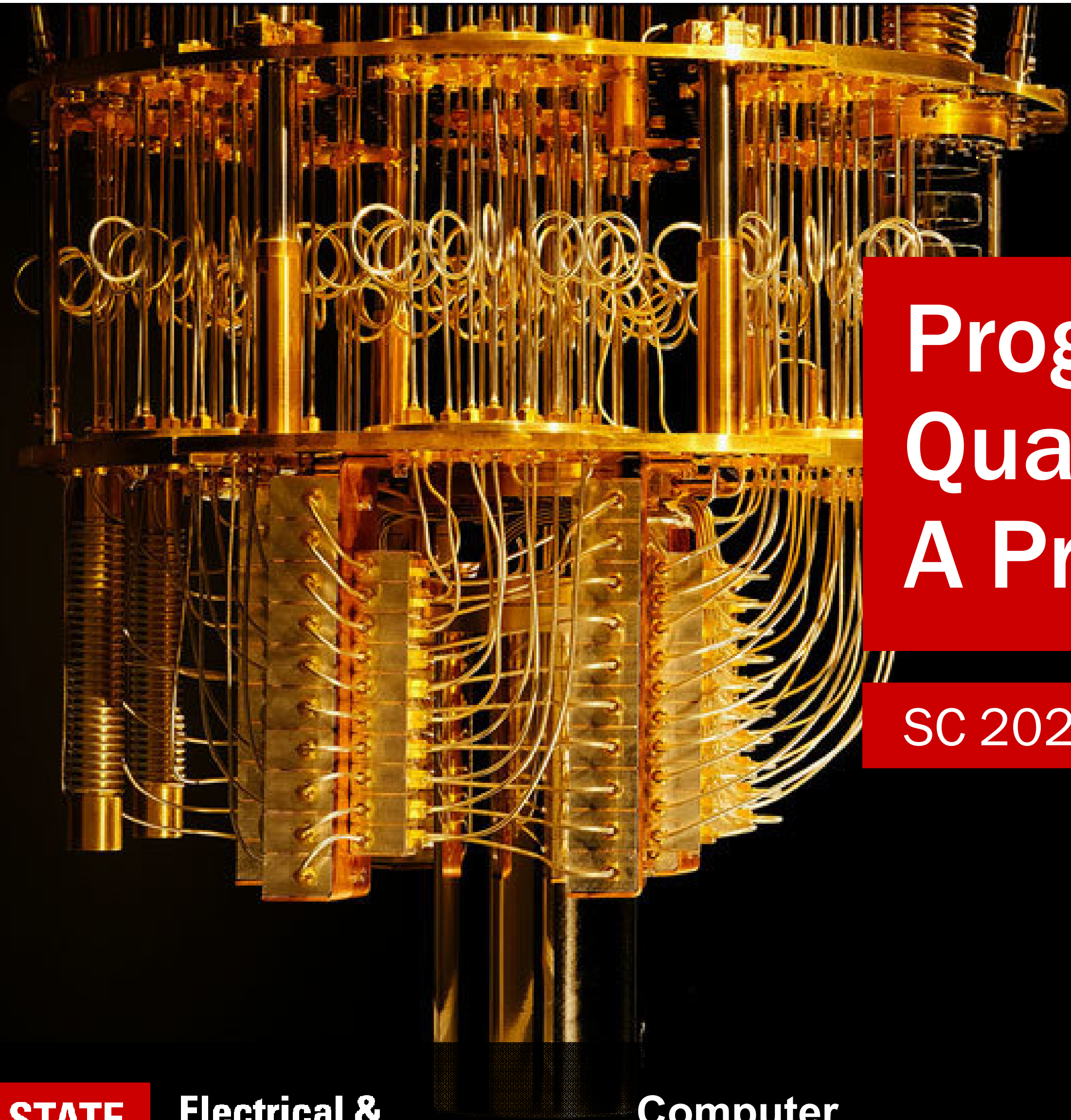

Programming Quantum Computers: A Primer

SC 2020 Tutorial

NC STATE UNIVERSITY
Electrical & Computer Engineering
Computer Science

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Introduction

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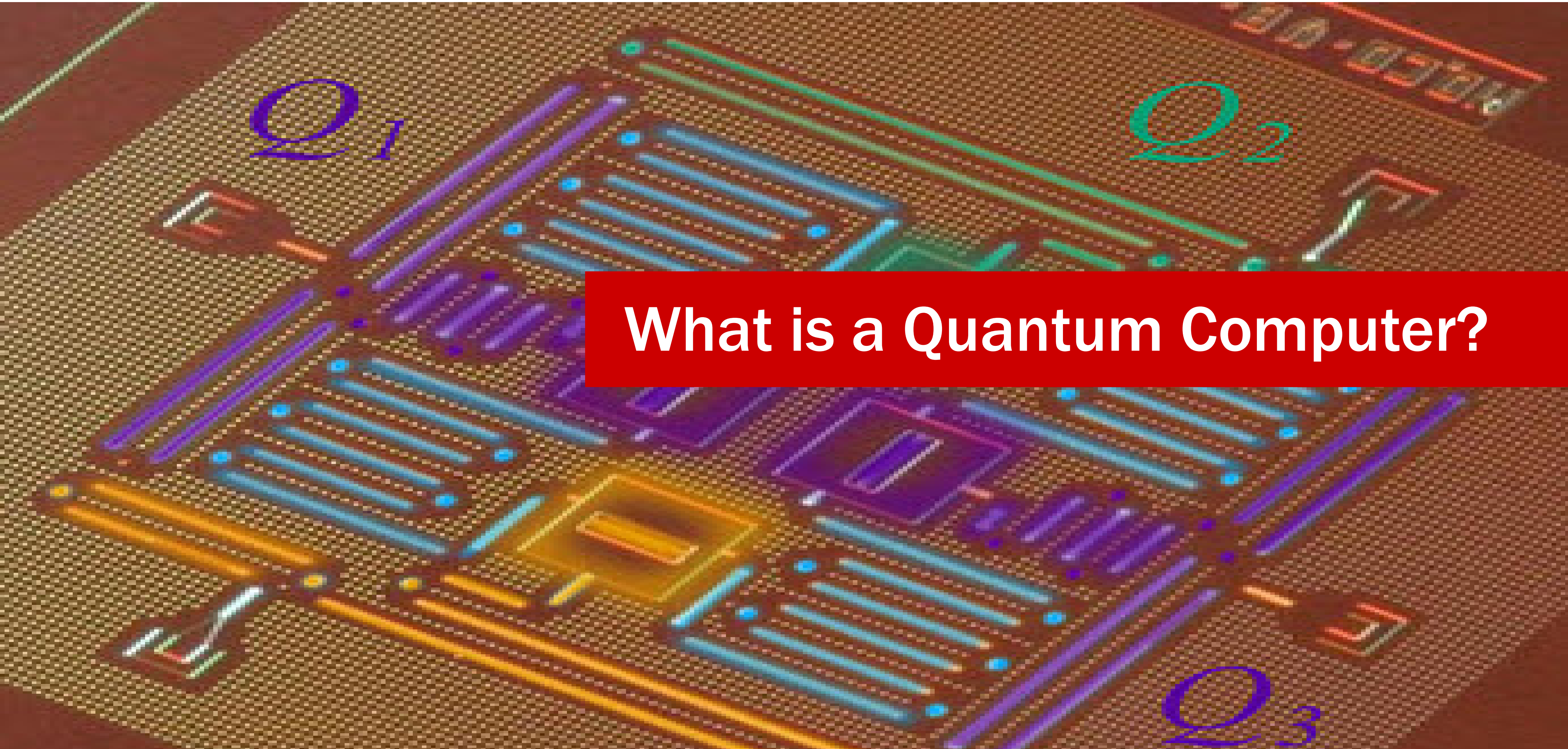
Agenda

2:30	Introduction
2:45	Foundations: Linear Algebra and Quantum Mechanics
3:25	Simulator: Quirk Exercises
3:40	Break
3:50	Quantum Gates, Circuits
4:20	IBM Q: Qiskit
4:30	Simple Qiskit Exercises
4:55	Break
5:05	Quantum Algorithms
5:50	More Qiskit Exercises

https://sites.google.com/ncsu.edu/qc-tutorial/

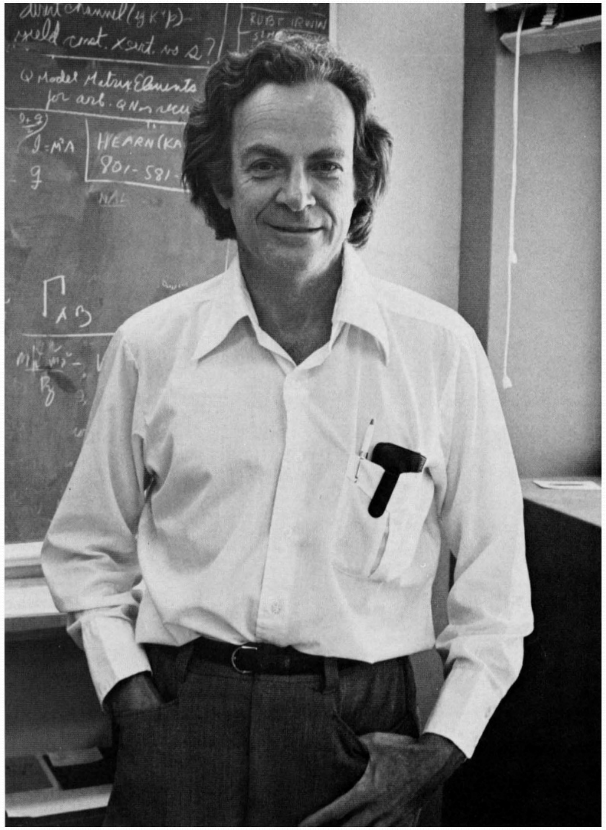
What is a Quantum Computer?



Simulating Physics with a Computer

Richard Feynman

> "...trying to find a computer simulation of physics, seems to me to be an excellent program to follow out...
>
> "...*nature isn't classical*, dammit, and if you want to make a simulation of nature, you'd better *make it quantum mechanical...*"
>
> (1981)



https://commons.wikimedia.org/wiki/File:Richard_Feynman_1988.png

Universal Quantum Computer

David Deutsch

"Computing machines resembling the universal quantum computer could, in principle, be built and would have many remarkable properties not reproducible by any Turing machine … Complexity theory for [such machines] deserves further investigation." (1985)

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http://www.daviddeutsch.org.uk/

Quantum Computation

Alexei Kitaev, A. Shen, M. Vyalyi

“Simulation of quantum mechanics is indeed an exponentially hard problem. One may think this is unfortunate, but let us take a different point of view: quantum mechanics being *hard* means it is *powerful*. Indeed a quantum system effectively ‘solves’ a complex computational problem -- it models its very self.” (1999)

https://www.macfound.org/fellows/802/

Qubit: Unit of quantum state

Classical bit = “0” or “1”

Quantum bit (qubit) can be “0” or “1” or some linear combination of “0” and “1”

$$\alpha|0\rangle + \beta|1\rangle, \text{ where } |\alpha|^2 + |\beta|^2 = 1$$

This is known as a *superposition*.

Qubit: Measurement

$$\alpha|0\rangle + \beta|1\rangle, \text{ where } |\alpha|^2 + |\beta|^2 = 1$$

When we measure (observe) the qubit, its value will be:

“0” with probability

“1” with probability

and is no longer in superposition.

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Classical vs. Quantum Computation

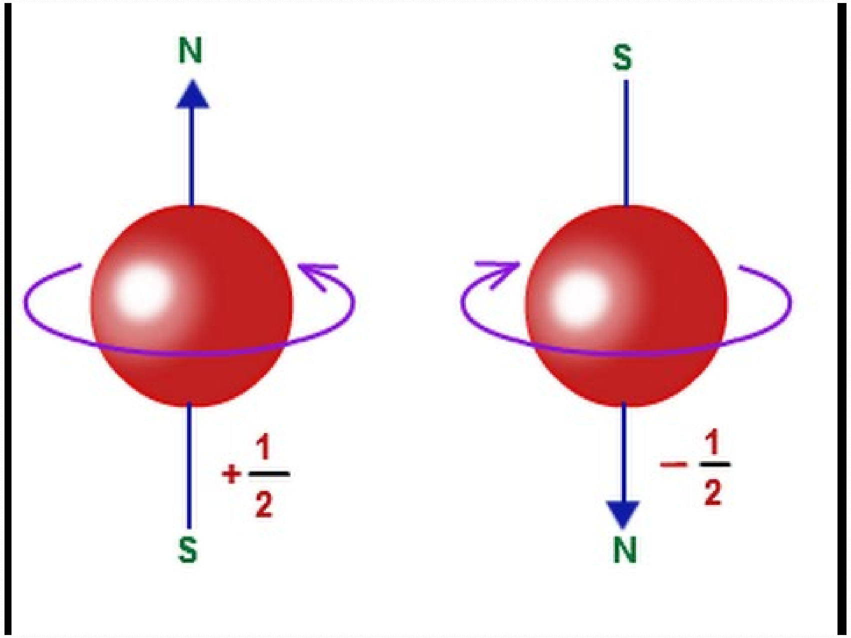
	Classical	Quantum
single bit/qubit	$\{0,1\}$	$\alpha\|0\rangle + \beta\|1\rangle$, linear combination of 0 and 1
n bits/qubits	$\mathbb{B}^n = \{0,1\}^n$	$\sum_x \alpha_x \|x\rangle,\ x \in \mathbb{B}^n$ linear combination of 2^n basis states
operation	Boolean	unitary (reversible)
measurement	no effect	“collapses” to a basis state

It takes 2^n complex numbers to represent the state of an n-qubit system.

Physical Qubit

Several types of physical systems exhibit quantum behavior

- individual atom or ion: electron energy levels
- electron: spin
- photon: polarization
- superconducting circuits: charge, flux, phase



Requirements for a Quantum Computer

Scalable physical system with well-characterized qubits.

Ability to initialize the qubits to a known state, e.g. $|0\rangle$

A “universal” set of quantum gates.

Long relevant decoherence time, much longer than the gate operation time.

A qubit-specific measurement capability.

David DiVincenzo (2008)

https://spectrum.ieee.org/tech-talk/computing/hardware/david-divincenzo-on-his-tenure-at-ibm-and-the-future-of-quantum-computing

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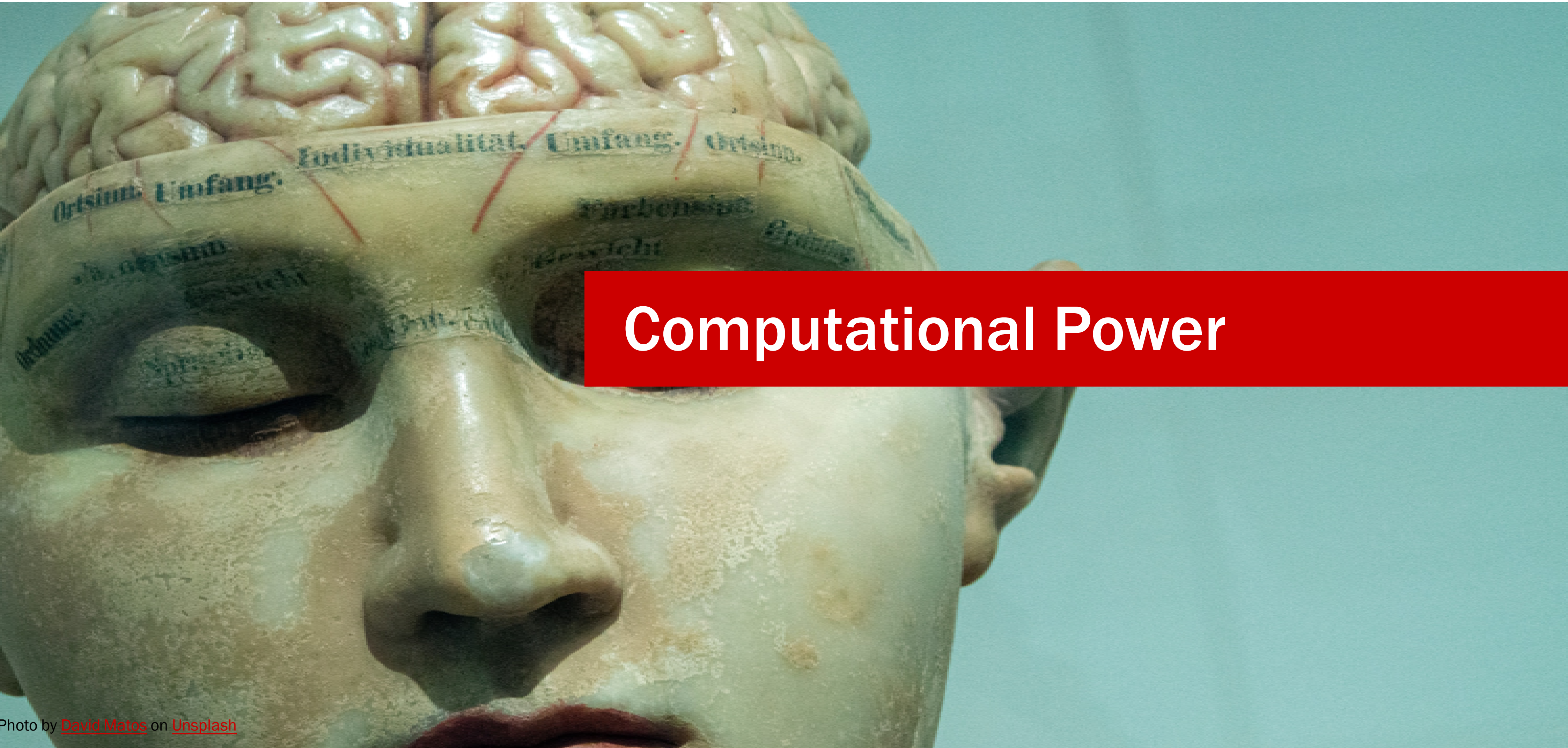
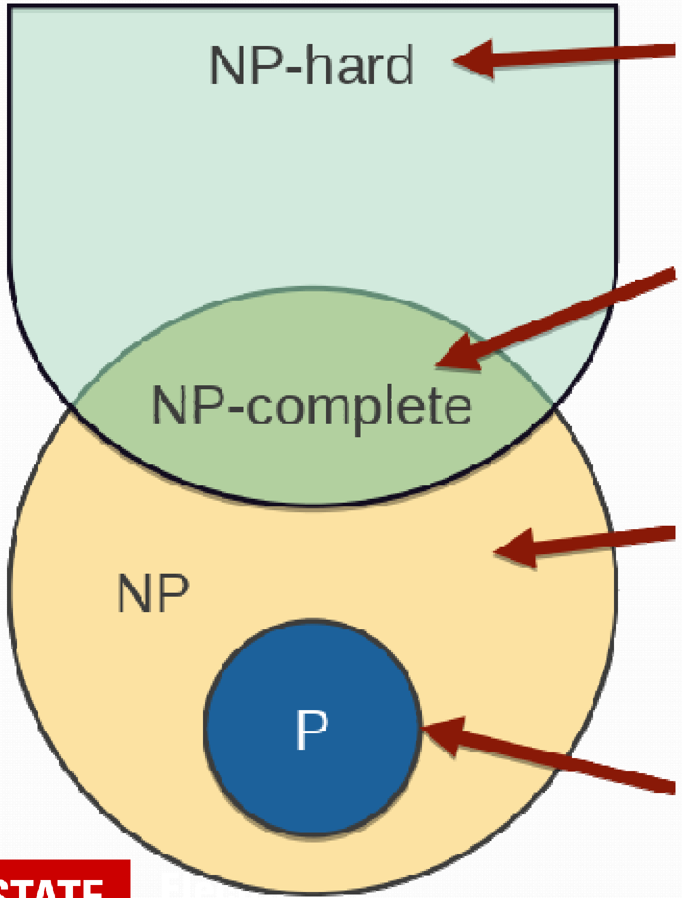


Computational Power

Photo by David Matos on Unsplash

Computational Complexity



- Problems at least as hard as those in NP
  - Not necessarily decision problems
  - Ex.: Given weighted graph, find shortest-length Hamiltonian path?
- Hardest of the problems in NP
  - Ex.: Given set of integers, is there a subset whose sum is 0?
- "Hard" decision problems
  - Can be solved in polynomial time on a nondeterministic Turing machine
  - Solutions can be verified in polynomial time on a deterministic Turing machine
  - Ex.: Does given integer have prime factor whose last digit is 3?
- "Easy" decision problems
  - Can be solved in polynomial time on a deterministic Turing machine
  - Ex.: Does given matrix have an eigenvalue equal to 1.2?

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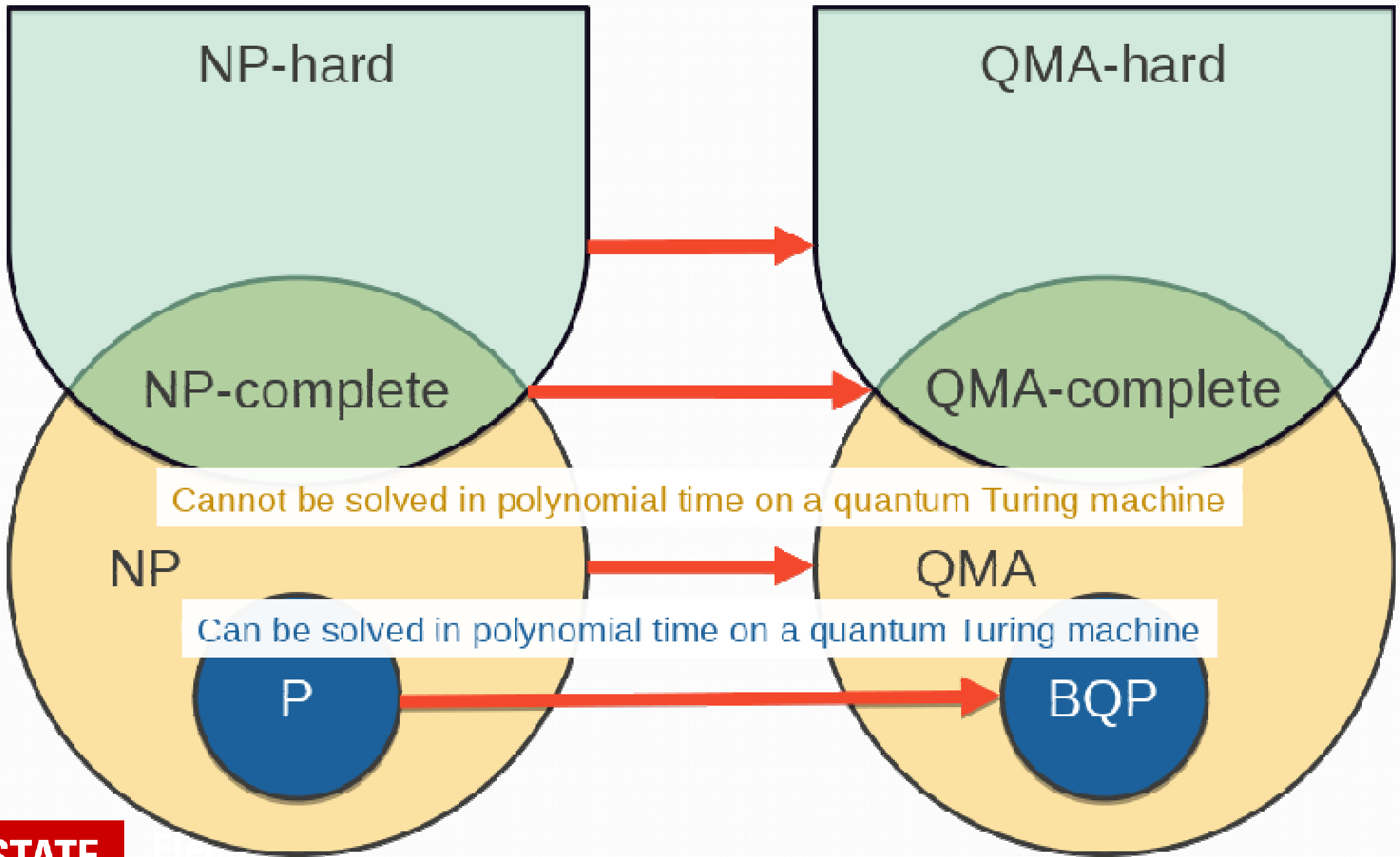
Quantum Complexity Classes

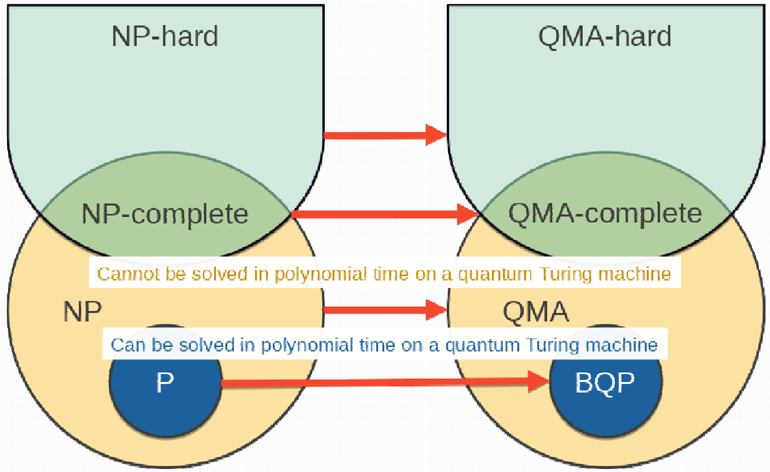


Classical vs. Quantum Complexity

What do we know? Short answer: very little!

P vs. BQP

- P $\subseteq$ BQP, but is P = BQP or P $\neq$ BQP?
- If P = BQP, then quantum offers no substantial (superpolynomial) benefit over classical.



BQP vs. NP-complete

- Conjectured that BQP $\subset$ NP-complete.
- Implication: Quantum cannot solve NP-complete problems in polynomial time.

Quantum Advantage

Quantum supremacy / superiority:

- Break a complexity class (e.g., NP-complete in poly time)
- Perform a calculation that is infeasible for any classical computer

Quantum advantage:

- Significantly outperform a state-of-the-art classical computer

Quantum computers are not expected to be better at *everything* than classical. Working in conjunction with classical computers.

- Looking for applications where quantum provides a significant performance advantage, or which cannot be done feasibly any other way.

Well-Known Algorithms

Grover's search algorithm

Search N items (unordered) in $O(\sqrt{N})$ time.

Shor's factoring algorithm

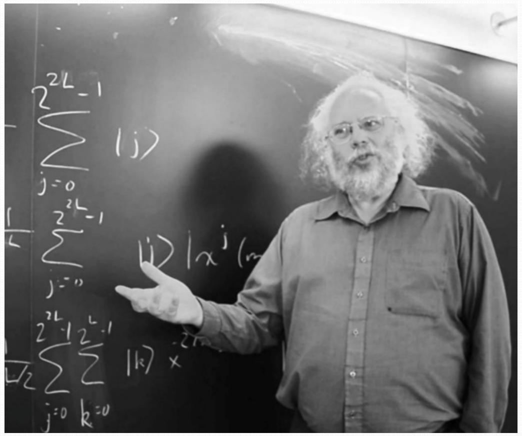
Factor an n-bit integer into primes

Classical: $O(\exp(n^{1/3}))$

Quantum: $O(n^3)$

Quantum Algorithm Zoo

Lov Kumar Grover



Peter Shor

https://www.dotquantum.io/en/quantum-biographies/

Types of Quantum Computer

Photo by Louis Hansel @shotsoflouis on Unsplash

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Quantum Annealer

Specialized for optimization and random sampling problems

Relies on quantum tunneling to find minimum energy configuration of qubits

- Weighting of qubits and interactions between qubits represent the problem to be solved

Not universal -- not designed to execute general quantum algorithms.

Example: D-Wave

Gate Model Quantum Computer

Implements a universal set of quantum gates (operations)

- Gates are applied in sequence to qubits (quantum circuit) to carry out computation

Examples: IBM, Google, Rigetti, IonQ, Xanadu, ...

NISQ = Noisy, Intermediate-Scale Quantum computers

- ~50 qubits, tens of gate delays

Fault-Tolerant Quantum Computer

Algorithmic corrections to noisy physical qubits

- Use error correction codes to exploit redundancy and maintain stable, correct logical state
- May require ~1000 physical qubits to implement 1 logical qubit

Example: none (yet)

Error correction: surface code, stabilizer codes, topological qubits