The Role of Statistical Science in Quantum Information - Theory and Application

- This introductory talk: discussion of loophole-free Bell experiments, esp. the Delft experiment of 2015

- That experiment "settles" the debate between Einstein and Bohr

  culminating in Einstein, Podolsky, Rosen (1935)

  turned on its head by Bell (1964)

  confirmed by Aspect (1981,1982) experiment

  still open to some doubt…

- and of more burning interest now than ever

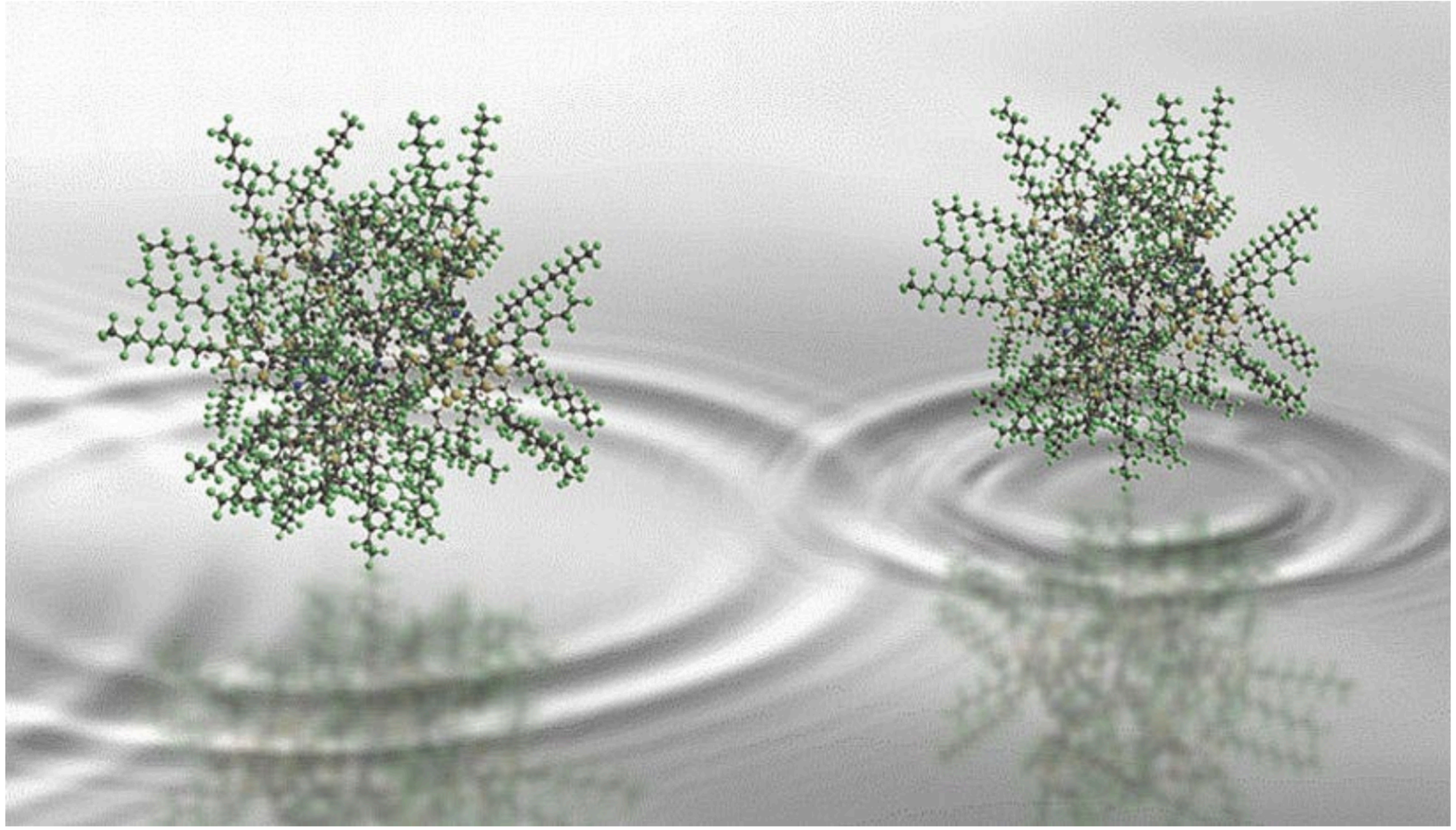
John Stewart Bell (b.1928, d. 1990)

https://scitechdaily.com/quantum-superposition-record-2000-atoms-in-two-places-at-once/

Quantum Superposition Record: 2000 Atoms in Two Places at Once

TOPICS: Nuclear Physics Particle Physics Quantum Mechanics University Of Vienna

By UNIVERSITY OF VIENNA OCTOBER 1, 2019



Artistic illustration of the delocalization of the massive molecules used in the experiment. Credit: © Yaakov Fein, Universität Wien

SUBSCRIBE

SciTechDaily: Home of the best science and technology news since 1998. Keep up with the latest scitech news via email or social media.

E-mail Submit

POPULAR ARTICLES

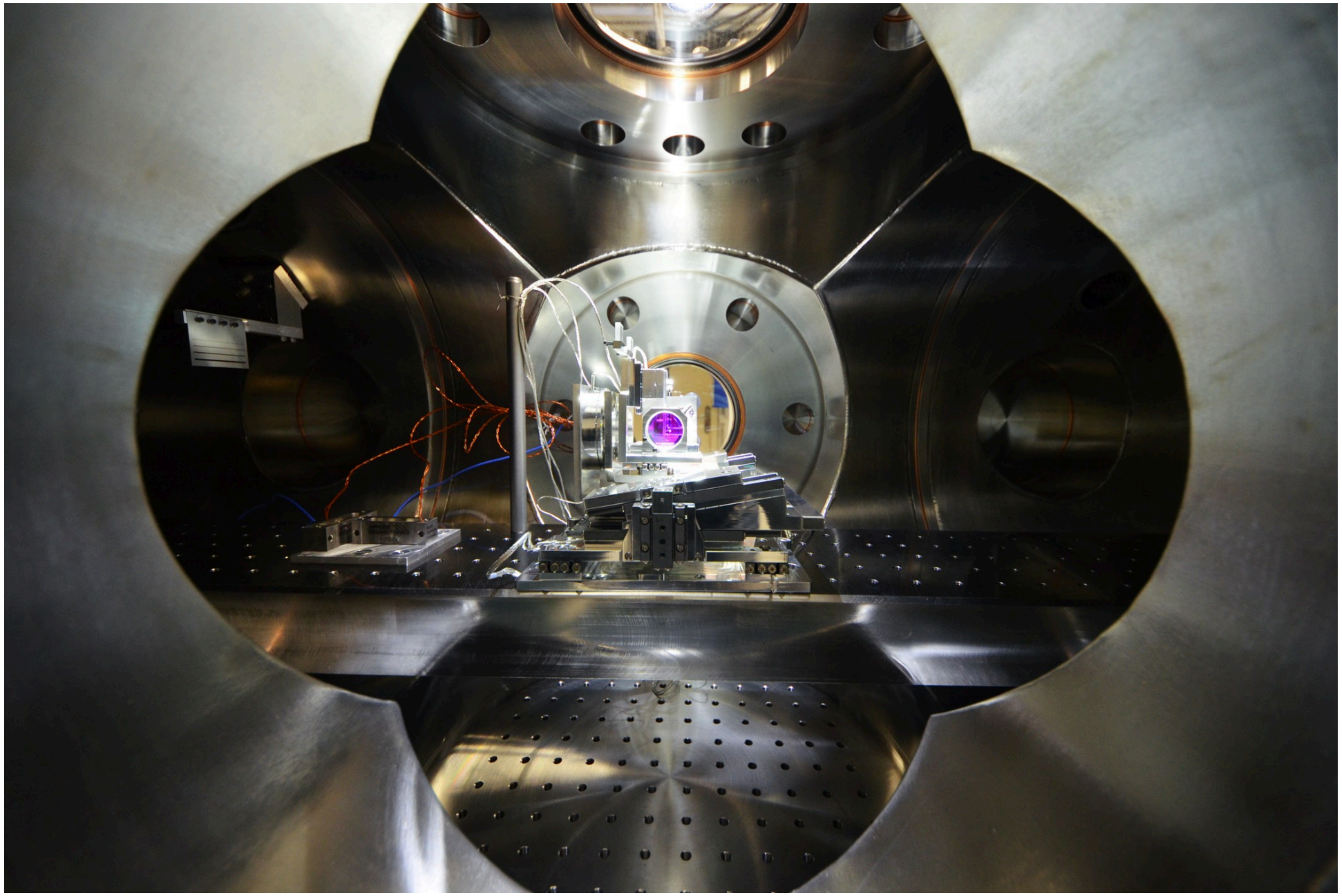
OCTOBER 6, 2019

Not Long Ago, the Center of the Milky Way Exploded – Cataclysmic Blast of Energy

SOPHIA CHEN SCIENCE 09.23.2019 11:02 AM

Even Huge Molecules Follow the Quantum World's Bizarre Rules

A record-breaking experiment shows an enormous molecule is also both a particle and a wave—and that quantum effects don't only apply at tiny scales.



To look for the strange wave-like properties of quantum particles, physicists hurtle them through a long tunnel-like instrument known as an interferometer. PHOTOGRAPH: QUANTUM NANOPHYSICS GROUP AT UNIVERSITY OF VIENNA

https://www.wired.com/story/even-huge-molecules-follow-the-quantum-worlds-bizarre-rules/

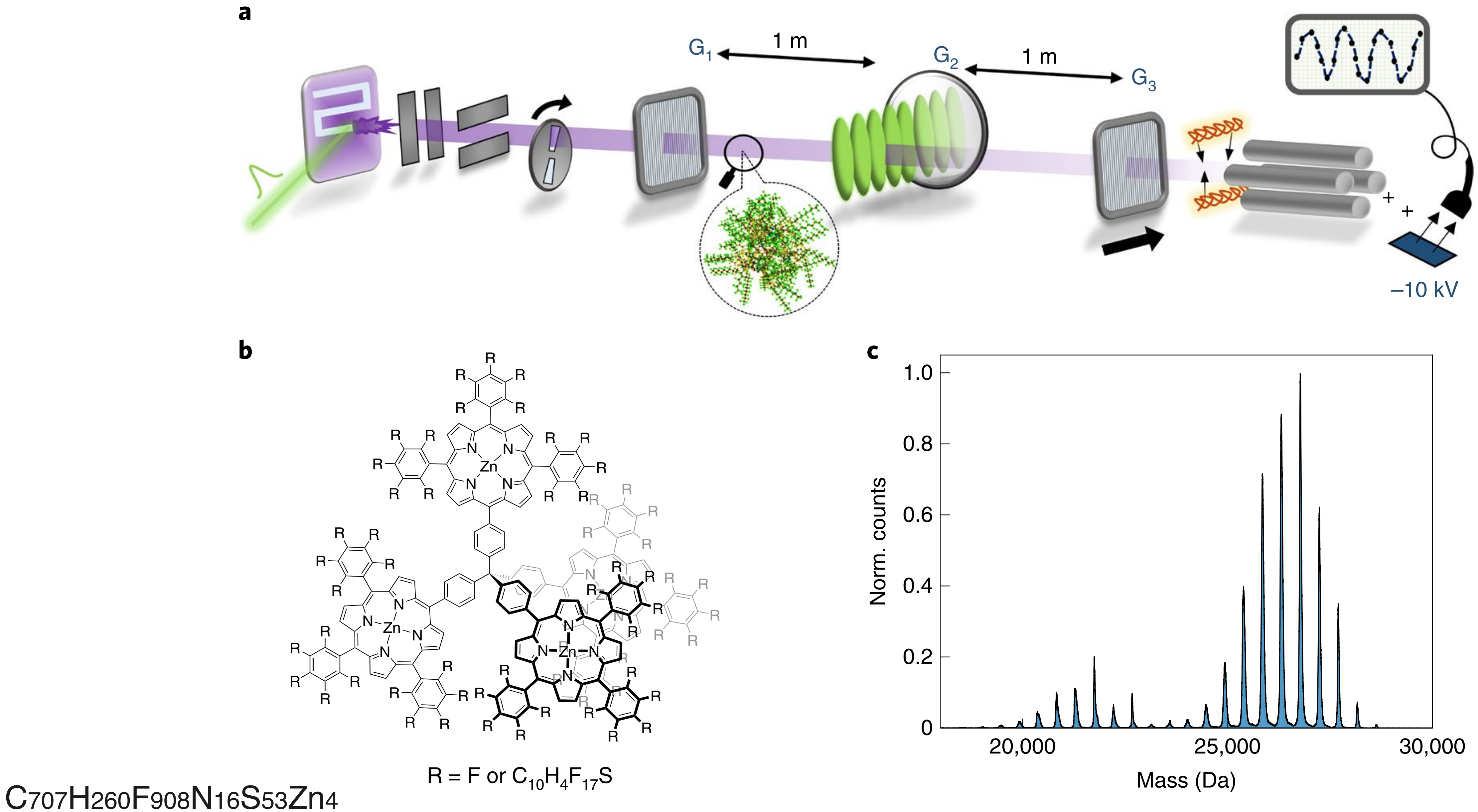


Fig. 1 | Experimental schematic and molecule details. a, The molecular beam is created via nanosecond laser desorption (532 nm, 1 kHz, $I \approx 1\times10^8$ W cm^{-2}), followed by collimation and TOF encoding via a pseudo-random chopper. The beam then enters the interferometer chamber, passing two SiN gratings G_1 and G_3 (266 nm period, 43% open fraction, 160 nm thick) and the optical grating G_2 ($\lambda = 532$ nm, vertical beam waist 690 μm), spaced by $L = 0.98$ m. The third grating shifts transversely across the molecular beam to detect the presence of quantum interference fringes that manifest as a molecular density pattern of period d. The molecules are then ionized by electron impact and are mass-selected and counted in a customized quadrupole mass spectrometer that can resolve masses beyond 1 MDa. **b**, The molecules in this study consist of a tetraphenylmethane core with four zinc-coordinated porphyrin branches. Each branch contains up to 15 fluoroalkylsulfanyl chains. **c**, The MALDI-TOF spectrum of the molecular library after matrix-free desorption. The mass resolution in LUMI during interference experiments was lower to maximize transmission, as discussed in the Methods.

MIT Technology Review

https://www.technologyreview.com/s/612596/the-man-turning-china-into-a-quantum-superpower/

Sign in | Subscribe

Topics | Magazine | Newsletters | Events

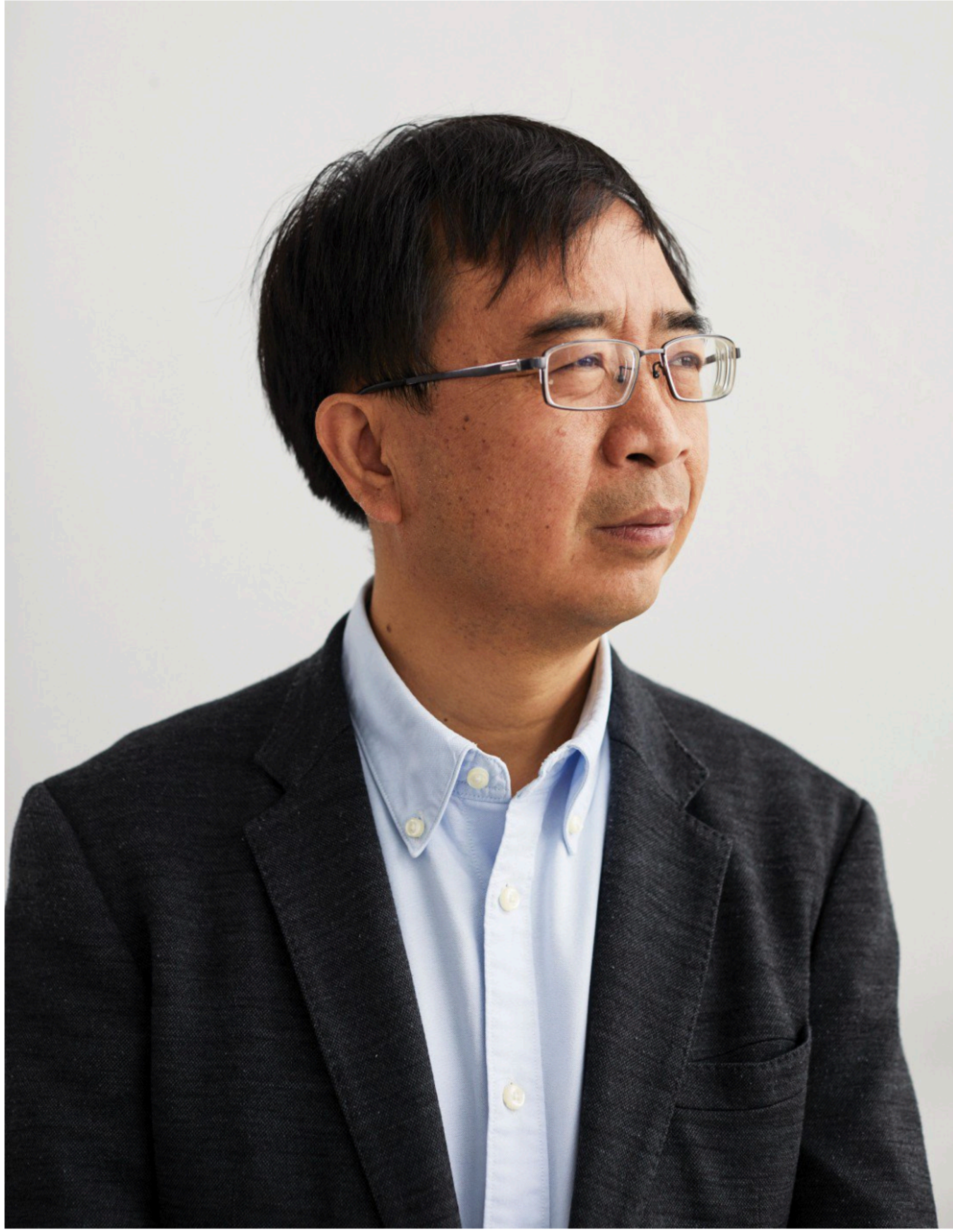
Computing / Quantum Computing

The man turning China into a quantum superpower

On September 29, 2017, a Chinese satellite known as Micius made possible an unhackable videoconference between Vienna and Beijing, two cities half a world apart. As it whisked across the night sky at 18,000 miles (29,000 kilometers) per hour, the satellite beamed down a small data packet to a ground station in Xinglong, a couple of hours' drive to the northeast of Beijing. Less than an hour later, the satellite passed over Austria and dispatched another data packet to a station near the city of Graz.

Jian-Wei Pan, China's "father of quantum", is masterminding its drive for global leadership in technologies that could change entire industries.

by **Martin Giles** Dec 19, 2018



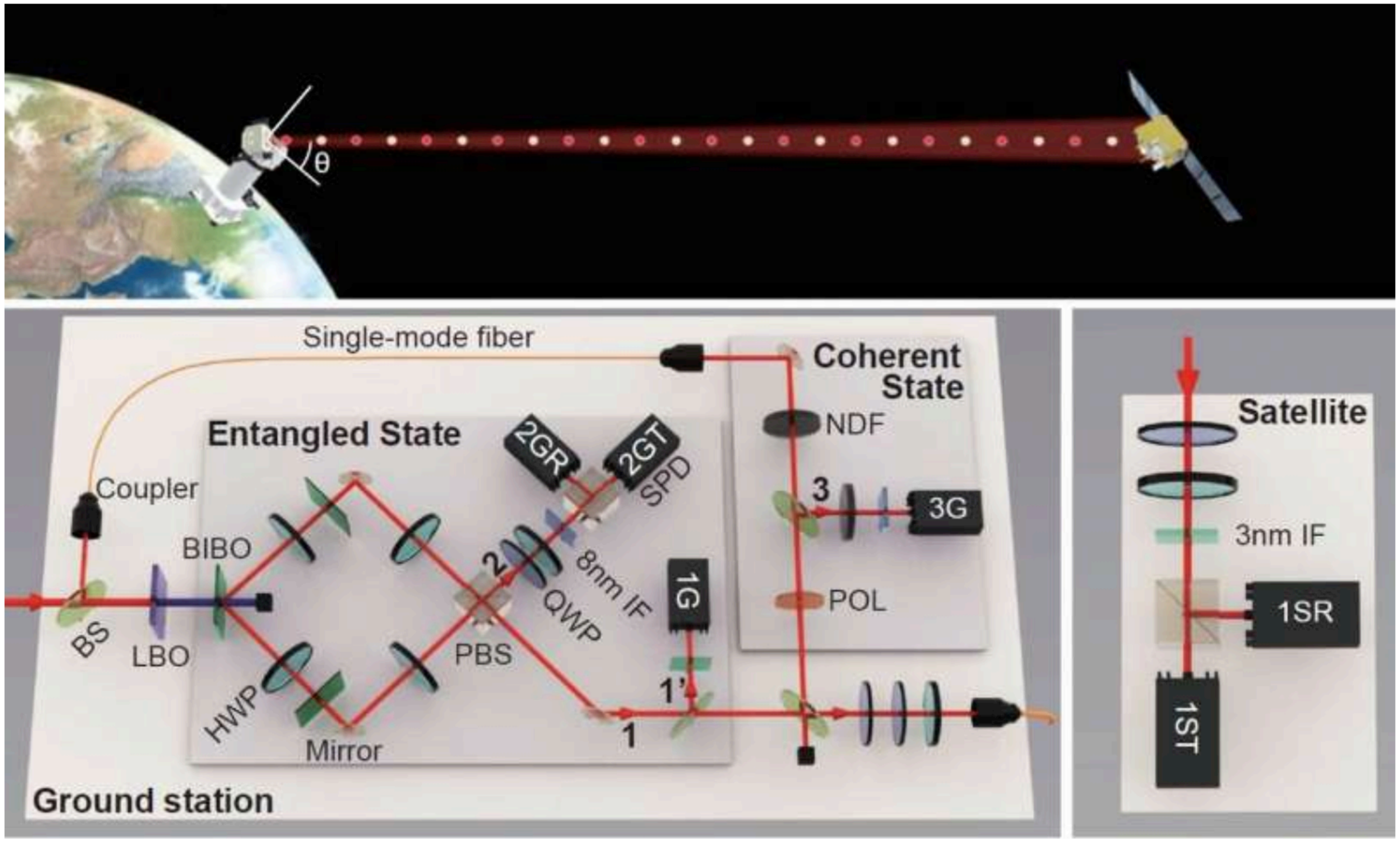
NOAH SHELDON

SEPTEMBER 19, 2019

https://science.sciencemag.org/content/366/6461/132.full

Bridge between quantum mechanics and general relativity still possible

by University of Science and Technology of China



Experimental diagram of testing gravitaty induced decoherence of entanglement Credit: provided by University …

Science

Satellite testing of a gravitationally induced quantum decoherence model

Ping Xu[1,2]*, Yiqiu Ma[3]*, Ji-Gang Ren[1,2]*, Hai-Lin Yong[1,2], Timothy C. Ralph[4], Sheng-Kai Liao[1,2], Juan Yin[1,2], Wei-Yue Liu[1,2], Wen-Qi Cai[1,2], Xuan Han[1,2], Hui-Nan Wu[1,2], Wei-Yang Wang[1,2], Feng-Zhi Li[1,2], Meng Yang[1,2], Feng-Li Lin[5], Li Li[1,2], Nai-Le Liu[1,2], Yu-Ao Chen[1,2], Chao-Yang Lu[1,2], Yanbei Chen[3], Jingyun Fan[1,2]†, Cheng-Zhi Peng[1,2]†, Jian-Wei Pan[1,2]†

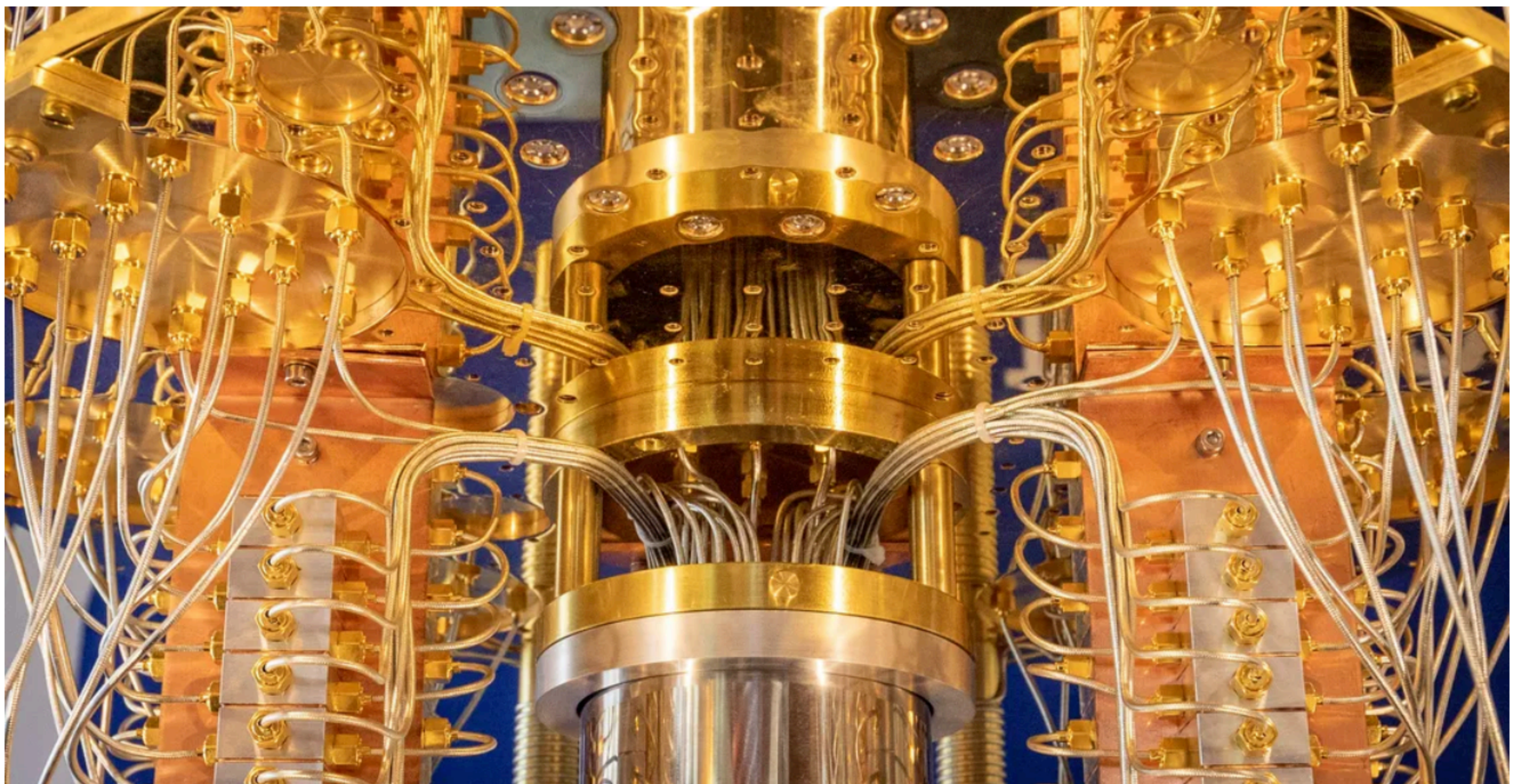
[1]Shanghai Branch, National Laboratory for Physical Sciences at Microscale and Department of Modern Physics, University of Science and Technology of China, Shanghai 201315, P. R. China. [2]Chinese Academy of Sciences (CAS) Center for Excellence and Synergetic Innovation Center in Quantum Information and Quantum Physics, University of Science and Technology of China, Shanghai 201315, P. R. China. [3]Theoretical Astrophysics, California Institute of Technology, Pasadena, CA 91125, USA. [4]Centre for Quantum Computation and Communication Technology, School of Mathematics and Physics, The University of Queensland, St. Lucia, Queensland 4072, Australia. [5]Department of Physics, National Taiwan Normal University, Taipei 116, China.

IBM's new 53-qubit quantum computer is its biggest yet

The system will go online in October.

BY STEPHEN SHANKLAND | SEPTEMBER 18, 2019 5:00 AM PDT

8



A close-up view of the IBM Q quantum computer. The processor is in the silver-colored cylinder.

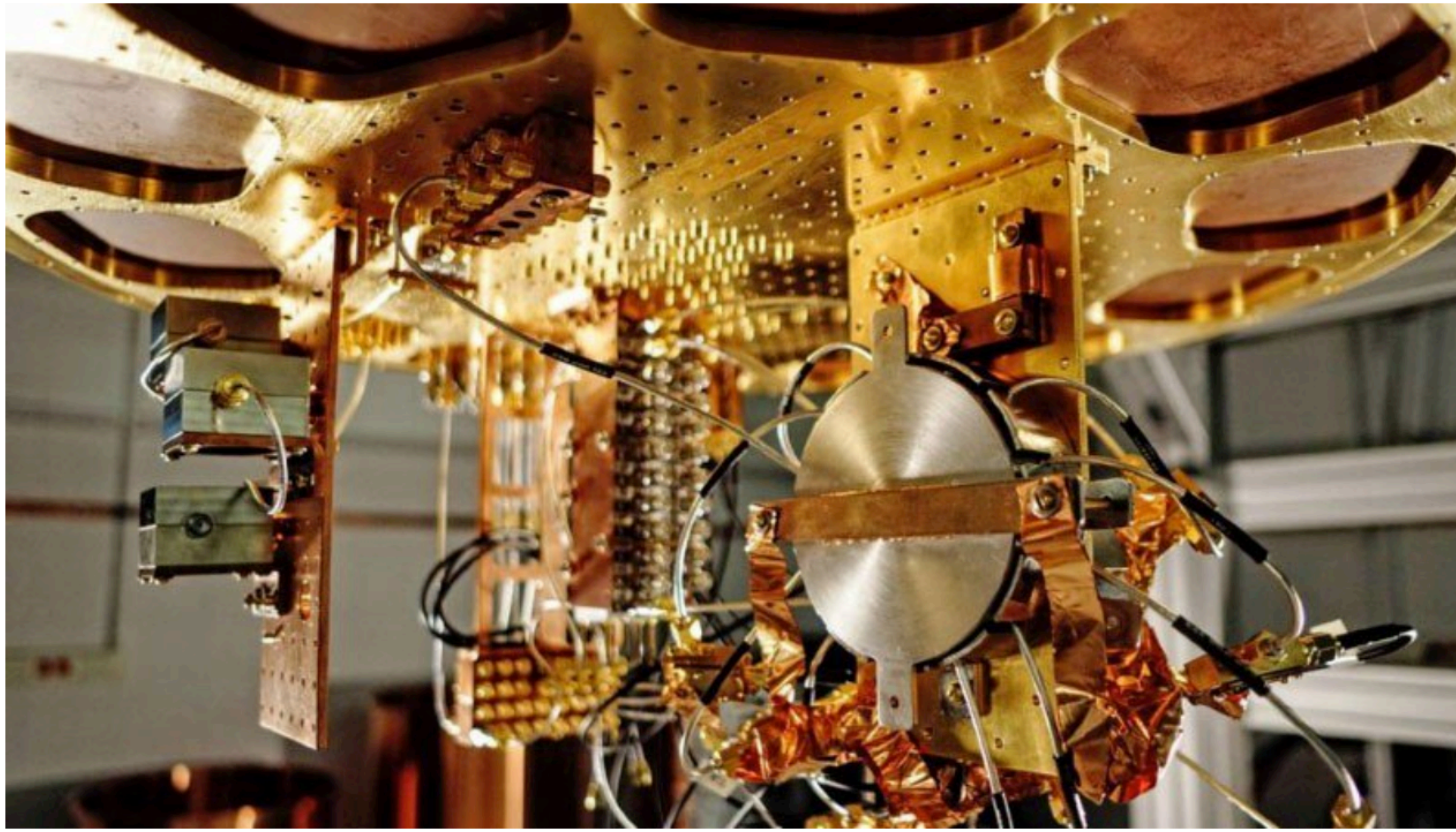
Stephen Shankland/CNET

https://www.cnet.com/news/ibm-new-53-qubit-quantum-computer-is-its-biggest-yet/

MIT
Technology
Review

Computing Sep 20

Google researchers have reportedly achieved "quantum supremacy"



The news: According to a report in the Financial Times, a team of researchers from Google led by John Martinis have demonstrated quantum supremacy for the first time. This is the point at which a quantum computer is shown to be capable of performing a task that's beyond the reach of even the most powerful conventional supercomputer. The claim appeared in a paper that was posted on a NASA website, but the publication was then taken down. Google did not respond to a request for comment from MIT Technology Review.

Lecture 0.

“Towards evidence-based physics” the Bell game, and the Delft Bell experiment

Rutherford: If you need statistics, you did the wrong experiment

Hensen et al. (2015, Nature) Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

Hensen et al. prove that Einstein was wrong,
with $N = 245$ and at significance level $p = 0.039$
They <u>need</u> sophisticated statistics and probability theory

Hensen et al. (2015, Nature)

Loophole-free Bell inequality violation
using electron spins (in Nitrogen-Vacancy defects in diamond)
separated by 1.3 kilometres

Hensen et al. prove that Einstein was wrong,
with $N = 245$ and at significance level $p = 0.039$
They <u>need</u> statistics and probability theory

[1]QuTech, Delft University of Technology, PO Box 5046, 2600 GA Delft, The Netherlands. [2]Kavli Institute of Nanoscience Delft, Delft University of Technology, PO Box 5046, 2600 GA Delft, The Netherlands. [3]ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain. [4]ICREA-Institució Catalana de Recerca i Estudis Avançats, Lluis Companys 23, 08010 Barcelona, Spain. [5]Element Six Innovation, Fermi Avenue, Harwell Oxford, Didcot, Oxfordshire OX11 0QR, UK. †Present address: Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA.

682 | NATURE | VOL 526 | 29 OCTOBER 2015
©2015 Macmillan Publishers Limited. All rights reserved

LETTER

doi:10.1038/nature15759

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]

More than 50 years ago[1], John Bell proved that no theory of nature that obeys locality and realism[2] can reproduce all the predictions of quantum theory: in any local-realist theory, the correlations between outcomes of measurements on distant particles satisfy an inequality that can be violated if the particles are entangled. Numerous Bell inequality tests have been reported[3–13]; however, all experiments reported so far required additional assumptions to obtain a contradiction with local realism, resulting in 'loopholes'[13–16]. Here we report a Bell experiment that is free of any such additional assumption and thus directly tests the principles underlying Bell's inequality. We use an event-ready scheme[17–19] that enables the generation of robust entanglement between distant electron spins (estimated state fidelity of 0.92 ± 0.03). Efficient spin read-out avoids the fair-sampling assumption (detection loophole[14,15]), while the use of fast random-basis selection and spin read-out combined with a spatial separation of 1.3 kilometres ensure the required locality conditions[13]. We performed 245 trials

sufficiently separated such that locality prevents communication between the boxes during a trial, then the following inequality holds under local realism:

$$S = \left| \langle x \cdot y \rangle_{(0,0)} + \langle x \cdot y \rangle_{(0,1)} + \langle x \cdot y \rangle_{(1,0)} - \langle x \cdot y \rangle_{(1,1)} \right| \leq 2 \qquad (1)$$

where $\langle x \cdot y \rangle_{(a,b)}$ denotes the expectation value of the product of x and y for input bits a and b. (A mathematical formulation of the concepts underlying Bell's inequality is found in, for example, ref. 25.)

Quantum theory predicts that the Bell inequality can be significantly violated in the following setting. We add one particle, for example an electron, to each box. The spin degree of freedom of the electron forms a two-level system with eigenstates $|\uparrow\rangle$ and $|\downarrow\rangle$. For each trial, the two spins are prepared into the entangled state $|\psi^-\rangle = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$. The spin in box A is then measured along direction Z (for input bit $a = 0$) or X (for $a = 1$) and the spin in box B is measured along $(-Z+X)/\sqrt{2}$ (for $b = 0$) or $(-Z-X)/\sqrt{2}$ (for $b = 1$). If the mea-

ref. 25. Bell, J.S (2004), Speakable and Unspeakable in Quantum Mechanics: Collected Papers on Quantum Philosophy 2nd ed., Cambridge Univ. Press,

Inputs (settings) a, $b \in \{0, 1\}$

Later in this talk: {1, 2}

Outputs (outcomes) x, $y \in \{-1, +1\}$

<…> = Expectation

"·" = multiplication

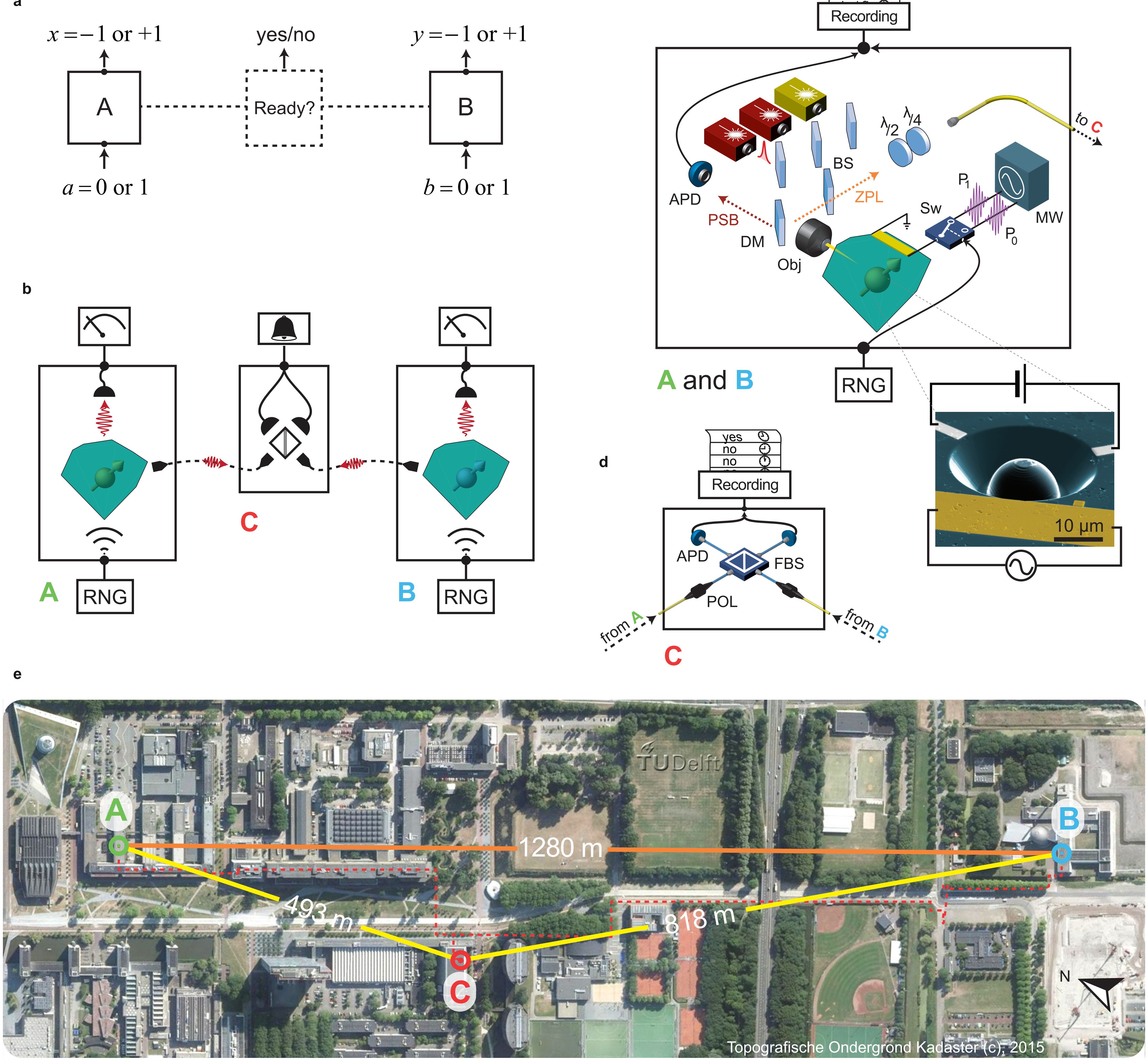
Bell's inequality

$$S = \left| \langle x \cdot y \rangle_{(0,0)} + \langle x \cdot y \rangle_{(0,1)} + \langle x \cdot y \rangle_{(1,0)} - \langle x \cdot y \rangle_{(1,1)} \right| \leq 2 \qquad (1)$$

To be more precise: this is Bell's "four correlations" inequality, aka the "Bell – CHSH inequality"

Clauser, Horne, Shimony, Holt (1969)

Bell (1964) "three correlations": Special case $\langle x \cdot y \rangle_{(0,0)} = 1$


a
x = −1 or +1
yes/no
y = −1 or +1
A
Ready?
B
a = 0 or 1
b = 0 or 1
b
C
A
RNG
B
RNG
Recording
to C
λ/2
λ/4
BS
APD
ZPL
PSB
P1
Sw
MW
DM
Obj
P0
A and B
RNG
10 μm
d
yes
no
no
Recording
APD
FBS
POL
from A
from B
C
e
TUDelft
A
B
1280 m
493 m
818 m
C
N
Topografische Ondergrond Kadaster (c), 2015

QUANTUM PHYSICS

Death by experiment for local realism

A fundamental scientific assumption called local realism conflicts with certain predictions of quantum mechanics. Those predictions have now been verified, with none of the loopholes that have compromised earlier tests. SEE LETTER P.682

HOWARD WISEMAN

The world is made up of real stuff, existing in space and changing only through local interactions — this local-realism hypothesis is about the most intuitive scientific postulate imaginable. But quantum mechanics implies that it is false, as has been known for more than 50 years[1]. However, brilliantly successful though quantum mechanics has been, it is still only a theory, and no definitive experiment has disproved the local-realism hypothesis — until now. On page 682 of this issue, Hensen *et al.*[2] report the first violation of a constraint called a Bell inequality, under conditions that prevent alternative explanations of the experimental data. Their findings therefore rigorously reject local realism, for the first time.

Bell inequalities are named after John Bell, the physicist who discovered in 1964 that the predictions of quantum mechanics are incompatible with the local-realism hypothesis[1]. There are many different ways to make this hypothesis precise[3], but Hensen and colleagues' exposition basically follows Bell's original formulation, which states it as the conjunction of two other hypotheses: realism (which Bell called predetermination), essentially meaning that measurements reveal pre-existing physical properties of the world; and locality, roughly meaning that any change

50 Years Ago

It may not be generally realized that work is in progress on the colossal project of constructing a 40-in. diameter, 300 miles long, Trans-Alpine oil pipeline to convey oil from the Adriatic to the heart of Germany … Among the many practical problems concerned with such a project, apart from tunnelling and mechanical excavation in the high Alps, are the necessity to dredge the harbour at Trieste so that it can eventually accommodate oil tankers of 160,000 dead weight tons; setting storage tanks there on piles because available land is a rocky hill site; construction of several thousand feet of piers in the Adriatic … Involved also in the scheme is the building of five separate pumping stations, each equipped with two 4,000-horse-power electric centrifugal pumps required to lift hundreds of thousands of tons of oil from sea-level to one of the highest points of Felber Tauern.

From *Nature* 30 October 1965

PAID POST: NETJETS
It's Possible: Around the World at a Moment's Notice
NETJETS

SCIENCE

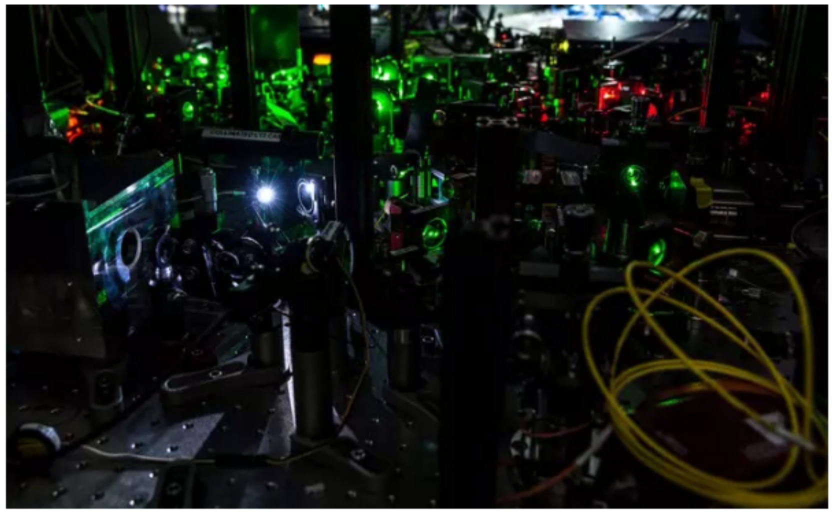
Sorry, Einstein. Quantum Study Suggests 'Spooky Action' Is Real.

By JOHN MARKOFF OCT. 21, 2015

710 COMMENTS

BROOKLYN
NOW PLAYING
GET TICKETS

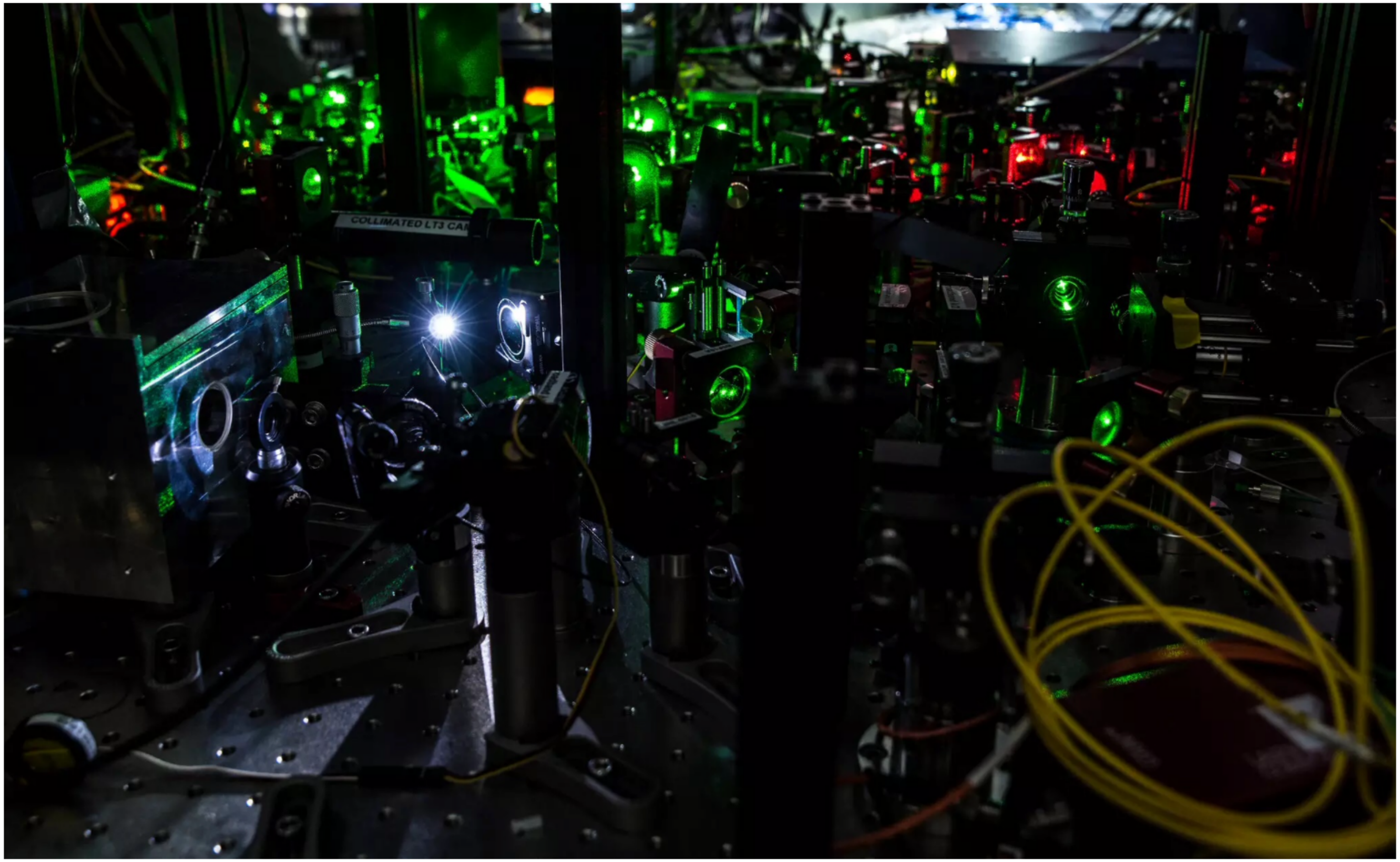
In a landmark study, scientists at Delft University of Technology in the Netherlands reported that they had conducted an experiment that they say proved one of the most fundamental claims of quantum theory — that objects separated by great distance can instantaneously affect each other's behavior.



Part of the laboratory setup for an experiment at Delft University of Technology, in which two diamonds were set 1.3 kilometers apart, entangled and then shared information.
Frank Auperle/Delft University of Technology

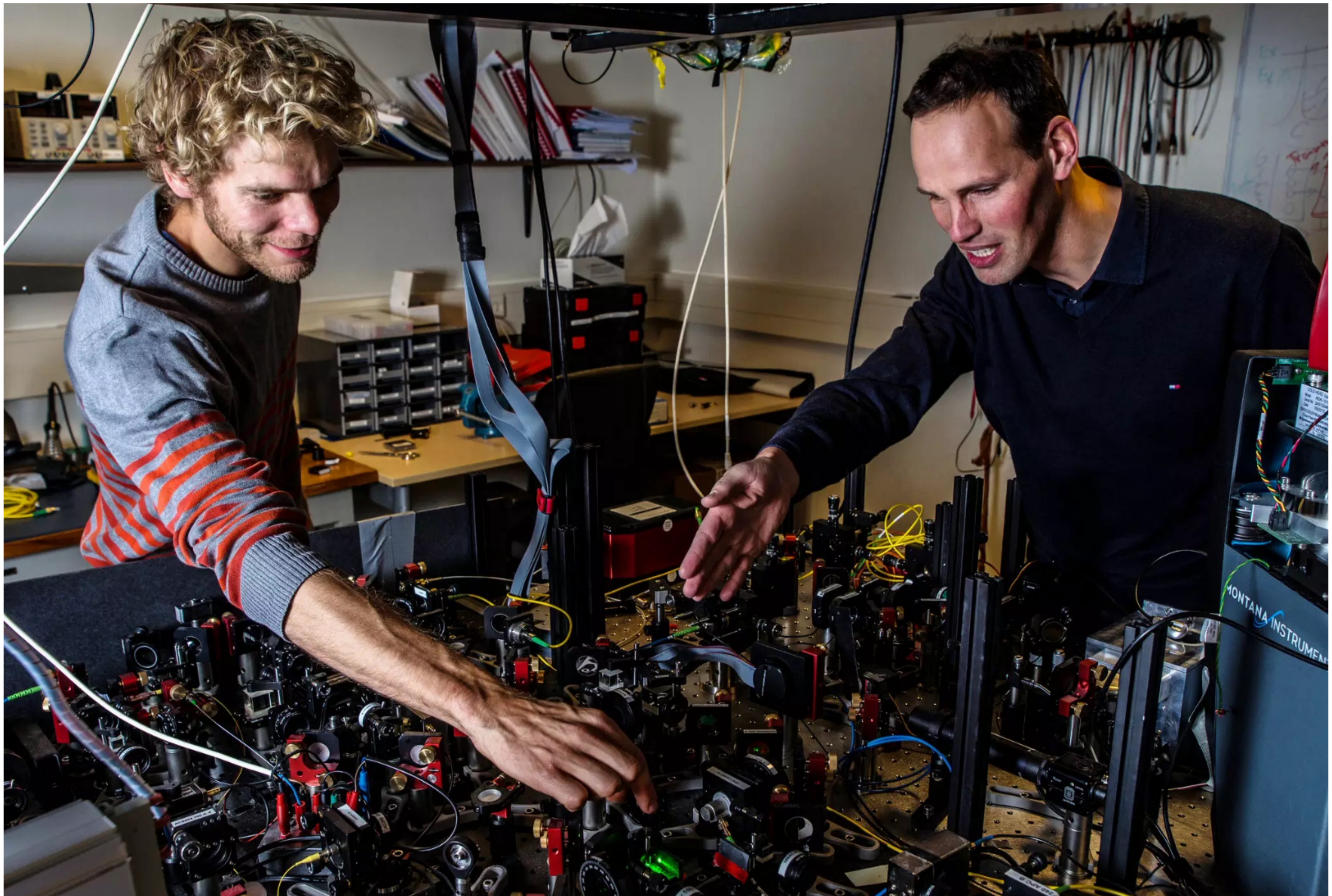
CHRISTIE'S

The finding is another blow to one of the bedrock



Part of the laboratory setup for an experiment at Delft University of Technology, in which two diamonds were set 1.3 kilometers apart, entangled and then shared information.

Frank Auperle/Delft University of Technology



Bas Hensen, left, and Ronald Hanson helped show that objects apart can instantly affect each other.

Frank Auperle/Delft University of Technology

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]

Delft co-author, mathematician Stephanie Wehner

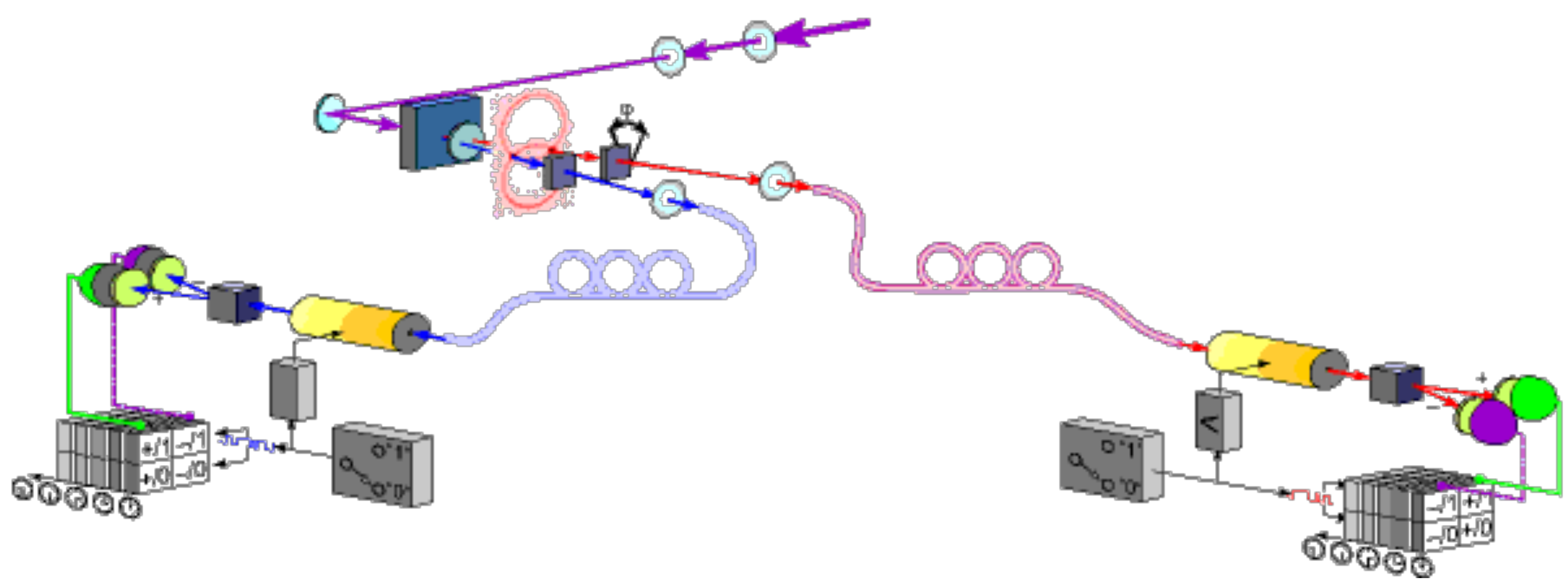
First loophole-free experimental violation of Bell's inequality

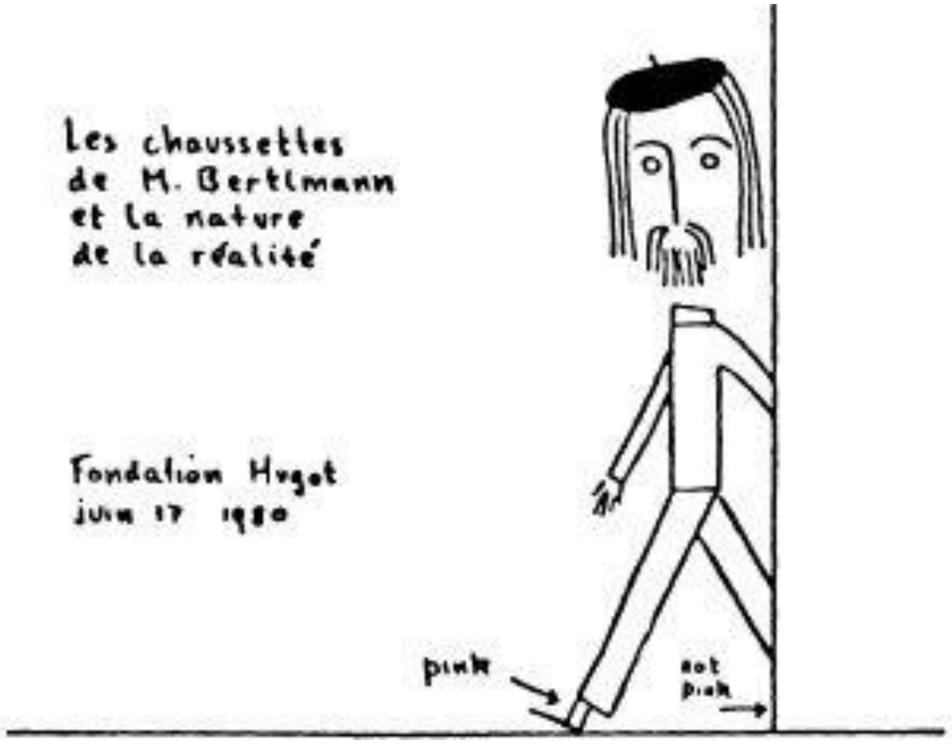
- Bell (1964) showed that according to quantum theory, quantum systems could exhibit correlations impossible under classical physics without faster-than-light communication

- Such quantum correlations have since been observed in many laboratory experiments, but till now, always in a setting where there is a classical explanation without FTL

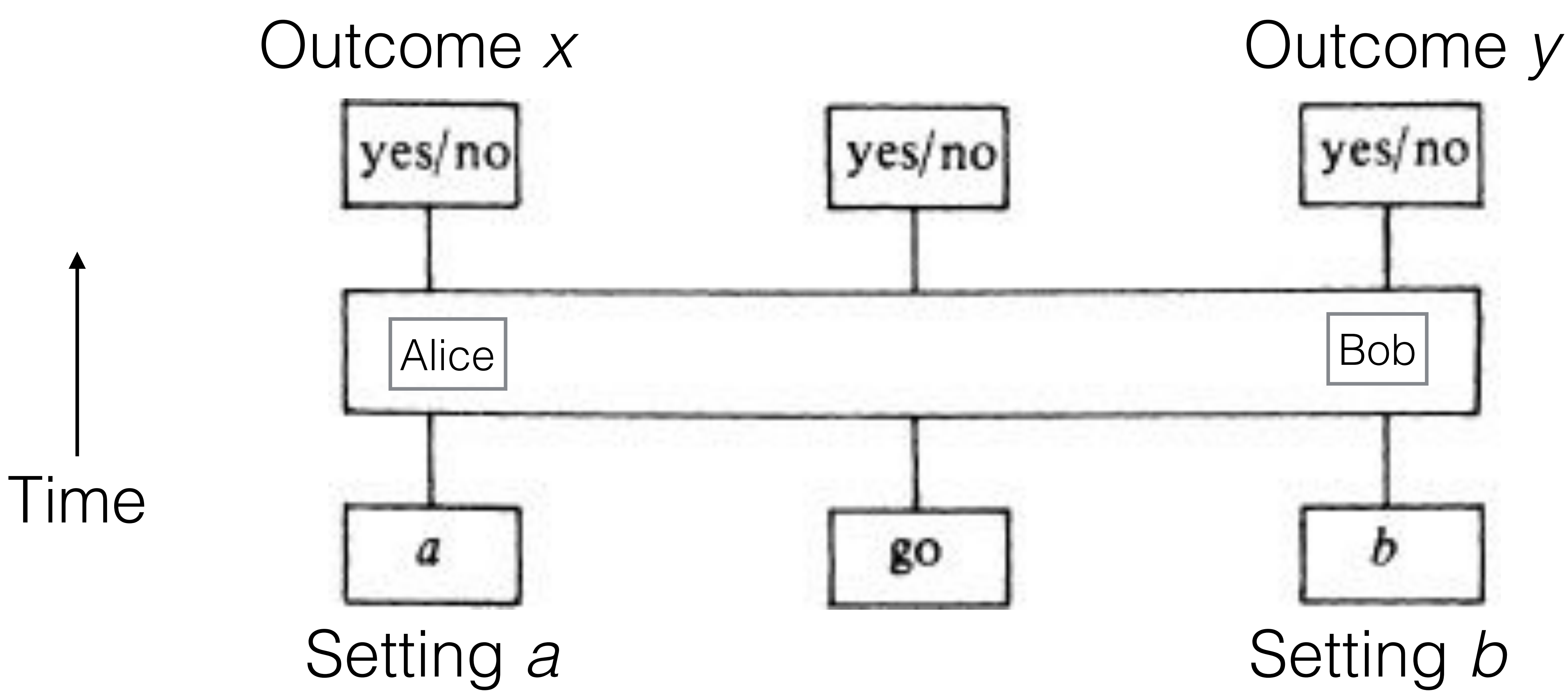
- They could not quite do the right experiment, and had to make do with surrogates; e.g.: Aspect et al. 1981, 1982, Weihs et al. 1998, …

Example: Weihs et al. (1998)





Bell (1981) “Bertlmann’s socks and the nature of reality”



One trial of
the Bell Game

- Alice and Bob make preparations
- They are separated, and may no longer communicate
- Each is given a **setting**: “1” or “2”
- They must both now deliver an **outcome**: “*red*” or “*green*”
- Their aim: their outcomes are **equal** unless <u>both</u> settings are “1”, when outcomes are **different**
- i.e.: outcomes *r,g* or *g,r* with settings 11; outcomes *r,r* or *g,g* with settings 12, 21, or 22
- Note: for variables *X*, *Y* taking values +/–1,

$$\langle X \cdot Y \rangle = E(XY) = \text{Prob}(X = Y) - \text{Prob}(X \neq Y) = 1 - 2\,\text{Prob}(X \neq Y)$$

One trial of
the Bell Game

- Alice and Bob make preparations
- They are separated, and may no longer communicate
- Each is given a **setting**: “1” or “2” (assume: fair coin tosses)
- They must both now deliver an **outcome**: “*red*” or “*green*”
- Their aim: their outcomes are **equal** unless <u>both</u> settings are “1”, when outcomes are **different**
- Aim: outcomes *r,g* or *g,r* with settings 11; outcomes *r,r* or *g,g* with settings 12, 21, or 22
- Note: for variables *X*, *Y* taking values +/–1,

$$\langle X \cdot Y \rangle = E(XY) = \text{Prob}(X = Y) - \text{Prob}(X \neq Y) = 1 - 2\,\text{Prob}(X \neq Y)$$

Repeat *N* times

Between trials, Alice and Bob may confer

Optimal play, per trial

- If Alice and Bob want to use any randomisation, they might as well perform all randomisations which they either might need, in advance, while they are still together

- Given all results of any randomisations, their strategy specifies an “instruction set”: colours for Alice for settings 1 and 2, colours for Bob for settings 1 and 2

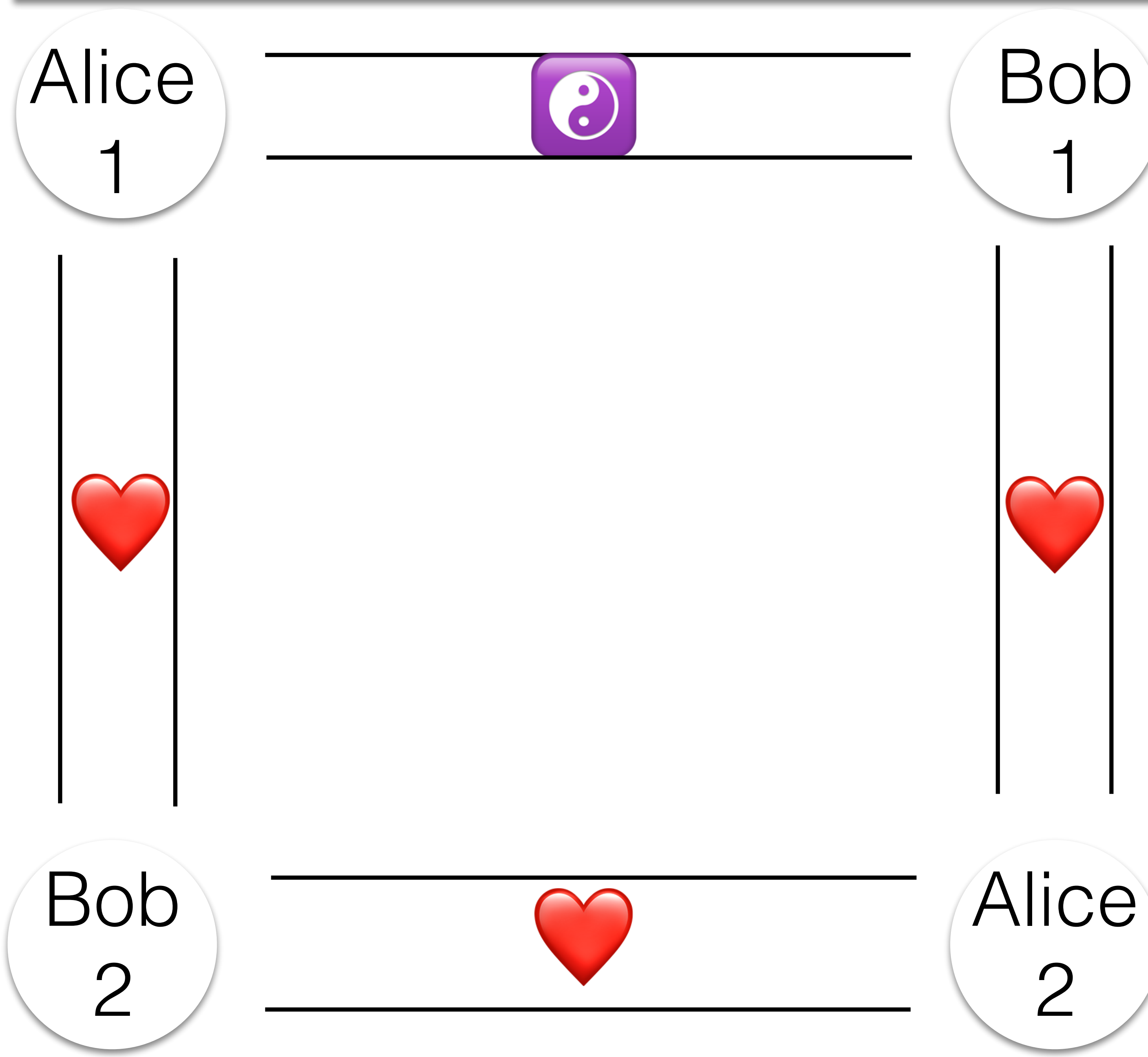
- There are exactly 2^4 = 16 different instruction sets

- Let’s take a look at some of them …

Their adversary, Caspar, will pick settings by fair coin tosses

Question: can you colour the four balls green and red so that

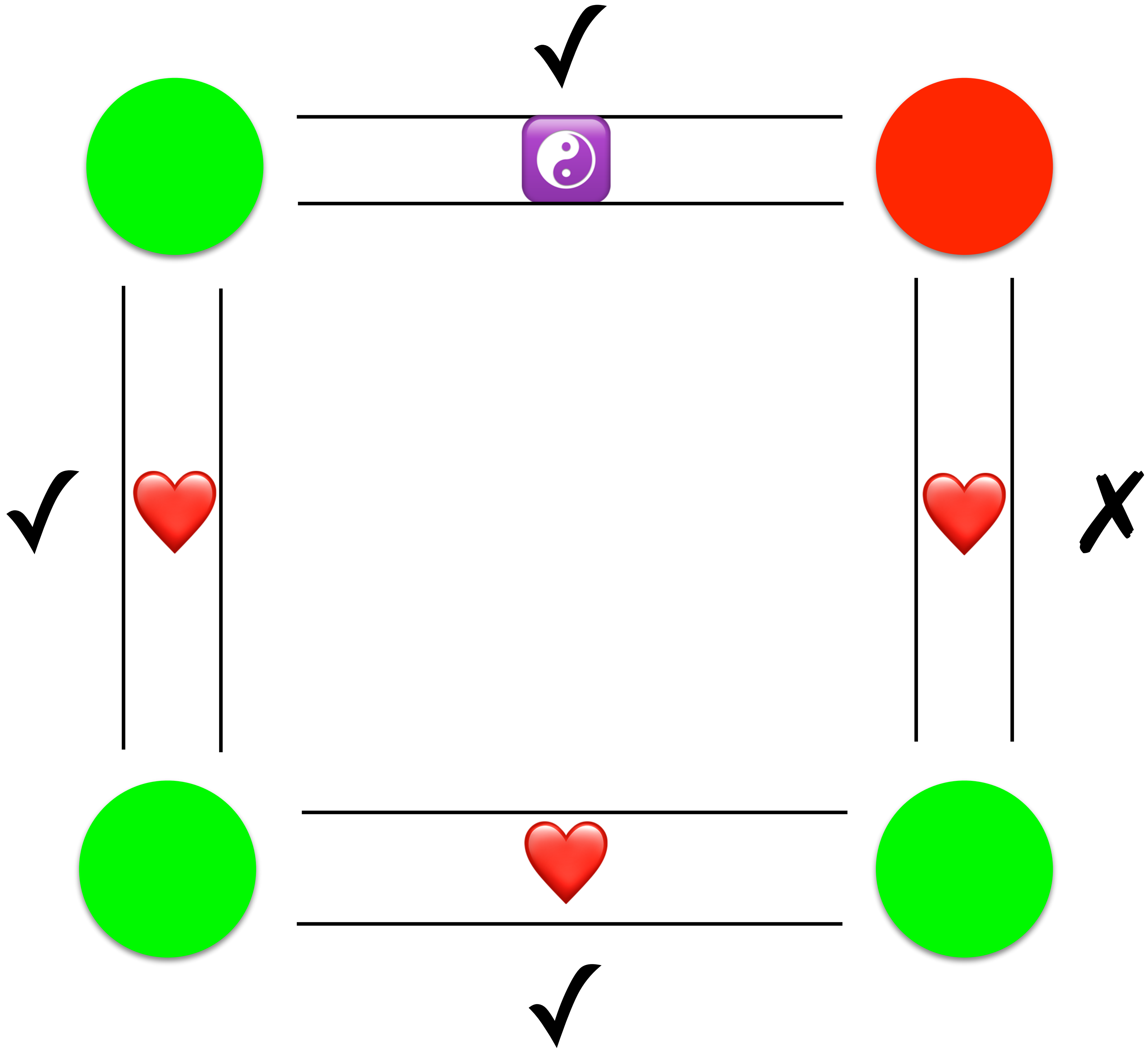
the two on top have different colours ☯

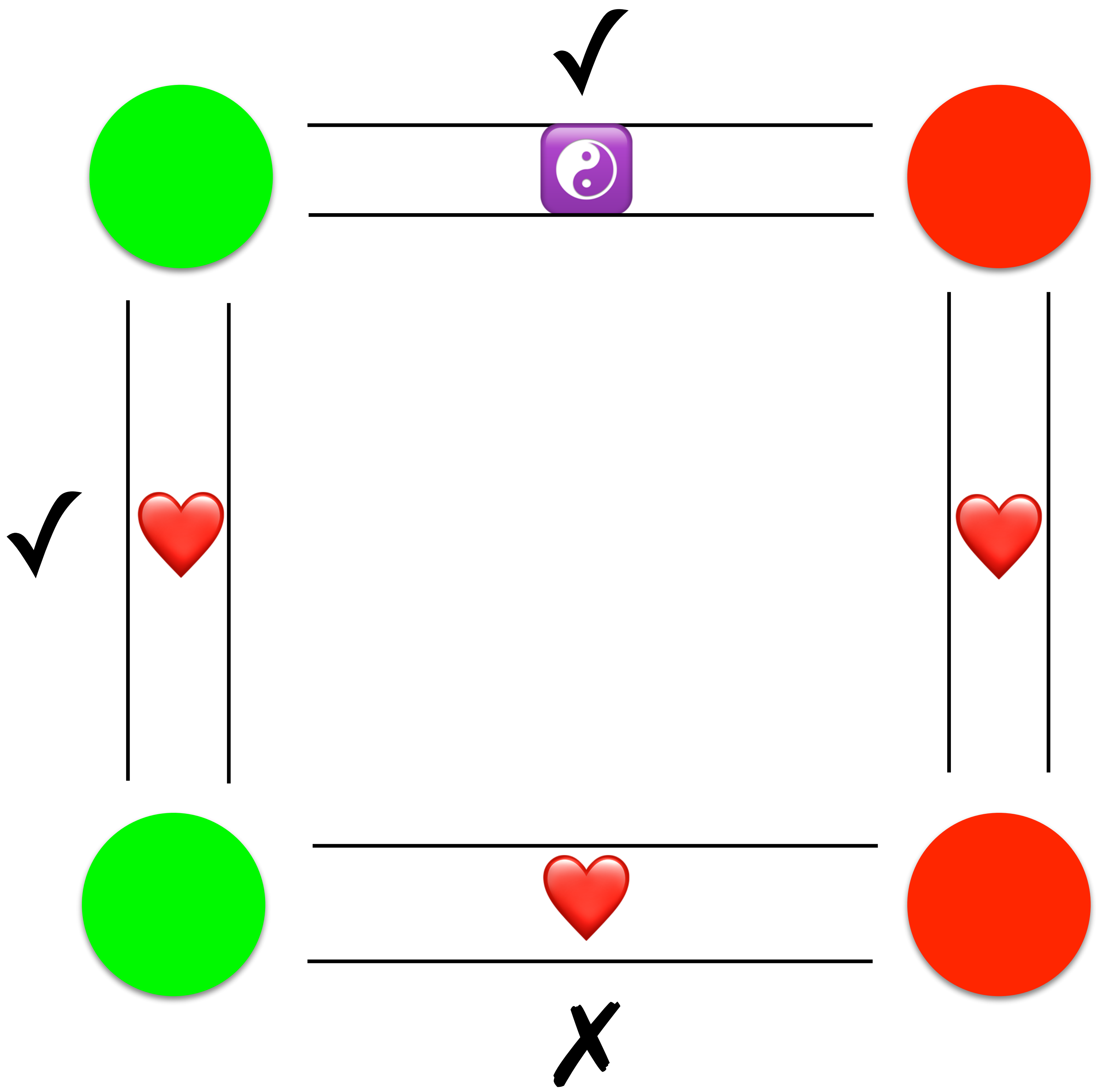


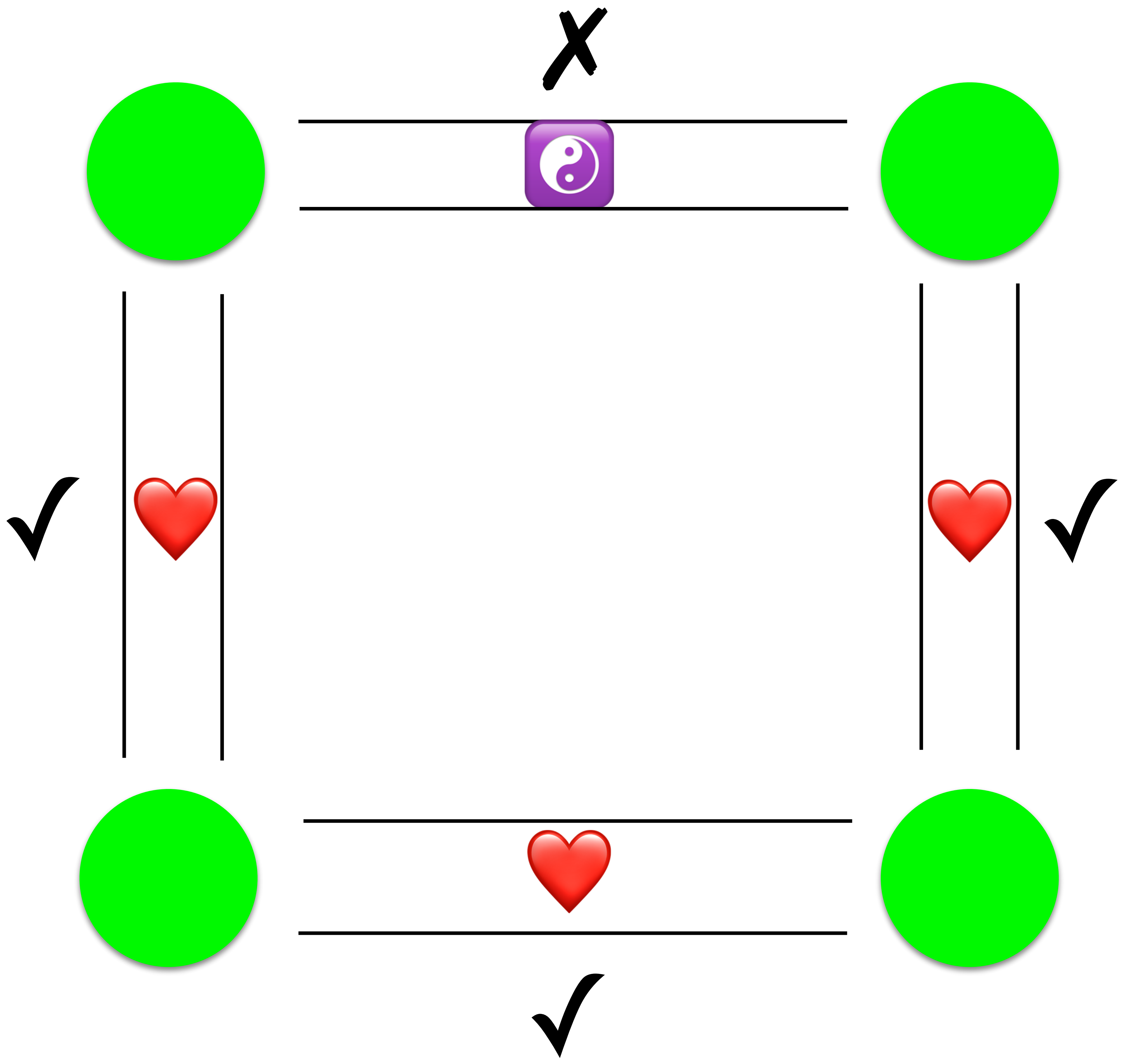
the two on the left have the same colour ❤️

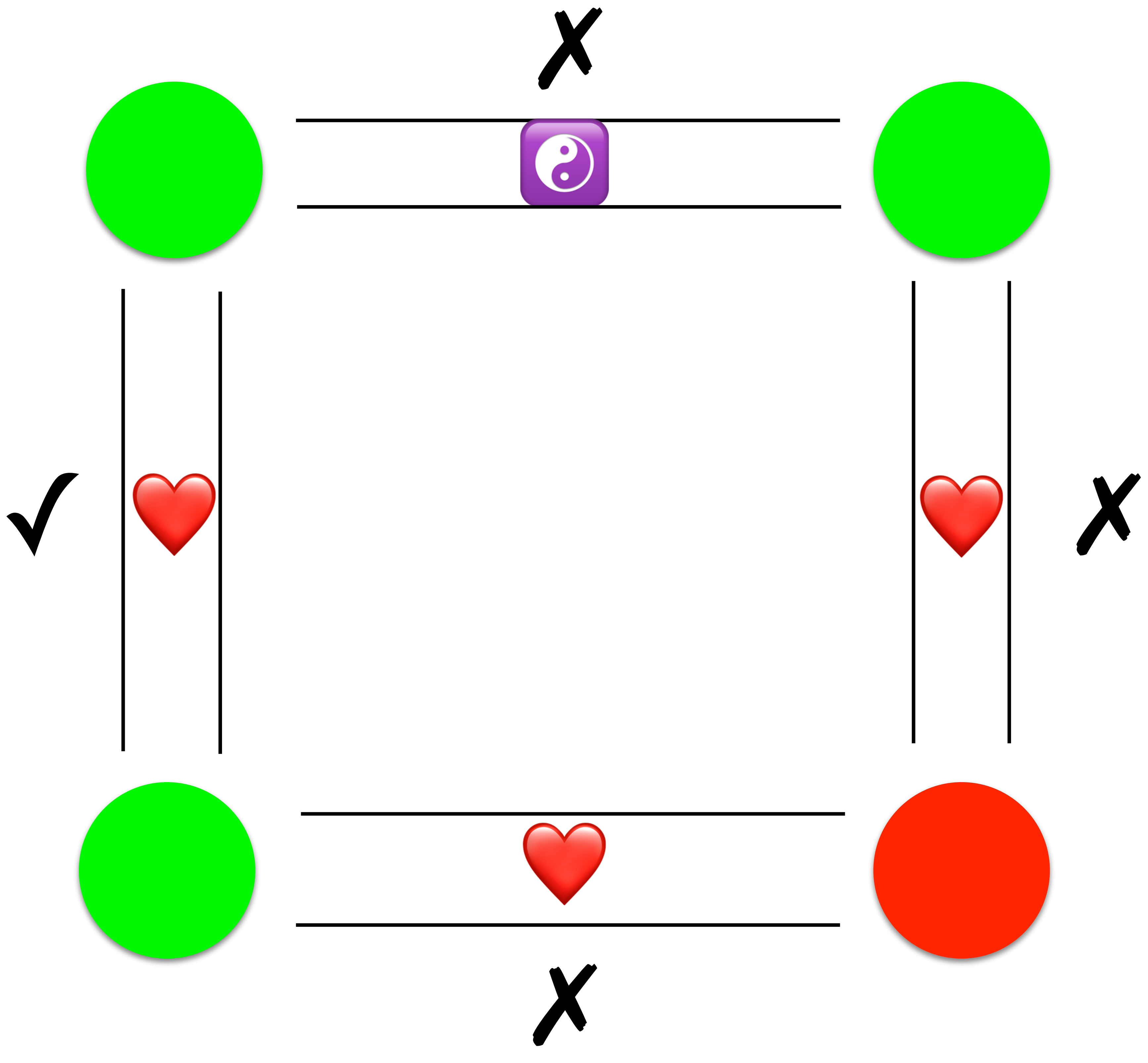
the two on the right have the same colour ❤️

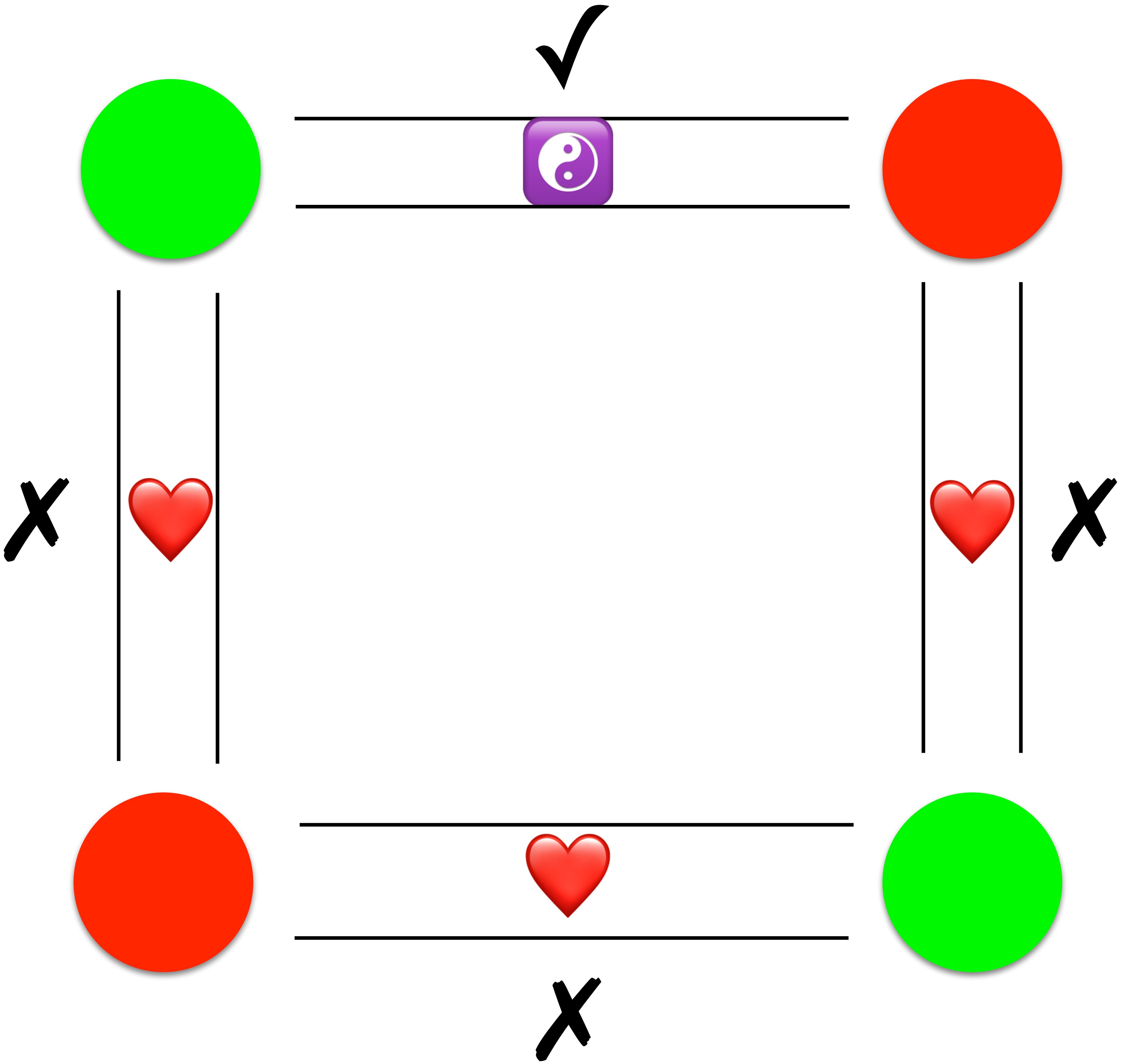
the two on the bottom have the same colour ❤️

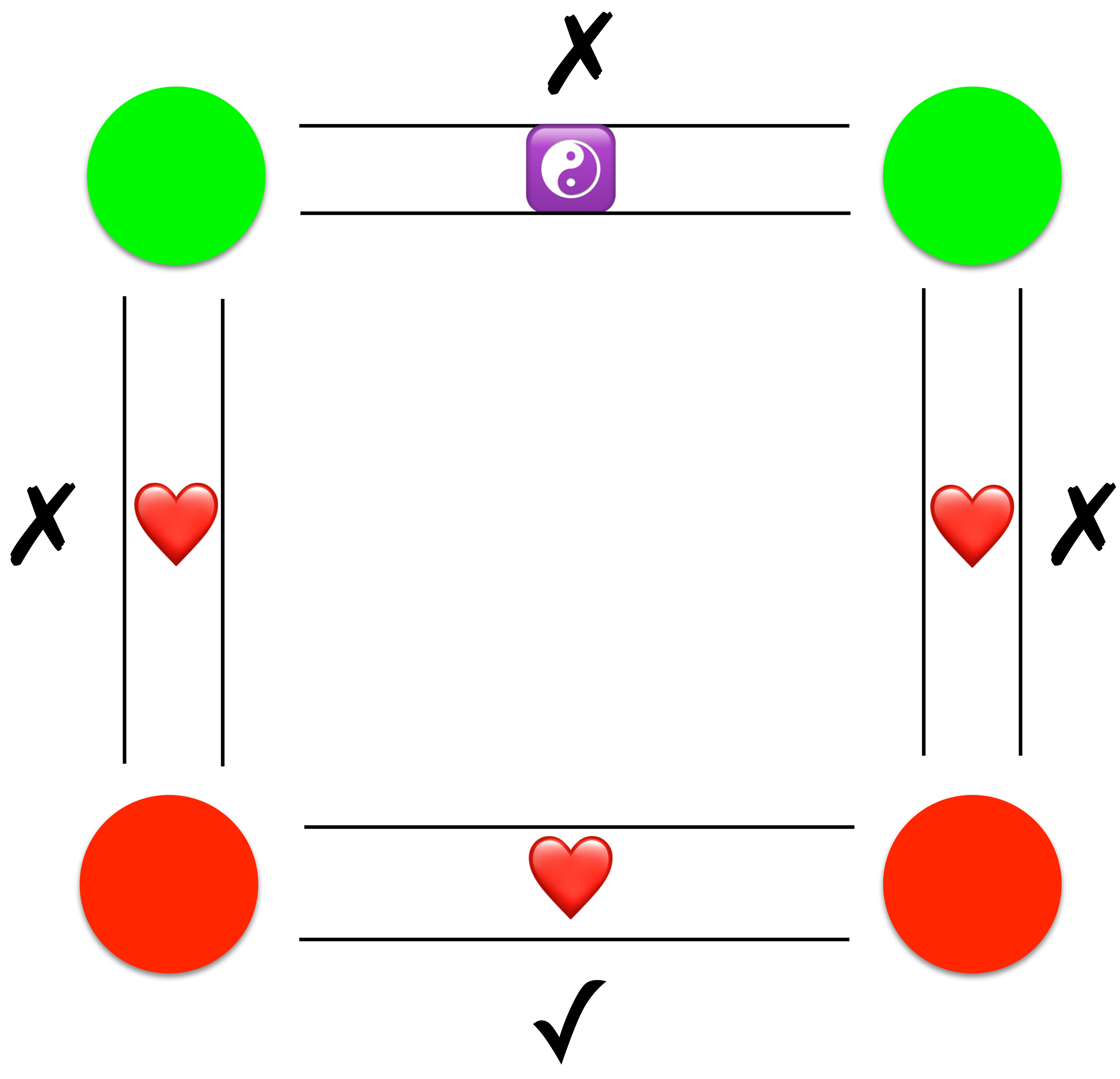












Question: can you colour the four balls green and red, so that

the two on top have different colours ☯

the two on the left have the same colour ❤️

the two on the right have the same colour ❤️

the two on the bottom have the same colour ❤️

Answer:
No you can't.
Either one or three failures

Optimal play for Alice & Bob vs adversary Caspar

- $8 = 2 \times 4$ instruction sets deliver 3 successes, 1 failure, as we run through the four setting pairs (11 = top, 12 = left, 21 = right, 22 = bottom)

- The other 8 deliver 3 failures, 1 success

- Choosing 1 of the first 8 **uniformly at random** is optimal (“equalizer strategy”)

- Caspar should choose settings uniformly at random (“minimax solution”)

Theorem

If Caspar supplies settings by independent fair coin tosses, then, whatever strategy is used by Alice and Bob, and for all x,

$$\Pr(\#\text{successes} \geq x)$$

$$\leq \Pr(\mathrm{Bin}(N, \tfrac{3}{4}) \geq x)$$

Note: This result is <u>essentially equivalent</u> to Bell's inequality: per trial, conditional on the past,

$$\tfrac{1}{4}\Pr(\text{“=”} \mid 12) + \tfrac{1}{4}\Pr(\text{“=”} \mid 22) + \tfrac{1}{4}\Pr(\text{“=”} \mid 21)$$

$$- \tfrac{1}{4}\Pr(\text{“=”} \mid 11) \quad \leq \quad \tfrac{3}{4}$$

Bell game results in Delft

- $N = 245$
- Success rate: 80%
- Optimal rate under “local realism” 75%
- Optimal rate under “quantum mechanics” 85%
(“Tsirelson bound”) $\frac{1}{2} + \frac{1}{4}\sqrt{2} = 0.85$

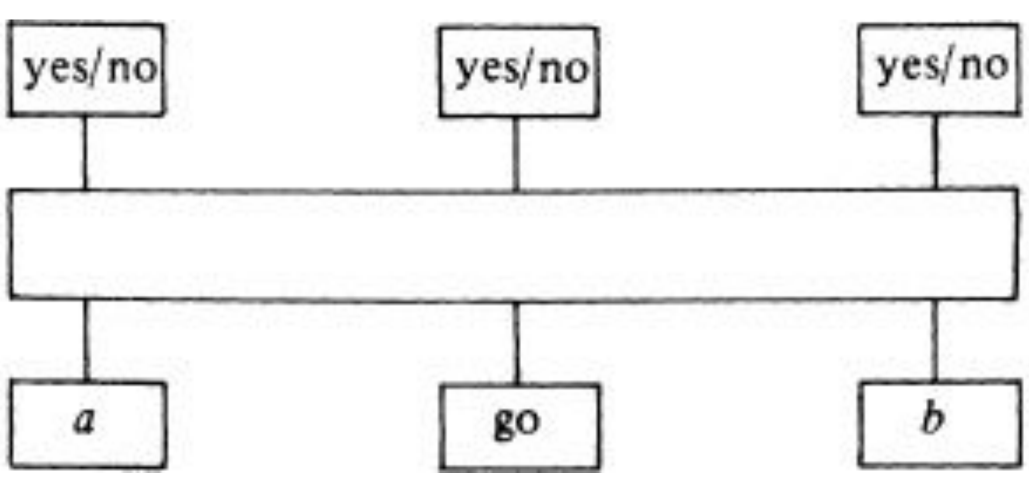
Why can’t QM do better?
Marcin Pawłowski et al.: “Information Causality”

Delft Bell results in round numbers

- 75% of 240 is 180
- 80% of 240 is 192
- Binomial variance $N = 240$, $p = ¾$ is $240 \times ¾ \times ¼ = 45$ not far from $49 = 7 \times 7$
- 192 – 180 = 12 = approx 2 standard deviations
- Actual result: $N = 245$, # successes = 196
- $\Pr(\ \mathrm{Bin}(245, ¾) \geq 196\ ) = 0.039$

Note: no gain in strategies which use memory and time

- First such results obtained by Gill (2001) using martingale theory; rewrite usual "combination of four correlations" as final result of a game
- My aim: protocol for bet against someone who claims he can simulate the quantum correlations with (classically) networked classical computers



$N = 2000$
Win/lose: success rate < > 80%
If either is right, probability lose < 10^{-7}

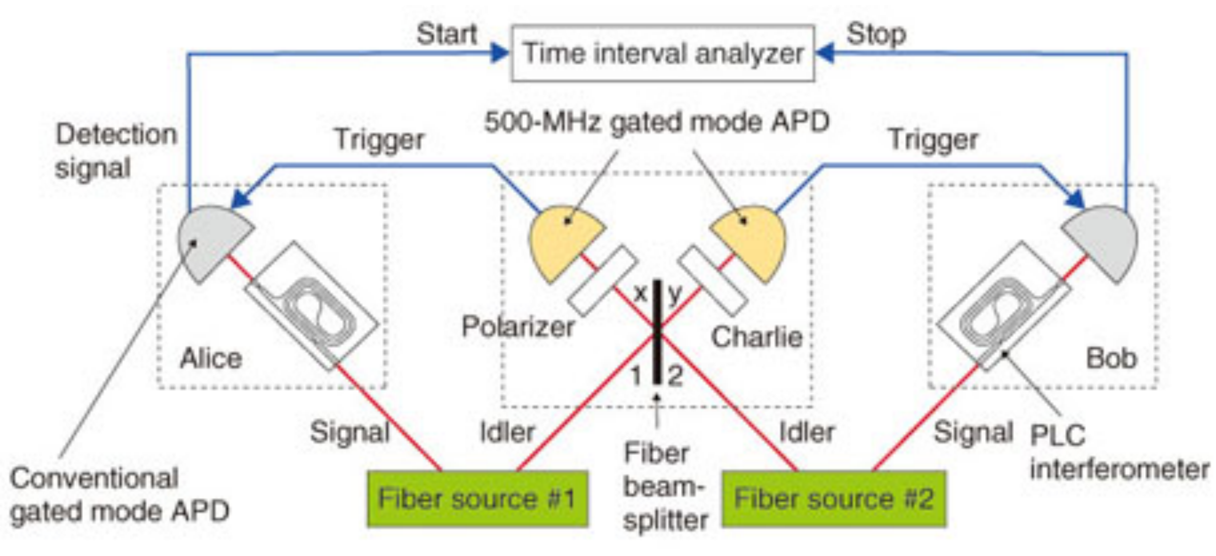
Martingale result

- The probability of at least 196 successes in 245 trials is at most Pr(Bin(245, ¾) ≥ 196) = 0.039, whatever strategy is used (possibly time dependent, possibly dynamic)

- What is essential: settings are chosen repeatedly completely at random

Delft innovation: use entanglement swapping

- Photons leave each spin system and (hopefully) reach central location and interact there
- Sometimes they are both detected after interaction



Algebra (abracadabra?)

(00 + 11) (00 + 11) = 0000 + 0011 + 1100 + 1111

= 0(00)0 + 0(01)1 + 1(10)0 + 1(11)1

= 11 + 22 + 33 + 44

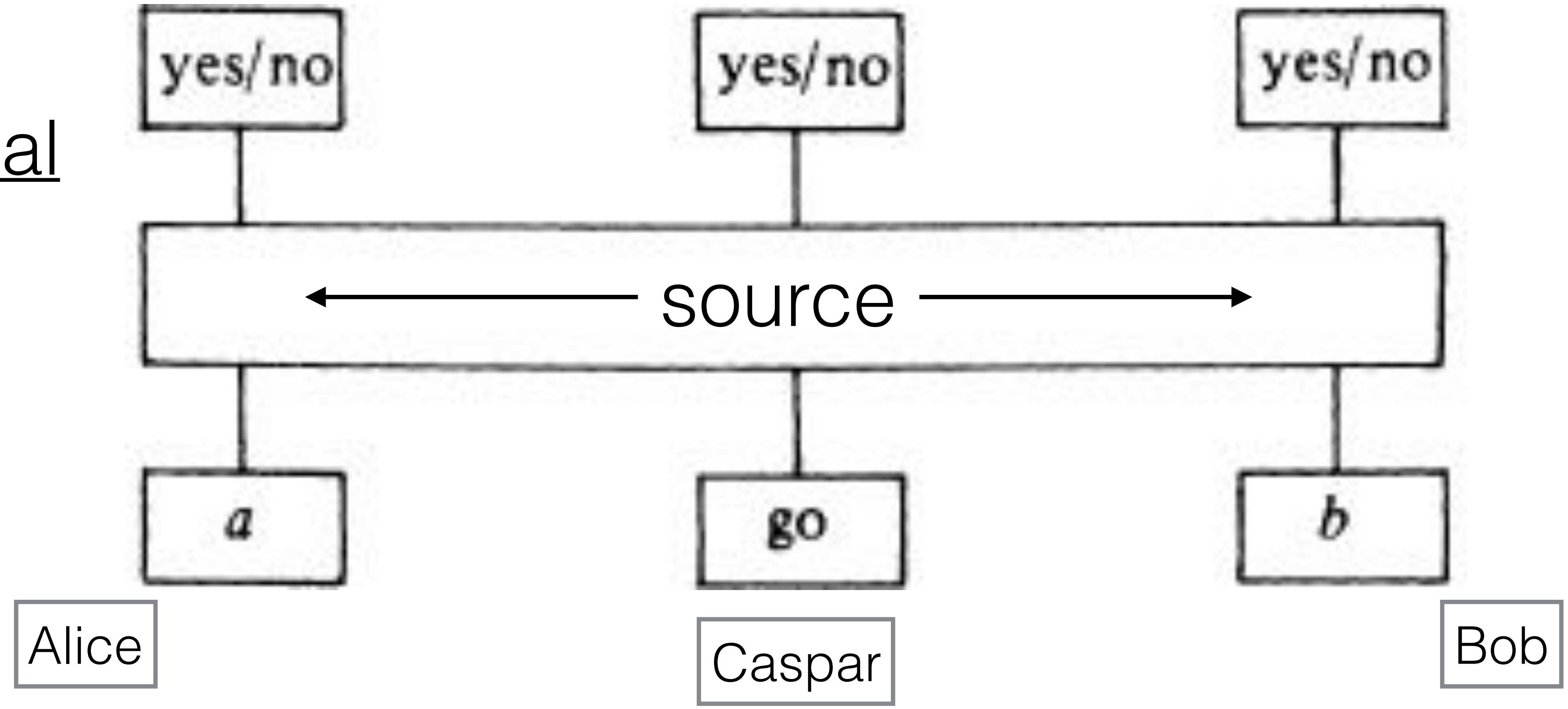
11 + 44 = 1((1 + 4) + (1 – 4)) + 4((1 + 4) – (1 – 4))

=(1 + 4)(1 + 4) + (1 – 4)(1 – 4)

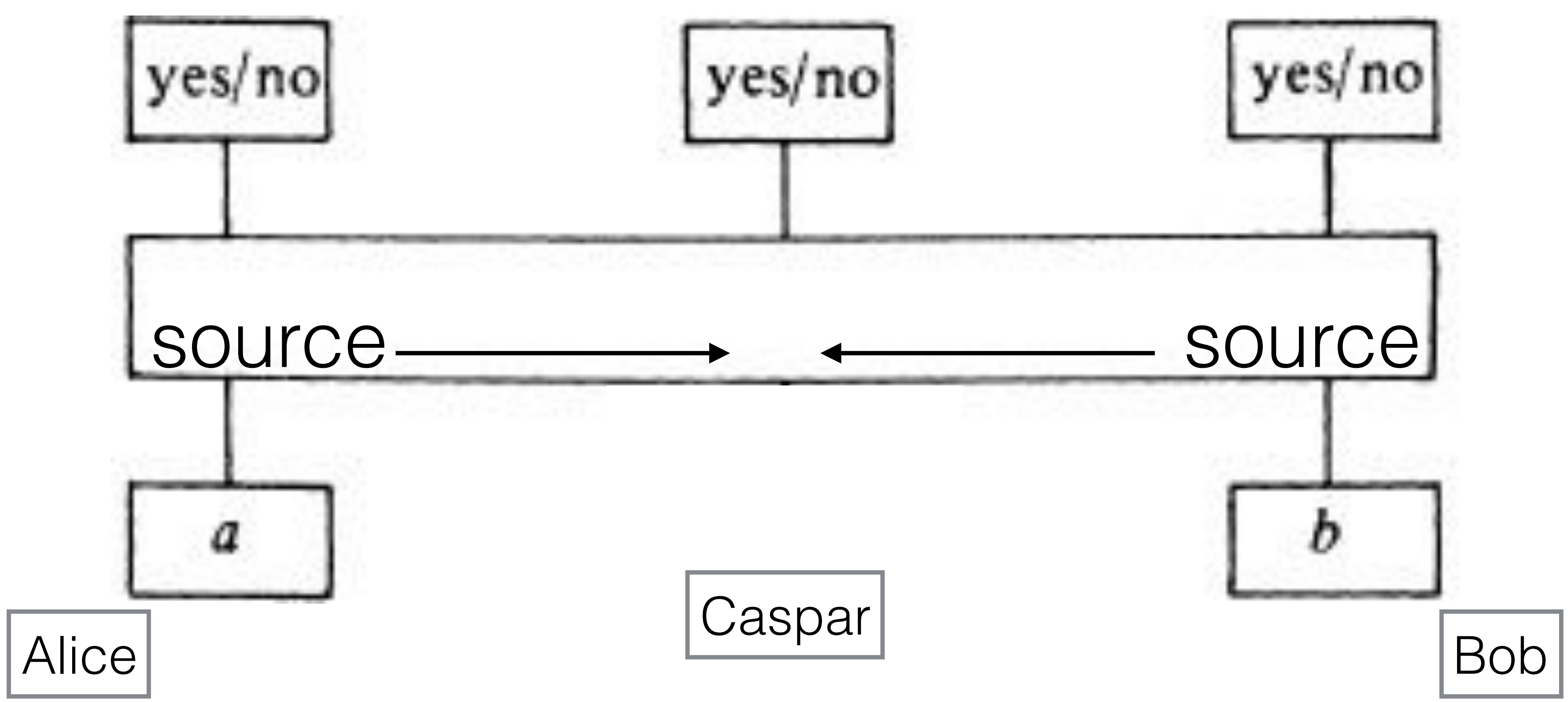
(00 + 11) (00 + 11)

= (00 + 11)(00 + 11) + (00 –11)(00 – 11) + (01 + 10)(01 + 10) + (01 – 10)(01 – 10)

Traditional



New



More precisely

- Alice, Bob and Caspar each choose a setting and make a measurement.We investigate the correlations between Alice and Bob’s outcomes given their settings, conditional on Caspar’s setting and outcome.

Another experiment

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,‡]

[1]*National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA*
[2]*Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, Canada, N2L 3G1*
[3]*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
[4]*National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, Maryland 20899, USA*
[5]*Département de Physique et d'Astronomie, Université de Moncton, Moncton, New Brunswick E1A 3E9, Canada*
[6]*Joint Quantum Institute, National Institute of Standards and Technology and University of Maryland, 100 Bureau Drive, Gaithersburg, Maryland 20899, USA*
[7]*Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA*
[8]*ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain*
[9]*ICREA-Institució Catalana de Recerca i Estudis Avançats, 08015 Barcelona, Spain*
[10]*Quantum Information Science Program, Canadian Institute for Advanced Research, Toronto, Ontario, Canada*

(Received 10 November 2015; published 16 December 2015)

We present a loophole-free violation of local realism using entangled photon pairs. We ensure that all relevant events in our Bell test are spacelike separated by placing the parties far enough apart and by using fast random number generators and high-speed polarization measurements. A high-quality polarization-entangled source of photons, combined with high-efficiency, low-noise, single-photon detectors, allows us to make measurements without requiring any fair-sampling assumptions. Using a hypothesis test, we compute p values as small as 5.9×10^{-9} for our Bell violation while maintaining the spacelike separation of our events. We estimate the degree to which a local realistic system could predict our measurement choices. Accounting for this predictability, our smallest adjusted p value is 2.3×10^{-7}. We therefore reject the hypothesis that local realism governs our experiment.

Yet another …

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,†]

[1]*Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Boltzmanngasse 3, Vienna 1090, Austria*
[2]*Quantum Optics, Quantum Nanophysics and Quantum Information, Faculty of Physics, University of Vienna, Boltzmanngasse 5, Vienna 1090, Austria*
[3]*Max-Planck-Institute of Quantum Optics, Hans-Kopfermann-Straße 1, 85748 Garching, Germany*
[4]*Institutionen för Systemteknik, Linköpings Universitet, 581 83 Linköping, Sweden*
[5]*ICFO – Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain*
[6]*ICREA – Institució Catalana de Recerca i Estudis Avançats, 08015 Barcelona, Spain*
[7]*Physikalisch-Technische Bundesanstalt, Abbestraße 1, 10587 Berlin, Germany*
[8]*National Institute of Standards and Technology (NIST), 325 Broadway, Boulder, Colorado 80305, USA*

(Received 10 November 2015; published 16 December 2015)

Local realism is the worldview in which physical properties of objects exist independently of measurement and where physical influences cannot travel faster than the speed of light. Bell's theorem states that this worldview is incompatible with the predictions of quantum mechanics, as is expressed in Bell's inequalities. Previous experiments convincingly supported the quantum predictions. Yet, every experiment requires assumptions that provide loopholes for a local realist explanation. Here, we report a Bell test that closes the most significant of these loopholes simultaneously. Using a well-optimized source of entangled photons, rapid setting generation, and highly efficient superconducting detectors, we observe a violation of a Bell inequality with high statistical significance. The purely statistical probability of our results to occur under local realism does not exceed 3.74×10^{-31}, corresponding to an 11.5 standard

Tiny violation, huge significance

- Giustina et al. (Vienna): success rate 75.00073%, N = 3503 million

- Shalm et al. (NIST, Boulder, Co): success rate 75.00142%, N = 177 million

- p-values …

- These are both "traditional" types of the experiment

Novelty of NIST, Vienna?

- Use Eberhard inequality instead of Bell-CHSH
- Use almost <u>not</u> entangled state, different measurements
- Peter Biermann: at ≥ 75% detector efficiency it is just possible for QM to violate Bell's inequality, provided we choose "best state and measurements" far from "usual" "optimal" choice.

Conclusion

- We need better experiments still …
- They will certainly need statistics

Want to know more?

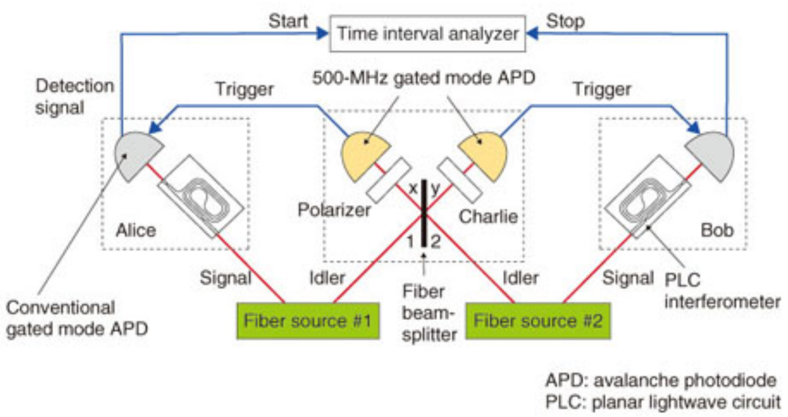
- http://www.math.leidenuniv.nl/~gill
- Survey paper in *Statistical Science*

Statistical Science
2014, Vol. 29, No. 4, 512–528
DOI: 10.1214/14-STS490
© Institute of Mathematical Statistics, 2014

Statistics, Causality and Bell's Theorem

Richard D. Gill

Abstract. Bell's [*Physics* **1** (1964) 195–200] theorem is popularly supposed to establish the nonlocality of quantum physics. Violation of Bell's inequality in experiments such as that of Aspect, Dalibard and Roger [*Phys. Rev. Lett.* **49** (1982) 1804–1807] provides empirical proof of nonlocality in the real world. This paper reviews recent work on Bell's theorem, linking it to issues in causality as understood by statisticians. The paper starts with a proof of a strong, finite sample, version of Bell's inequality and thereby also of Bell's theorem, which states that quantum theory is incompatible with the conjunction of three formerly uncontroversial physical principles, here referred to as *locality*, *realism* and *freedom*.



Postscript

I cannot say that action at a distance is required in physics. But I cannot say that you can get away with no action at a distance. **You cannot separate off what happens in one place with what happens at another** – John Bell

https://www.youtube.com/watch?v=V8CCfOD1iu8 (video of a talk at CERN)
http://www.quantumphil.org./Bell-indeterminism-and-nonlocality.pdf (transcript)
https://www.informationphilosopher.com/solutions/scientists/bell/Bell-Davies.pdf (transcript of BBC radio interview)

Nature produces chance events (irreducibly chance-like!) which can occur at widely removed spatial locations without anything propagating from point to point along any path joining those locations. … **The chance-like character of these effects prevents any possibility of using this form of non locality to communicate**, thereby saving from contradiction with one of the fundamental principles of relativity theory according to which no communication can travel faster than the speed of light – Nicolas Gisin

Quantum Chance: Nonlocality, Teleportation and Other Quantum Marvels. Springer, 2014