Towards evidence-based physics

Richard Gill
Leiden

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

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LETTER

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

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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

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 $|\psi^-\rangle = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

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

Bell’s inequality

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

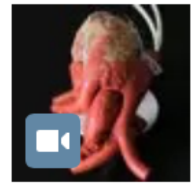
The world is made up of real stuff, existing in space and changing only through local interactions — this local-realism hypothesis is about the most intuitive scientific postulate imaginable. But quantum mechanics implies that it is false, as has been known for more than 50 years[1]. However, brilliantly 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

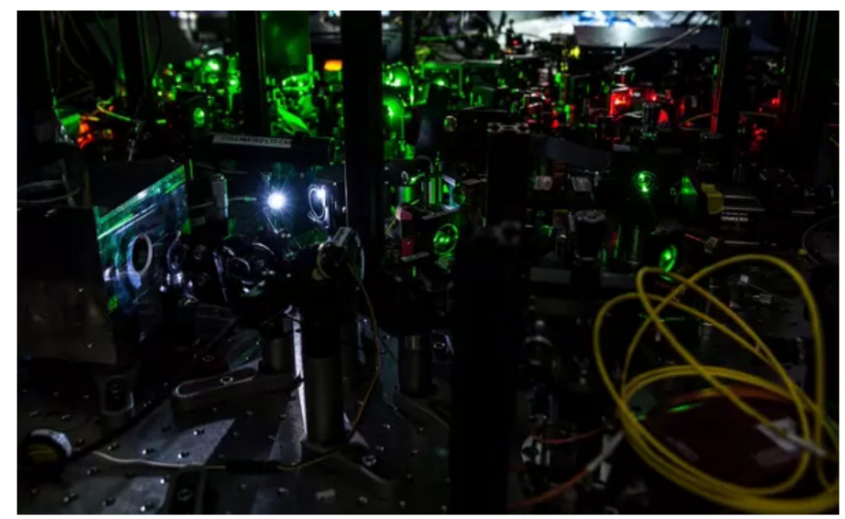


SCIENCE

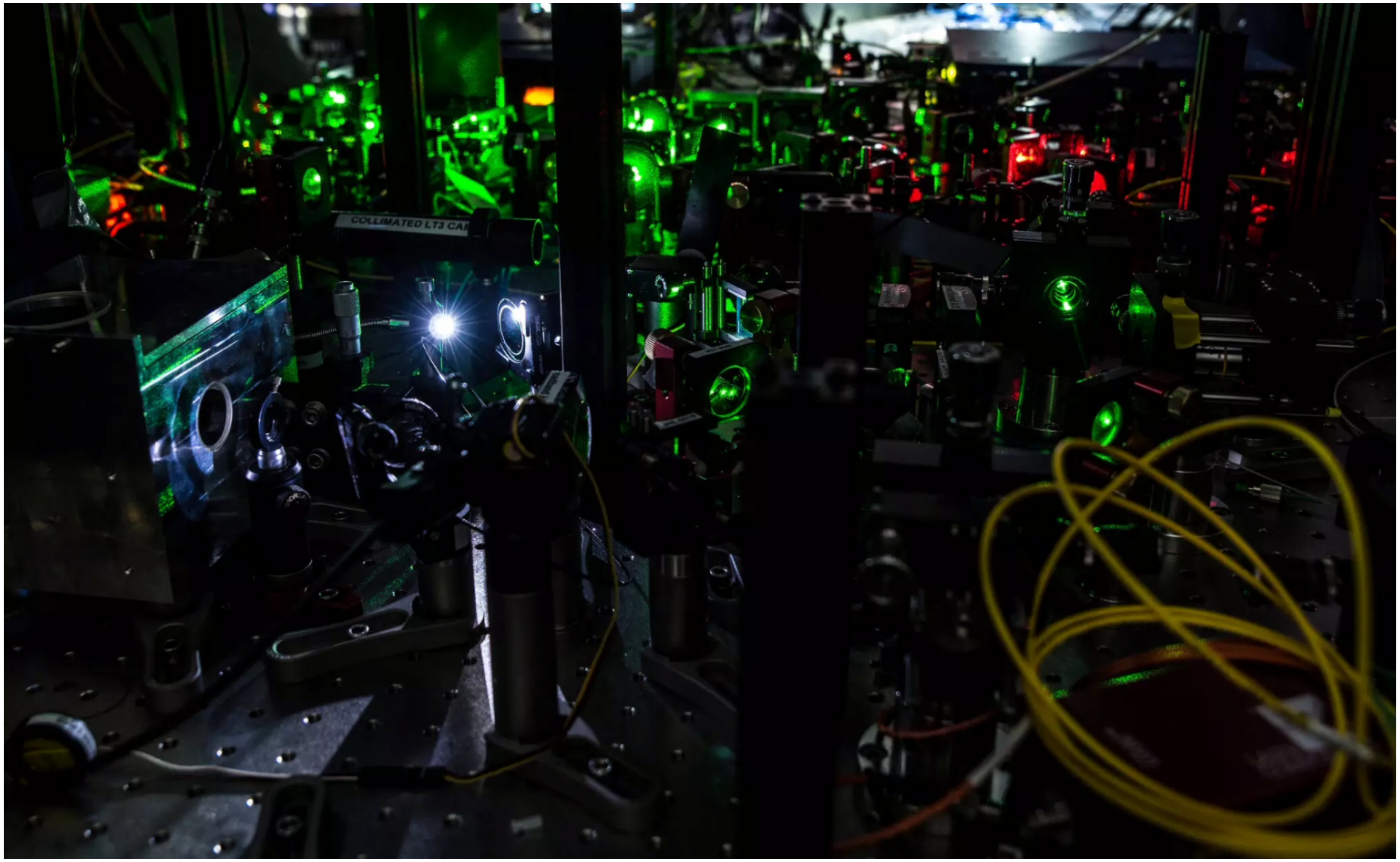
Sorry, Einstein. Quantum Study Suggests 'Spooky Action' Is Real.

By JOHN MARKOFF OCT. 21, 2015

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

The finding is another blow



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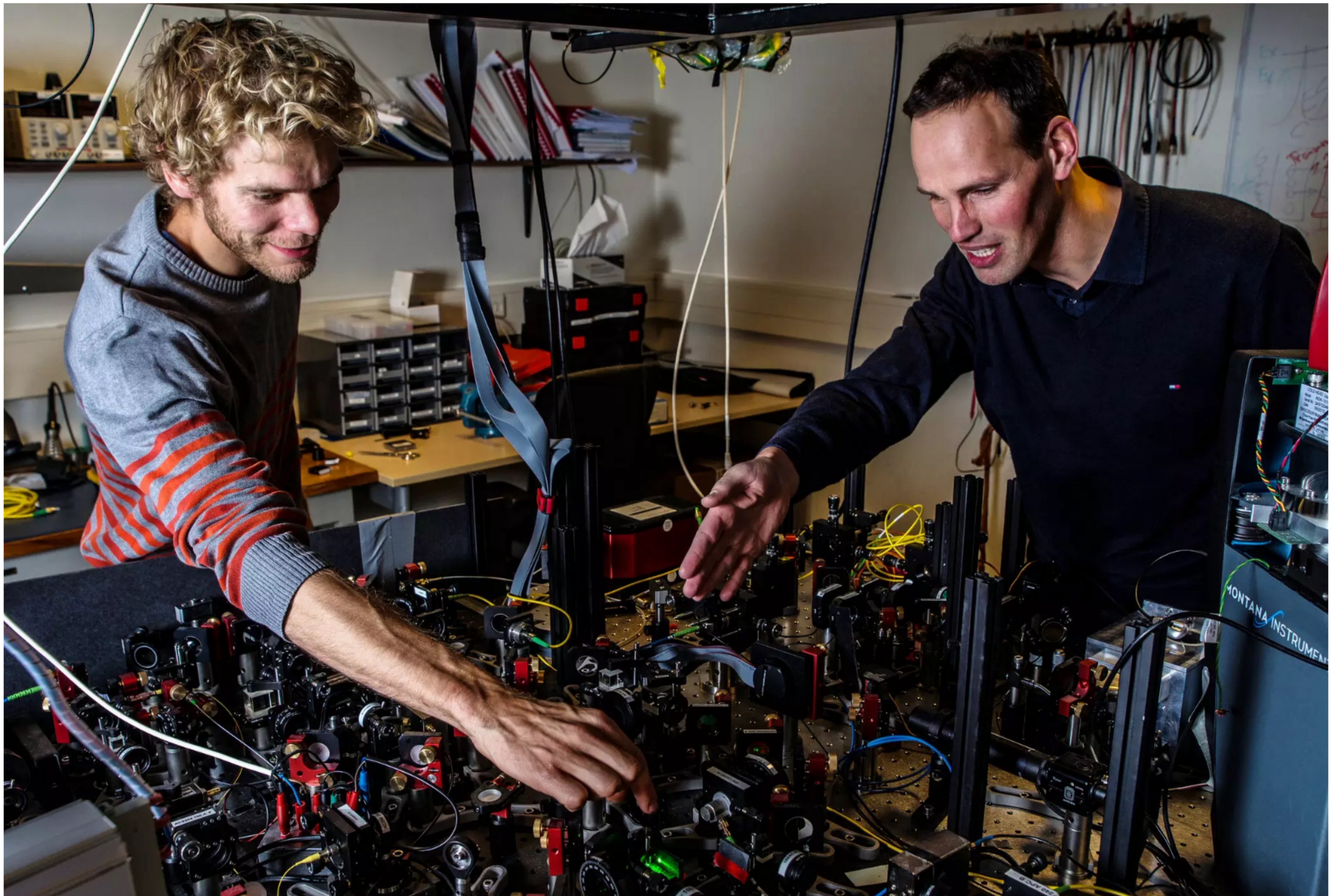

Bas Hensen, left, and Ronald Hanson helped show that objects apart can instantly affect each other.

Frank Auperle/Delft University of Technology

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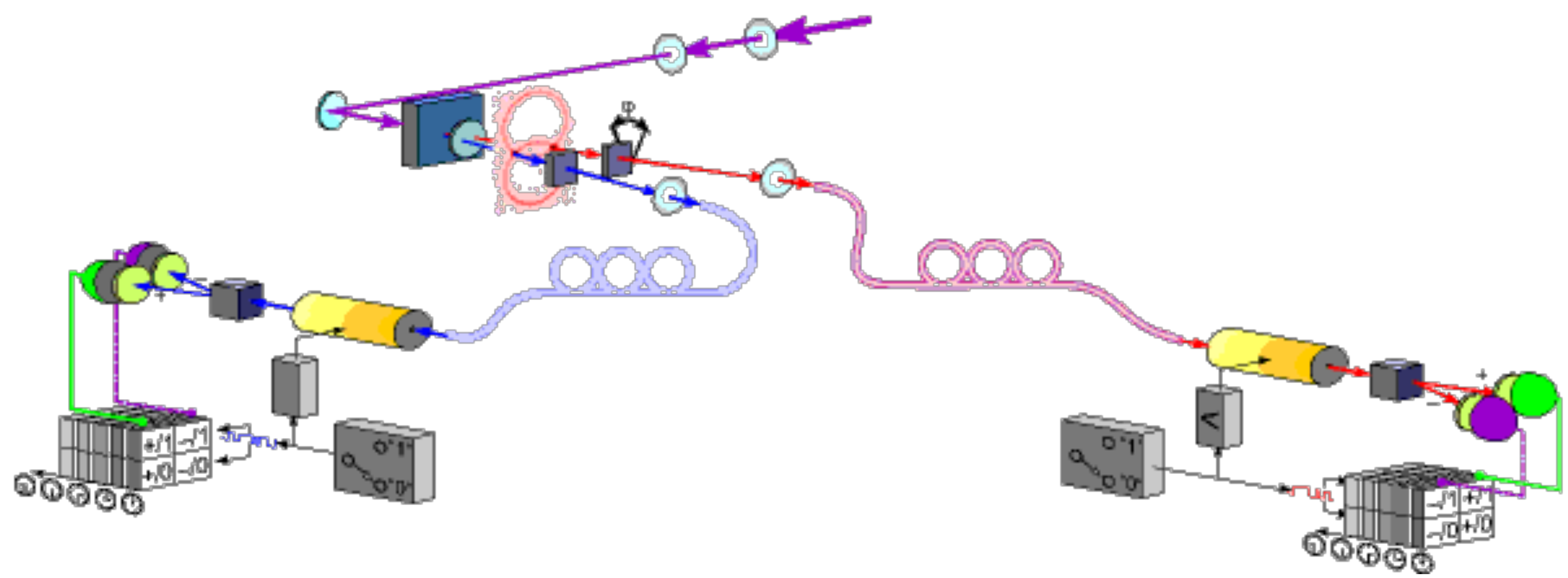
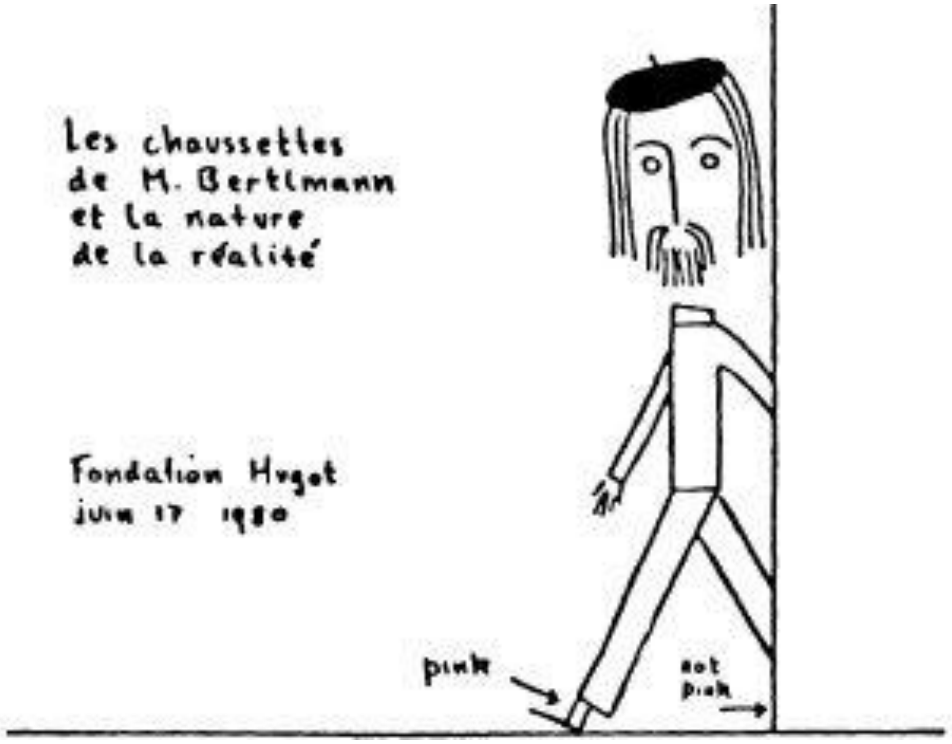
co-author, Mathematician Stéphanie Wehner

First loophole-free experimental violation of Bell's inequality

- John S. 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
- In other words, they could not do the right experiment, and had to make do with surrogates (e.g.: Aspect et al. 1982; Weihs et al. 1998: …)

Example: Weihs et al. (1998)

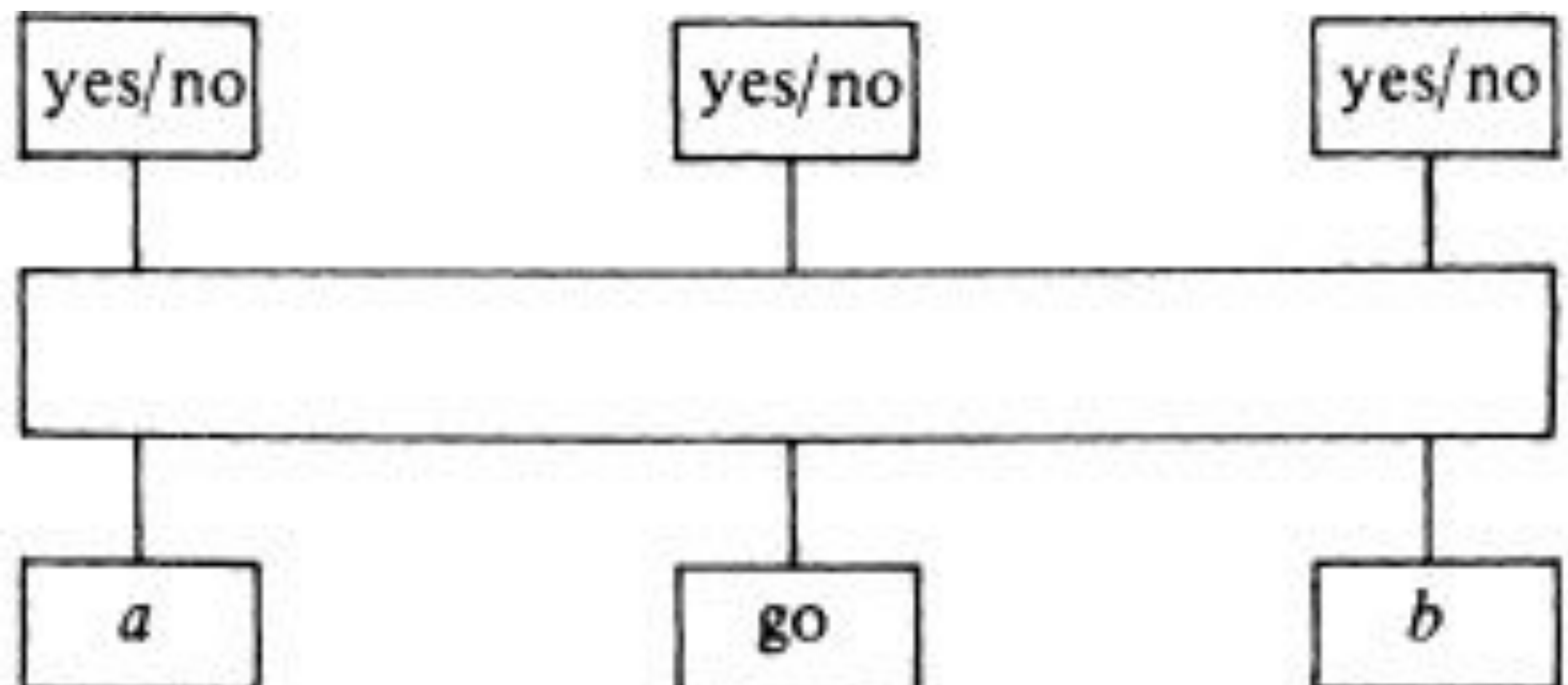




Bell (1981) “Bertlmann’s socks and the nature of reality”

Alice Outcome

Bob Outcome



Time

Alice Setting

Bob Setting

The Bell game

- Alice and Bob make preparations
- They are separated, and may no longer communicate
- Each is told 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**
- Aim: outcomes rg or gr with settings 11; outcomes rr or gg with settings 12, 21, or 22

The Bell Game (continued)

- This is repeated *N* times (“trials”)
- Between each trial, Alice and Bob may confer
- Their opponent can be expected to generate the settings with independent, fair, coin tosses

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

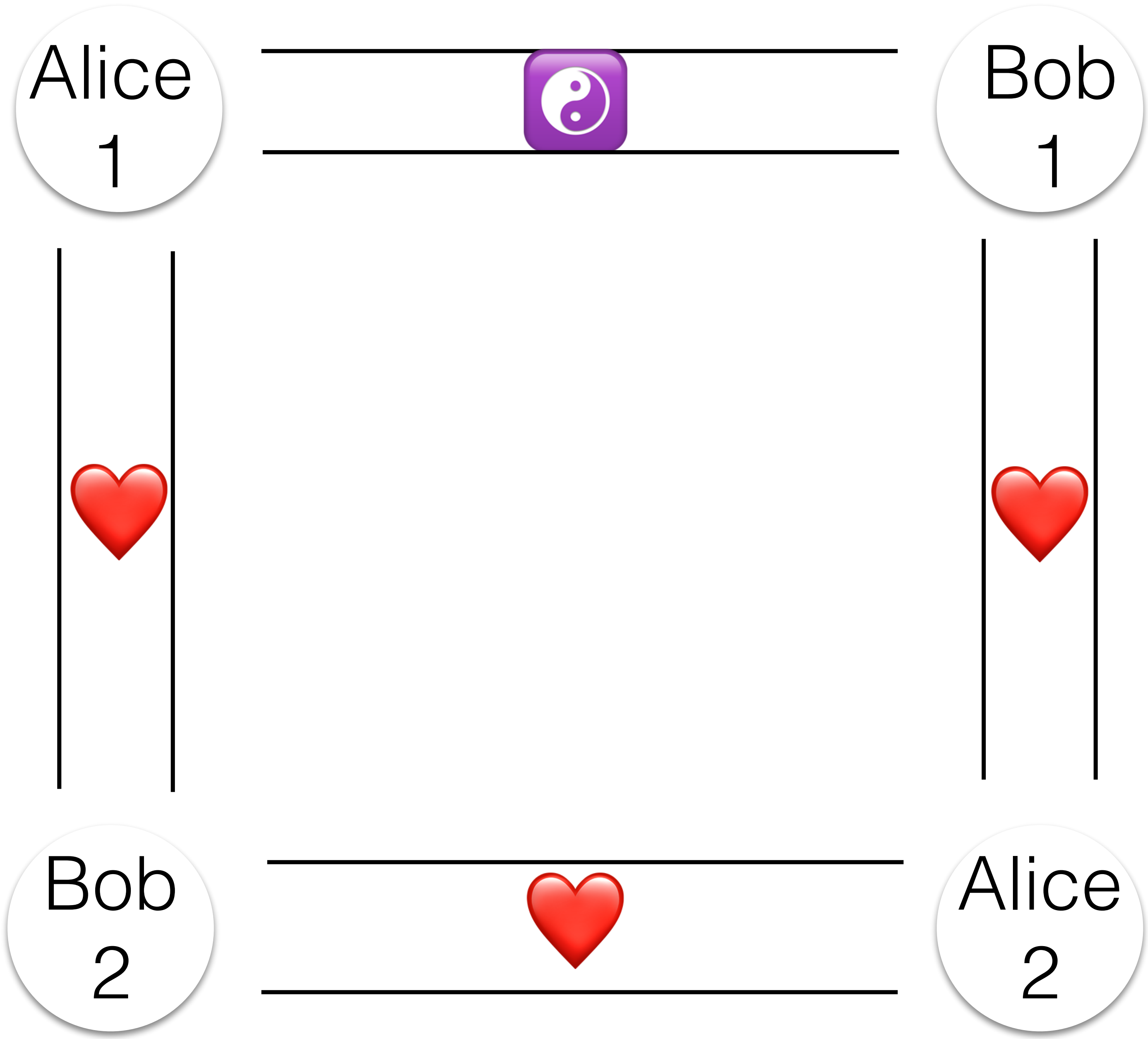
- Given all results of any randomisations, their strategy specifies an “instruction set”: colours for Alice for settings 1 and 2, colours for Bob for settings 1 and 2

- There are exactly 16 different instruction sets

- Let’s take a look at some of them …

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

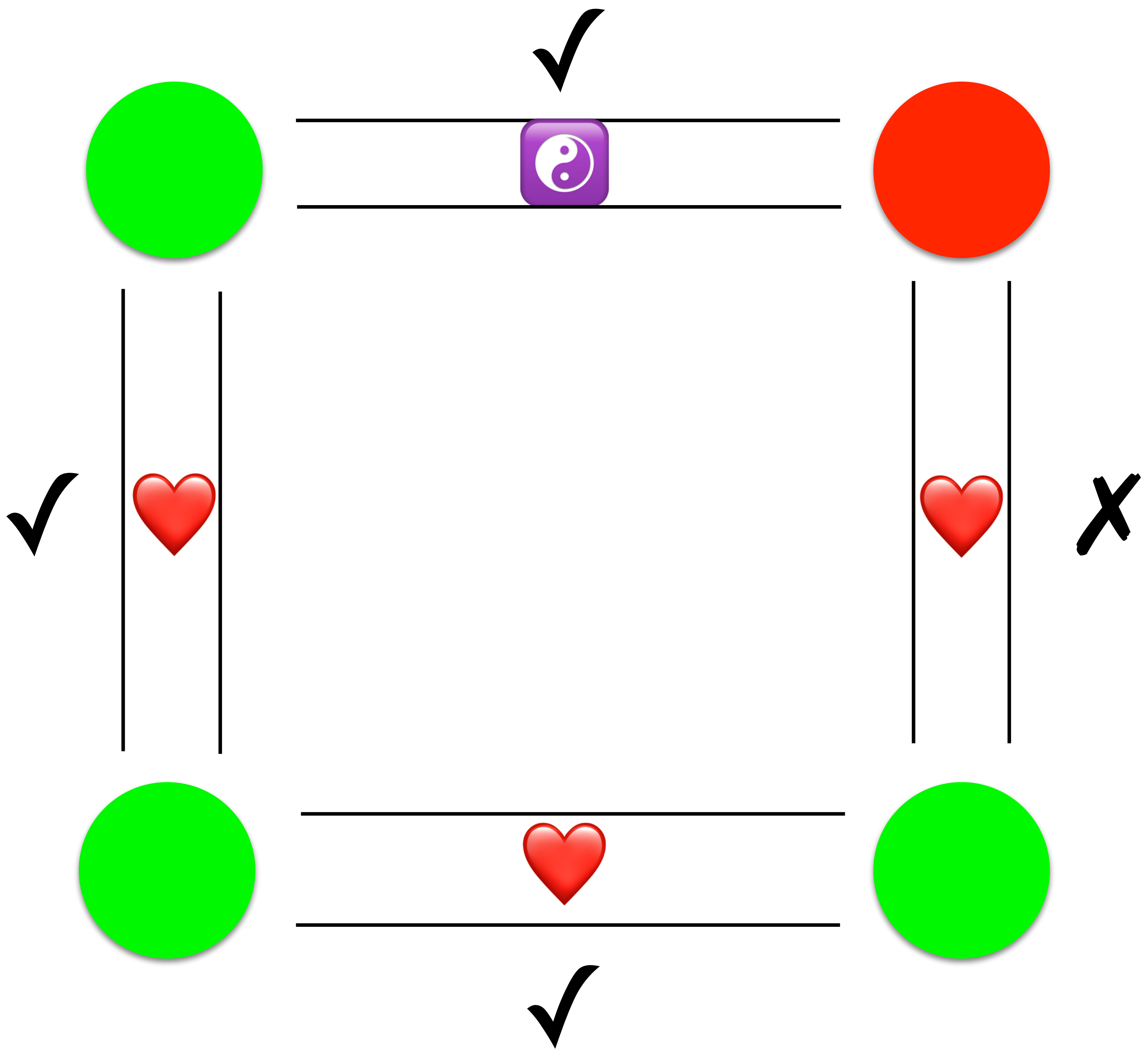
the two on top have different colours ◒

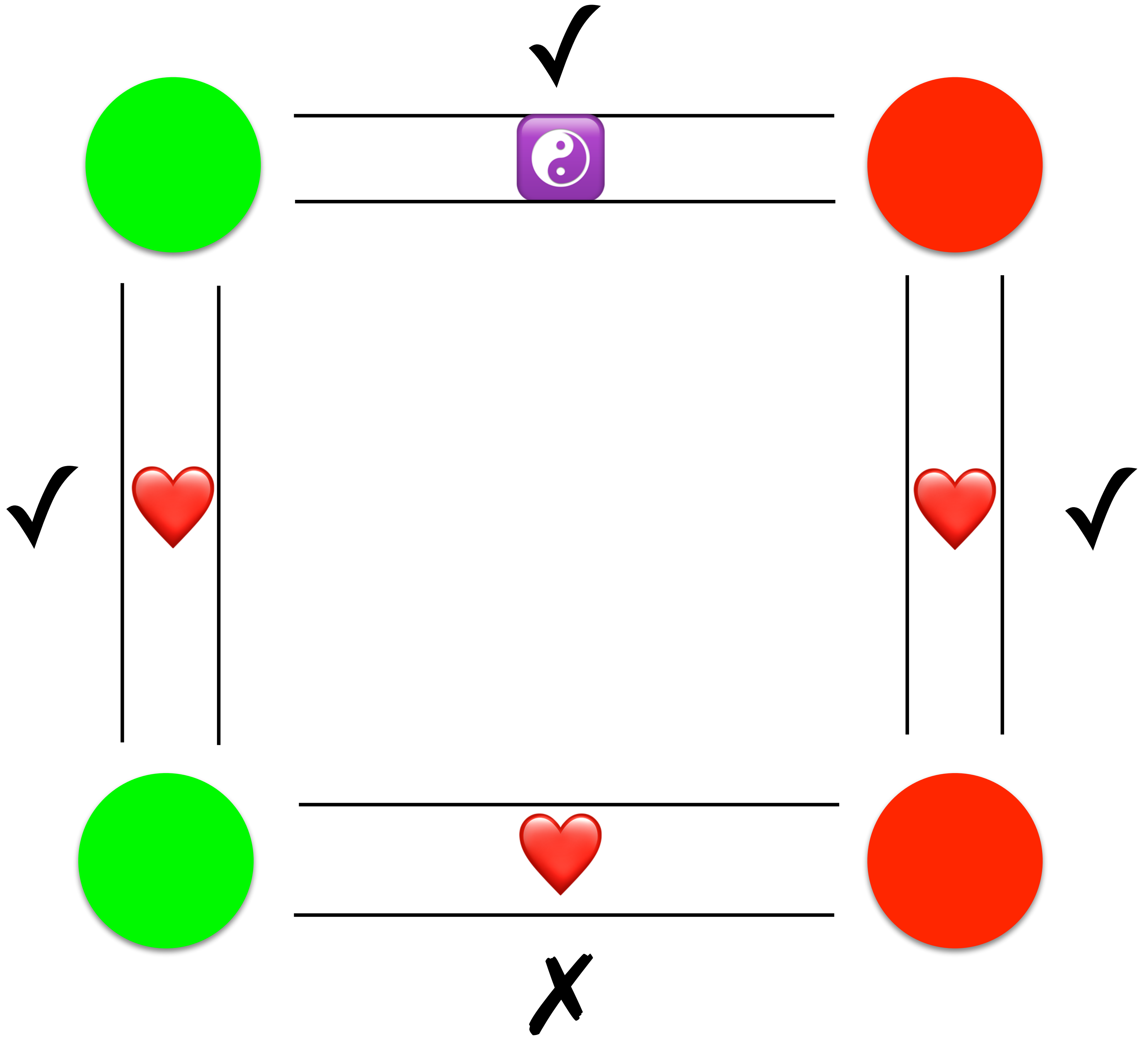


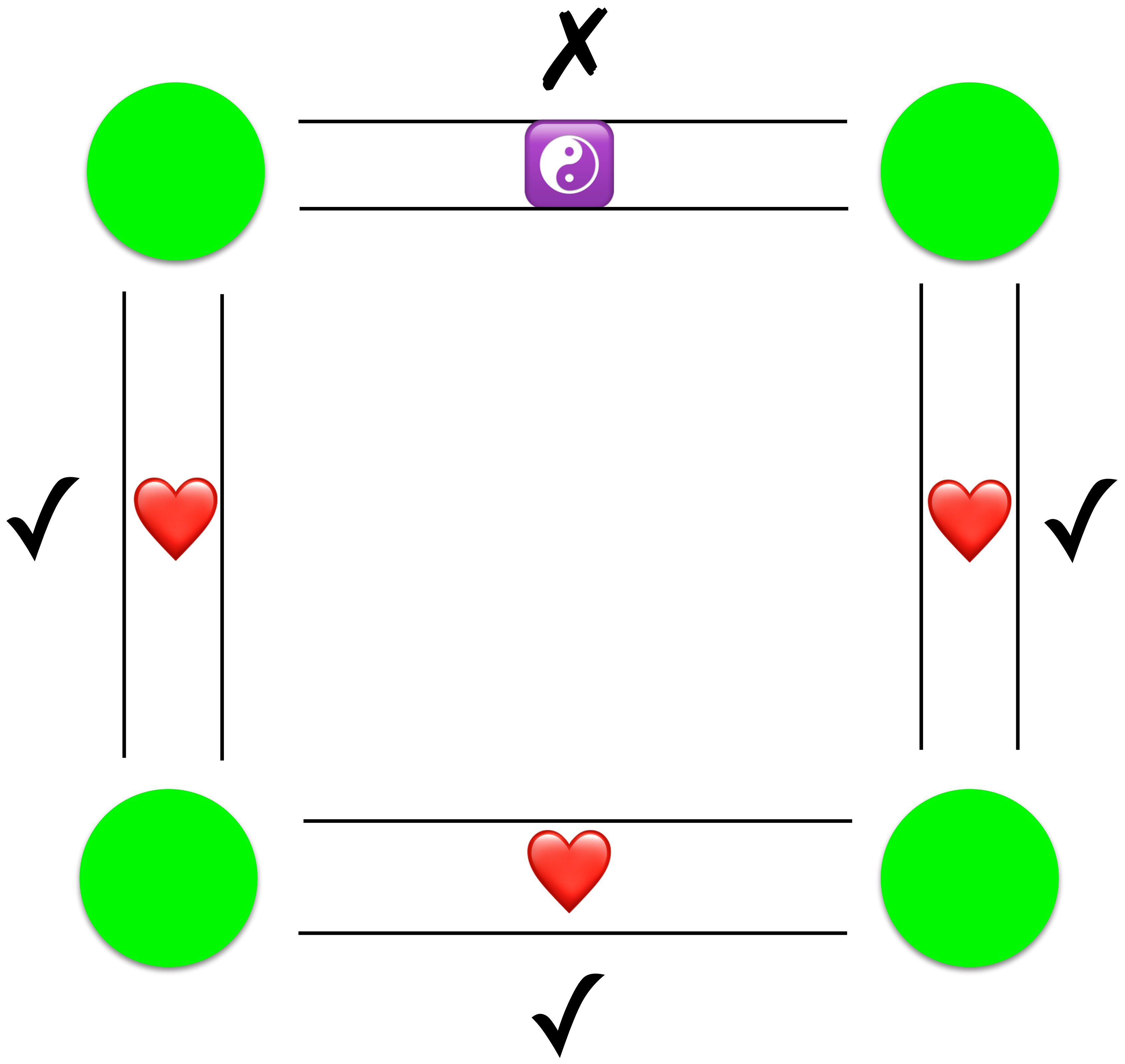
the two on the left have the same colour ❤️

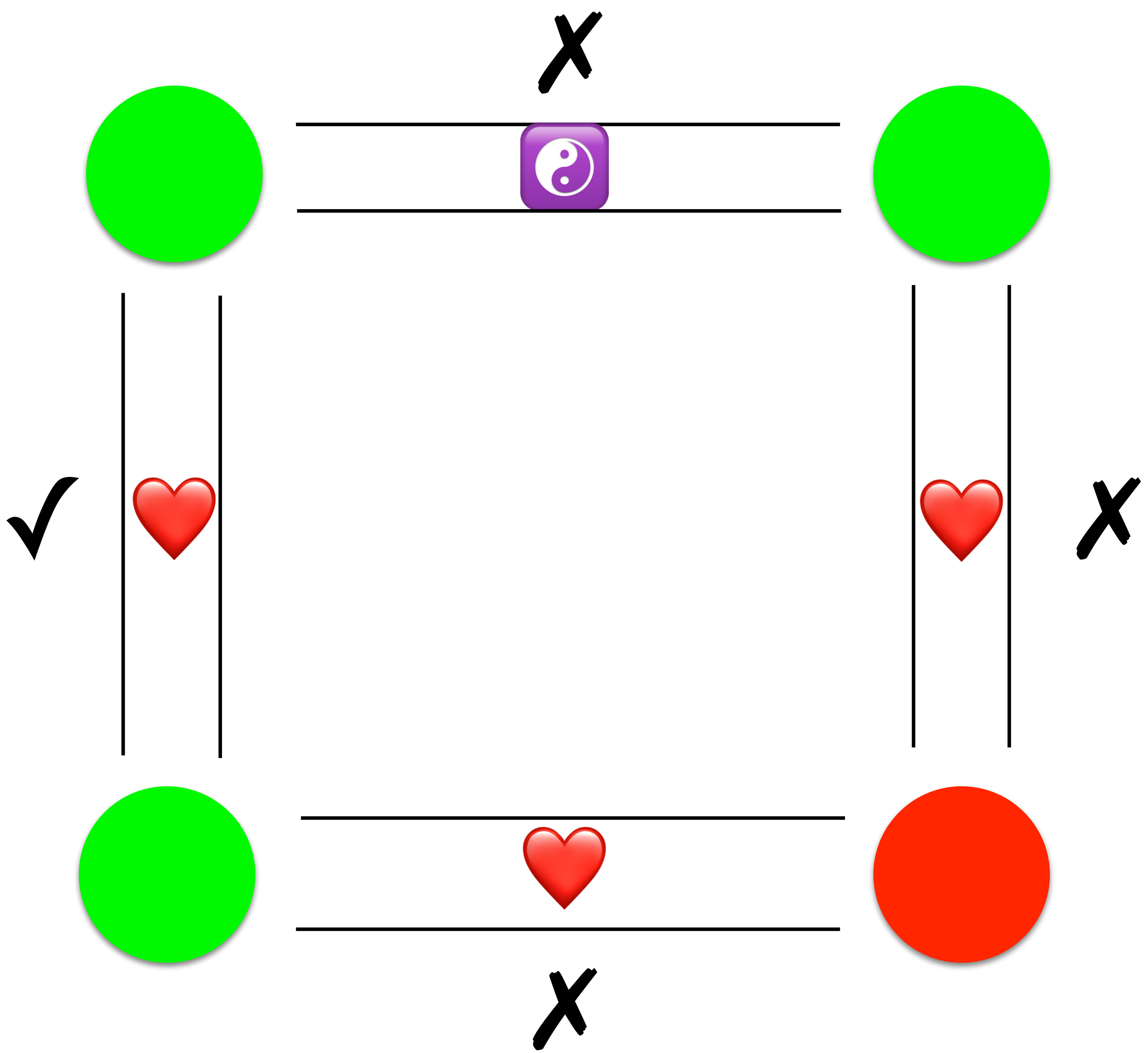
the two on the right have the same colour ❤️

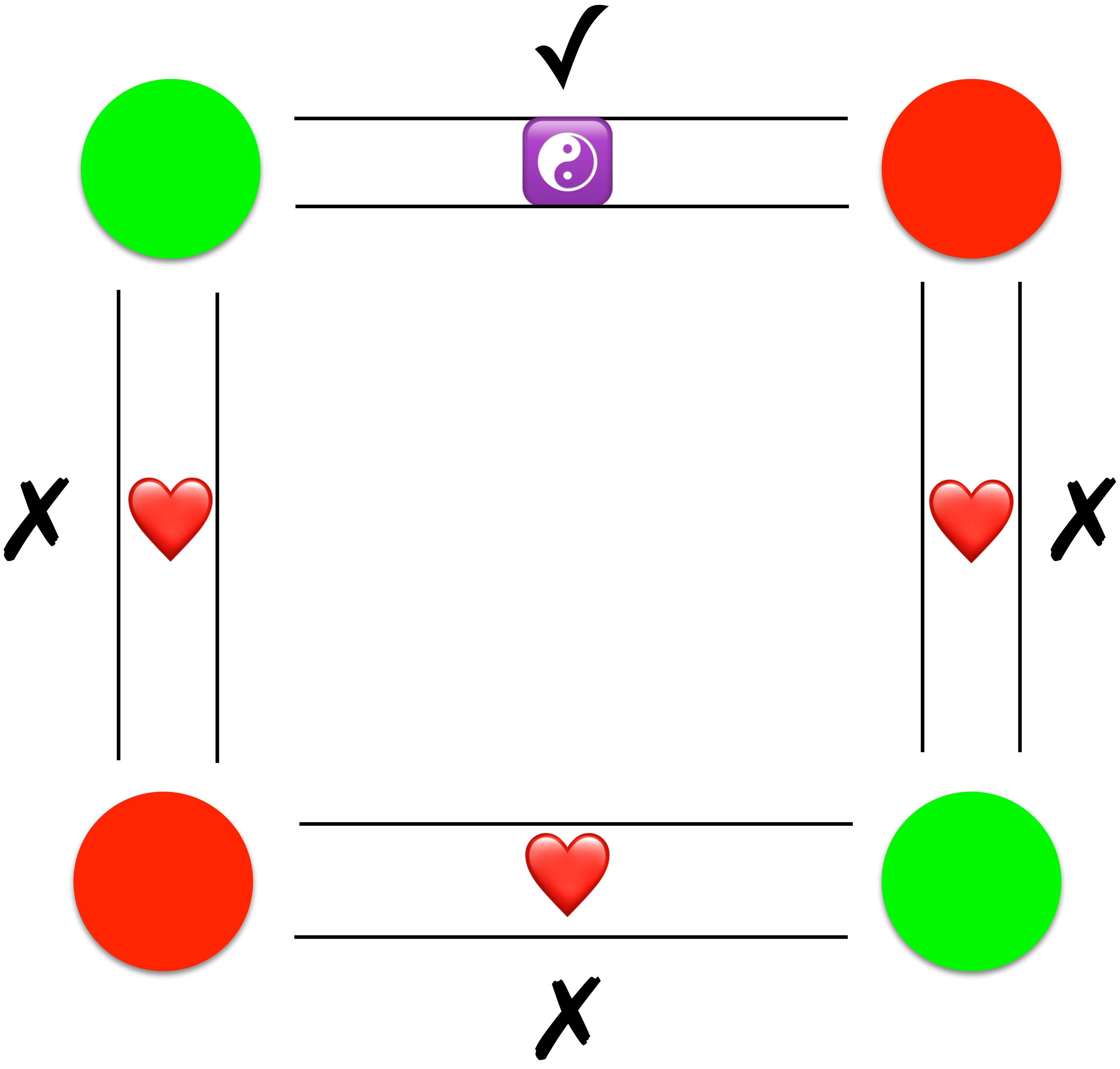
the two on the bottom have the same colour ❤️

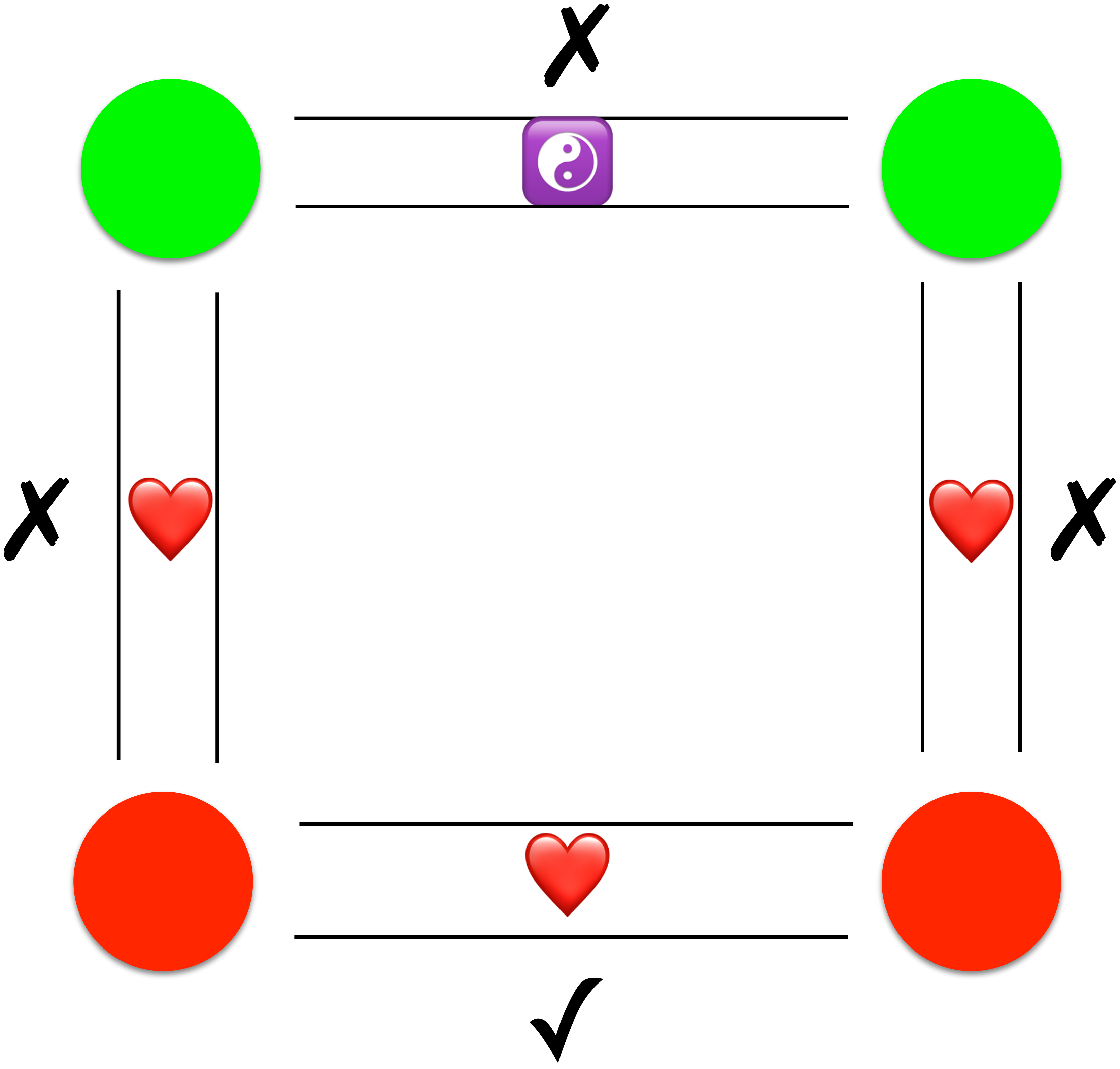






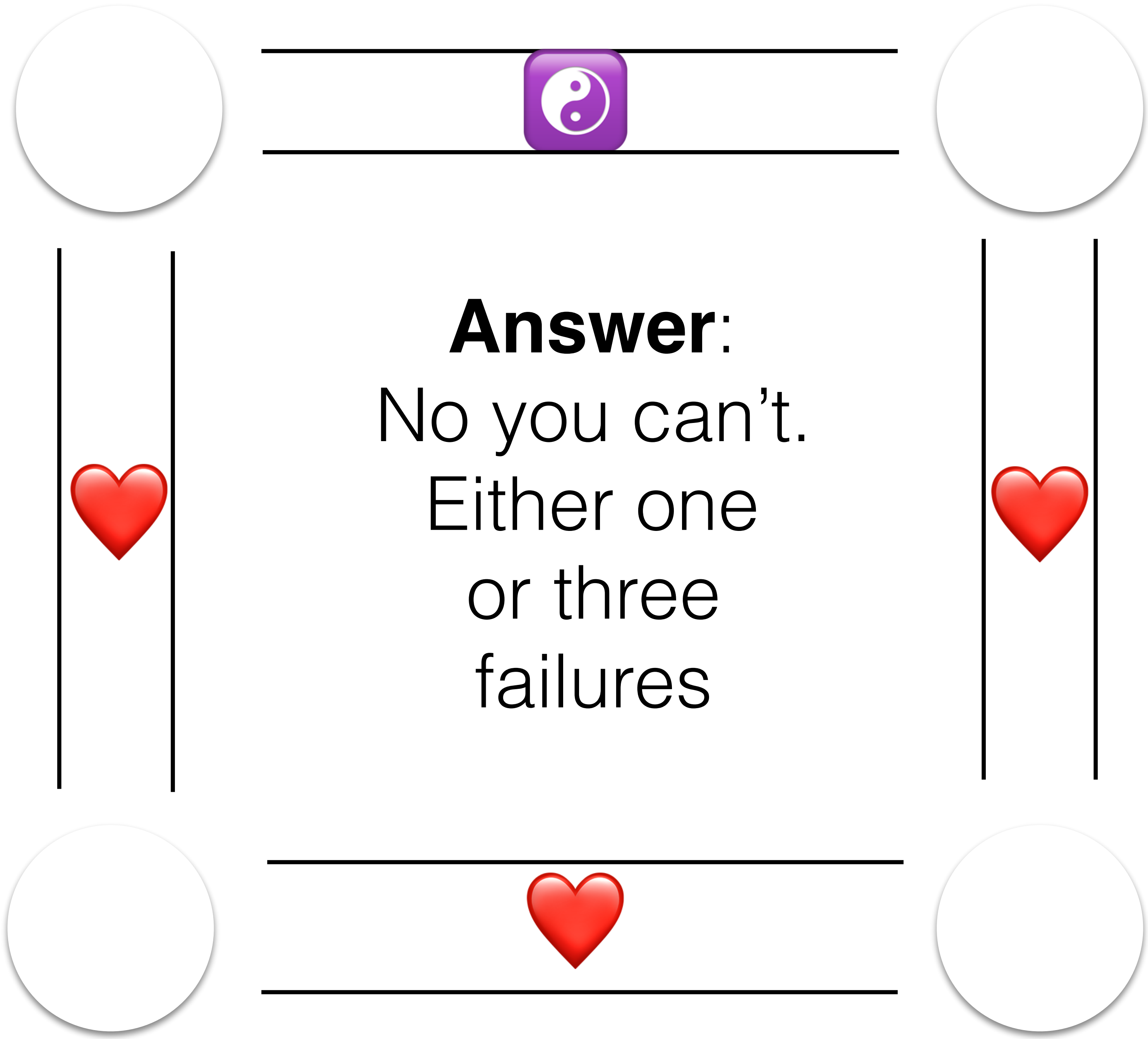






Question: can you colour the four balls green and red, so that

the two on top have different colours ☯



the two on the left have the same colour ❤️

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

the two on the right have the same colour ❤️

the two on the bottom have the same colour ❤️

Optimal play for Alice and Bob

- 8 = 2 x 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** seems smart

- Could it be that when playing many rounds of the game, it is better to vary the strategy, possibly depending on results obtained so far??

Bell game results in Delft

- N = 245
- Success rate: 80%
- Optimal rate under “local realism” 75%
- Optimal rate under “quantum mechanics” 85%

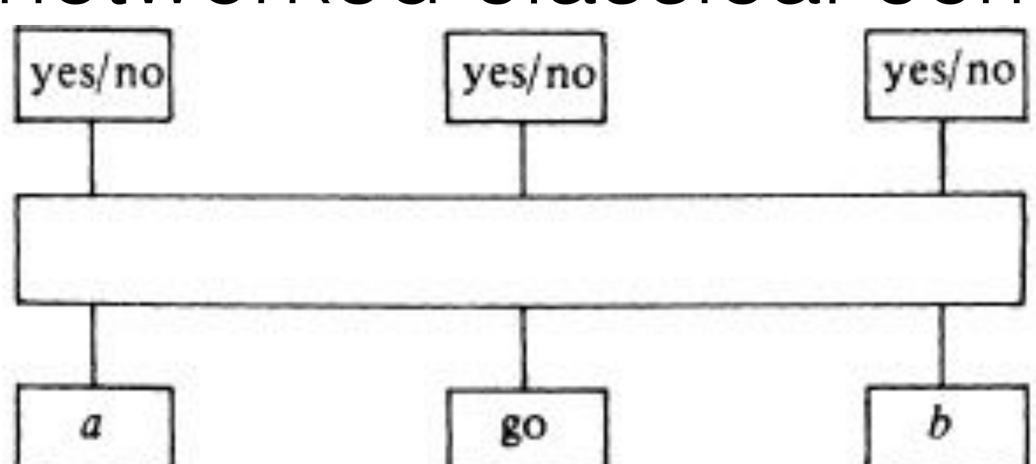
(why can’t QM do better?)

Delft Bell results in round numbers

- 75% of 240 is 180
- 80% of 240 is 192
- Binomial variance $N = 240$, $p = 3/4$ is $240 \times 3/4 \times 1/4 = 45$ not far from $49 = 7 \times 7$
- $192 - 180 = 12$ = approx 2 standard deviations
- Actual result: $N = 245$, # successes = 196
- $\mathrm{Prob}(\mathrm{Binomial}(245, 3/4) \geq 196) = 0.039$

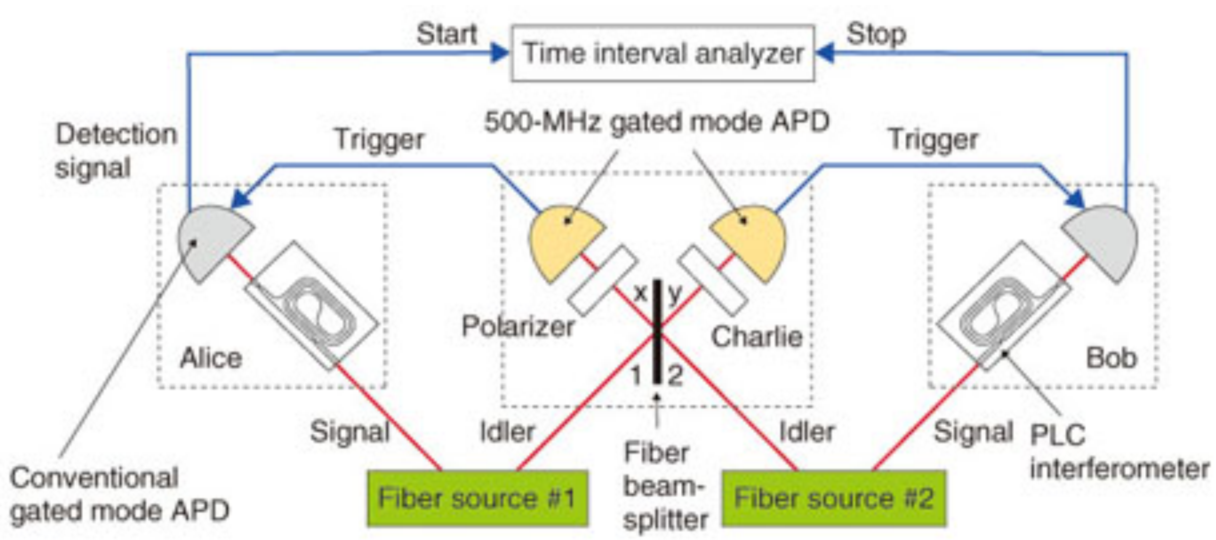
There is no gain in strategies which use memory and time

- First such results obtained by Gill (2001) using martingale theory; rewrite usual “combination of four correlations” as final result of a game
- My aim: design a bet against someone who claims to be able to simulate the quantum correlations with (classically) networked classical computers



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?)

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

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

$= 11 + 22 + 33 + 44$

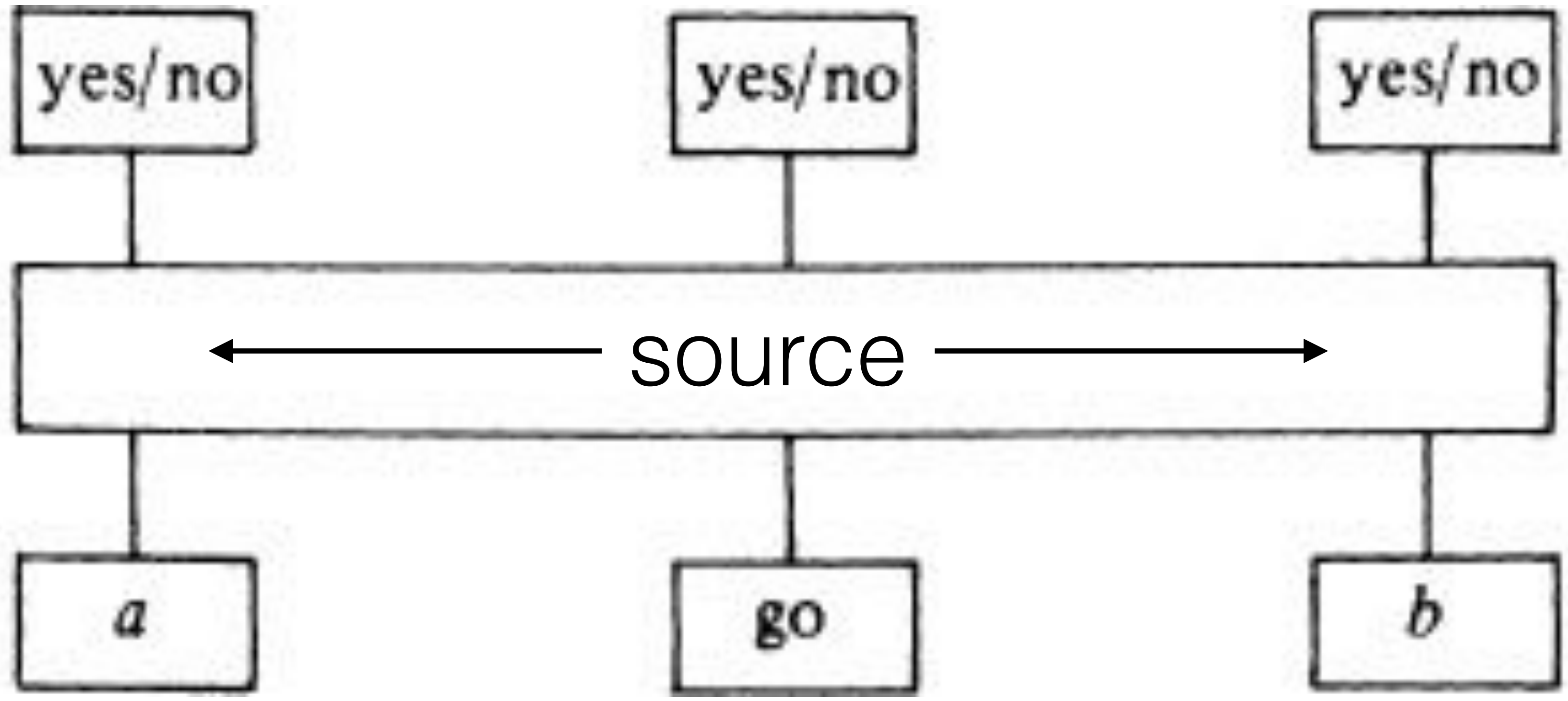
$11 + 44 = 1((1 + 4) + (1 - 4)) + 4((1 + 4) - (1 - 4))$

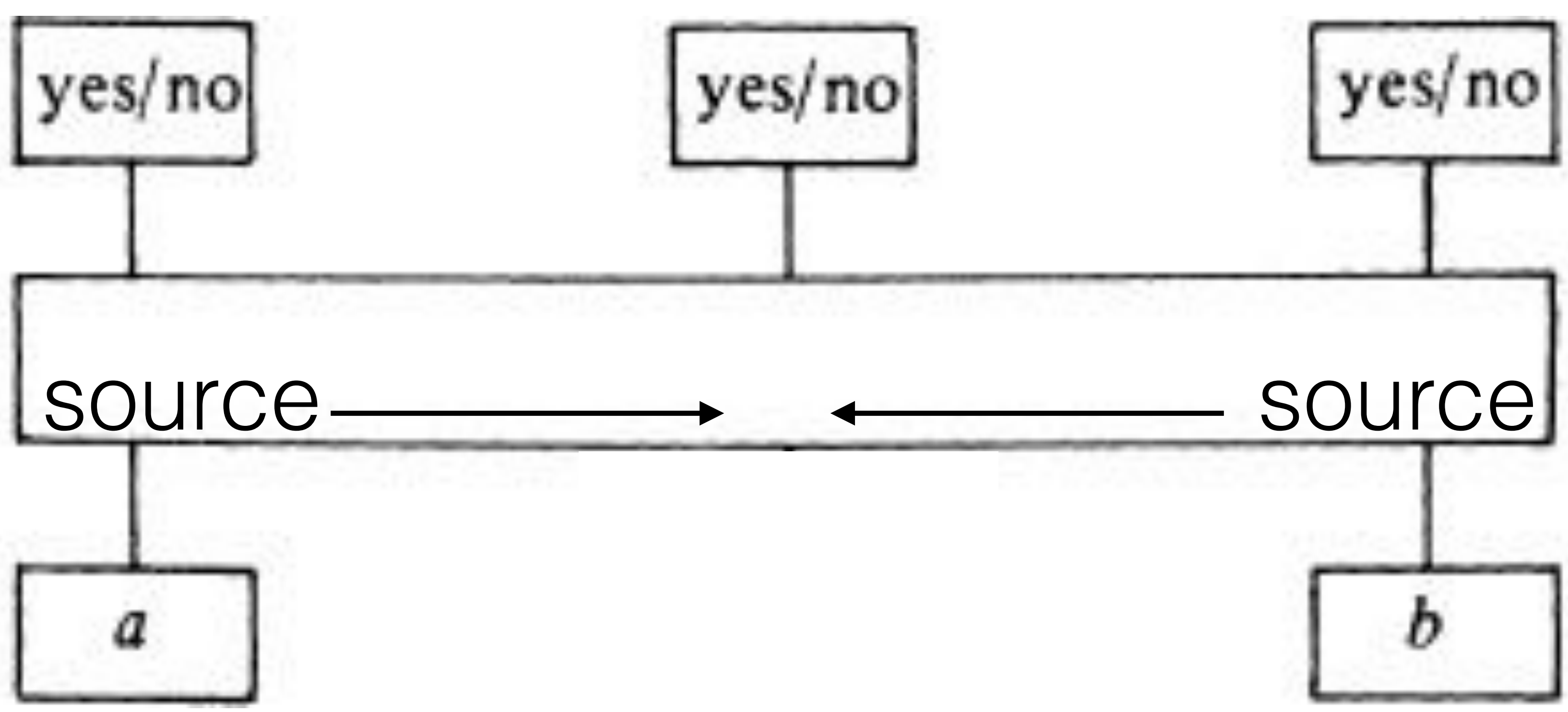
$=(1 + 4)(1 + 4) + (1 - 4)(1 - 4)$

$(00 + 11)\ (00 + 11)$

$= (00 + 11)(00 + 11) + (00 - 11)(00 - 11) + (01 + 10)(01 + 10) + (01 - 10)(01 - 10)$

Traditional





New

Conclusions

- Three sorts of mathematicians: number people, space people, noise people?
- Statisticians and probabilists are traditionally not appreciated by the algebraists and analysts but times are changing
- Follow your instinct and find your own way!