The structures of spatially and temporally separated measurements

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Quantum measurement: a dialog of big and small

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Acknowledgments

Časlav Brukner

J.K. and Č. Brukner, PRA **87**, 052115 (2013)

Lucas Clemente

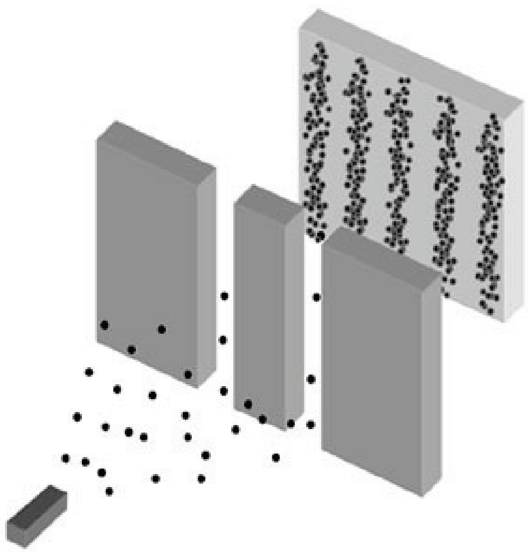
L. Clemente and J.K., PRA **91**, 062103 (2015)

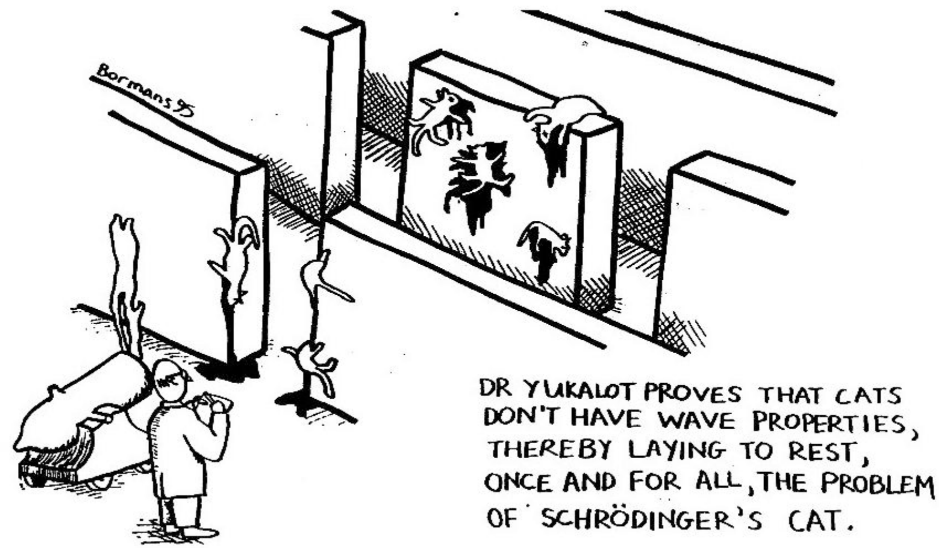
L. Clemente and J.K., PRL **116**, 150401 (2016)

Quantum-to-classical transition

With photons, electrons, neutrons, atoms, molecules

With cats?

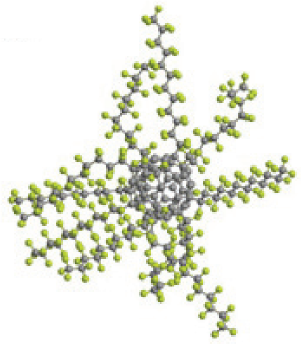




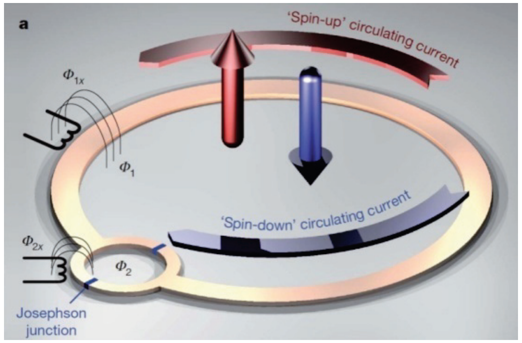
Measurement problem

Candidates

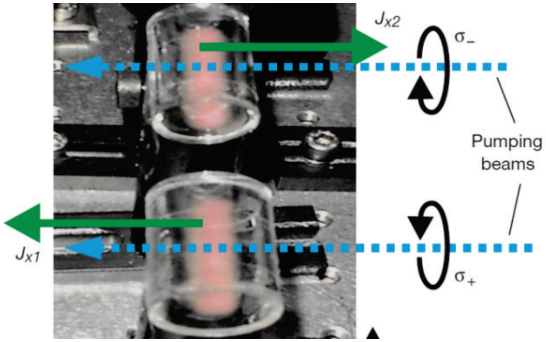
Heavy molecules[1]
(position)



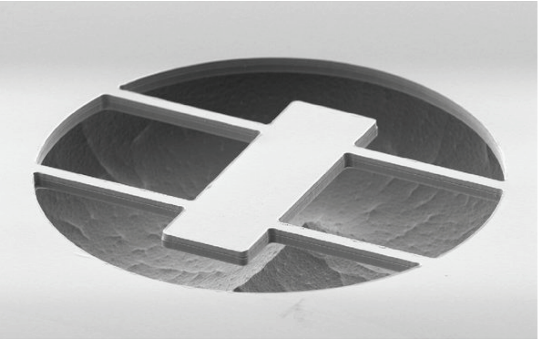
Superconducting devices[2]
(current)



Atomic gases[3]
(spin)



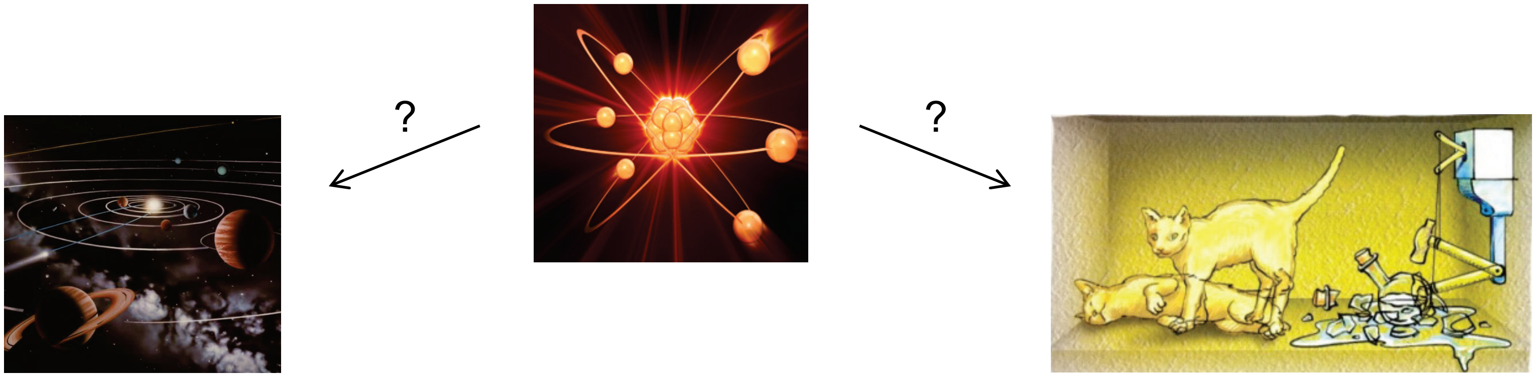
Nanomechanics[4]
(position, momentum)



[1] S. Gerlich *et al.*, Nature Comm. **2**, 263 (2011)
[2] M. W. Johnson *et al.*, Nature 473, 194 (2011)

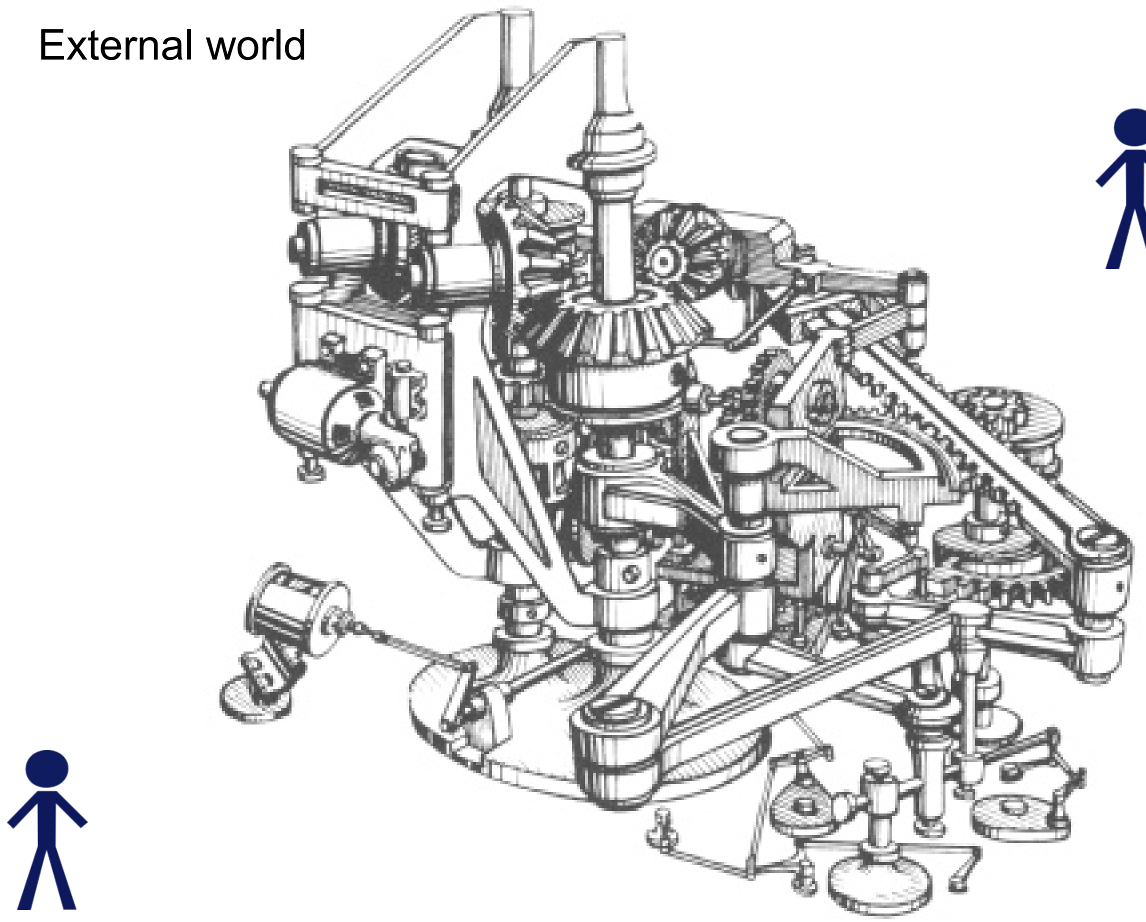
[3] B. Julsgaard *et al.*, Nature **413**, 400 (2001)
[4] G. Cole *et al.*, Nature Comm. **2**, 231 (2011)

Motivation and outline

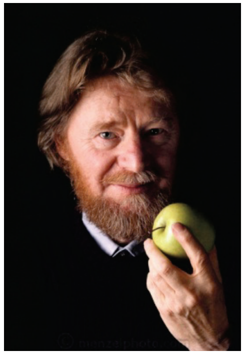


- How does our macroscopic & classical world arise out of quantum mechanics?
  - Within quantum mechanics: Decoherence
Coarse-grained measurements
  - Altering quantum mechanics: Spontaneous collapse models (GRW, Penrose, etc.)
- Are there macroscopic superpositions (“Schrödinger cats”)?
  - Quantum mechanics: in principle yes
  - Macrorealism: no, Leggett-Garg inequalities (LGIs) must hold
- This talk: Comparison of local realism and macrorealism
Alternative to the LGIs

Local realism



Local realism

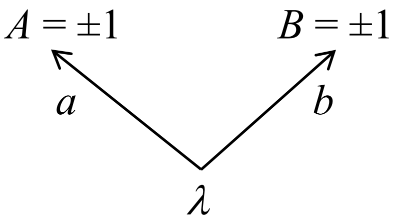


1. Realism is a worldview ”according to which external reality is assumed to exist and have definite properties, whether or not they are observed by someone.”[1] [Existence of hidden variables]

2. Locality demands that ”if two measurements are made at places remote from one another the [setting of one measurement device] does not influence the result obtained with the other.”[2]

3. Freedom of choice: settings can be chosen freely

Joint assumption: Local realism (LR) or “local causality”:[2]



$$\text{LR:}\quad P(A,B|a,b) = \sum\nolimits_{\lambda} \rho(\lambda)\, P(A|a,\lambda)\, P(B|b,\lambda)$$

- LR $\rightarrow$ Bell inequalities (BI): $\langle A_1 B_1 \rangle + \langle A_1 B_2 \rangle + \langle A_2 B_1 \rangle - \langle A_2 B_2 \rangle \leq 2$
  - very well developed research field
  - important for quantum information technologies (qu. cryptography, randomness certif.)
  - 2015: 3 loophole-free BI violations (NV centers – Delft, photons – Vienna, Boulder)

[1] J. F. Clauser and A. Shimony, Rep. Prog. Phys. **41**, 1881 (1978)
[2] J. S. Bell, Physics (New York) **1**, 195 (1964)

The local realism polytope

Fine theorem:[1]

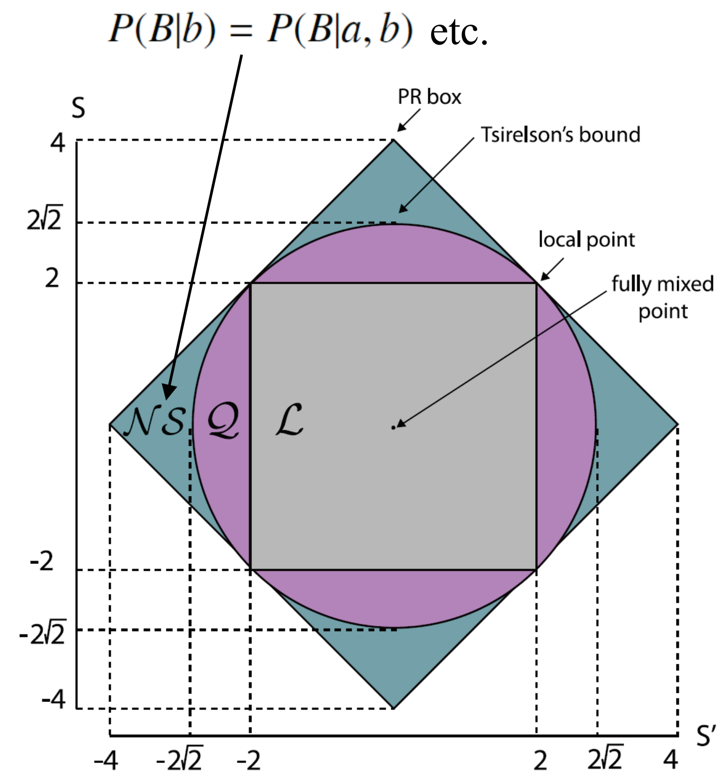
There exists a global joint probability distribution $P(A_1,A_2,B_1,B_2,)$ for all outcomes whose marginals are the experimentally observed probabilities

⇕

There exists a local hidden variable (i.e. local realistic) model for all probabilities

⇕

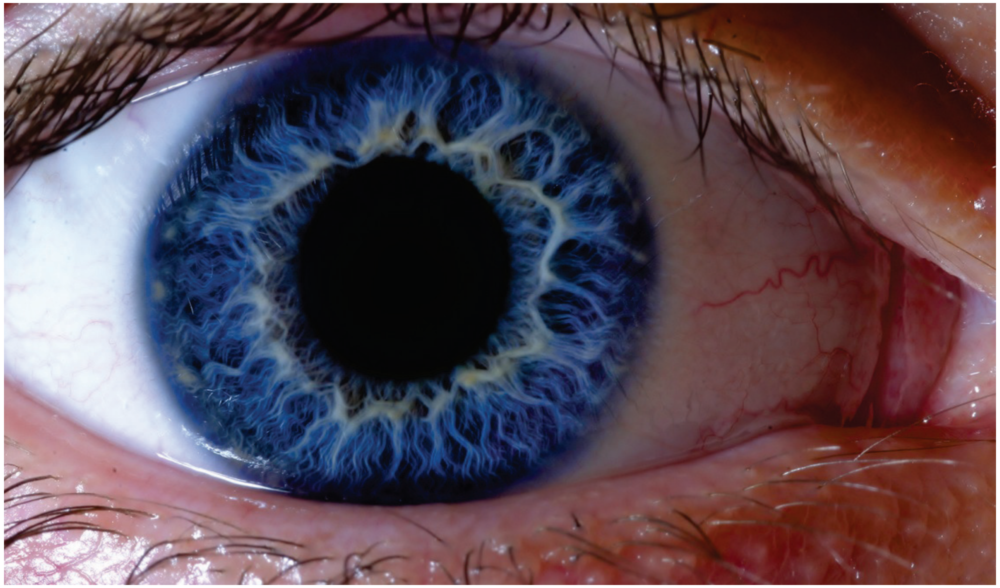
All Bell inequalities are satisfied



Picture: Rev. Mod. Phys. **86**, 419 (2014)

[1] A. Fine, PRL **48**, 291 (1982)

Macrorealism

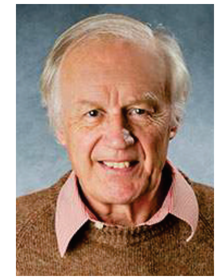


Macrorealism

1. Macrorealism per se: " A macroscopic object which has available to it two or more macroscopically distinct states is at any given time in a definite one of those states."[1]

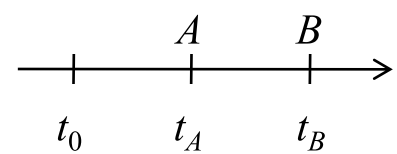
2. Non-invasive measurability: "It is possible in principle to determine which of these states the system is in without any effect on the state itself or on the subsequent system dynamics."[1]

3. Freedom of choice & Arrow of Time (AoT)



- Joint assumption: Macrorealism (MR):

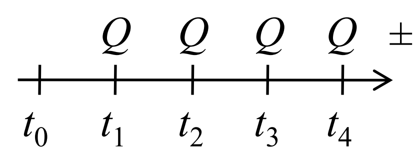
$$\text{MR:} \quad P(A_{t_A}, B_{t_B}) = \sum\nolimits_{\lambda} \rho(\lambda)\, P(A_{t_A}|\lambda)\, P(B_{t_B}|\lambda)$$



- MR restricts *temporal correlations* → Leggett-Garg inequality (LGI):

$$K := \langle Q_1 Q_2 \rangle + \langle Q_2 Q_3 \rangle + \langle Q_3 Q_4 \rangle - \langle Q_1 Q_4 \rangle \leq 2$$

= non-invasiveness



- Quantum mechanics (QM):

$$\text{QM:} \quad P(A_{t_A}, B_{t_B}) = \mathrm{Tr}[\hat{\rho}(t_A)\, \hat{M}_A]\, \mathrm{Tr}[\hat{\rho}_{A_{t_A}}(t_B)\, \hat{M}_B] \qquad K_{\mathrm{QM}} = 2\sqrt{2} \approx 2.83$$

[1] A. J. Leggett and A. Garg, PRL **54**, 857 (1985)

LGI violations for microscopic systems

PRL **106,** 040402 (2011) PHYSICAL REVIEW LETTERS week ending 28 JANUARY 2011

Experimental Violation of Two-Party Leggett-Garg Inequalities with Semiweak Measurements

J. Dressel, C. J. Broadbent, J. C. Howell, and A. N. Jordan

Experimental violation of a Bell's inequality in time with weak measurement

Agustin Palacios-Laloy[1], François Mallet[1], François Nguyen[1], Patrice Bertet[1*], Denis Vion[1], Daniel Esteve[1] and Alexander N. Korotkov[2]

PRL **107,** 090401 (2011) PHYSICAL REVIEW LETTERS week ending 26 AUGUST 2011

Violation of a Temporal Bell Inequality for Single Spins in a Diamond Defect Center

G. Waldherr,[1,*] P. Neumann,[1] S. F. Huelga,[2] F. Jelezko,[1,3] and J. Wrachtrup[1]

Violation of a Leggett-Garg inequality with ideal non-invasive measurements

George C. Knee[1], Stephanie Simmons[1], Erik M. Gauger[1,2], John J.L. Morton[1,3], Helge Riemann[4], Nikolai V. Abrosimov[4], Peter Becker[5], Hans-Joachim Pohl[6], Kohei M. Itoh[7], Mike L.W. Thewalt[8], G. Andrew D. Briggs[1] & Simon C. Benjamin[1,2]

PRL **112,** 190402 (2014) PHYSICAL REVIEW LETTERS week ending 16 MAY 2014

Probing Macroscopic Realism via Ramsey Correlation Measurements

A. Asadian,[1] C. Brukner,[2,3] and P. Rabl[1]

Violation of the Leggett–Garg inequality with weak measurements of photons

M. E. Goggin[a,b,1], M. P. Almeida[a], M. Barbieri[a,c], B. P. Lanyon[a], J. L. O'Brien[d], A. G. White[a], and G. J. Pryde[e]

PRL **115,** 113002 (2015) PHYSICAL REVIEW LETTERS week ending 11 SEPTEMBER 2015

Experimental Detection of Quantum Coherent Evolution through the Violation of Leggett-Garg-Type Inequalities

Zong-Quan Zhou,[1,2] Susana F. Huelga,[3,*] Chuan-Feng Li,[1,2,†] and Guang-Can Guo[1,2]

Preserving entanglement during weak measurement demonstrated with a violation of the Bell–Leggett–Garg inequality

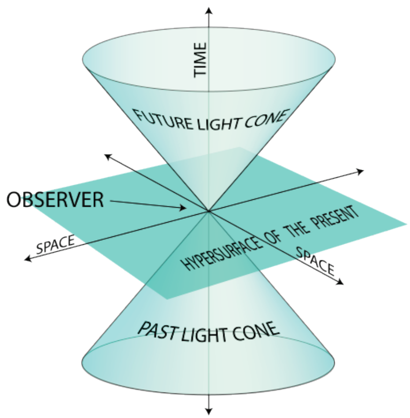
TC White[1,4,5], JY Mutus[1,4,5], J Dressel[2], J Kelly[1], R Barends[1,5], E Jeffrey[1,5], D Sank[1,5], A Megrant[1,3], B Campbell[1], Yu Chen[1,5], Z Chen[1], B Chiaro[1], A Dunsworth[1], I-C Hoi[1], C Neill[1], PJJ O'Malley[1], P Roushan[1,5], A Vainsencher[1], J Wenner[1], AN Korotkov[2] and John M Martinis[1,5]

Locality vs. non-invasiveness

How to enforce locality?

Space-like separation

Special relativity guarantees impossibility of physical influence



Bohmian mechanics

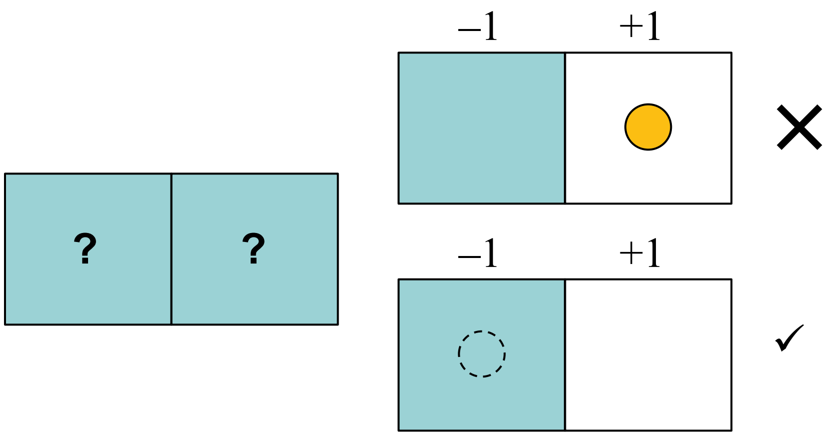
Space-like separation is of no help: non-local influence on hidden variable level

Realistic, non-local

How to enforce non-invasiveness?

Ideal negative measurements

Taking only those results where no interaction with the object took place



Bohmian mechanics

Ideal negative measurements are of no help: wavefunction "collapse" changes subsequent evolution

Macrorealistic per se, invasive

Analogy LR – MR

"One-to-one correspondence"

Local realism (LR)	Macrorealism (MR)
Realism	Macrorealism per se
Locality	Non-invasiveness
Freedom of choice	Freedom of choice & AoT
Bell inequalities (BI) for spatial correlations	Leggett-Garg inequ. (LGI) for temporal correlations

Now the analogy will break

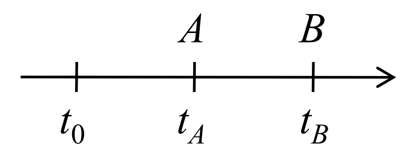
No signaling (in time)

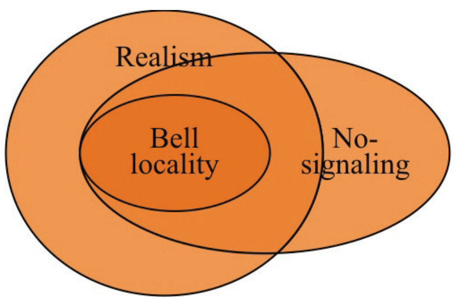
[LR] No-signaling (NS): “A measurement on one side does not change the outcome statistics on the other side.”

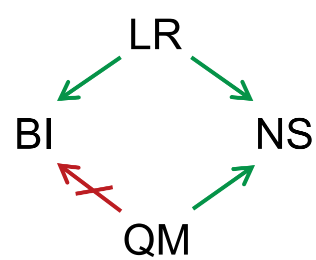
$$\text{NS:}\quad P(B|b) = P(B|a,b) = \sum_A P(A,B|a,b)$$

[MR] No-signaling in time (NSIT): “A measurement does not change the outcome statistics of a later measurement.”[1]

$$\text{NSIT:}\quad P(B_{t_B}) = P(B_{t_B|t_A}) = \sum_A P(A_{t_A}, B_{t_B})$$

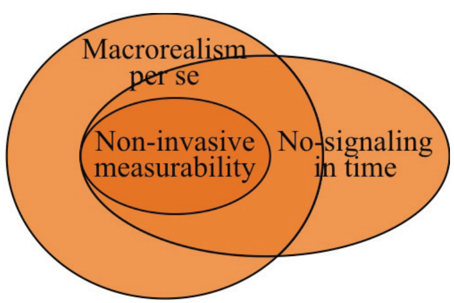


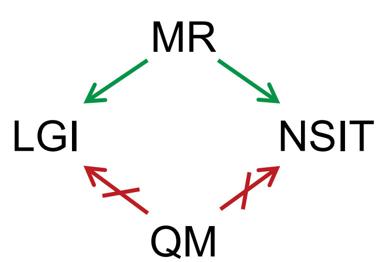




BI necessary for LR tests

NS “useless”

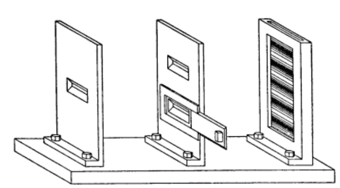




LGI not essential for MR tests

alternative: NSIT (interference)

more physical, simpler, stronger, more robust to noise



[1] J. K. and Č. Brukner, PRA **87**, 052115 (2013)

Necessary conditions for MR

$\mathrm{MR} \Rightarrow \mathrm{LGIs}, \mathrm{NSIT} \ldots$

Variety of necessary conditions for macrorealism[1]

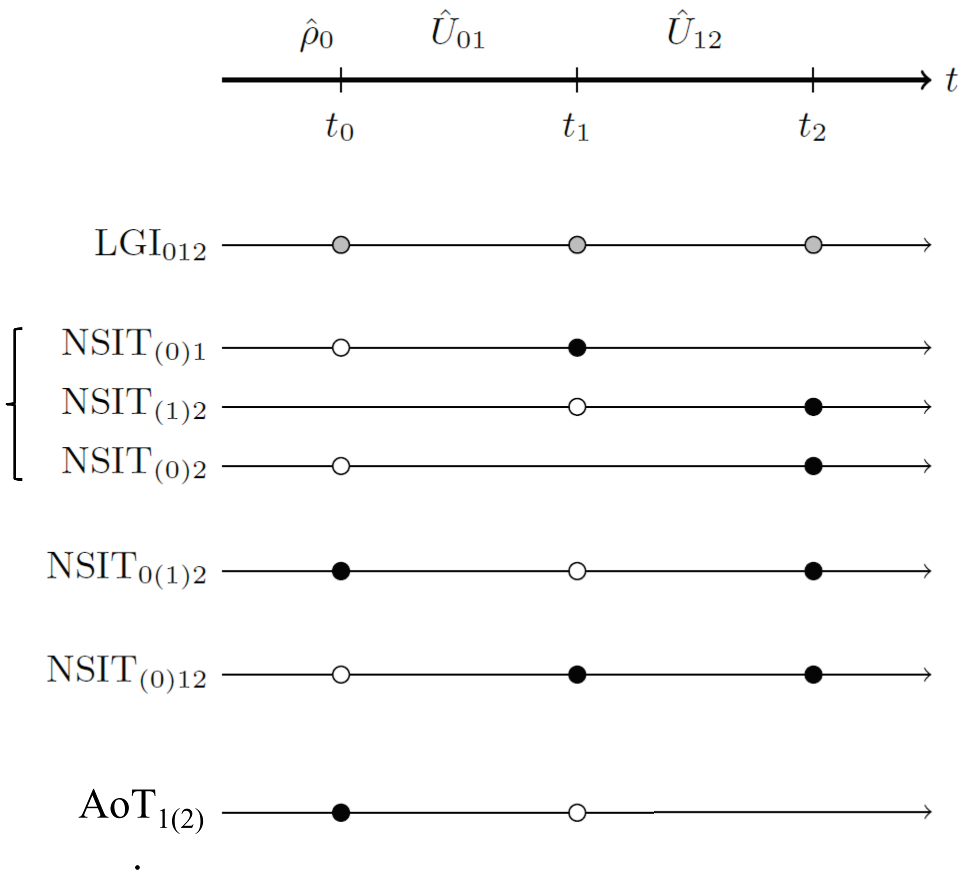
$\mathrm{LGI}_{012}: C_{01} + C_{12} - C_{02} \leq 1$

$\mathrm{NSIT}_{(i)j}: P_j(Q_j) = P_{ij}(Q_j) \equiv \sum_{Q_i'} P_{ij}(Q_i', Q_j)$

$\mathrm{NSIT}_{0(1)2}: P_{02}(Q_0, Q_2) = P_{012}(Q_0, Q_2)$

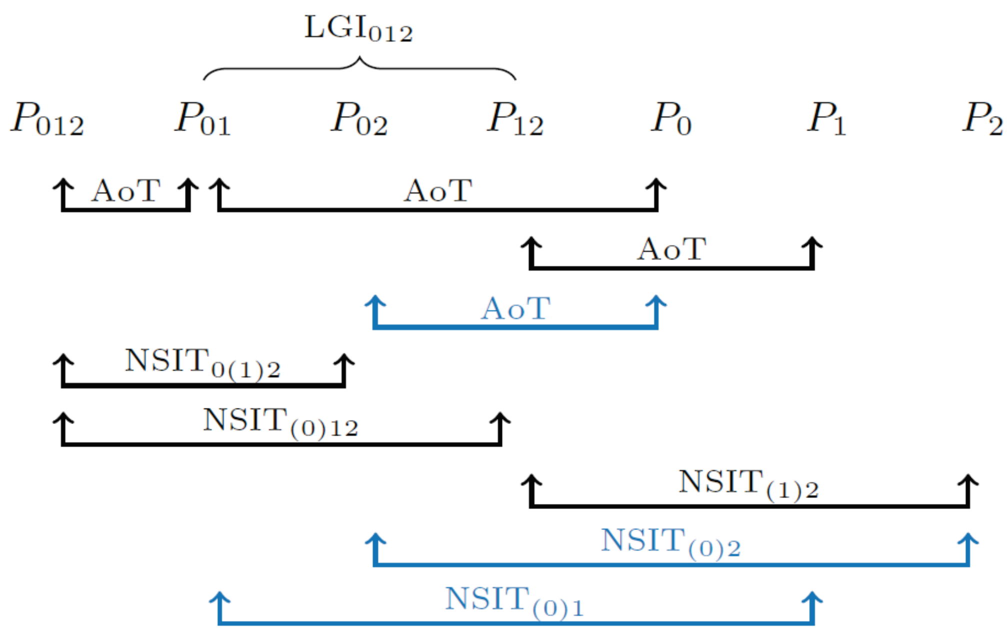
$\mathrm{NSIT}_{(0)12}: P_{12}(Q_1, Q_2) = P_{012}(Q_1, Q_2)$

Arrow of time (AoT): e.g. $P_1(Q_1) = P_{12}(Q_1)$



[1] L. Clemente and J.K., PRA **91**, 062103 (2015)

Necessary and sufficient for MR



Sufficient[1] for LGI$_{012}$

$$\mathrm{NSIT}_{0(1)2} \wedge \mathrm{NSIT}_{(0)12} \wedge \mathrm{AoT} \Rightarrow \mathrm{LGI}_{012}$$

Necessary and sufficient[2] for MR$_{012}$

$$\mathrm{NSIT}_{(1)2} \wedge \mathrm{NSIT}_{0(1)2} \wedge \mathrm{NSIT}_{(0)12} \wedge \mathrm{AoT} \Leftrightarrow \mathrm{MR}_{012}$$

Is there a set of LGIs which is necessary and sufficient for MR?

[1] O. J. E. Maroney and C. G Timpson, arXiv:1412.6139

[2] L. Clemente and J.K., PRA **91**, 062103 (2015)

Comparison of LR and MR

	LR test	MR test
$i = 1,2,\ldots,n$	n parties i (Alice, Bob, Charlie,…)	n measurement times i
$s_i = 0,1,2,\ldots,m$	$m+1$ possible settings for party i	$m+1$ possible settings for time i
	(s = 0: no measurement is performed)	
$q_i = 1,2,\ldots,\Delta$	Δ possible outcomes for party i	Δ possible outcomes for time i
	(for s = 0: Δ = 1)	

No. of unnorm. prob. distributions: $(m\Delta + 1)^n$

$(m+1)^n$ norm. conditions: $\forall s_1, \ldots, s_n : \sum_{q_1,\ldots,q_n} p_{q_1,\ldots,q_n|s_1,\ldots,s_n} = 1$

Positivity conditions: $\forall s_1, \ldots, s_n, q_1, \ldots, q_n : p_{q_1,\ldots,q_n|s_1,\ldots,s_n} \geq 0$

Dimension of the prob. polytope (P): $(m\Delta + 1)^n - (m+1)^n$

Comparison of LR and MR

LR test ⟵ $\dim \mathsf{P}$ ⟶ MR test

No-Signaling (NS) conditions

$$p_{q_1,\ldots,0,\ldots,q_n|s_1,\ldots,0,\ldots,s_n} = \sum_{q_i=1}^{\Delta} p_{q_1,\ldots,q_n|s_1,\ldots,s_n}$$

$$\dim \mathsf{NS} = [m(\Delta-1)+1]^n - 1$$

Arrow of time (AoT) conditions

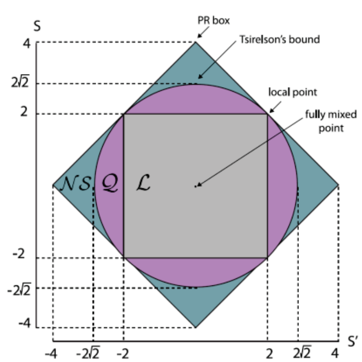
$$p_{q_1,\ldots,q_{i-1}|s_1,\ldots,s_{i-1}} = \sum_{q_i=1}^{\Delta} p_{q_1,\ldots,q_i|s_1,\ldots,s_i}$$

$$\dim \mathsf{AoT} = \frac{[(m\Delta+1)^n - 1](\Delta-1)}{\Delta}$$

$$\dim \mathsf{NS} = \dim \mathsf{QM_S} = \dim \mathsf{LR} < \dim \mathsf{AoT} = \dim \mathsf{QM_T}$$

BIs are hyperplanes in NS polytope

LGIs are hyperplanes in AoT polytope



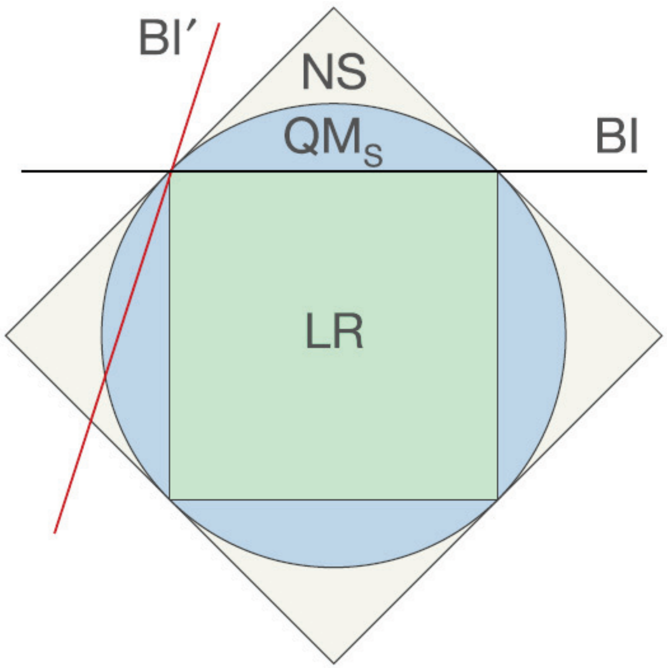
NSIT conditions

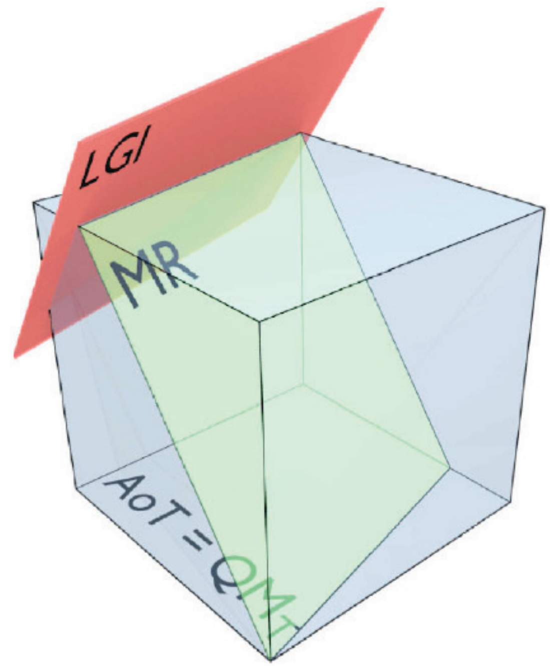
$$p_{q_1,\ldots,0,\ldots,q_n|s_1,\ldots,0,\ldots,s_n} = \sum_{q_i=1}^{\Delta} p_{q_1,\ldots,q_n|s_1,\ldots,s_n}$$

$$\dim \mathsf{MR} = [m(\Delta-1)+1]^n - 1$$
$$= \dim \mathsf{LR}$$

L. Clemente and J.K., PRL **116**, 150401 (2016)

Local realism versus macrorealism





	LR test		MR test
Number of unnormalized distributions		$(m\Delta + 1)^n$	
dim P		$(m\Delta + 1)^n - (m+1)^n$	
dim QM$_S$, dim QM$_T$	$[m(\Delta - 1) + 1]^n - 1$	$<$	$[(m\Delta + 1)^n - 1](\Delta - 1)/\Delta$
dim LR, dim MR		$[m(\Delta - 1) + 1]^n - 1$	

L. Clemente and J.K., PRL **116**, 150401 (2016)

No Fine theorem for MR

Fine's theorem in fact requires NS in its proof:

$$\text{BIs} \mathrel{\substack{\Leftarrow \\ \nRightarrow}} \text{LR} \Leftrightarrow \text{NS} \wedge \text{BIs}$$

NS (obeyed by QM) has two temporal 'cousins': AoT (obeyed by QM)
NSIT (violated by QM)

LGIs can never be sufficient for MR (except the "pathological case" where they pairwise form all NSIT equalities)

$$\text{LGIs} \mathrel{\substack{\Leftarrow \\ \nRightarrow}} \text{MR} \Leftrightarrow \text{AoT} \wedge \text{NSIT} \mathrel{\substack{\nLeftarrow \\ \Rightarrow}} \text{AoT} \wedge \text{LGIs}$$

Reason: MR lives in a different dimension than QM_T
LGIs are hyper-planes in a higher dimension than MR

$\rightarrow$ LGIs are non-optimal witnesses
LGIs needlessly restrict parameter space where a violation of MR can be found
Experiments should use NSIT criteria instead of LGIs

L. Clemente and J.K., PRL **116**, 150401 (2016)

Experimental advantage

- Superconducting flux qubit

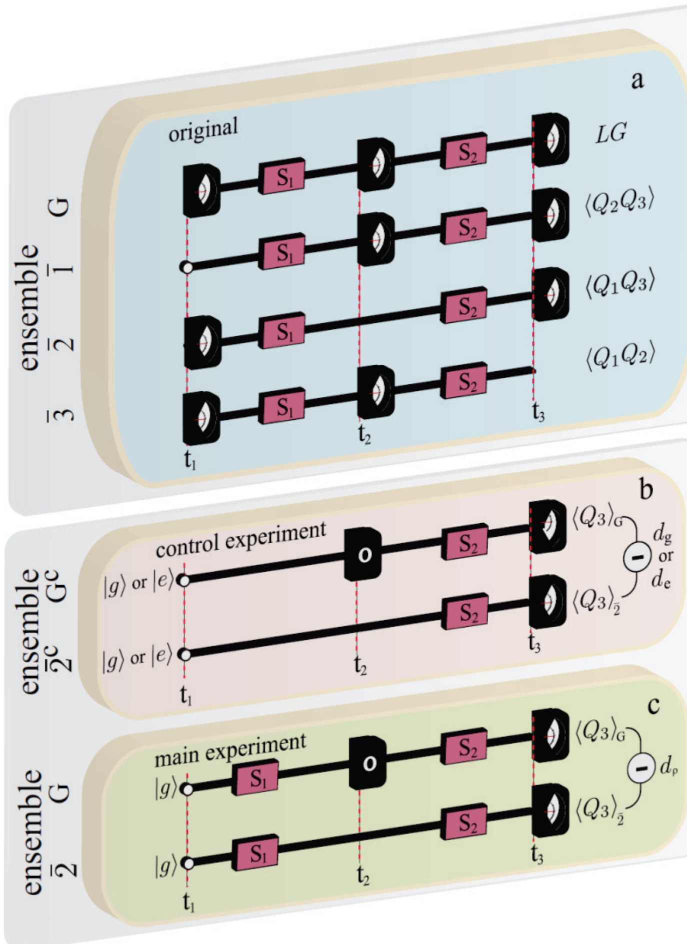
  Coherent superposition of 170 nA over a 9 ns timescale

- Experimental visibility "is far below that required to find a violation of the LGI"

- Violation of a NSIT criterion (with ~80 standard deviations)

$$\langle Q_3 \rangle_G - \langle Q_3 \rangle_{\bar{2}}$$

- Paves the way for experiments with much higher macroscopicities



G. C. Knee, K. Kakuyanagi, M.-C. Yeh, Y. Matsuzaki, H. Toida, H. Yamaguchi, S. Saito, A. J. Leggett, W. J. Munro, arXiv:1601.03728

Conclusion & Outlook

- Are macoscopic superpositions possible?

  QM: yes, MR: no
- Experimental tests are still many years or even decades away
- LGIs have been used (theoretically and experimentally) for many decades
- LGIs thought to be on equal footing with BIs
- The analogy breaks: NS obeyed by QM

  NSIT not obeyed by QM
- Fine theorem: for LR, not for MR
- NSIT is a better (simpler and stronger) criterion than the LGIs
- First experiments already take advantage