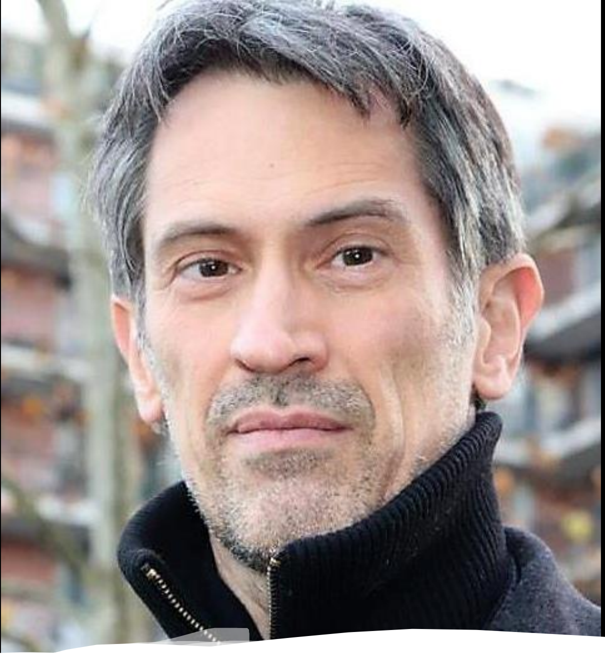
Using and Evaluating Quantum Computing for Information Retrieval and Recommender Systems

SIGIR 2024

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Università di Padova

Useful References

- Ferrari Dacrema, Moroni, Nembrini, Ferro, Faggioli, Cremonesi.
  Towards feature selection for ranking and classification exploiting quantum annealers
  SIGIR 2022
  https://doi.org/10.1145/3477495.3531755
- Nembrini, Carugno, Ferrari Dacrema, Cremonesi.
  Towards recommender systems with community detection and quantum computing
  RecSys 2022
  https://doi.org/10.1145/3523227.3551478
- Nembrini, Ferrari Dacrema, Cremonesi.
  Feature selection for recommender systems with quantum computing
  Entropy 2021
  https://doi.org/10.3390/e23080970

Outline of the Tutorial

- Part 1: Quantum Computing Foundations (40 min, Paolo)
  - Introduction to Quantum Computing
  - Introduction to Quantum Annealing
- Part 2: QUBO Formulation (50 min, Maurizio)
  - How to write NP-complete binary decision problems in QUBO formulation
  - Feature selection and clustering with Quantum Annealing
  - Architecture of a Quantum Annealer: number of available qubits and their topology
- Break (30 min)
- Part 3: Evaluation of Quantum Computing for IR and RecSys (20 min, Nicola)
  - Effectiveness and efficiency
  - The QuantumCLEF lab
- Part 4: Hands-on (70 min, Andrea)
  - The QuantumCLEF infrastructure
  - How to program a Quantum Annealer
  - Hands-on: feature selection and clustering

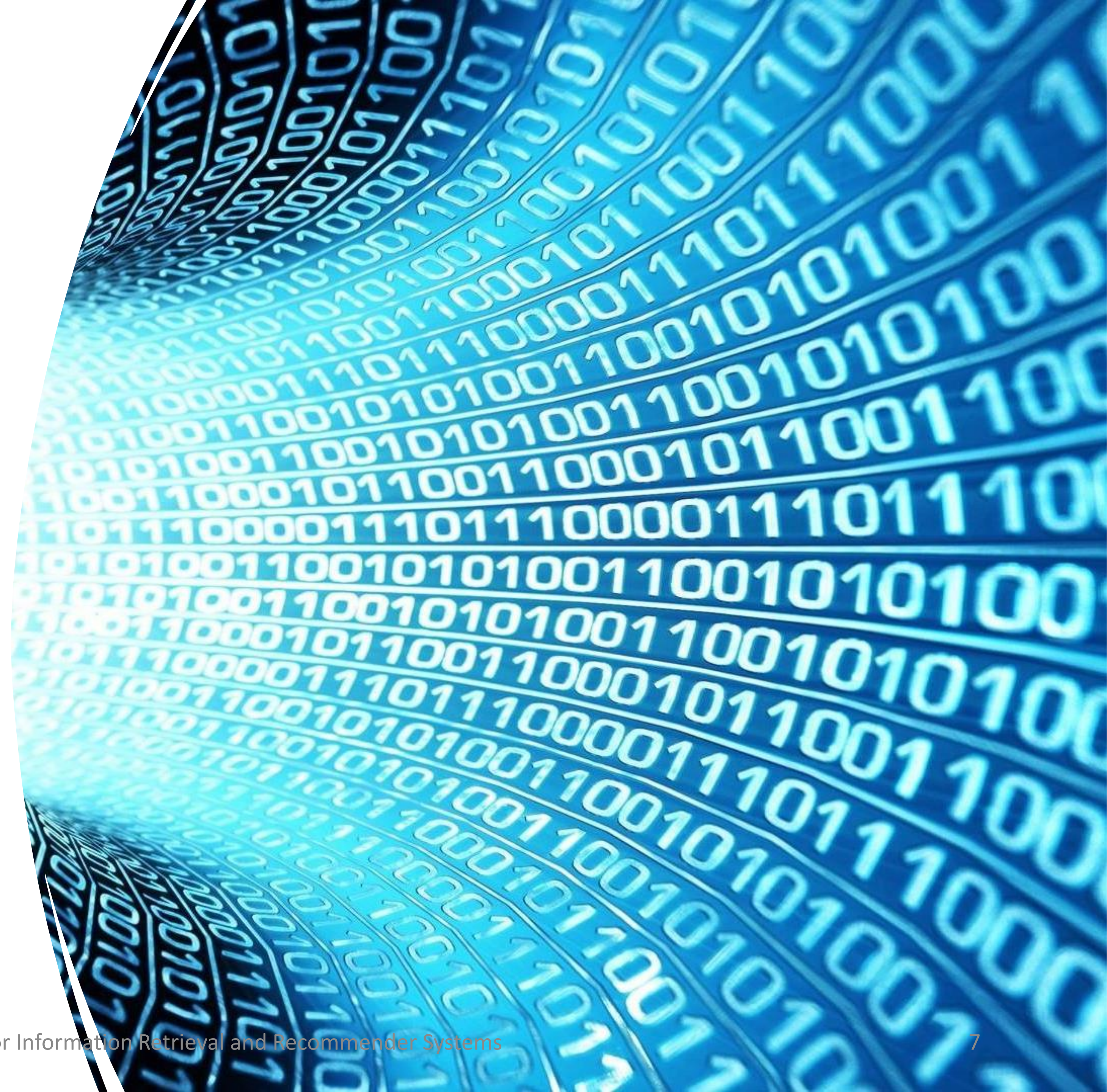
Part 1.

Quantum Computing Foundations

(High Level) Introduction to Quantum Computing

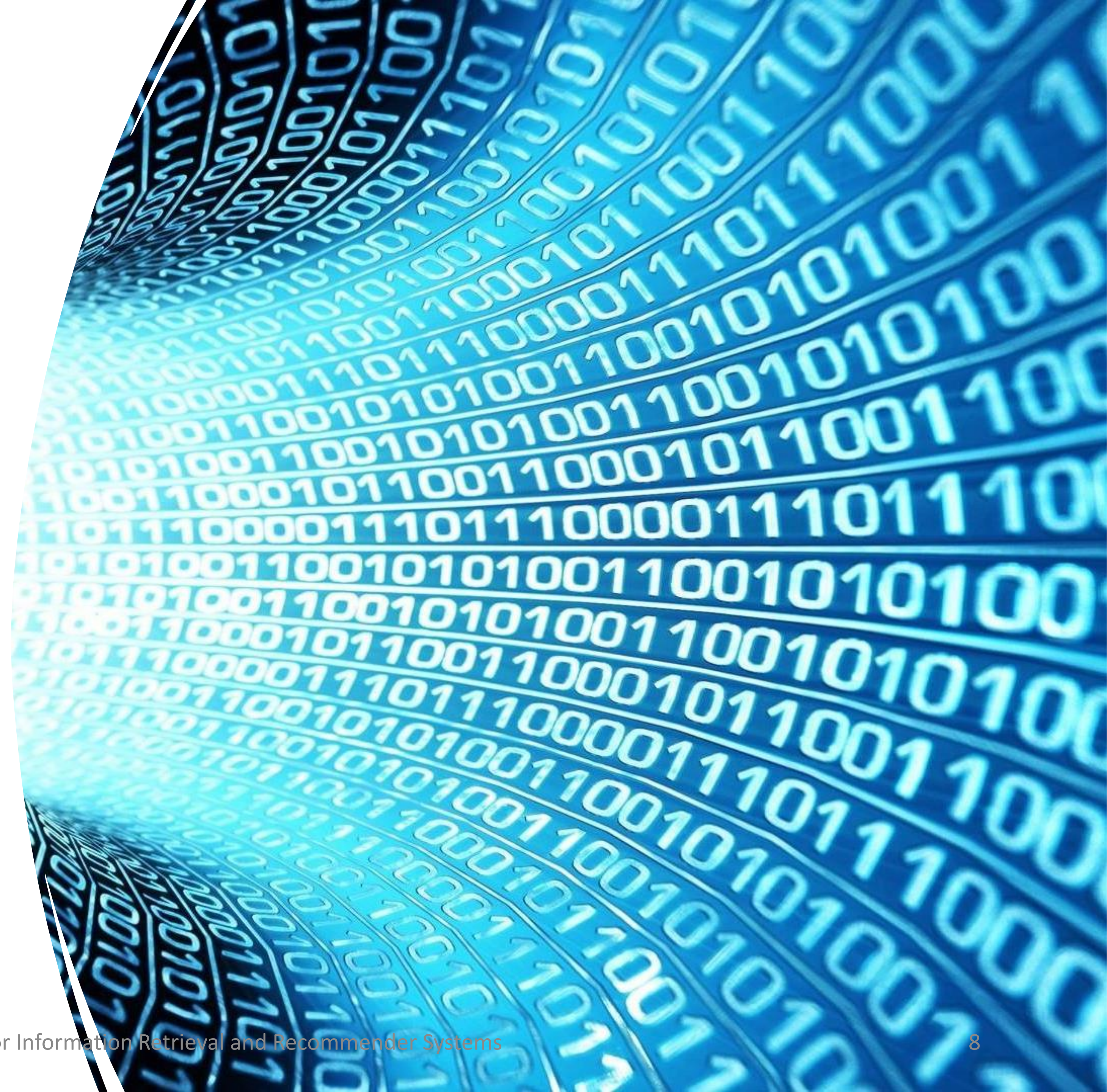
A quantum computer ...

- .... It's not just a more powerful version of the computers we use today

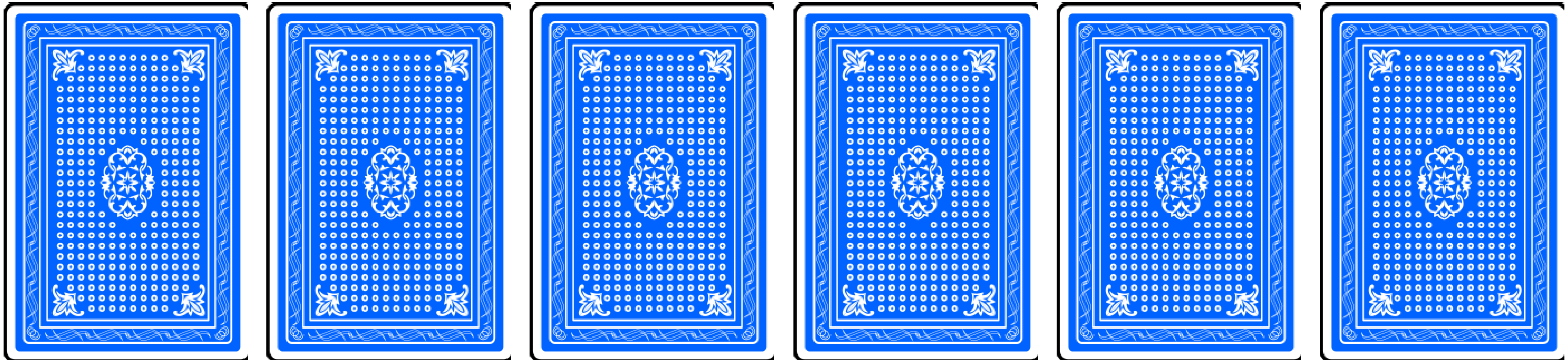


A quantum computer ...

- ... It is something completely different, based on new and **seemingly mysterious** scientific knowledge, where the boundary between reality and science fiction is blurring



Play cards with a QC: Deutsch–Jozsa algorithm



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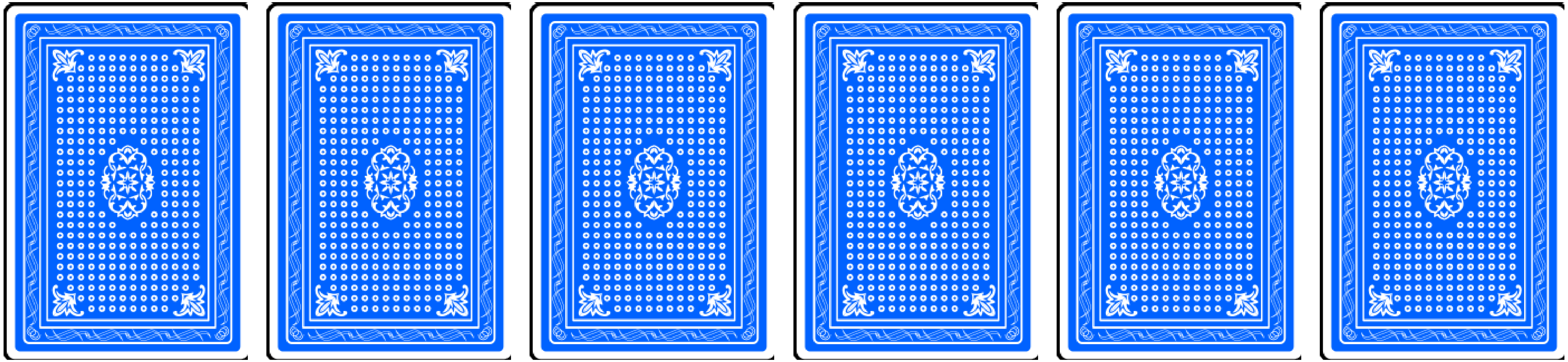
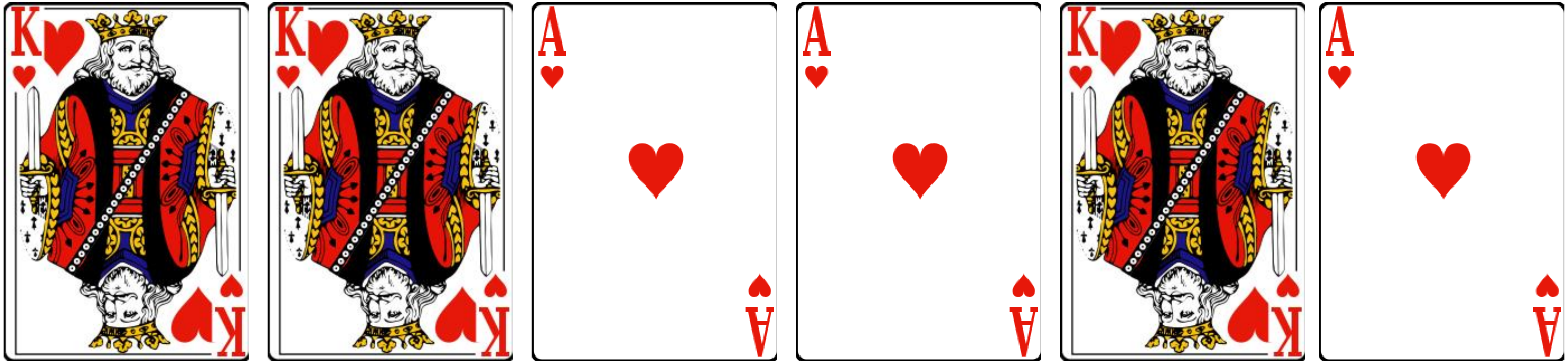


In this game there are three scenarios

Play cards with a QC: Deutsch–Jozsa algorithm

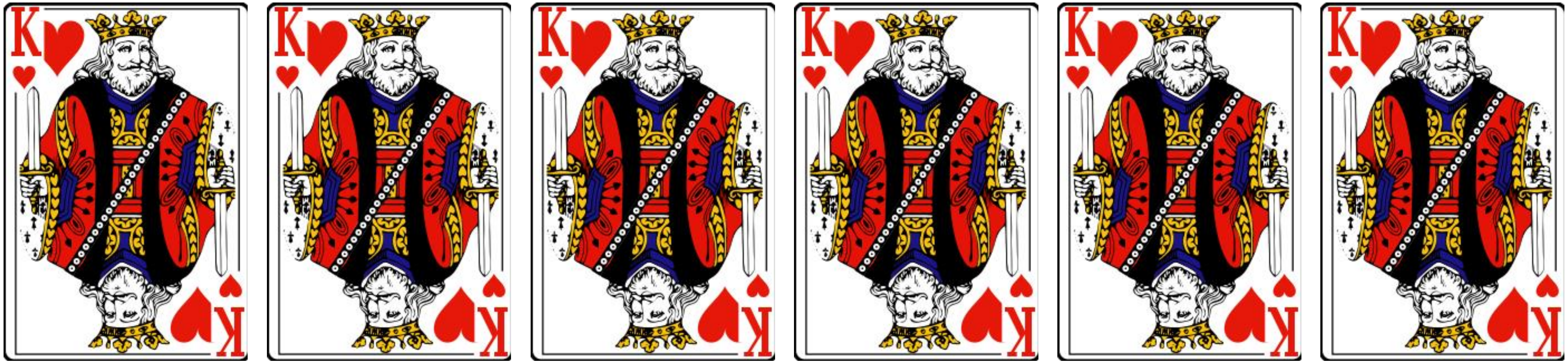


Scenario 1: Balanced

50% Kings

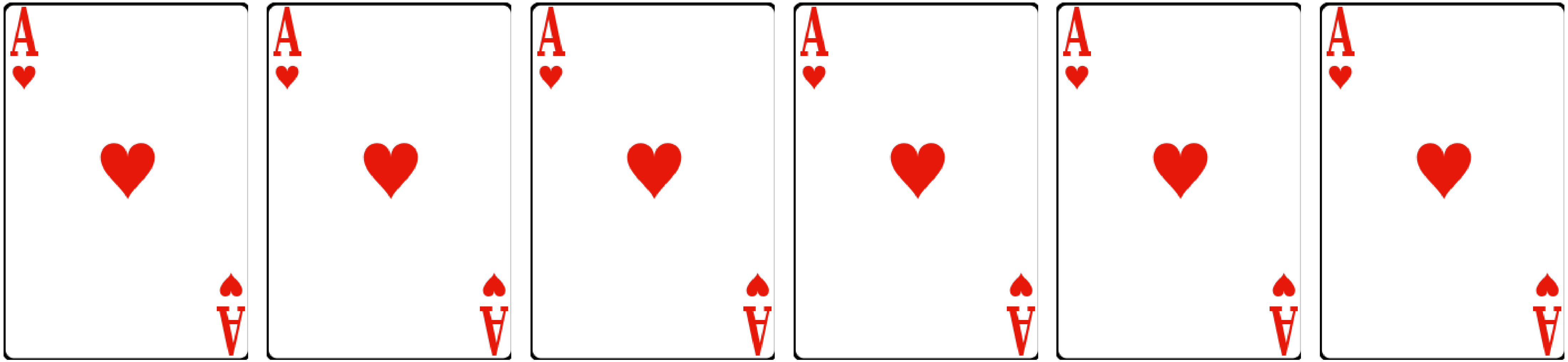
50% Aces

Play cards with a QC: Deutsch–Jozsa algorithm



Scenario 2: all Kings

Play cards with a QC: Deutsch–Jozsa algorithm



Scenario 3: all Aces

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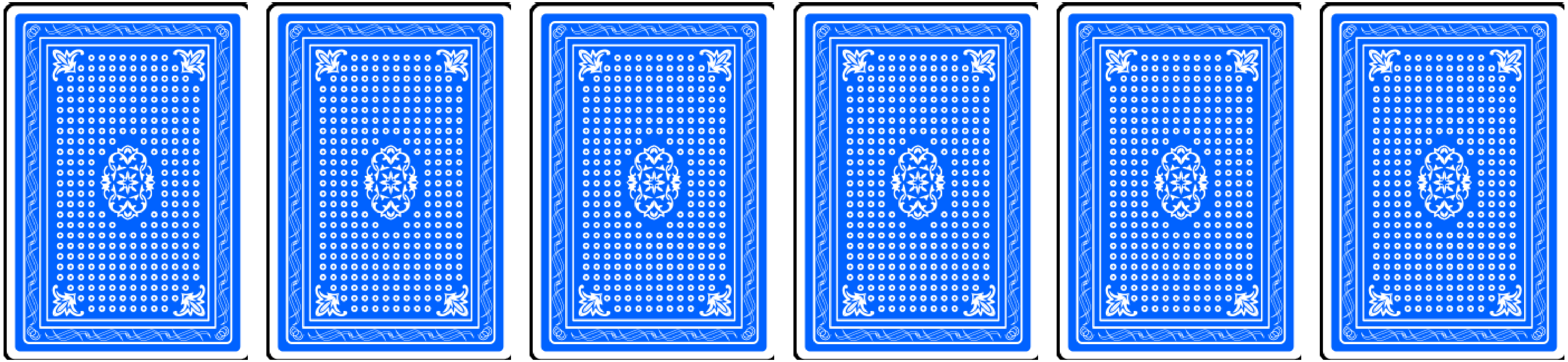
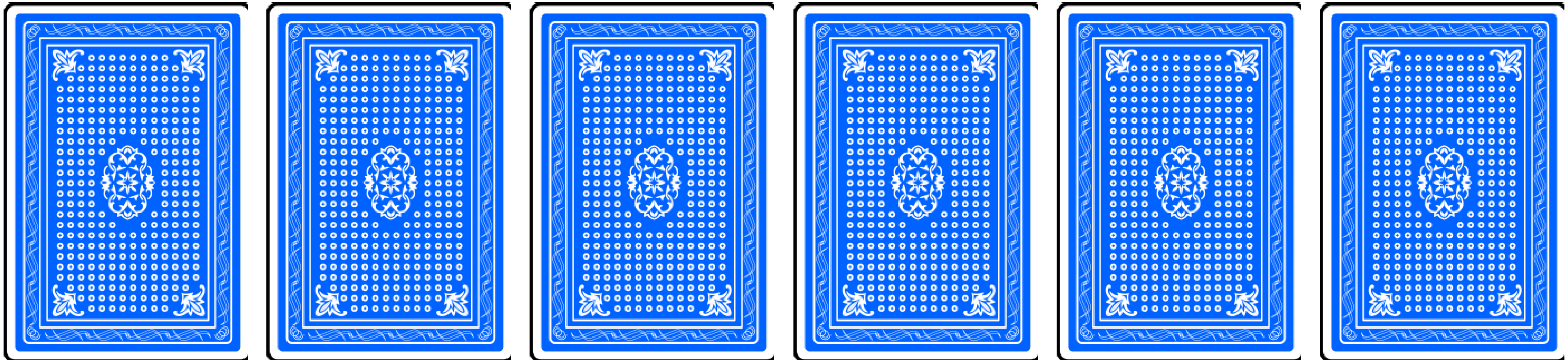
Play cards with a QC: Deutsch–Jozsa algorithm



Cards are now covered and shuffled

How many cards do we need to look at to discover if we are in scenario 1, 2 or 3?

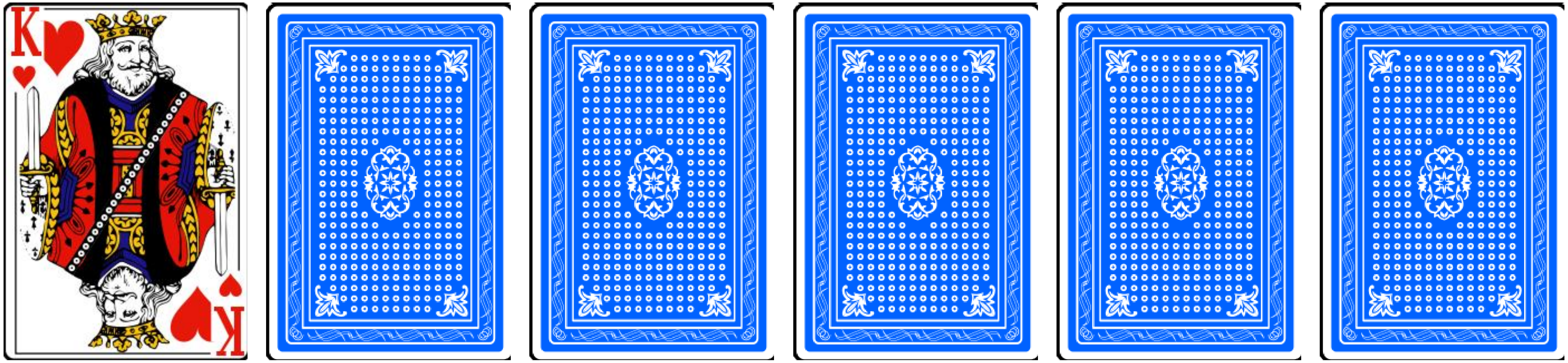
Play cards with a QC: Deutsch–Jozsa algorithm



Classical Computing:

$n/2 + 1$

Play cards with a QC: Deutsch–Jozsa algorithm



Quantum Computing:

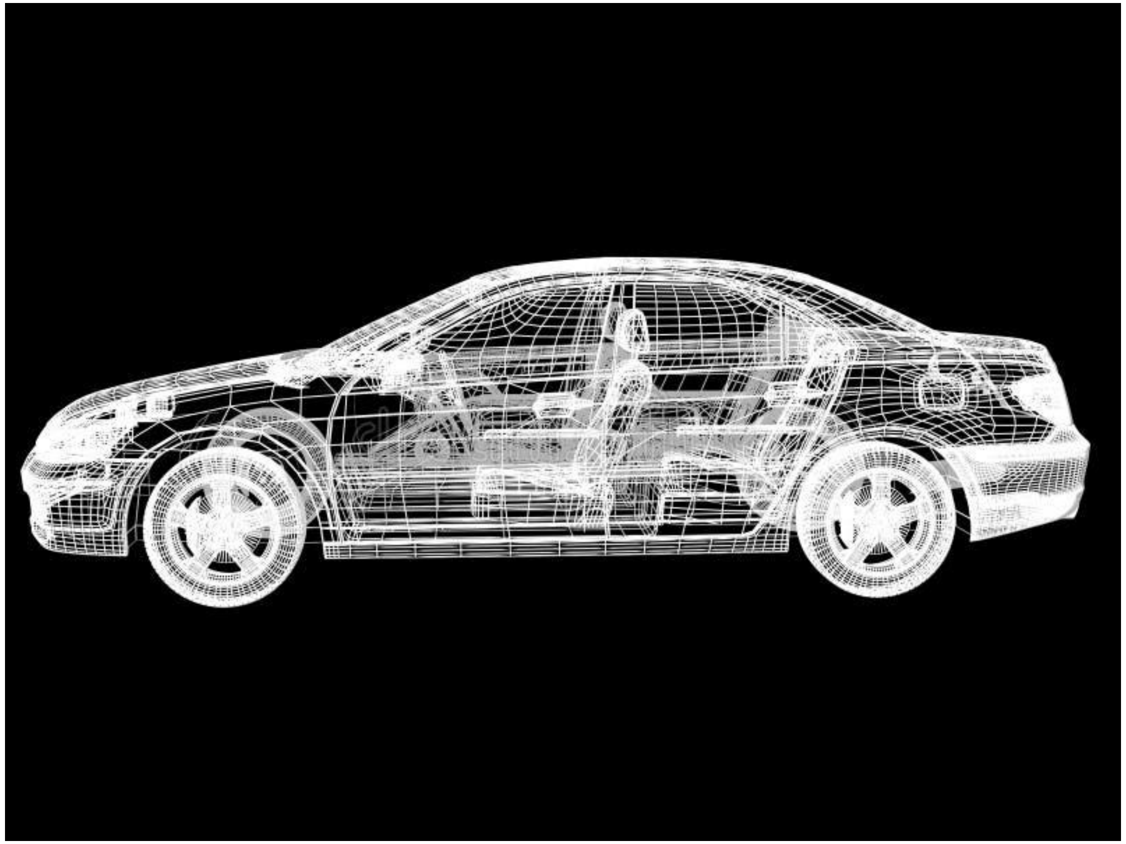
only one !

Build a Quantum Computer

In the world there are **normal** and **quantum** objects

In the world there are **normal** and **quantum** objects

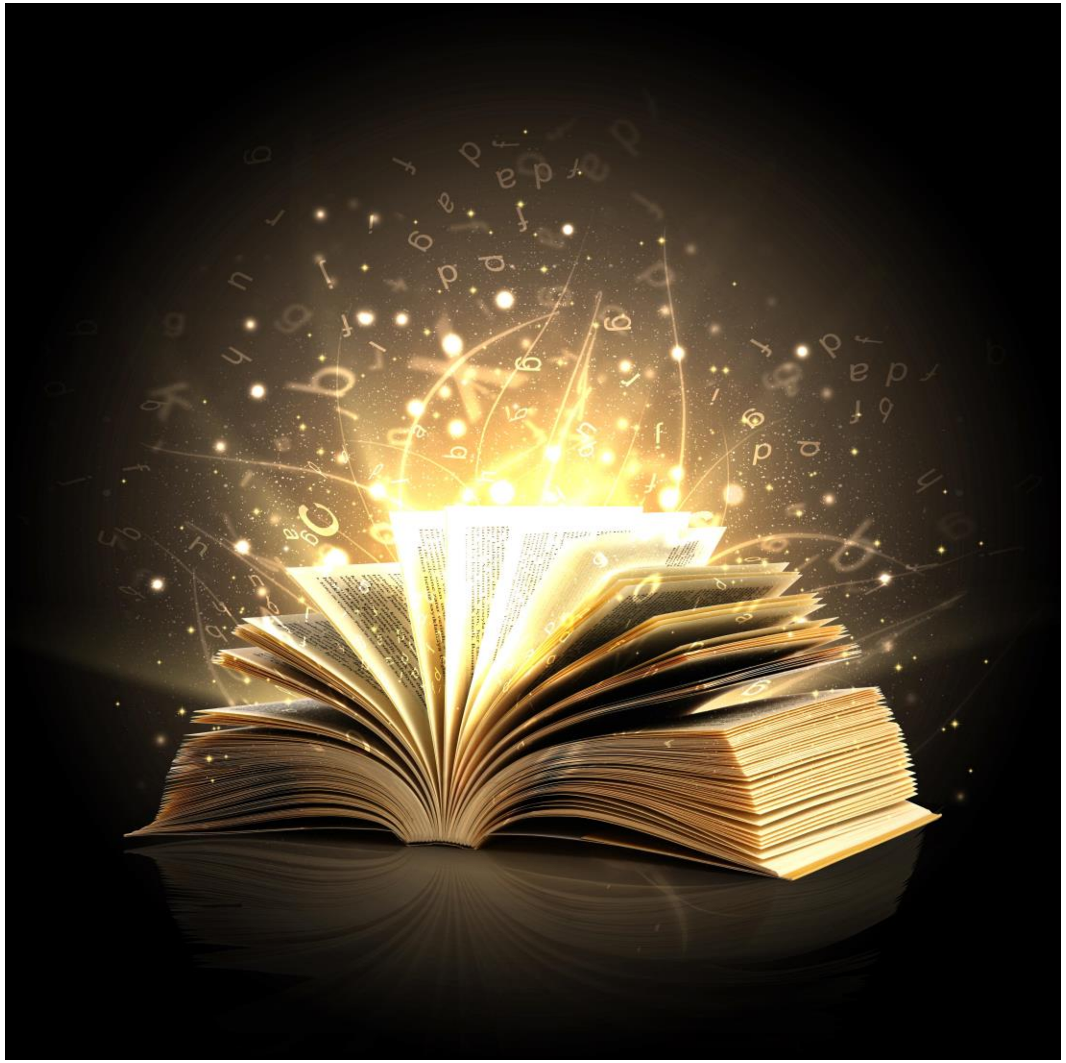
- Normal objects behave according to the rules of common sense and follow the laws of traditional physics



In the world there are **normal** and **quantum** objects

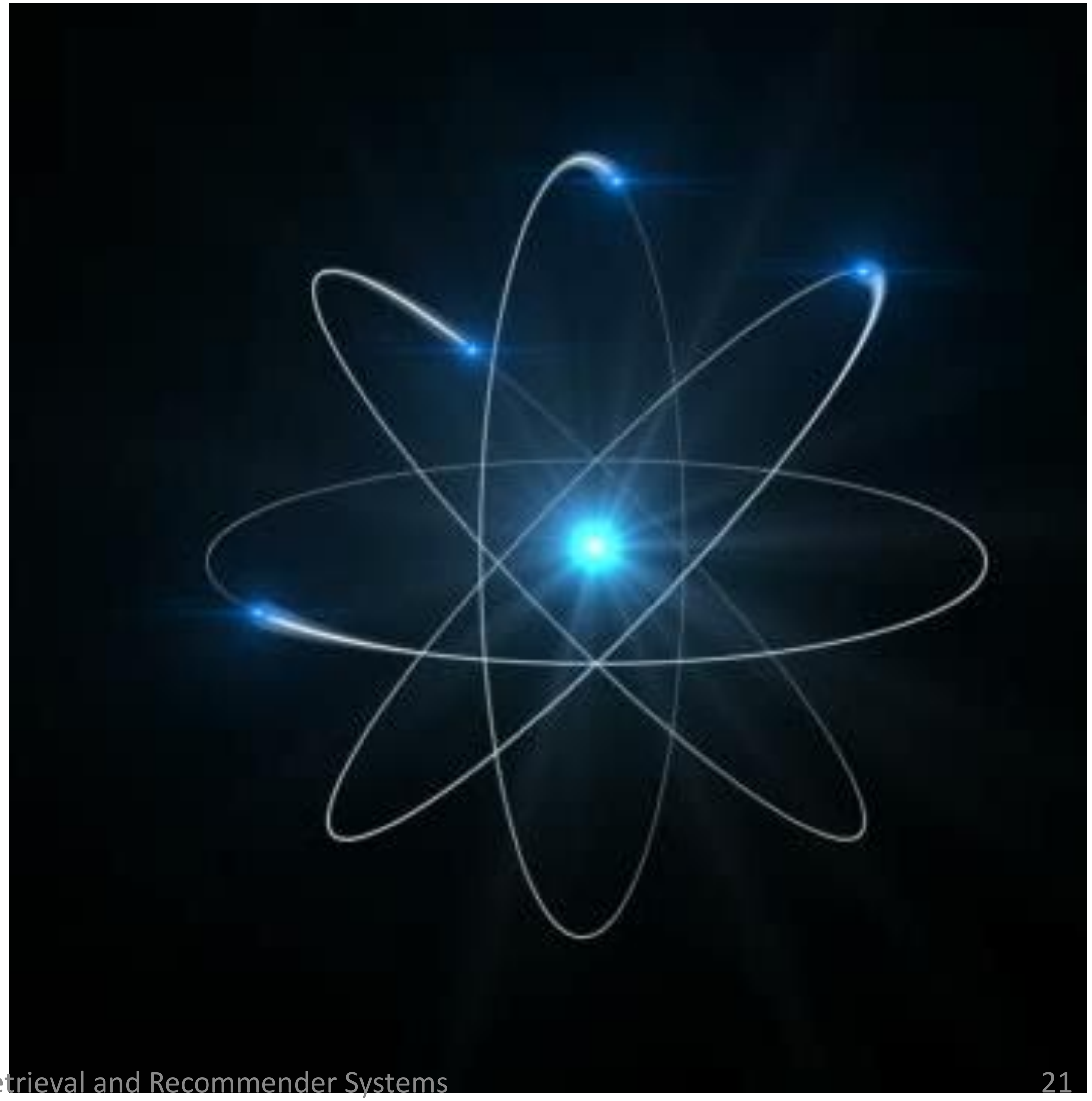
- Normal objects behave according to the rules of common sense and follow the laws of traditional physics

- Quantum objects behave in a funny and strange way, because they follow the laws of quantum physics



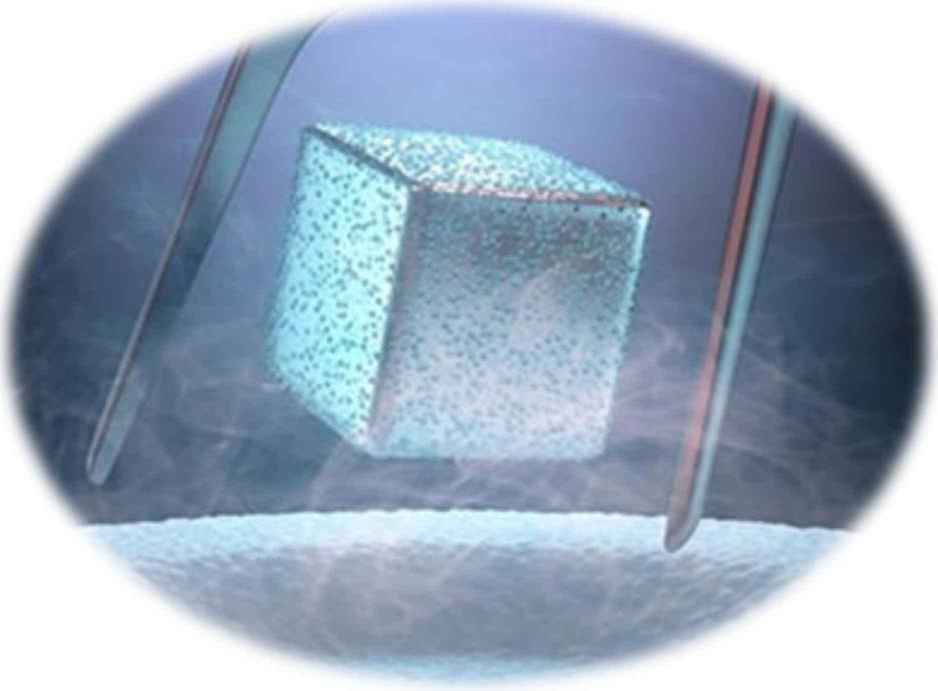
But what are quantum objects?

- Very small, microscopic particles, such as atoms, electrons, photons, if isolated from the rest of the world, behave like quantum objects



But what are quantum objects?

- Very small, microscopic particles, such as atoms, electrons, photons, if isolated from the rest of the world, behave like quantum objects
- Superconducting objects, cooled to temperatures very close to absolute zero, behave like quantum objects



What is a Quantum Computer?

A computer composed of quantum objects called

qubits

which follows the laws of

quantum mechanics

We perform computations by **manipulating** qubits

How is a qubit made?

Technology	*Operation*
Superconductors	20 mK
Photons	1 K
Electrons	1 K
Ions	High vacuum
Atoms	High vacuum
Diamonds	Environment
Topological	…

Principles of Quantum Mechanics

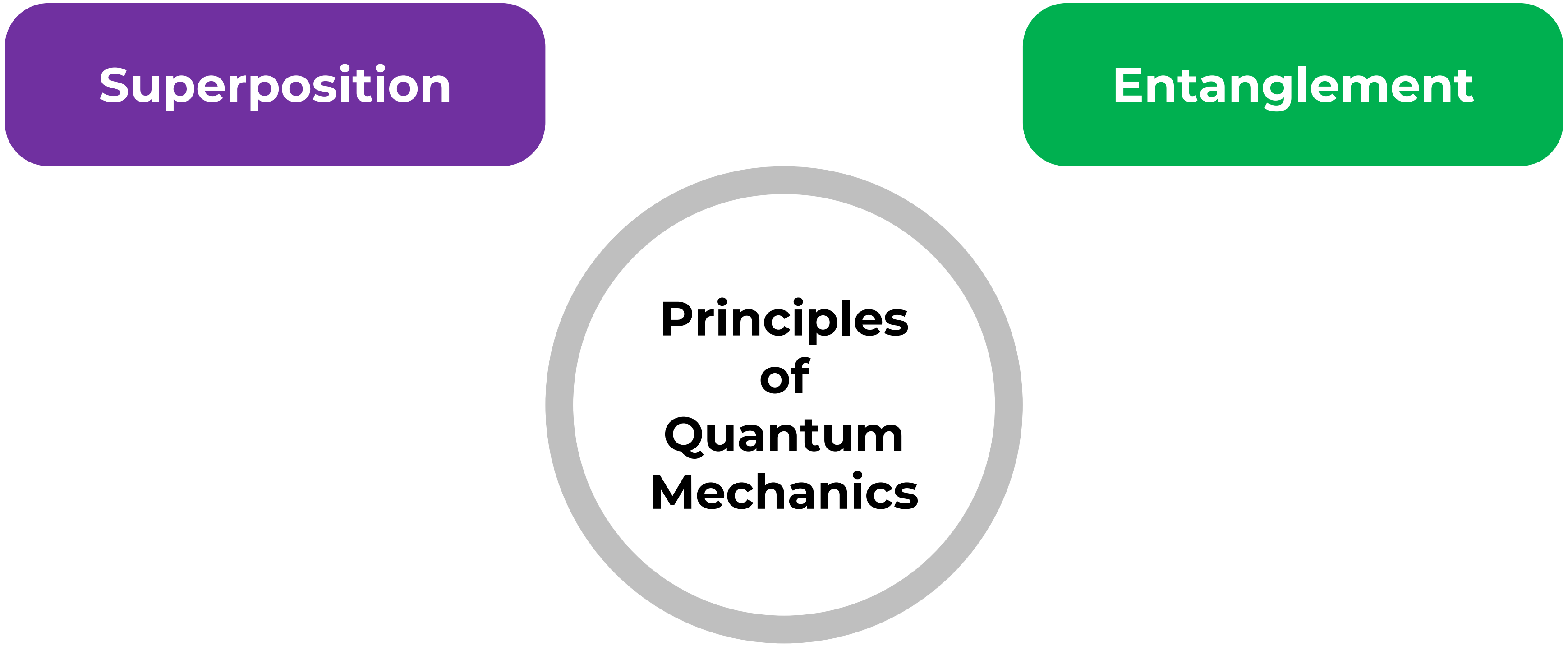
Principles of Quantum Mechanics

Principles of Quantum Mechanics

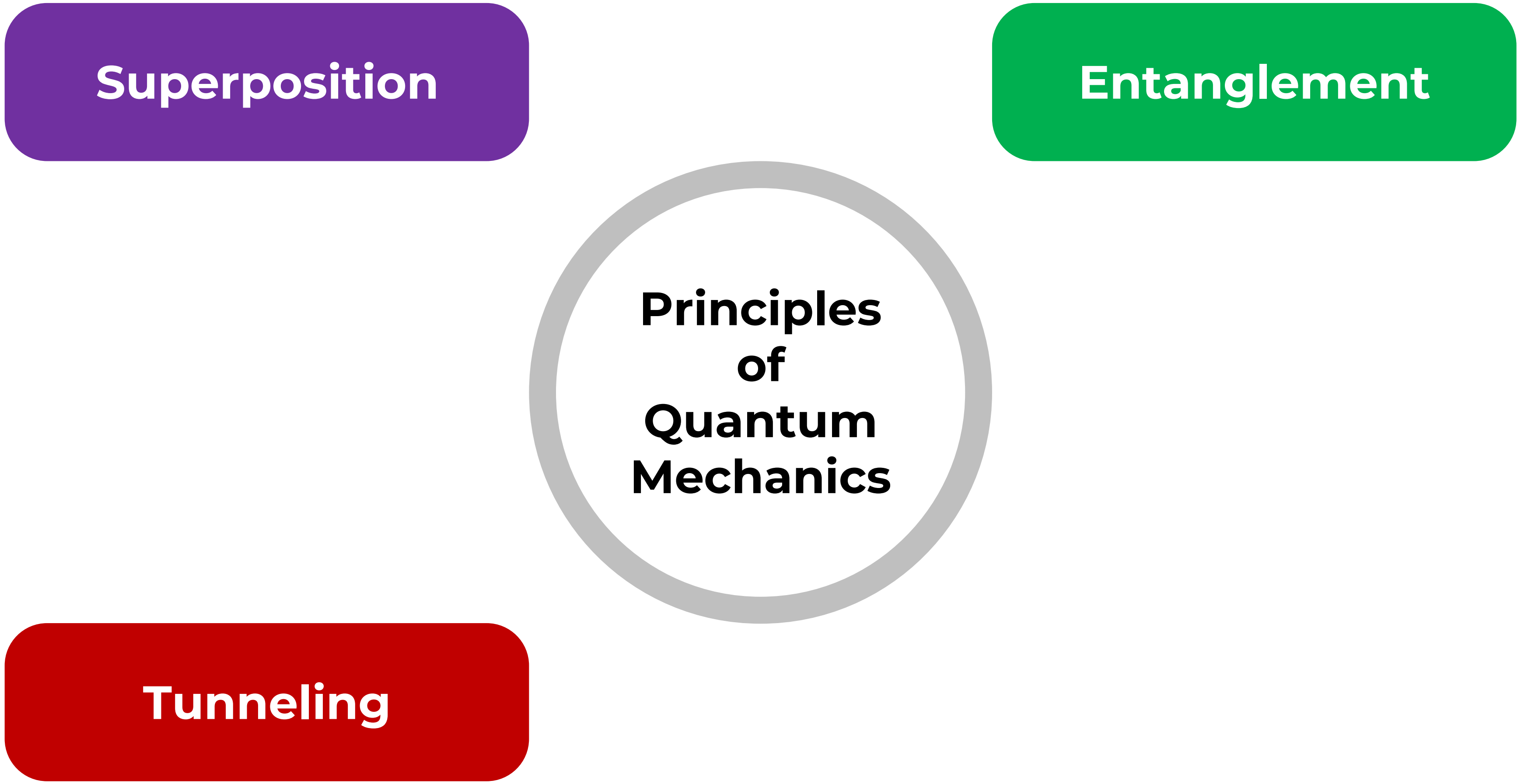
Superposition

Principles of Quantum Mechanics

Principles of Quantum Mechanics



Principles of Quantum Mechanics



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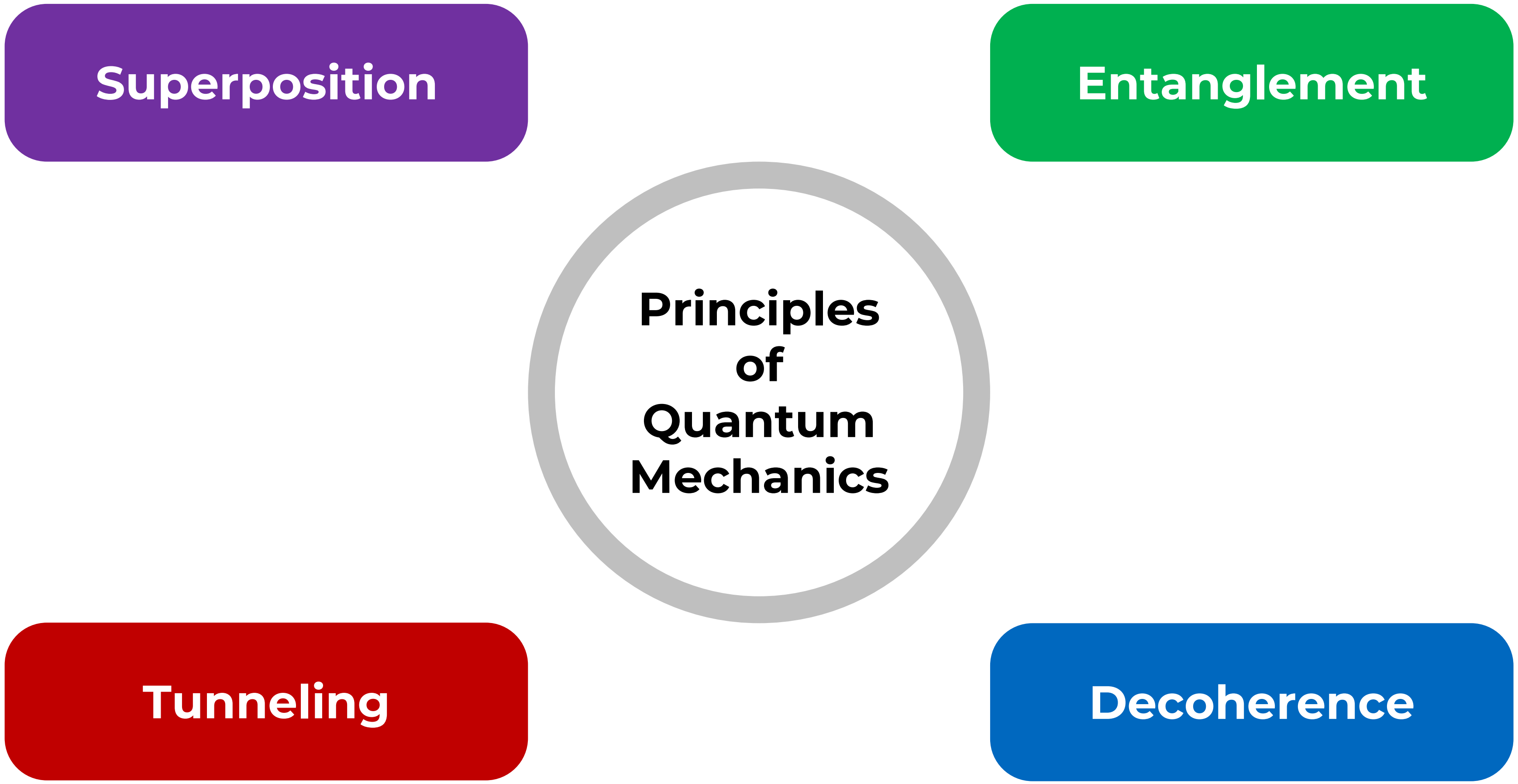

What makes a Quantum Computer fast?

Classical Computing	Quantum Computing
With **n bits** you can run up to **n operations** at the same time	With **n qubits** you can run up to **2^n operations** at the same time

How is a Quantum Computer made?

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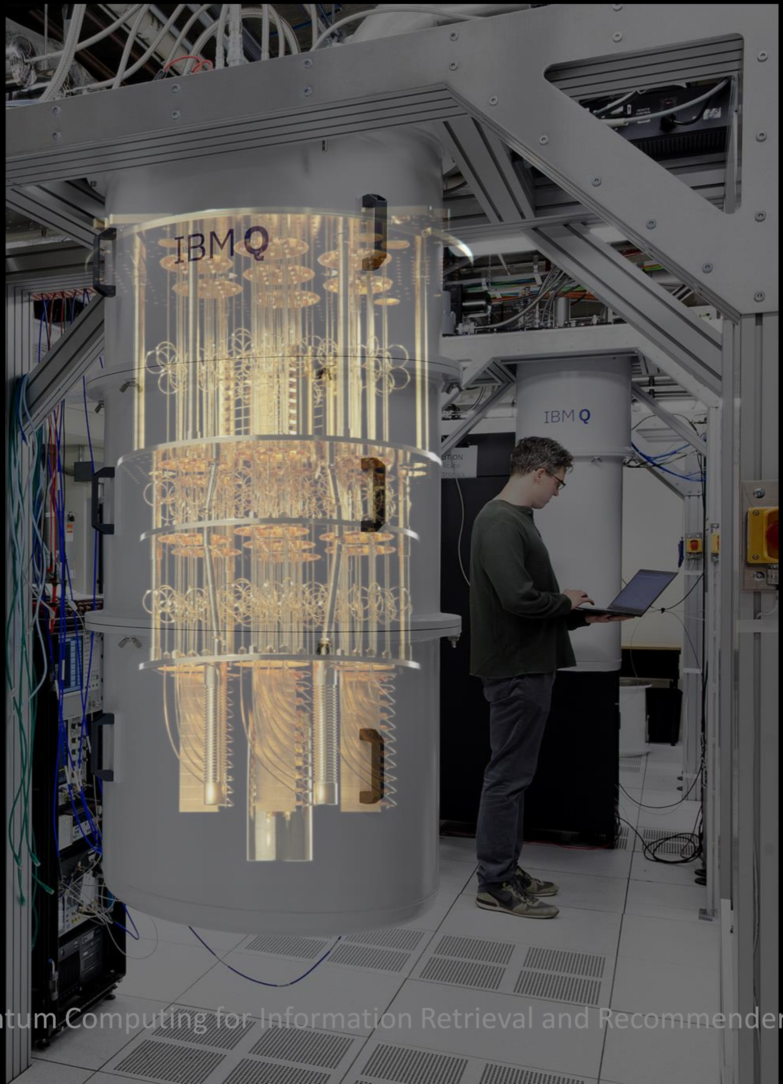

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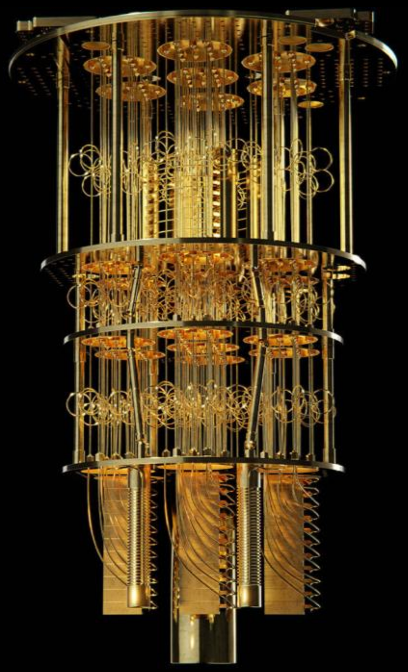
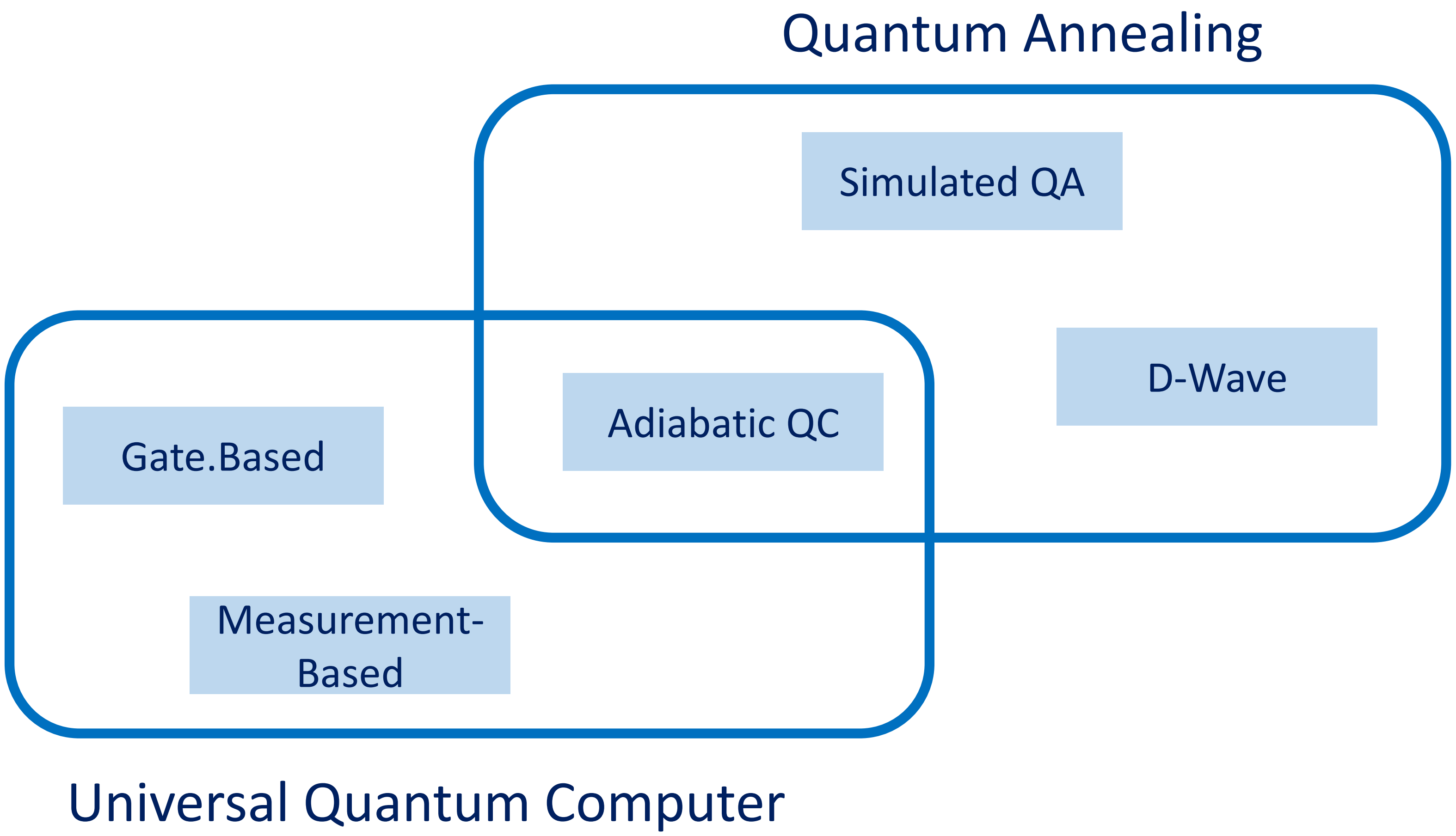


Quantum Computing Models and Architectures: how do you manipulate qubits …



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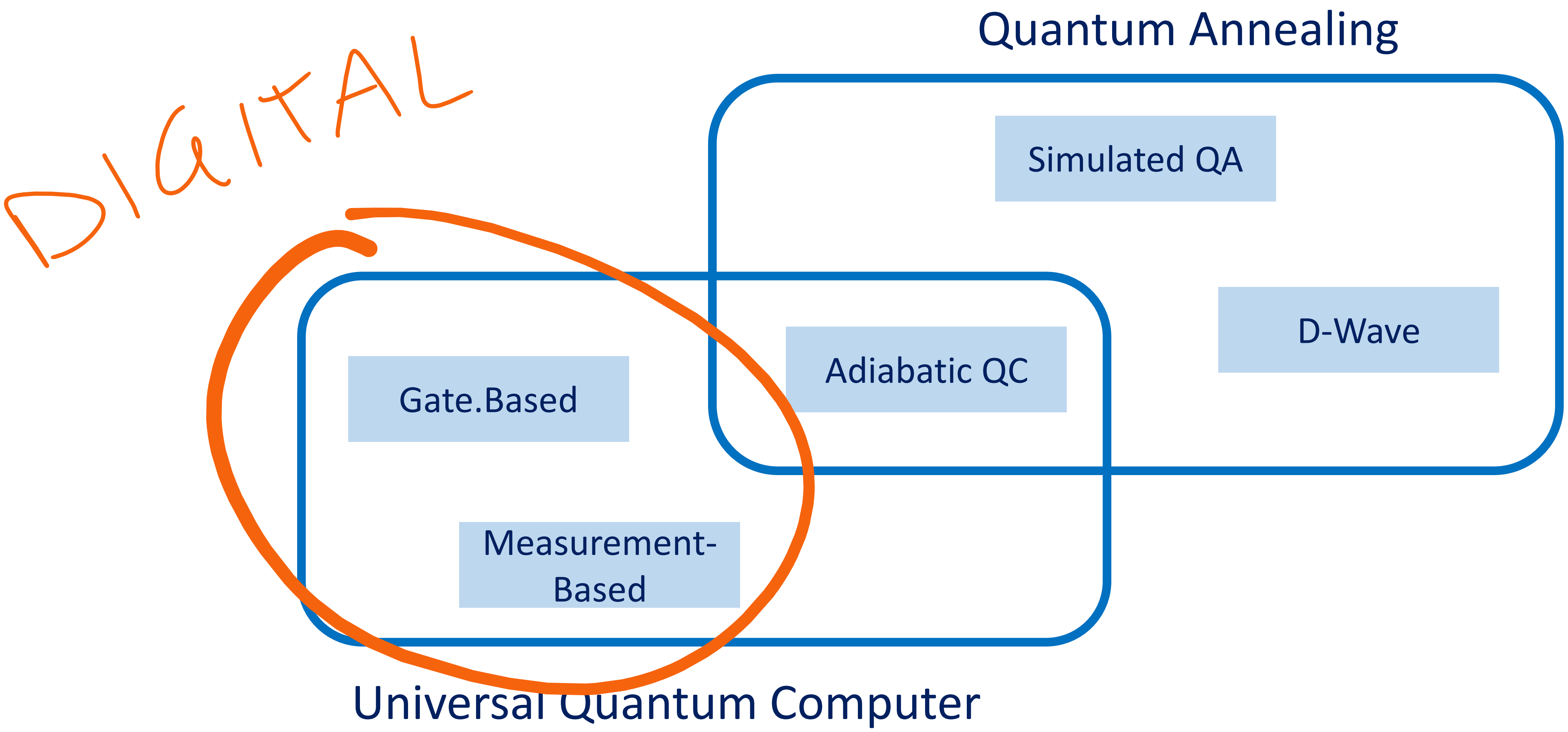

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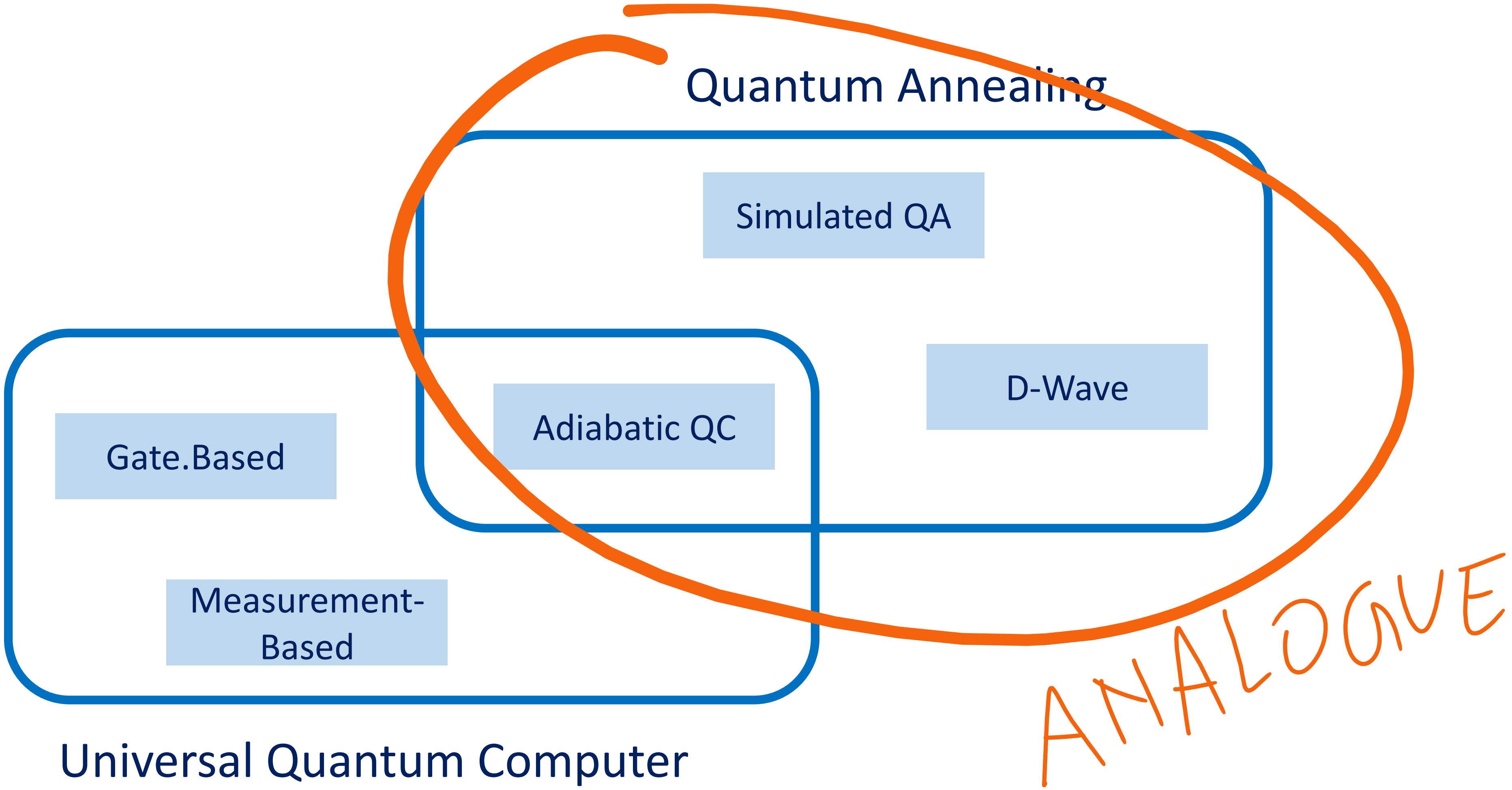
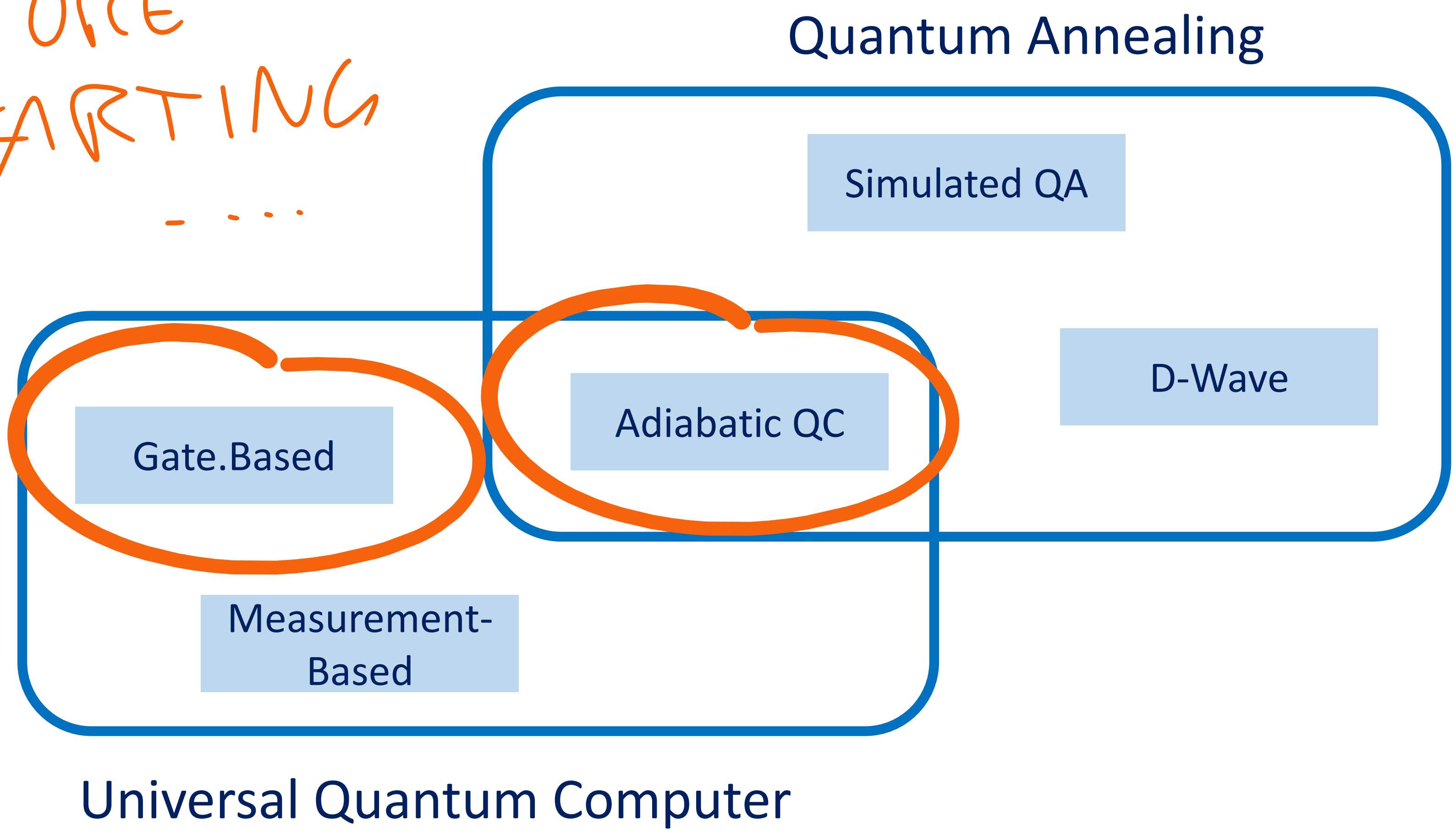


Quantum Computing Models and Architectures: how do you manipulate qubits ...

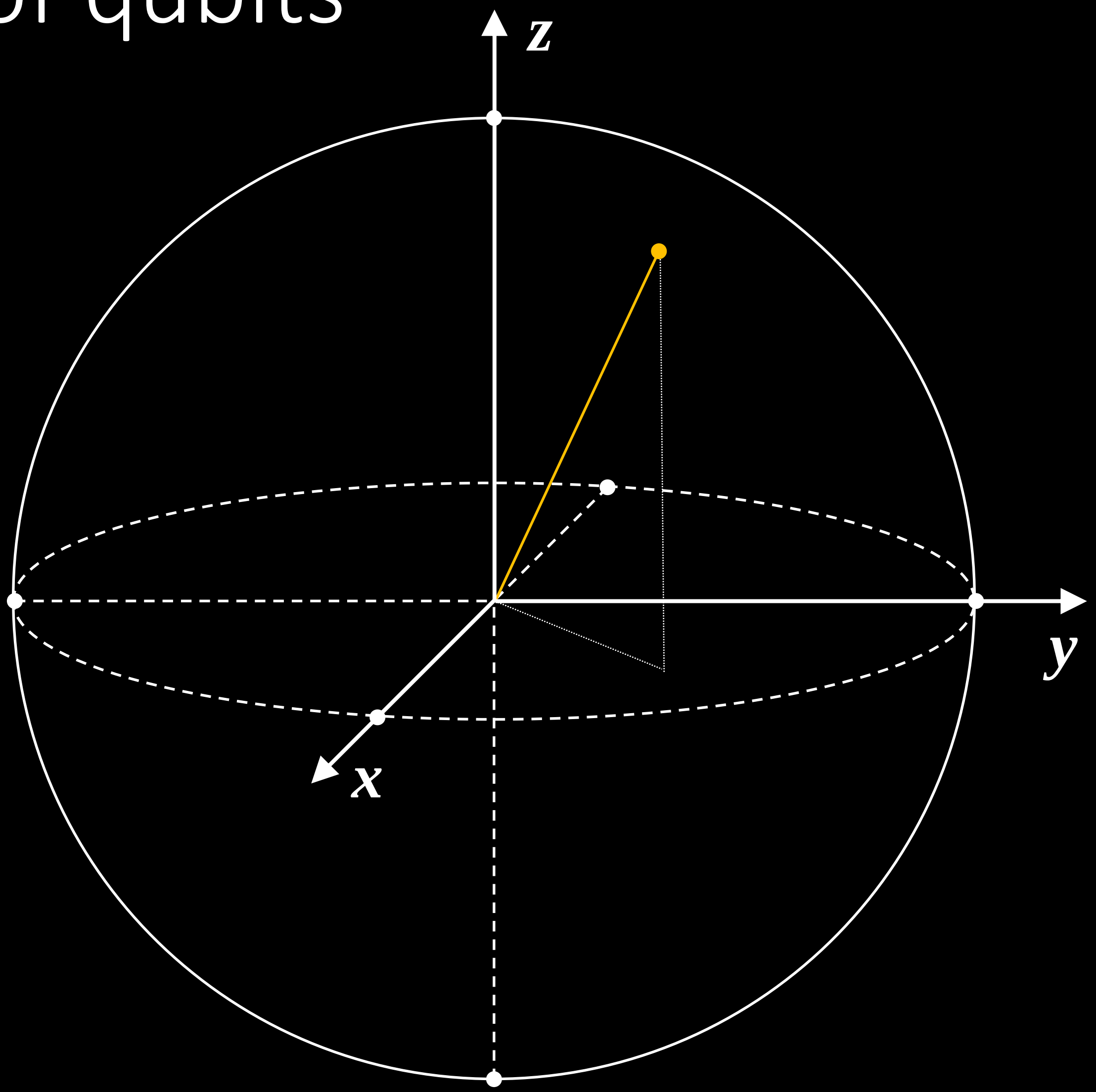
BEFORE STARTING ...



(Scary) Introduction to Quantum Computing

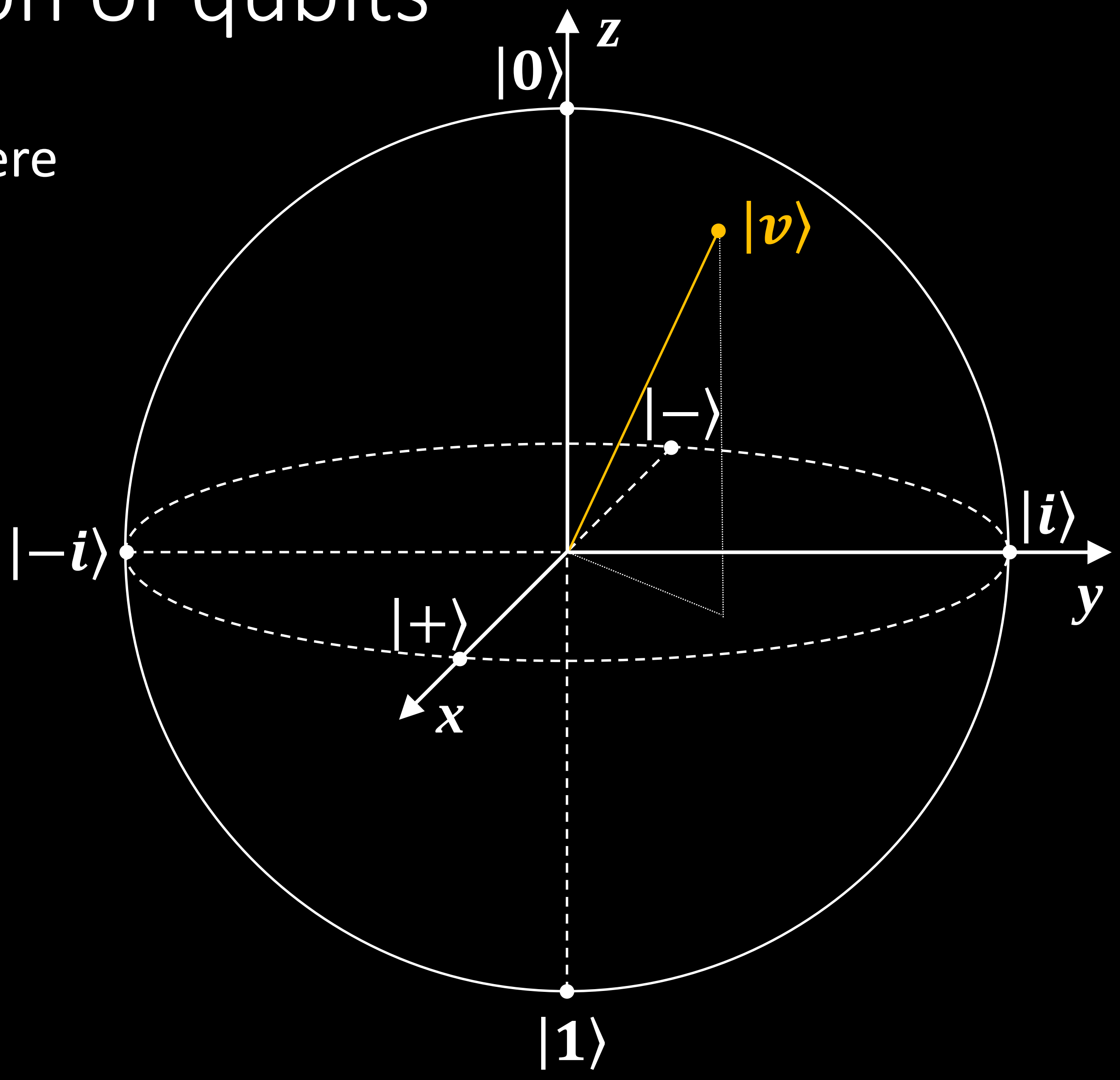
Bloch sphere representation of qubits

- Qubits can take infinite values on the sphere



Bloch sphere representation of qubits

- Qubits can take infinite values on the sphere
- Special values for qubits
- $|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$
- $|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$
- $|+\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$
- $|-\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \end{pmatrix}$



Dirac’s notation:

- Writing QC algorithms mostly reduce to manipulate **unitary** matrices and vectors (of complex numbers)
- Dirac's notation (also know as **bra-ket** notation): compact notation for the most common manipulations that happens in QC algos

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- **ket** = $|v\rangle \leftrightarrow \vec{v}$ (column vector)
- **bra** = $\langle v| \leftrightarrow \vec{v}^H$ (row vector)
- $\langle x|y\rangle \leftrightarrow \vec{x}^H \cdot \vec{y}$ (scalar product between vectors $\vec{x}$ and $\vec{y}$)
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Adiabatic Quantum Computing & Quantum Annealing

Adiabatic Quantum Computing (AQC)

- Instead of building a circuit to do what we want, one operation at a time, we leverage the natural tendency of a physical system to evolve towards (and remain into) a state of minimal energy
- Adiabatic process
  - a process occurring without transferring energy or mass with the systems surroundings
- The adiabatic theorem for the evolution of a quantum system states that
  - if there is an **energy gap** between the ground state and other states

    and
  - if the evolution of the system in time is **sufficiently slow**

    then
  - the system remains in a state of minimal energy (ground state)

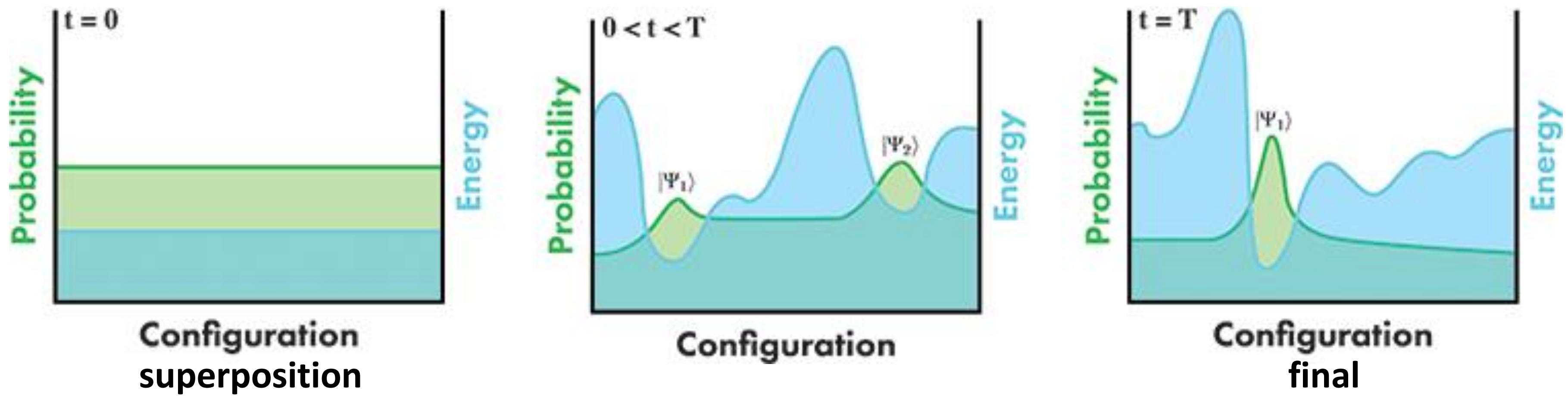
AQC: The idea

- I have a problem to solve which I can represent as the energy of a quantum system called the Hamiltonian
  - the minimum energy state (**ground state**) corresponds to the **solution** I want
  - it is difficult to find
- I can evolve a quantum system maintaining it in a minimum energy state

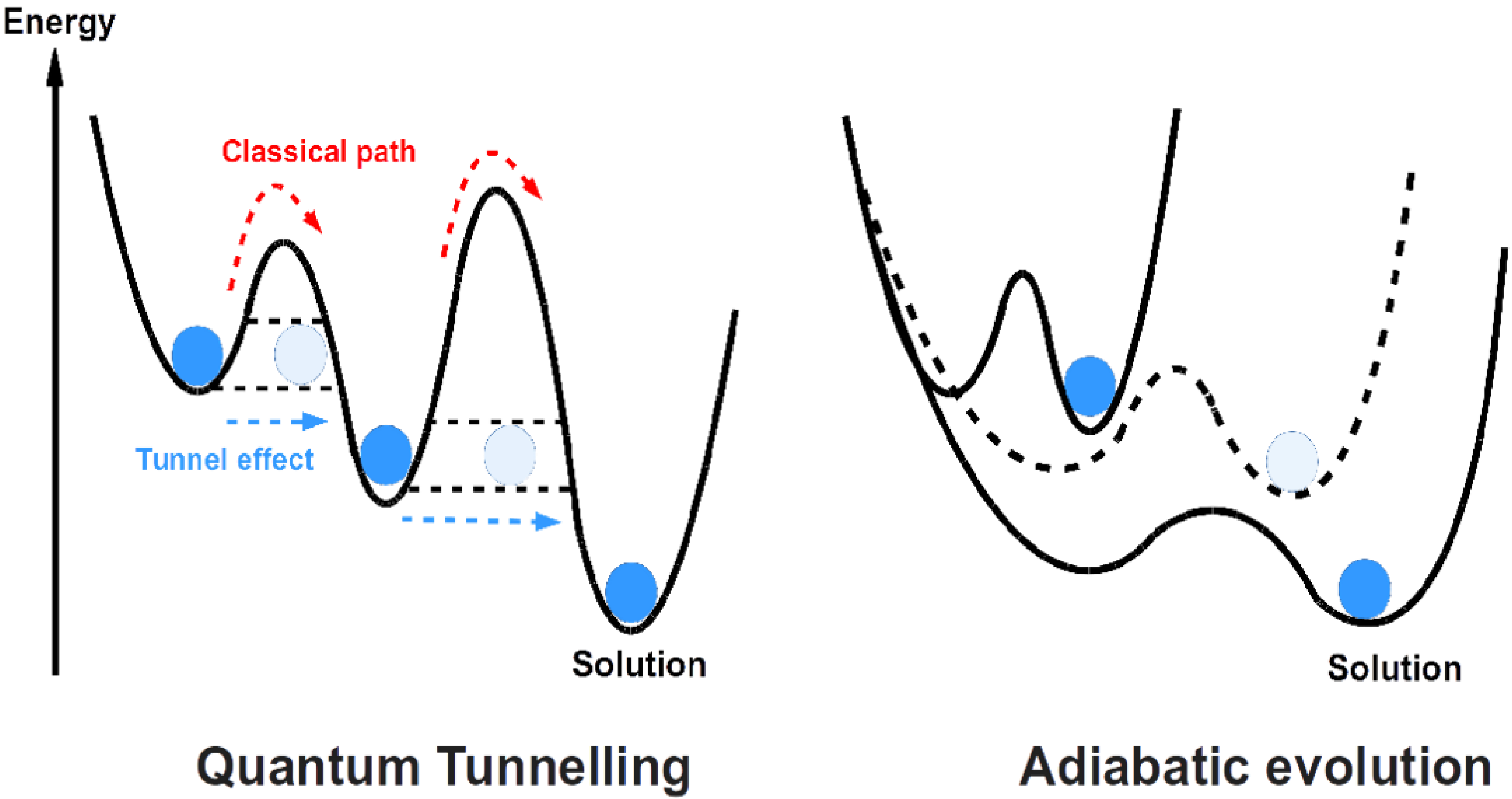
adiabatic condition: slow evolution

AQC: Procedure

- Start from an **initial** configuration (**superposition**) in which we can easily find the ground state
- **Slowly** alter the system to include the problem I want to solve while reducing the weight of the initial configuration
- Once the initial configuration weight goes to zero, the system only depends on the problem I want to solve, and it remains in the ground state



Quantum Annealing vs. Adiabatic Evolution



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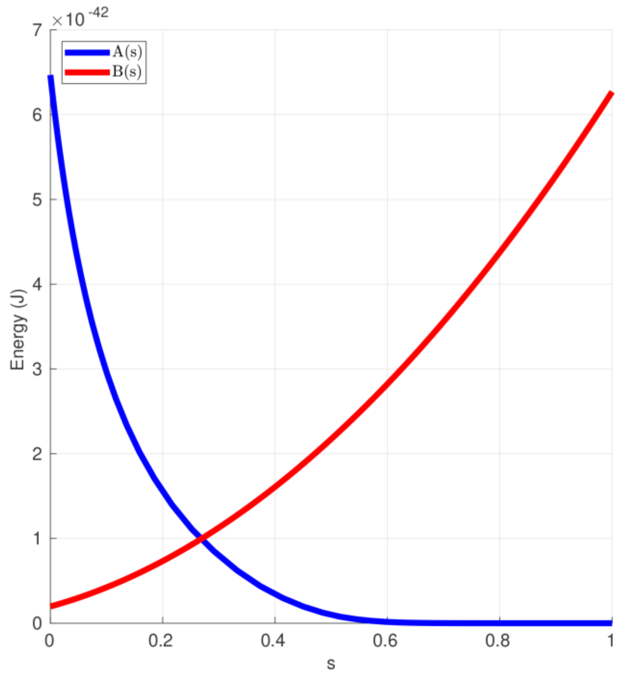
Time-dependent Hamiltonian

- The energy of a quantum system can be represented by a time dependent Hamiltonian
- which is composed by two terms

$$H(t) = A(t)H_A + B(t)H_B$$

- Here H_A and H_A represent the two Hamiltonians for the initial state (A) and the problem that we want to solve (B)
- $\boldsymbol{A(t)}$ and $\boldsymbol{B(t)}$ control the weight of the two Hamiltonians over time
  - analogous to the temperature schedule used in Simulated Annealing



Ising model and QUBO problems

- Currently available QA hardware uses Hamiltonian that describes an Ising model
- The Ising model describe the interactions between qubits z

$$H_B = \sum_i h_i z_i + \sum_{i>j} J_{i,j}\, z_i z_j$$

- where h_i represents a bias on qubit *i* and $J_{i,j}$ describes the coupling strength between qubits *i* and *j*
- A problem can be described by setting the values of h_i and $J_{i,j}$
- The Ising Hamiltonian describes a quadratic unconstrained binary optimization problem (**QUBO**)

Ising model and QUBO problems

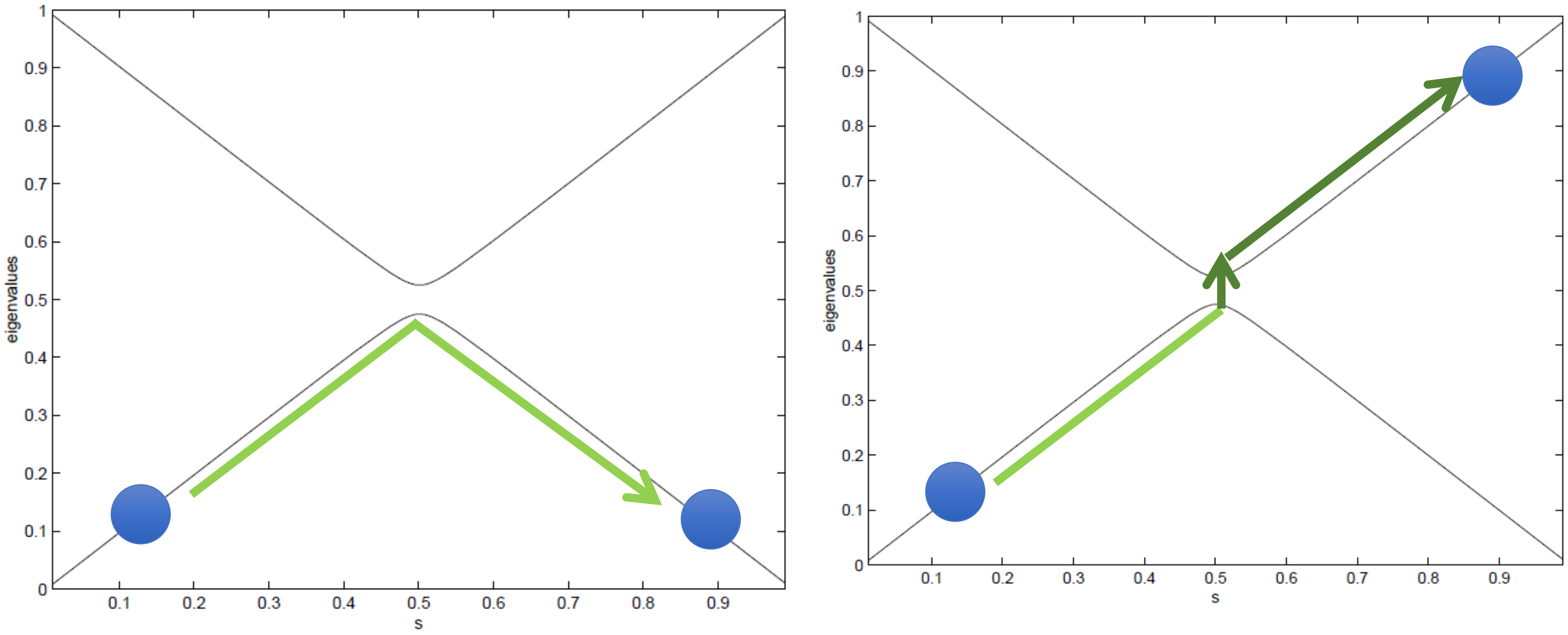
- With a change of variables, it is possible to show that the Ising problem is equivalent to a Quadratic Unconstrained Binary Optimization problem (**QUBO**)

$$\underset{\boldsymbol{x}}{\operatorname{argmin}} \left(\sum_{i} a_i \, x_i + \sum_{i \geq j} Q_{i,j} \, x_i x_j \right) = \underset{\boldsymbol{x}}{\operatorname{argmin}} \, \boldsymbol{x}^T Q \boldsymbol{x}$$

- The problem is often represented in terms of spins $s_i \in \{-1, +1\}$
- We can easily transform the problem formulation from spins $s_i \in \{-1, +1\}$ to binary variables $x_i \in \{0,1\}$

$$x_i = \frac{1}{2} s_i + \frac{1}{2}$$

The Eigenspectrum



Remains in the ground state

Jumps into a higher energy state
“Landau–Zener” transition
due to heat or evolution too fast

AQC vs. Quantum Annealing

- Adiabatic QC leverages quantum tunneling, just as Quantum Annealing, and in general has a wider computational power

- Adiabatic convergence is stricter than QA, so the first implies the latter
  - adiabatic QC is a specific type of QA, which is also universal

- Quantum Annealing evolves the same Hamiltonian but relaxes some of the stringent requirements of the adiabatic theorem.

Quantum Annealing and D-Wave

- Adiabatic Quantum Computing is equivalent to quantum circuit model (universal)
- D-Wave QPU
  - **non-positive real off-diagonal elements** of the Ising formulation *J*
  - as such, is not not universal
- D-Wave QPU
  - coupling every qubit to every other qubit is physically impractical
  - *J* must be very sparse …
- One of the most immediate consequences is that we cannot rely on a single measurement, but we need to run the experiment multiple times to account for the impact of both the noise and the limited evolution schedule
- We use QA to do **sampling** from a “distribution”

Thanks