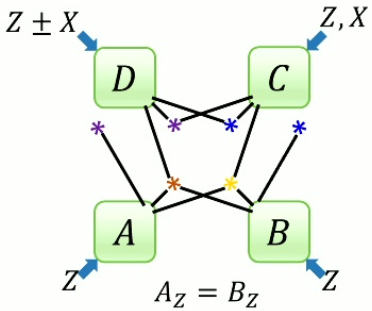

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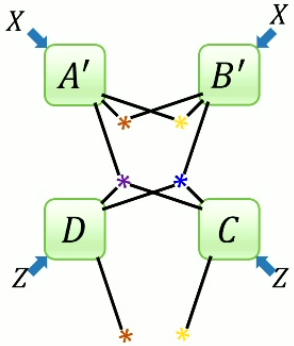

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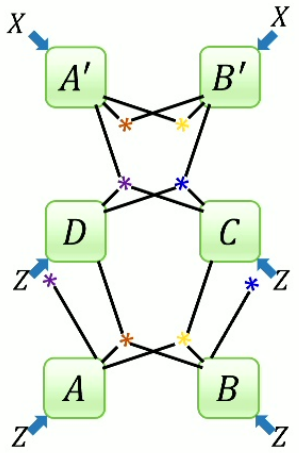

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Concept

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Technical result

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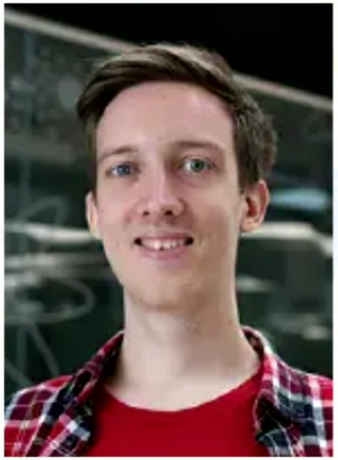
Benchmarck large nonclassicality

- Historical definitions are **problematic**
- One needs to carefully think at the **alternative model the referee wants to rule out**
- Depends on the concrete experiment

Acknowledgments



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