INTRO TO QUANTUM COMPUTING

Week 23 Lab

TYING IT ALL TOGETHER

Corbin McElhanney

April 27, 2021

LOOK HOW FAR YOU'VE COME!

- We are almost at the end of the course ☹
- You have accomplished **so much** in this course – congratulations!
- This lab is a review, but it is also a celebration ☺

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PROGRAM FOR TODAY

- Announcements
- Canvas attendance quiz
- Pre-lab zoom feedback
- Lab content
- Post-lab zoom feedback

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ANNOUNCEMENTS

Instead of a regular homework assignment this week, you will need to complete two separate assignments:

1. **Technical assessment**
   1. The technical assessment will be available to submit for **three days** following your lab section this week.
   2. You will have **50 minutes** to complete the assessment any time within that **3-day** window.
   3. Please complete the assessment to the best of your ability.
   4. Like previous versions, the technical assessment will be graded based on **completion** (if you submit the assessment, you will receive full credit regardless of your score).
   5. We will be posting them on Canvas on May 5th.
2. **Post-course survey**

   We will email you a link to a post-course survey (we will also post the link on Canvas). This is really important information for our team to have as we evaluate our programs and teaching. Please submit the survey no later than May 5th. Completing the survey is required in order to receive the certificate.

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ANNOUNCEMENTS

- Do you still have questions about quantum computing?
- Would you like to stay connected with this amazing community of students?
- Would you like to hear members of the instructor team talk about their favorite topics in quantum?
- Join us on **Schrodinger's Chat**

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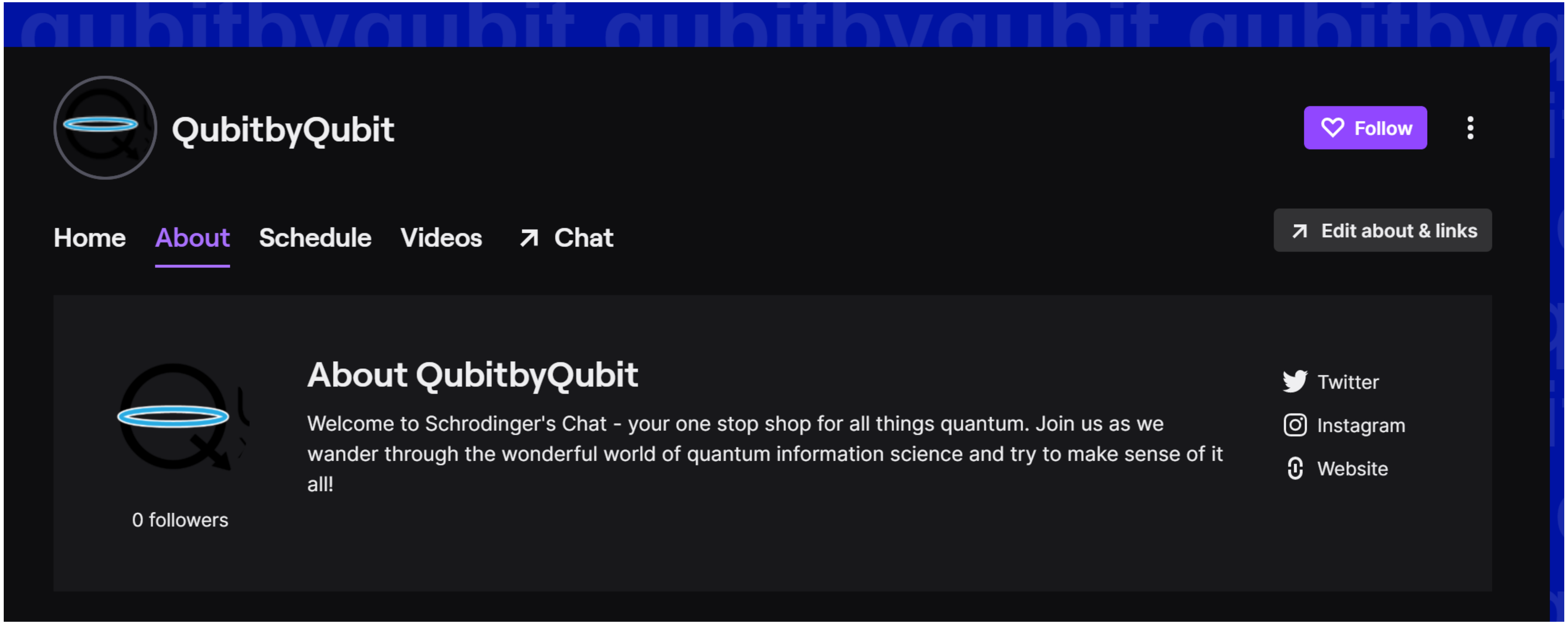
ANNOUNCEMENTS

- Schrodinger' Chat will stream on twitch over the summer. Schedule coming soon (look out for a canvas announcement)!
- Follow us on **twitch.tv/qubitbyqubit**



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CANVAS ATTENDANCE QUIZ

- Please log into Canvas and answer your lab section's quiz

Lab Number: 1 | Quiz Password: 4050

- **Question:** Which potential applications of quantum computing are you most excited about?

- **This quiz is not graded but counts for your lab attendance!**

PRE-LAB ZOOM FEEDBACK

On a scale of 1 to 5, how would you rate your understanding of this week's content?

- 1 –Did not understand anything
- 2 – Understood some parts
- 3 – Understood most of the content
- 4 – Understood all of the content
- 5 – The content was easy for me/I already knew all of the content

In lecture this week, we discussed different qubit technologies

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LEARNING OBJECTIVES FOR LAB 23

Revisiting core quantum concepts

- Qubits
- Operations – Gates and measurements
- Circuits
- Algorithms and protocols
- Applications

Next week (final lab!) – Near term algorithms

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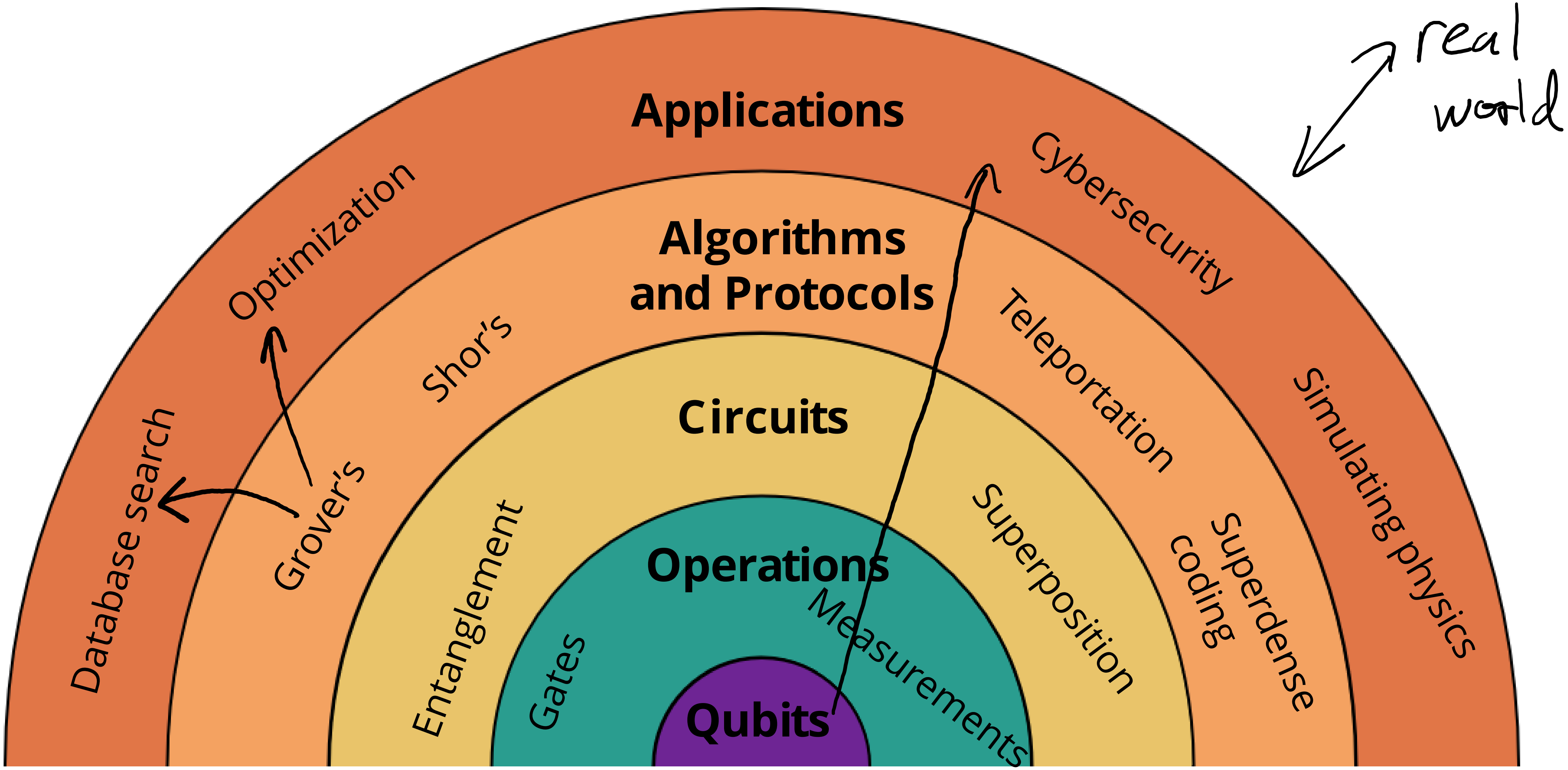
QUANTUM COMPUTING

- We've spent 8 months learning quantum computing
- How would you define quantum computing?
- Quantum computing is the use of the properties of quantum mechanics to solve certain problems more efficiently than classical computers
- Let's revisit the tree of concepts that we learnt!

THE TREE OF QUANTUM CONCEPTS



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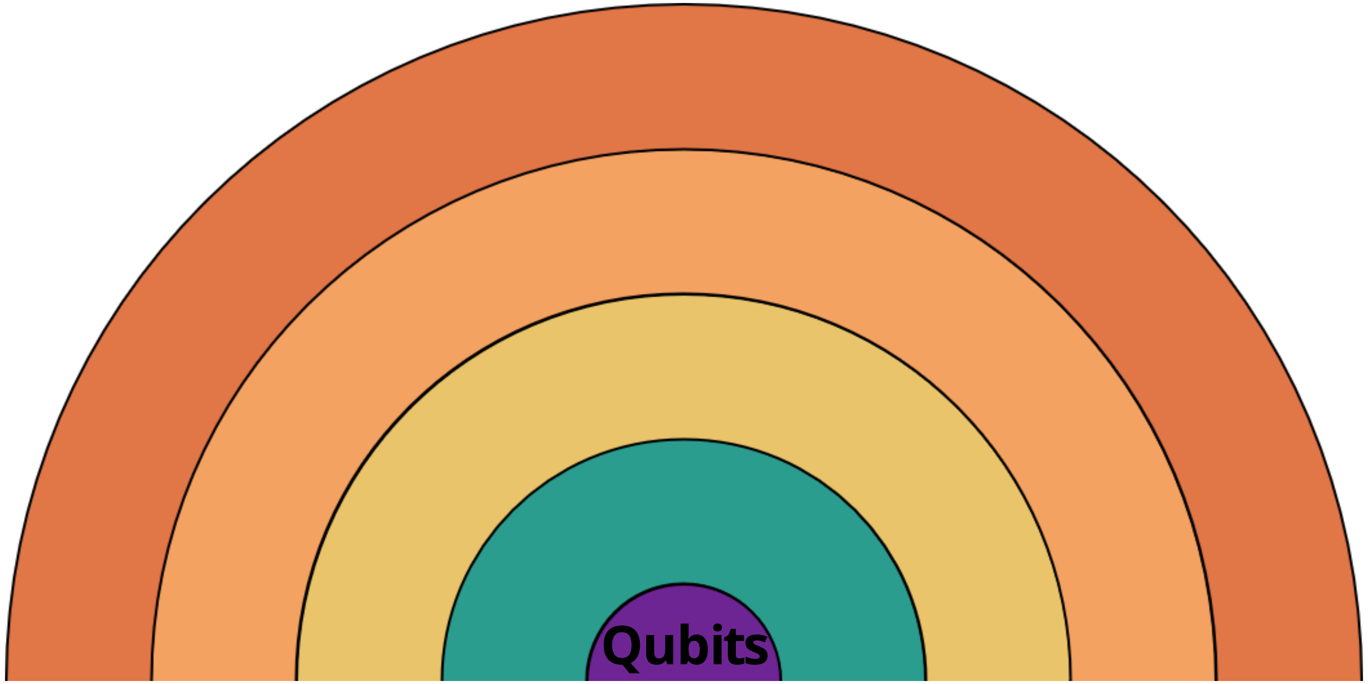
QUBITS



- A qubit is the fundamental unit of quantum information
- Unlike a classical bit, which can be either 0 or 1, a qubit can represent a superposition of the states $|0\rangle$ and $|1\rangle$

$$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

$$\updownarrow$$

$$\frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

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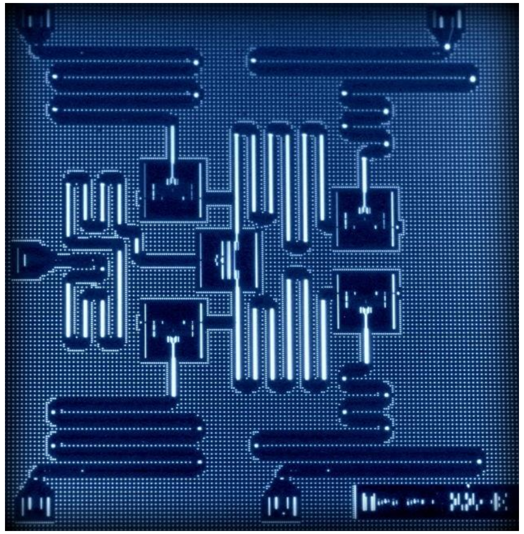
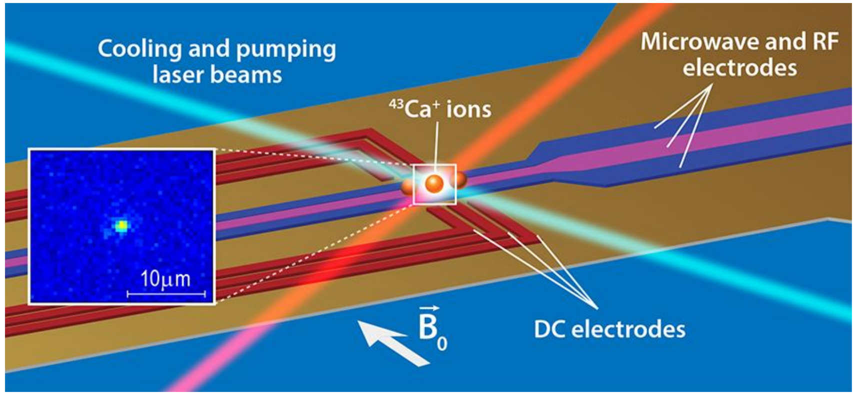
PHYSICAL IMPLEMENTATION

- Qubits can be encoded in many different quantum systems, such as superconducting circuits, light polarization, ion energy states, etc.
- The fundamental requirement is to create a **two-level system**
- **Decoherence** is the loss of quantum information stored in qubits due to interactions with the environment

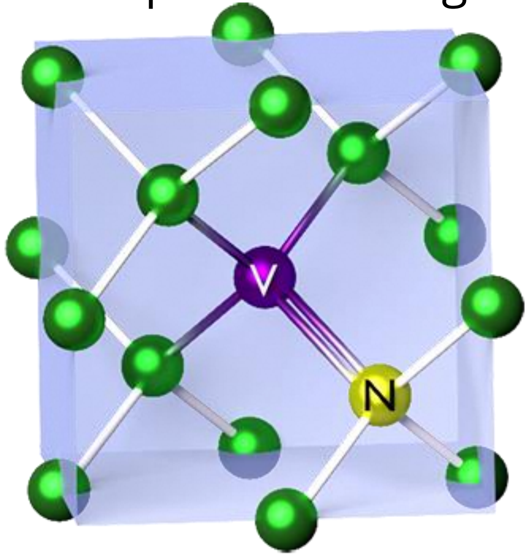
Relevant course weeks: 22, 23

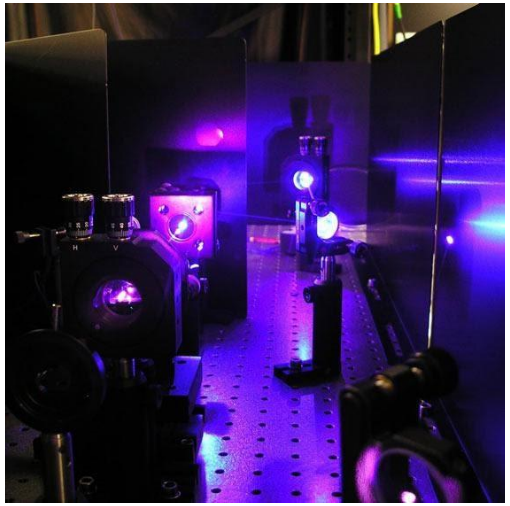


superconducting



trapped ion





photonic

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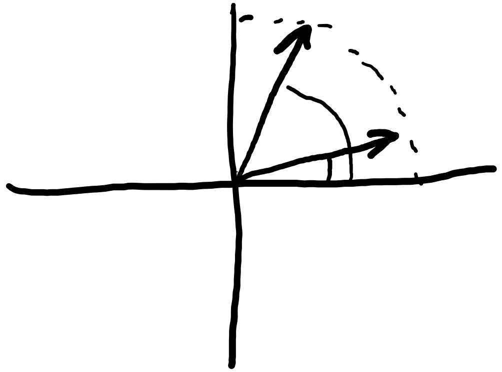
REPRESENTING QUBITS

scalar

vector



$$v = 2$$

$$\vec{v} = \begin{pmatrix} 2 \\ 1 \end{pmatrix}$$

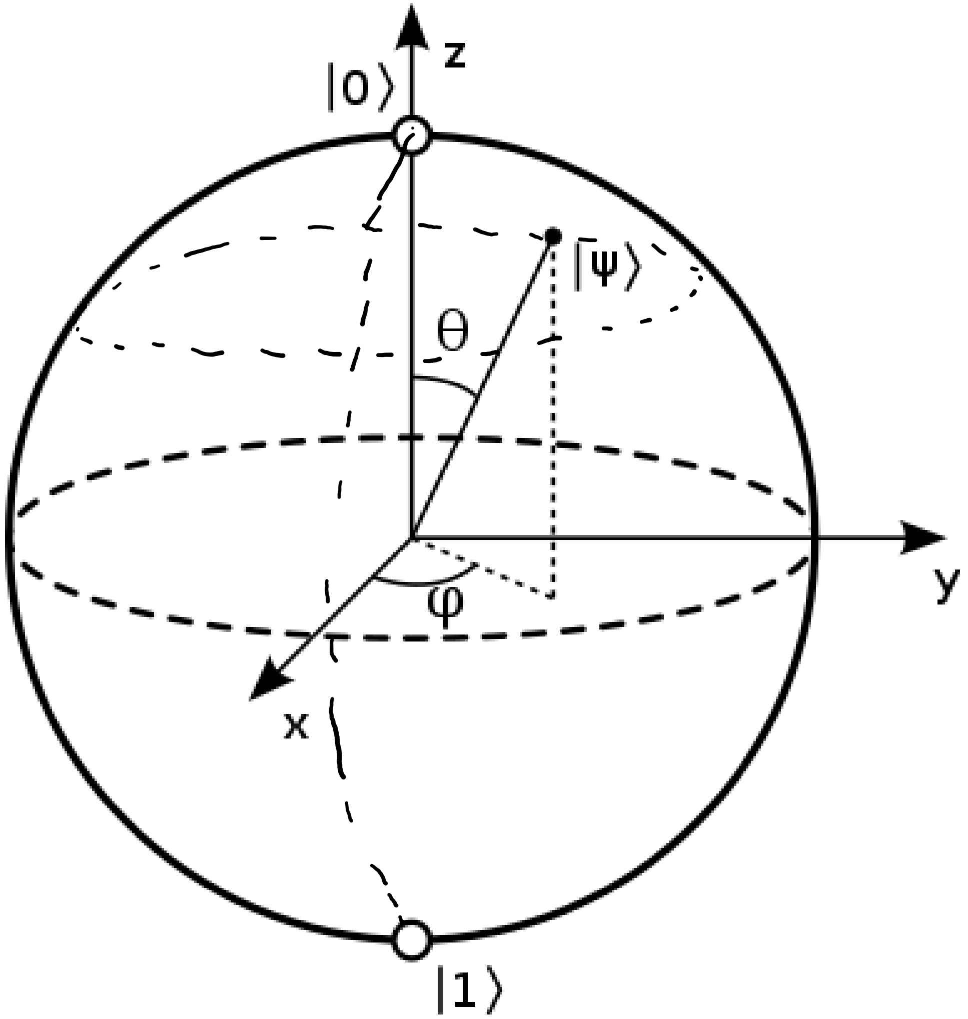
$|\psi\rangle = \begin{pmatrix} i \\ 0 \end{pmatrix}$

We represent qubits using **vectors** (to show the contributions of 0 and 1) and complex numbers (to account for phase)

Relevant course weeks: 1,2, 3, 4, 8

BLOCH SPHERE REPRESENTATION

Qubit states are represented as vectors on the surface of the Bloch sphere



Relevant course weeks: 14

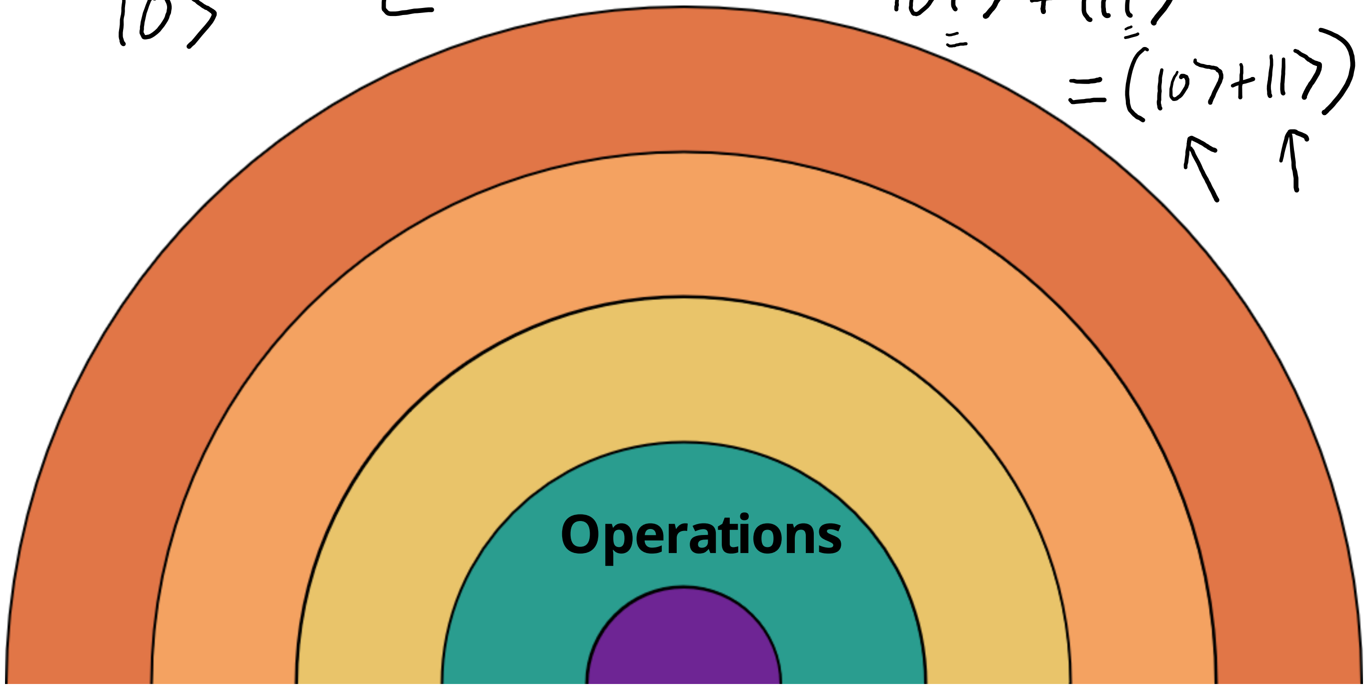
OPERATIONS

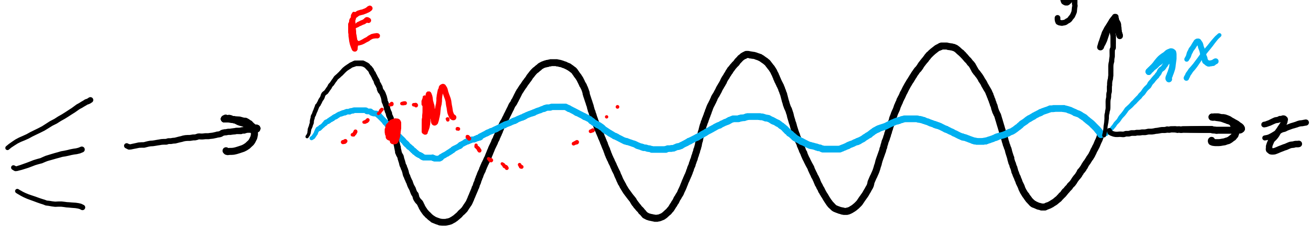
$|0\rangle + |1\rangle \Leftarrow$

$|0\rangle \Leftarrow$

$|00\rangle + |11\rangle$

$|01\rangle + |11\rangle = (|0\rangle + |1\rangle)|1\rangle$





- In quantum computation, we want to manipulate qubit states
- These manipulations are called **gates**
- Gates allow us to use the **three major quantum resources: superposition, interference, and entanglement**
- At the end of our manipulations, we perform a **measurement** of the qubit state

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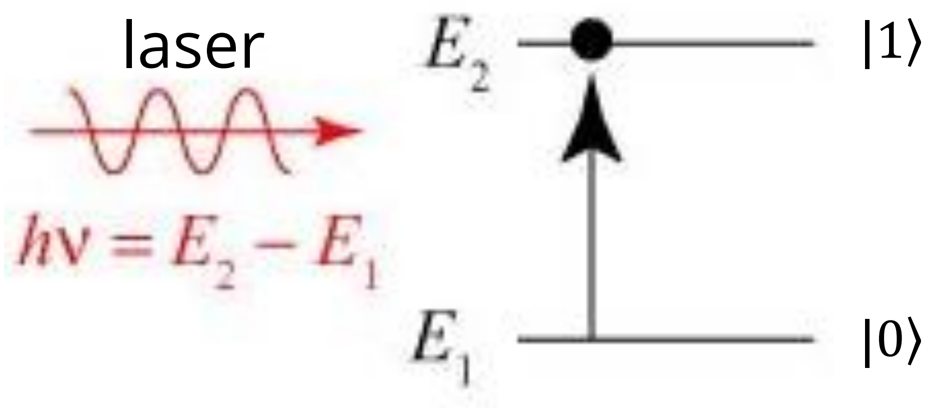
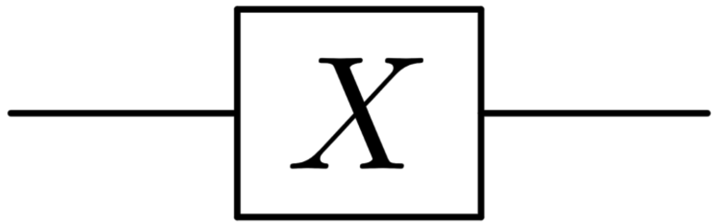
PHYSICAL IMPLEMENTATIONS OF GATES

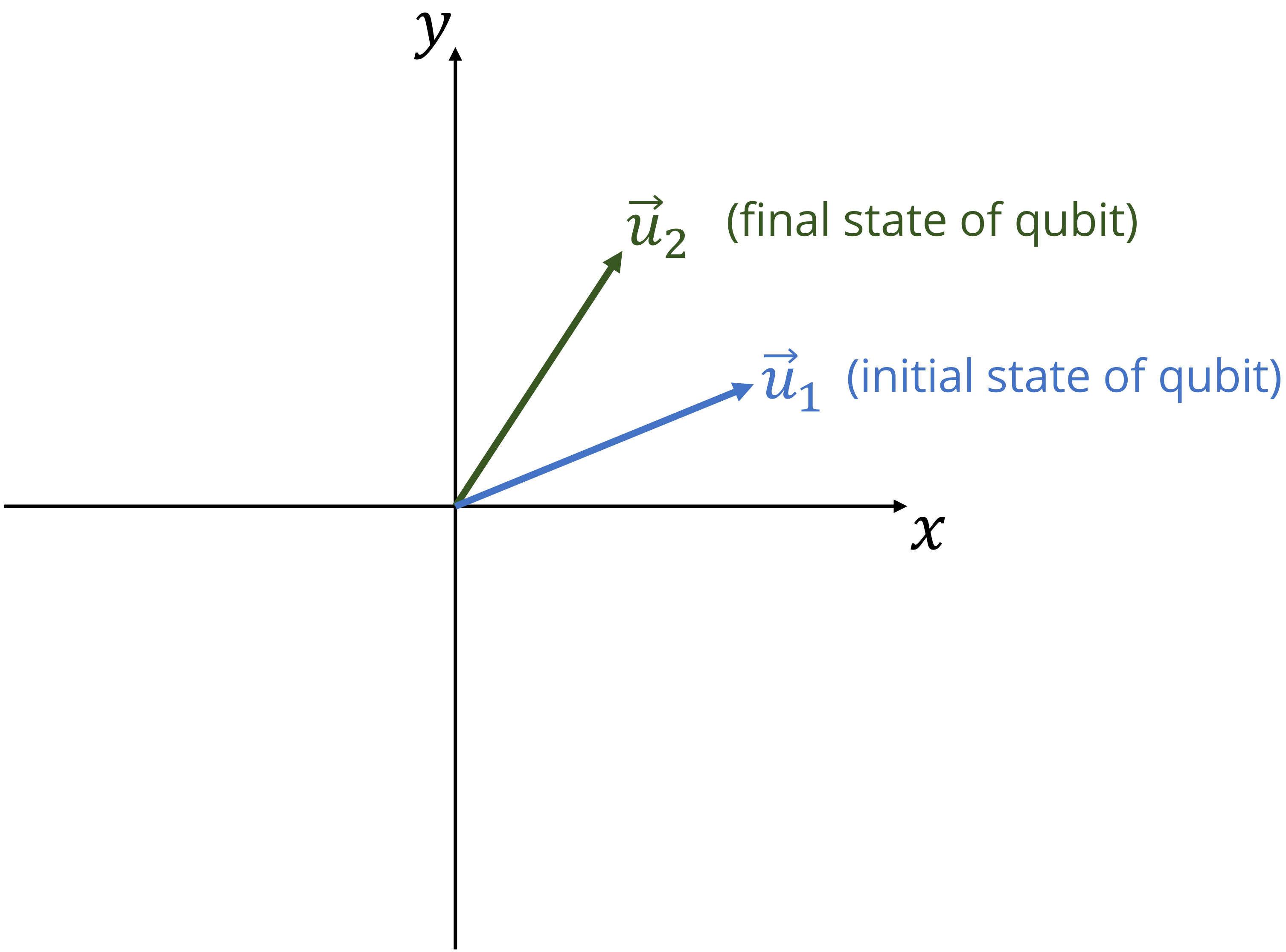
- Physical implementation of gates depends on the qubit implementation
- **Example**: For trapped ion systems, a laser beam applied to the ion is a gate





Relevant course weeks: 23

REPRESENTING QUBIT TRANSFORMATIONS



Relevant course weeks: 4, 8,14

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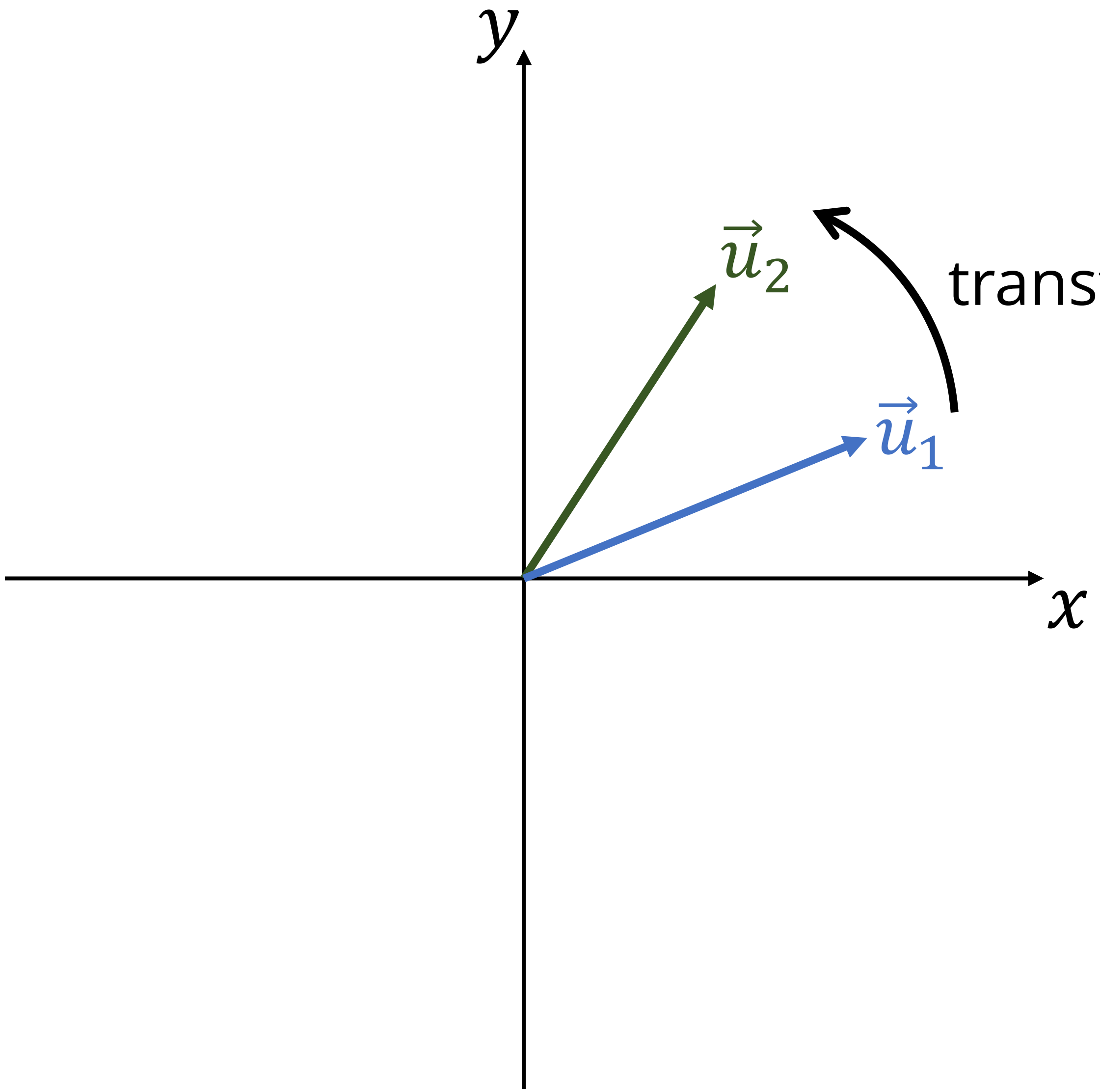
REPRESENTING QUBIT TRANSFORMATIONS



Relevant course weeks: 4, 8, 14

REPRESENTING GATES AS MATRICES

Vector: Qubit

Matrix: Gate

$$\vec{v} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$\boldsymbol{S} = \begin{pmatrix} 1 & 2 \\ 2 & 1 \end{pmatrix}$$

Relevant course weeks: 4, 8, 14

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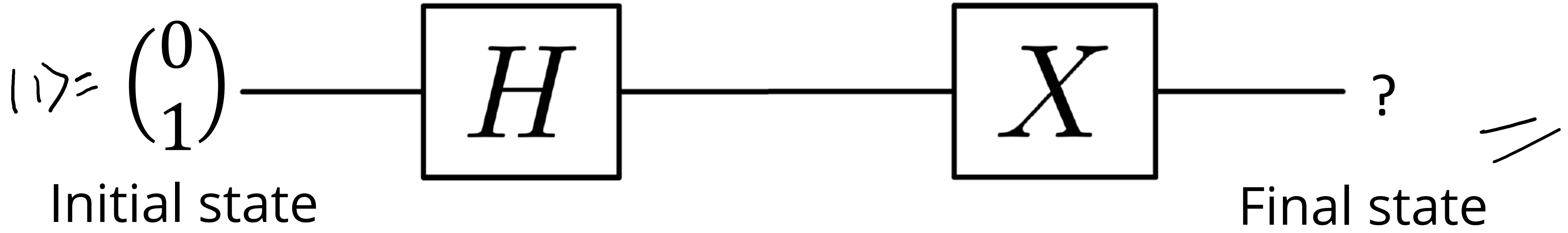
APPLYING GATES TO QUBIT STATES

To understand how to apply gates to qubit states, we learnt **linear algebra**

Applying gates to a qubit state



Finding the final state using matrix multiplication

$$\textbf{Final state} = \underbrace{\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}}_{X\text{ gate}} \underbrace{\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}}_{H\text{ gate}} \underbrace{\begin{pmatrix} 0 \\ 1 \end{pmatrix}}_{\text{Initial state}} = \begin{pmatrix} -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{pmatrix}$$

Relevant course weeks: 4, 8, 9, 14

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MEASURING QUANTUM STATES

What are the possible results of measuring the state

$$|\psi\rangle = 3/5|0\rangle + 4/5|1\rangle$$

0 or 1

What are the probabilities of each of these results?

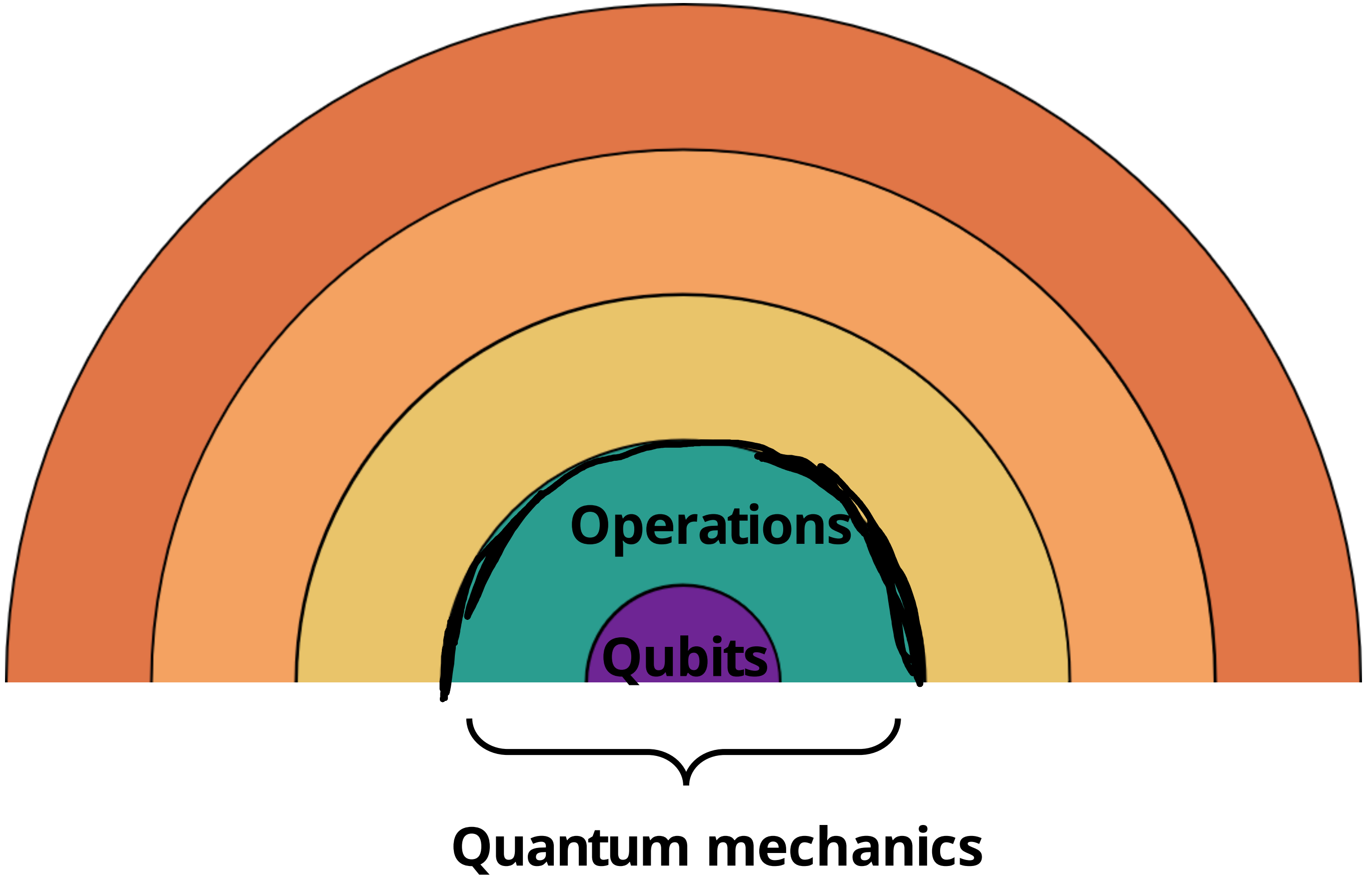
$$\left|\frac{3}{5}\right|^2 = \frac{9}{25}$$

$$\left|-\frac{4}{5}\right|^2 = \frac{16}{25}$$

$$+ \quad 1$$

QUANTUM MECHANICS

- Qubit states, gates, and measurements follow the postulates of **quantum mechanics**
- Quantum mechanics tells us the different possible results of an experiment, as well as the **probabilities of measuring** them
- To understand quantum mechanics, we looked at the Stern-Gerlach and double-slit experiments



Relevant course weeks: 5, 9, 11, 12, 13

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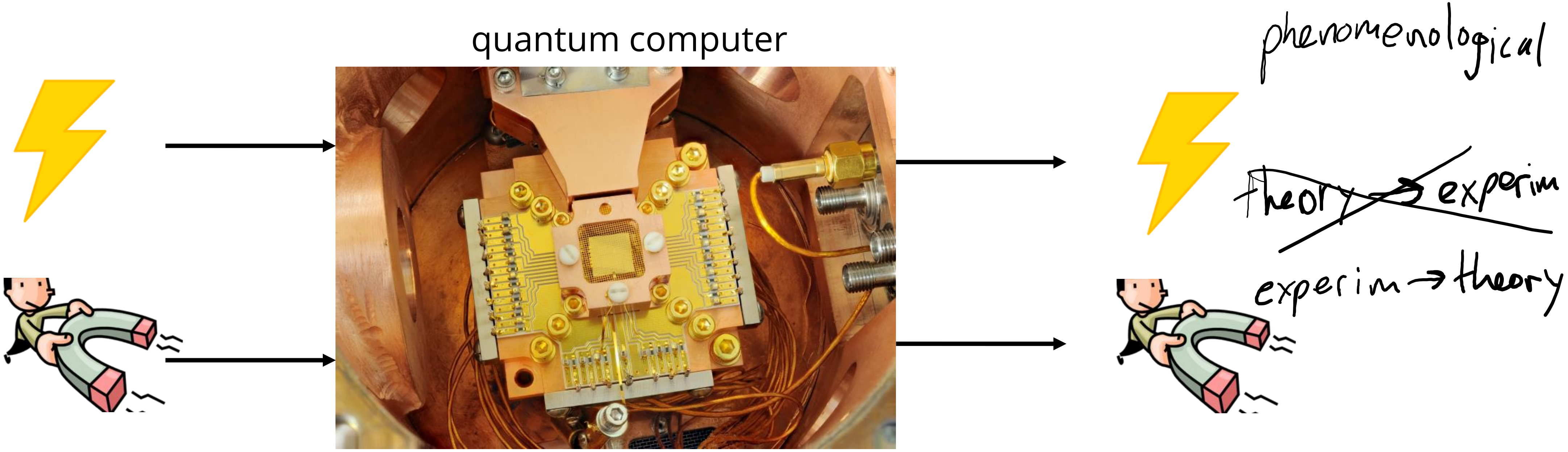
WHY ALL THE MATH?



- Qubits show effects like superposition, interference, and entanglement. Quantum computers use these effects to perform computations
- **The math is our attempt at describing and visualizing the physics in a quantum computer**
- **Why use vectors for qubits?** They can't be described by just a single current or magnetic field number → 0.5
- **Why use complex numbers for qubits?** Interference cannot be easily described by real numbers
- **Why use matrices for quantum gates?** Gates change qubits in the same way that matrices change vectors

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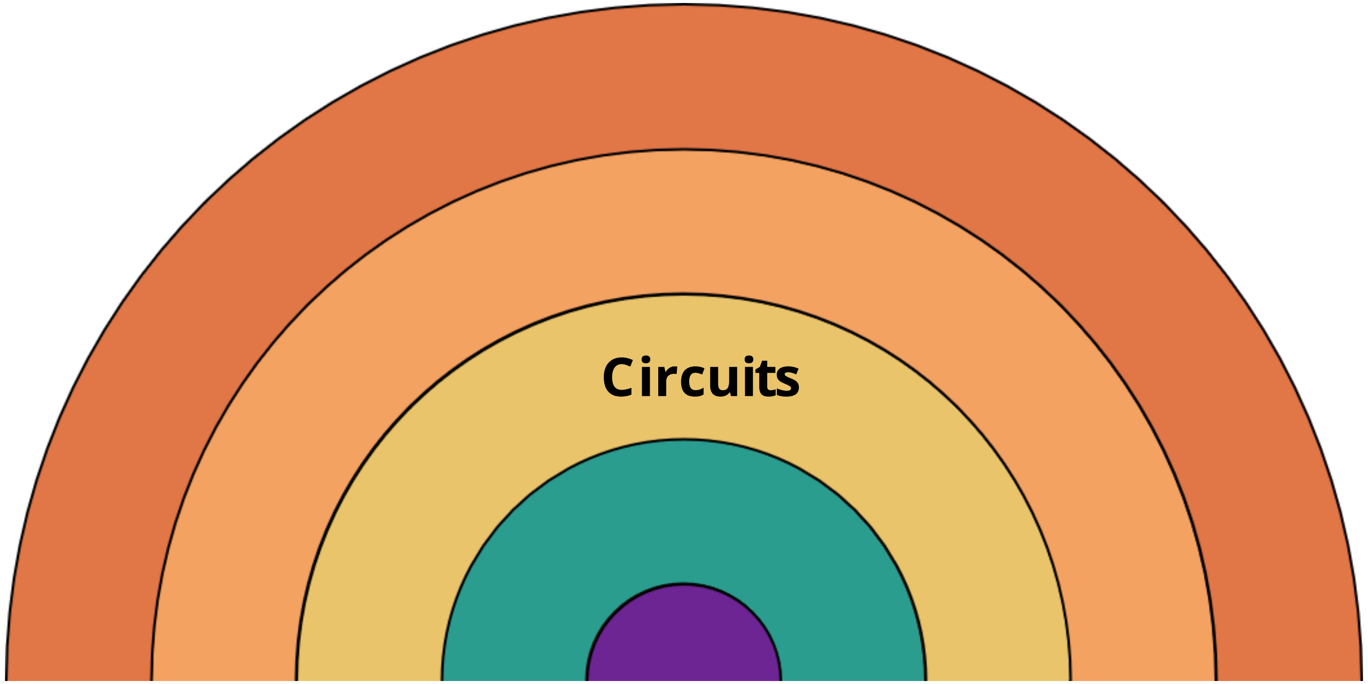
THE THREE QUANTUM RESOURCES

These three resources contribute to quantum speedups

- **Superposition:** $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$
  - N qubits can be in a combination of 2^N classical states
  - **Implication:** Quantum computers use fewer resources than classical computers to represent a lot of information
- **Interference:**
  - Some of the classical states in superposition can cancel out, and some can add up
  - **Implication:** Quantum computers can converge to the “right” solution by canceling out the wrong choices and amplifying the right one
- **Entanglement:** $|\psi\rangle = 1/\sqrt{2}|00\rangle + 1/\sqrt{2}|11\rangle \neq (\alpha|0\rangle + \beta|1\rangle)(\gamma|0\rangle + \delta|1\rangle)$
  - Some multi-qubit states cannot be represented classically
  - **Implication:** Quantum computers can access states that are inaccessible to classical computers

Relevant course weeks: 11, 12, 13, 20, 21

QUANTUM CIRCUITS



- We combined states, gates and measurements to create quantum circuits
- We used **qiskit**, a python library by IBM, to create and run quantum circuits

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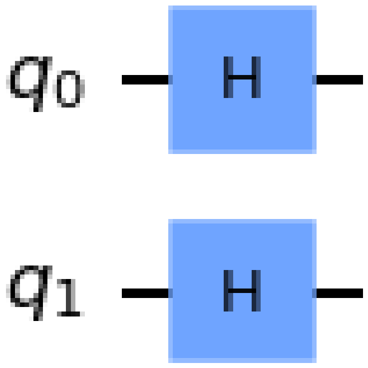
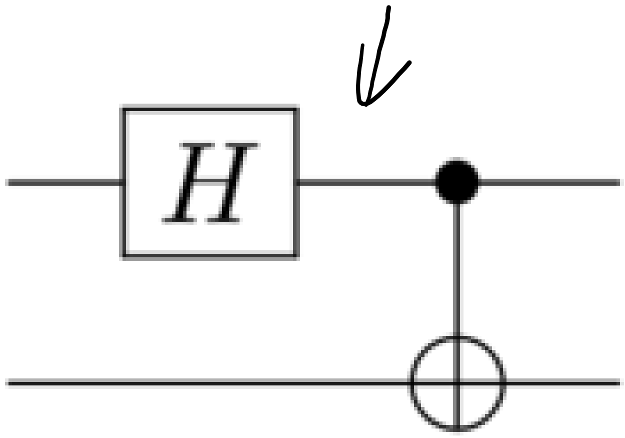
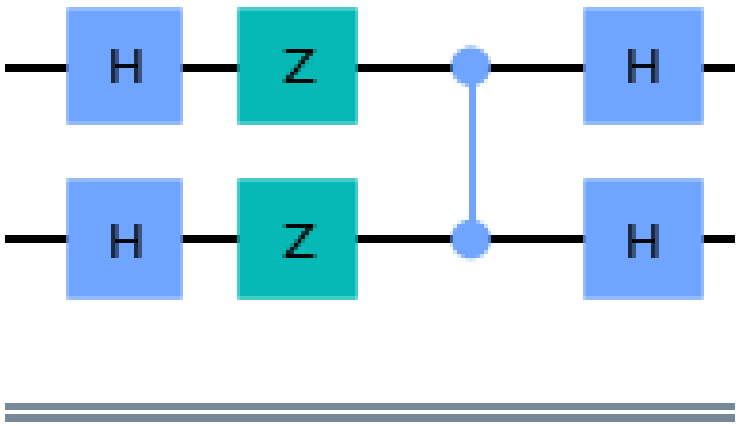
EXAMPLES OF QUANTUM CIRCUITS



Putting qubits in superposition



Bell measurements



2-qubit Grover diffusion circuit

Relevant course weeks: 6, 7, 15,16, 17

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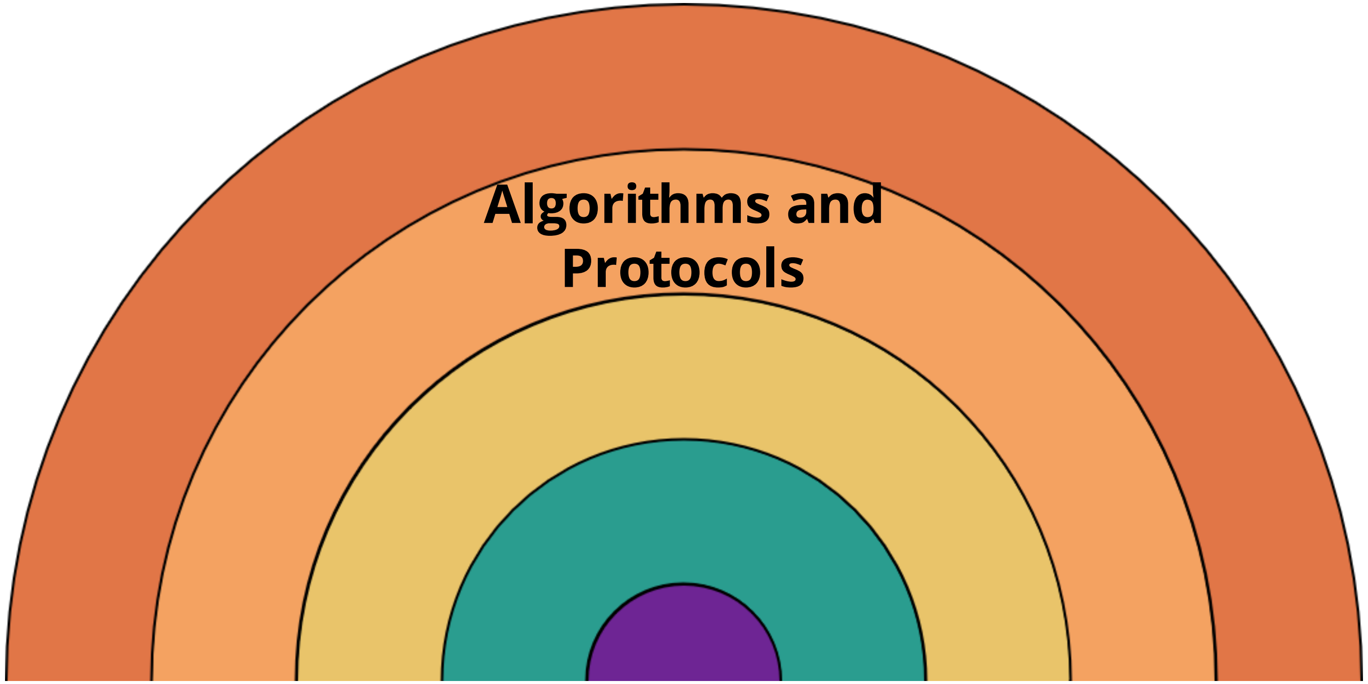
USING QISKIT TO CREATE AND RUN CIRCUITS

- 4 steps of running circuits using qiskit

- Step 1: Circuit creation
  - We tell the computer to initialize qubit states and add gates
- Step 2: Circuit simulation (statevector simulator/QASM simulator)
  - We tell the computer to simulate the circuit using quantum mechanics ~10q
- Step 3: Running on hardware (ibmq_belem, ibmq_5_yorktown…..)
  - We tell the computer to send the circuit to IBM's quantum hardware to execute and make measurements
- Step 4: Evaluate outcome, quantify errors

Relevant course weeks: 6, 7, 15, 16, 17

ALGORITHMS AND PROTOCOLS



- A **quantum algorithm** is a set of steps that uses quantum resources to provide a speed advantage for **certain types** of problems
- To carry out the algorithm, we translated it to a circuit, and coded it using qiskit

Relevant course weeks: 18, 19, 20, 21

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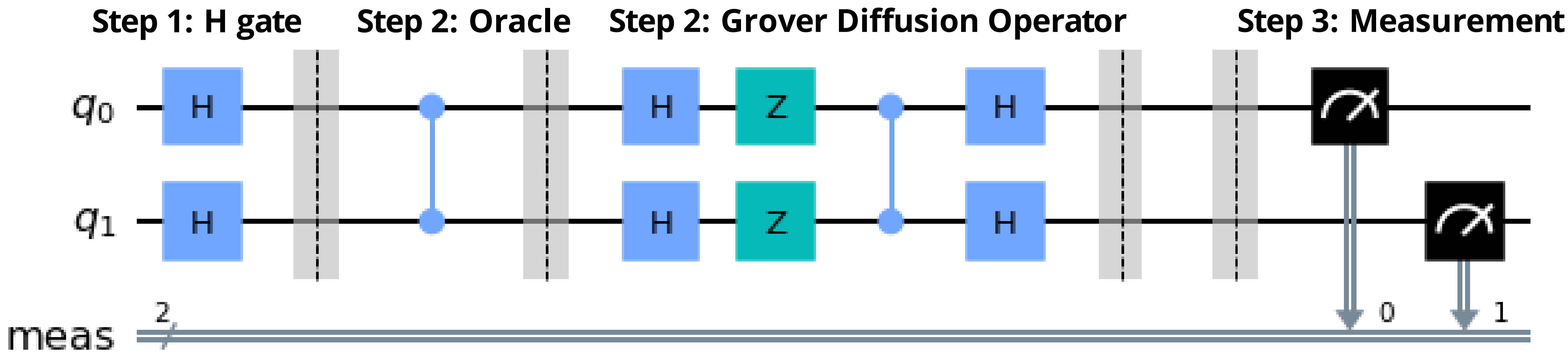
GROVER'S ALGORITHM

- Steps in Grover's algorithm:
  1. Apply H gate to all qubits – **superposition**
  2. Apply **oracle** to all qubits, and apply Grover's **diffusion operator** – **interference**
  3. Measure all qubits



through simulations and hardware!

Relevant course weeks: 18, 19, 20, 21

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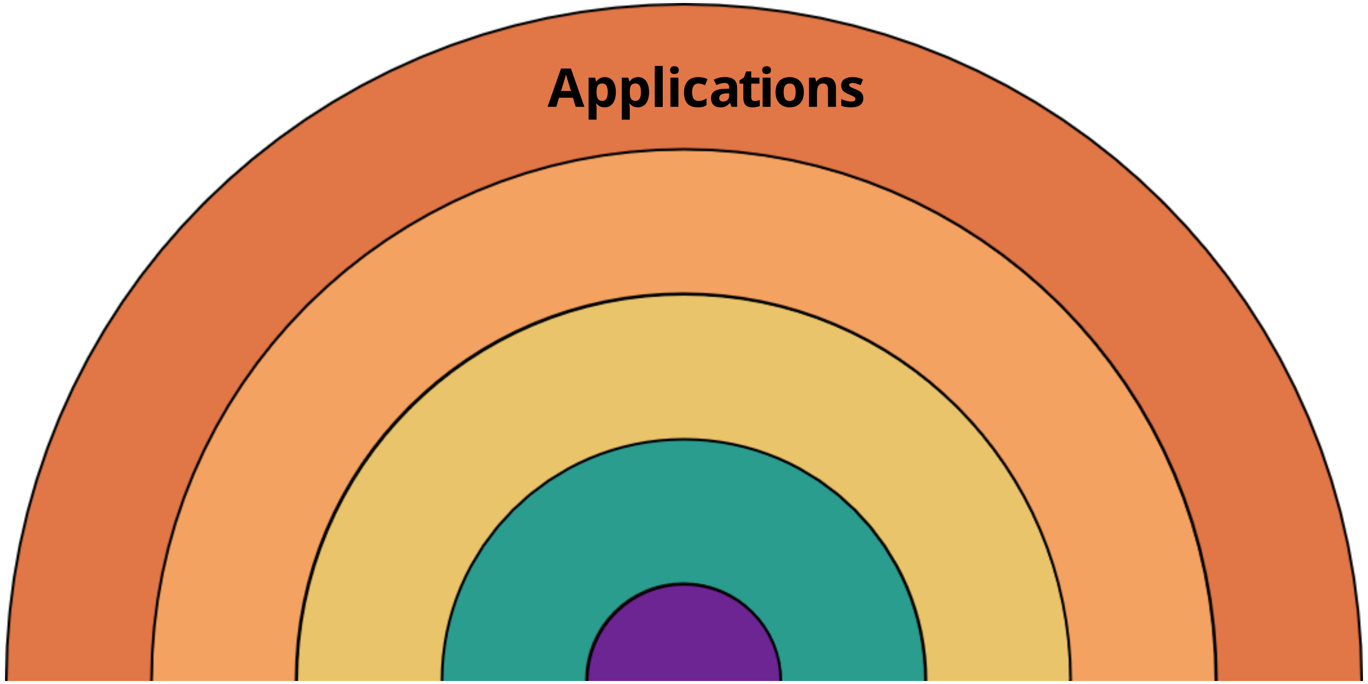
APPLICATIONS



~~Linear combination~~ → sum

~~Oracle~~ → function

Relevant course weeks: 1, 10

- Quantum algorithms are aimed at solving real-world problems!
- **Grover's algorithm**: Database search, optimization problems
  - Finance
  - Ecology
  - Chemistry
- **Shor's algorithm, quantum key distribution**: Cybersecurity, cryptography
- Simulation of quantum systems ←

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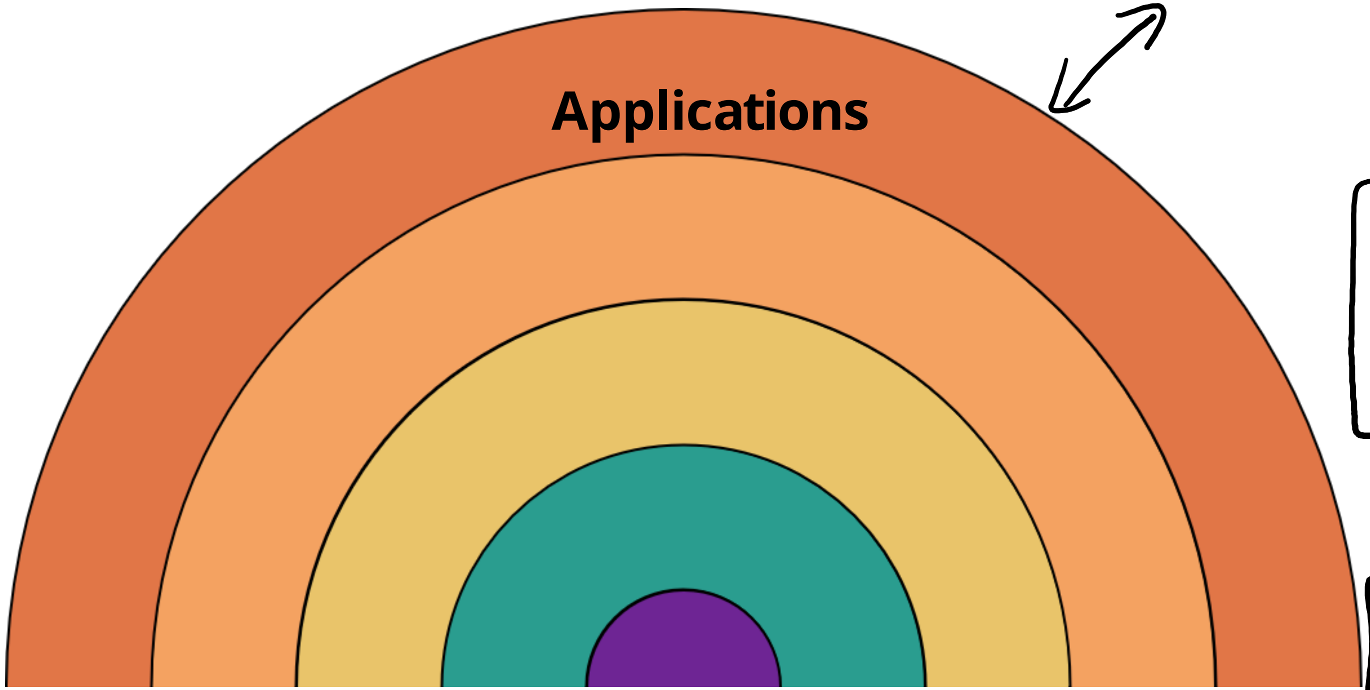
QUESTIONS AT DIFFERENT LEVELS

What questions do people think about at different levels of the tree?



- Can we predict what quantum computers will be useful for in 10 years? 50 years?
- What are quantum computers useful for right now? What can we do with noisy quantum computers? (**coming up next week!**) NISQ
- How can businesses prepare for quantum technology?
- How can society prepare for changes in the workforce due to quantum technology?
- How can we ensure equitable access to these new technologies?
- .....

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QUESTIONS AT DIFFERENT LEVELS

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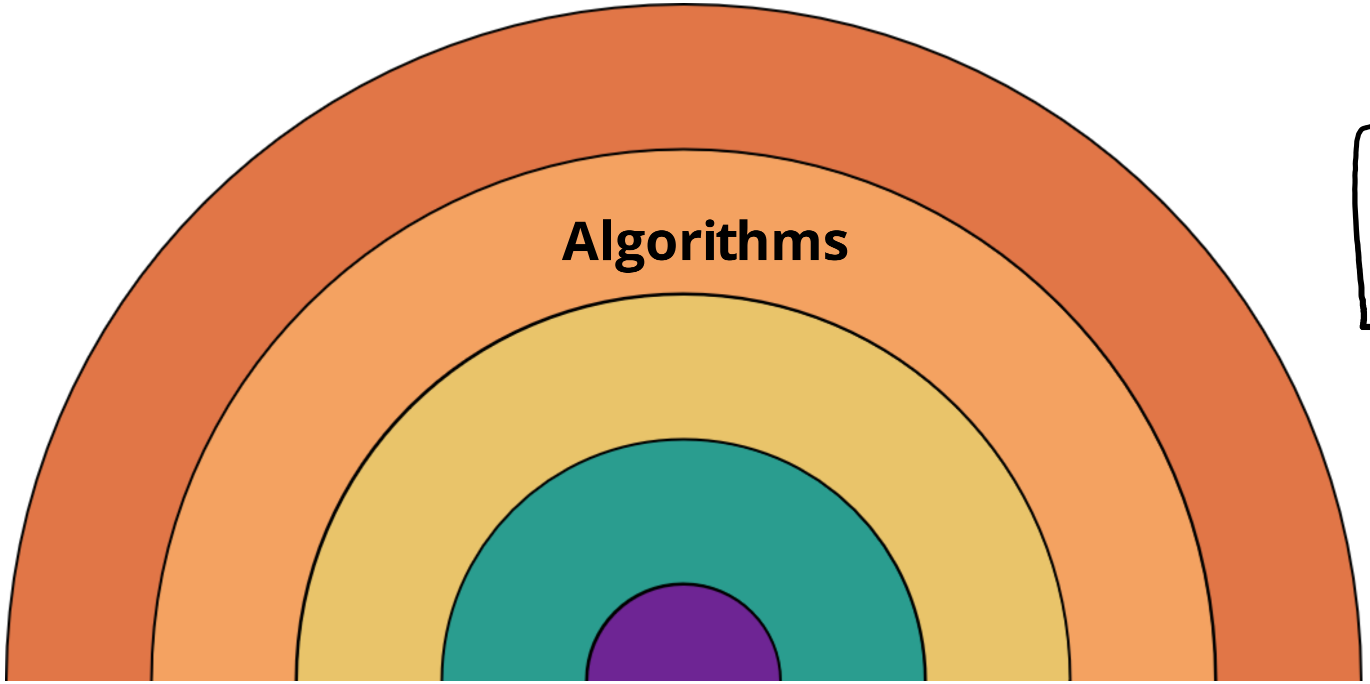

- How many qubits, and what level of connectivity, do we need to implement different quantum algorithms?
- Can we make fault-tolerant algorithms?
- Can we find new quantum algorithms to solve problems faster than classical computing?
- What is the complexity of quantum algorithms? Are there fundamental limits to the types of problems that quantum computers can solve?
- ……

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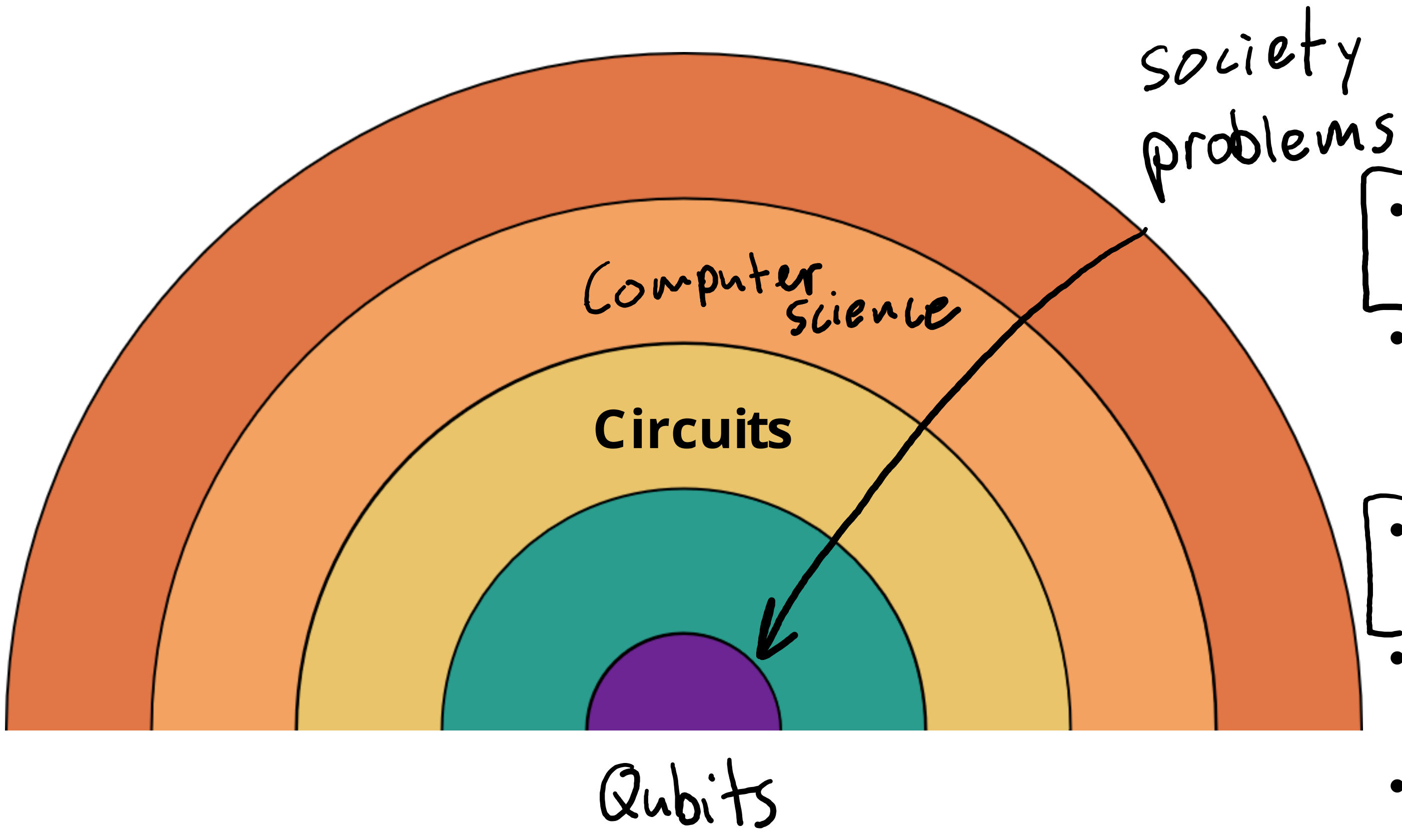

- What is the gate fidelity for this quantum processor?
- How can we convert a given circuit into one that can be implemented on the quantum processor?
- How do we convert code into an optimized circuit?
- Can we make circuits fault-tolerant? Can we correct errors made in a circuit?
- .....

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QUESTIONS AT DIFFERENT LEVELS

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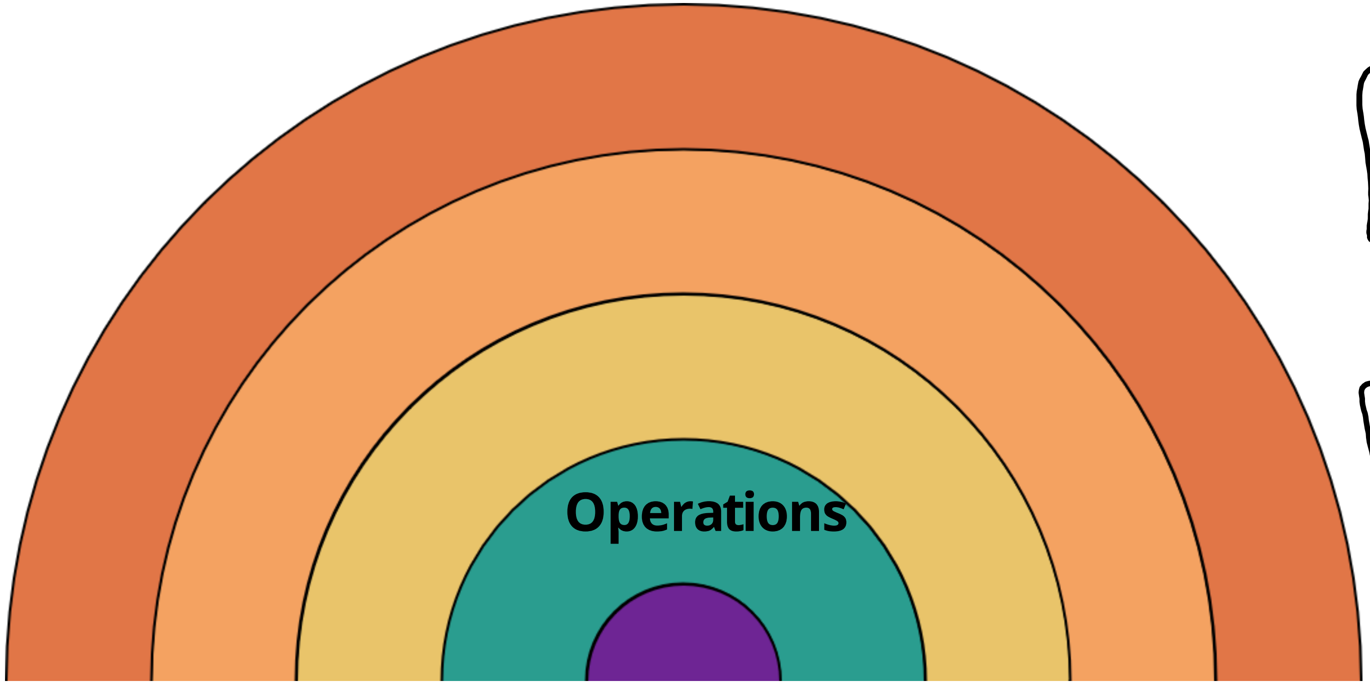

- How can we best engineer pulses to perform gate operations on superconducting qubits?
- Which types of gates are possible to apply with diamond N-V qubits?
- How can we measure qubit states in a way that doesn't increase the chances of them being disturbed by the environment?
- How can we mathematically model the interactions between qubits in this technology?
- ……

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QUESTIONS AT DIFFERENT LEVELS

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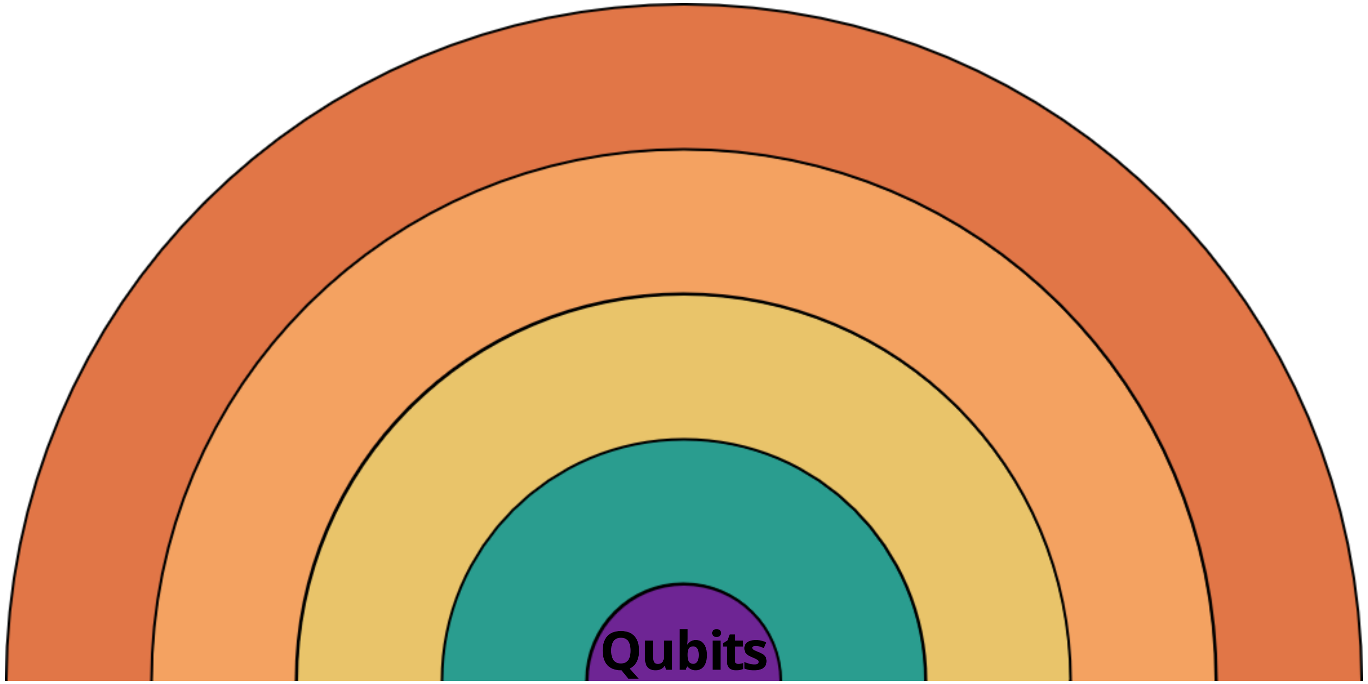

- How can we improve the coherence time for a particular qubit technology?
- Can we engineer new types of superconducting qubits which have lower errors?
- How can we improve the fabrication process for diamond N-V centers to control the number and placement of defects?
- How can we make qubits interact with each other reliably, to apply 2 qubit gates?
- .....

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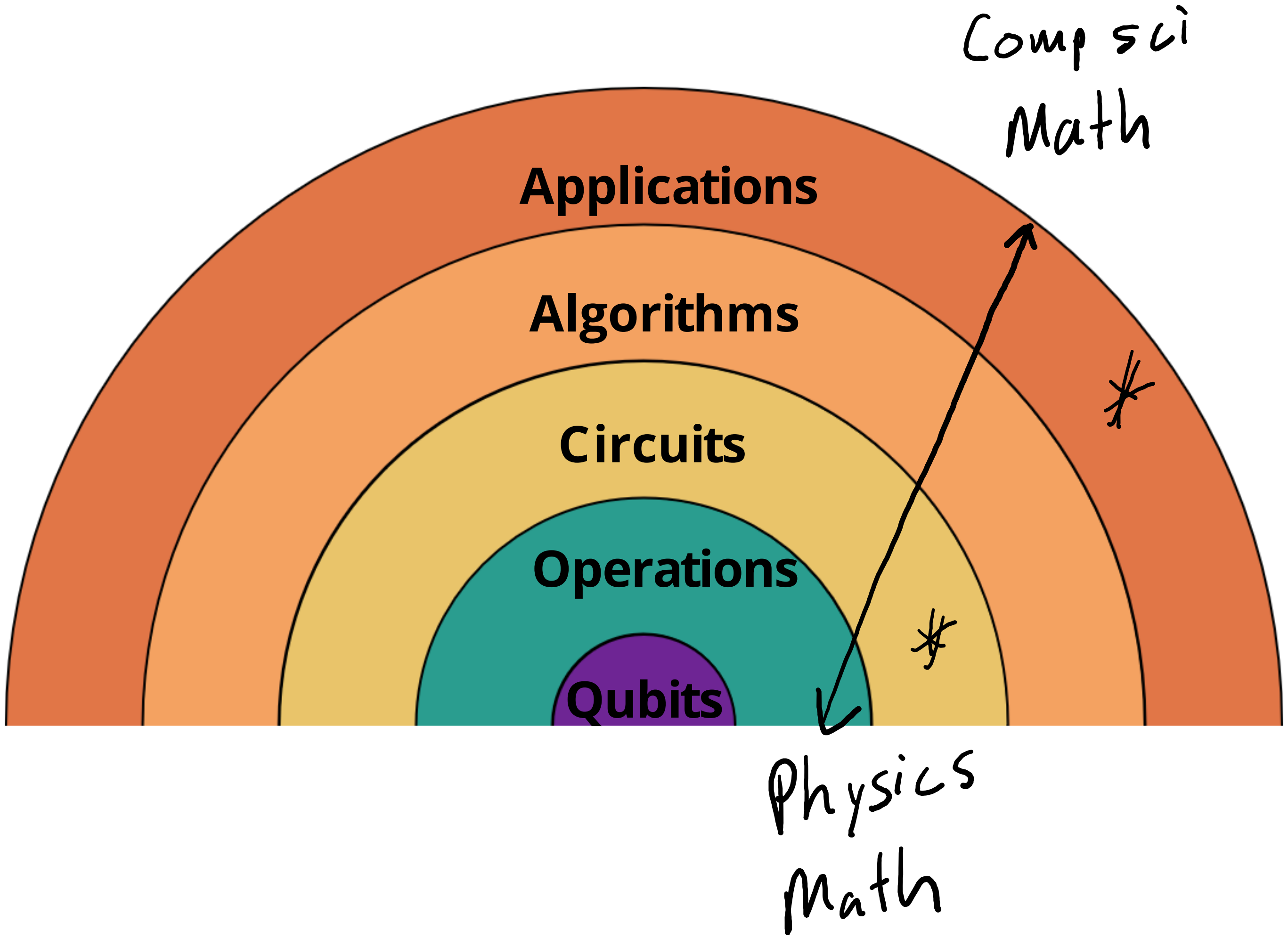
WHAT DO YOU FIND MOST INTERESTING?



Which level(s) of the stack do you find interesting? What would you like to work on? ☺

KEY TAKEAWAYS

- You've come so far!

- The skills (such as linear algebra, probability, coding) you learnt in this course are useful in many other STEM fields, not just quantum computing

- Quantum computing is a rapidly growing, interdisciplinary field. There is a place for all of you! Find a question that interests you, and you'll find a community of people to collaborate with

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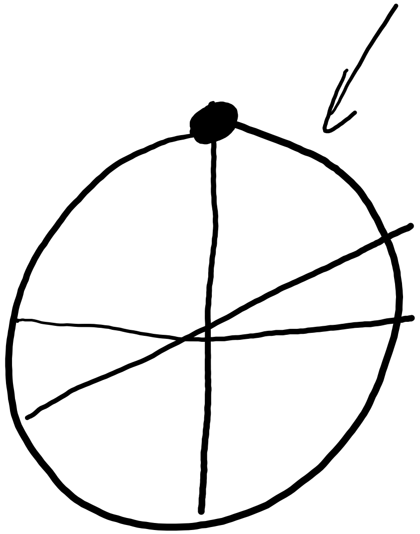
FURTHER READING AND RESOURCES

- QxQ reading and resource guide (on Canvas)
- Unitary fund hackathon (May 14-30)
- QOSF open-source quantum projects
- Akshay's Youtube playlist of QIS videos

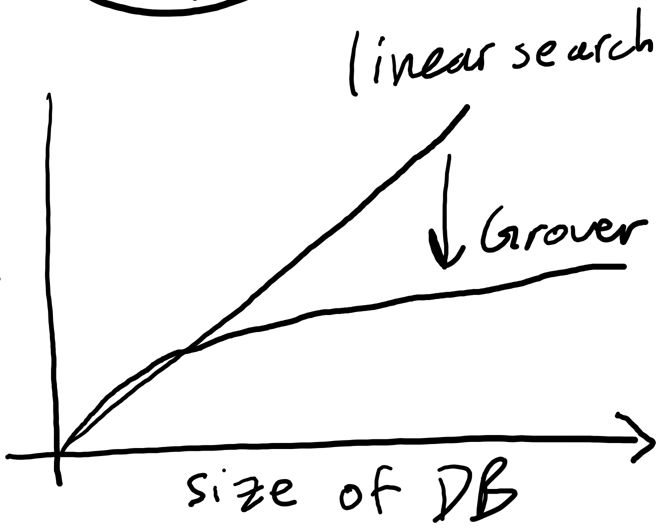


$O(\sqrt{N})$

$|1\rangle - |0\rangle$

$|1\rangle + |0\rangle$

[{superposition, phase}] Time



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POST-LAB ZOOM FEEDBACK

After this lab, on a scale of 1 to 5, how would you rate your understanding of this week's content?

- 1 –Did not understand anything
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