Quantum Computing

Lecture 2

Ahmed Abdelmotteleb

University of Warwick

ahmed.abdelmotteleb@cern.ch

iCSC 2023 – CERN

8th of March 2023

“The history of the universe is, in effect, a huge and ongoing quantum computation. The universe is a quantum computer.”

-Seth Lloyd

Mathematical aside 2 – Matrix Operations

- Quantum theory is **unitary**, a unitary matrix U is such that $\boxed{U^{\dagger}U = I_n,}$ where I_n is the identity matrix and n represents the dimension of the square matrix U

† = Hermitian conjugate

$$\boxed{e.g. I_2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}}$$

- $U^{\dagger}$ (U-dagger) is the transposed, complex-conjugated version of the matrix U

- Let $U = \begin{pmatrix} U_{00} & U_{01} \\ U_{10} & U_{11} \end{pmatrix}$, $U^{\dagger} = \begin{pmatrix} U_{00}^{*} & U_{10}^{*} \\ U_{01}^{*} & U_{11}^{*} \end{pmatrix}$ $(a = 2 - 3i \rightarrow a^{*} = 2 + 3i)$

- Can express U in Dirac notation as follows:

$$U = \begin{pmatrix} U_{00} & U_{01} \\ U_{10} & U_{11} \end{pmatrix} = U_{00}|0\rangle\langle 0| + U_{01}|0\rangle\langle 1| + U_{10}|1\rangle\langle 0| + U_{11}|1\rangle\langle 1|$$

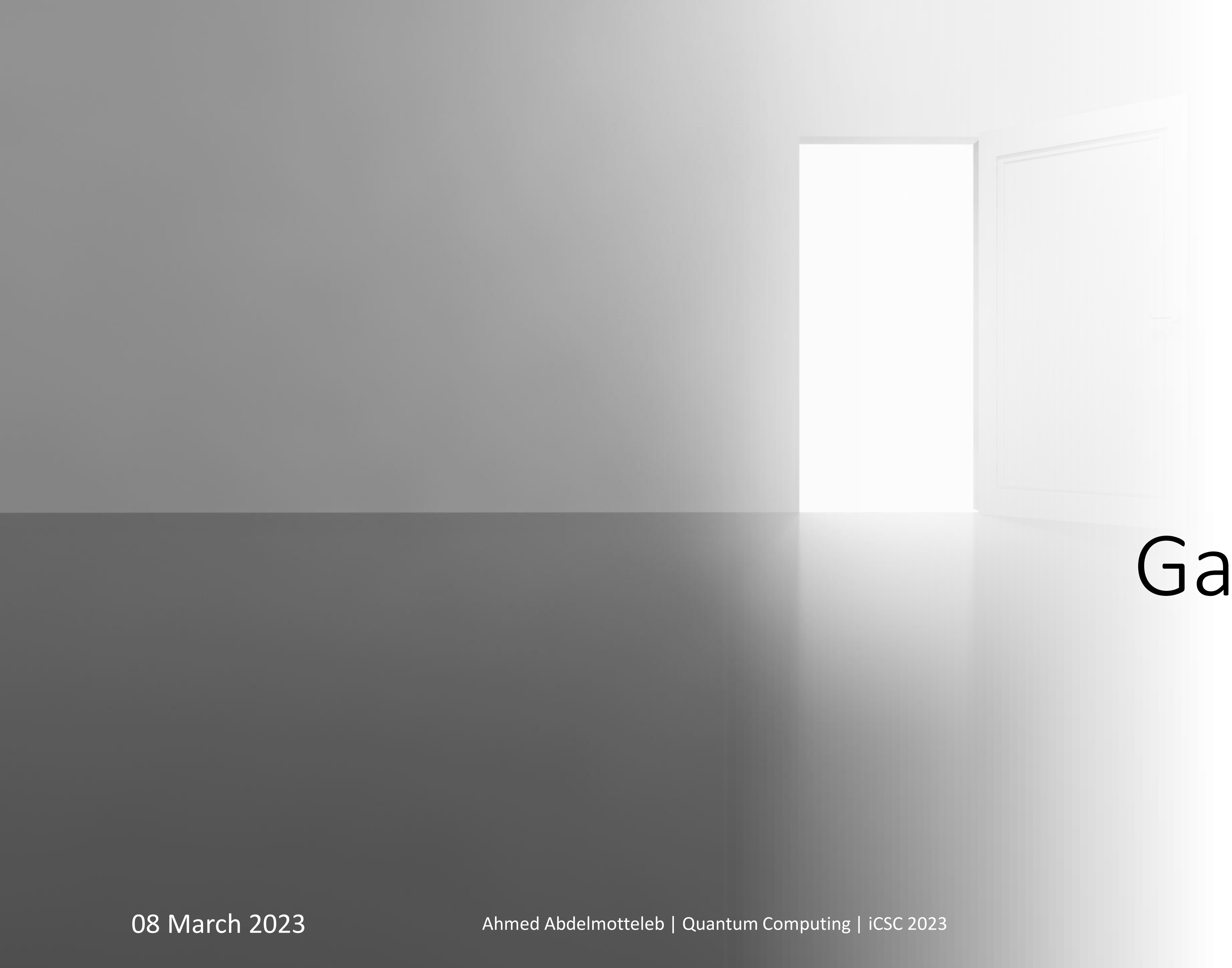
e.g. $U = \begin{pmatrix} 5 & 6 \\ 7 & 8 \end{pmatrix} = 5|0\rangle\langle 0| + 6|0\rangle\langle 1| + 7|1\rangle\langle 0| + 8|1\rangle\langle 1|$

Matrix Operations - continued

- Recap on how to multiply two 2x2 matrix with a 2x1 matrix (2D-vector):
- A = $\begin{pmatrix} 1 & 2 \\ 3 & 4 \end{pmatrix}$ B=$\begin{pmatrix} 5 \\ 6 \end{pmatrix}$
- AB = $\begin{pmatrix} 1 & 2 \\ 3 & 4 \end{pmatrix}\begin{pmatrix} 5 \\ 6 \end{pmatrix}$

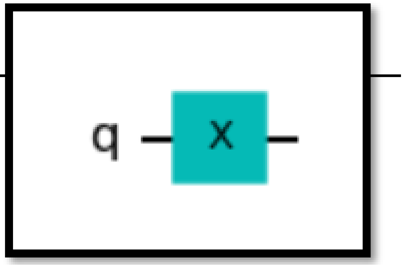
$$= \begin{pmatrix} 1.5 + 2.6 \\ 3.5 + 4.6 \end{pmatrix}$$

$$= \begin{pmatrix} 17 \\ 39 \end{pmatrix}$$



Gates

Quantum Logic Gates (qubit gates)



- Quantum computing relies on **quantum circuits**

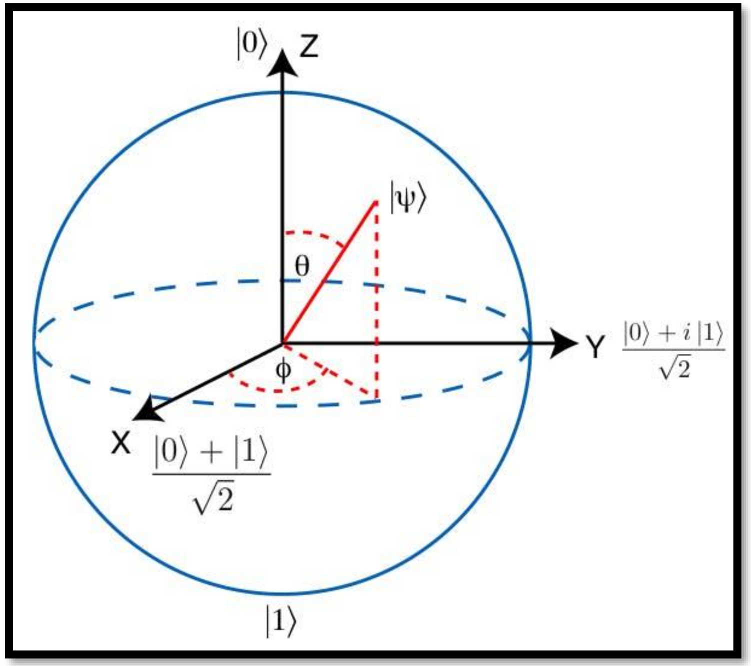
- A quantum circuit is a sequence of blocks or gates that carry out computations (input-output)

- A quantum gate is represented by unitary matrices ($U^{\dagger}U = I_n$)

- **Pauli (spin) matrices (gates):** $\sigma_x, \sigma_y, \sigma_z$
- $\boxed{\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} = |0\rangle\langle 1| + |1\rangle\langle 0|}$

   - ➢ $\sigma_x|0\rangle = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} = |1\rangle$

   - ➢ $\sigma_x|1\rangle = (|0\rangle\langle 1 + |1\rangle\langle 0|).|1\rangle = |0\rangle\overbrace{\langle 1|1\rangle}^{1}+|1\rangle\cancelto{0}{\langle 0|1\rangle} = |0\rangle$



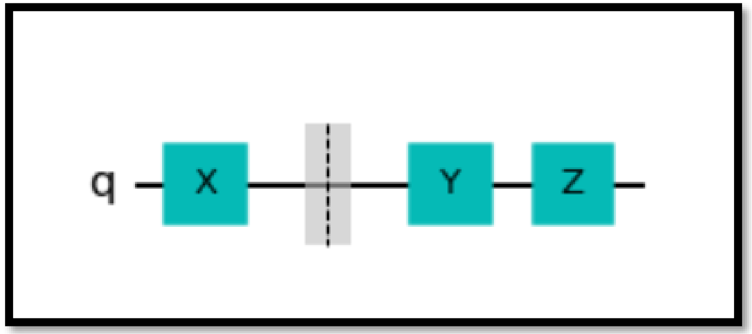
➡ **Bit flip (rotation about x-axis by π) (analogous to classic NOT gate)**

Quantum Logic Gates (qubit gates) - continued

- $\boxed{\sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} = |0\rangle\langle 0| - |1\rangle\langle 1|}$

  - $\sigma_z|+\rangle = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \end{pmatrix} = |-\rangle \quad (|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle))$

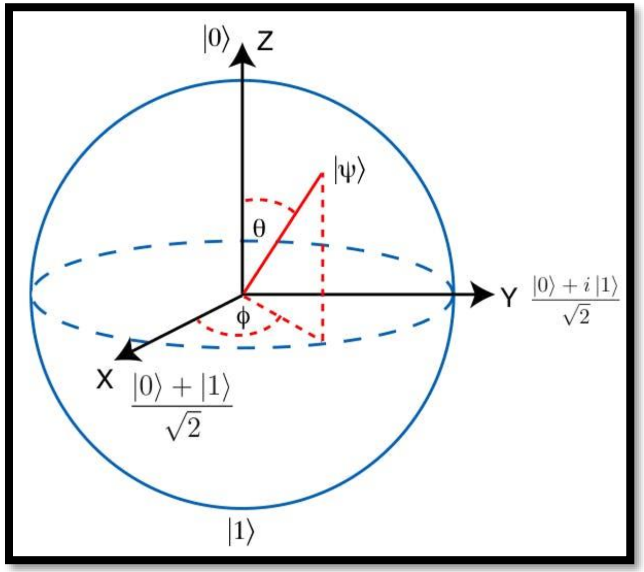
  - $\sigma_z|-\rangle = (|0\rangle\langle 0| - |1\rangle\langle 1|).\left(\frac{1}{\sqrt{2}}|0\rangle - |1\rangle\right) = \frac{1}{\sqrt{2}}|0\rangle + |1\rangle = |+\rangle$



Phase flip (rotation about z-axis by π)

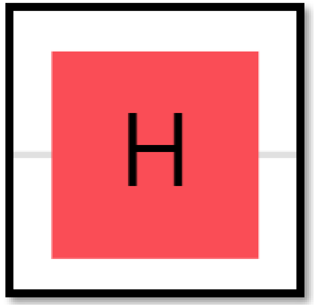
- $\boxed{\sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} = -i|0\rangle\langle 1| + i|1\rangle\langle 0| = i\sigma_x.\sigma_z}$

Bit and phase flip (rotation about y-axis by π)



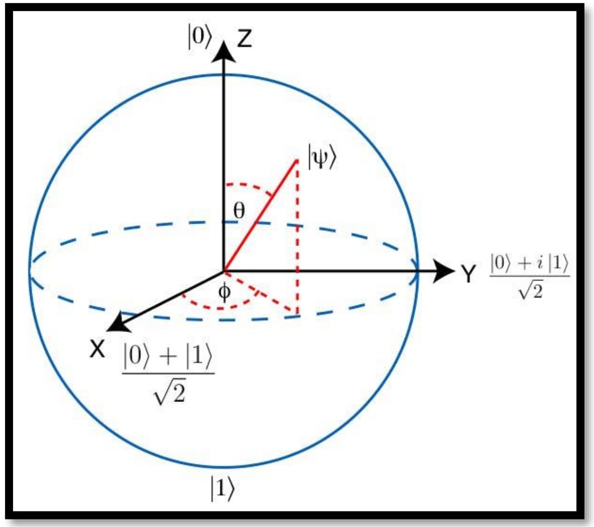
- $\sigma_i^2 = I_2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$, i.e. applying the same Pauli gate twice does nothing to a state

Quantum Logic Gates (qubit gates) - continued



Hadamard gate:

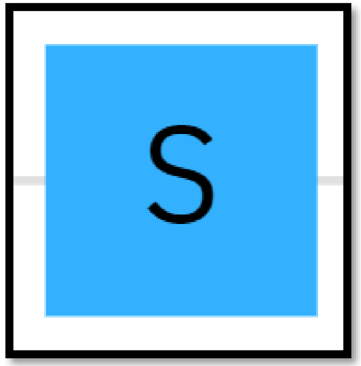
- Can be found in (almost) every quantum circuit
- $H = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} = \frac{1}{\sqrt{2}}(|0\rangle\langle 0| + |0\rangle\langle 1| + |1\rangle\langle 0| - |1\rangle\langle 1|)$
  - $H|0\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}\begin{pmatrix} 1 \\ 0 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix} = |+\rangle$
  - $H|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle\langle 0| + |0\rangle\langle 1| + |1\rangle\langle 0| - |1\rangle\langle 1|).|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) = |-\rangle$
  - $H|+\rangle = |0\rangle$ $\qquad$ $H|-\rangle = |1\rangle$



➡ **Creates and destroys superposition (switch between z and x bases)**

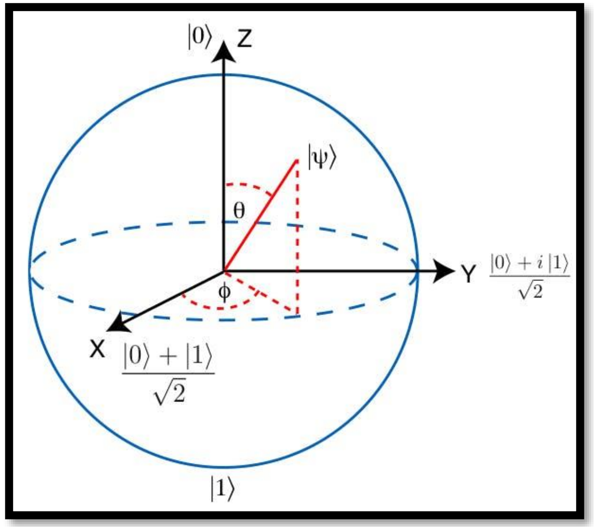
Quantum Logic Gates (qubit gates) - continued

S gate:



- $S = \begin{pmatrix} 1 & 1 \\ 1 & i \end{pmatrix} = |0\rangle\langle 0| + |0\rangle\langle 1| + |1\rangle\langle 0| + i|1\rangle\langle 1|$
  - ➢ $S|+\rangle = |i\rangle$ $S|-\rangle = |-i\rangle$

Adds 90° to the phase φ (switch between x and y bases)



- $\boldsymbol{S.H}$ allows us to **switch between z and y bases**

https://javafxpert.github.io/grok-bloch/

Two qubits and tensor products

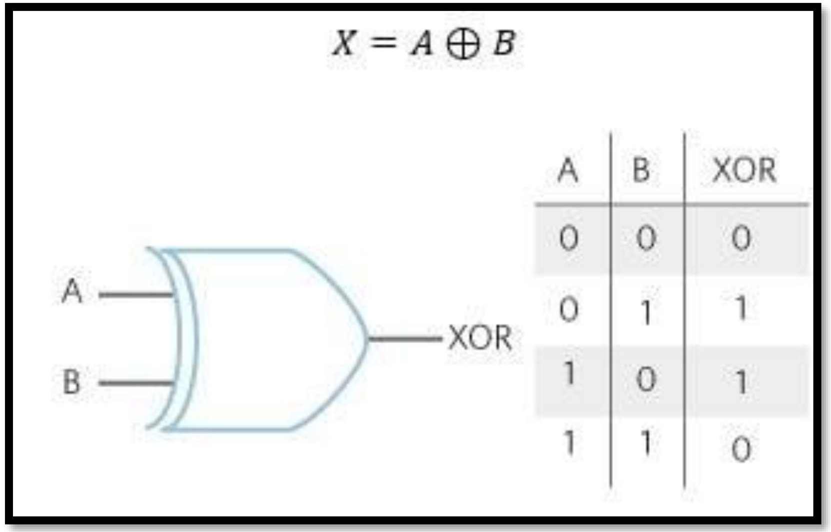
$$|00\rangle = \begin{pmatrix}1\\0\\0\\0\end{pmatrix} \qquad |01\rangle = \begin{pmatrix}0\\1\\0\\0\end{pmatrix} \qquad |10\rangle = \begin{pmatrix}0\\0\\1\\0\end{pmatrix} \qquad |11\rangle = \begin{pmatrix}0\\0\\0\\1\end{pmatrix}$$

- $\langle e|d\rangle = \langle ed\rangle -$ inner product
- $|d\rangle\langle e| = |de| -$ outer product
- $|d\rangle|e\rangle = |d\rangle\otimes|e\rangle = |de\rangle -$ tensor product

e.g. $|0\rangle_1|0\rangle_2 = |0\rangle_1\otimes|0\rangle_2 = |0_1 0_2\rangle$

Two qubit gates

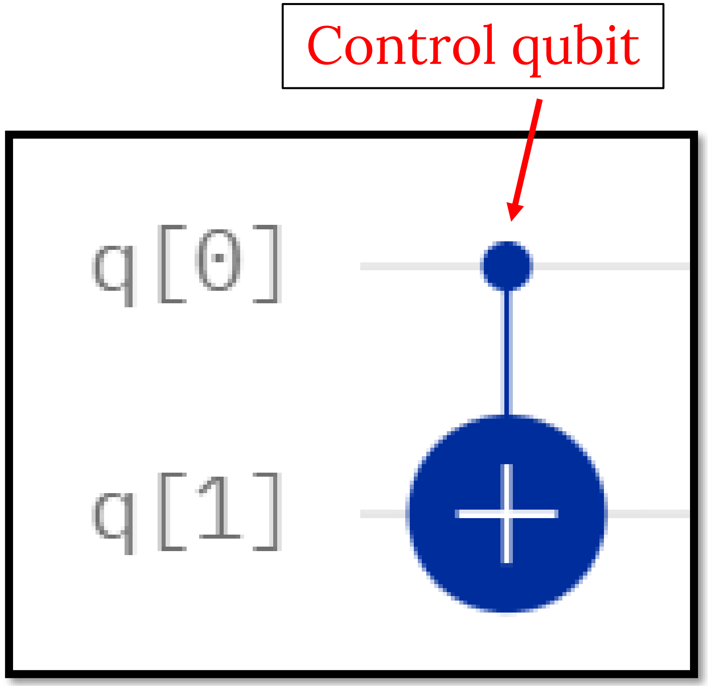
CNOT gate:



$X = A \oplus B$

A	B	XOR
0	0	0
0	1	1
1	0	1
1	1	0

Input		Output	
x	y	x	x⊕y
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0



Control qubit

- Note that a classical XOR gate is non-reversible
- However, since all quantum gates are unitary, they are, in fact, **reversible**
- CNOT stands for Controlled-NOT. The qubit in control does not change by the gate

Two qubit gates - continued

CNOT gate:

- $CNOT = \begin{array}{c|cccc} & 00 & 01 & 10 & 11 \\ \hline 00 & 1 & 0 & 0 & 0 \\ 01 & 0 & 1 & 0 & 0 \\ 10 & 0 & 0 & 0 & 1 \\ 11 & 0 & 0 & 1 & 0 \end{array} = |00\rangle\langle 00| + |01\rangle\langle 01| + |10\rangle\langle 11| + |11\rangle\langle 10|$

  - ➢ $CNOT|00\rangle = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}\begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} = |00\rangle$

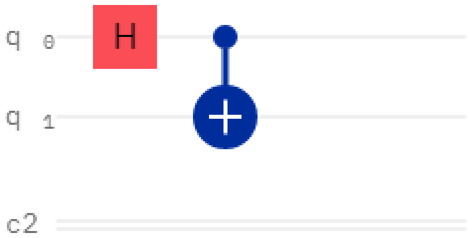
  - ➢ $CNOT|10\rangle = (|00\rangle\langle 00| + |01\rangle\langle 01| + |10\rangle\langle 11| + |11\rangle\langle 10|).|10\rangle$

$$|00\rangle\cancel{\langle 00|10\rangle} + |01\rangle\cancel{\langle 01|10\rangle} + |10\rangle\cancel{\langle 11|10\rangle} + |11\rangle\langle 10|10\rangle$$
$$= |11\rangle$$

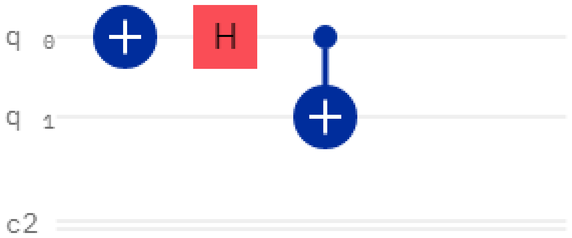
Bell states

- 4 states (2 qubits) that are **maximally-entangled** and build an **orthonormal basis**

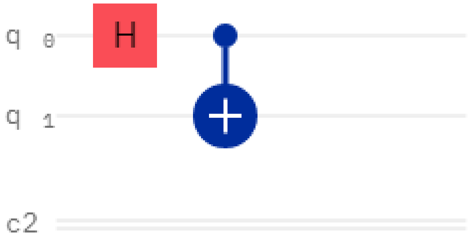
$$|\psi^{00}\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$



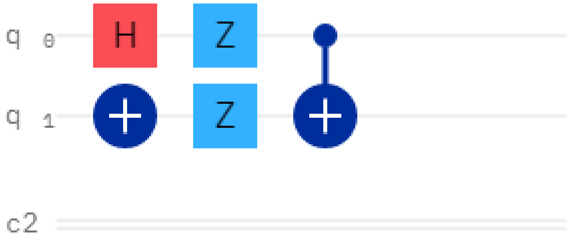
$$|\psi^{01}\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$



$$|\psi^{10}\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$$



$$|\psi^{11}\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$



More entanglement

$\boxed{|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)}$ → Global state

$|\psi_1\rangle = \alpha_1|0\rangle + \beta_1|1\rangle$ ← local state → $|\psi_2\rangle = \alpha_2|0\rangle + \beta_2|1\rangle$

Given the global state, what are the local states?

$$|\psi_1\rangle\otimes|\psi_2\rangle = |\psi_1\psi_2\rangle = \boxed{\alpha_1\alpha_2|00\rangle} + \boxed{\alpha_1\beta_2|01\rangle + \beta_1\alpha_2|10\rangle} + \boxed{\beta_1\beta_2|11\rangle}$$

Therefore, require:

$\otimes$ – tensor product

- $\alpha_1\alpha_2 = \beta_1\beta_2 = \frac{1}{\sqrt{2}}$
- $\alpha_1\beta_2 = \beta_1\alpha_2 = 0$

⇒ $\alpha_1 = 0$ or $\beta_2 = 0$

Contradiction!

More entanglement - continued

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |10\rangle) = \frac{1}{\sqrt{2}}(|0\rangle\otimes|0\rangle + |1\rangle\otimes|0\rangle) = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)\otimes|0\rangle$$

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|10\rangle + |01\rangle) = \frac{1}{\sqrt{2}}(|1\rangle\otimes|0\rangle + |0\rangle\otimes|1\rangle) = ?$$

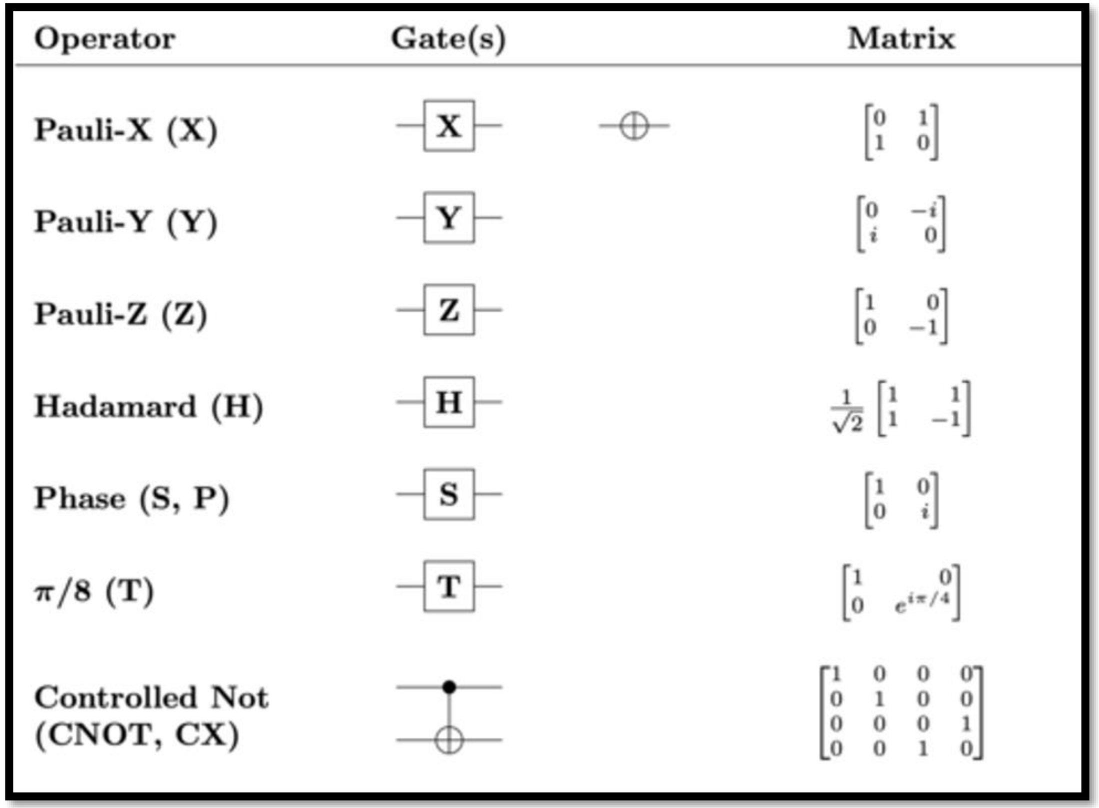
We have full knowledge of the global state,
but no knowledge of the local states.

→

Entanglement!

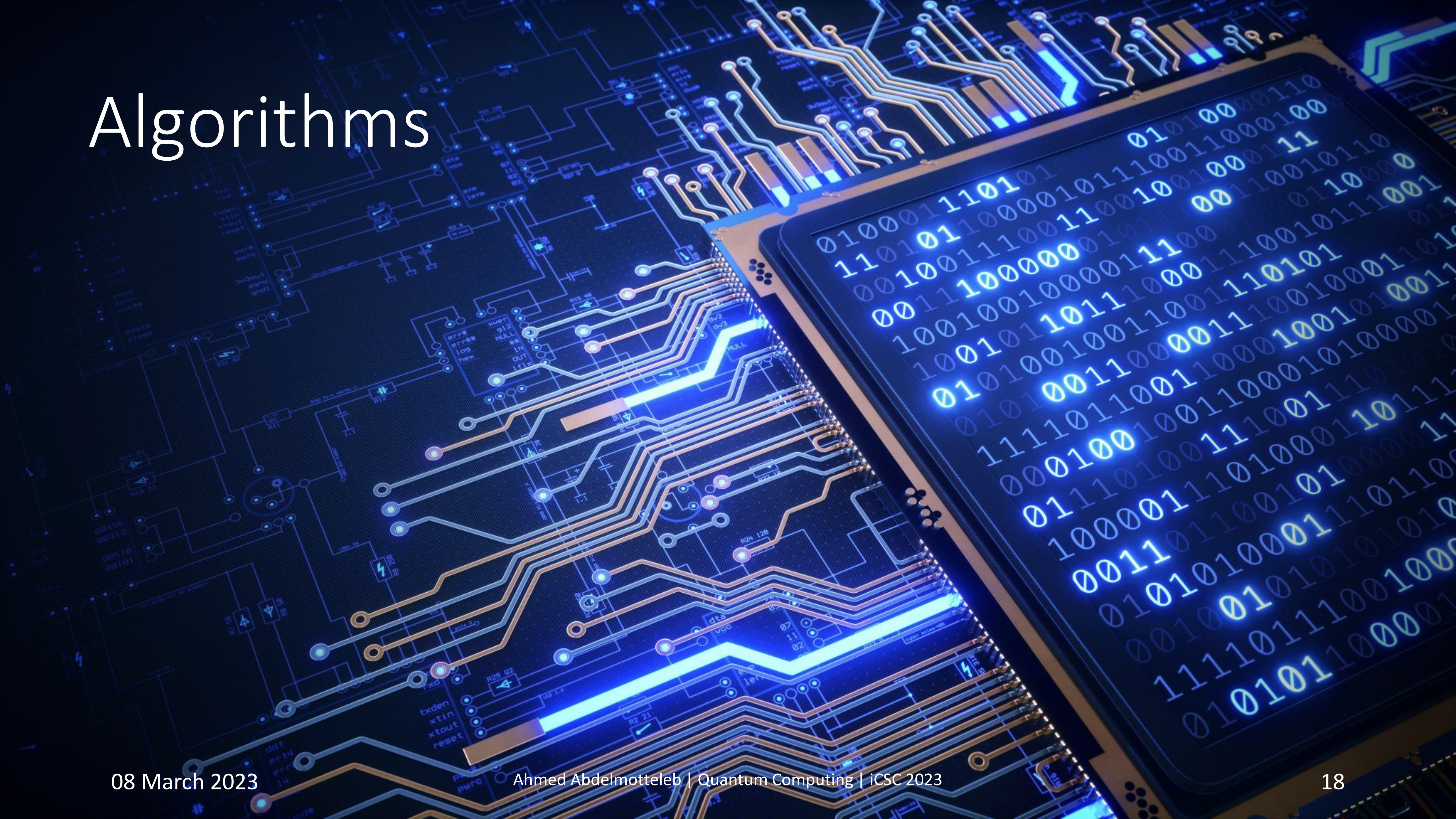
Gates summary

- Pauli (spin) matrices (gates) cause spins around x,y, or z axes of a Bloch sphere (bit or phase flip)
- Hadamard gates create and destroy superposition
- S gate(also in combination with H gate) switches between bases
- CNOT gates (2 qubit gate) help us achieve entanglement
- Bell states (4 of them – 2 qubits) are maximally-entangled and build an orthonormal bases
  → help you get a Nobel prize



Operator	Gate(s)		Matrix
Pauli-X (X)	X	⊕	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)	Y		$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)	Z		$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)	H		$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)	S		$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$ (T)	T		$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$
Controlled Not (CNOT, CX)	● ⊕		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$

Algorithms



Grover's Algorithm

- An (quantum) algorithm used to search and locate a specific element in an unordered list/unsorted database
- Imagine you have a list of 2 columns: name and phone number
- You have a phone number, and you want to find the corresponding name using this list
- Using a classical computer, you would need to use brute-forcing or some other method (not highly efficient)
- With Grover's algorithm and the superposition principle, one can exponentially decrease the time needed to find the phone number
- This process happens with the help of two sub-functions called the **oracle function** and the **amplification function**
- Other fun examples is solving a **sudoku puzzle** or **polynomial root** finding problems

Grover's Algorithm - continued

- Suppose you have 2 qubits, corresponding to 4 possibilities: 00, 01, 10, and 11

- All possible states can be described using this equation:

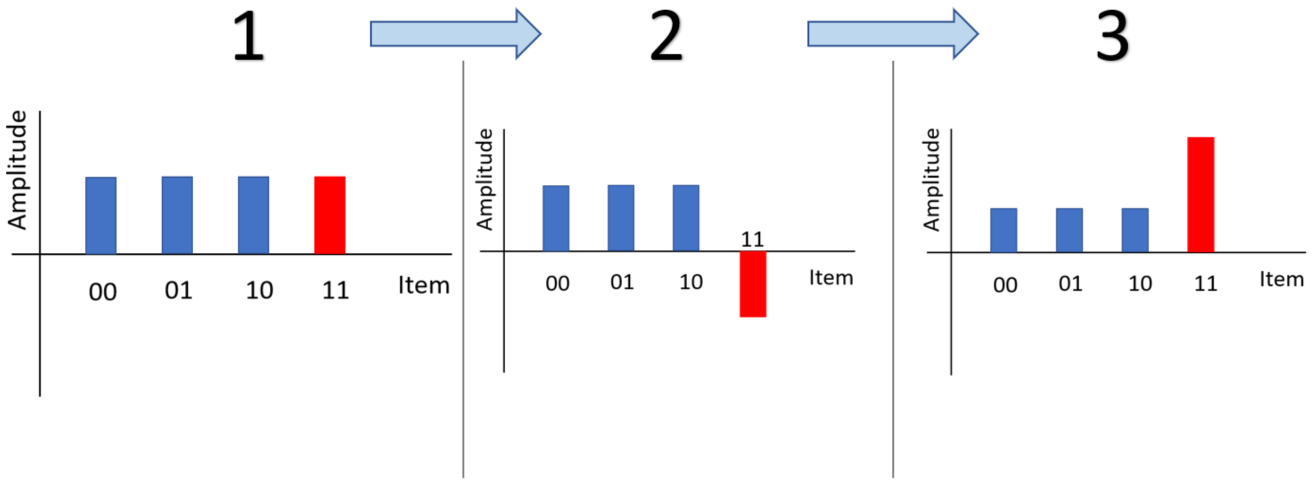
$$a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle,$$

where a, b, c, and d correspond to the amplitudes of the states (remember, probability of the state is the amplitude-squared)

- Assume for example that our phone number is associated with the state $|11\rangle$

- This means the associated amplitude of interest is "d"

Grover’s Algorithm - continued



- The oracle function **flips** the corresponding amplitude "d“ so that it becomes " $-d$“ ; a **unique amplitude**

- The amplification function **amplifies** the difference between the amplitude corresponding to the number we’re looking and the other amplitudes

- This makes the probability of locating the number much higher

- **Repeat** as many times as one pleases to further increase the probability

Grover’s Algorithm - demo

More details/explanations can be found here (Qiskit Textbook)

Cryptography

- Protecting information and communications using codes
- RSA cryptography utilizes **prime numbers** to securely encrypt data. It is fundamental for the operation of internet protocols
- Need to have the factors of a number to be able to decrypt data
- E.g. given the number a number $n = pq = 226{,}579$, try to find p, q, given that they are prime numbers (answer: $p = 419$, $q = 541$)
- Nowadays, we use **RSA-2048** which utilized a 2048 bit key (an integer on the order of 2^{2048})
- Estimated it would take a classical computer around **300 trillion years** to break an RSA-2048-bit encryption key

Example of an RSA-2048 integer

2519590847565789349402718324004839857142928212620403202777713783604366202070
7595556264018525880784406918290641249515082189298559149176184502808489120072
8449926873928072877767359714183472702618963750149718246911650776133798590957
0009733045974880842840179742910064245869181719511874612151517265463228221686
9987549182422433637259085141865462043576798423387184774447920739934236584823
8242811981638150106748104516603773060562016196762561338441436038339044149526
3443219011465754445417842402092461651572335077870774981712577246796292638635
6373289912154831438167899885040445364023527381951378636564391212010397122822
120720357

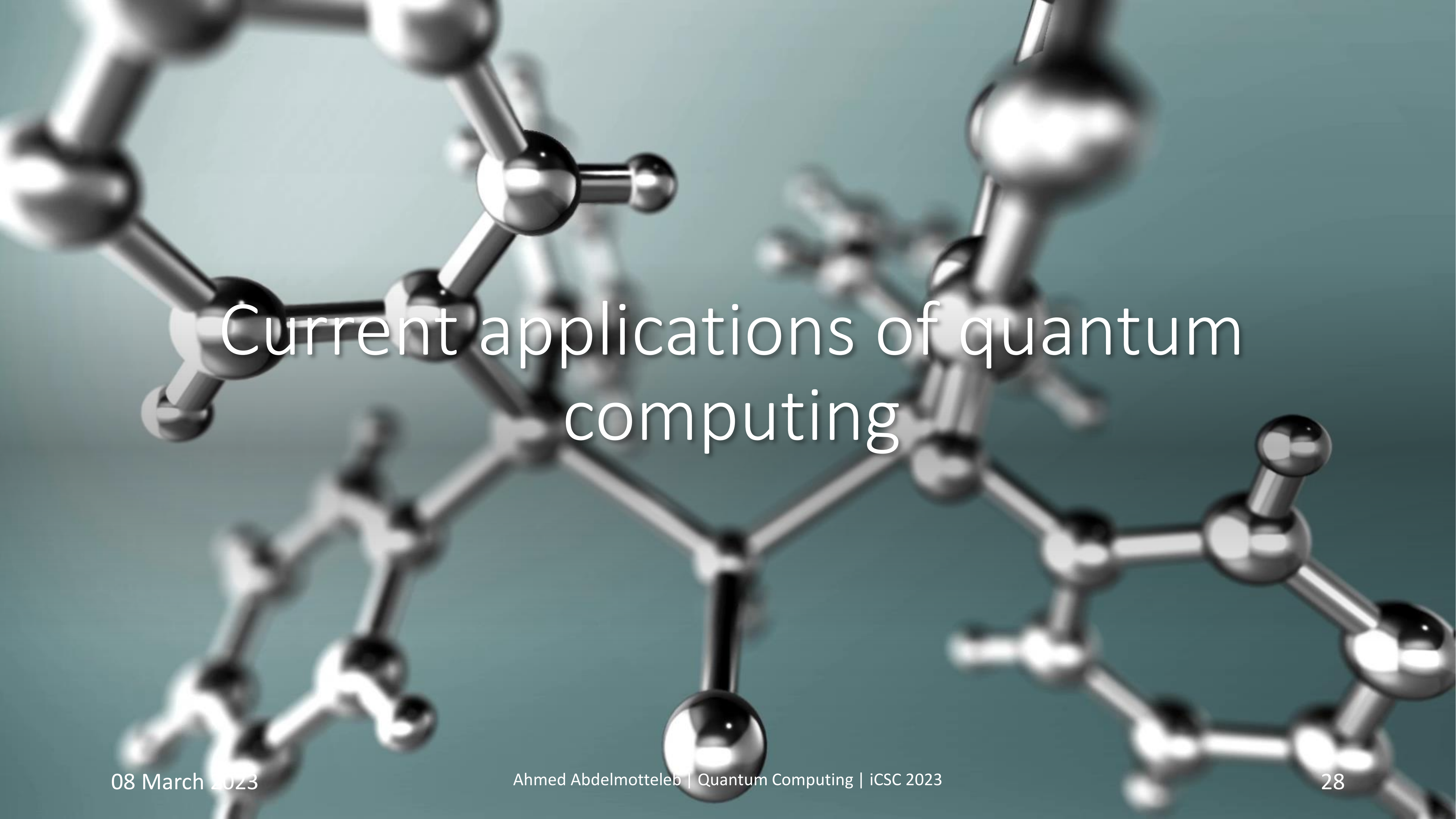

RSA Cryptosystem: *exists*
Quantum Computers:

(very basic) introduction to Shor's Algorithm

- By no means a proper explanation to how Shor's Algorithm works – actual explanation could take more than one lecture
- Using a perfect quantum computer, finding the factors of an RSA-2048-bit integer could take mere **seconds**
- The basic premise is that you setup a **special periodic function** (modulo function), with a period "*r*", which you try to obtain. This then leads you to obtaining the factors of the big number
- With **superposition**, you can test many values for the period simultaneously
- You use **interference** to zero-in on the correct value of the period (constructive interference) and reduce the probability of landing on the incorrect value (destructive interference)
- To find the period of this modulo function, you use **"Quantum Fourier Transform"** – a very useful tool in quantum computing

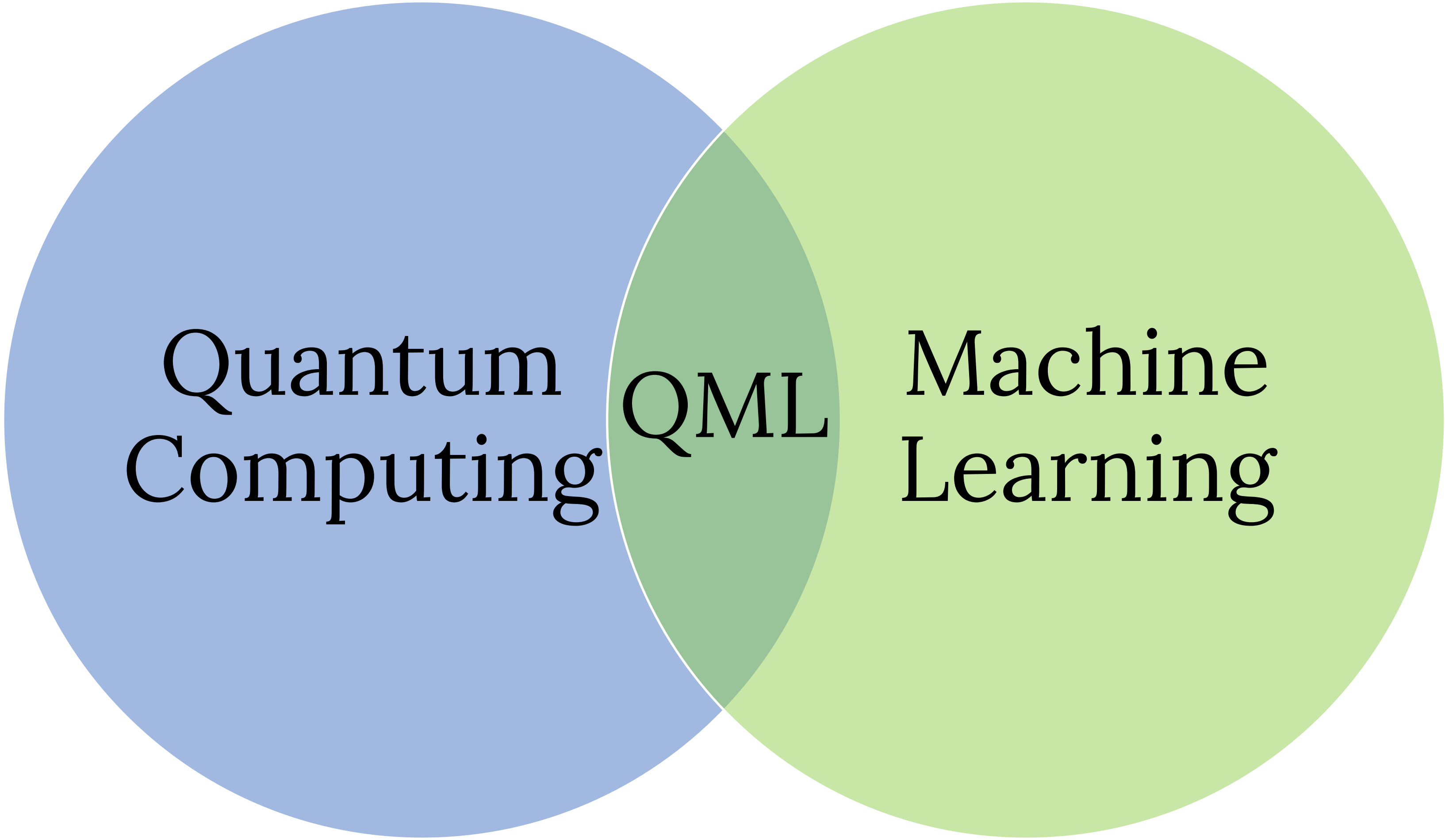
Quantum-safe cryptography

- RSA encryption is the basis of a lot of encryption schemes used to protect many assets
- Shor's algorithm poses a threat to these kind of commonly used encryption methods
- Need to have a quantum computer with **millions** of physical qubits to be able to do that (due to decoherence and noise)
- Quantum-safe algorithms which typically rely on mathematical problems that can't be solved easily by both classical and quantum computers already available
- Algorithms that rely on geometric problems based on lattices such as CRYSTALS-Kyber and CRYSTALS-Dilithium are now recommended by NIST
- Expected that industries will transition over to quantum-safe cryptographic algorithms as soon as **2024**. Therefore, there is (almost) no reason to worry about quantum computers destroying the world



Current applications of quantum computing

Quantum Machine Learning (QML)



Quantum Computing

QML

Machine Learning

Quantum Machine Learning (QML) - continued

- Machine Learning is linear algebra, and quantum computing heavily relies on linear algebra → excellent match up

- QML can be used to solve Fourier Transformation, finding eigenvectors and eigenvalues, and solving linear sets of equations with an **exponential speedup**

- **Quantum Support Vector Machines** (QSVM) are also one of the more popular QML techniques.
  - ➢ Classical SVMs can be performed only up to a certain number of dimensions while QSVMs do not suffer from these restrictions

- **Quantum Optimization:** try to produce best possible output by using the least possible resources.
  - ➢ Entanglement → produce multiple copies of the present solution encoded in a quantum state

Current applications of quantum computing

- **Condensed matter physics** has important implications for our understanding of nature and the development of new technologies
- It is also one of the main building blocks behind building computers, both classical and quantum
- One of the most popular models of ferromagnetism in statistical mechanics is called the "**Ising model**"
- Utilizes spins as its variables, and its coefficients comprise couplings and fields
- Each spin configuration is assigned an energy and a corresponding Boltzmann probability
- The connectivity of qubits allows researchers to simulate the dynamics of spin lattices

Current applications of quantum computing - continued

- One of many research papers on this subject include this one from IBM Quantum
- They perform Markov chain Monte Carlo (MCMC), a popular iterative sampling technique, to sample from the Boltzmann distribution of classical Ising models
- A new quantum algorithm that with many current applications including ones in machine learning (Boltzmann Machines) and statistical physics (thermal averages)
- Uses relatively simple quantum circuits using current hardware
- Many similar efforts trying to create solutions for optimization, statistical, and machine learning problems

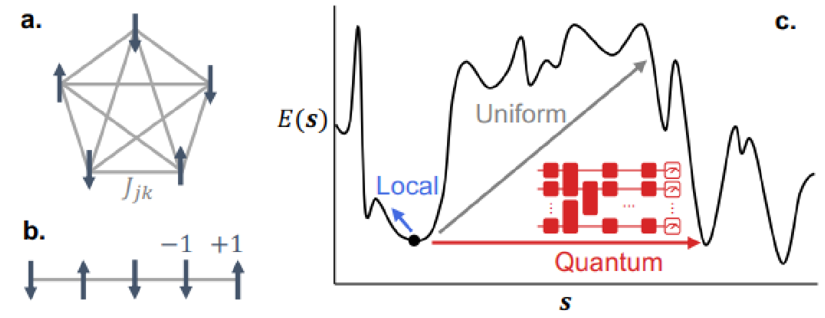


FIG. 1. **Ising model representations.** **a.** Graph depicting an $n = 5$ model instance where arrows (vertices) represent spins and edges represent the $\binom{n}{2}$ non-zero couplings J_{jk}. Fields h_j are not shown. **b.** An $n = 5$ model instance with only $n - 1$ non-zero couplings. **c.** A rugged energy landscape typical of spin glasses, with the configurations $\boldsymbol{s} \in \{-1, 1\}^n$ depicted in 1D. Typical proposed jumps for three MCMC algorithms, from a local minimum, are shown for illustration.

Current applications of quantum computing - HEP

- Many applications in HEP, focusing on things like track reconstruction, Lattice Electrodynamics, signal versus background separation, and finding rare processes with QML
- The field of quantum computing in HEP is super recent → lots of opportunities to explore!
- I am going to be biased and focus on one recent paper published by my current experiment, LHCb
- Main premise is utilizing QML to identify the **charge of the b hadron-jets**
- Proponents utilize a Variational Quantum Classifier (VQC) on LHCb data and compare it against a Deep Neural Network model

Current applications of quantum computing – HEP – continued

- Measurements mapped to probabilities for different labels
- Probabilities used to estimate a cost function
- Cost function optimized using a classical optimizer
- QML algorithms achieve performance consistent with classical methods like the DNN with low-complexity circuits and a smaller number of training events
- Room for improvement, especially when using a larger number of features and utilizing better hardware

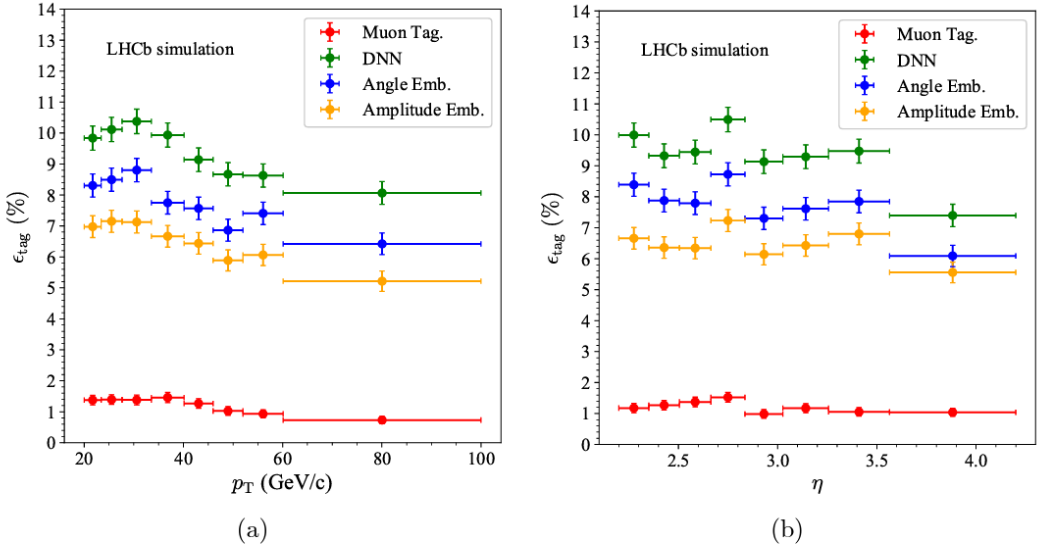


Figure 8: Tagging power ϵ_{tag} with respect to (a) jet p_T and (b) jet η for the *complete dataset*. The quantum algorithms perform slightly worse than the DNN, with the Angle Embedding circuit performing better than the Amplitude Embedding circuit.

Prospects and future applications

- High Energy Physics
- Complex Manufacturing and Industrial Design
- Logistics
- Finance and financial modelling
- Chemical and biological Engineering
- Pharmacy and drug development
- Artificial Intelligence
- Cybersecurity
- Material Science
- … and many more!

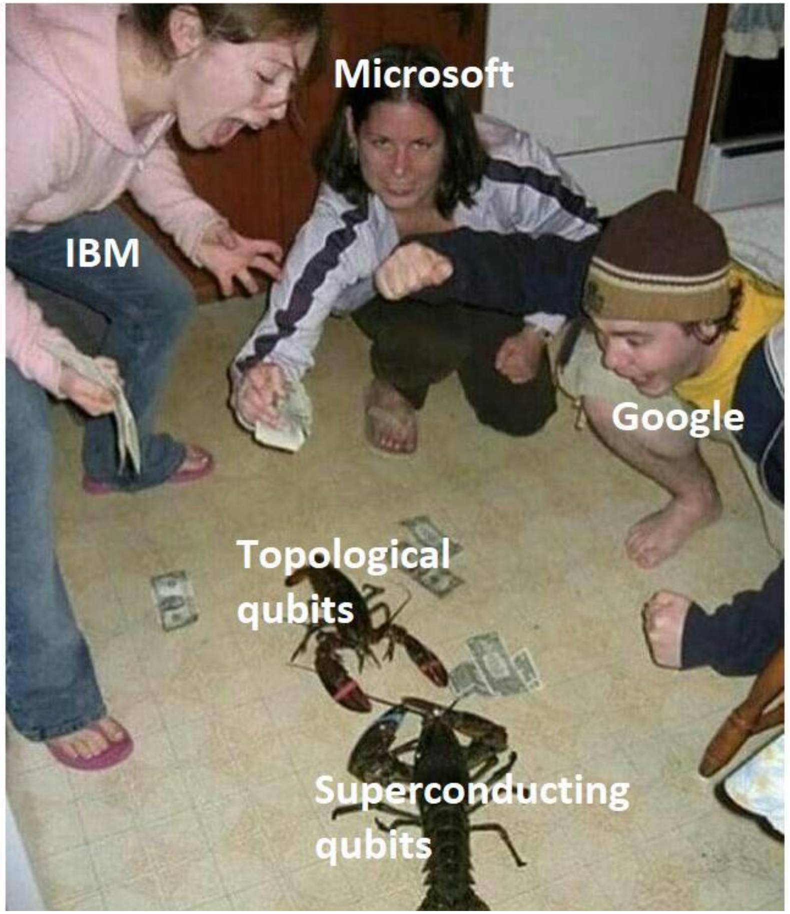
Future Predictions

- IBM currently have 433 qubits – expect to reach 1,000,000 qubits in **2027**

- Google has 53 qubits – expect to reach 1,000,000 qubits in **2029**

- Google announced their first error correct logical qubit last month (Feb 2023)

- Many others are joining “the race”



- When do you think quantum computers w become “useful”?

- **Do you think it would happen at all?**

How can I participate?

CERN Quantum Technology Initiative

- First workshop on Quantum Computing in HEP at CERN in 2018
- Conference on Quantum Technologies in HEP last Novemeber
- Established a comprehensive R&D, academic and knowledge-sharing initiative for quantum technologies

- Currently focusing on:
  - Quantum computing and algorithms
  - Quantum theory and simulation
  - Quantum sensing, metrology and materials
  - Quantum communications and networks

QUANTUM
TECHNOLOGY
INITIATIVE

- Collaborating with universities and institutions all over the world with a lot of them being in Europe
- In 2021, CERN became a quantum hub in partnership with the IBM Q-Network
- Quantum Technology Initiative Journal Club – meeting on Thursdays
- https://quantum.cern/

Qiskit Quantum Developer Certificate

- Certification awarded for learning quantum computation using Qiskit
- Demonstrates you having fundamental knowledge of quantum computing concepts
- Demonstrates you being able to create and execute quantum computing programs on IBM Quantum computers and simulators
- Defining, executing, and visualizing results of quantum circuits with different gates, etc.
- Useful if you want to demonstrate your ability in quantum computing
- https://www.ibm.com/training/certification/C0010300

Takeaways

- Quantum computing is an emerging field that's still far away from being useful in solving real life problems at an exponential rate

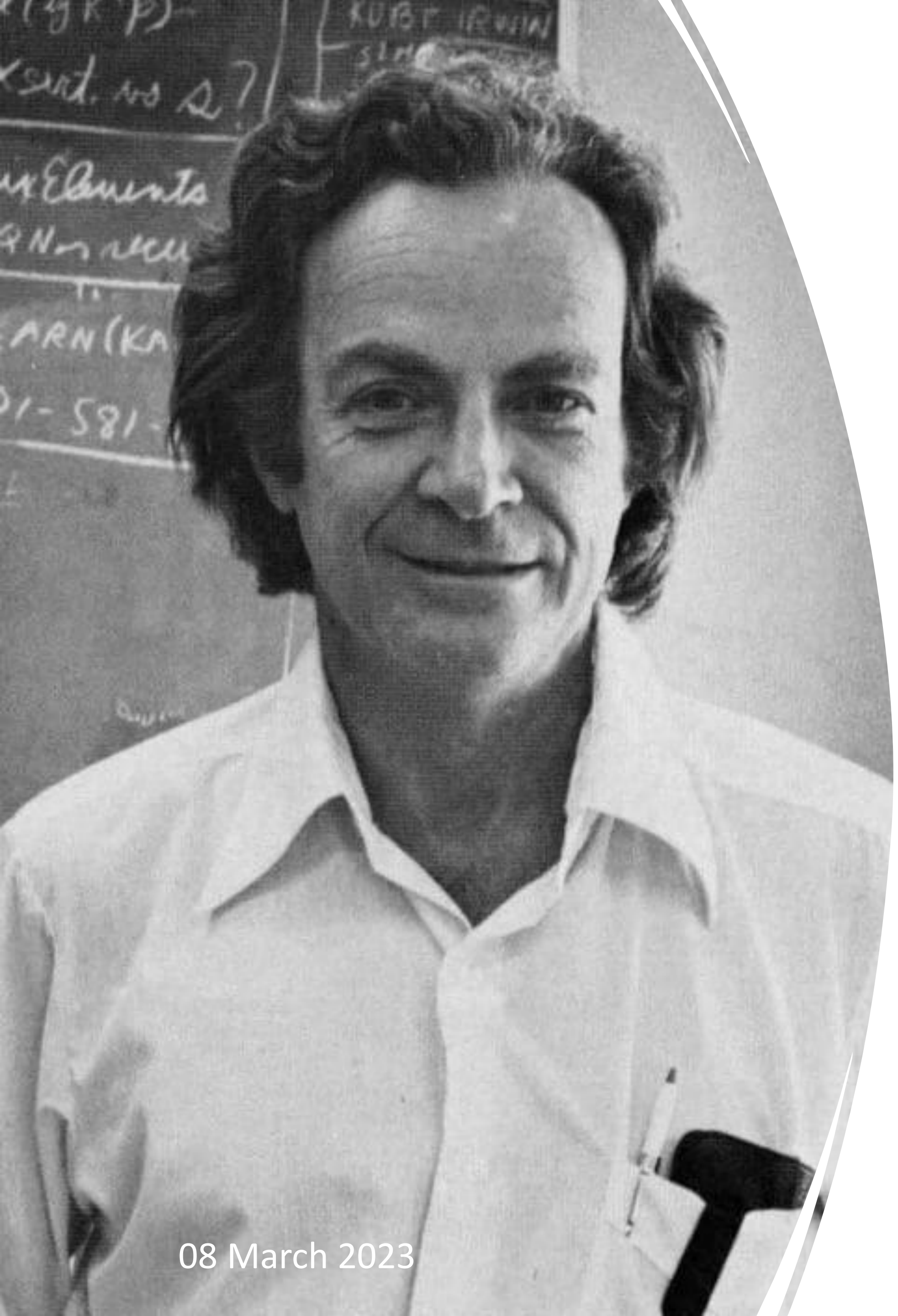
- Quantum computing is basically linear algebra and complex variables (unless you're working on developing the hardware)

- Current main problems revolve around error correction and increasing number of useful qubits

- When people first created the classical computer, they did not imagine how it would evolve. They probably never imagined the Internet and the horrors you can now find there

- Prospects are looking **okay** for the time being – just need to be cautiously optimistic and not blindly follow the hype train

- There are many ways you can get involved in quantum computing today!



“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.”

-Richard Feynman

Blooket

https://play.blooket.com

More resources

- Introduction to Quantum Computing and Quantum Hardware (Qiskit on YouTube)
- Qiskit textbook
- Xanadu textbook
- Quantum Machine Learning demonstrations (Pennylane)
- A course on Quantum Machine Learning (Github – Pennylane)
- 1 Minute Qiskit (Qiskit on YouTube)
- Why Did Quantum Entanglement Win the Nobel Prize in Physics? (PBS Spacetime on YouTube)
- What is Quantum Safe (IBM Technology on YouTube)

Thank you for your attention!

https://forms.gle/2dz2Cu6uoXmfYpKa9

Reminders

- Please fill out original survey if you haven’t already (only takes a couple of minutes)
- Please create accounts on IBM and Xanadu if you haven’t already (need them for tomorrow’s practice session)

Connect with me

https://ahmedabdelmotteleb.github.io/

Bonus!

More entanglement

$$\boxed{|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |01\rangle)} \longrightarrow \text{Global state}$$

$$|\psi_1\rangle = \alpha_1|0\rangle + \beta_1|1\rangle \longleftarrow \text{local state} \longrightarrow |\psi_2\rangle = \alpha_2|0\rangle + \beta_2|1\rangle$$

Given the global state, what are the local states?

$$|\psi_1\rangle\otimes|\psi_2\rangle = |\psi_1\psi_2\rangle = \boxed{\alpha_1\alpha_2|00\rangle + \alpha_1\beta_2|01\rangle} + \boxed{\beta_1\alpha_2|10\rangle + \beta_1\beta_2|11\rangle}$$

Therefore, require:

- $\alpha_1\alpha_2 = \alpha_1\beta_2 = \frac{1}{\sqrt{2}}$
- $\beta_1\alpha_2 = \beta_1\beta_2 = 0$

$$\Longrightarrow \quad \begin{gathered} \alpha_2 = \beta_2 \\ \beta_1 = 0 \end{gathered}$$

No contradiction

Quantum lingo cheat sheet

- **Noisy Intermediate-Scale Quantum (NISQ) era:** era with intermediate number of qubits (~100) that still have problems with noise/decoherence – era we are currently in

- **Fault tolerant computer:** Less affected by noise/decoherence

- **Fidelity:** a measure of how close the final quantum state of the real-life qubits is to the ideal case. The threshold for fault-tolerant quantum computing is over 99%

- **Quantum volume:** a metric that measures the capabilities and error rates of a quantum computer based on the size of the successfully running circuits. It was invented by IBM

- **Coherence time:** the length of time a quantum superposition state can survive

- **Transmon:** a superconducting loop-shaped qubit that can be created at extremely low temperatures

Cracking RSA encryption with a quantum computer

- Chinese scientists released a paper in Dec 2022 claiming to have cracked low-level RSA encryption using a hybrid of a quantum and classical computer
- 48-bit numbers using a 10-qubit quantum computer
- They combine classical lattice reduction factoring techniques (Schnorr's algorithm – not be confused with Shor's algorithm) with a quantum approximate optimization algorithm
- They calculated that it's possible to scale their algorithm for use with 2048-bit keys using a quantum computer with only **372 qubits**!
- IBM already has a 433-qubit quantum computer…
- Experts are saying these claims don't add up and shouldn't be scalable to higher qubit computer. Expect IBM to do some tests soon