Title: Recently discovered, stronger forms of quantum noncality

Date: Feb 06, 2018 03:30 PM

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Abstract: <p>In this talk I will discuss recently-identified classes of quantum correlations that go beyond nonlocal classical hidden-variable models equipped with communication. First, in the bipartite scenario, I will focus on so-called instrumental causal networks, which are a primal tool in causal inference. There, I will show that it is possible to â€œfakeâ€• classical causal influences with quantum common causes, in a formal sense quantified by the average causal effect (ACE). Furthermore, I will show that it is possible to violate instrumental inequalities with quantum resources, both in the device-independent and in the 1-sided device-independent settings. Second, in the multipartite setting, I will present a causal hierarchy of multipartite nonlocality. I will make special emphasis on quantum correlations in the upper classes of the hierarchy that define stronger forms of genuinely multipartite quantum non-locality than those previously known. The seminar will touch upon concepts like Bell nonlocality and quantum steering as well as Bayesian nets and causal inference.</p>

Recently discovered, stronger forms of quantum non-locality

Leandro Aolita

IF-UFRJ (Rio), ICTP/SAIFR (São Paulo), and IIP (Natal)

Perimeter Institute - February 2018


Brazil
International Boundary
State Boundary
Road
River
National Capital
State Capital
City or Town
North Atlantic Ocean
South Atlantic Ocean
South Pacific Ocean
Equator
Caracas
Port-of-Spain
Maracaibo
Barcelona
Maturin
Barquisimeto
Valencia
Cucuta
San Cristobal
Bucaramango
Ciudad Bolivar
VENEZUELA
Georgetown
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SURINAME
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Bogota
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Belem
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Manaus
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Careiro
Altamira
Sao Luis
Parnaiba
Fortaleza
Iquitos
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Benjamin Constant
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Rio Purus
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Picos
Joao Pessoa
Cruzeiro do Sul
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Guajara-Mirim
Guayaramerin
Assis Brasil
Inapari
Aracaju
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Barreiras
Rio Juruena
Rio Teles Pires
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Cochabamba
Ilo
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Oruro
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Puerto Suarez
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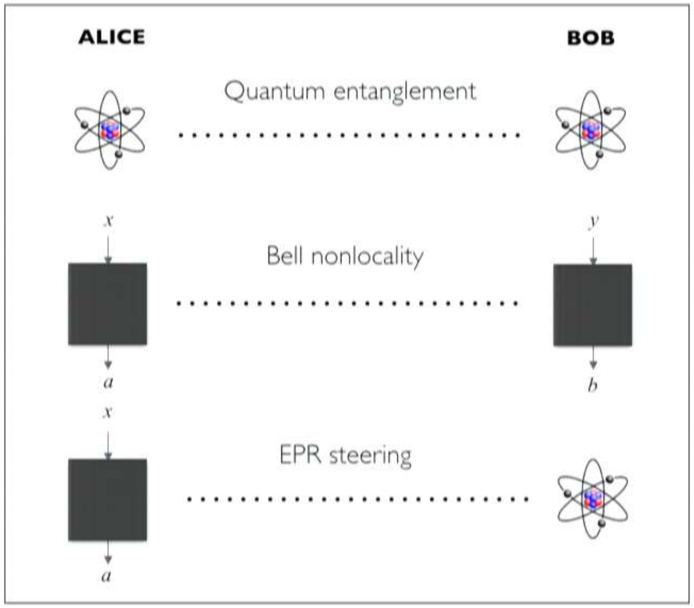
Bipartite quantum nonlocality in its three variants

Device dependent (DD)

Device independent (DI)

Semi-DI or 1-sided DI



Mathematical description

(quantum state)

$$\varrho_{AB} \neq \sum_{\lambda} p(\lambda)\, \varrho_A^{(\lambda)} \otimes \varrho_B^{(\lambda)}$$

R. Horodecki, P. Horodecki, M. Horodecki, and K. Horodecki, "Quantum entanglement", Rev. Mod. Phys. **81**, 865 (2009).

(black-box behaviour)

$$p(a,b|x,y) \neq \sum_{\lambda} p(\lambda)\, p(a|x,\lambda)\, p(b|y,\lambda)$$

N. Brunner, D. Cavalcanti, S. Pironio, V. Scarani, and S. Wehner, "Bell nonlocality", Rev. Mod. Phys. **86**, 419 (2014).

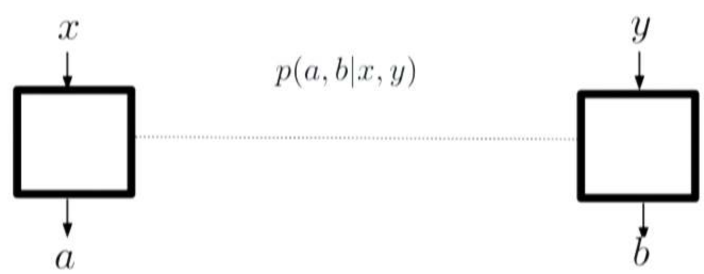
$$\sigma_{a|x} = p(a|x)\, \varrho_{a,x} \quad \text{(assemblage)}$$

$$\neq \sum_{\lambda} p(\lambda)\, p(a|x,\lambda)\, \varrho_B^{(\lambda)}$$

M. D. Reid et al, "The EPR paradox: from concepts to applications", Rev. Mod. Phys. **81**, 1727 (2009); D. Cavalcanti and P. Skrzypczyk, "Quantum steering: a review with focus on semidefinite programming", Rep. Prog. Phys. **80**, 024001 (2017).

Bell correlations (fully DI scenario)

Alice



Bob

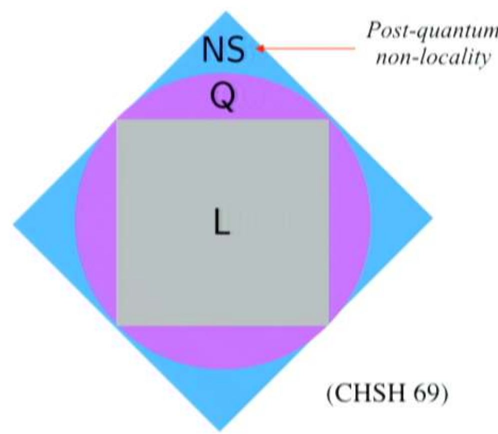
Local correlations: $$p(a,b|x,y) = \sum_\lambda p(\lambda)\, p(a|x,\lambda)\, p(b|y,\lambda)$$

Quantum correlations: $$p(a,b|x,y) = \mathrm{Tr}\big[M_x^{(a)} \otimes M_y^{(b)}\, \varrho_{AB}\big]$$ *(Born's rule)*

No-signalling correlations: $$\begin{cases} p(a|x,y) := \sum_b p(a,b|x,y) = p(a|x) \\ p(b|x,y) := \sum_a p(a,b|x,y) = p(b|y) \end{cases}$$

$$\mathrm{L} \subset \mathrm{Q} \subseteq \mathrm{NS}$$

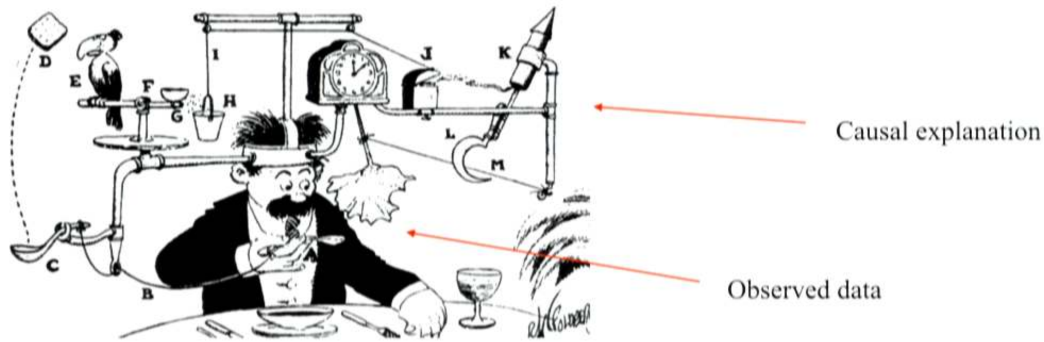
(Bell´s theorem 64)



(CHSH 69)

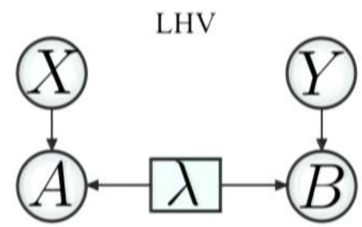
Bell tests as causal-inference problems

Causal inference:



A typical Bell experiment:

Can I explain experimental observed correlations with an LHV causal model?



$$p(a,b|x,y) = \sum_{\lambda} p(\lambda)\, p(a|x,\lambda)\, p(b|y,\lambda)$$

How much can one strengthen LHV models while still having a gap with quantum correlations?

What is the simplest causal structure that admits a gap between classical and quantum causal models?

Superior forms of quantum nonlocality
(stronger than non-local hidden variable models)!!!

Outline of the talk:

- DI bipartite case with outcome communication.

nature physics
ARTICLES
https://doi.org/10.1038/s41567-017-0008-5

Quantum violation of an instrumental test

Rafael Chaves[1*], Gonzalo Carvacho[2], Iris Agresti[2], Valerio Di Giulio[2], Leandro Aolita[3], Sandro Giacomini[2] and Fabio Sciarrino[2*]

- 1-sided DI bipartite case with outcome communication.

Quantum steering beyond instrumental causal networks

R. V. Nery,[1] M. M. Taddei,[1] R. Chaves,[2] and L. Aolita[1,3]

- DI multipartite case with no communication.

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the open journal for quantum science
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Causal hierarchy of multipartite Bell nonlocality

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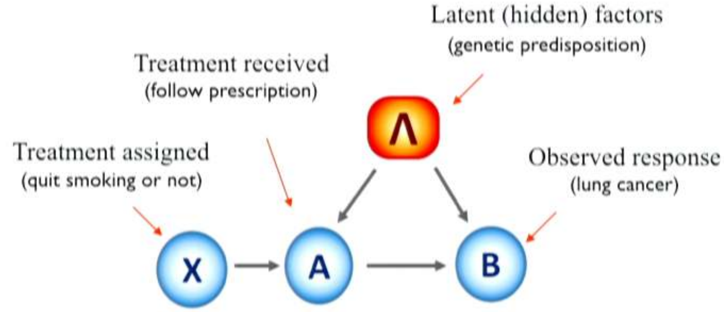
Device-independent bipartite case with outcome communication

R. Chaves, G. Carvacho, I. Agresti, V. Di Giulio, L. Aolita, S. Giacomini, and F. Sciarrino, Nature Physics (2017).

Classical causal models: Bayesian networks

- **Causal structures represented by *directed acyclic graphs* (DAGs):**



The instrumental DAG
(randomised clinical trials)

- **Causal models represented by distributions *Markov* with respect to the DAG:**

Parents of b

$$p(a, b, x, \lambda) = p(\lambda)\, p(x)\, p(a|x, \lambda)\, p(b|a, \lambda)$$

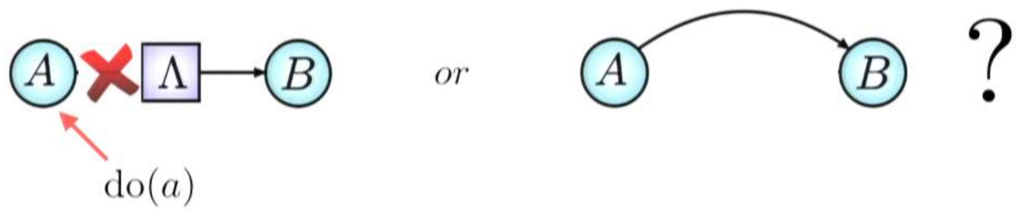
P. Spirtes, N. Glymour, and R. Scheienes (01); J. Pearl (09).

What is the simplest causal structure displaying a gap between quantum and classical correlations?

... the answer was always in front of our noses. 

The simplest causal inference problem

Does A causally influence B?



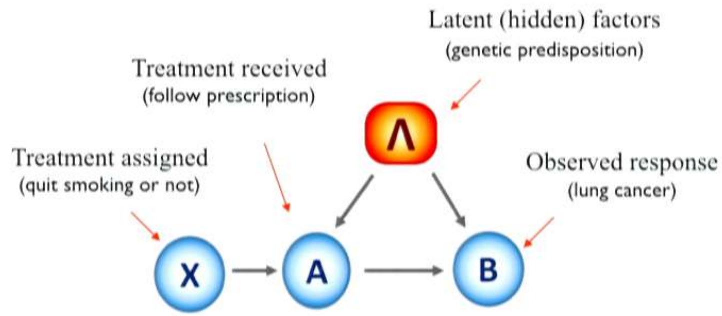
…but both causal models can explain all distributions $p(a, b)$

Interventions allow one to *infer* the underlying causal structure: $p(b|a) \neq p\big(b|\mathrm{do}(a)\big)$?

…but they assume one can ***physically modify the internal dynamics*** *of the system, including hidden nodes (****not device-independent****)*

Instrumental variables

Introduced in econometrics (Wright, 1928) to estimate parameters in linear models of supply and demand.



The instrumental DAG
(randomised clinical trials)

Strength of causal influence from A to B

$$\text{If } b = \gamma\, a + \lambda \Rightarrow \gamma = \frac{\mathrm{Cov}(X,B)}{\mathrm{Cov}(X,A)}$$

Observed data

Unobserved random variable

$$\left(\mathrm{Cov}(X,\Lambda) = 0\right)$$

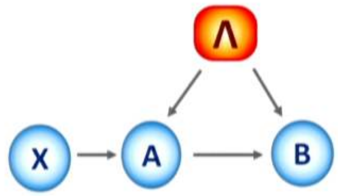
In full generality, the causal influence from A to B can be quantitatively assessed ***even in the presence of hidden common causes and without interventions (device-independent)****.*

A. Balke and J. Pearl, "Bounds on treatment effects from studies with imperfect compliance", JASA (1997).

... but how does one know if a given observed statistics has an instrumental model as underlying causal explanation?

Instrumental inequalities

Instrumental causal models:



$$p(a, b|x) = \sum_{\lambda} p(\lambda)\, p(a|x, \lambda)\, p(b|a, \lambda)$$

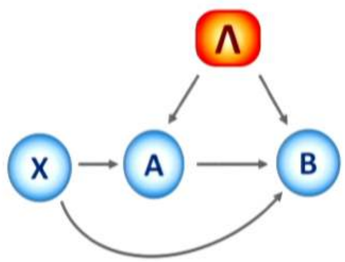
… they all satisfy:

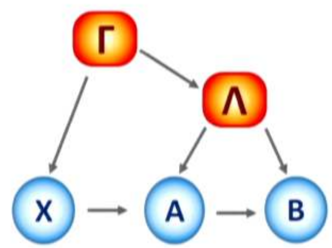
$$\max_a \sum_b \max_x p(a, b|x) \leq 1$$

The instrumental inequalities

J. Pearl, UAI (1995).

- ***Classical*** instrumental-inequality ***violations possible only by non-instrumental*** *causal* **models**:





- Quantum mechanically, ***no violation by quantum instrumental causal models***.

J. Henson, R. Lal, and M. Pussey, New J. Phys. **16**, 113043 (2014) .

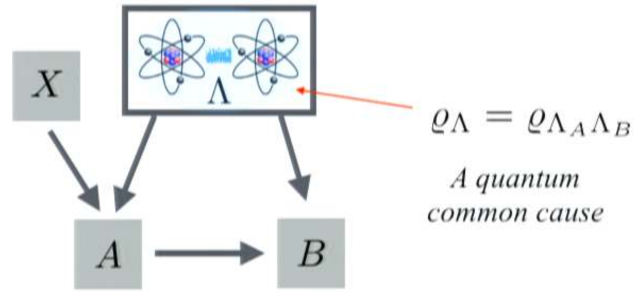
Even without violations, do quantum instrumental offer an observable discrepancy with classical ones?

Quantum instrumental causal models

Quantum instrumental causal models:

$$p_Q(a,b|x) := \mathrm{Tr}\left[M_x^{(a)} \otimes M_a^{(b)} \varrho_\Lambda\right]$$

(measurement setting x, measurement outcome a) (measurement setting a, measurement outcome b)



L. Hardy (2005-2007);
F. Costa and S. Shrapnel, New J. Phys. **18**, 063032 (2016);
J.-M. Allen, J. Barrett, D. C. Horsman, C. M. Lee, and R. W. Spekkens, Phys. Rev. X **7**, 031021 (2017).

R. Chaves, G. Carvacho, I. Agresti, V. Di Giulio, L. Aolita, S. Giacomini, and F. Sciarrino, Nature Physics (2017).

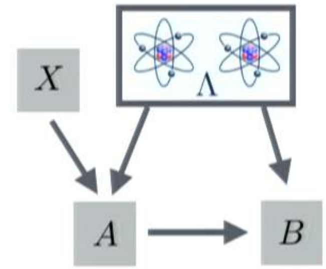
Quantum average causal effect (QACE)

The quantum average causal effect (QACE):

$$\mathrm{QACE}_{A\to B} = \sup_{a,a',b} |p_Q(b|\mathrm{do}(a)) - p_Q(b|\mathrm{do}(a'))|$$

$$= \sup_{a,a',b} \left|\mathrm{Tr}\left[\left(M_b^{\mathrm{do}(a)} - M_b^{\mathrm{do}(a')}\right) \varrho_{\Lambda_B}\right]\right|$$

$$\equiv 0 \qquad \textit{(for all v!!!)}$$



$$p_{\mathrm{Q}}(a,b|x) = \mathrm{Tr}\left[M_a^x \otimes M_b^a \, \varrho_\Lambda\right]$$

$$\Rightarrow p_{\mathrm{Q}}(b|\mathrm{do}(a)) = \mathrm{Tr}\left[\mathbf{1} \otimes M_b^{\mathrm{do}(a)} \, \varrho_\Lambda\right]$$

$$= \mathrm{Tr}_B\left[M_b^{\mathrm{do}(a)} \, \varrho_{\Lambda_B}\right]$$

$$\varrho_\Lambda = v\,|\Phi^+\rangle\langle\Phi^+| + (1-v)\,\mathbf{1}/4$$

$$\Rightarrow \rho_{\Lambda_B} = \mathrm{Tr}_A\left[\varrho_\Lambda\right] = \frac{\mathbf{1}}{2}$$

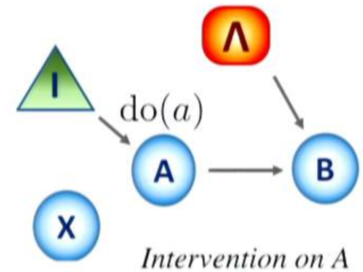
- The average statistics observable at B must be *more sensitive to interventions in A if the causal model is classical!* 🙂
- Can be seen as a *quantum enhancement in terms of the causal strength* required to reproduce data! 🙂
- Observation of this discrepancy *requires interventions* (not DI!) 🙁

Average causal effect (ACE)

The classical average causal effect (ACE):

$$\mathrm{ACE}_{A\to B} = \sup_{a,a',b} |p(b|\mathrm{do}(a)) - p(b|\mathrm{do}(a'))|$$

Maximum observable effect on B caused by interventions on A (on average)

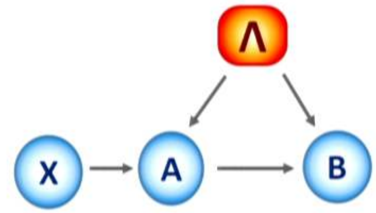


Intervention on A

DI lower bound to the ACE:

$$\mathrm{ACE}_{A\to B} \geq 2\,p(a=0,b=0|x=0) - 2 + p(a=1,b=1|x=0) + p(b=1|x=1)$$

(for any classical instrumental causal model)



A. Balke and J. Pearl (1997).

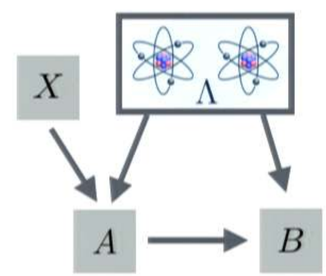
Example:

$$p_Q(a,b|x) = \mathrm{Tr}\left[M_a^x \otimes M_b^a\, \varrho_\Lambda\right]$$

σ_Z or σ_X $\qquad -\sin(\pi/8)\,\sigma_X + \cos(\pi/8)\,\sigma_Z$ or $\dfrac{\sigma_X + \sigma_Z}{\sqrt{2}}$

(compatible with a classical instrumental model for all v)

$$\mathrm{ACE}_{A\to B} \gtrsim 0.91\,v - 0.75$$

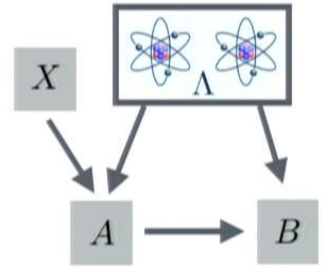


$$\varrho_\Lambda = v\,|\Phi^+\rangle\langle\Phi^+| + (1-v)\,\mathbf{1}/4$$

$$|\Phi^+\rangle := \left(|0_{\Lambda_A}\,0_{\Lambda_B}\rangle + |1_{\Lambda_A}\,1_{\Lambda_B}\rangle\right)/\sqrt{2}$$

Quantum average causal effect (QACE)

The quantum average causal effect (QACE):



$$\mathrm{QACE}_{A\to B} = \sup_{a,a',b} |p_Q(b|\mathrm{do}(a)) - p_Q(b|\mathrm{do}(a'))|$$

$$= \sup_{a,a',b} \left|\mathrm{Tr}\left[\left(M_b^{\mathrm{do}(a)} - M_b^{\mathrm{do}(a')}\right) \varrho_{\Lambda_B}\right]\right|$$

$$\equiv 0$$ *(for all v!!!)*

$$p_{\mathrm{Q}}(a,b|x) = \mathrm{Tr}\left[M_a^x \otimes M_b^a \, \varrho_\Lambda\right]$$

$$\Rightarrow p_{\mathrm{Q}}(b|\mathrm{do}(a)) = \mathrm{Tr}\left[\mathbf{1} \otimes M_b^{\mathrm{do}(a)} \, \varrho_\Lambda\right]$$

$$= \mathrm{Tr}_B\left[M_b^{\mathrm{do}(a)} \, \varrho_{\Lambda_B}\right]$$

$$\varrho_\Lambda = v\,|\Phi^+\rangle\langle\Phi^+| + (1-v)\,\mathbf{1}/4$$

$$\Rightarrow \rho_{\Lambda_B} = \mathrm{Tr}_A\left[\varrho_\Lambda\right] = \frac{\mathbf{1}}{2}$$

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Can one observe a discrepancy device-independently?

How about other instrumental inequalities (potentially violated with quantum common causes)?

Violation of a classical instrumental test with quantum instrumental causal models

If X is trichotomic, another instrumental inequality appears:

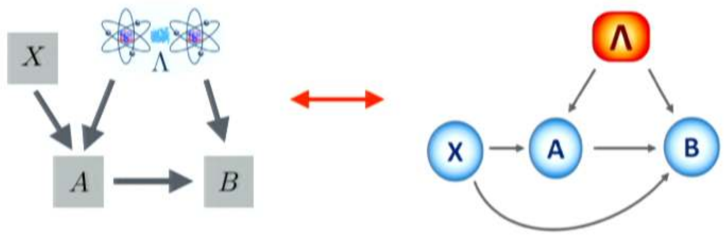
$$I_{\text{inst}} := -\langle B\rangle_{x=1} + 2\langle B\rangle_{x=2} + \langle A\rangle_{x=1} - \langle A\,B\rangle_{x=1} + 2\langle A\,B\rangle_{x=3} \leq 3$$

B. Bonet, UAI (2001).

R. Chaves, G. Carvacho, I. Agresti, V. Di Giulio, L. Aolita, S. Giacomini, and F. Sciarrino, Nature Physics (2017).

Interpretations of quantum violations

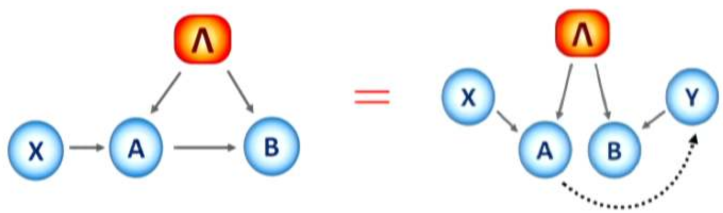
• **Causal-inference viewpoint**: Quantum effects ***change the interpretation*** of instrumental-inequality violations:



$$\Rightarrow \quad \min C_{X\to B} = \max\left[\frac{I_{\mathrm{inst}}(Q)-3}{4}, 0\right]$$

Direct causal influence from X to B required to classically reproduce the quantum violation

• **Bell non-locality viewpoint**: Instrumental-inequality violations by quantum instrumental causal models can be seen as a ***novel, stronger form of non-classicality***.



Quantum entanglement + outcome communication produces correlations more nonlocal than LHV models + outcome communication!!!

R. Chaves, G. Carvacho, I. Agresti, V. Di Giulio, L. Aolita, S. Giacomini, and F. Sciarrino, Nature Physics (2017).

Experimental demonstration (Rome)

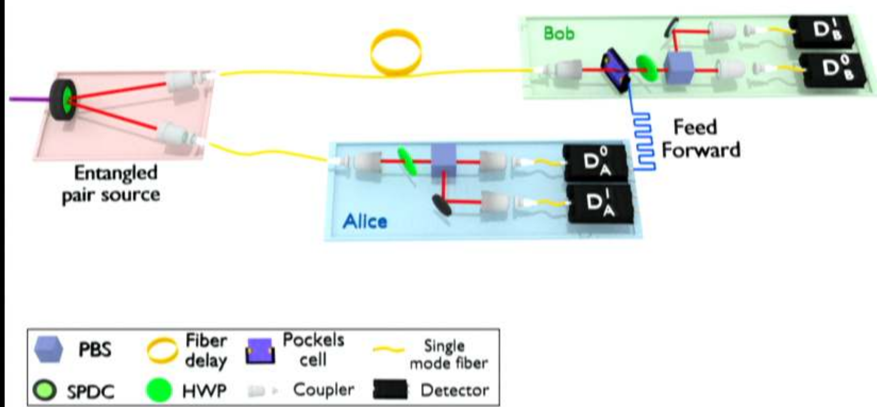
Experimental scheme:

$\frac{-\sigma_x + \sigma_z}{\sqrt{2}}$ σ_x σ_z

$$\varrho_\Lambda = |\Phi^+\rangle := \frac{1}{\sqrt{2}}\Big(|0_{\Lambda_A} 0_{\Lambda_B}\rangle + |1_{\Lambda_A} 1_{\Lambda_B}\rangle\Big)$$

$\frac{\sigma_x + \sigma_z}{\sqrt{2}}$ $\frac{\sigma_z - \sigma_x}{\sqrt{2}}$

Implementation:



Partial Conclusions:

• The instrumental causal structure is a *cornerstone of* classical *causal inference*: allows to *estimate causal influences* in the presence of *hidden common causes and without interventions.*

• Introduction of quantum ACE. Classical causality concepts can lead to a significant overestimation of the ACE for quantum causal models.

• Can also be seen as a *quantum advantage* in terms of descriptive power of observed data.

• Simplest causal structure with a *quantum-classical gap* (and we found the quantum violation)!

• Quantum violation changes the *interpretation of instrumental-inequality violations*.

• Experiment with entangled-photon pairs + active feedforward: *demonstration of a novel, stronger form of non-classicality*.

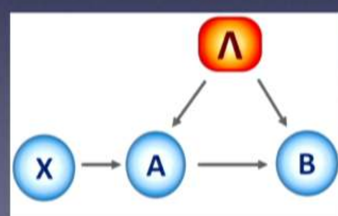
Partial outlook:

1. Multi-partite generalisations: anything interesting?

2. Quantum causal inference: DI lower bound to QACE? definition of *quantum direct causal influence*?

3. Post-quantum instrumental causal models.

4. Quantum instrumental causal models as a resource? … for what?



Randomness generation ?

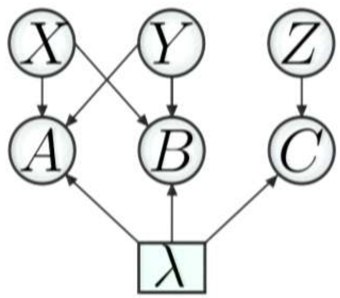
R. Gallego, L. Masanes, G. de la Torre, C. Dhara, L. Aolita, and A. Acín, "Full randomness from arbitrarily deterministic events", Nature Communications **4**, 2654 (2013).

Device-independent multipartite no-signalling case

R. Chaves, D. Cavalcanti, and L. Aolita, Quantum **1**, 23 (2017).

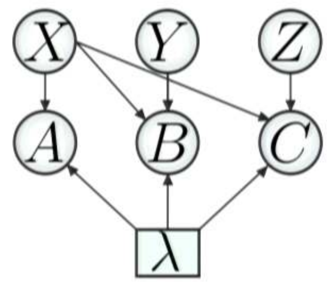
Relaxations of locality in the multipartite scenario

Bi-LHV (split into 2 halves)



G. Svetlichny (87); D. Collins et al. (02); M. Seevinck and G. Svetlichny (02); J. Lavoie, R. Kaltenbaek, and K. J. Resch (09).

Input-broadcasting



J. D. Bancal, C. Branciard, N. Gisin, and S. Pironio (09).

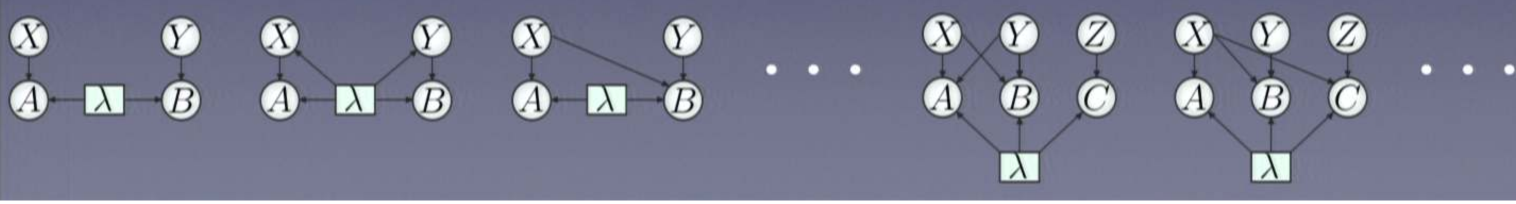
- These models give rise to ***genuinely multipartite Bell non-locality***.
- They satisfy the ***Svetlichny inequality***:

$$-\langle A_0B_0C_0\rangle + \langle A_0B_0C_1\rangle + \langle A_0B_1C_0\rangle + \langle A_0B_1C_1\rangle + \langle A_1B_0C_0\rangle + \langle A_1B_0C_1\rangle + \langle A_1B_1C_0\rangle - \langle A_1B_1C_1\rangle \leq 4.$$

- The Svetlichny inequality is ***violated by*** quantum correlations from ***the GHZ state***: $|\Psi_{\mathrm{GHZ}}\rangle := (|000\rangle + |111\rangle)/\sqrt{2}$.
- ***No stronger inequality*** known ***violated by quantum correlations***.

Bell DAGs are exponentially complex objects, can one find a unifying, systematic, and practical way to classify them?

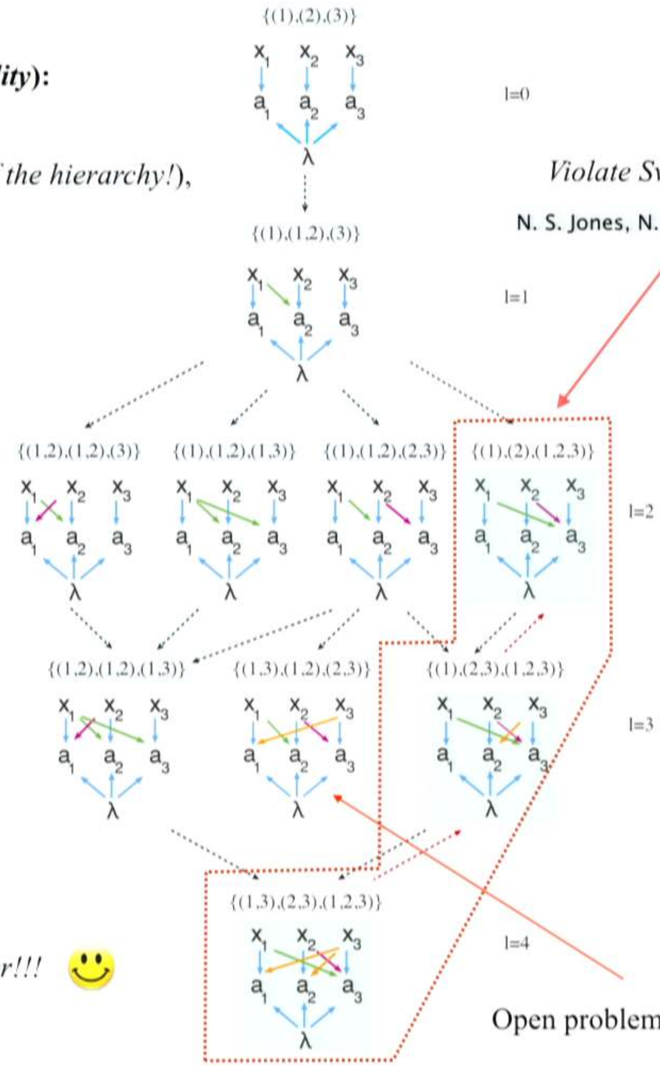
Idea: exploit the no-signalling constraint!!!



Causal hierarchy of classes of multipartite Bell non-locality

Theorem (*Classes of 3-partite Bell non-locality*):

- 10 *NS-interesting* causal classes,
- 3 of them turn out NS-equivalent (*collapse of the hierarchy!*),
- at least *7 have quantum violations.*



Violate Svetlichny's inequality

N. S. Jones, N. Linden, and S. Massar (05).

Satisfy Svetlichny's inequality

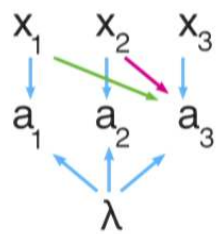
N. S. Jones, N. Linden, and S. Massar (05).

We find quantum correlations even stronger!!!

Open problem: *quantum violations?*

Quantum genuinely multipartite "super non-locality"

The *star* Bell DAG: one party receives all inputs.

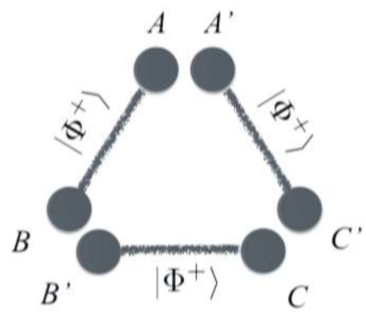


It satisfies all inequalities of the generic form:

$$I_3 := I_2(A,B) + I_2(A',C) + I_2(B',C') \leq \beta_{\mathrm{L}} + 2\beta_{\mathrm{NS}}$$

• These ***inequalities*** *are* ***maximally violated by quantum correlations***!!!

A. Cabello (01); T. Yang et al. (05); J. Barrett, A. Kent, and S. Pironio (06); L. Aolita et al. (11); T. E. Stuart et al. (12); B. G. Christensen et al. (12).



Type of state required for the violation

*The **strongest form of multipartite quantum nonlocality known***
(even stronger than conventional genuinely multipartite)!!!

Partial conclusions:

- We studied how to reproduce multipartite NS correlations with generic causal relaxations.
- The NS principle imposes non-trivial equivalences between different Bell DAGs.
- Practical classification of multipartite Bell non-locality: the causal hierarchy.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Causality: relaxing before exploring

POSTED ON 2017-08-04 BY QUANTUM VIEWS

This is a Perspective on "Causal hierarchy of multipartite Bell nonlocality" by Rafael Chaves, Daniel Cavalcanti, and Leandro Aolita, published in Quantum 1, 23 (2017).

Quantum Views 1, 3 (2017).

https://doi.org/10.22331/qv-2017-08-04-3

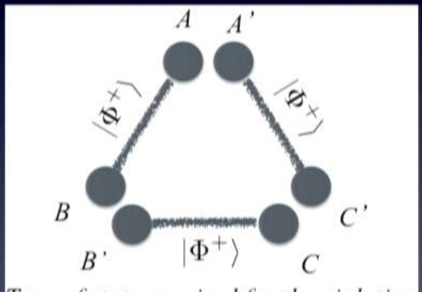
By Paul Skrzypczyk, School of Physics, University of Bristol, UK.

*The true power of the results comes in the **unifying and simplified view** they provide for studying relaxed causal structures. **What was previously a vast forest is now a well organised playground, ready to be explored, and played in**, as we continue to push forward our understanding of quantum non-locality.*

- Quantum correlations even stronger than genuinely multipartite nonlocality dicovered (open problem since 05).
- Post-quantum (?) tripartite super non-locality.

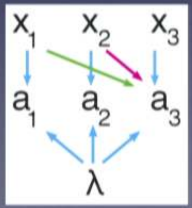
Partial outlook:

1. More compact/practical quantum realisations of multipartite super non-locality?, experiments?



Type of state required for the violation

2. Multipartite super non-locality as a resource?, for what?



Useful for DI secret sharing

So, for what stronger form of multipartite secrecy is super non-locality useful?

L. Aolita, R. Gallego, A. Cabello, and A. Acín, "Fully nonlocal, monogamous, and random genuinely multipartite quantum correlations", Phys. Rev. Lett. **108**, 100401 (2012).

General conclusions:

- Quantisation of the classical notion of causality not trivial.

- Stronger forms of quantum correlations discovered.

- Quantum multipartite super non-locality and supra-instrumental correlations are just-born babies.

- Potential applications in multipartite cryptographic schemes and randomness generations may appear, any other?

- Quantum causal inference, resource-theory approaches, novel information-theoretic physical protocols, novel experiments, etc……

- Many exciting open questions!

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Thank you for your attention!

Quantum violation of an instrumental test:
R. Chaves, G. Carvacho, I. Agresti, V. Di Giulio, L. Aolita, S. Giacomini, and F. Sciarrino, Nature Physics (2017).

Quantum steering beyond instrumental causal networks:
R. Neri, M. Taddei, R. Chaves, and L. Aolita, arXiv: 1712.08624 (2017).

Quantum multipartite super non-locality and the causal hierarchy:
R. Chaves, D. Cavalcanti, and L. Aolita, Quantum **1**, 23 (2017);
P. Skrzypczyk, Quantum Views **1**, 3 (2017).

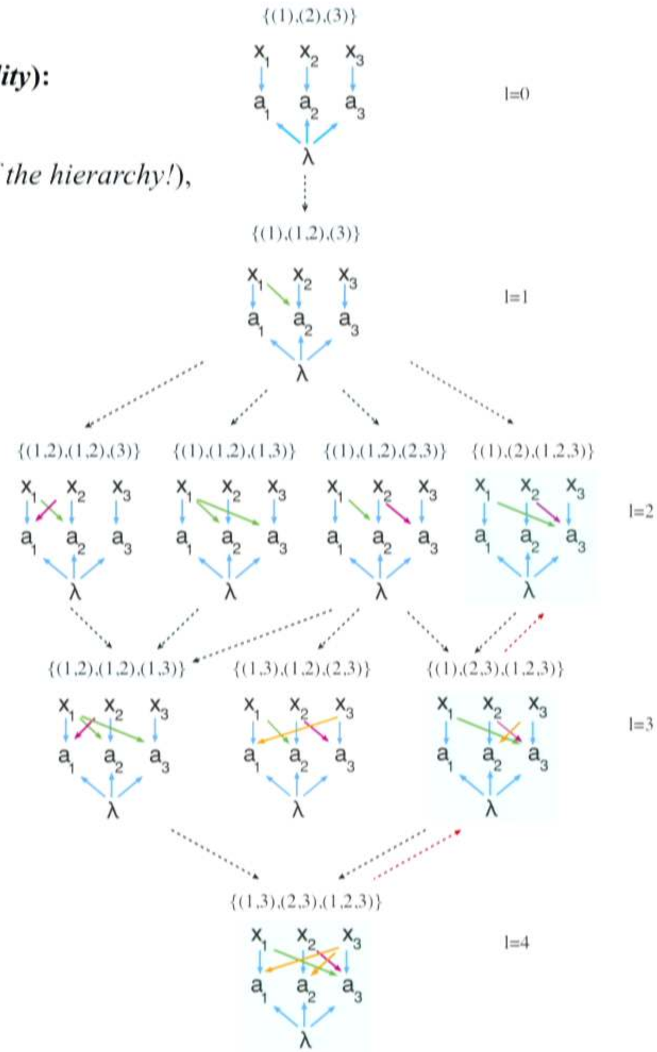
Causal hierarchy of classes of multipartite Bell non-locality

Theorem (*Classes of 3-partite Bell non-locality*):

- 10 *NS-interesting* causal classes,
- 3 of them turn out NS-equivalent (*collapse of the hierarchy!*),
- at least *7 have quantum violations.*

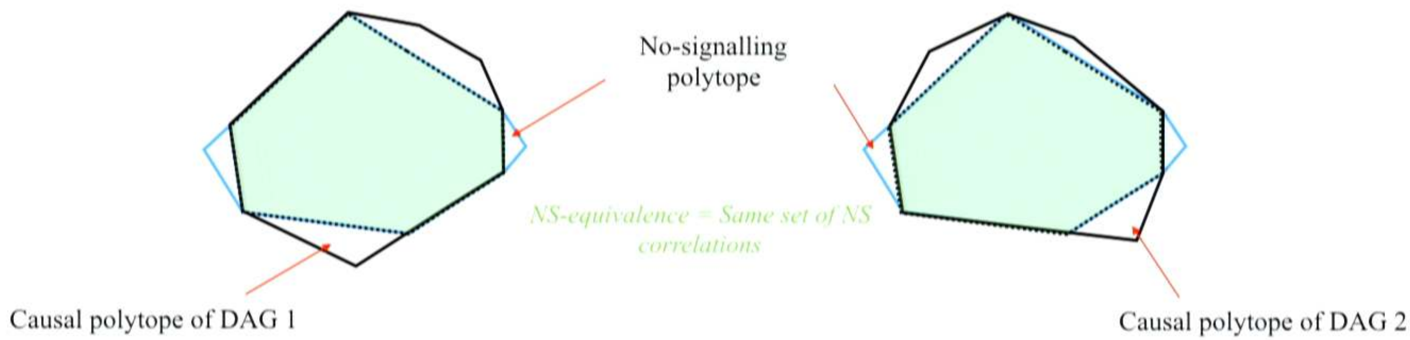
Satisfy Svetlichny's inequality →

N. S. Jones, N. Linden, and S. Massar (05).

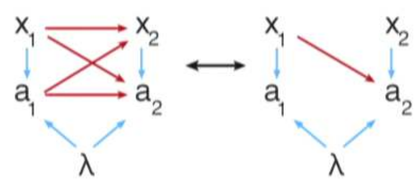


No-signalling equivalent Bell DAGs

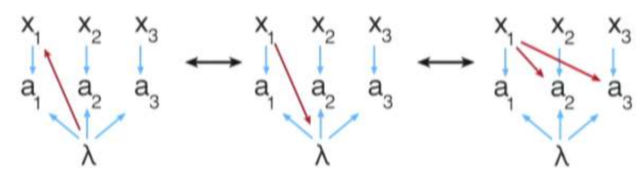
No-signalling equivalence: same set of observable no-signalling correlations.



Lemma 1: The most *general locality relaxation* is *NS-equivalent to* an *input-output locality relaxation.*



Lemma 2: Any *measurement independence* relaxation is *NS-equivalent to input broadcasting*.



lifies the problem