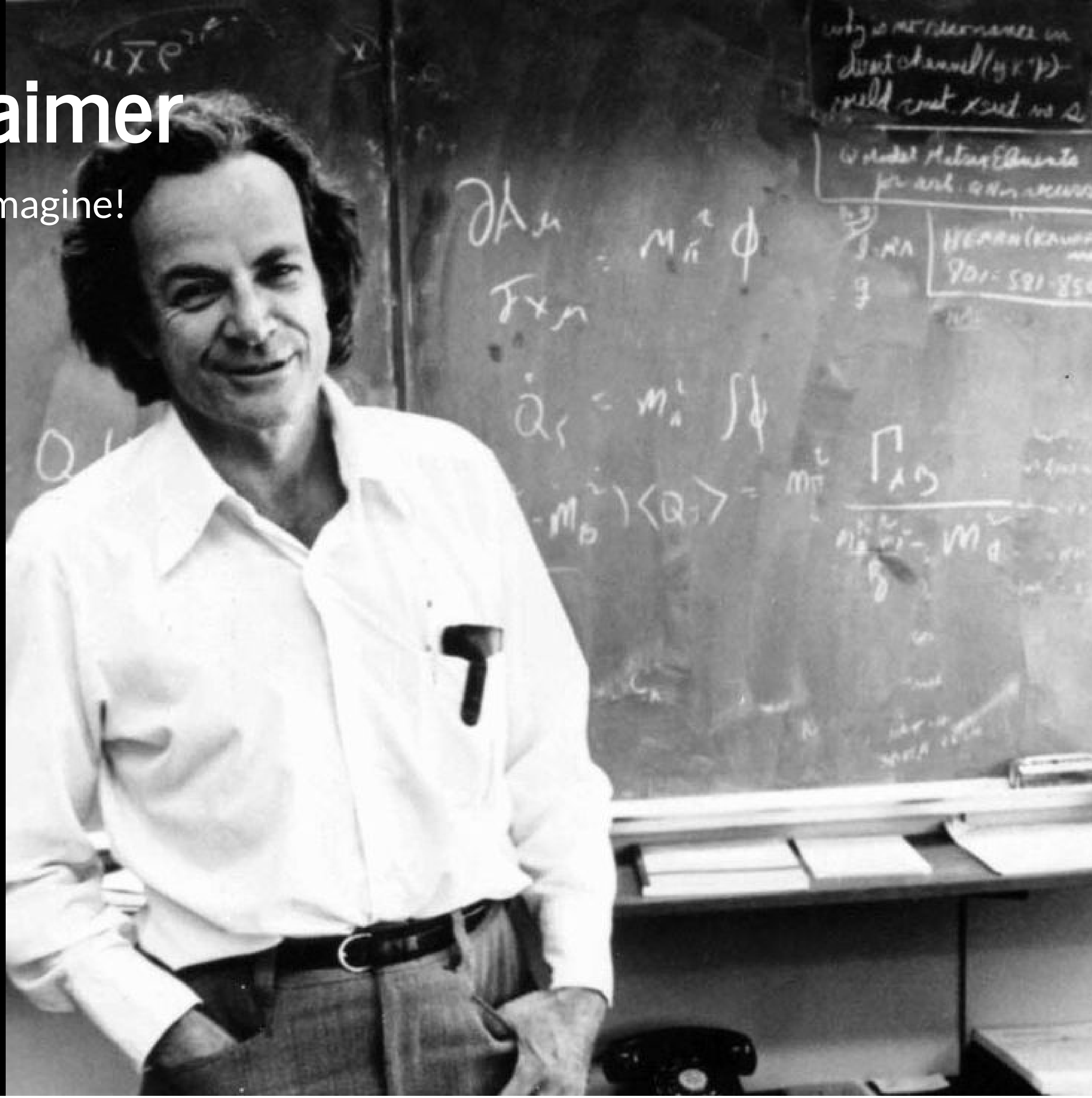
Non Computational Neuroscience in a nutshell

Disclaimer

It’s fun to imagine!



Meet Alice

“Alice is 25 years old, single, outspoken, and very bright. She majored in physics. As a student she was deeply concerned with issues of discrimination and social justice, and also participated in anti-nuclear demonstrations.”

Which of the following is more probable?

a. Alice is looking for a Ph.D.

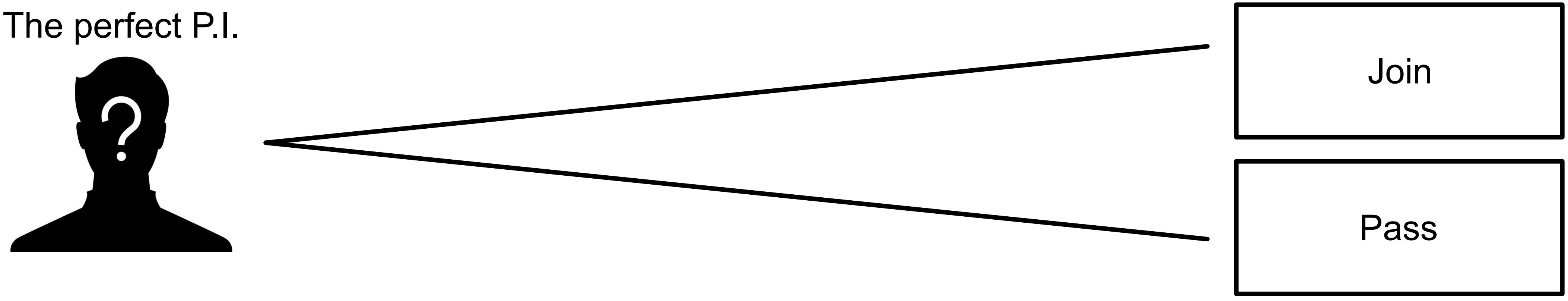
b. Alice is looking for a Ph.D. and works in a climate activist group.

Alice looks for a Ph.D.

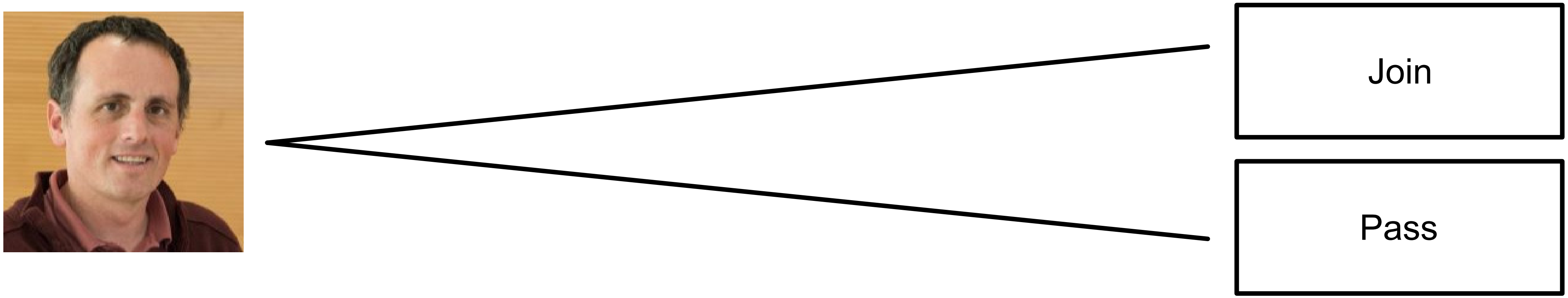
Alice is considering joining BARCYSN but is having a hard time choosing a PI.

The perfect P.I.

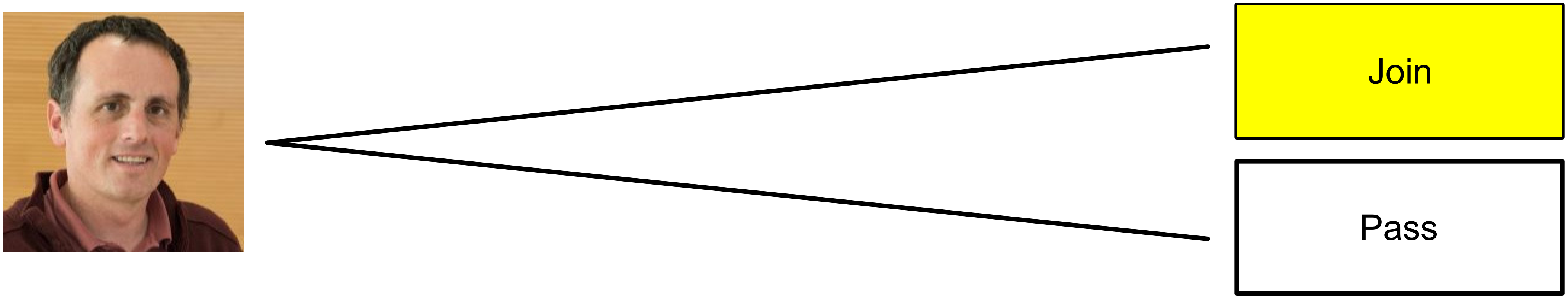
Alice looks for a Ph.D.



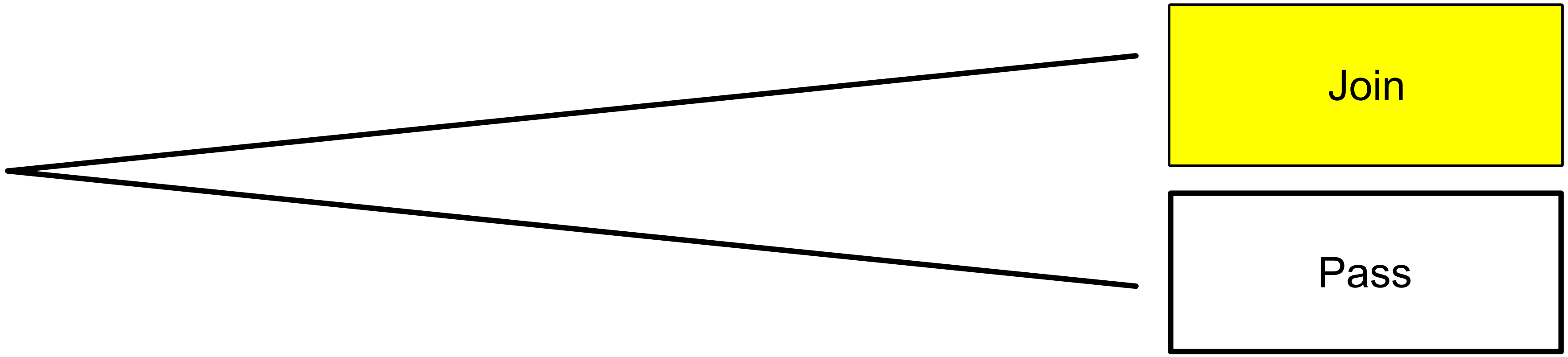
Alice looks for a Ph.D.



Alice looks for a Ph.D.



Alice looks for a Ph.D.



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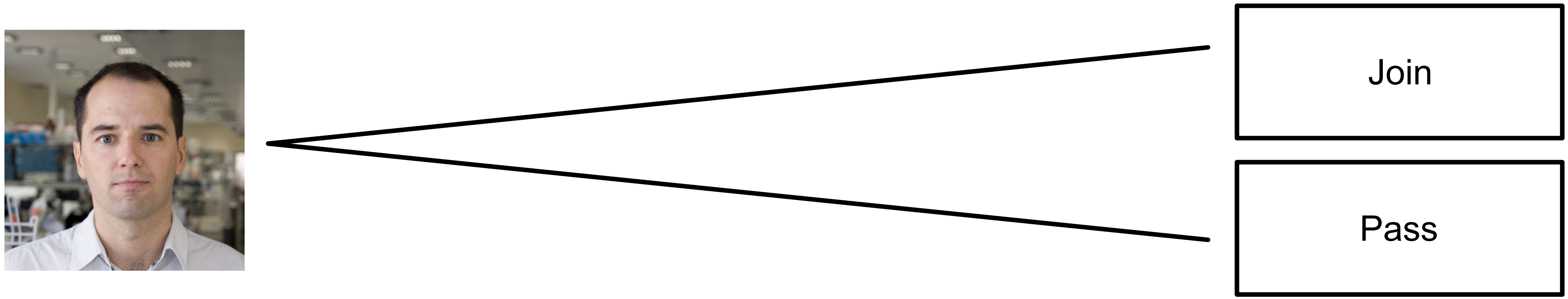

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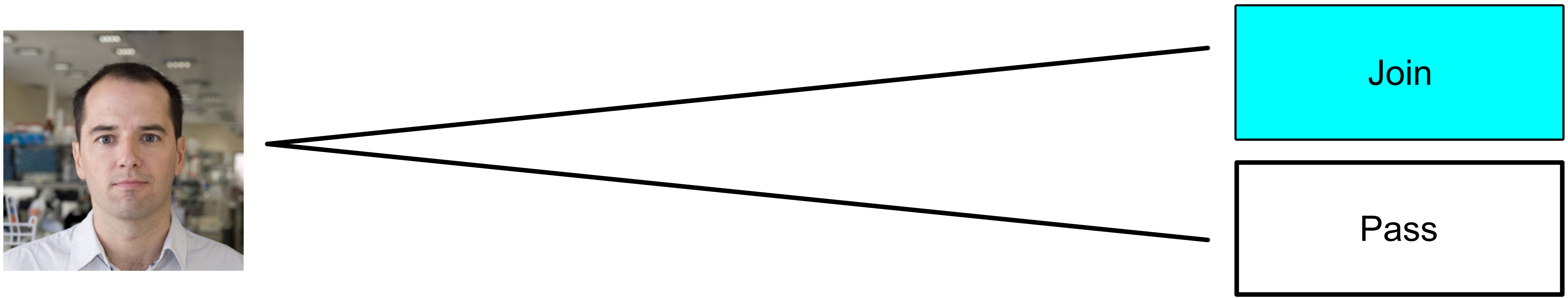
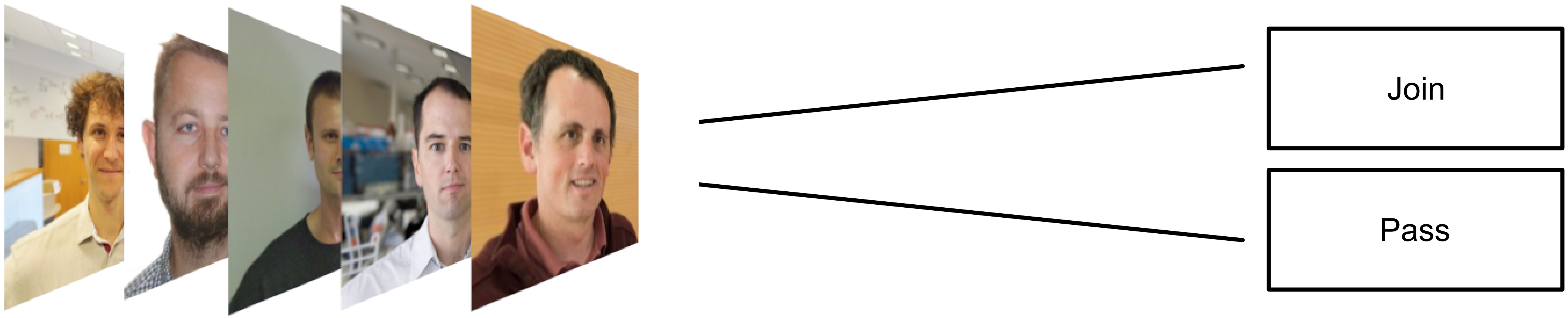
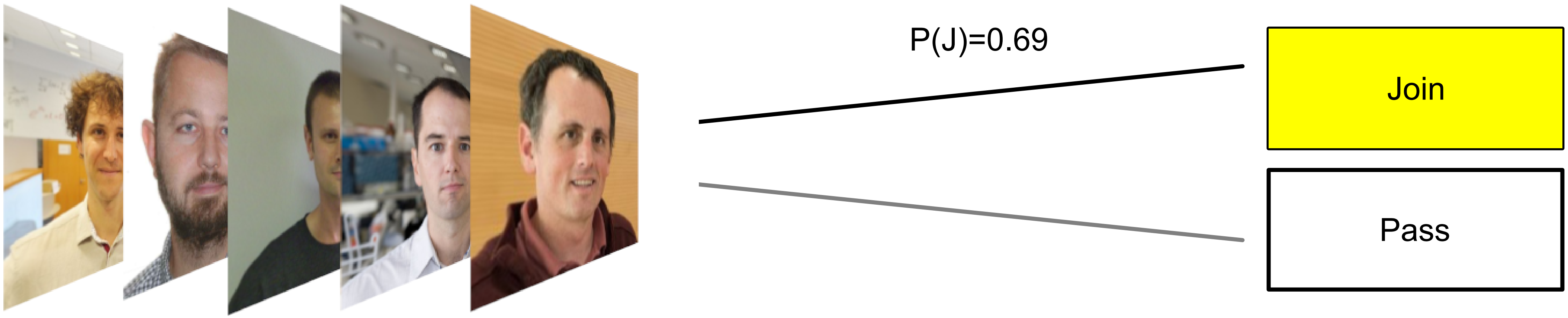


Alice looks for a Ph.D.

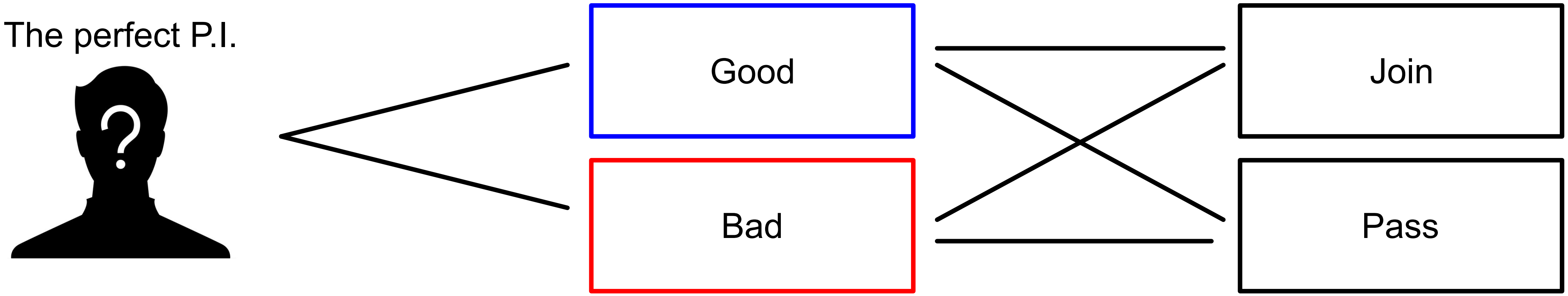


Alice looks for a Ph.D.

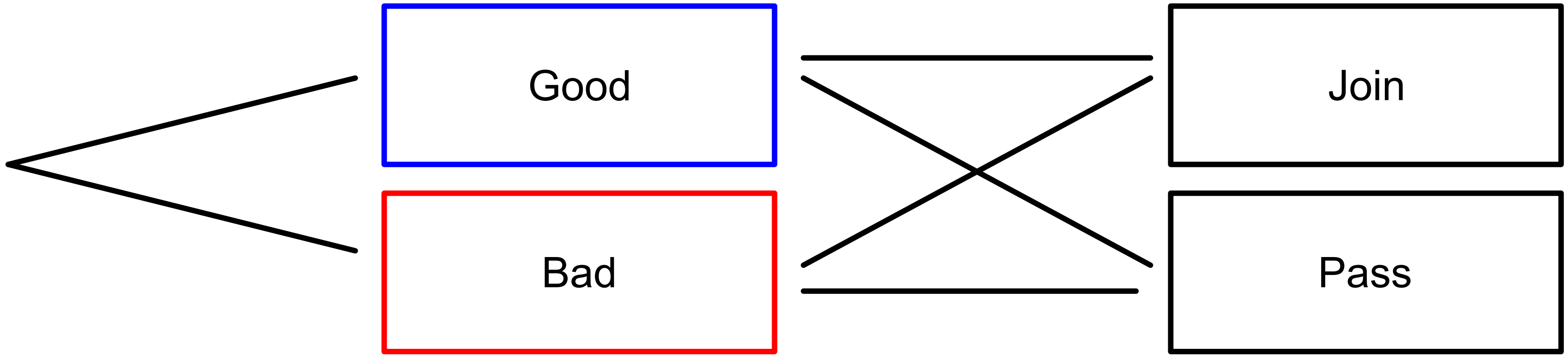


Alice looks for a Ph.D.

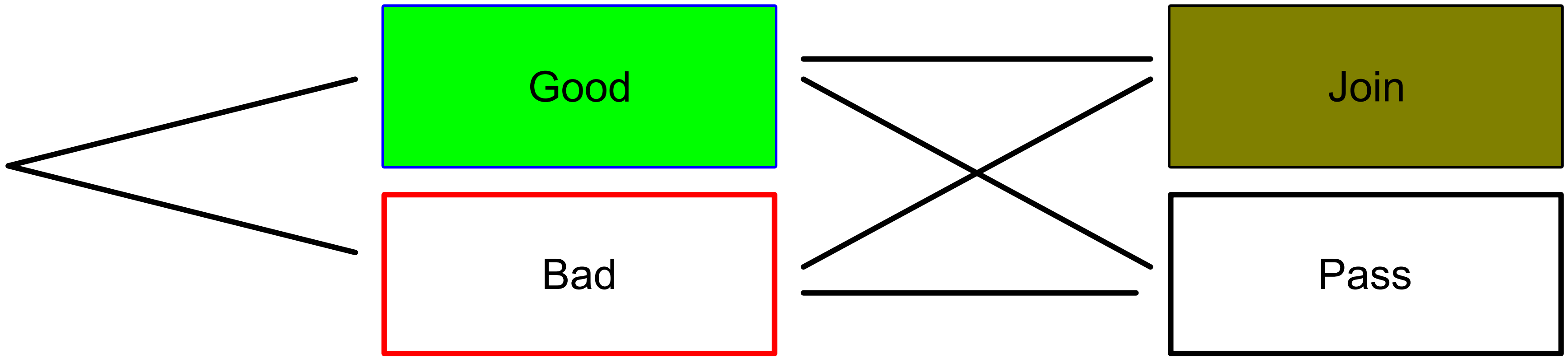
What if we gave Alice a little help?
And asked her to categorize before deciding.



Alice looks for a Ph.D.



Alice looks for a Ph.D.



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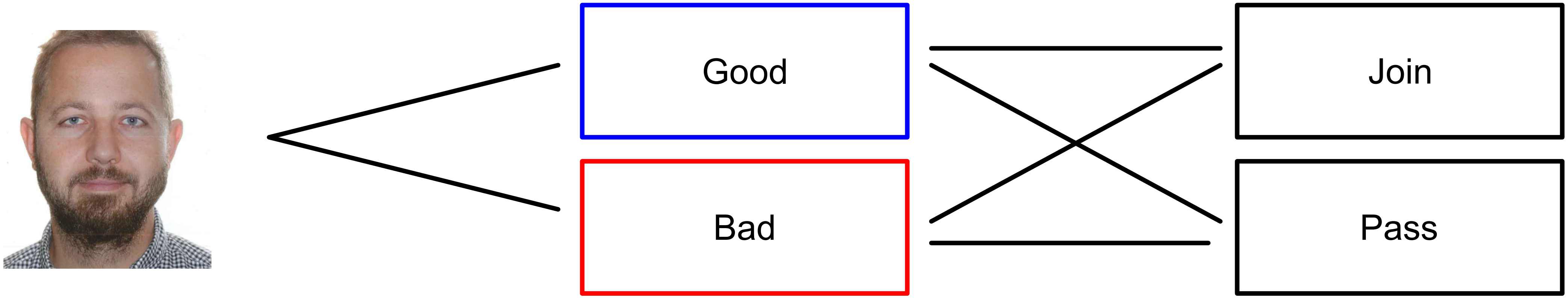
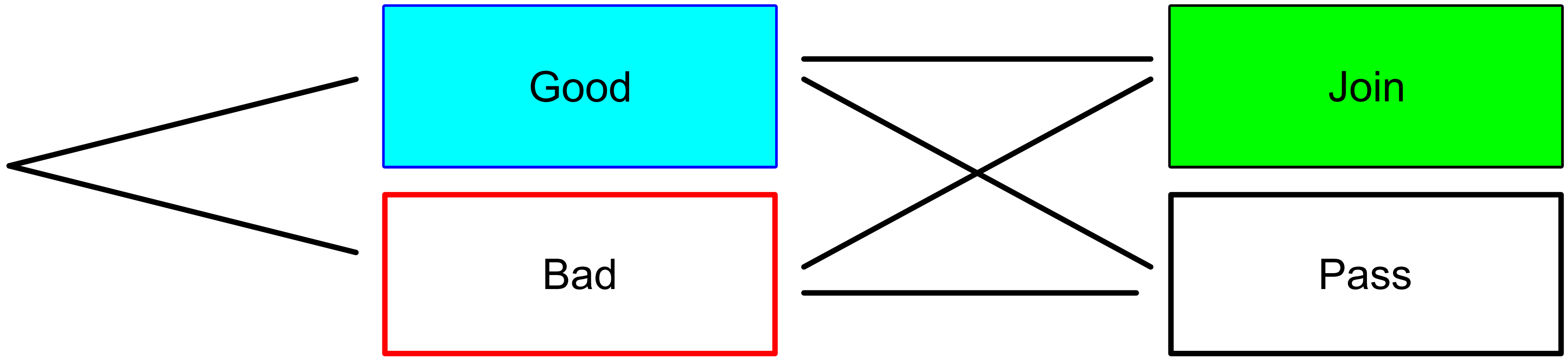


Alice looks for a Ph.D.



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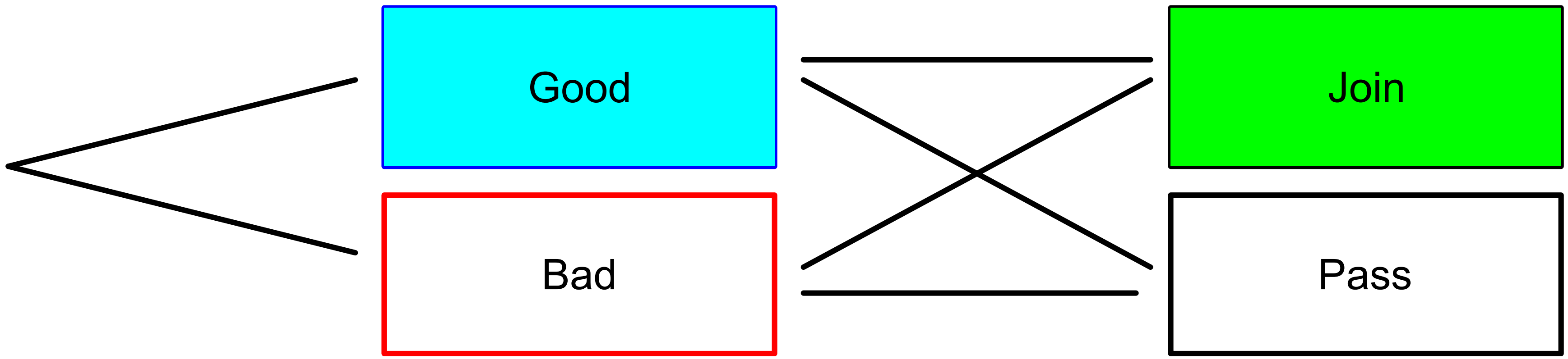
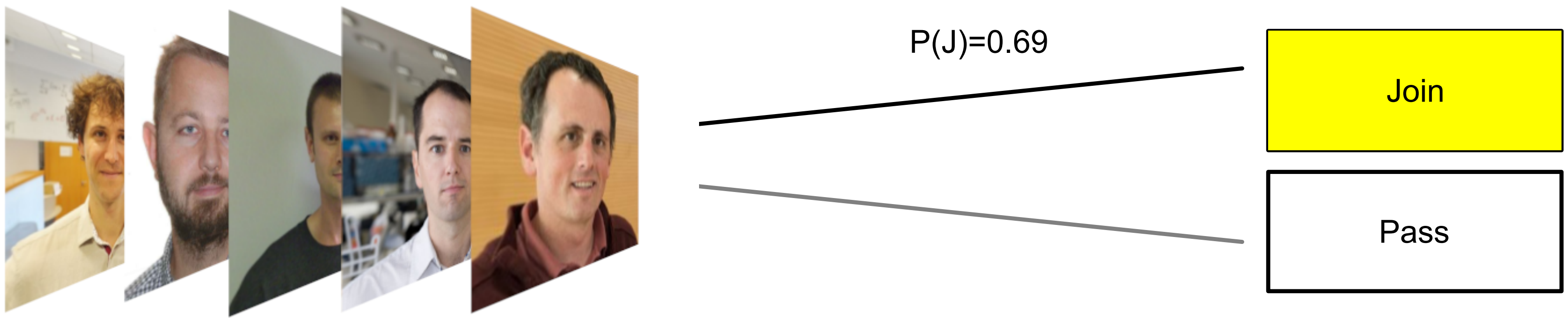
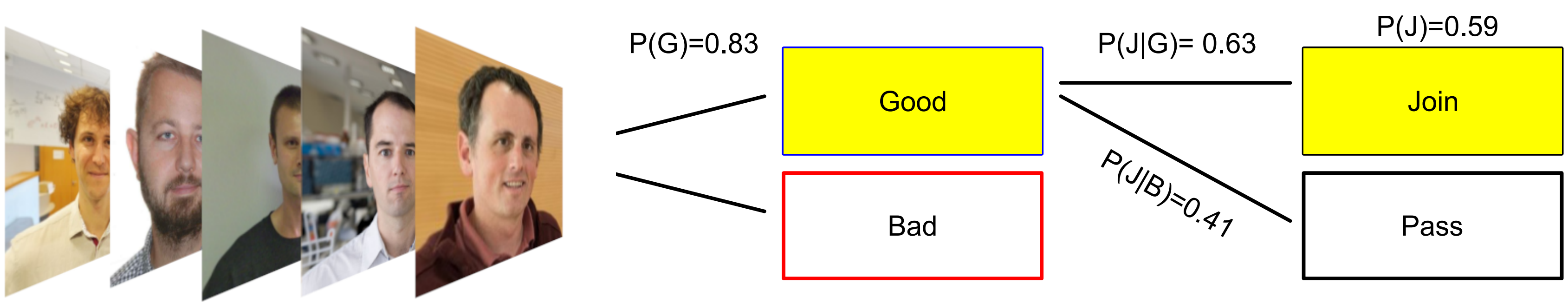


Will Alice join Barcsyn?

Decision only



Categorization then decision



Alice runs a hard bargain

Alice shares the animal facility with Alexis.

	Alexis Defects	Alexis Cooperates
Alice Defects	Alice gets 8h and Alexis too	Alice gets 10h and Alexis 6h
Alice Cooperates	Alice gets 6h and Alexis 10h	Alice gets 10h and Alexis too

As is, Alice defects 66 % of the time.

Knowing that Alexis defects/cooperates, Alice defects 97% / 84% of the time.

What did we discover?

- The “Meet Alice” problem is a typical example showing conjunction fallacy,

$$P(A \cap B) > P(A) \text{ or } P(B)$$

- In the second example, categorization leads to interference effects, so that

$$P(G)P(J|G) + P(B)P(J|B) > P(J)$$

What did we discover?

- In the last example, we see a violation of the sure-thing principle:

  if you prefer action A over B under the state of the world X, and you also prefer action A over B under the opposite state of the world not X, then you should prefer action A over B even if the state of the world is unknown.

- Alice defects when she knows Alexis' choice
- but Alice cooperates when the state of Alexis' choice is unknown …

Classical probability theory

Events are subsets of a universal set U. Events, such as A and B, are subsets of U.

The state of the cognitive system is represented by a function P defined on the subsets in U, and the probability of an event A equals P(A).

$$P(A) \geq 0, \text{ and } P(U) = 1$$

If $A \cap B = 0$, then $P(A \cup B) = P(A) + P(B)$

The probability of event B given A equals

$$P(B|A) = \frac{P(A \cap B)}{P(A)}$$

Law of total probability:

$$P(B) = P(A \cap B) + P(\bar{A} \cap B)$$

Quantum probability theory

Events are subspaces of a Hilbert space H. Events, such as A correspond to subspaces H_A, respectively of H. Associated with these subspaces are projectors P_A.

If their projectors are commutative, that is, $P_A P_B = P_B P_A$, then the events A and B are compatible. Otherwise, they are incompatible.

The state of the cognitive system is represented by a unit length vector S in the vector space, and the probability of event A equals

$$||P_A.\, S||^2 \geq 0 \text{ and } ||P_H.\, S||^2 = 1$$

If $P_A P_B = 0$, then $||(P_A + P_B)\, .S||^2 = ||P_A\, .\, S||^2 + ||P_B\, .\, S||^2$

The probability of event B given A equals

$$\frac{||P_B P_A.\, S||^2}{||P_A.\, S||^2}$$

No law of total probability

What did we solve?

- Conjunction fallacy (A->PhD, B->Activist)
  A and B are incompatible events and must be then treated sequentially.

$$S \to B \to A \text{ or } S \to A$$

$$|\langle A|B\rangle\langle B|S\rangle|^2 > |\langle A|S\rangle|^2$$

- Interference of categorization on decision making
  Decide Only: (sum two path amplitudes and square)

$$P(S \to J) = |\langle G|S\rangle\langle J|G\rangle + \langle B|S\rangle\langle J|B\rangle|^2$$

  Categorize then decide: (sum path probabilities across two paths)

$$P(S \to J) = |\langle J|S\rangle|^2 = |\langle G|S\rangle\langle J|G\rangle|^2 + |\langle B|S\rangle\langle J|B\rangle|^2$$

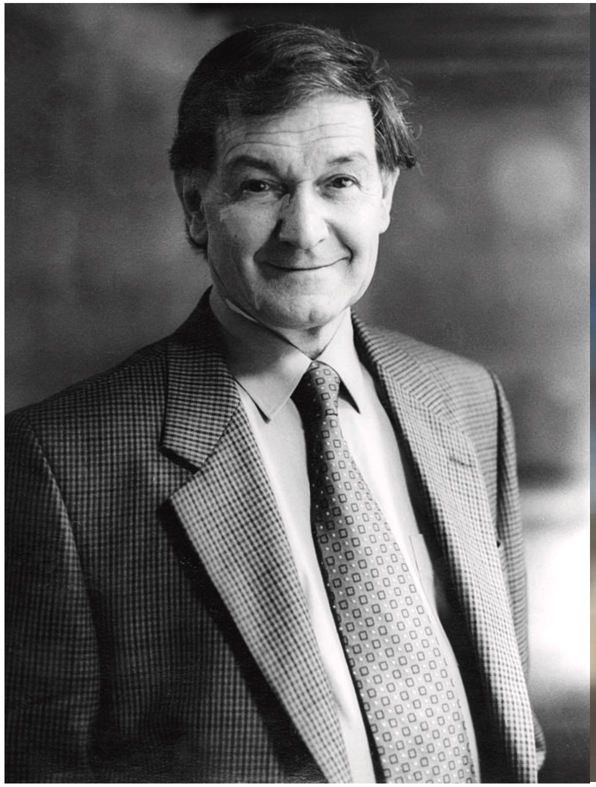
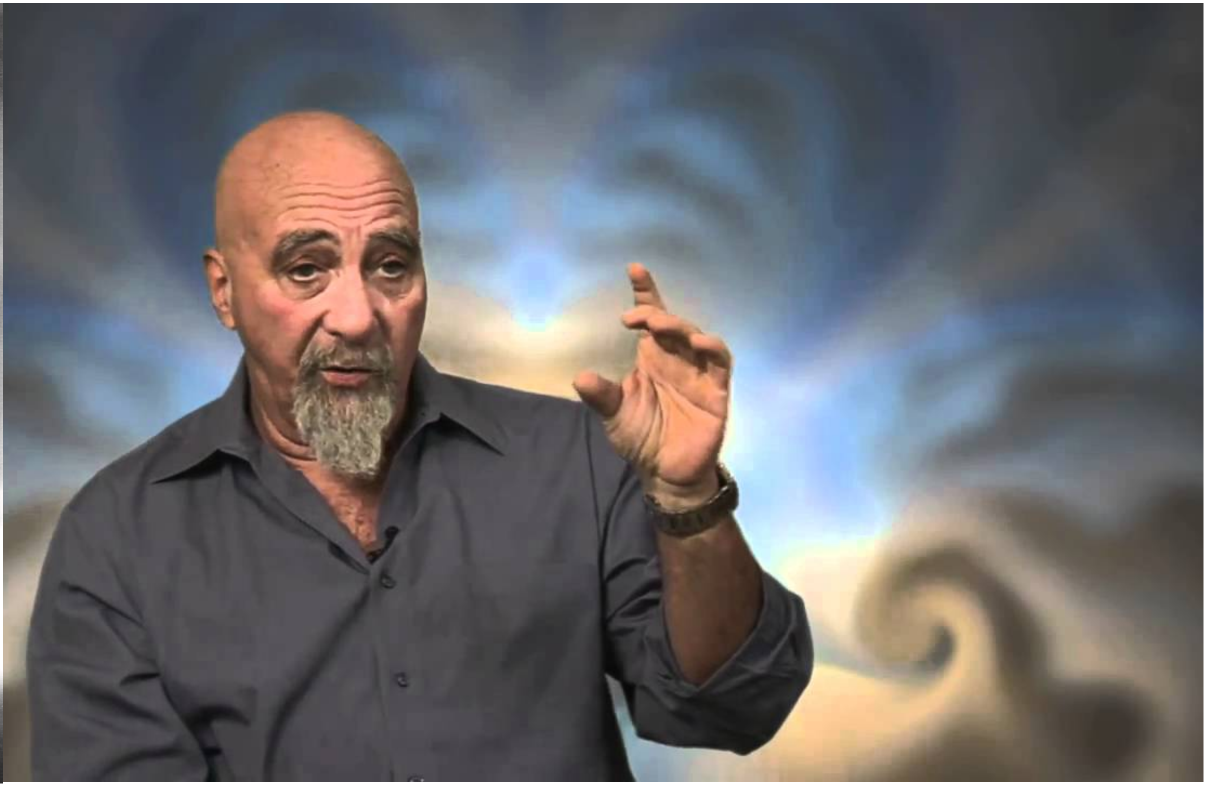
To sum up

- Psychological measures, such as judgments, often require one to take different perspectives, which have to be taken sequentially, and the context generated by the first measure disturbs subsequent ones.
- Some psychological states cannot be defined with respect to definite values but, instead, that all possible values within the superposition have some potential for being expressed
- Go for a quantum description

The measurement problem

- One of the key features of quantum theory is that observing the system changes the behavior of the system.
- Observation causes a superposition state, containing the disposition for many states to be measured, to reduce to one definite state that will be observed in the actual measurement.
- Some quantum theorists (e.g.,von Neumann, London and Bauer, Wigner) occasionally speculated that human consciousness plays a role to cause the reduction of superposition states.

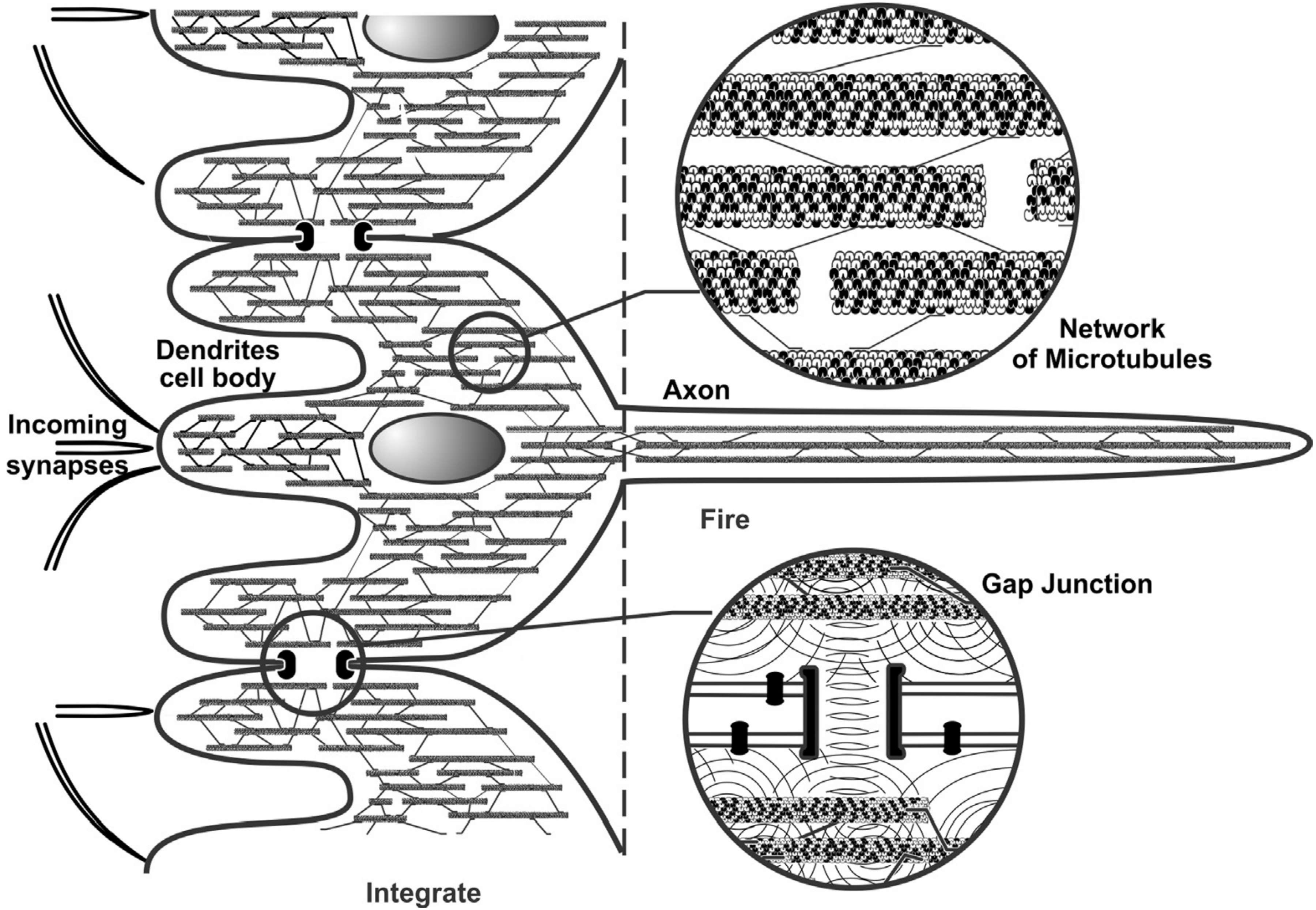
Penrose and Hameroff's idea

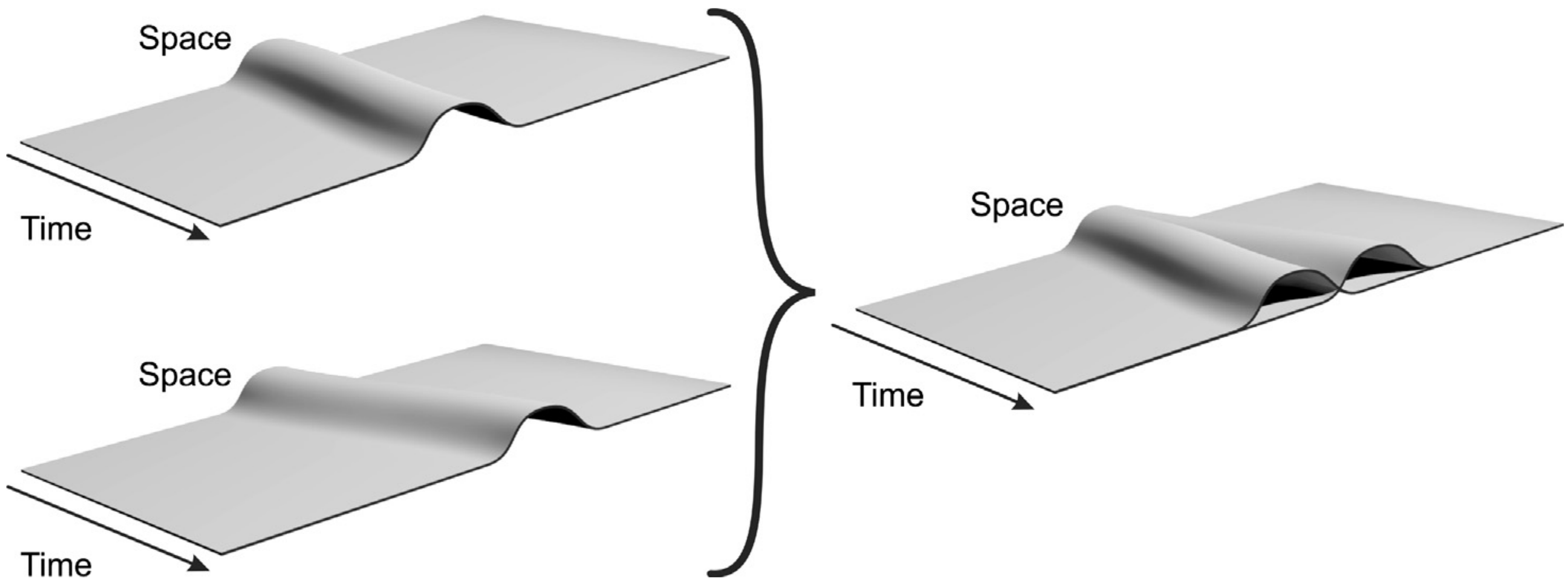
Orch Or in a few sentences

- Quantum brain computations occur inside microtubules that lie within the protection of the cytoskeleton of a neuron.
- The microtubules are interconnected at the gap junctions of dendrites, and these connections extend throughout the cortex to produce a coherent entangled quantum state.
- The collapse of the quantum superposition state within the microtubules can trigger axonal spikes and govern behavior.
- This state reduction also generates a conscious experience.

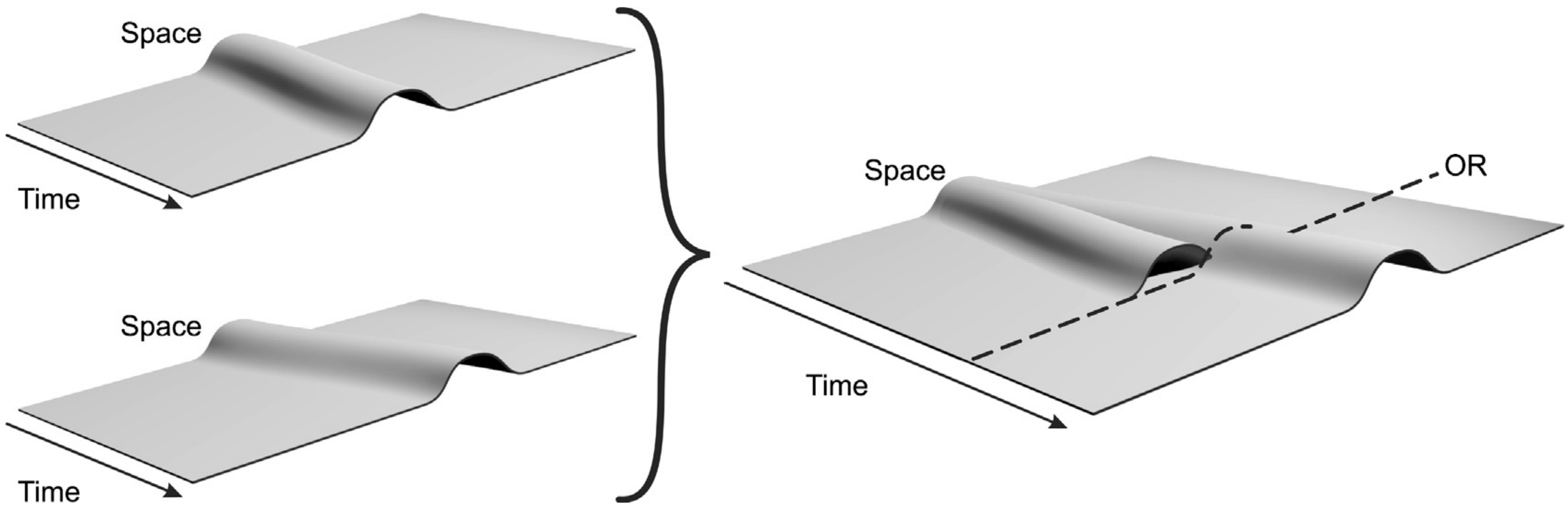
Orch Or in one diagram


Network
of Microtubules
Dendrites
cell body
Axon
Incoming
synapses
Fire
Gap Junction
Integrate

Diosi-Penrose's theory



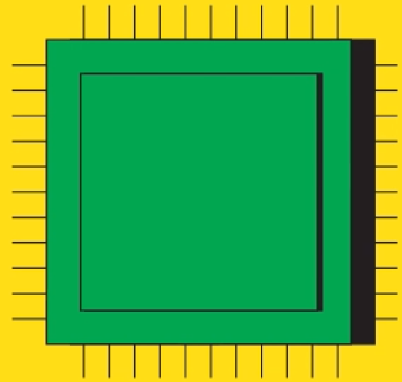
Diosi-Penrose's theory



Criticisms

- The hypothesis by Penrose and Hameroff has received a lot of criticism.
- It is argued that in the “hot and wet” highly interacting brain, decoherence (the breakdown of the superposition state) occurs much too fast to allow any relevant effects of quantum states for comparably slow brain processes, and even more so for psychological thought processes.

Quantum Computing 101



Quantum Leaps

- 1980 Physicist Paul Benioff suggests quantum mechanics could be used for computation.
- 1981 Nobel-winning physicist Richard Feynman, at Caltech, coins the term quantum computer.
- 1985 Physicist David Deutsch, at Oxford, maps out how a quantum computer would operate, a blueprint that underpins the nascent industry of today.
- 1994 Mathematician Peter Shor, at Bell Labs, writes an algorithm that could tap a quantum computer's power to break widely used forms of encryption.
- 2007 D-Wave, a Canadian startup, announces a quantum computing chip it says can solve Sudoku puzzles, triggering years of debate over whether the company's technology really works.
- 2013 Google teams up with NASA to fund a lab to try out D-Wave's hardware.
- 2016 IBM puts some of its prototype quantum processors on the internet for anyone to experiment with.

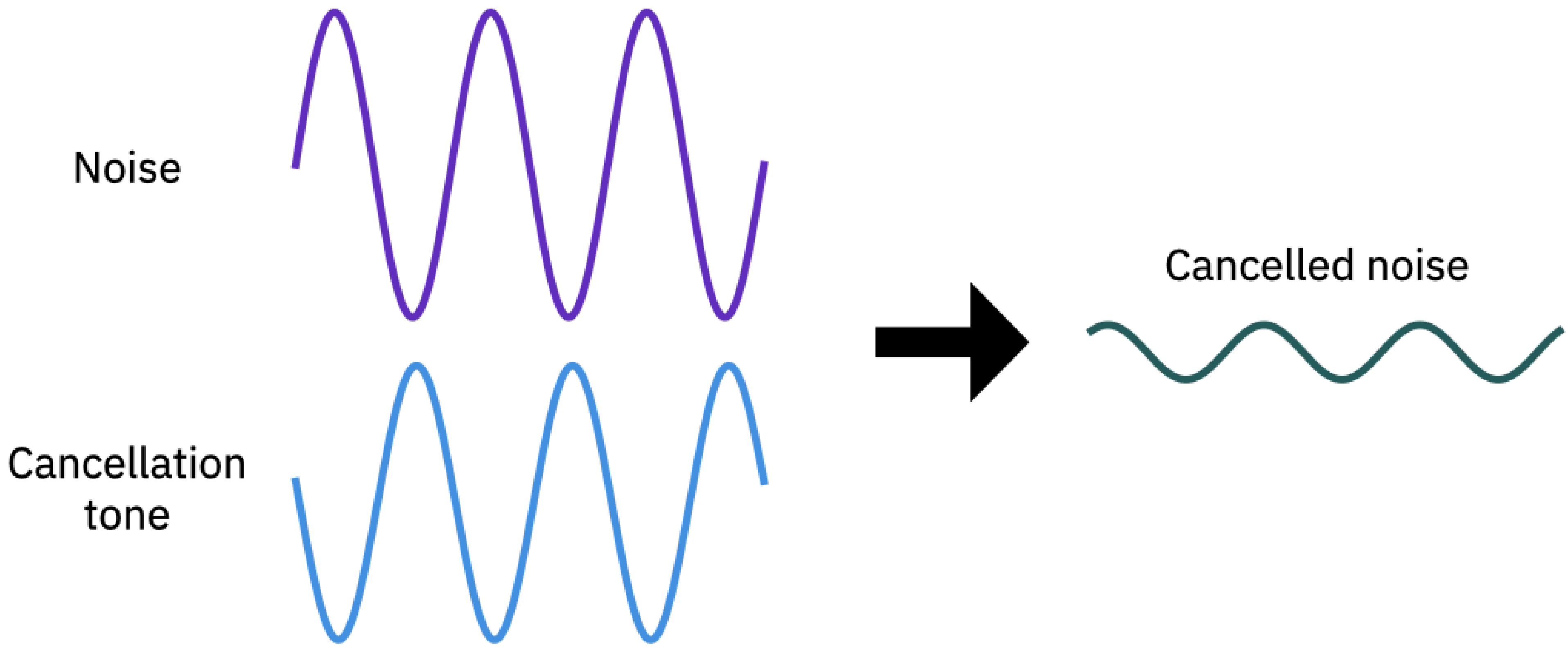
Qubits

Like a classical computer, a quantum computer operates on bits.

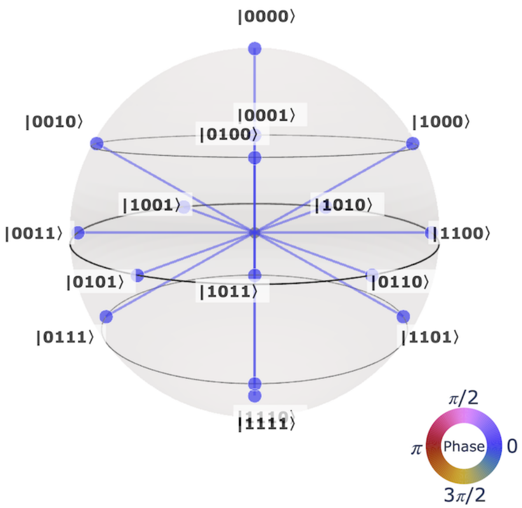
Quantum bits, or qubits, can represent the values 0 and 1, or linear combinations of both.

Interference

To see how this resource is utilized in quantum computation we first turn to a classical analog: noise cancellation.

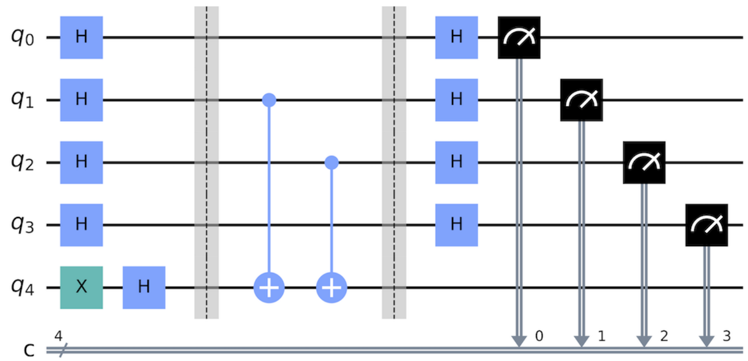


Interference

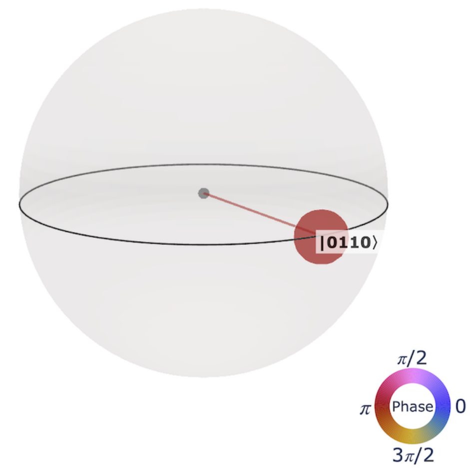


Superposition of
all possibilities

Quantum circuit



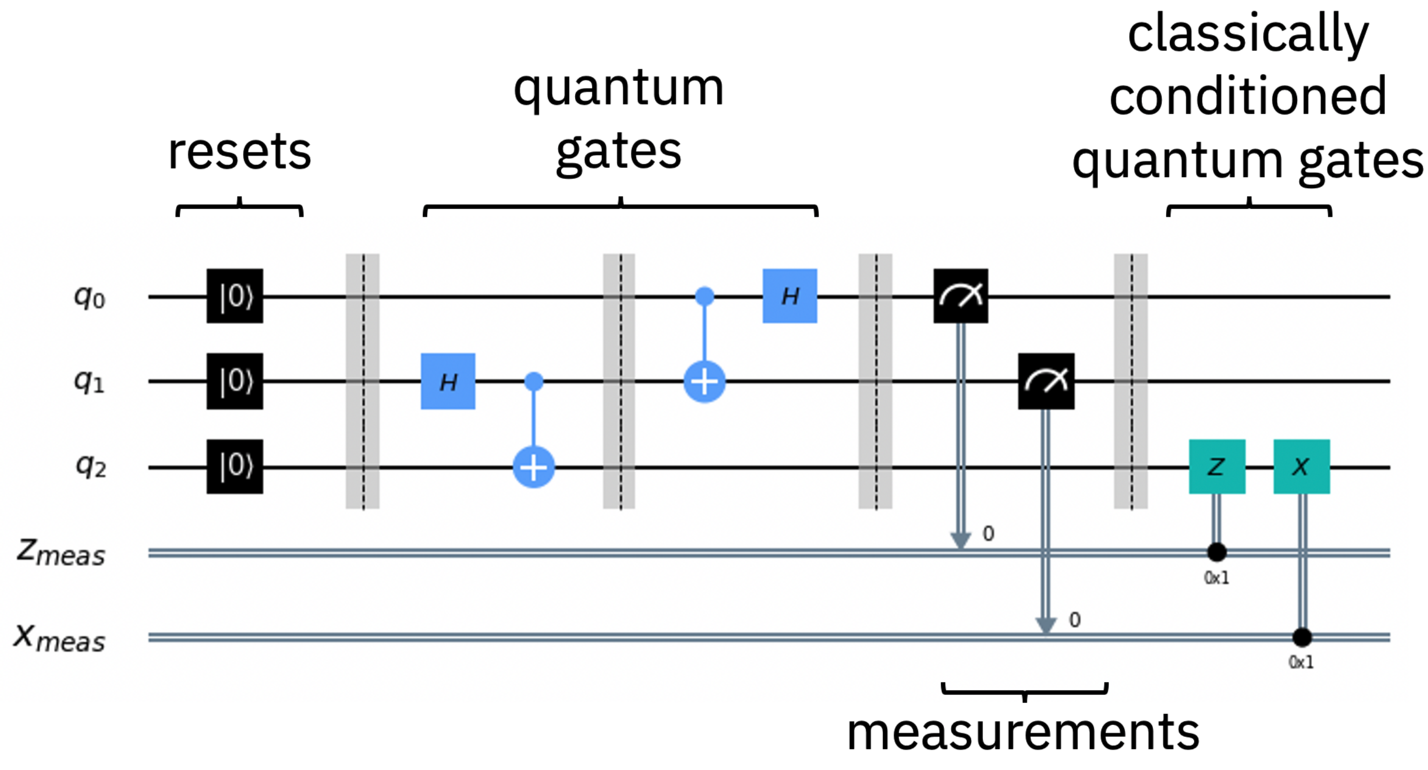
Computation driven interference



Solution

Quantum circuits

Quantum circuits enable a quantum computer to take in classical information and output a classical solution, leveraging quantum principles such as interference and entanglement to perform the computation.



Quantum circuits

A typical quantum algorithm workflow consists of:

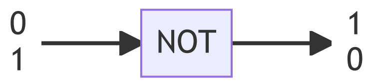
- The problem we want to solve,
- A classical algorithm that generates a description of a quantum circuit,
- The quantum circuit that needs to be run on quantum hardware,
- And the output classical solution to the problem that it produces.

Quantum gates

Quantum gates form the primitive operations on quantum data. Quantum gates represent information preserving, reversible transformations on the quantum data stored in qubits. These "unitary" transformations represent the quantum mechanical core of a quantum circuit.

- Single qubit gates

Classical example: The NOT gate

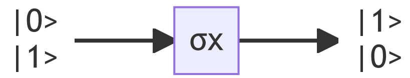


Quantum example: quantum gates are represented by unitary matrices:

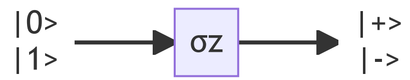
$$\mathcal{U}^\dagger \mathcal{U} = \mathbb{1}$$

Pauli Matrices

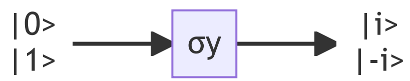
- bit flit



- phase flip

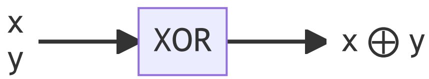


- bit and phase flip

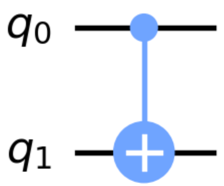


Two qubit gates

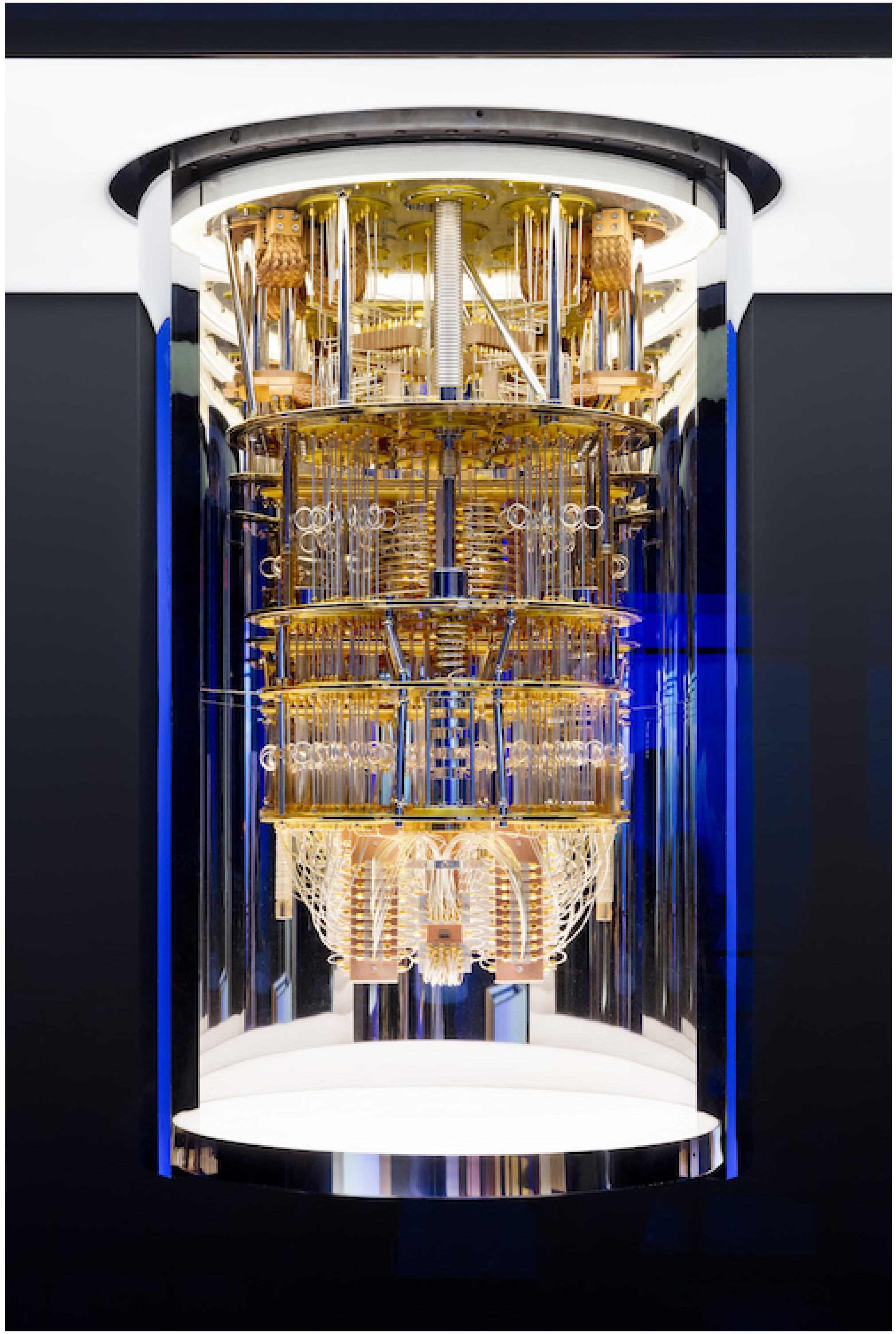
Classical example



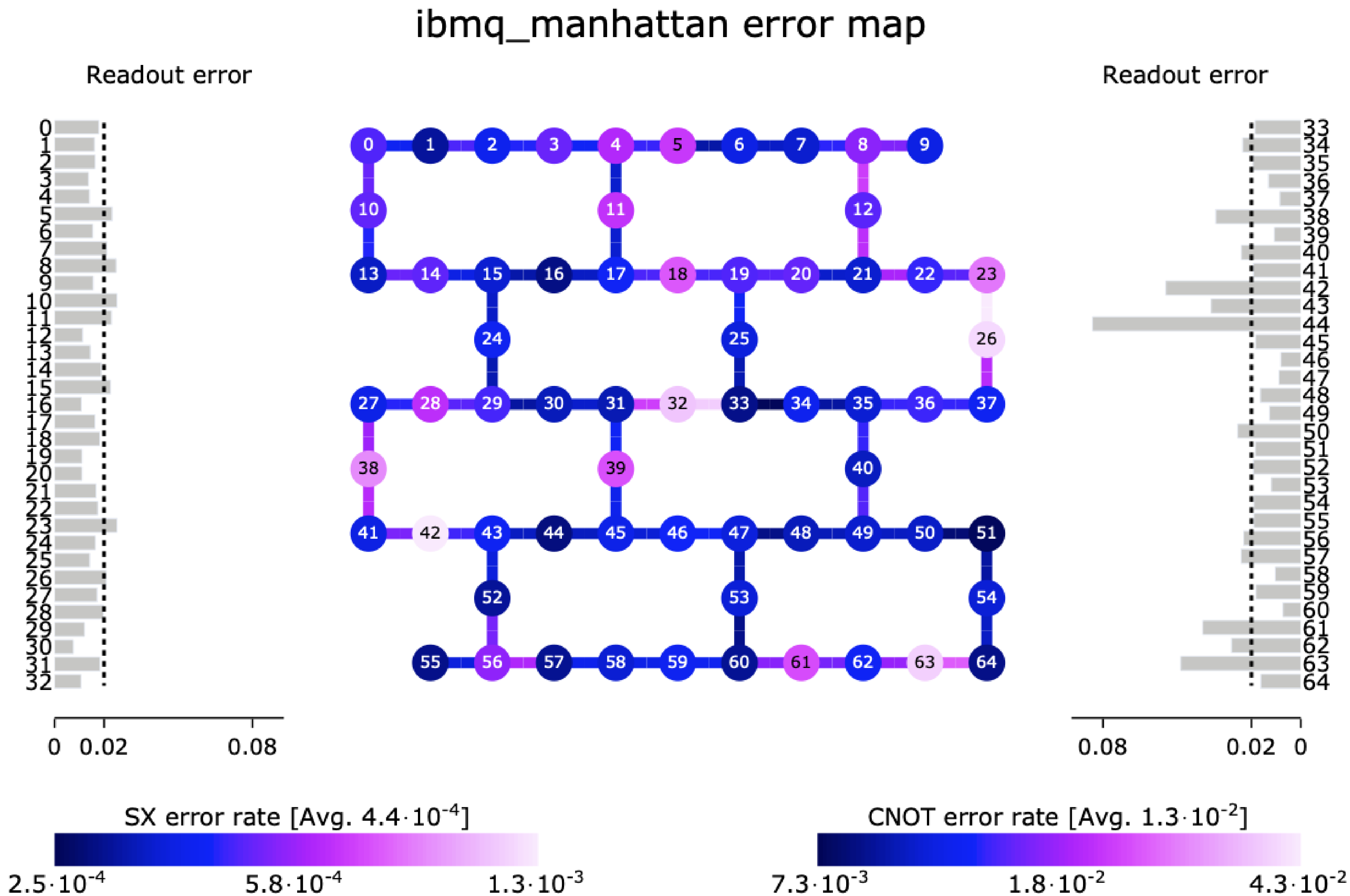
Quantum example: CNOT <=> reversible XOR



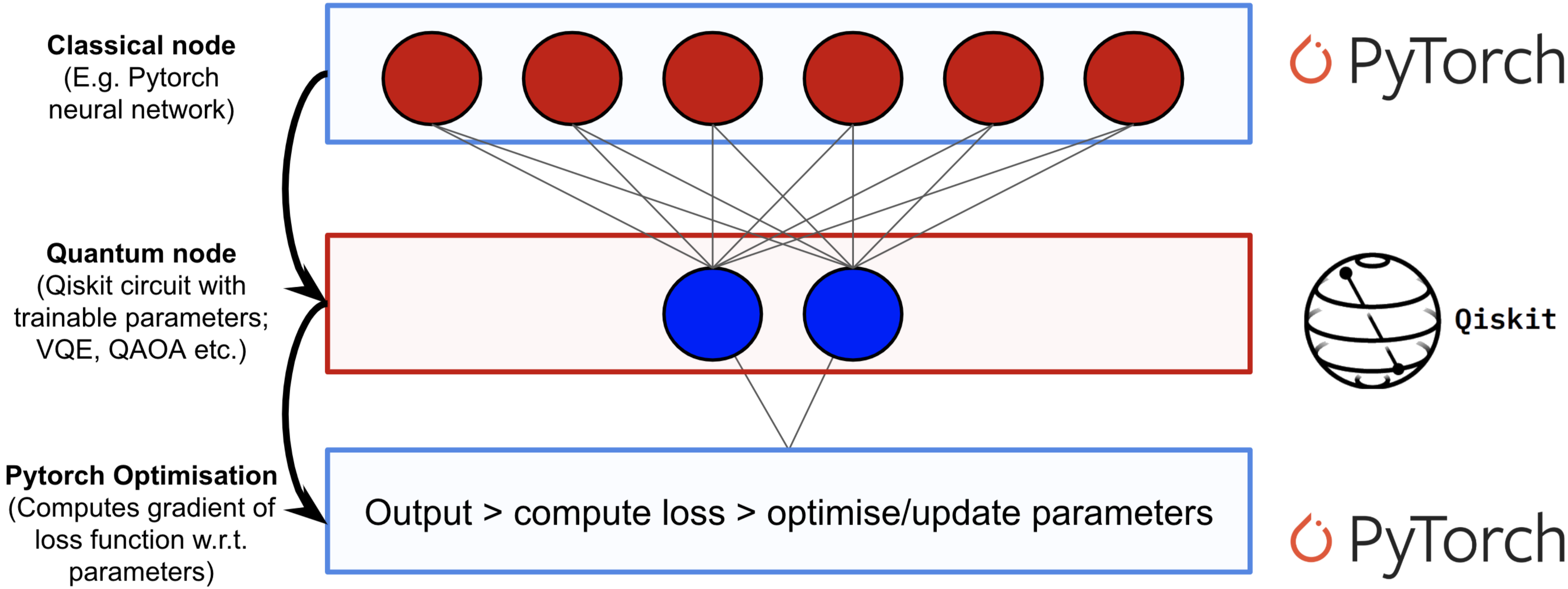
Quantum Computers

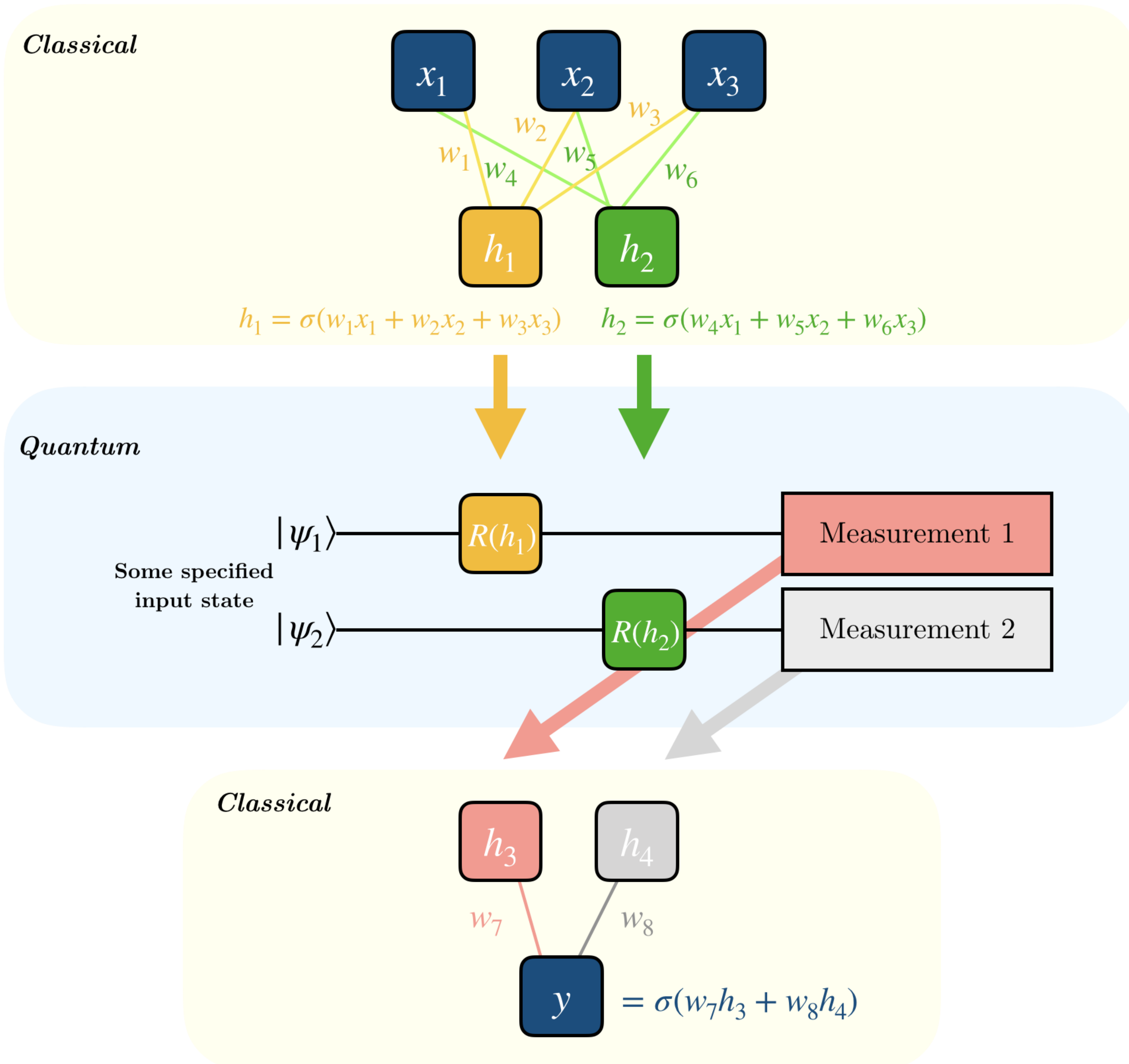


Quantum Computers


ibmq_manhattan error map
Readout error
Readout error
0 0.02 0.08
0.08 0.02 0
SX error rate [Avg. 4.4·10^-4]
2.5·10^-4 5.8·10^-4 1.3·10^-3
CNOT error rate [Avg. 1.3·10^-2]
7.3·10^-3 1.8·10^-2 4.3·10^-2

Quantum ML


Classical node
(E.g. Pytorch
neural network)
Quantum node
(Qiskit circuit with
trainable parameters;
VQE, QAOA etc.)
Pytorch Optimisation
(Computes gradient of
loss function w.r.t.
parameters)
Output > compute loss > optimise/update parameters
PyTorch
Qiskit
PyTorch


Classical
x_1
x_2
x_3
w_1
w_2
w_3
w_4
w_5
w_6
h_1
h_2
$h_1 = \sigma(w_1x_1 + w_2x_2 + w_3x_3)$
$h_2 = \sigma(w_4x_1 + w_5x_2 + w_6x_3)$
Quantum
$|\psi_1\rangle$
$R(h_1)$
Measurement 1
Some specified input state
$|\psi_2\rangle$
$R(h_2)$
Measurement 2
Classical
h_3
h_4
w_7
w_8
y
$= \sigma(w_7h_3 + w_8h_4)$

Thank you