Thermodynamical cost of contextuality: A new way for device-independent quantum information

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Thermodynamics constrains interpretations of quantum mechanics

Theories that incorporate hidden variables are consistent with quantum mechanics only if the systems they describe can store unlimited information.

Steven K. Blau

Our work

PHYSICAL REVIEW A **94**, 052127 (2016)

Thermodynamical cost of some interpretations of quantum theory

Adán Cabello,[1,*] Mile Gu,[2,3,4] Otfried Gühne,[5] Jan-Åke Larsson,[6] and Karoline Wiesner[7]

Karoline Wiesner

The team

Karoline Wiesner

Plan

- Thermodynamical cost of interpretations of QT
- Thermodynamical cost of quantum contextuality
- How to use it for device-independent applications

2015: 3 "loophole-free" Bell inequality violations

Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

B. Hensen[1,2], H. Bernien[1,2]†, A. E. Dréau[1,2], A. Reiserer[1,2], N. Kalb[1,2], M. S. Blok[1,2], J. Ruitenberg[1,2], R. F. L. Vermeulen[1,2], R. N. Schouten[1,2], C. Abellán[3], W. Amaya[3], V. Pruneri[3,4], M. W. Mitchell[3,4], M. Markham[5], D. J. Twitchen[5], D. Elkouss[1], S. Wehner[1], T. H. Taminiau[1,2] & R. Hanson[1,2]

Nature **526**, 682 (2015)

Selected for a Viewpoint in *Physics*
PRL **115**, 250401 (2015) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2015

Significant-Loophole-Free Test of Bell's Theorem with Entangled Photons

Marissa Giustina,[1,2,*] Marijn A. M. Versteegh,[1,2] Sören Wengerowsky,[1,2] Johannes Handsteiner,[1,2] Armin Hochrainer,[1,2] Kevin Phelan,[1] Fabian Steinlechner,[1] Johannes Kofler,[3] Jan-Åke Larsson,[4] Carlos Abellán,[5] Waldimar Amaya,[5] Valerio Pruneri,[5,6] Morgan W. Mitchell,[5,6] Jörn Beyer,[7] Thomas Gerrits,[8] Adriana E. Lita,[8] Lynden K. Shalm,[8] Sae Woo Nam,[8] Thomas Scheidl,[1,2] Rupert Ursin,[1] Bernhard Wittmann,[1,2] and Anton Zeilinger[1,2,†]

Selected for a Viewpoint in *Physics*
PRL **115**, 250402 (2015) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2015

Strong Loophole-Free Test of Local Realism*

Lynden K. Shalm,[1,†] Evan Meyer-Scott,[2] Bradley G. Christensen,[3] Peter Bierhorst,[1] Michael A. Wayne,[3,4] Martin J. Stevens,[1] Thomas Gerrits,[1] Scott Glancy,[1] Deny R. Hamel,[5] Michael S. Allman,[1] Kevin J. Coakley,[1] Shellee D. Dyer,[1] Carson Hodge,[1] Adriana E. Lita,[1] Varun B. Verma,[1] Camilla Lambrocco,[1] Edward Tortorici,[1] Alan L. Migdall,[4,6] Yanbao Zhang,[2] Daniel R. Kumor,[3] William H. Farr,[7] Francesco Marsili,[7] Matthew D. Shaw,[7] Jeffrey A. Stern,[7] Carlos Abellán,[8] Waldimar Amaya,[8] Valerio Pruneri,[8,9] Thomas Jennewein,[2,10] Morgan W. Mitchell,[8,9] Paul G. Kwiat,[3] Joshua C. Bienfang,[4,6] Richard P. Mirin,[1] Emanuel Knill,[1] and Sae Woo Nam[1,‡]

Question

- What's the physical meaning of the violation of Bell inequality?

What’s the meaning of the violation ?

It means that the Universe is *nonlocal*

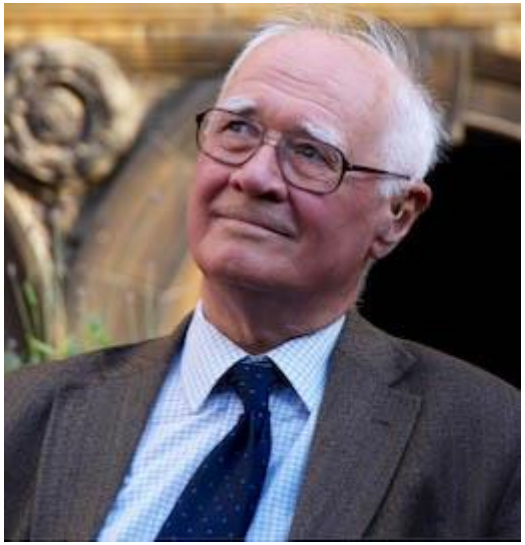
The message is that outcomes are *irreducibly random*

Descartes prize ceremony, members of the QuComm project winning team from left to right: V. Berger, N. Gisin, A. Karlsson, M. Aspelmeyer, A. Zeilinger, and T. Jennewein.

What's the meaning of the violation of Bell inequality?

The choice cannot be made simply on purely physical grounds but it requires an act of *metaphysical* judgement

John Charlton Polkinghorne is a theoretical physicist, theologian, writer and Anglican priest. He was professor of Mathematical physics at the University of Cambridge from 1968 to 1979, when he resigned his chair to study for the priesthood, becoming an ordained Anglican priest in 1982. He served as the president of Queens' College, Cambridge from 1988 until 1996. He was knighted in 1997 and in 2002 received the £1 million Templeton Prize.



Questions, questions

- Is entanglement an objective property of a system?
- What is the physical meaning of quantum contextuality?
- What is teleported in quantum teleportation?
- How does a quantum computer really work?

Answers?

- Yes!
- Outcome contextuality!
- A real state!
- Many universes!

No!
Outcome indeterminism!
An agent’s expectations!
…

Reflection

- How do you plan to make progress if, after 90 years of QT, you still don't know what does it *mean*?

- How can you possibly identify the *physical* principles behind QT or extend QT into gravity if you don't agree on what QT *is about*?

Interpretations of quantum theory

Quantum theory is the most useful and powerful theory physicists have ever devised. Yet today, nearly 90 years after its formulation, disagreement about the meaning of the theory is stronger than ever. New interpretations appear every day. None ever disappear

Interpretations of quantum theory

Ithaca

Bub

Ballentine

Bohmian mechanics

Brukner

Einstein

No “interpretation”

Bell’s “beables”

Copenhagen

Wheeler

Many worlds

Modal interpretations

QBism

Consistent histories

Spekkens

Many minds

Collapse theories

Kochen

Relational interpretations

Zeilinger

A map of madness

	ψ-Ontic	ψ-Epistemic
Type-I (intrinsic realism)	Bohmian mechanics[10,11] Many worlds[12,13] Modal[14,15] Bell's "beables"[16] Collapse theories*[17,18]	Einstein[19] Ballentine[20] Consistent histories[21,22] Spekkens[23]

	About knowledge	About belief
Type-II (participatory realism)	Copenhagen[24,25] Wheeler[26,27] Relational[28,29] Zeilinger[3,30] No "interpretation"[31] Brukner[32]	QBism[33–35]

Let’s classify the interpretations of QT

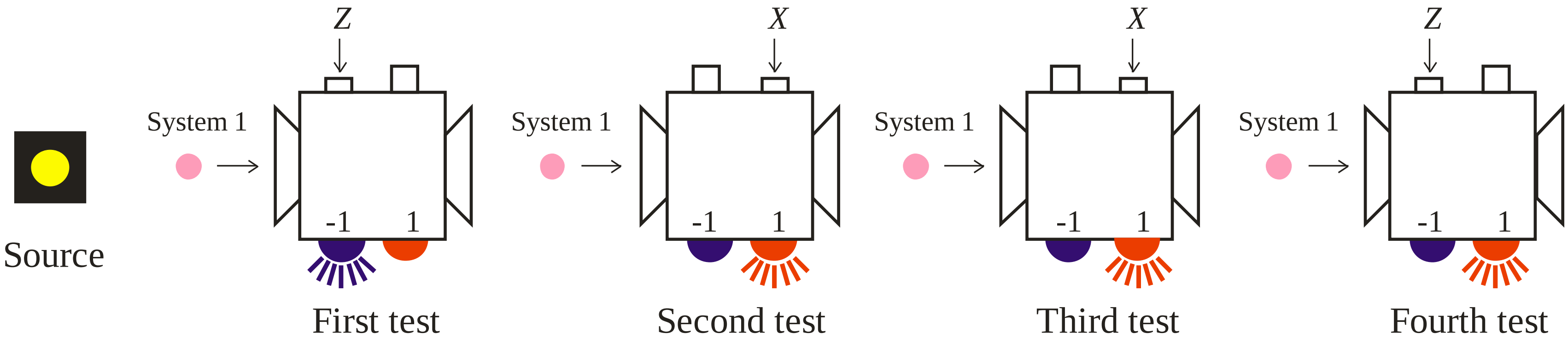
- Type I: Probabilities of measurement outcomes are determined by objective properties
    - ψ-ontic: The quantum state is an objective property
    - ψ-epistemic: The quantum state represents the observer's knowledge of an underlying reality
- Type II: QT does not deal with objective properties, but with an experiences of an agent. Probabilities of measurement outcomes are *not* determined by objective properties. The quantum state is an agent’s collection of expectations about the results of future experiments

Plan

- Thermodynamical cost of interpretations of QT
- Thermodynamical cost of quantum contextuality
- How to use it for device-independent applications

Consider an ideal experiment

- One qubit
- Projective measurements, randomly chosen between σ_z and σ_x, are sequentially performed
- Infinite times



Assumptions

(i) The choice of which measurement is performed can be made randomly and independently of the system under observation

(ii) The system has limited memory

(iii) Landauer's principle holds: the erasure of one bit of information in the system must be accompanied by a corresponding entropy increase in its environment, therefore causing that the system dissipates at least $kT \ln 2$ units of heat

R. Landauer, Irreversibility and heat generation in the computing process, IBM J. Res. Dev. **5**, 183 (1961).

For type-I interpretations (i.e., intrinsic realism)

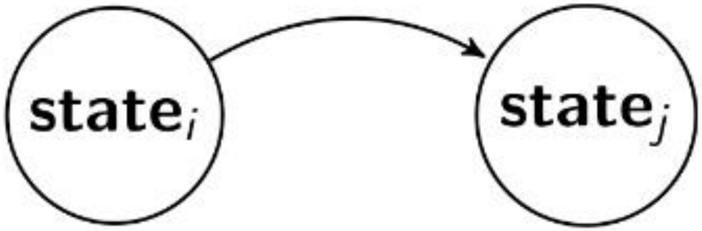
- (i) At any *t*, the quantum probabilities are determined by objective properties that may change depending on which measurements are performed
- (ii) The system cannot have the values for all possible sequences of measurements. To avoid a “memory overflow error”, ***the system should erase information***
- (iii) ***The system should dissipate***, at least, an amount of ***heat*** proportional to the information erased

Task

Calculate the minimum information that the system must erase

Tool: Finite-state machines

- A realist model would necessarily need to have a *change of state*.



... but how many states are needed?

- States must contain information of any possibly relevant user history.
- A suitable language could be that of finite-state machines. (Kleinmann *et al.* 2011)

Minimum finite-state machine

Observation 1. Our ideal experiment is an *input-output process*. Therefore there exists a unique minimal and optimal predictor of the process, i.e., a unique abstract machine with minimal statistical complexity and maximal predictive power of the process' future output given the process' input-output past and the process' future input. This machine is called the process' ϵ-*transducer*.

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N. Barnett and J. P. Crutchfield, Computational mechanics of input-output processes: Structured transformations and the ε-transducer, J. Stat. Phys. **161**, 404 (2015).

Minimum heat machine

Observation 1. Our ideal experiment is an *input-output process*. Therefore there exists a unique minimal and optimal predictor of the process, i.e., a unique abstract machine with minimal statistical complexity and maximal predictive power of the process' future output given the process' input-output past and the process' future input. This machine is called the process' ϵ-*transducer*.

… and we can prove that it **is** also **the finite-state machine** simulating our experiment **which produces minimum heat** due to Landauer's principle.

Result 1

on average, the system should dissipate, at least, $\frac{3}{2}kT\ln 2$ units of heat per measurement.

For type-II interpretations (i.e., participatory realism)

Measurement outcomes are randomly created by measurements, without “overwriting” information in the system and thus without the system dissipating heat

The difference

Landauer’s principle also applies to type II interpretations as it applies to, e.g., the measurement apparatus, the observer’s brain or her notebook.

However these heats are:

- **Common** to type I and type II interpretations
- **Bounded** as measurements have finite precision

The difference

Landauer’s principle also applies to type II interpretations as it applies to, e.g., the measurement apparatus, the observer’s brain or her notebook.

However these heats are:

- **Common** to type I and type II interpretations
- **Bounded** as measurements have finite precision

What is different is that in, type I, in addition, there is a classical system that produces an **EXTRA** heat

Result 2

For the experiment in which a qubit is submitted to sequential measurements randomly chosen from

$$\mathcal{X}(n) = \left\{ \cos\left(\tfrac{\pi k}{2^n}\right)\sigma_z + \sin\left(\tfrac{\pi k}{2^n}\right)\sigma_x ; k = 0, \ldots, 2^n - 1 \right\},$$

on average, the system should dissipate an amount of heat per measurement that tends to infinity linearly with n.

Conclusions (1)

- Type-I interpretations + (i)-(iii): **the system dissipates an unbounded amount of heat in each measurement**
- One has to abandon either type-I or one of (i)-(iii)
- Another possible escape would be that the set of possible measurements and states is actually **discrete** or that precision is **bounded**
- This would imply that QT is only a continuous idealization of a deeper discrete theory. And yet the system would dissipate a certain amount of heat

Moral

- Bell’s theorem: Any hidden variable theory whose predictions are compatible with QT must have action at a distance

Moral

- Bell’s theorem: Any hidden variable theory whose predictions are compatible with QT must have action at a distance
- Here: Any hidden variable theory whose predictions are compatible with QT must have infinite memory

Plan

- Thermodynamical cost of interpretations of QT
- Thermodynamical cost of quantum contextuality
- How to use it for device-independent applications

Contextuality

Contextuality is the leading notion of nonclassicality:

- It applies to single systems (unlike nonlocality)
- It is well-defined (unlike the failure of macroscopic realism)
- It has a direct interpretation (unlike Wigner negativity)

The Kochen-Specker theorem

The KS theorem addresses the following question:

- Is it possible that, at any instant of time, sharp measurements possess a definite value, regardless of whether they have been measured?

The Kochen-Specker theorem

The KS theorem addresses the following question:

- Is it possible that, at any instant of time, sharp measurements possess a definite value, regardless of whether they have been measured?

It is impossible for quantum systems of dimension > 2

The Peres-Mermin inequality

$$\boxed{\langle ABC\rangle+\langle abc\rangle+\langle\alpha\beta\gamma\rangle+\langle Aa\alpha\rangle+\langle Bb\beta\rangle-\langle Cc\gamma\rangle\leq 4}$$

$$\begin{array}{lll}
A=\sigma_z^{(1)}, & B=\sigma_z^{(2)}, & C=\sigma_z^{(1)}\otimes\sigma_z^{(2)}, \\
a=\sigma_x^{(2)}, & b=\sigma_x^{(1)}, & c=\sigma_x^{(1)}\otimes\sigma_x^{(2)}, \\
\alpha=\sigma_z^{(1)}\otimes\sigma_x^{(2)}, & \beta=\sigma_x^{(1)}\otimes\sigma_z^{(2)}, & \gamma=\sigma_y^{(1)}\otimes\sigma_y^{(2)}.
\end{array}$$

6… for any qubit-qubit state!

A. Cabello, Phys. Rev. Lett. **101**, 210401 (2008).

Why is it impossible?

Two options are offered:

- *Outcome indeterminism*. It is because the observables <u>do not have predetermined values</u>; the values are created when the measurements are performed
- *Outcome contextuality*. It is because the observables <u>have predetermined values</u>, but they are contextual; i.e., they depend on which other compatible observables are measured

Imitating quantum contextuality with classical systems

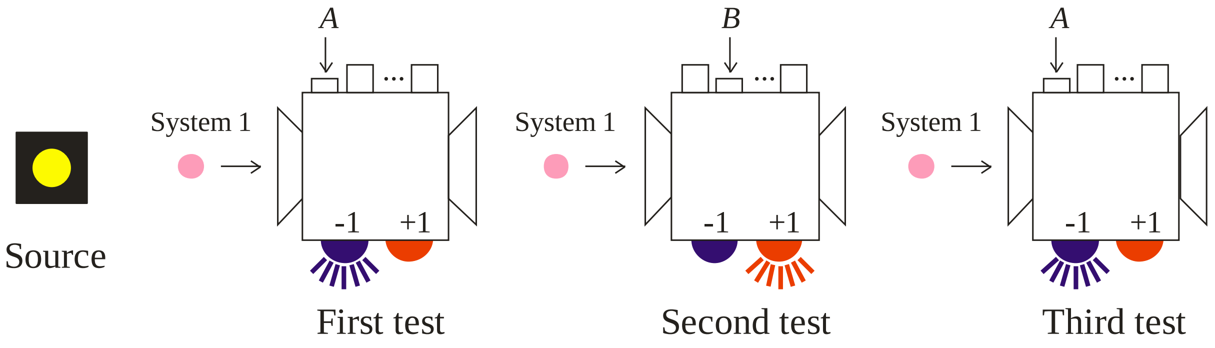
B. R. La Cour, Quantum contextuality in the Mermin-Peres square: A hidden-variable perspective, Phys. Rev. A **79**, 012102 (2009).
M. Kleinmann, O. Gühne, J. R. Portillo, J.-Å. Larsson, and A. Cabello, Memory cost of quantum contextuality, New J. Phys. **13**, 113011 (2011).
W. N. Plick and R. Lapkiewicz, Explicit contextualized hidden-variable model replicating an indivisible quantum system, Phys. Rev. A **89**, 022108 (2014).
P. Blasiak, Classical systems can be contextual too: Analogue of the Mermin-Peres square, Ann. Phys. **353**, 326 (2015).

Consider the following ideal experiment

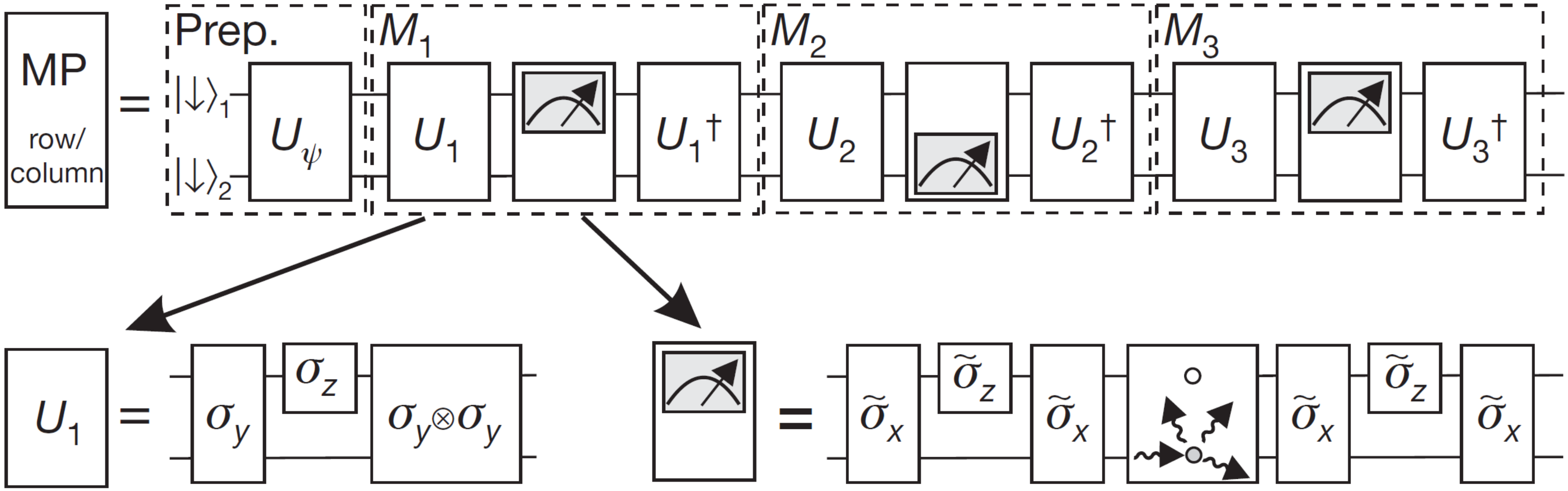
- System: Two qubits

- Projective measurements, randomly chosen from the Peres-Mermin KS set, are sequentially performed at regular instants of time

- Infinite times

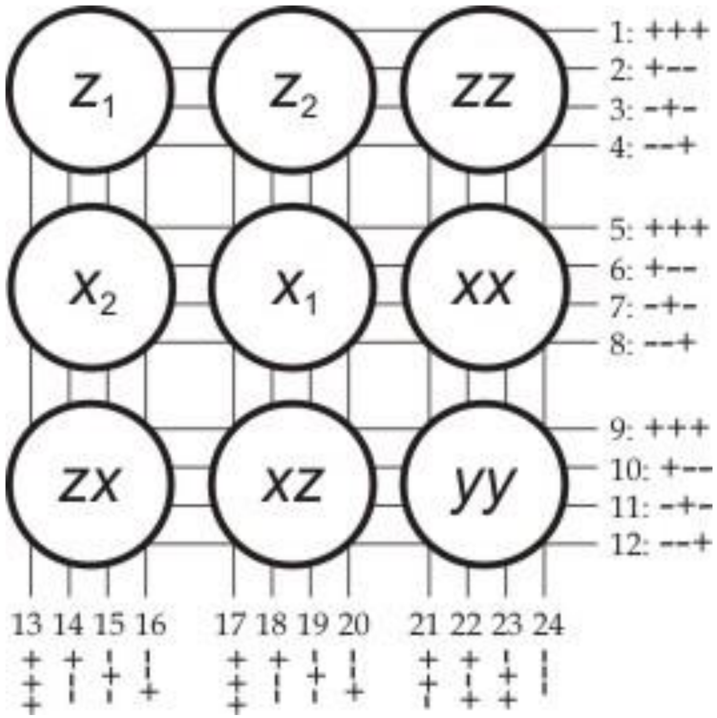


Sequential sharp measurements on trapped ions

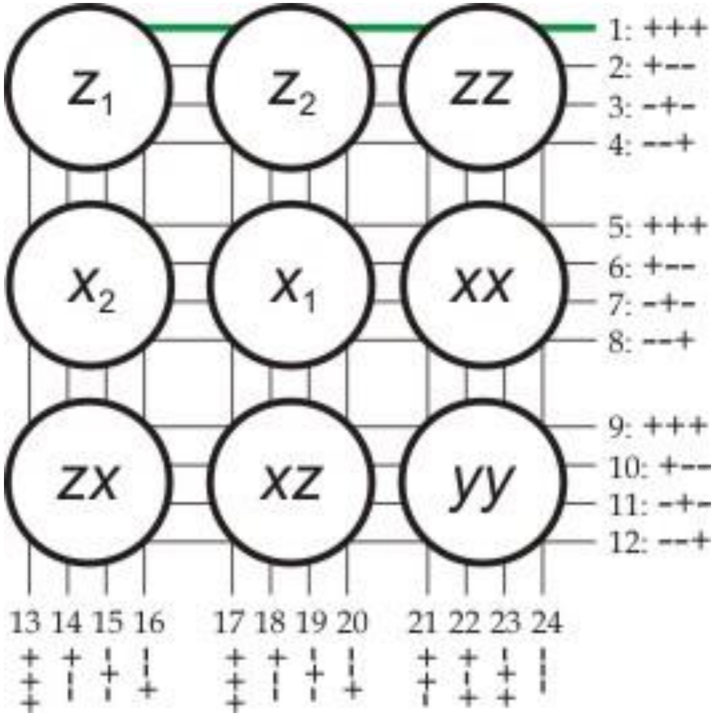


G. Kirchmair, F. Zähringer, R. Gerritsma, M. Kleinmann, O. Gühne, A. Cabello, R. Blatt and C. F. Roos, Nature **460**, 494 (2009).

The 24 states of the Peres-Mermin table

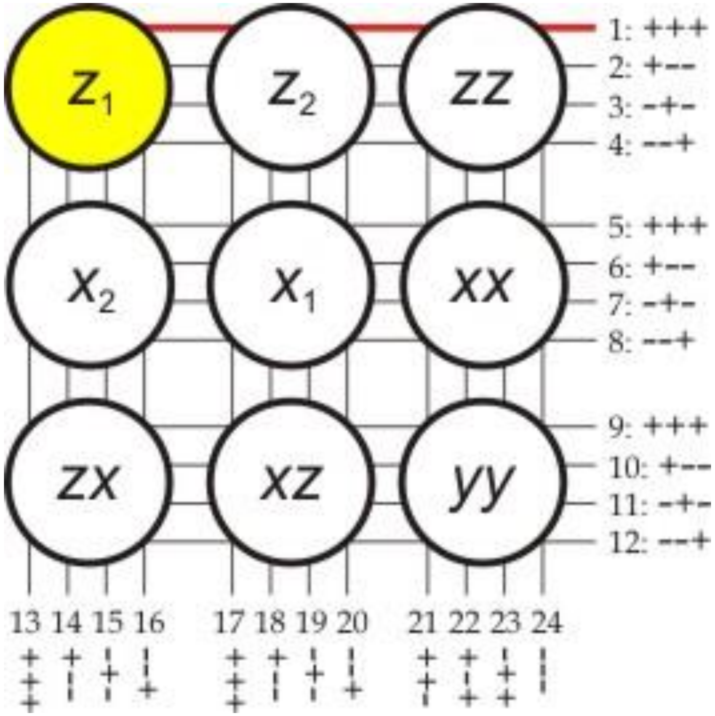


How to end up in state 1?

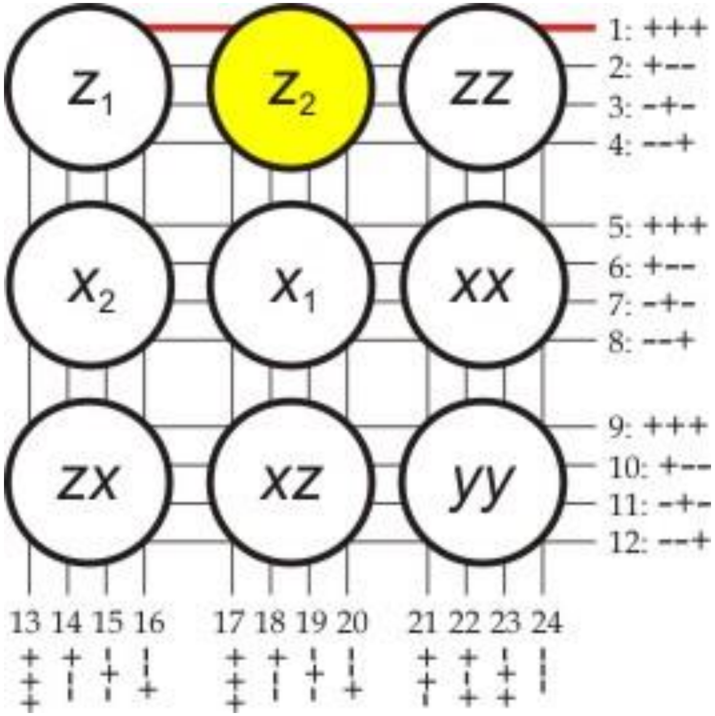


There are 15 ways

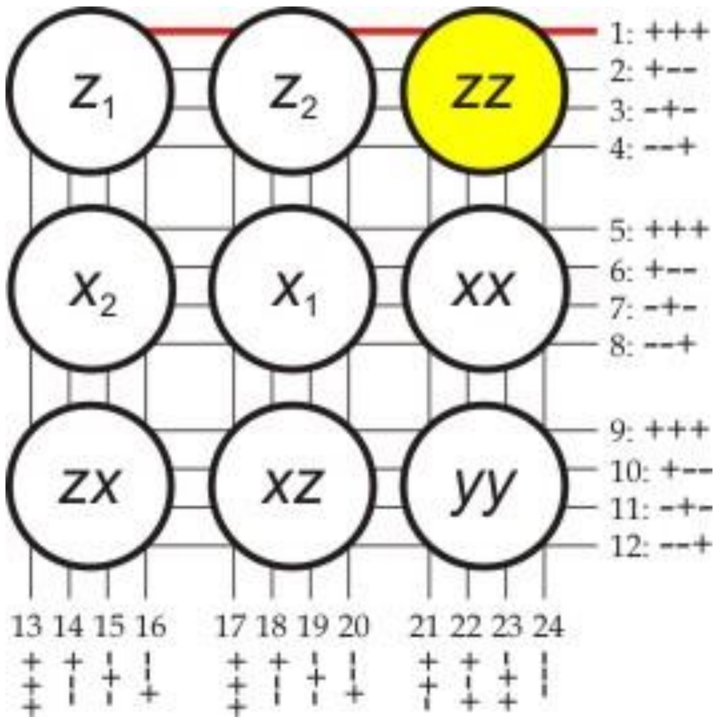
#1: To end up in state 1 with probability 1



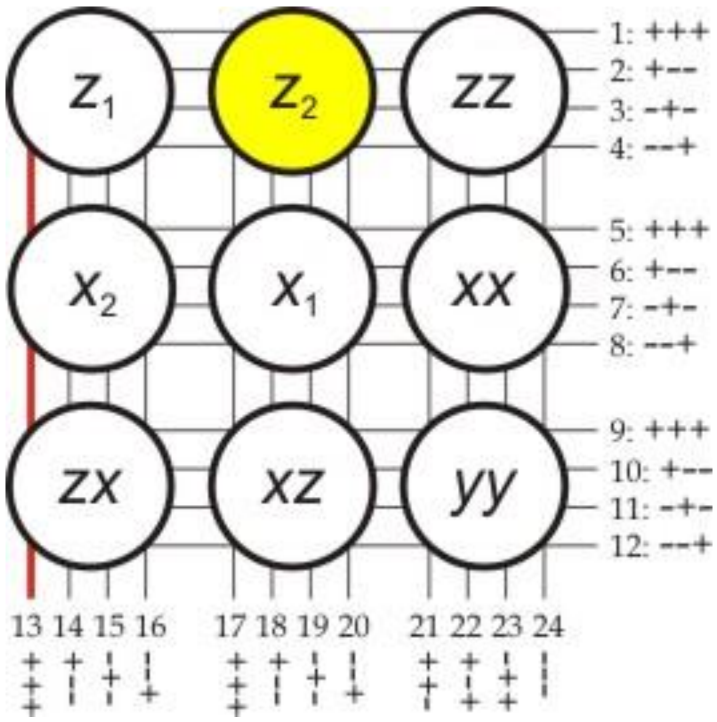
#2: To end up in state 1 with probability 1



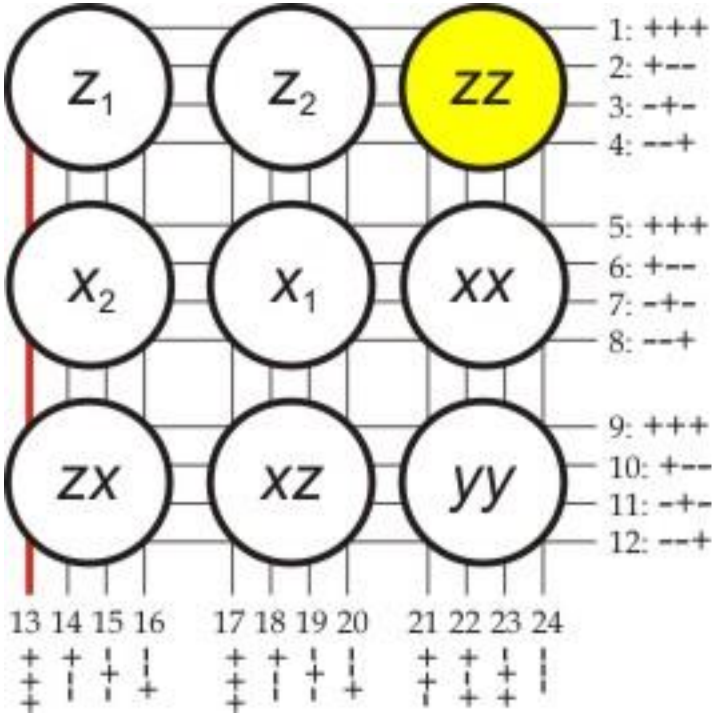
#3: To end up in state 1 with probability 1



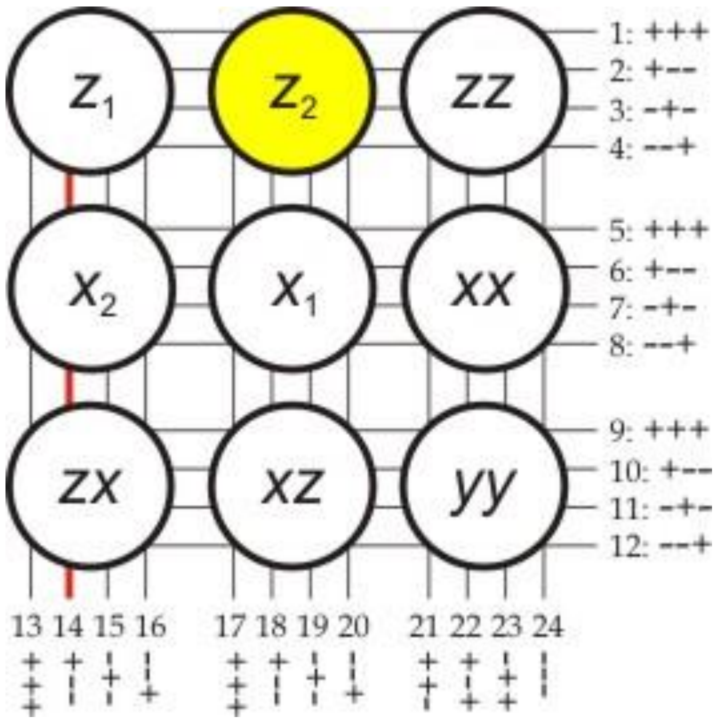
#4: To end up in state 1 with probability 1/2



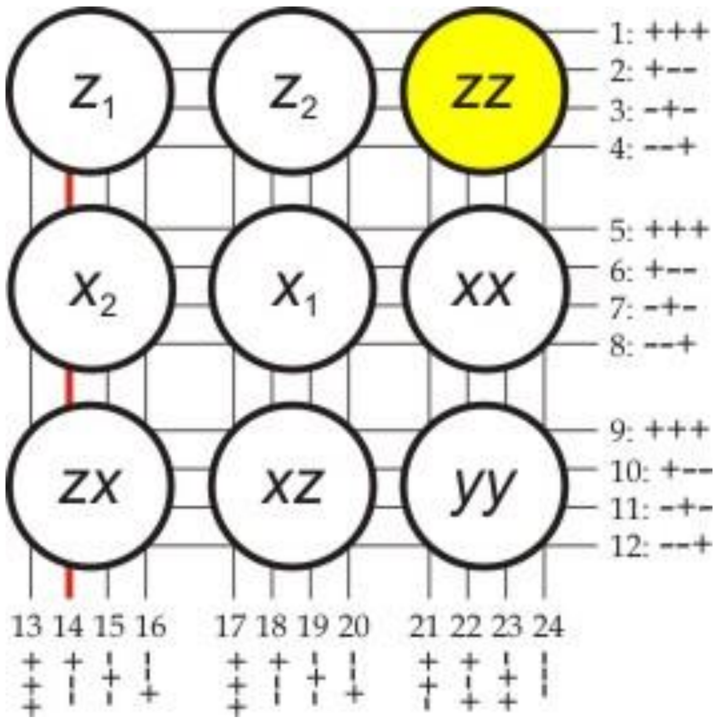
#5: To end up in state 1 with probability 1/2



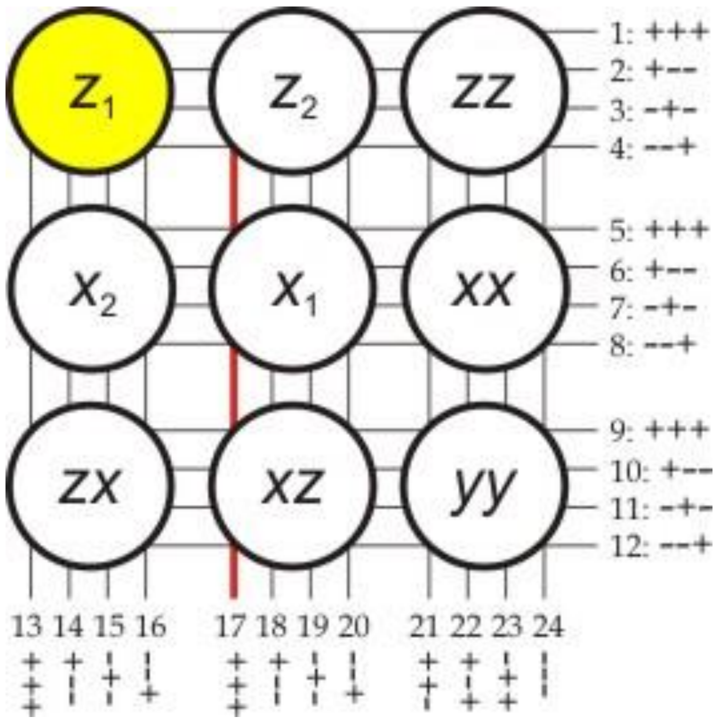
#6: To end up in state 1 with probability 1/2



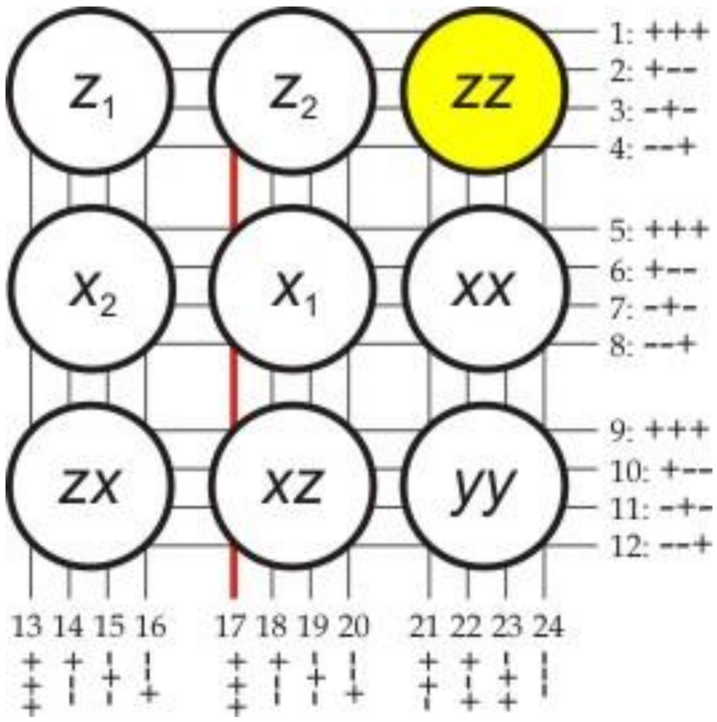
#7: To end up in state 1 with probability 1/2



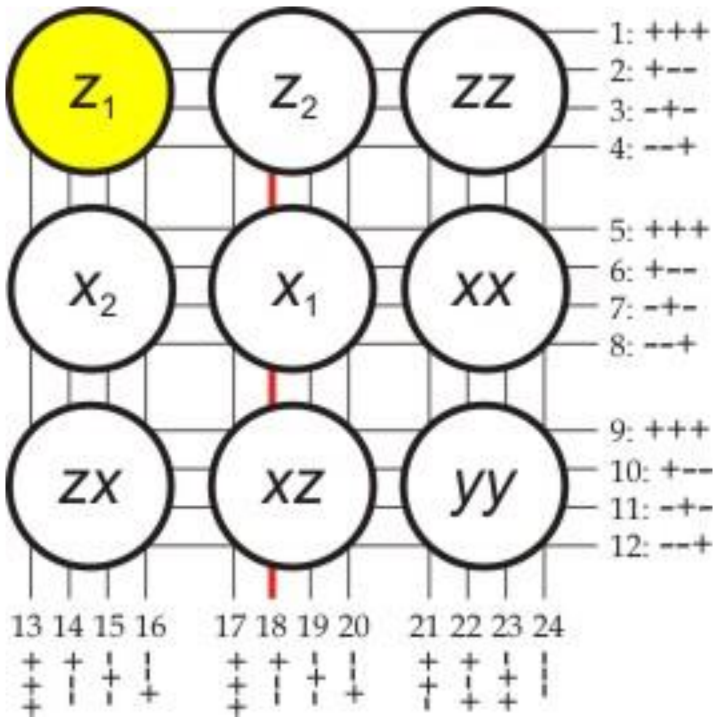
#8: To end up in state 1 with probability 1/2



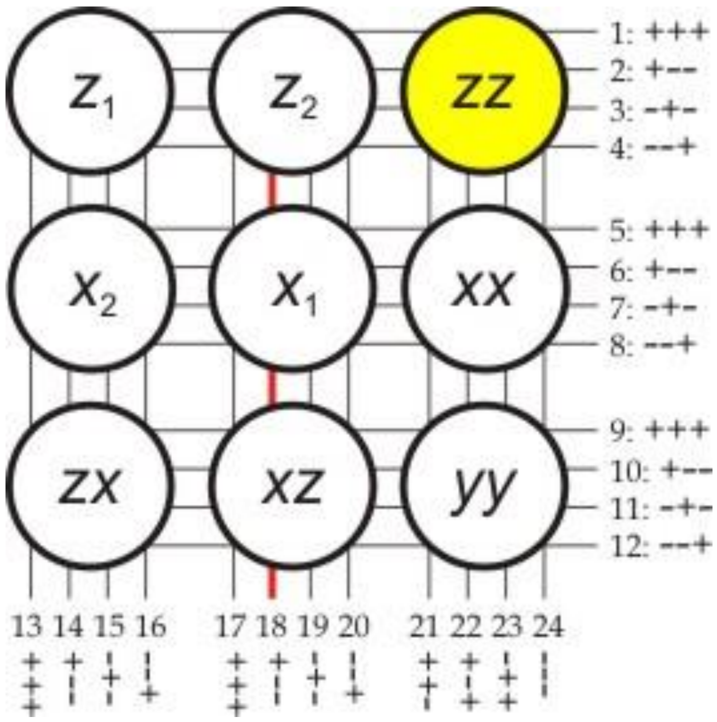
#9: To end up in state 1 with probability 1/2



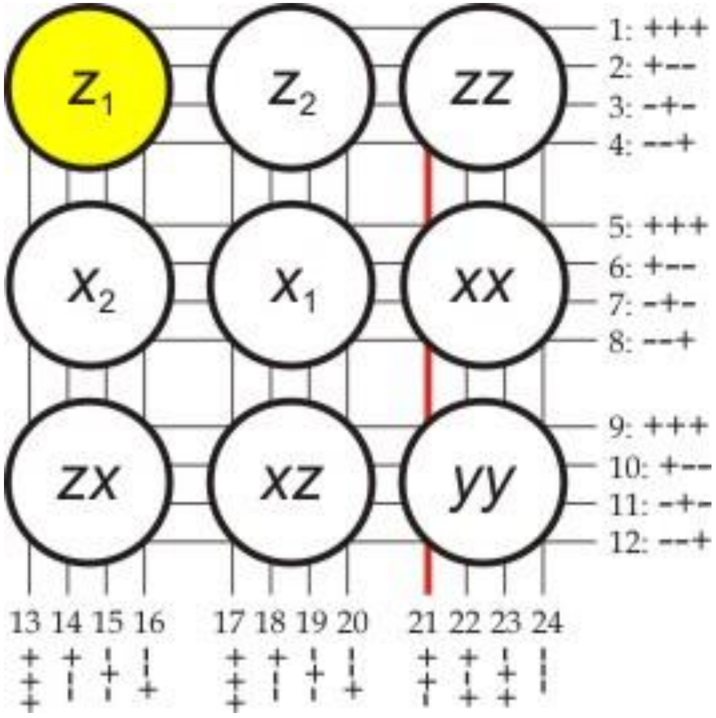
#10: To end up in state 1 with probability 1/2



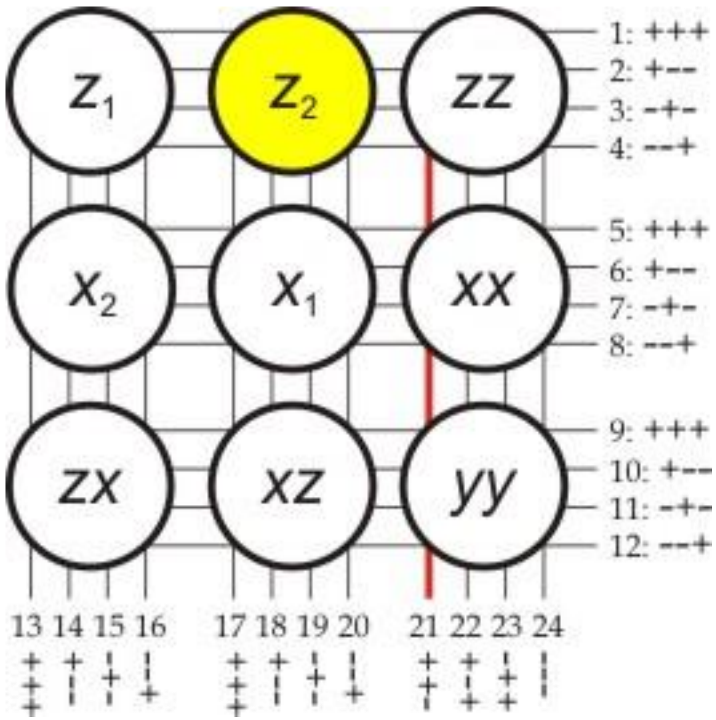
#11: To end up in state 1 with probability 1/2



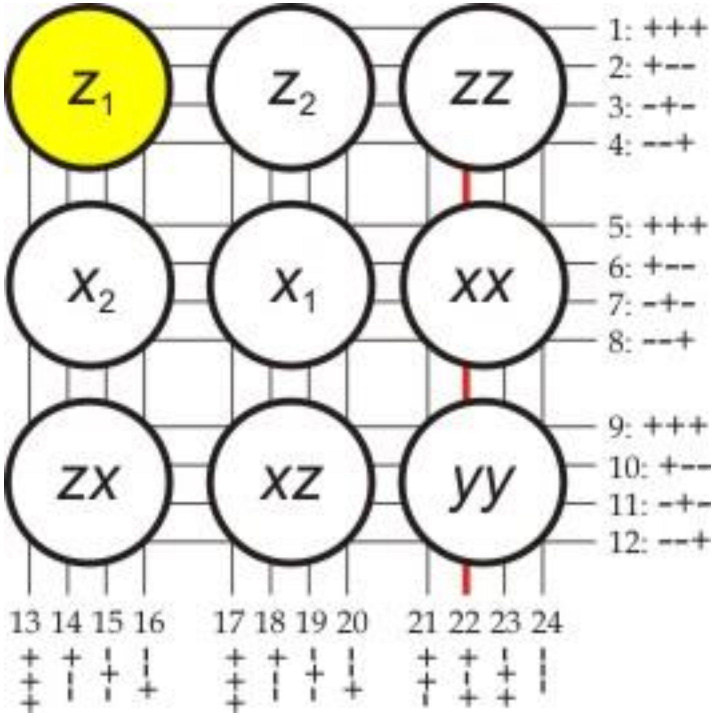
#12: To end up in state 1 with probability 1/2



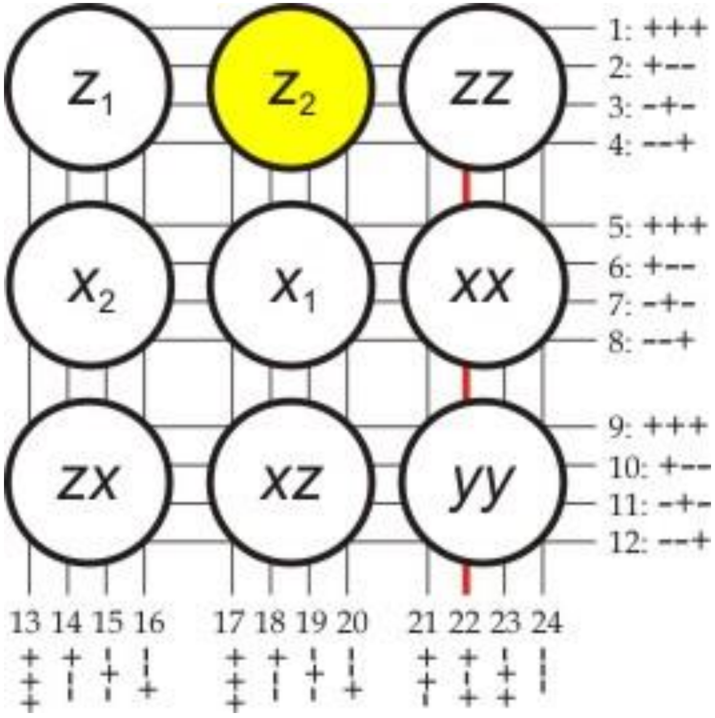
#13: To end up in state 1 with probability 1/2



#14: To end up in state 1 with probability 1/2



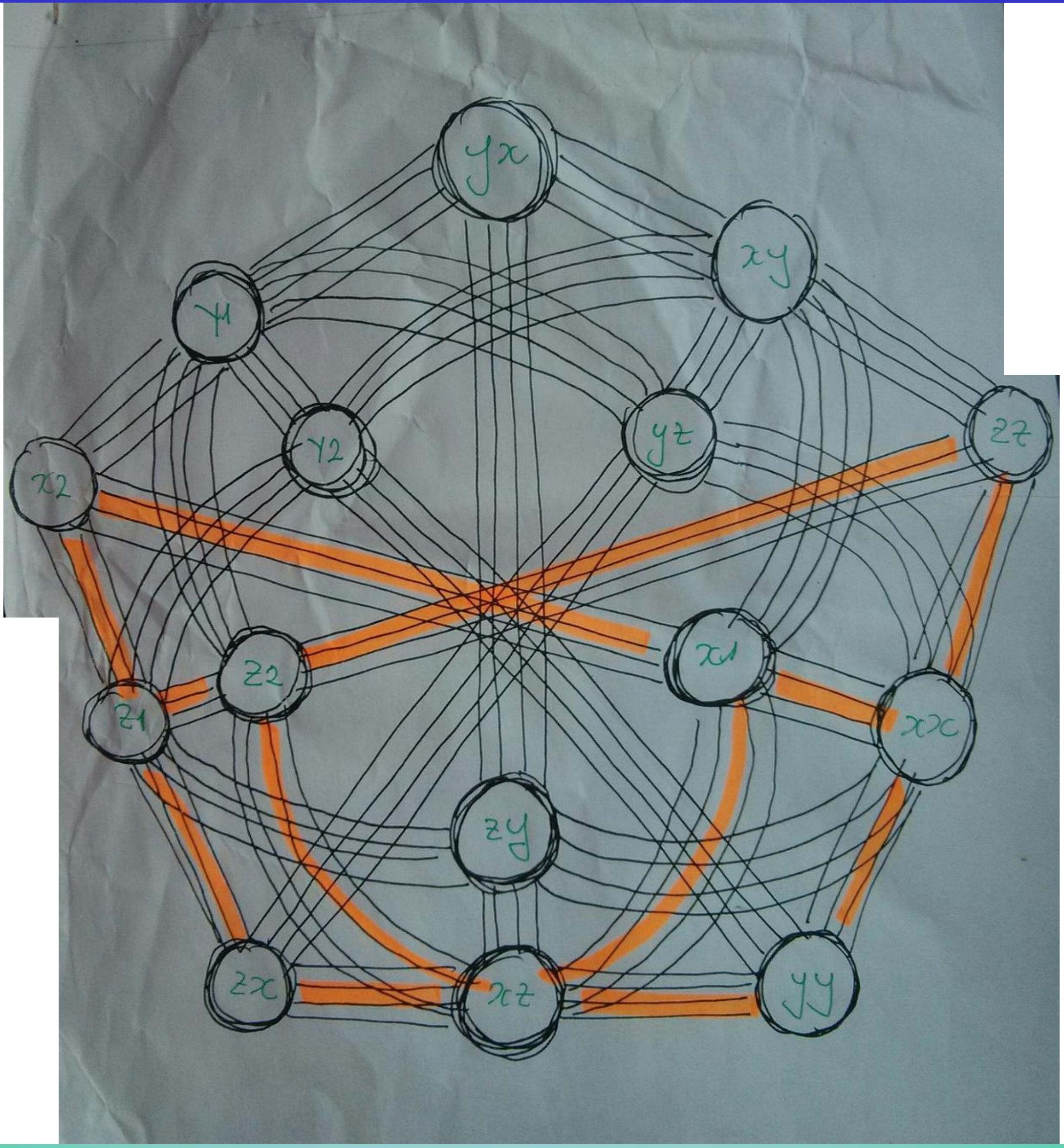
#15: To end up in state 1 with probability 1/2



Result 3

the system should dissipate, at least, $2.25kT\ln 2$ units of heat per measurement.

Extended Peres-Mermin: 15 observables, 60 states



Result 4

on average, the system should dissipate, at least, $3.12kT \ln 2$ units of heat per measurement.

Result 5

In an experiment in which a 3-qubit system is submitted to sequential measurements randomly chosen from a set of n, the system should dissipate an amount of heat per measurement that tends to infinity linearly with n

Conclusion

- Quantum contextuality can be experimentally distinguished from classical contextuality produced with finite-size machines by measuring the heat released

Plan

- Thermodynamical cost of interpretations of QT
- Thermodynamical cost of quantum contextuality
- How to use it for device-independent applications

A new way for device-independent QI

Quantum contextuality offers a new way for DI tests:

Traditional DI:

- Checking space-like separation
- and assuming that adversaries cannot signal between space-like separated regions,
- the violation of Bell’s inequality certifies quantumness.

A new way for device-independent QI

Quantum contextuality offers a new way for DI tests:

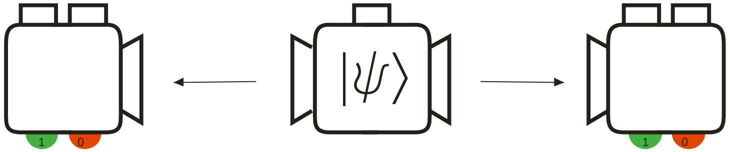
Traditional DI:

- Checking space-like separation
- and assuming that adversaries cannot signal between space-like separated regions,
- the violation of Bell's inequality certifies quantumness.

- Contextuality-based DI:
  - Checking absence of extra Landauer's heat
  - and assuming that adversaries have finite memory,
  - the violation of a noncontextuality inequality certifies quantumness.

Advantages

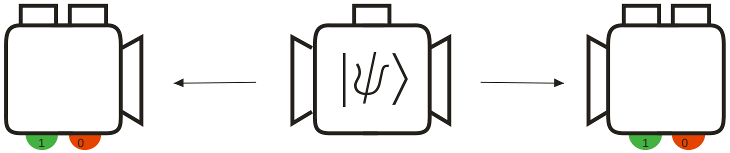
(a)



Advantages

- No spacelike separation is needed

(a)



Advantages

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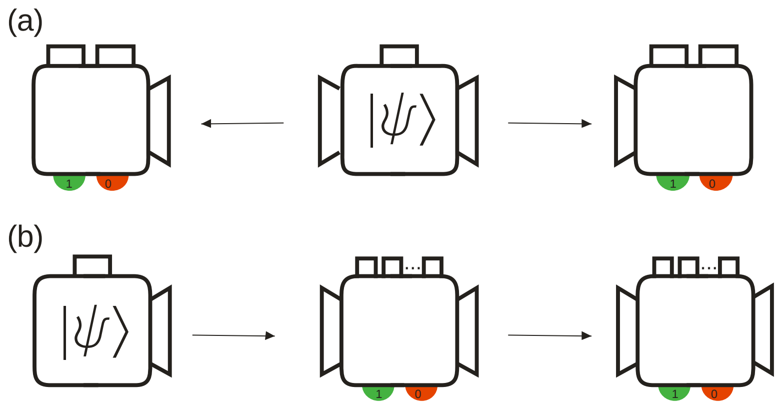
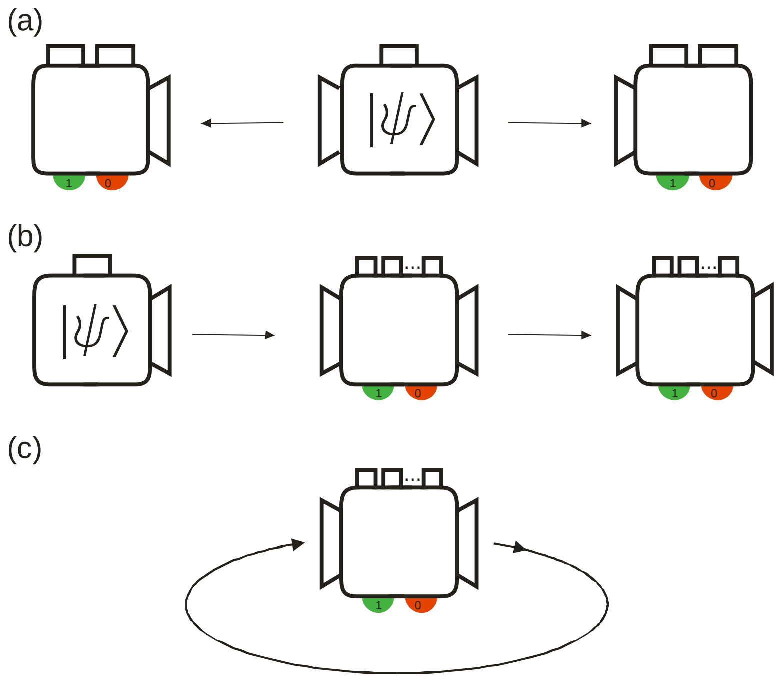


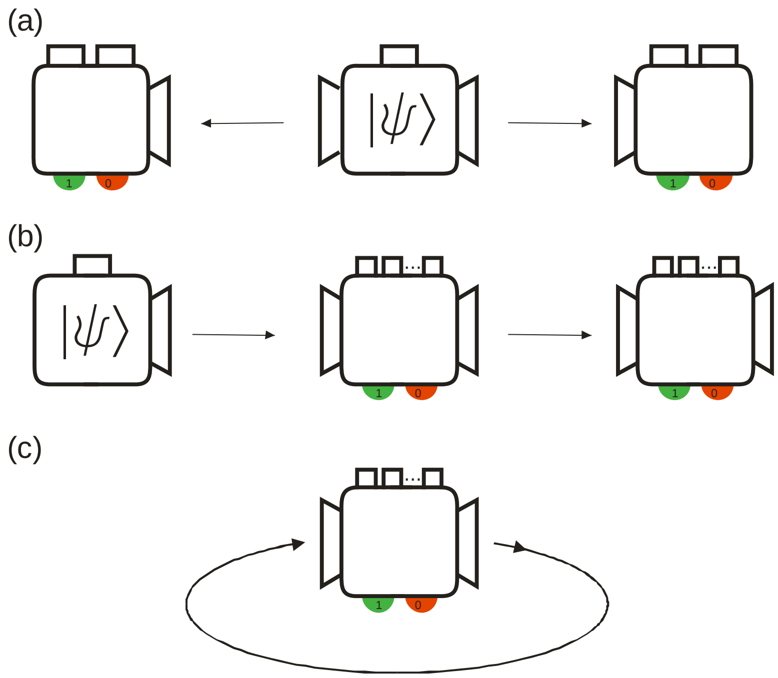
Advantages

- No spacelike separation is needed
- The system does not need to be initialized in any particular quantum state



Advantages

- No spacelike separation is needed
- The system does not need to be initialized in any particular quantum state
- The method is self-correcting and there is no limit to the number of correlations one can obtain with the same system



Comment in Physics Today

- Bell’s theorem: Any hidden variable theory whose predictions are compatible with QT must have action at a distance

- Here: Any hidden variable theory whose predictions are compatible with QT must have infinite memory

DKO • 23 days ago

This is a fascinating result. A naive question: Does anyone know if there is a way to link "no action at a distance" to "no infinite information storage", so that these two notions interpret each other, or even become equivalent?

3 • Reply • Share ›

Cartoon: “Heating at a distance”

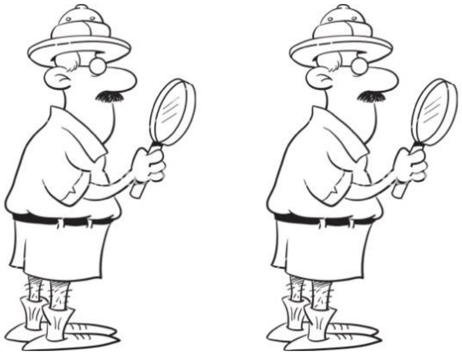
What if

there is action at a distance

but finite memory?

AI is measuring

AI keeps measuring again and again



Bob is in a pot

Eventually, if Bob has finite memory

Al heats Bob!

...