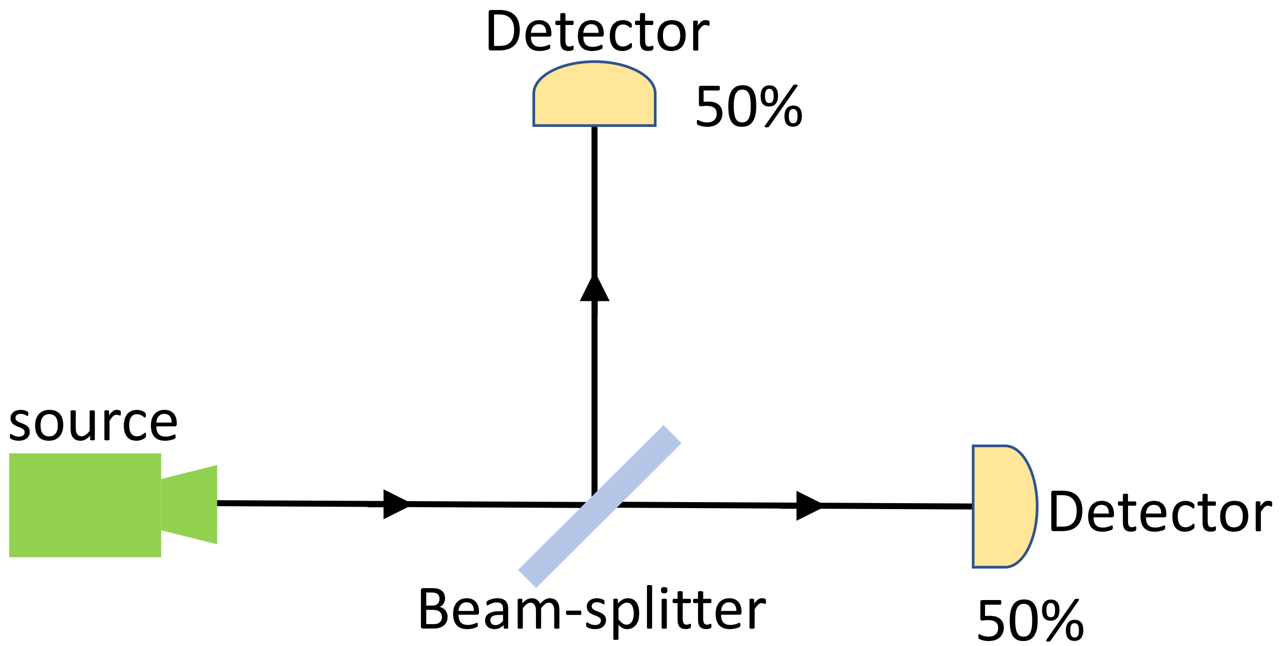
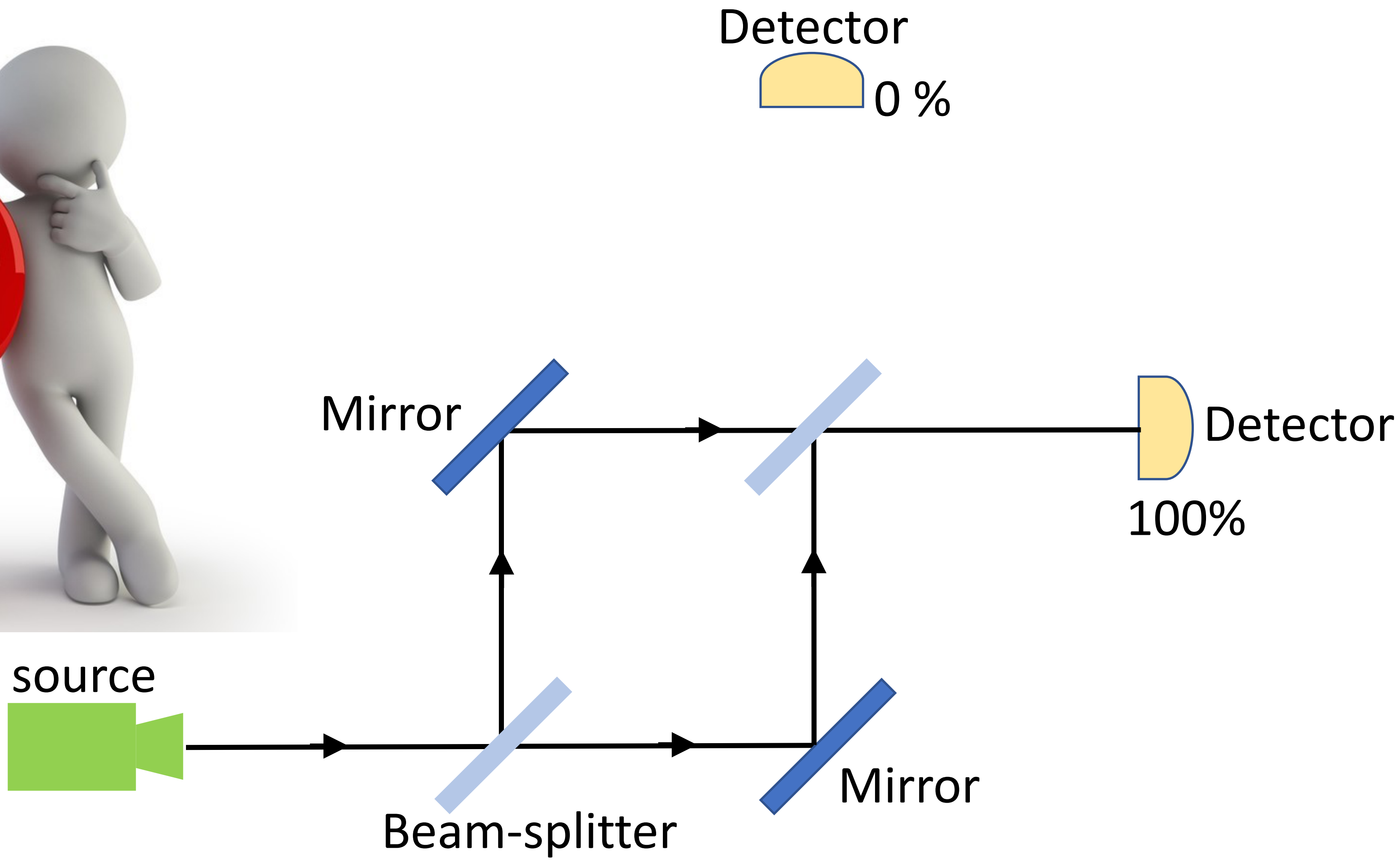
0. Intro & Useful info

Quantum Computing

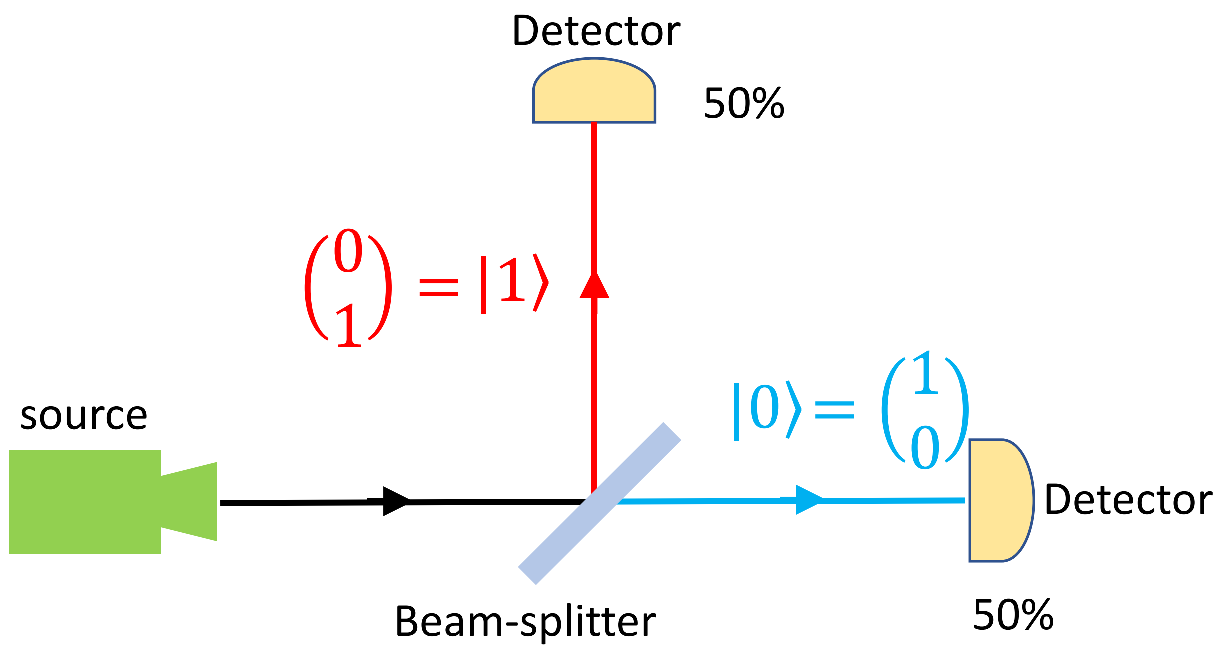
Into the Quantum



Into the Quantum



Into the Quantum



$$\frac{1}{\sqrt{2}}\begin{pmatrix}1 & i\\ i & 1\end{pmatrix}$$

$$\frac{1}{\sqrt{2}}\begin{pmatrix}1 & i\\ i & 1\end{pmatrix}\begin{pmatrix}1\\0\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\i\end{pmatrix}$$

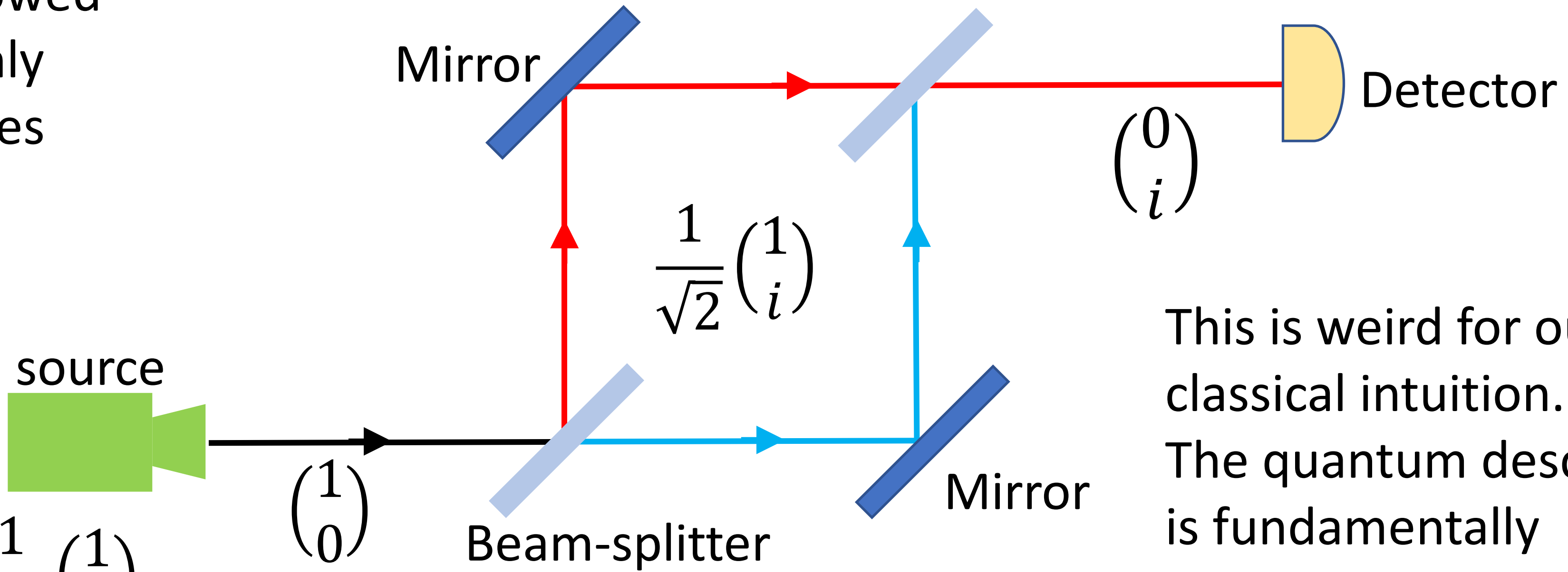
We correctly get 0.5 probability of detection for each path

Into the Quantum

https://www.st-andrews.ac.uk/physics/quvis/simulations_html5/sims/Mach-Zehnder-Interferometer/Mach_Zehnder_Interferometer.html

$$\frac{1}{\sqrt{2}}\begin{pmatrix}1 & i\\ i & 1\end{pmatrix}\frac{1}{\sqrt{2}}\begin{pmatrix}1\\ i\end{pmatrix}=\begin{pmatrix}0\\ i\end{pmatrix}$$

Superposition followed by **interference**: only the red path survives



This is weird for our classical intuition.
The quantum description is fundamentally different, but it works!

$$\frac{1}{\sqrt{2}}\begin{pmatrix}1 & i\\ i & 1\end{pmatrix}\begin{pmatrix}1\\ 0\end{pmatrix}=\frac{1}{\sqrt{2}}\begin{pmatrix}1\\ i\end{pmatrix}$$

Into the Quantum

https://www.youtube.com/watch?v=rg4Fnag4V-E

Quantum magnet
(spin quantization)

https://www.youtube.com/watch?v=rQJ4yX1l6to

Double slit experiment
(superposition, interference)

NIELS
BOHR

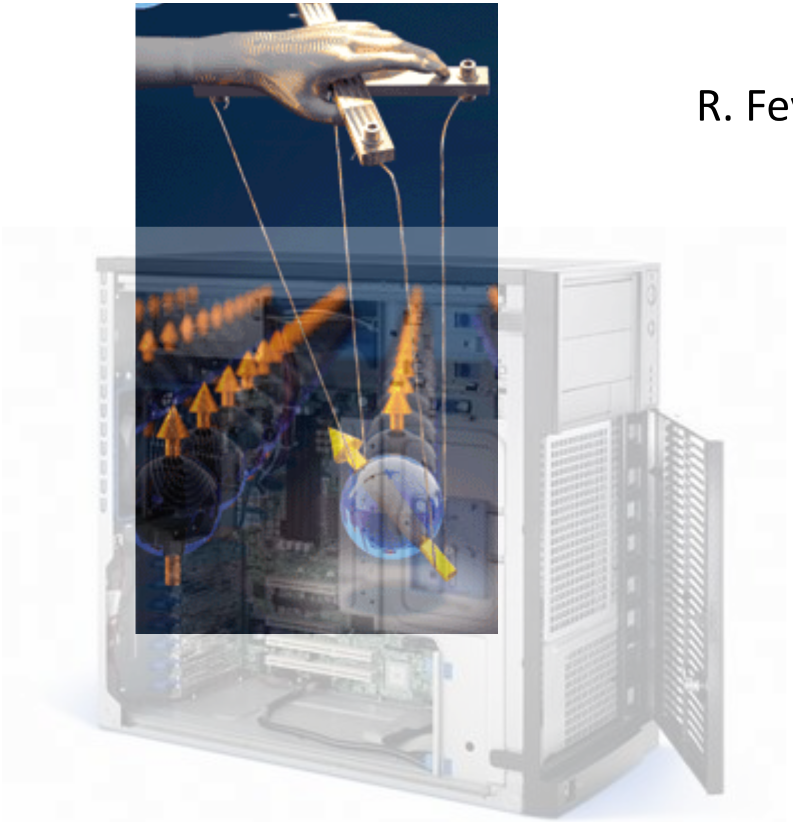
"If quantum mechanics hasn't profoundly shocked you, you haven't understood it yet."

I think it is safe to say that no one understands Quantum Mechanics.

RICHARD
FEYNMAN

Why quantum computing?

"Nature isn't classical, dammit, and if you want to make a ***simulation of nature****, you'd better make it* ***quantum mechanical****, and by golly it's a wonderful problem, because it doesn't look so easy"*



R. Feynman, 1982

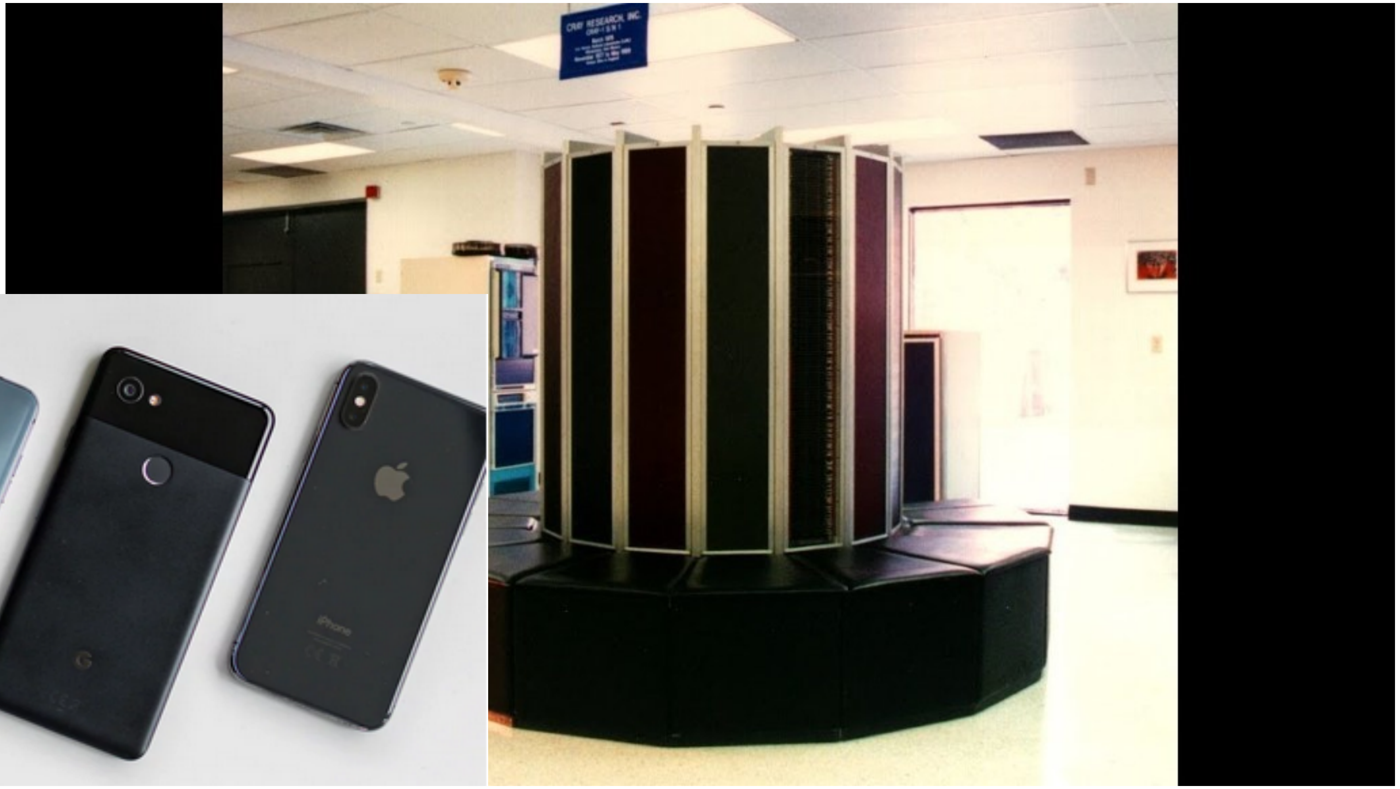
Why quantum computing?

- Quantum Mechanics is the most precise description we have of Nature.
- By mimicking nature, a quantum computer will be able to solve problems intractable for any classical device.
- We know several problems characterized by quantum speedup
- … many others still have to be identified!
- In general we need to design new algorithms different from classical ones, based on some key ingredients in a quantum computer: **superposition, interference, entanglement**. This could pave the way to the solution of hard classical.
- We need to develop hardware and **software**
- We need **quantum-programmers!**

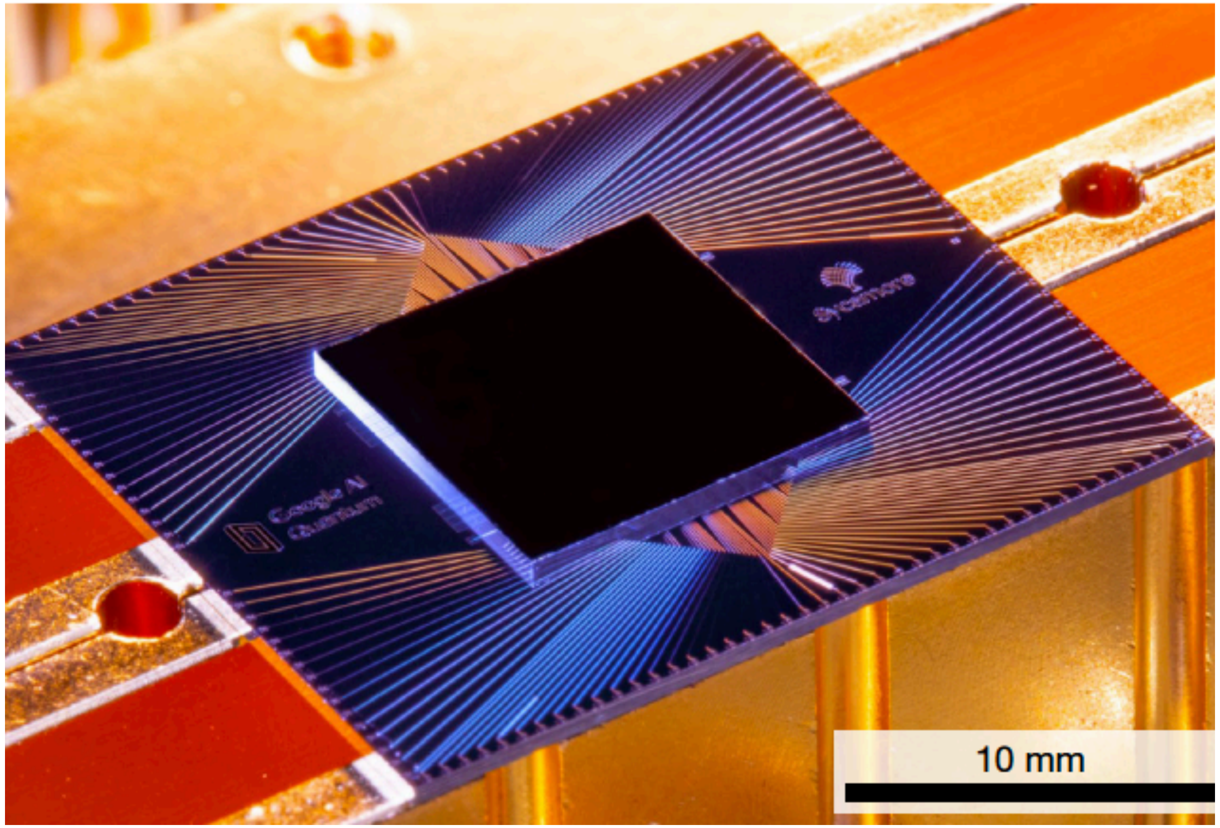
Why quantum computing?

1976 Apple

CERN & CINECA Cray 1



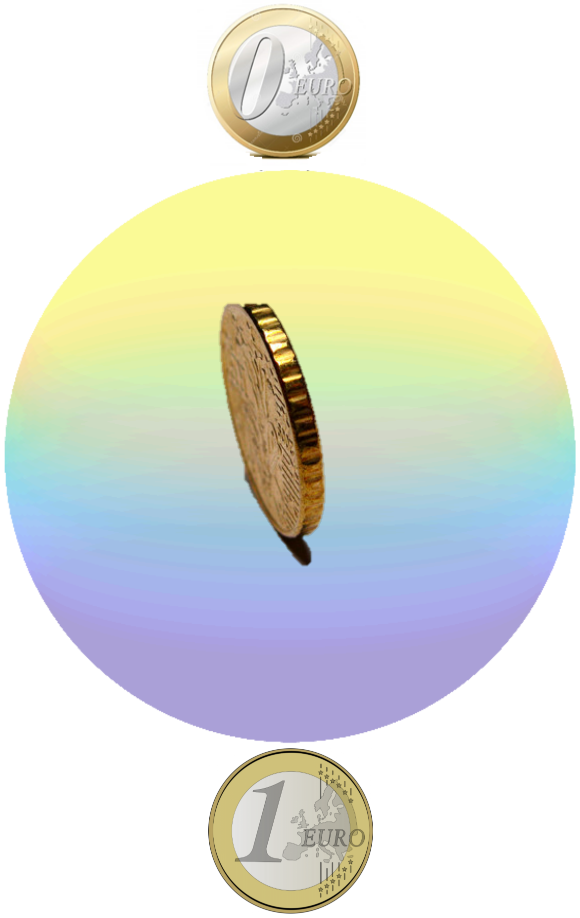
The 2nd quantum revolution



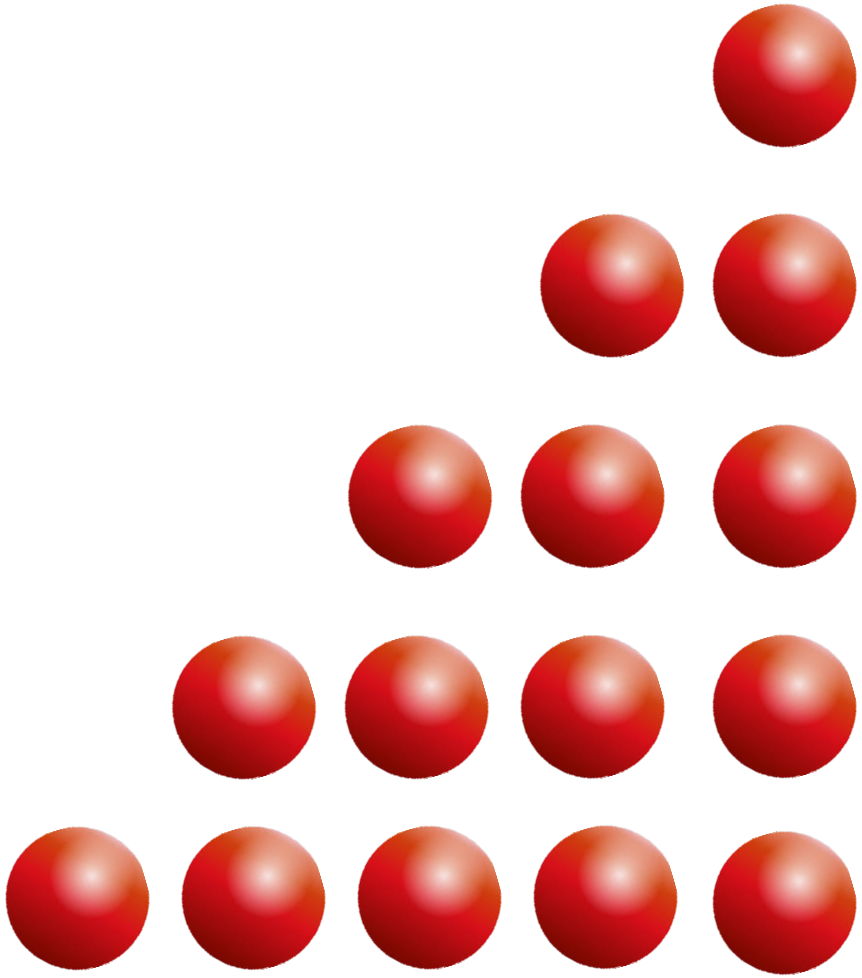
Google says that Sycamore takes 200 s instead of 10,000 years

Nature **574**, 505 (2019)

Quantum Computing

BIT	QU-BIT
	

QU-BITS | **BITS**



$0, 1$

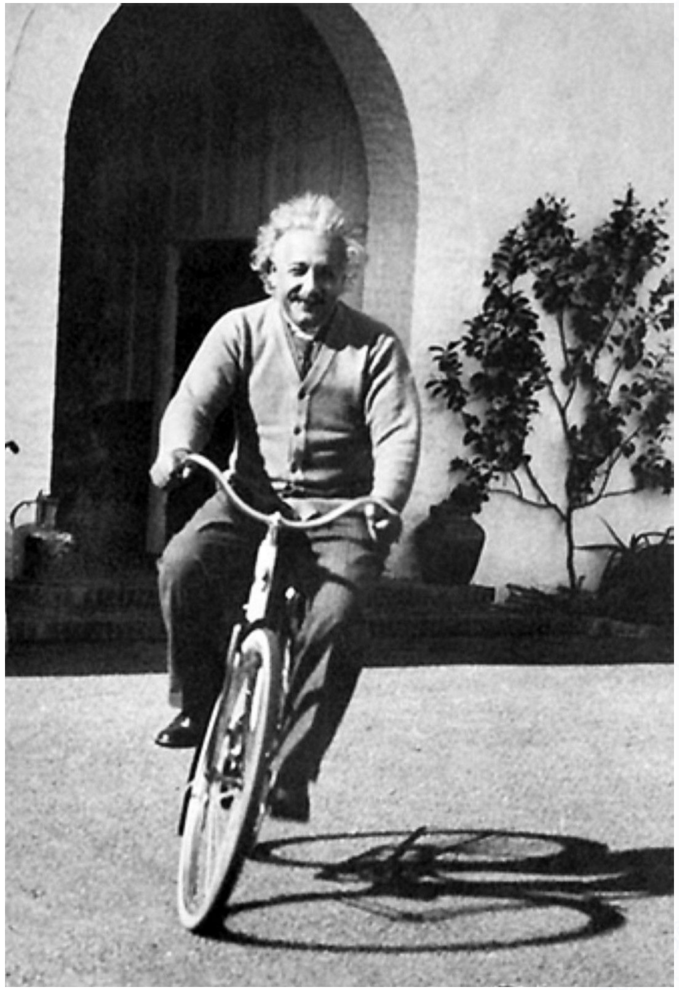
$00, 01, 10, 11$

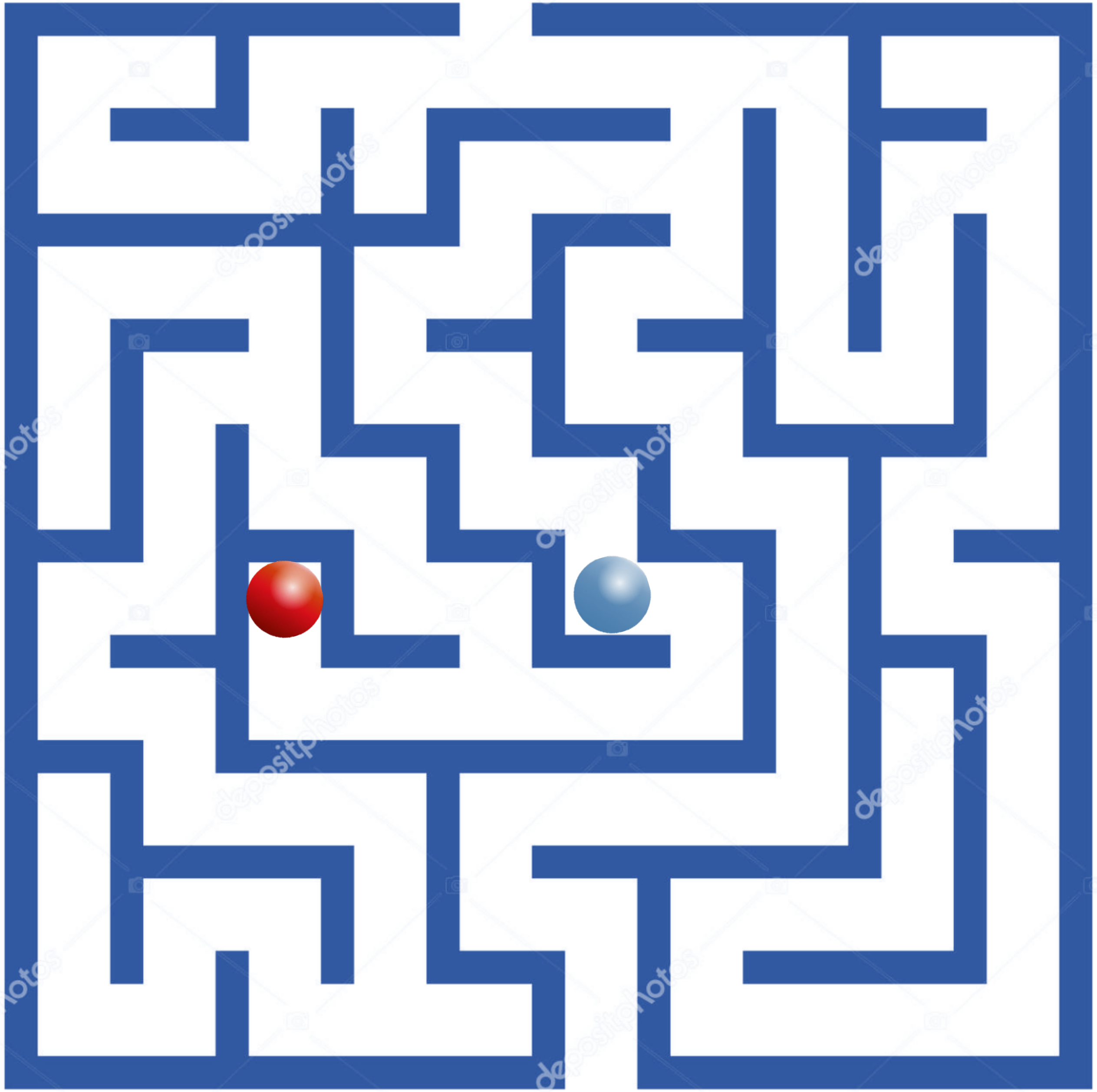
$000, 001, 010, 011, 100, 101, 110, 111$

$0000, 0001, 0010, 0011, 0100, 0101, 0110, 0111,$
$1000, 1001, 1010, 1011, 1100, 1101, 1110, 1111$

$00000, 00001, 00010, 00011, 00100, 00101, 00110, 00111,$
$01000, 01001, 01010, 01011, 01100, 01101, 01110, 01111,$
$10000, 10001, 10010, 10011, 10100, 10101, 10110, 10111,$
$11000, 11001, 11010, 11011, 11100, 11101, 11110, 11111$

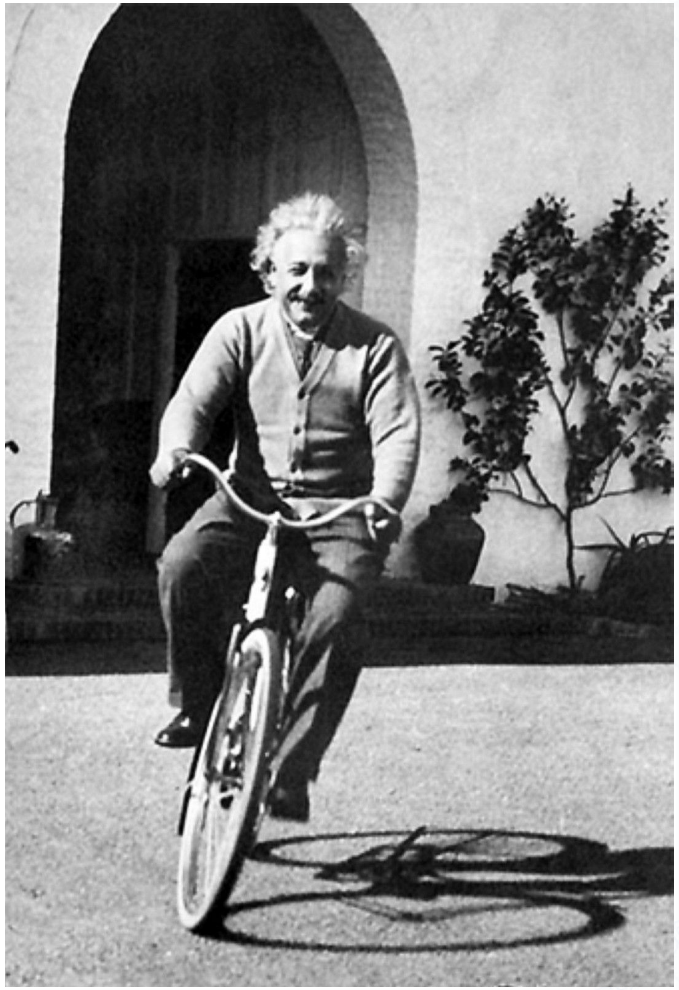
CLASSICAL COMPUTER

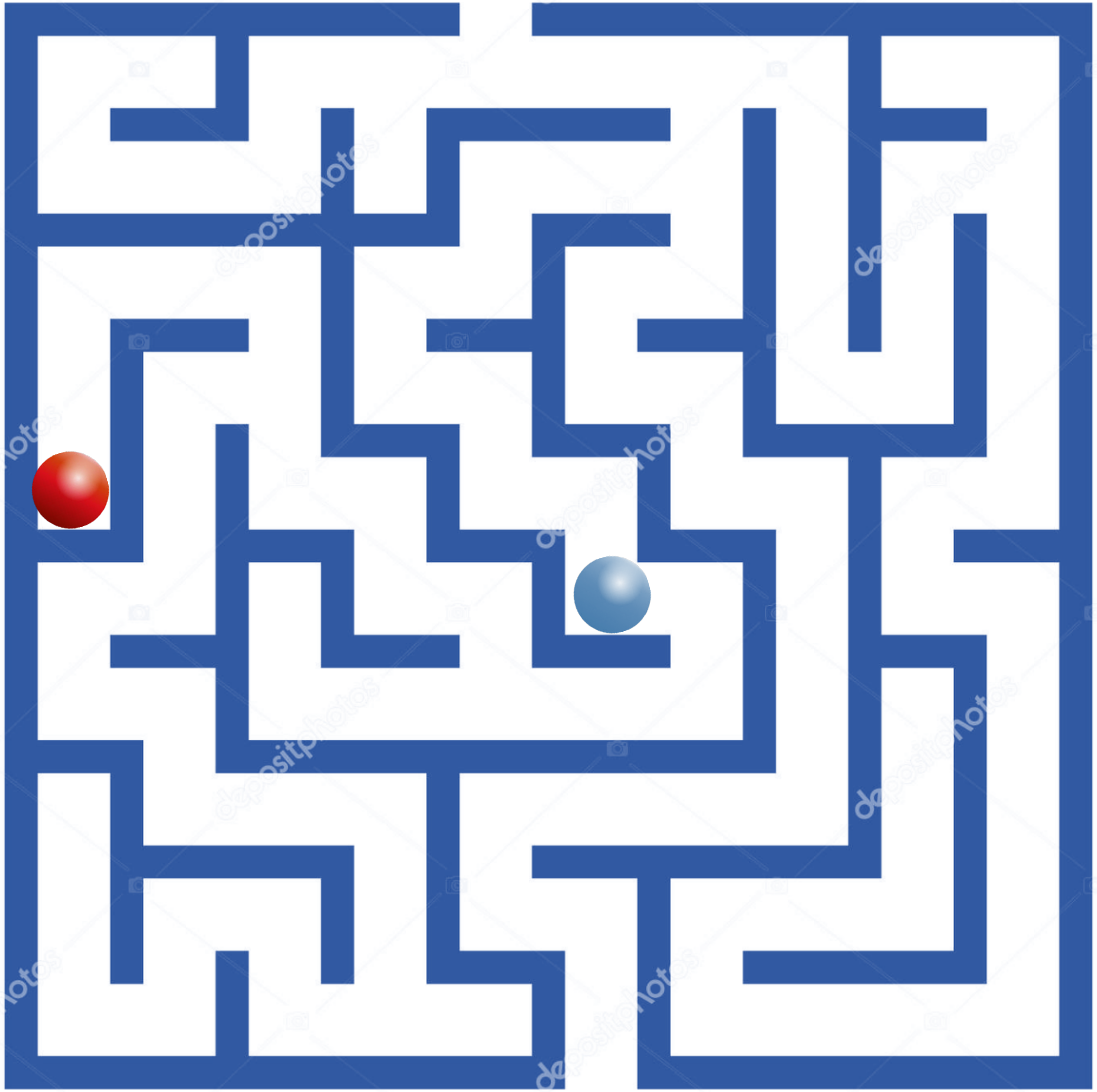




Quantum Computing

CLASSICAL COMPUTER





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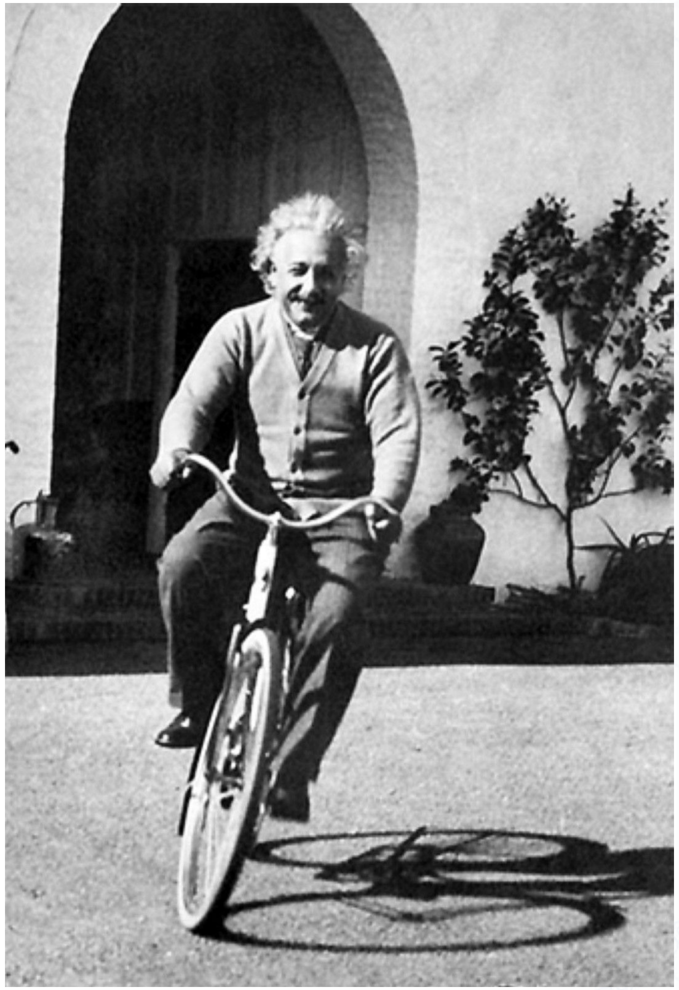

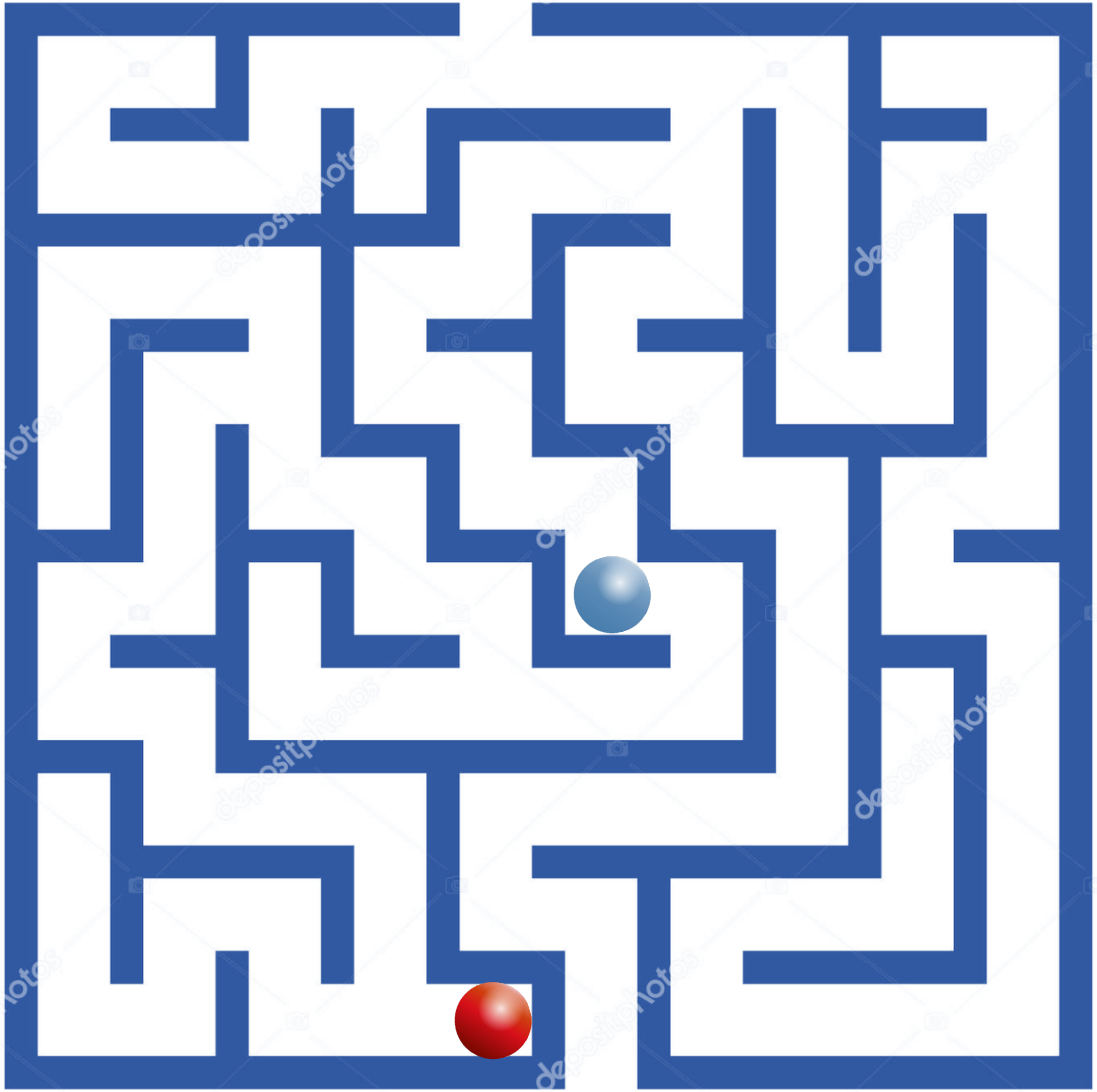

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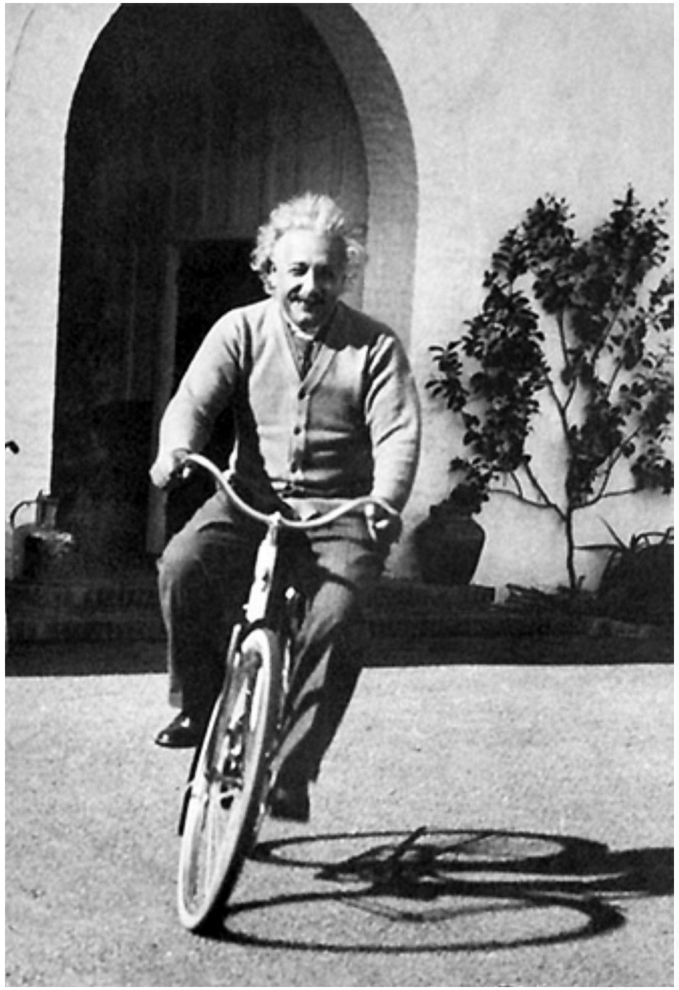
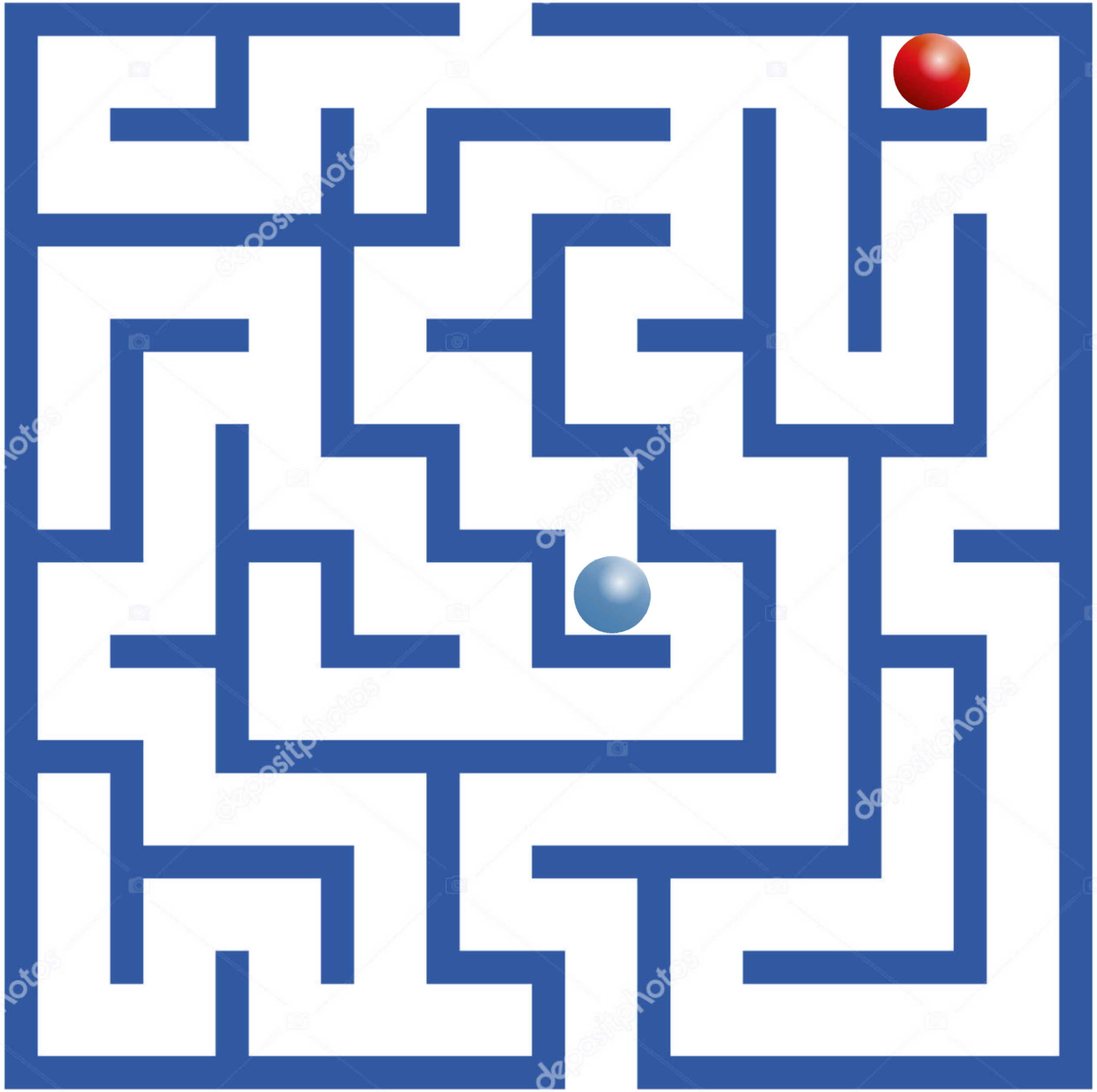
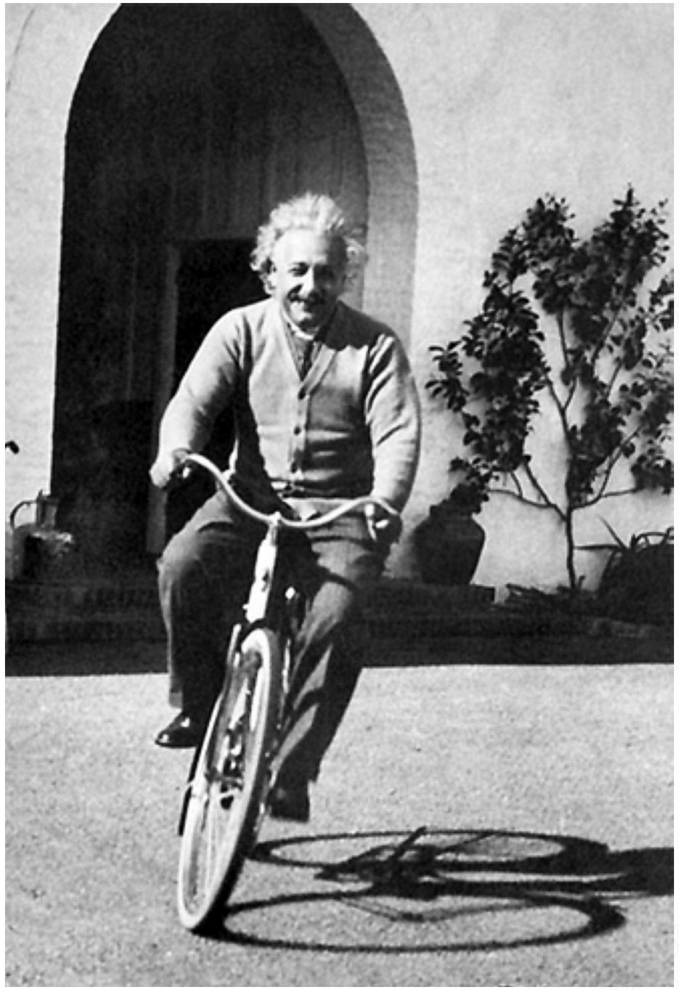
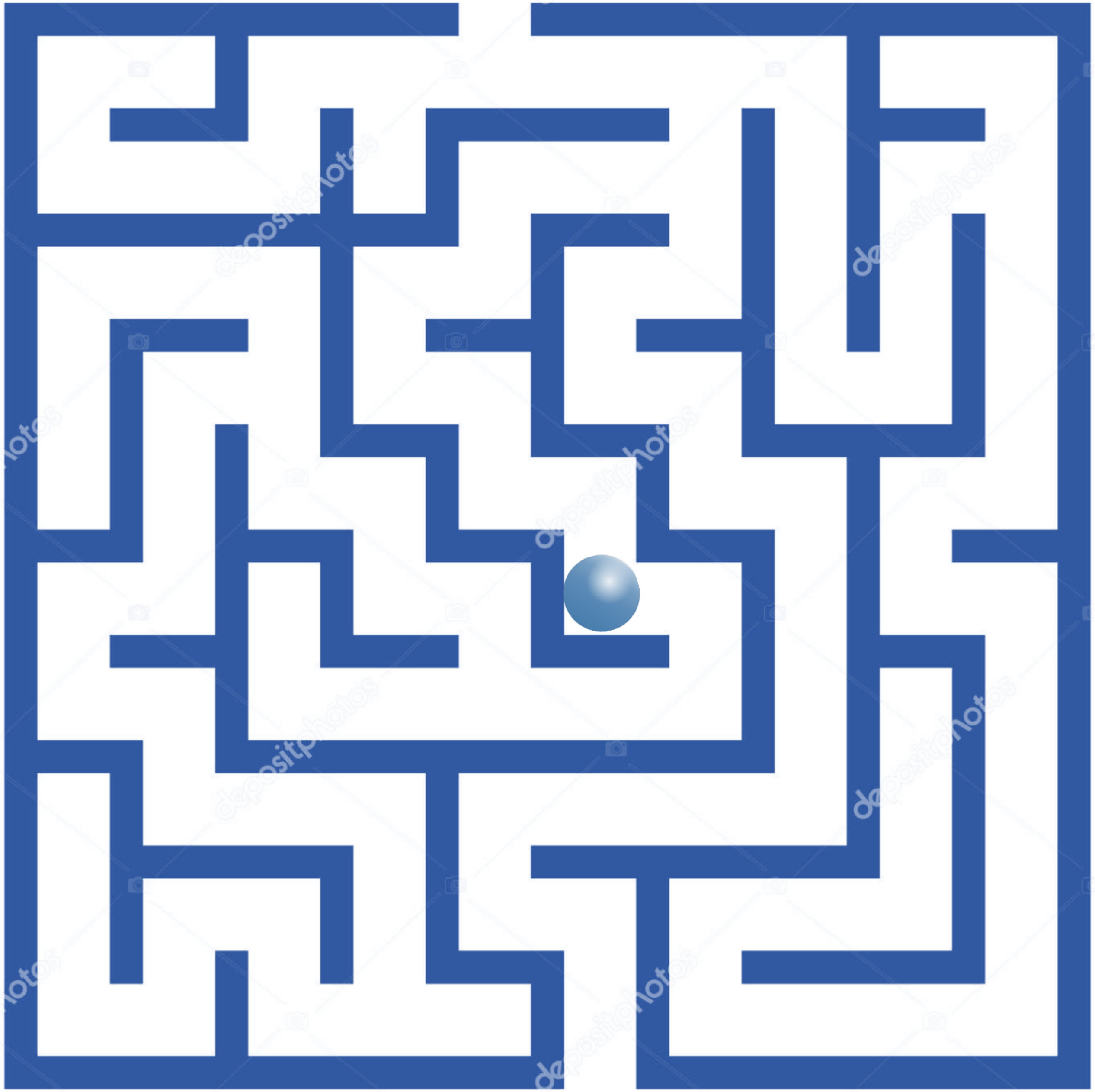


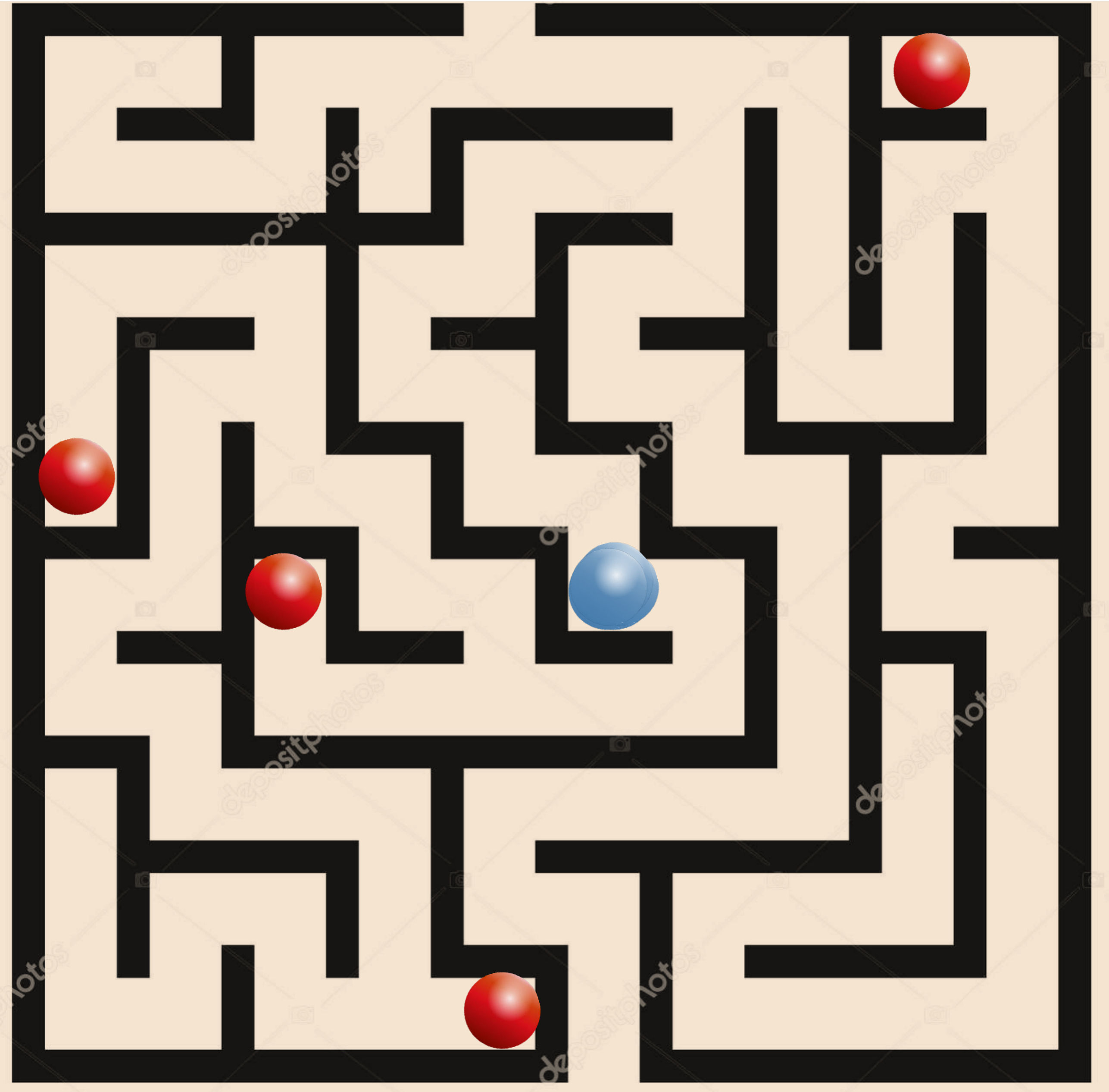


CLASSICAL COMPUTER





QUANTUM COMPUTER



Quantum Computing

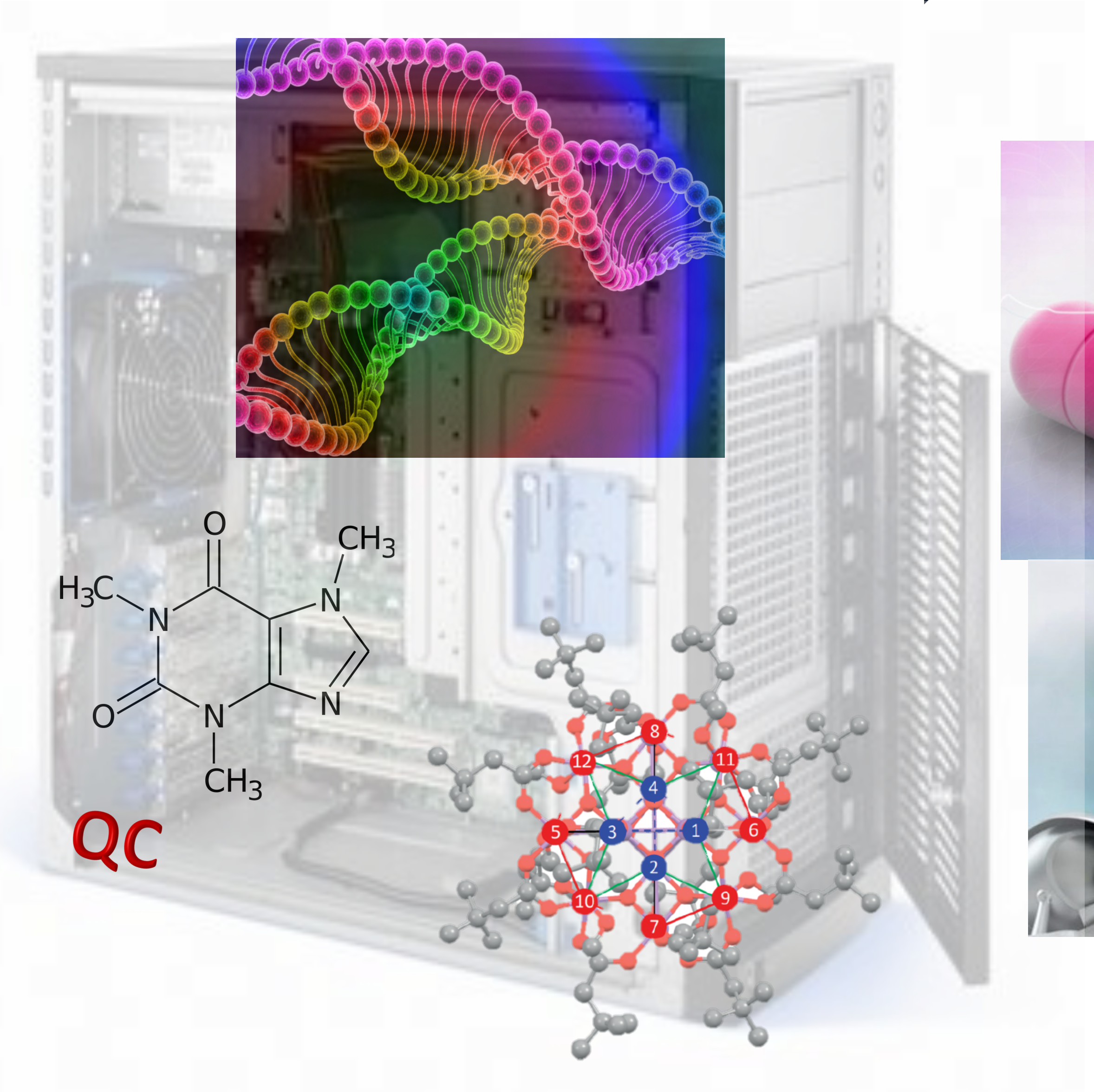
Complexity theory

- Study of the computational effort required to run any algorithm. Usually given in terms of runtime/resources as a function of input size.
- By considering the best possible algorithm to solve a given problem, we can also study the computational effort inherent in solving this problem.
- It is useful to compare complexity of some problems for digital (slightly depending on the theoretical model used) and quantum computers.
- **Digital** computers: use discrete variables but can be built with arbitrarily high precision and methods for detecting and correcting errors exist.
- **Analog** computers: are based on precise manipulations of continuously varying parameters. They may quickly solve problems that are intractable for digital computers, but they cannot be built to reach arbitrarily precision.
- A **quantum** computers tries to combine the robustness of a digital computer with the subtle manipulations of an analog computer (exploiting in some sense the wave-particle duality typical of Quantum Mechanics).

When to use a Quantum Computer

- To determine **global properties of a given function** (e.g. period or minimum). Rather then repeating the computation many times for a variety of different inputs, we can prepare a superposition of input states. By measuring the results we cannot access all of these states, but we can exploit interference to enhance the correct solution and infer the global property we require. E.g.: Grover's algorithm, $O(\sqrt{N})$ speedup.
- **Factoring** large numbers in primes. Shor's algorithm: super-polynomial speedup, from $O(e^{\sqrt[3]{n}})$ to $O(n^3)$.
- **Simulating quantum systems**, to design new materials, compute evolution of strongly interacting many-body systems, model molecules, drug design.
- **Optimization** problems: finance, protein-folding, traffic
- ……

Understand → Design

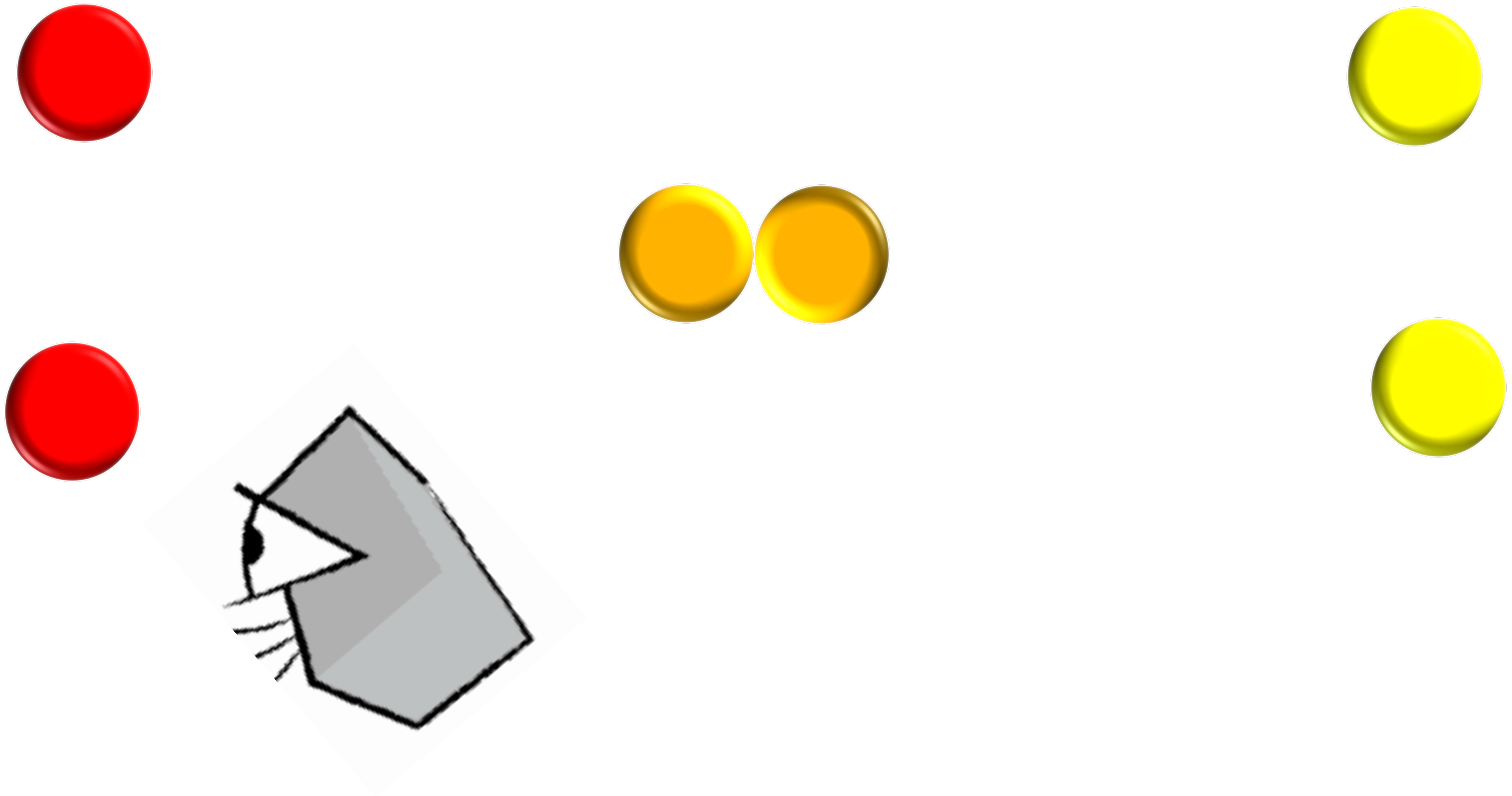


QC

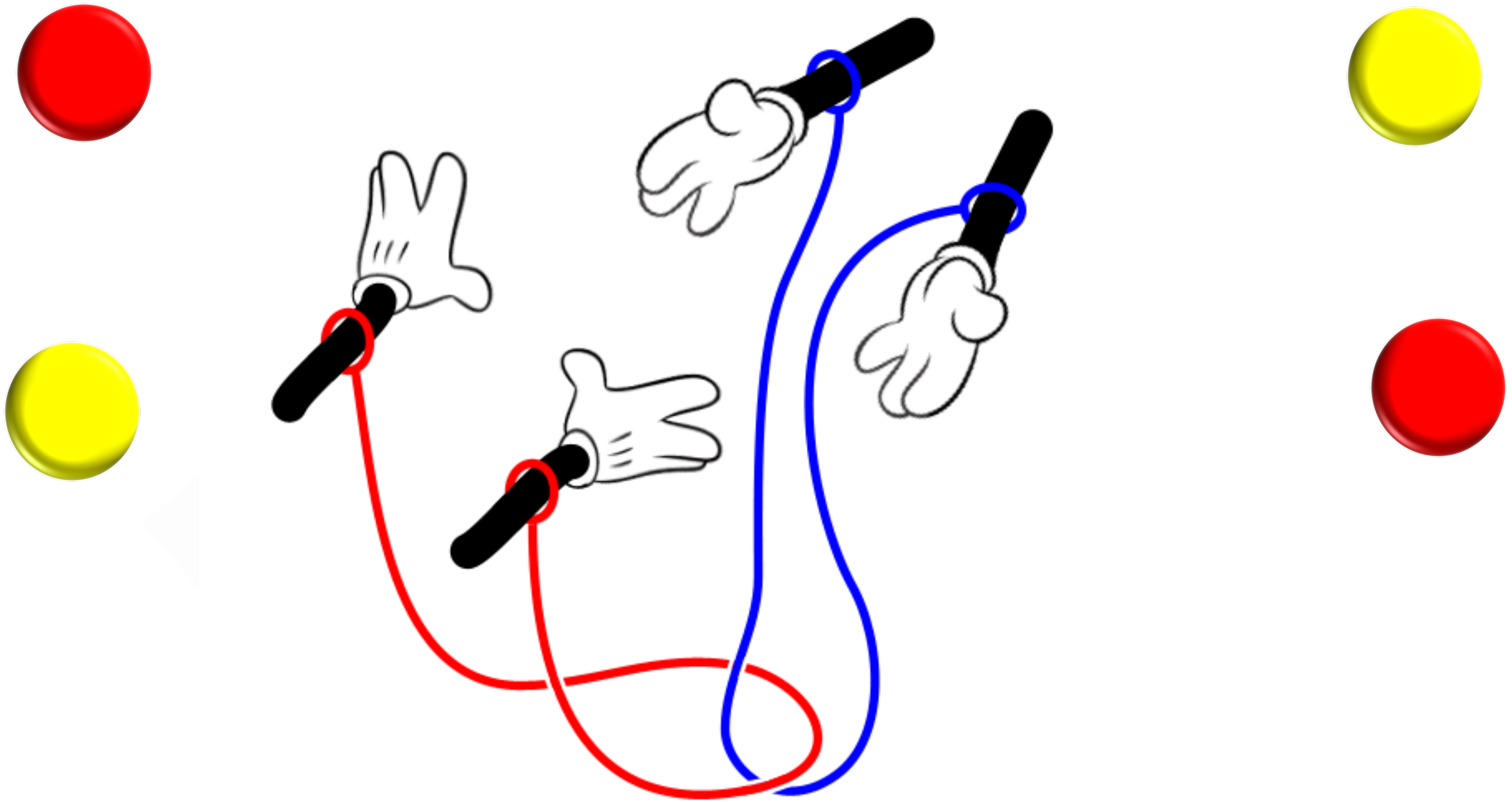
Unfortunately… we need some QM

Ingredients

Entanglement



Entanglement



Quantum Computing

Outline del corso

1. Prerequisites:
   I. the mathematical language (linear algebra)
   II. the programming language (Pyhton)
2. The Quantum Mechanical Tool-Box
3. Qubits
4. From one to multiple qubits: entangled states
5. Basic principles of Quantum Computing and Quantum Algorithms
6. Quantum Algorithms for Applications (including simulators)
7. From the code-world to reality: physical implementations, errors, decoherence, NISQs

Durante il corso useremo Qiskit, pacchetto Python per quantum-programmare e far girare I codici su simulatore o su hardware da remoto.

Testi consigliati

- M. Le Bellac, *A short introduction to Quantum Information and Quantum Computation*, Cambridge, UK (2006).
- P. Kaye, R. Laflamme, M. Mosca, *An introduction to Quantum Computing, Oxford University Press*, New York (2007).
- S. M. Barnett, *Quantum Information*, Oxford University Press, New York (2009).
- M. A. Nielsen, I. L. Chuang, *Quantum Computation and Quantum Information*, Cambridge University Press, New York (2000).
- A. Asfaw et al., https://qiskit.org/textbook/preface.html

Quantum Computing

Modalità esame e contatti

A. Orale tradizionale.

B. Progetto in Qiskit (simulatore) per risolvere un problema proof-of-principle (pochi qubit) che mostri uno speed-up quantistico. Breve relazione e discussione orale dei metodi utilizzati e dei risultati.

Mi trovate presso il Plesso di Fisica, previo contatto email alessandro.chiesa@unipr.it

- Lunedì 15-17
- Martedì 15-17

https://personale.unipr.it/it/ugovdocenti/person/110347