At the turn of the 80s ...

… quantum <u>objects</u> become <u>subjects</u> of an emergent technology.

For the first time, atoms and photons can be manipulated (and measured) individually, with increasing spatial and temporal precision, due to the progress of the experimental conditions (mechanics, electronics, vacuum).

From now on, quantum mechanics has a chance to be verified through quite straightforward experiments which open the path for new possible applications.

Computing (in a more general sense) is one of them, why and how to do it was explained for the first time by the physicist Richard Feynman.

John Bell on a proposal by Alain Aspect to improve the setup of the polarizers changing orientation before measuring the two photons from an atomic cascade, **while** the photons are still in flight (classical causality).

To solve an old controversy (1935) about the completeness and "reality" of the quantum theory.

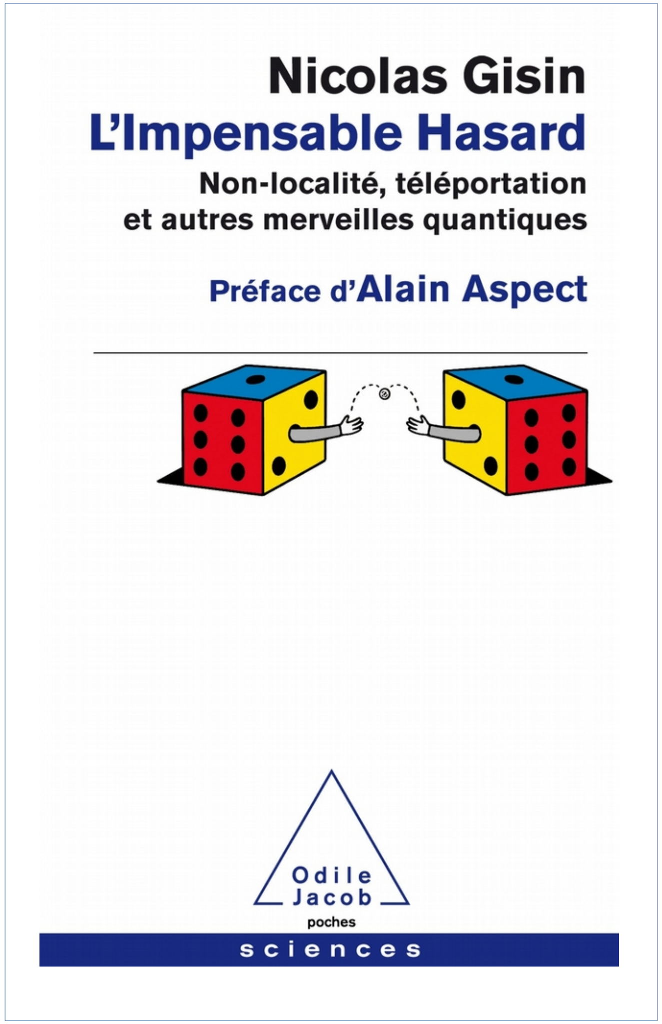
Reprinted from *Proceedings of the Symposium on Frontier Problems in High Energy Physics*, Pisa, June 1976

Einstein-Podolsky-Rosen Experiments

J. S. Bell
CERN, Geneva

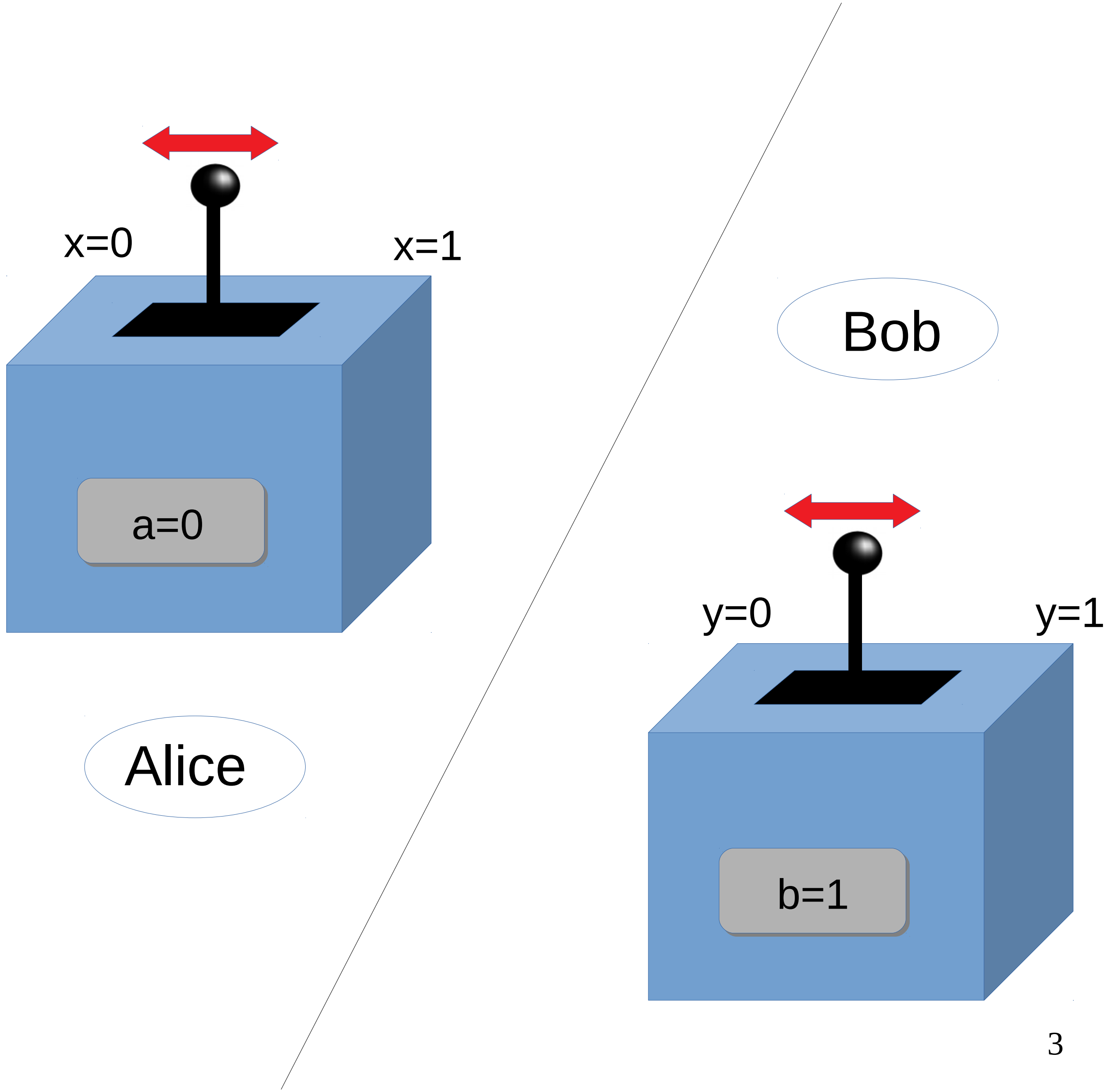
that can rapidly redirect the incident photon from one filter to the other. He believes that such switching can be effected by the generation of ultrasonic standing waves on which the photon undergoes Bragg reflection. If this experiment gives the expected result it will be a confirmation of what is, to my mind, in the light of the locality analysis,[21] one of the most extraordinary predictions of quantum theory.

Testing local / non-local correlations with the Bell game



(2012)

N.G. was awarded the "John Stuart Bell" Prize in 2009



The rules of the game

Np	Alice	Bob	Win	Nw
p1	Left (x=0)	Left (y=0)	if a=b	w1
p2	Left (x=0)	Right (y=1)	if a=b	w2
p3	Right (x=1)	Left (y=0)	if a=b	w3
p4	Right (x=1)	Right (y=1)	if a≠b	w4

Can one build a "box device" in order to allow a maximum winning rate ?

Yes, but not more than: $$\frac{w_1 + w_2 + w_3 + w_4}{p_1 + p_2 + p_3 + p_4} = \frac{3}{4} = 0.75$$

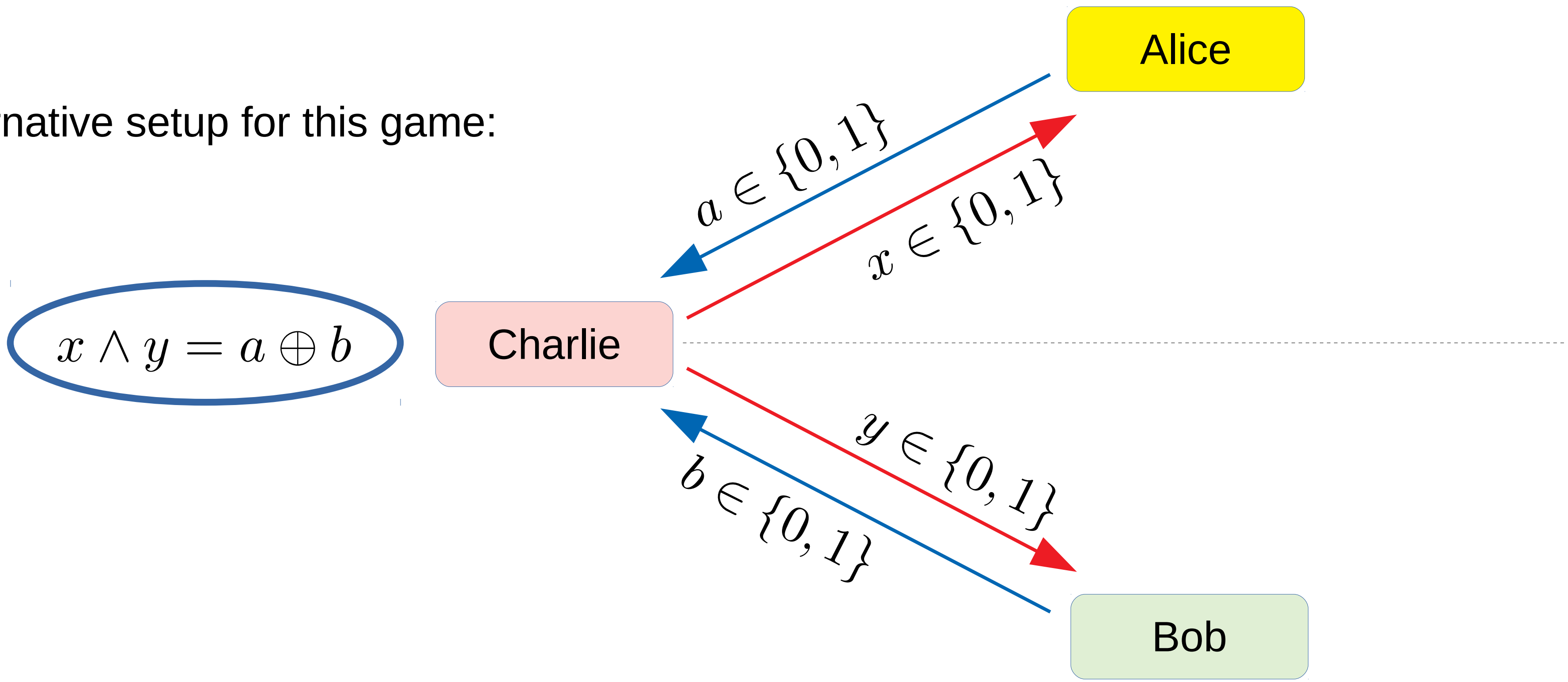
… unless ...

Alice	Bob	Win	$x \wedge y$	$a \oplus b$
Left (x=0)	Left (y=0)	if a=b	0	$0\oplus0=0$ or $1\oplus1=0$
Left (x=0)	Right (y=1)	if a=b	0	$0\oplus0=0$ or $1\oplus1=0$
Right (x=1)	Left (y=0)	if a=b	0	$0\oplus0=0$ or $1\oplus1=0$
Right (x=1)	Right (y=1)	if a≠b	1	$0\oplus1=1$ or $1\oplus0=1$

a	b	$a \wedge b$
0	0	0
0	1	0
1	0	0
1	1	1

a	b	$a \oplus b$
0	0	0
0	1	1
1	0	1
1	1	0

An alternative setup for this game:

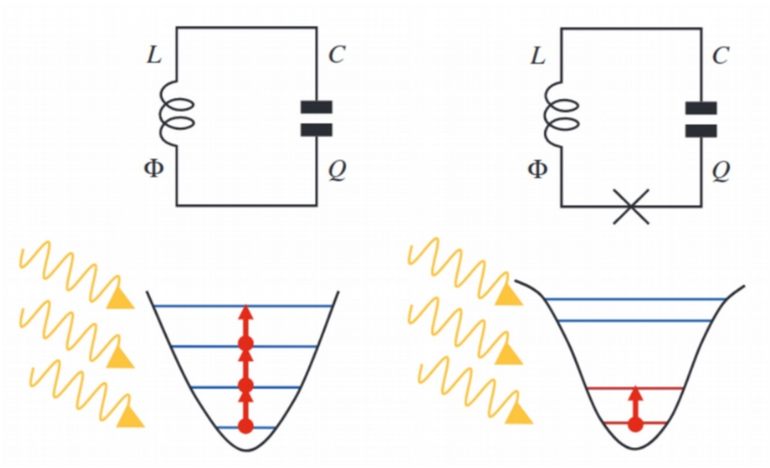


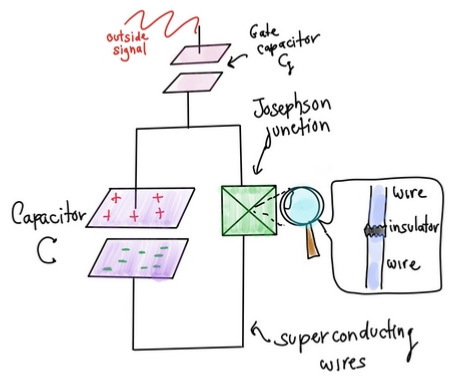
Let’s do it with qubits

A **qubit** is a quantum object: a microscopic system whose state and evolution are governed by the laws of **quantum mechanics**. In order to keep a good resemblance with the classical bit, this system will be chosen such that only two quantum states will be accessible, corresponding to some measurable physical property. Those two states are **orthogonal** and any arbitrary state of the system can be described as a linear combination (superposition) of those two states :

$$|\psi\rangle = c_1\,|0\rangle + c_2\,|1\rangle \quad , \quad |c_1|^2 + |c_2|^2 = 1 \;\; , \;\; c_1, c_2 \in \mathbb{C}$$

Linear harmonic oscillator with a *Josephson junction*, to introduce a non-linearity through the tunneling of the superconducting Cooper pairs in the circuit.





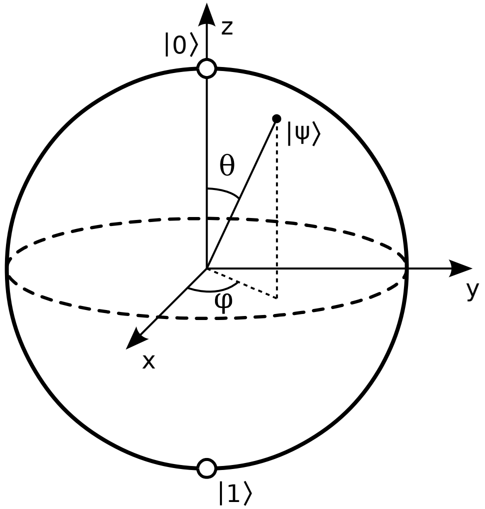
Circuit with a Josephson junction and a gate capacitor

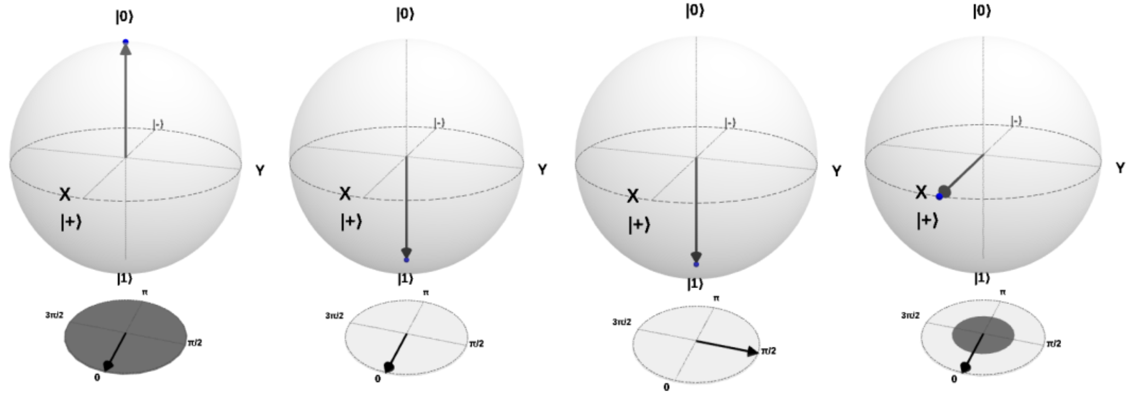
https://pennylane.ai

T≈20 mK

The Bloch sphere representation

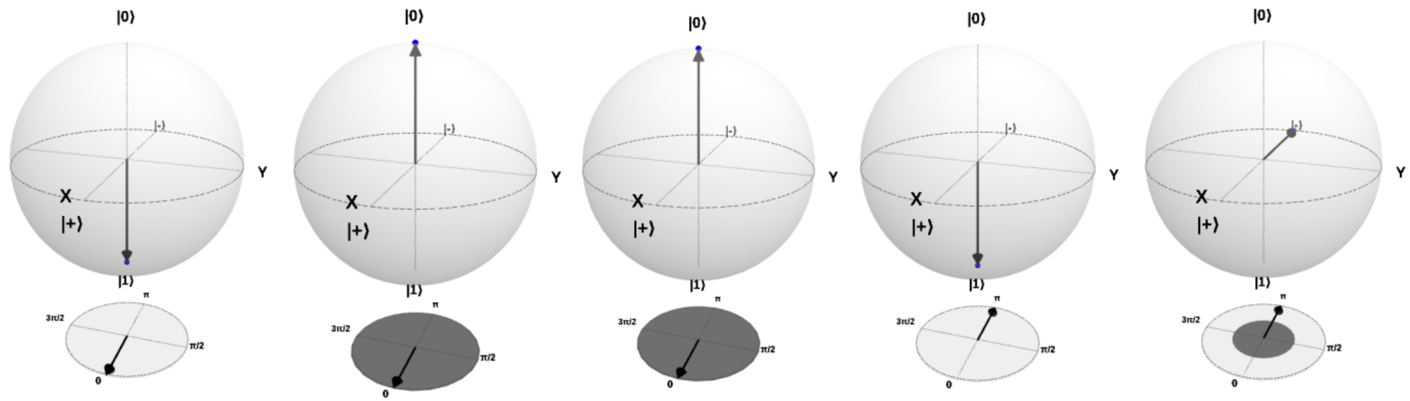
$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle = \begin{bmatrix}\cos\frac{\theta}{2}\\ e^{i\phi}\sin\frac{\theta}{2}\end{bmatrix}$$





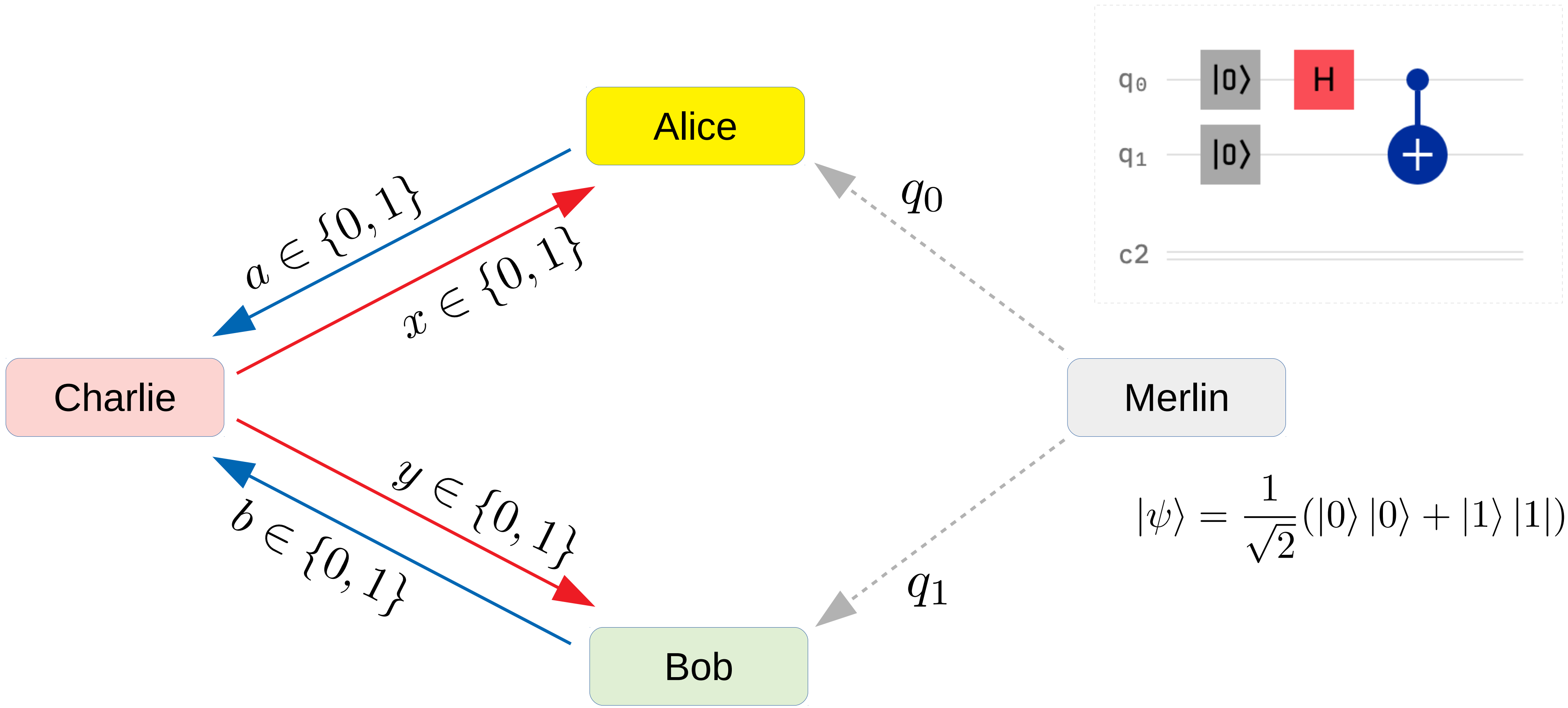
$$|0\rangle = \begin{bmatrix}1\\0\end{bmatrix} \qquad X=\begin{bmatrix}0&1\\1&0\end{bmatrix} \qquad Y=\begin{bmatrix}0&-i\\i&0\end{bmatrix} \qquad H=\frac{1}{\sqrt{2}}\begin{bmatrix}1&1\\1&-1\end{bmatrix}$$

The Pauli spin operators X, Y, Z and the Hadamard operator H.



$$|1\rangle = \begin{bmatrix}0\\1\end{bmatrix} \qquad X=\begin{bmatrix}0&1\\1&0\end{bmatrix} \qquad Y=\begin{bmatrix}0&-i\\i&0\end{bmatrix} \qquad Z=\begin{bmatrix}1&0\\0&-1\end{bmatrix} \qquad H=\frac{1}{\sqrt{2}}\begin{bmatrix}1&1\\1&-1\end{bmatrix}$$

The maximally entangled state of two qubits : a Bell state



$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle\,|0\rangle + |1\rangle\,|1|)$$

The game

- Charlie sends 0 or 1 to Alice, 0 or 1 to Bob (classical binary information)
- Merlin (or even Charlie) prepares a maximum entangled state of **two qubits** (a *Bell state*) and sends one qubit to Alice and the other one to Bob
- if Alice receives 0 from Charlie:
  - she applies to **her qubit** a rotation around the "y" axis by an angle "a0"
- if Alice receives 1 from Charlie:
  - she applies to **her qubit** a rotation around the "y" axis by an angle "a1"
- if Bob receives 0 from Charlie:
  - he applies to **his qubit** a rotation around the "y" axis by an angle "b0"
- if Bob receives 1 from Charlie:
  - he applies to **his qubit** a rotation around the "y" axis by an angle "b1"
- Alice and Bob measure, respectively, the qubit in their possession (in a basis corresponding to the Z observable) and send to Charlie the obtained result (having values 0 or 1)

The code in Qiskit programming language

```python
def CHSH_circuit(x,y,a0=0,a1=np.pi/2,b0=np.pi/4,b1=-np.pi/4):

    #x: bit received by Alice
    #y: bit received by Bob
    #a0: measure angle used by Alice when she receives 0
    #a1: measure angle used by Alice when she receives 1
    #b0: measure angle used by Bob when he receives 0
    #b1: measure angle used by Bob when he receives 1

    circ = QuantumCircuit(2,2)

    # First, we create a Bell pair

    circ.h(0)
    circ.cx(0,1)

    # Now, we apply rotations for Alice and Bob depending on the bits they have received

    if(x==0):
        circ.ry(a0,0)
    else:
        circ.ry(a1,0)

    if(y==0):
        circ.ry(b0,1)
    else:
        circ.ry(b1,1)

    # We measure

    circ.measure(range(2),range(2)) # Medimos

    return circ
```

Amazon Braket

The 4 angles $a_0 = 0\ ,\ a_1 = \pi/2\ ,\ b_0 = +\pi/4\ ,\ b_1 = -\pi/4$ are for particles with spin 1/2; for particles with spin 1 (photons) the values must be divided by 2.

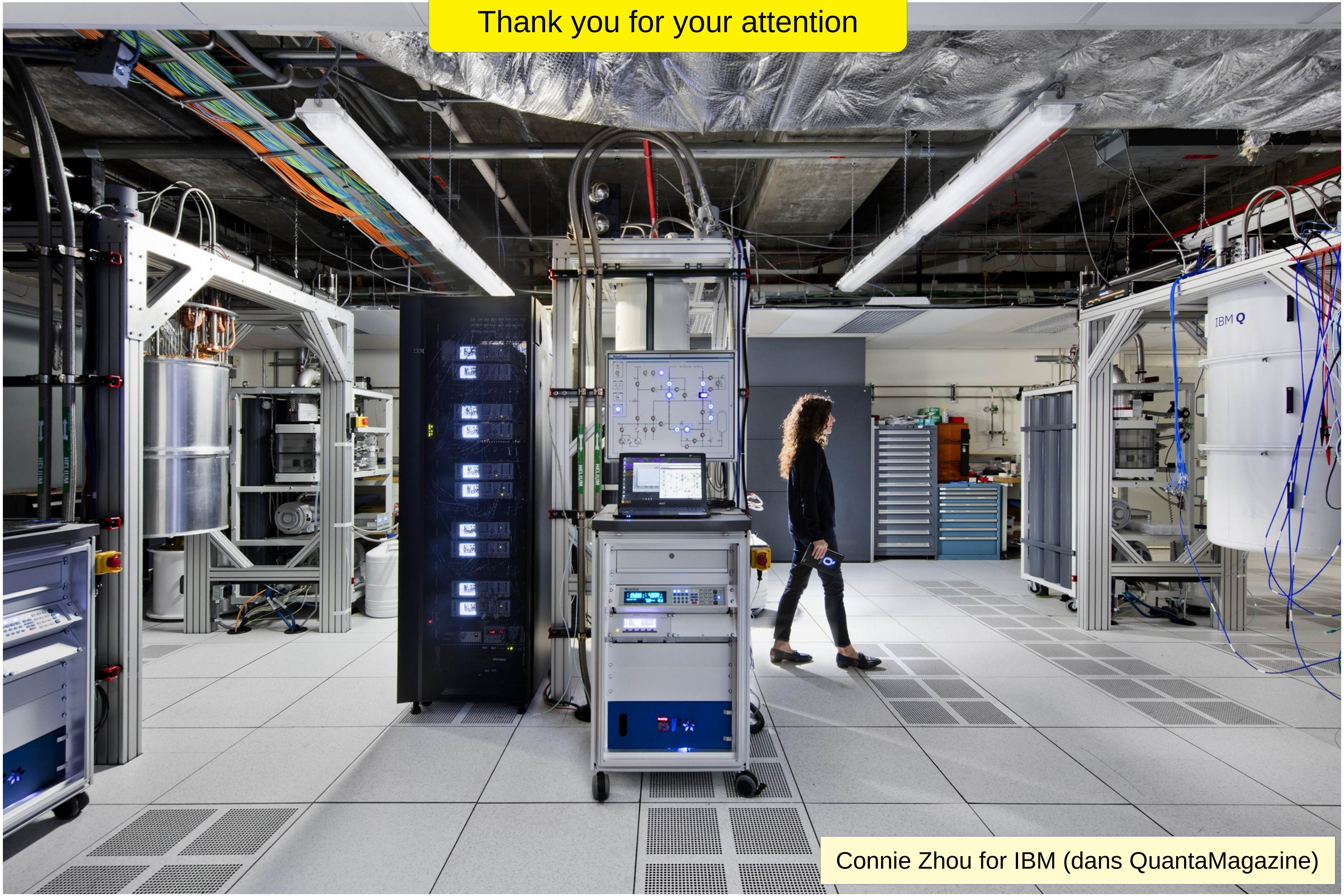
Q: $$\frac{w_1 + w_2 + w_3 + w_4}{p_1 + p_2 + p_3 + p_4} = \ ? > 0.75$$

What	Processor	Result	When	Shots
Simulation	w/o noise	0.859	-	8192
Simulation	FakeQuitoV2	0.799	-	8192
IBMQ	ibmq_ourense	0.827	November 11th, 2020	8192
IBMQ	ibmq_quito	0.795	October 22nd, 2022	8192
IBMQ	ibmq_belem	0.797	November 2nd, 2022	8192
OQC*	Lucy	0.770	October 21st, 2022	1024
OQC*	Lucy	0.754	October 21st, 2022	8192
Rigetti*	Aspen-M-2	0.759	October 21st, 2022	1024
Rigetti*	Aspen-M-2	0.755	October 21st, 2022	4096
IonQ*	IonQ	0.825	November 16th, 2022	1024

so … do you believe in "magic" ?

OQC = Oxford Quantum Circuits, IBMQ = IBM Quantum Experience, * = Amazon Braket

Thank you for your attention



Connie Zhou for IBM (dans QuantaMagazine)