OAK RIDGE National Laboratory | LEADERSHIP COMPUTING FACILITY

2025 OLCF HPC Crash Course

Quantum Computing Primer

Dr. Michael Sandoval, Dr. Jordan Winetrout, Dr. Ryan Landfield

National Center for Computational Sciences

U.S. DEPARTMENT OF ENERGY

ORNL IS MANAGED BY UT-BATTELLE LLC
FOR THE US DEPARTMENT OF ENERGY

Agenda / Overview

- QCUP Overview
- What is Quantum Computing? (in a nutshell)
- Why is it important?
- Deep dive into the building blocks
    - Entanglement
    - Superposition
    - Quantum Principles
    - Quantum Computing (for real this time)
- Conclusions (i.e., apologize for the fire hose of information)

Quantum Computing User Program

Enable Research

Provide a broad spectrum of user access to the best available quantum computing systems

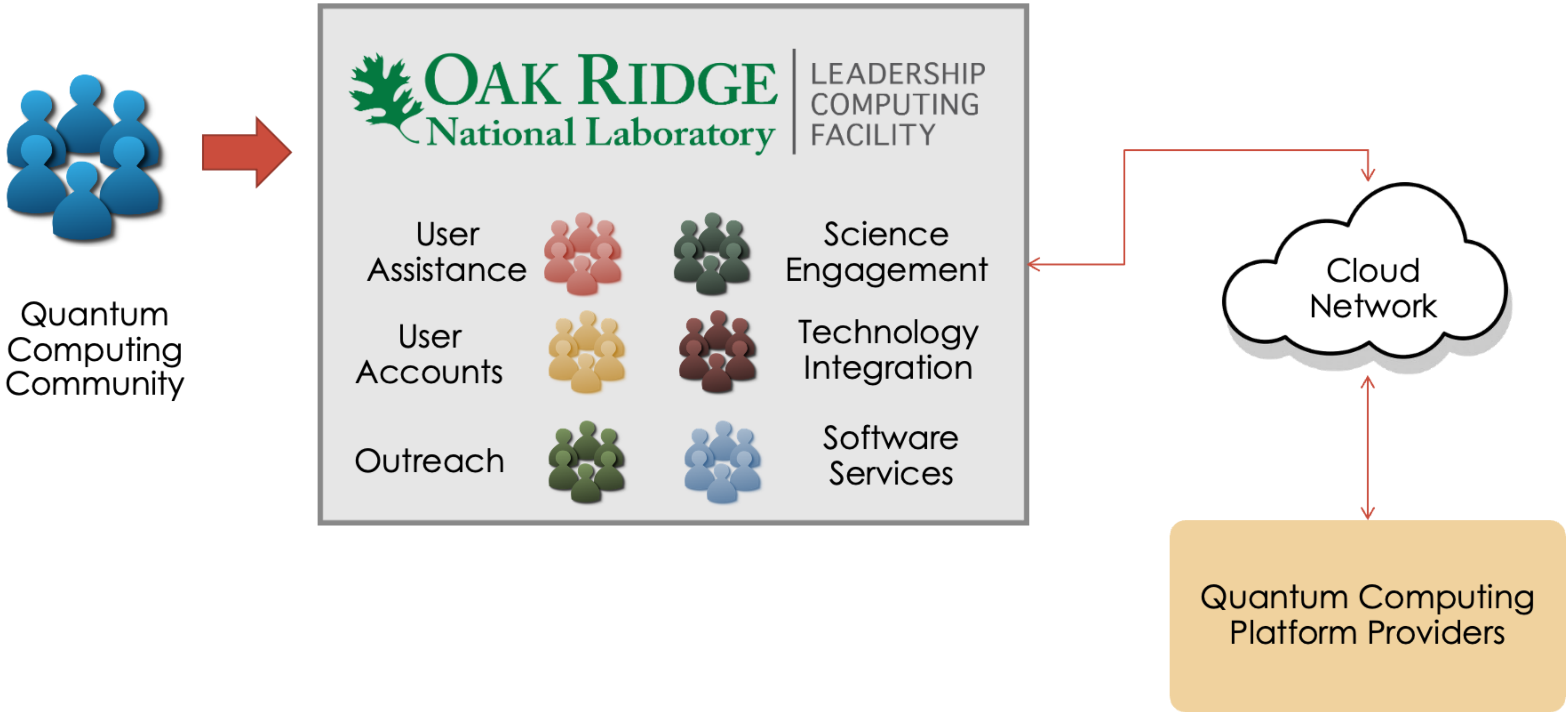
Evaluate Technology

Monitor the breadth and performance of early quantum computing applications

Engage Community

Support growth of the quantum ecosystem by engaging with users, developers, vendors, and providers

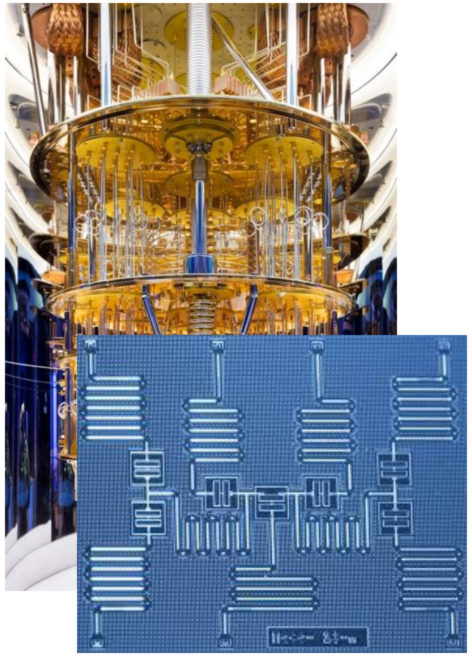
QCUP Operations Model: Cloud Access



Multiple Quantum Computing Resources

IBM Quantum

General-purpose trasnmon systems provide up to 156 qubits



IQM

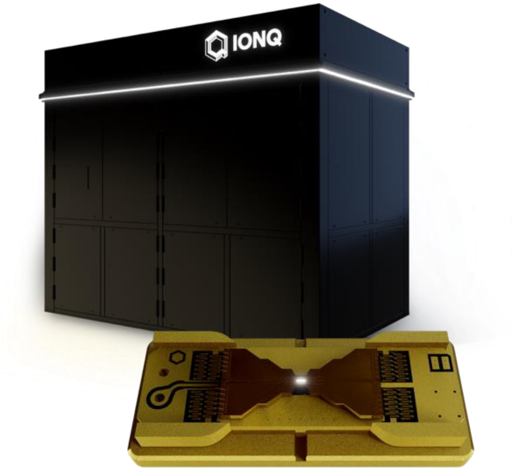
General-purpose trasnmon systems provide up to 56 qubits

Quantinuum

General-purpose ion trap systems provide up to 56 qubits

IonQ

General-purpose ion trap systems provide up to 36 qubits



Current system count is 18

What is Quantum Computing?

- In Quantum Mechanics, a wave function ("state") describes knowledge of a system
- Quantum Computing (**QC**) involves manipulating this wave function to do computation while taking advantage of quantum "effects"
    - **<u>Entanglement</u>**: correlations between different parts of quantum system
        - "spooky action at a distance"
    - **<u>Superposition</u>**: representing multiple possible system configurations at the same time

<u>Schrödinger Equation</u>

$$i\hbar \frac{\partial}{\partial t} \Psi(t) = H(t)\Psi(t)$$

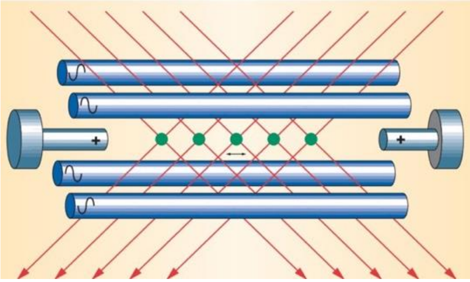
Wave function Energy / "Hamiltonian"

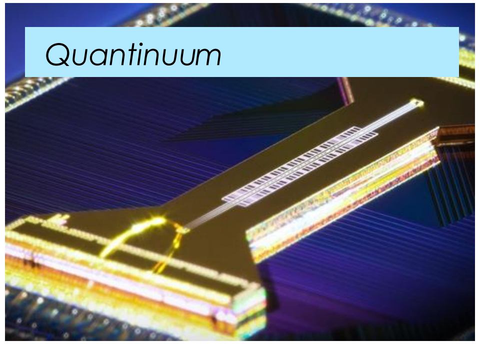
What is a Qubit?

- A qubit is the quantum equivalent of a classical bit!
- While a classical bit can only be 0 or 1, a qubit can represent 0 and 1 at the same time!
  - With **N** qubits you can represent **2^N** configurations! (e.g., for N=50 → 1,125,899,906,842,624)
    - 1 qubit: 0, 1
    - 2 qubits: 0 0, 0 1, 1 0, or 1 1
  - Helps solve problems that scale exponentially
  - Nifty trick, but introduces “noise” (will talk about this more later)
- Physical representation depends on the technology
- Classical computers can only simulate so many qubits before running out of memory…

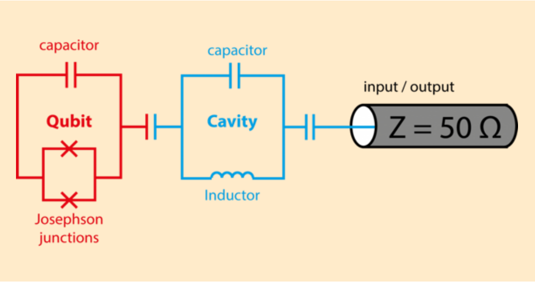
Many Types of Technology

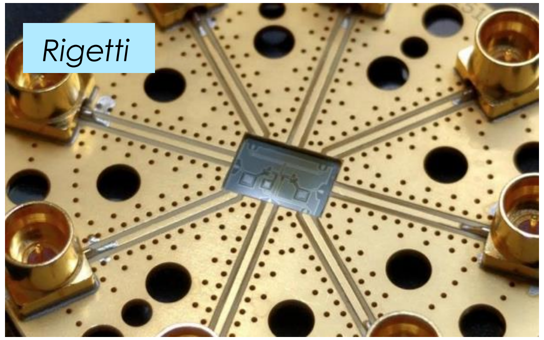
"Trapped" Atoms & Ions

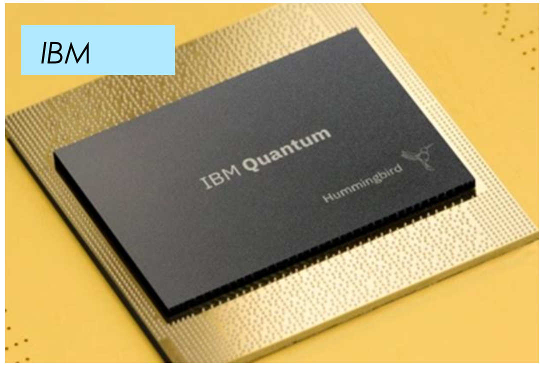




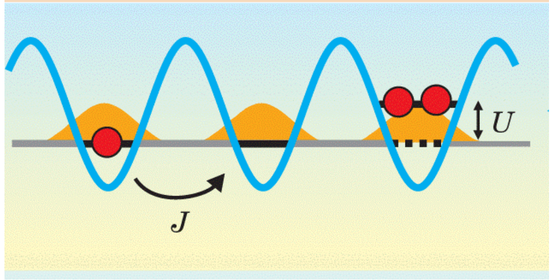
Superconducting Material

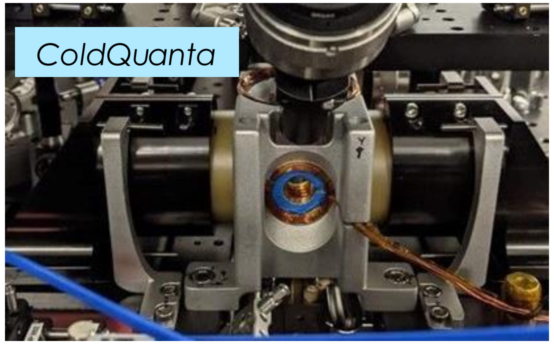


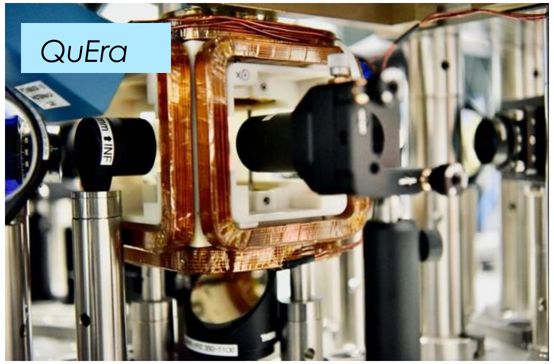




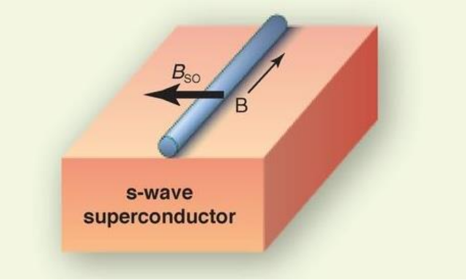
Neutral Atoms

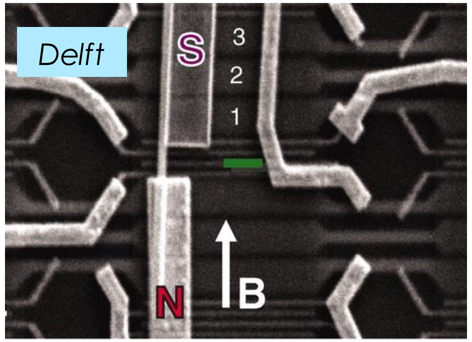


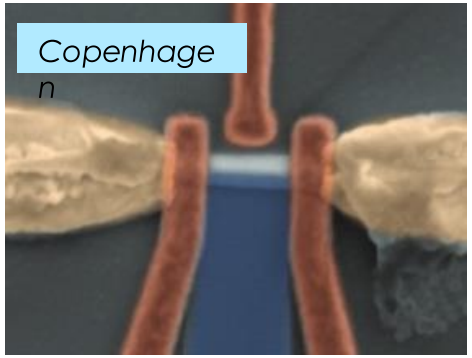




Topological Materials







Why is QC Important?

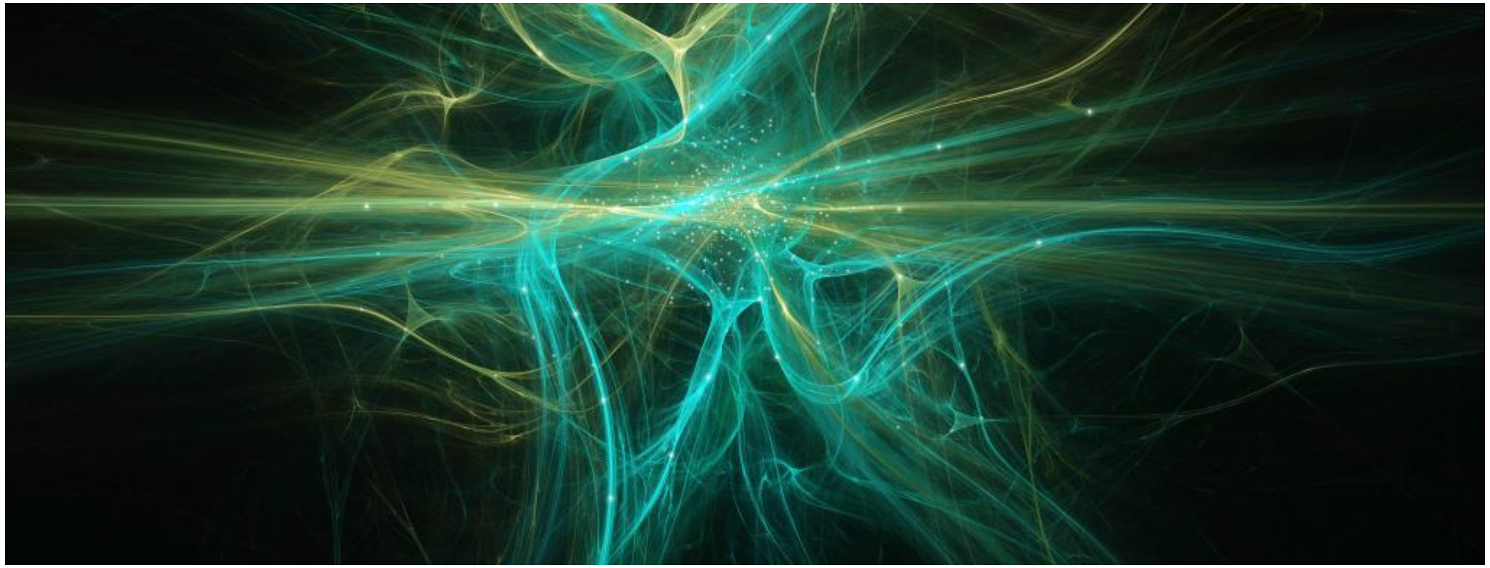
Nature is quantum mechanical

Breakthrough Potential for Intractable Problems

- New models of computation capable of addressing classes of problems that are infeasible for classical HPC
  - Factoring large integers
  - Simulating quantum systems
  - Optimization and sampling problems
  - Sorting massive datasets
- Strategic complement to HPC
  - QC won't replace high-performance computing, it's not suited to
  - QC is poised to act as an accelerator & force multiplier for specific problem domains
- Quantum computing is increasingly viewed as a critical technology, necessary for global competitiveness

Quantum Simulation for Scientific Discovery

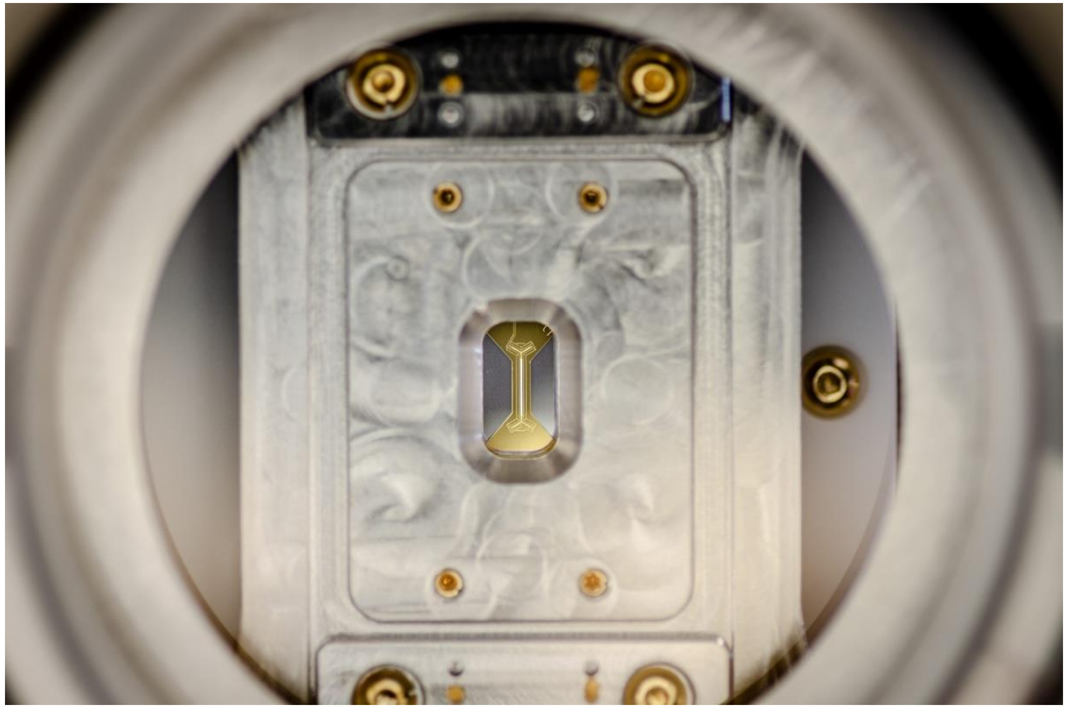
- Simulating quantum systems (many body systems and entangled particles) is exponentially hard classically but naturally suited for quantum computers, in fields such as Materials Science, Chemistry & Quantum Chemistry, and Nuclear Physics
- Pathway to Breakthroughs in Materials and Drug Discovery
    - QC enables accurate modeling of molecular systems (e.g. novel catalysts, high-temperature superconductors, and proteins), accelerating innovation in pharmaceuticals, quantum materials, etc.
- Complementary to HPC in Multiscale Modeling
    - Augmentation of Classical HPC workflows by tackling quantum-scale bottlenecks



Optimization and Machine Learning Use Cases

Quantum approaches (e.g., QAOA, quantum kernel methods) show promise for improving solutions to complex optimization and machine learning problems.

- QAOA: Quantum Approximate Optimization Algorithm, used for combinatorial optimization
  - Supply chain logistics
  - Traffic flow/vehicle routing
  - Manufacturing scheduling
  - Risk minimization
  - Power grid load balancing
- Machine learning
  - Quantum Kernel Methods
  - Variational Quantum Classifiers (VQCs)
  - Quantum Generative Models (QGANs)



Rapid Advancements in Hardware and Algorithms

We're transitioning from NISQ to early fault-tolerant regimes in the near term.

Progress in error correction, qubit scaling, and benchmarking continues to open new frontiers for exploration and utility.

- Scaling hardware toward fault-tolerance
- Smarter algorithms for noisy hardware
- Benchmarking, HPC integration/Hybrid runtimes/Co-processing workflows

Interdisciplinary Catalyst for Workforce Development

- QC Upskilling:
  - The field uniquely drives cross-disciplinary engagement, uniting physics, computer science, math, and engineering
- Training the Next Generation:
  - QC presents unique challenges and opportunities for training the next generation of computational scientists, HPC integration specialists, and cross-domain application experts & communicators.
- Bridging Research and Real-World Impact
  - Translation from theory into real-world use cases, mapping to emerging industry and research needs

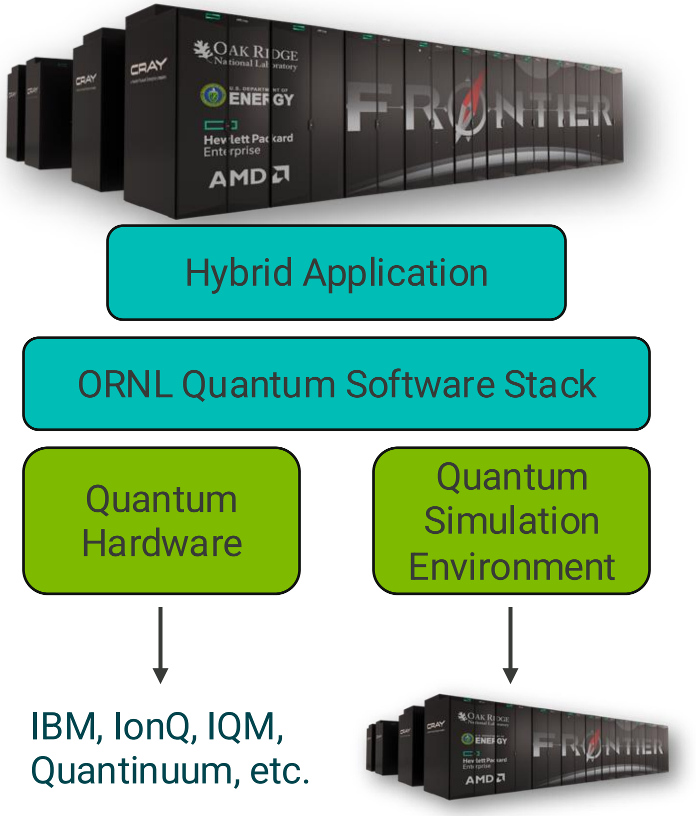
Urgency of Leadership-Class Integration

Quantum systems must be tightly integrated with classical HPC environments to be useful at scale.

Leadership facilities like the OLCF have a critical role in key areas:

- Benchmarking:
- Infrastructure co-design:
- Workflow development:

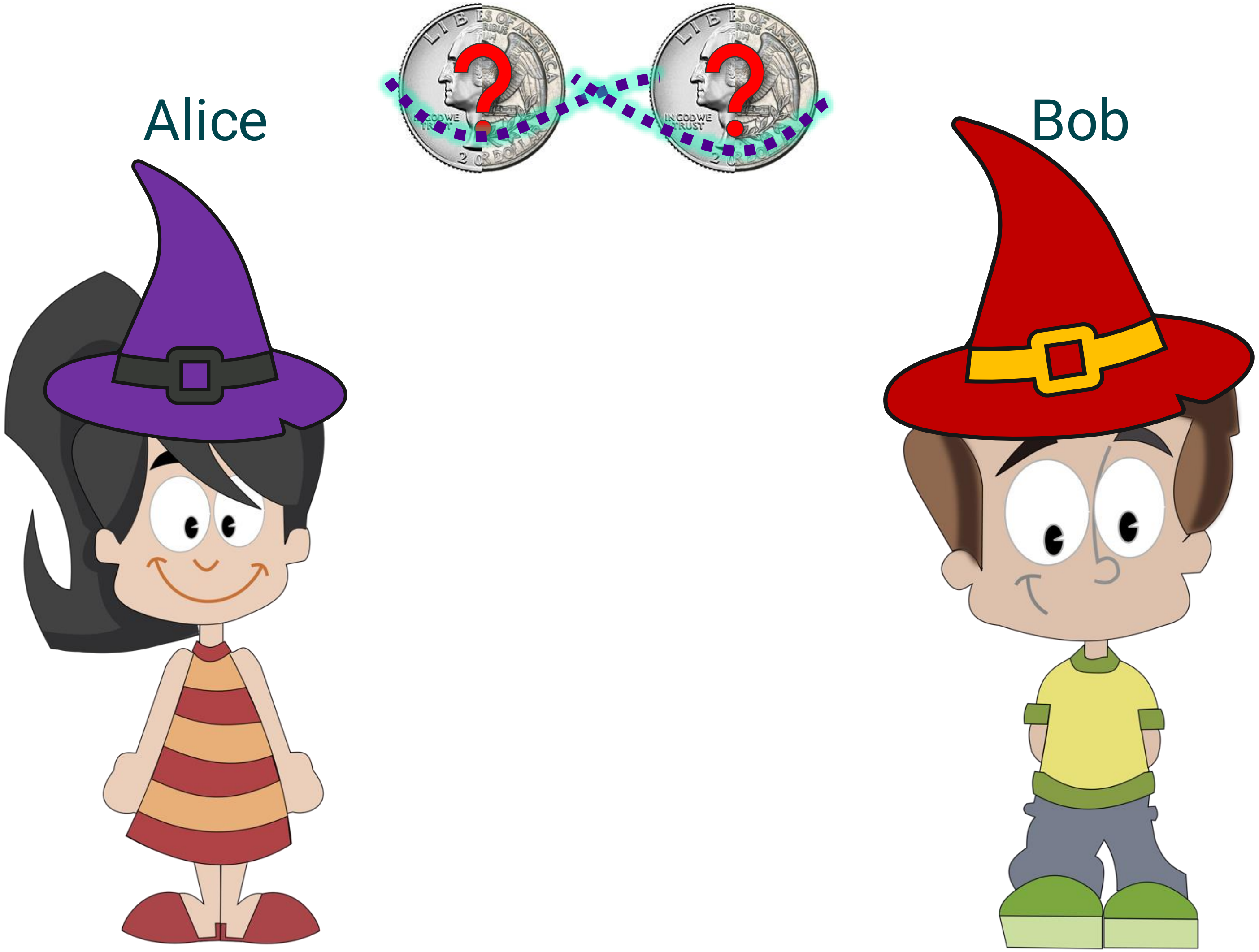
All needed to prepare for practical quantum advantage.



Now, let’s get into the weeds a bit…

Entanglement

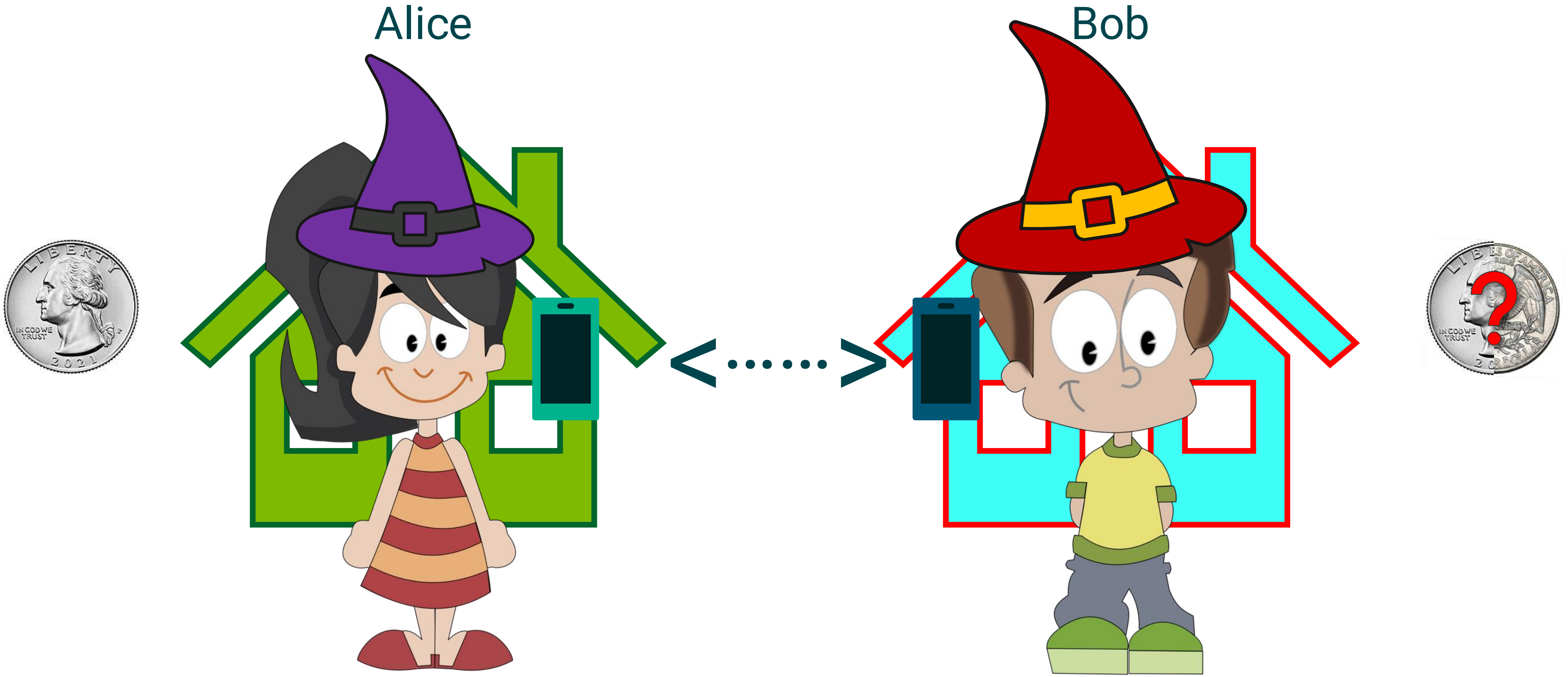
Entangled Coins



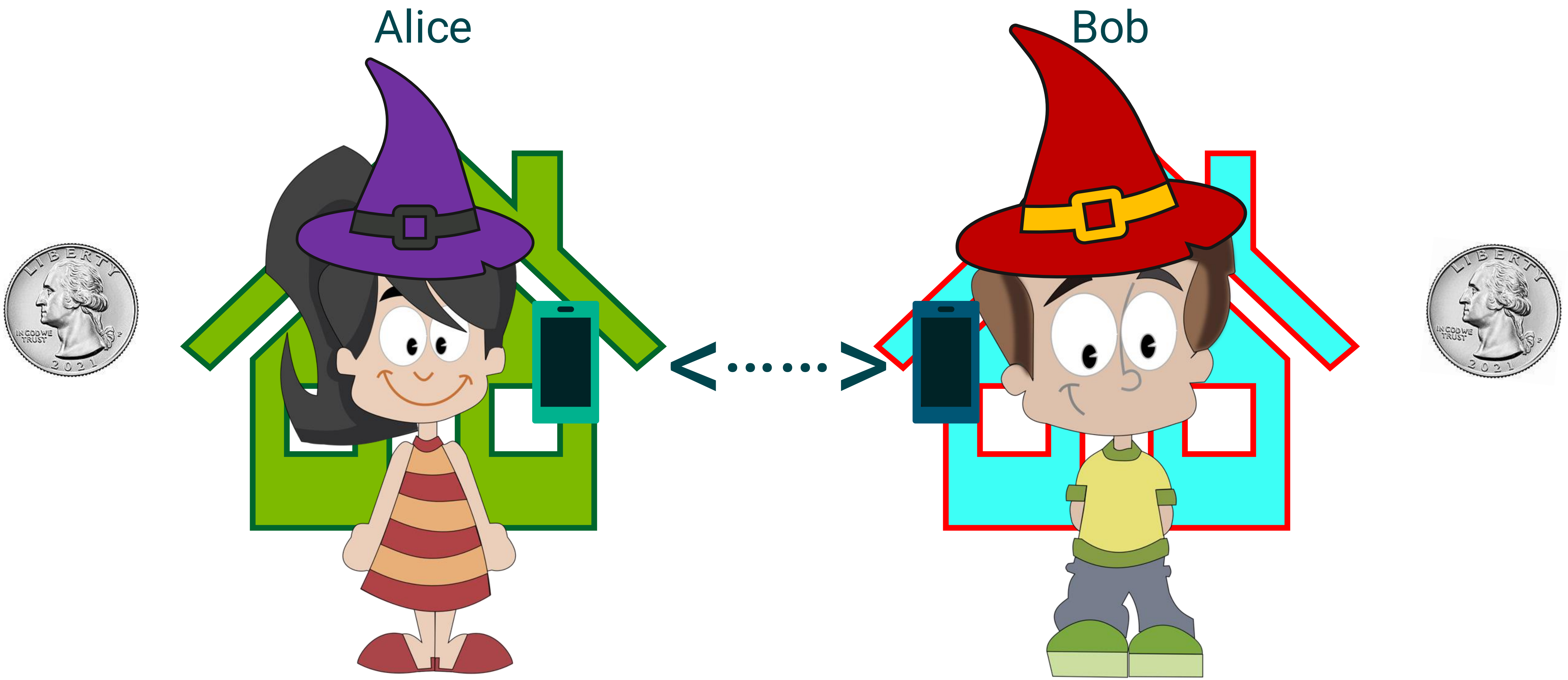
Entangled Coins

Entangled Coins

Entangled Coins



Entangled Coins



Charlie and Danielle example: Avoiding Confusion!

Charlie Danielle

Possible Combinations:

The takeaway: **Correlation**, not necessarily the combination

Charlie and Dainelle example: Avoiding Confusion!

Takeaways:

- The results were perfectly correlated
- The correlation persists over an infinite distance
- The outcomes were completely *uncertain* beforehand
- The correlation was instantaneous

Entanglement in a nutshell: "Spooky action at a distance"

- ”Spooky” - The coins (qubits in a superposition) had a *shared fate:*
  - By knowing the outcome of one coin, we *instantly* know what the outcome of the other, entangled coin will be (Note: this does *not* mean heads=heads every time!)
- "Action at a distance" – the *shared fates* persists over an infinite distance
- Vital for quantum parallelism, error correction, and so much more!
- **Not shown** more than 2 qubits can be entangled at a given time (as of mid-2025, up to 50 at once)

Entanglement isn’t just magical, it’s essential and practical

1. Quantum teleportation
2. Super dense coding
3. Massive parallelism
4. Error correction
5. Most quantum algorithms

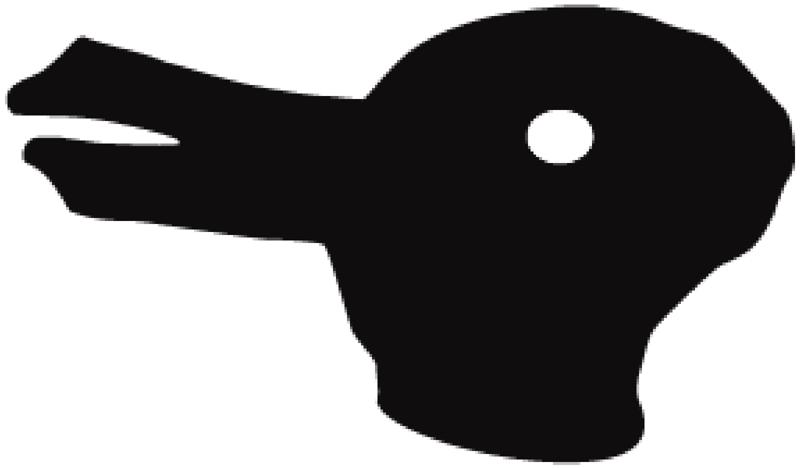
Superposition

Getting Your Mindset Ready (Superposition)

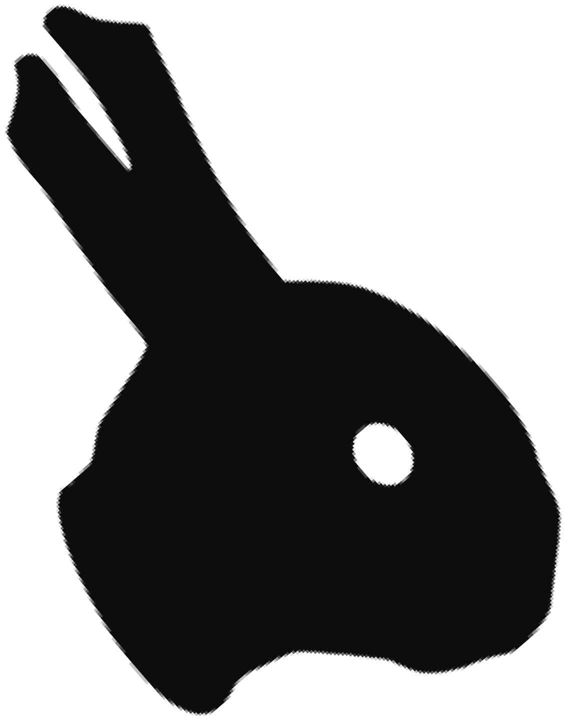
- At the end of the day, the power of quantum computing is that a qubit can be both a 0 and 1 at the same time.
- My goal is to convince you that one “system” can represent two (or more) “outcomes” at the same time, just like a qubit.
    - A “system” (e.g., a coin) is the thing you’re measuring or observing
    - An “outcome” (e.g., “heads” or “tails”) is the possible result when measuring or observing the system
- Let’s start small!

Superposition - I

- What is this?



A duck?

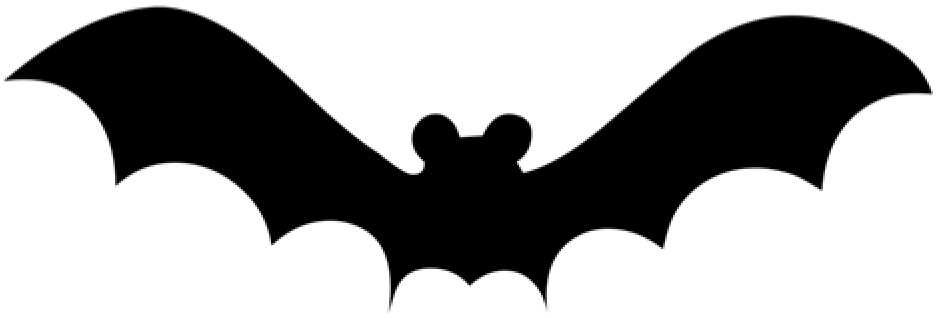


A rabbit?

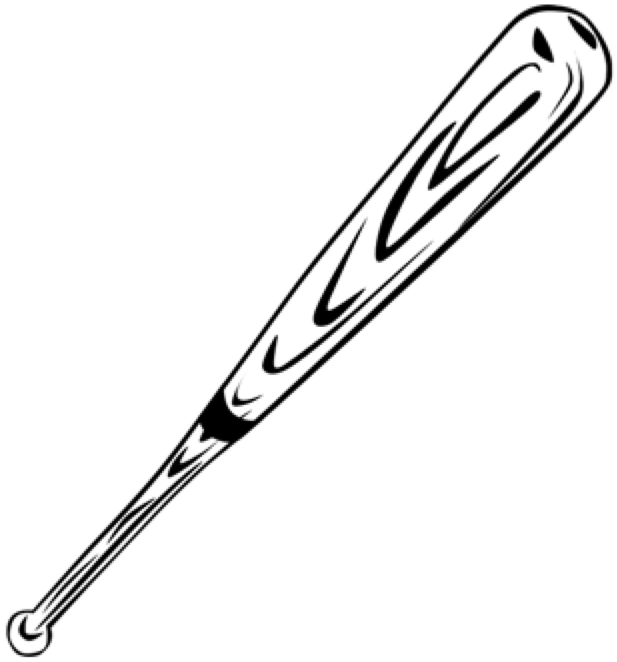
Depending how you look at it, it's a duck and a rabbit at the same time! Superposition!

Superposition - II

- How about these?



A bat?



A bat?

"Bat" meaning two things at the same time! Superposition!

Superposition - III

- If you flip a coin, and it's still in the air, you don't know what it's going to be yet
- It's both "heads" and "tails" at the same time. Superposition!
- Let's build off this example…

Quantum Principles

Diving into the math (...sorry)

Visualizing the Coin Example Differently

- Let's shift things into a math formula:

$$|coin\rangle = |tails\rangle + |heads\rangle$$

- But we know that it's a 50% chance for either outcome, so let's modify it a bit:

$$|coin\rangle = \frac{1}{\sqrt{2}}|tails\rangle + \frac{1}{\sqrt{2}}|heads\rangle$$

- This is our "quantum state"! (or "state vector")
- We find out the outcome when the coin lands -- that's when we "measure" our state, which will "collapse" it to the measured value
- If we measure "tails", then our state collapses to:

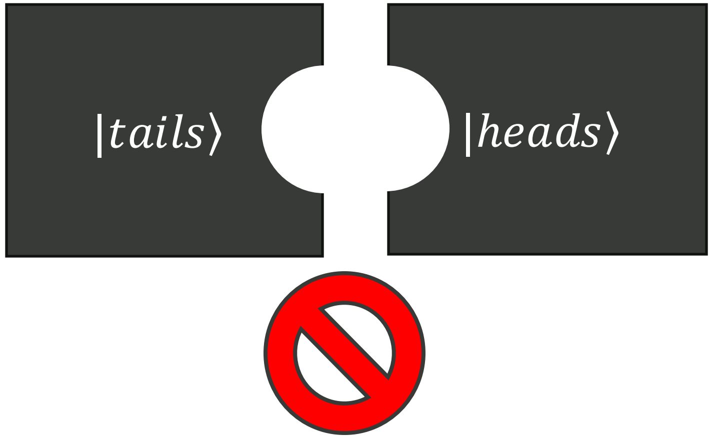
$$|coin\rangle = |tails\rangle$$

Putting Puzzle Pieces Together - I

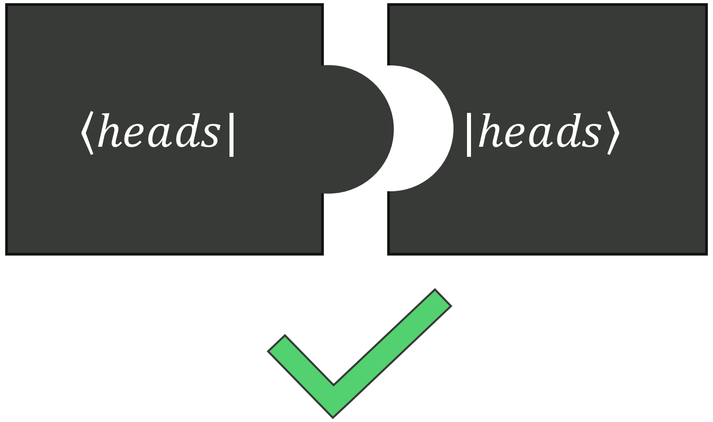
- Think of a quantum state like a combination of puzzle pieces
- Each puzzle you get will have corner pieces
    - They represent your core foundation/basis that you'll be working with

Putting Puzzle Pieces Together - II

- Some pieces fit together, some don't
- What would happen if you had an inverted form of your puzzle piece?
    - They would fit together!



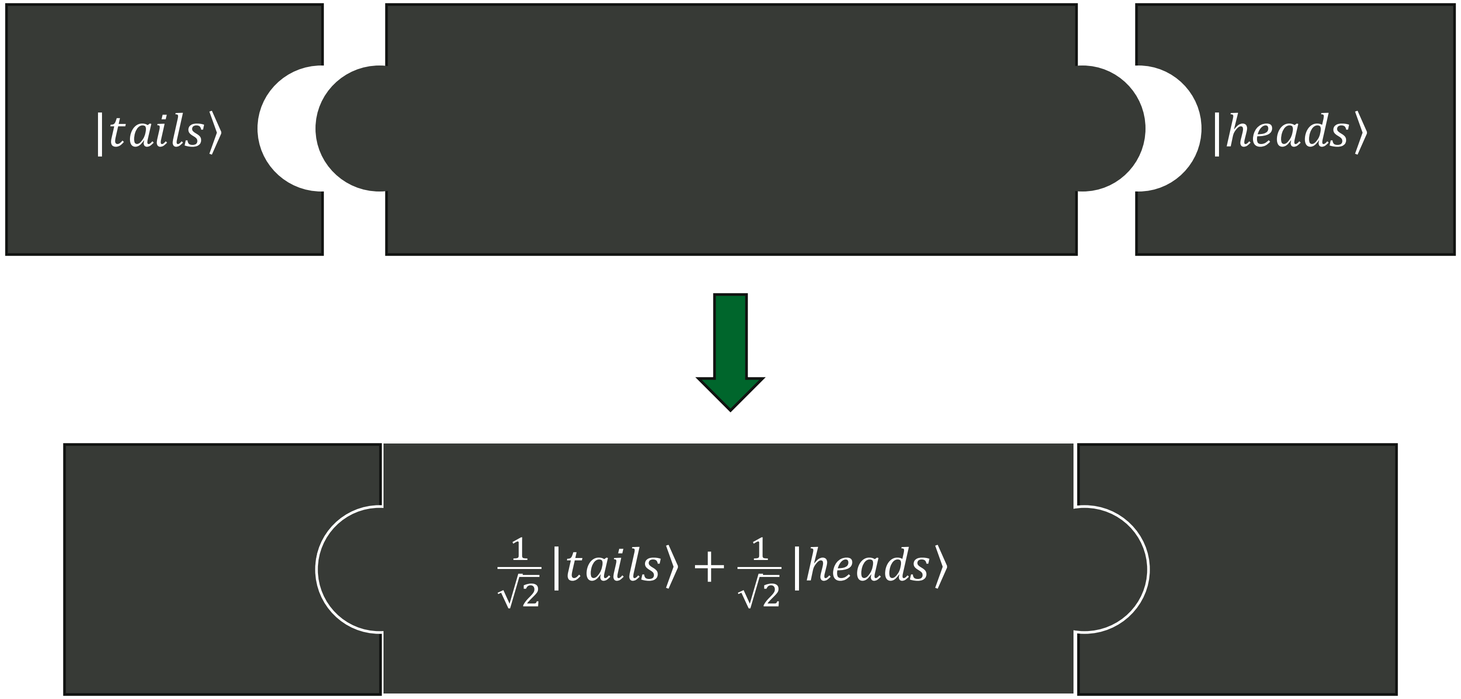
= 0



= 1

Putting Puzzle Pieces Together - III

- Based on how other puzzle pieces interact with each other determines what the final “picture” is



Quick Aside: Some Quantum Jargon and Math Principles - I

- The way we wrote out: $|coin\rangle = \frac{1}{\sqrt{2}}|tails\rangle + \frac{1}{\sqrt{2}}|heads\rangle$ is known as "**bra-ket notation**"

"*" Means complex conjugate (i.e., "i" goes to "$-i$")

- A "**bra**" is known as this: $\langle a|$. As a matrix it looks like this: $\begin{bmatrix} a_1^* & a_2^* & a_3^* \end{bmatrix}$

- A "**ket**" is known as this: $|a\rangle$. As a matrix it looks like this: $\begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}$

- The "inner product" (i.e., dot product) looks like this: $\langle a|a\rangle$
  - This is a matrix multiplication that results in a single number:

$$\begin{bmatrix} a_1^* & a_2^* & a_3^* \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = a_1^* a_1 + a_2^* a_2 + a_3^* a_3$$

Quick Aside: Some Quantum Jargon and Math Principles - II

- An "**eigenstate**" (or "eigenvector") is a type of quantum state that represents a specific result of measuring a physical quantity (like energy, spin, or momentum).
- The possible result itself that can be measured is known as an "**eigenvalue**".
- For example, if I'm measuring the energy "E", maybe some of the values I could measure are E_1,E_2, E_3, etc. (those are the possible "eigenvalues" or outcomes of my system).
    - If my quantum state is an eigenstate representing E_1, for example, then that means when I go and measure the energy then I will expect to measure the E_1 value with 100% certainty.
- Initial quantum states are usually given as a superposition of eigenvectors: $|coin\rangle = \frac{1}{\sqrt{2}}|tails\rangle + \frac{1}{\sqrt{2}}|heads\rangle$
- For our coin, "heads" and "tails" are the possible eigenvalues.
    - If the coin lands and we see "tails", then that means our state collapses to the "tails" eigenstate

$$|coin\rangle = |tails\rangle$$

Quick Aside: Some Quantum Jargon and Math Principles - III

- The "Born Rule": if quantum state is "ψ" the probability of measuring "A" is: $P(A) = |\langle A|\psi\rangle|^2$
  - Implies that $|\langle\psi|\psi\rangle|^2 = 1$ (ensures all probabilities add up to 1 – things are "normalized")
- For **orthonormal** vectors (won't get into it), you can assume: $\langle A|A\rangle = 1$ and $\langle A|B\rangle = 0$
- For our coin, let's say that the eigenvectors $|tails\rangle$ and $|heads\rangle$ are $\begin{bmatrix}0\\1\end{bmatrix}$ and $\begin{bmatrix}1\\0\end{bmatrix}$, respectively
- To find the probability of measuring "tails": $P(tails) = |\langle tails|coin\rangle|^2$
  - $\langle tails|coin\rangle = \frac{1}{\sqrt{2}}\langle tails|tails\rangle + \frac{1}{\sqrt{2}}\langle tails|heads\rangle$, use orthonormal identity above or do math
  - Math: $\frac{1}{\sqrt{2}}\begin{bmatrix}0 & 1\end{bmatrix}\begin{bmatrix}0\\1\end{bmatrix} + \frac{1}{\sqrt{2}}\begin{bmatrix}0 & 1\end{bmatrix}\begin{bmatrix}1\\0\end{bmatrix} = \frac{1}{\sqrt{2}}(0*0+1*1) + \frac{1}{\sqrt{2}}(0*1+1*0) = \frac{1}{\sqrt{2}}$
  - Identity: $\frac{1}{\sqrt{2}}(1) + \frac{1}{\sqrt{2}}(0) = \frac{1}{\sqrt{2}}$
  - Either way, $|\langle tails|coin\rangle|^2 = |\frac{1}{\sqrt{2}}|^2 = \frac{1}{2} = 50\%$
- We knew this already, but it was nice to verify!

So What?

$$|coin\rangle = \frac{1}{\sqrt{2}}|tails\rangle + \frac{1}{\sqrt{2}}|heads\rangle$$

- In a nutshell: these are the probabilities for measuring “tails”/“heads”
- So, why would you ever do it the “long” way?
- Well, maybe there’s some other observable you’re trying to measure. Maybe the momentum of this system is called “M” and its eigenvector is $\begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix}$, which isn’t an eigenstate of the coin (it isn’t a vector representing “heads” or “tails”). That makes you *have* to do the math.

Quantum Computing

Shifting to the computing aspect

Reframing the Coin Example

- Now that we're familiar with the coin flipping example, let's change the notation a bit

$$|coin\rangle = \frac{1}{\sqrt{2}}|tails\rangle + \frac{1}{\sqrt{2}}|heads\rangle$$

$$\downarrow$$

$$|\psi\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

$$\downarrow$$

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

This is how a qubit is represented! Just with different α and β!

Qubit Math Representation

- At the end of the day, $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ is the most general form of a 2-level quantum state
    - A single qubit can be 0 or 1, thus “2 levels”
    - A flipped coin can be “tails” or “heads”, thus “2 levels”
- How do we actually visualize the qubit though?
    - Need to find out our α and β first
- To represent it in 3D-space, math (won’t get into it) gets us our α and β:
    - $\alpha = \cos\left(\frac{\theta}{2}\right)$
    - $\beta = e^{i\phi}\sin\left(\frac{\theta}{2}\right)$
    - Where θ is the “polar” angle, and ϕ is the “azimuthal” angle in spherical coordinates
- All of this brings us to…the Bloch Sphere, a way of visualizing a qubit’s state!

Bloch Sphere

$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$

- The poles of the **z-axis** represent $|0\rangle$ and $|1\rangle$, which is equivalent to “0” and “1” for classical bits
- The **x-axis** represent the “real” part of the state $|\psi\rangle$
    - The x-axis poles represent equal superposition of both 0 and 1
    - You may also see mentions of $|+\rangle$ and $|-\rangle$
- The **y-axis** represent the “imaginary” part of the state $|\psi\rangle$
    - The y-axis poles also represent superposition but consider the phase, which is imaginary
    - You may also see mentions of $|+i\rangle$ and $|-i\rangle$

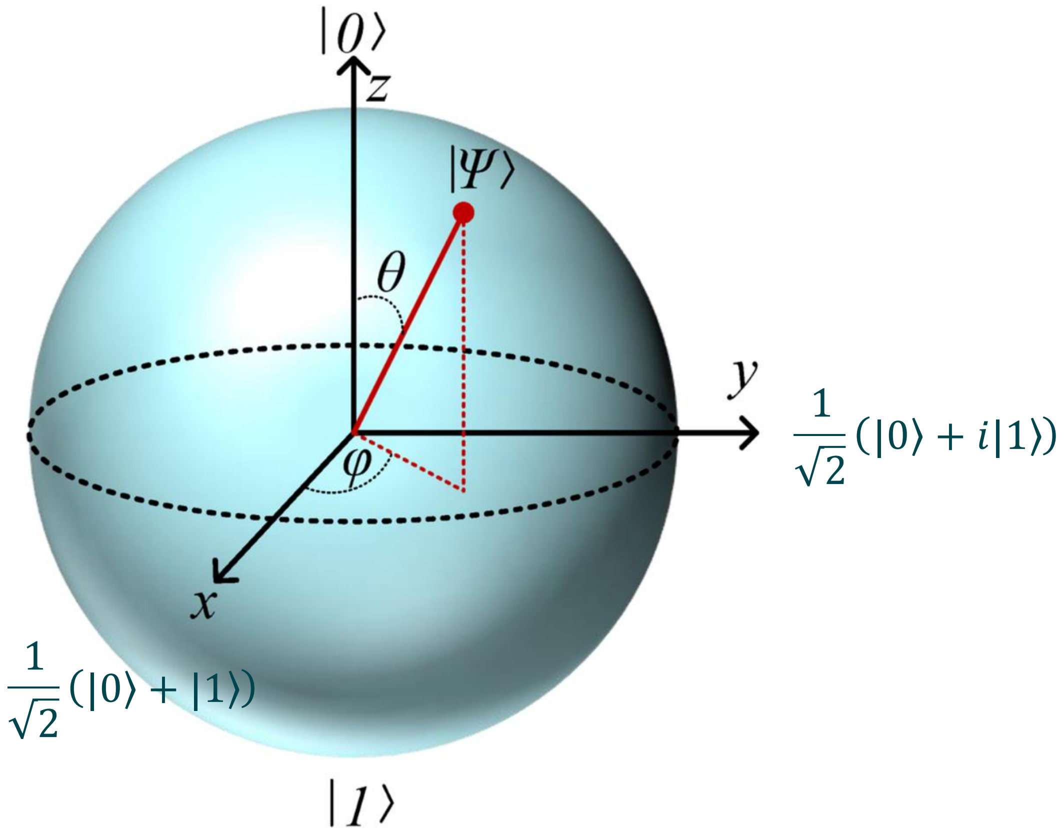
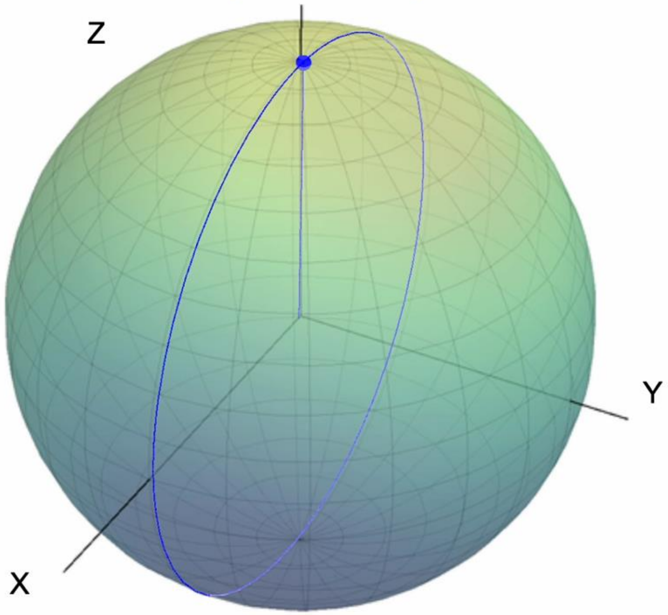


Figure 1. Visualization of the state of a qubit, 'Power and Energy Applications Based on Quantum Computing: The Possible Potentials of Grover’s Algorithm. Electronics'. Habibi et al 2022. Electronics, 11(18), 2919. https://doi.org/10.3390/electronics11182919

Bloch Sphere Visualization (Movie)

https://www.st-andrews.ac.uk/physics/quvis/simulations_html5/sims/blochsphere/blochsphere.html

Bloch sphere representation of quantum states for a spin ½ particle



The Bloch sphere is a graphical representation of quantum states of a two-level system (here a spin ½ particle). For a spin ½ particle, the only possible outcomes of a measurement of the z-component of spin are $S_z = +\hbar/2$ and $S_z = -\hbar/2$, where $\hbar = h/2\pi$ and h is Planck's constant. If we denote the two states with spin components $S_z = +\hbar/2$ and $S_z = -\hbar/2$ as $|\uparrow\rangle$ and $|\downarrow\rangle$ respectively, then a general superposition state can be written as

$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|\uparrow\rangle + \sin\left(\frac{\theta}{2}\right)\exp(i\phi)|\downarrow\rangle$$

As you can see in the image on the left, the angles θ and ϕ can be interpreted as the azimuthal and polar angles (in spherical polar coordinates) of points on a sphere of radius one. Thus, you can see that there is a one-to-one correspondence between points on the sphere and the quantum states of the spin ½ particle.

Quantum state

$|\psi\rangle = \cos(0\pi/20)\,|\uparrow\rangle + \sin(0\pi/20)\exp(\,i\,0\pi/12)\,|\downarrow\rangle$?

$|\psi\rangle = |\uparrow\rangle$

Polar angle θ = 0π/10

0 π/2 π

Azimuth Φ = 0π/12

0 π/2 π 3π/2 2π

Measurement outcome probabilities

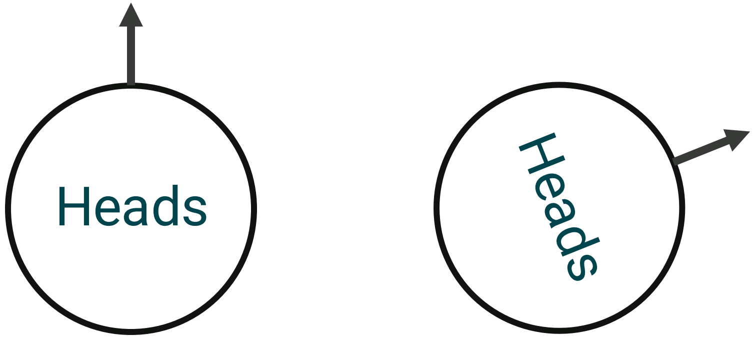
$S_z = +\hbar/2$: 1.000 **$S_z = -\hbar/2$:** 0.000

Display controls

☑ Show theoretical measurement outcome probabilities

Bloch Sphere Takeaway

- Not only can a qubit be measured as “0” or “1”, but qubits come with a phase
- Although the phase doesn’t affect the outcome probability, you can think of it as an additional “direction” it can point
- What if you put an arrow on the top of your coin before you flip it
    - Let’s say it lands “heads” ($|1\rangle$)
    - If the coin rotated, it’s still “heads”, the arrow is just pointing in a different direction
        - Maybe the arrow can guide you into what you do next
        - E.g., flip a coin to find which restaurant you go to, but where the arrow points is what part of town you’re going to



How do Qubits "work" though? - Interacting

Schrödinger equation

$$i\hbar\frac{\partial}{\partial t}|\Psi(t)\rangle = \hat{H}_{\mathrm{sys}}(t)\,|\Psi(t)\rangle$$

quantum state

"Hamiltonian" (tune to do gates)

- Quantum annealing
  - Gradually varying external conditions to slowly evolve the most stable energy state, which makes it more complex over time (guided to the most optimal solution)
  - Won't talk about much of this here (current QCUP vendors are all gate-based)
- Gate-based interactions
  - Matrices that transform a qubit's state on the Bloch Sphere
  - In "real life" can come in the form of laser pulses, modifying E&M fields, or physical materials that can force certain qubit behavior that mimic the math
    - Superconducting Qubits: Microwave pulses of specific frequencies/duration
    - Ion Trap Qubits: Laser pulses manipulate the energy levels
    - Photonic Qubits: Waveplates can be used to manipulate photon polarization

Coin equivalent: flicking the coin with different force or techniques

How do Qubits “work” though? - Measuring

- “Measuring” a qubit determines if it is “0” or “1”, just like a classical bit
    - When you measure a qubit, you are ending any notion of superposition
    - Typically do this at the end your experiments (although, mid-circuit measurements do exist)
- How you physically measuring a qubit varies on the technology
    - Superconducting Qubits
        - Measure the frequency shift of the system, which translates to a 0 or 1
        - Sometimes known as “dispersive readout”
            - For astro people, can think of it as velocity dispersion / redshift affecting the peaks in a spectra
    - Trapped Ion Qubits
        - Shooting the ion with a laser and measuring the photons emitted
        - The number of photons counted indicate which state the qubit is in

Coin equivalent: when you open your eyes to look at the coin, you’ll know if it’s “heads” or “tails”

How do Qubits “work” though? - Resetting

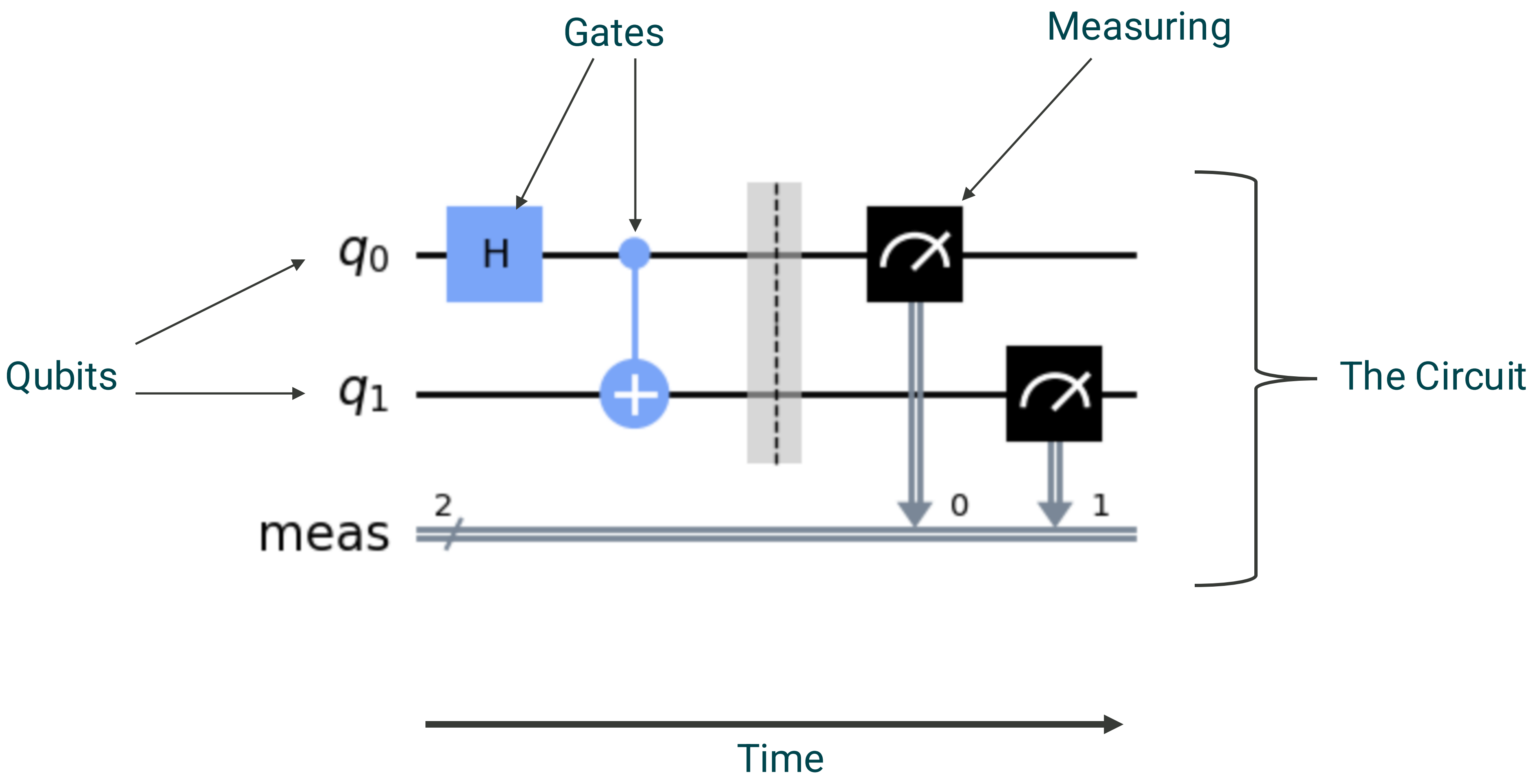
- “Resetting” a qubit is important for keeping experiments consistent and reproducible
    - E.g., in classical computing, you wouldn’t want memory from a previous computation interfering with a new simulation
- In general, the goal is to reset a qubit to its ground-state (a simple base-level state that is known)
- As with measuring, resetting is different based on the technology
    - Superconducting Qubits
        - Wait for the qubit to decay (if you wait long enough, qubits eventually “relax” to its natural state)
        - Use pulses to force it into the ground-state
    - Trapped Ion Qubits
        - More lasers!
        - Exploiting the resonant frequency of an Ion lets you force it into the ground-state with a laser

<u>Coin equivalent</u>: placing the coin back on your thumb to flip it again

Quantum Gates and Circuits

- Quantum gates and circuits aren't physical transistors like their "classical" counterpart
- <u>**Quantum Gates**</u>: Matrices that are designed to transform a qubit's state on the Bloch Sphere
    - Operationally act the same way as classical logic gates, just different physically (see Interacting slide)
    - Quantum gates are reversible, meaning they can be reversed to return a qubit to its original state
    - There are single-qubit gates, which can flip a qubit from 0 to 1 as well as allowing superposition states to be created
        - E.g., Hadamard Gate: Creates superposition (allowing a qubit to be in multiple states simultaneously)
    - There are also two-qubit gates that allow the qubits to interact with each other
        - E.g., Controlled-NOT (CNOT) Gate: If the first qubit measures as "1", the second qubit will flip
- <u>**Quantum Circuits**</u>: Sequences of gates and measurements acting on qubits during an experiment
    - Represents the flow of information amongst the qubits
    - Qubits are sometimes referred to as "wires", visually, where gates are present on each "wire" in a circuit

Quantum Circuit Visually



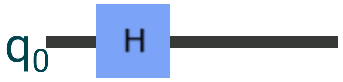
Hello World Equivalent

- The “Bell State” is the “hello world” of quantum computing, let’s build it!
- Shows off both superposition and entanglement in action

Step 1: Start w/ 1 qubit

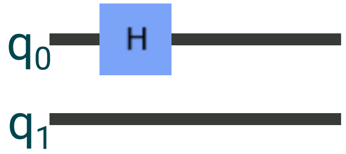
$$|\psi\rangle = |0\rangle$$

Step 2: Add a Hadamard Gate (puts things into superposition)



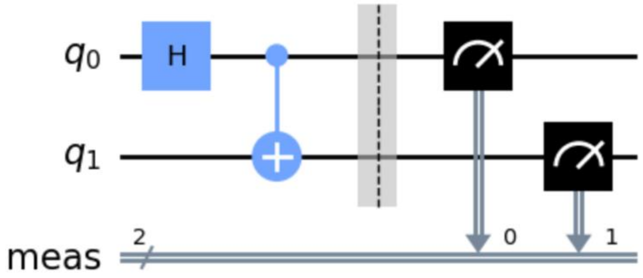
$$|\psi\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

Step 3: Add a 2nd qubit



$$|\psi\rangle = \frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|10\rangle$$

Step 4: Add a CNOT gate (entangles the qubits). The 2nd qubit will flip to 1 if the first is 1, otherwise it will stay as 0



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

Why Qubits Are Important In Computing (now in context)

- Superposition and Entanglement allow a quantum computer to explore more possibilities at once compared to a classical computer
    - This means that certain **<u>exponentially complex</u>** problems might be faster on a quantum computer
        - For sparse linear solvers, the classical cost is at least O(N) whereas the quantum cost is O(log(N))
    - HPC uses “parallel computing” by distributing tasks,
    - Quantum Computing uses “parallel computing” in a sense where it’s able to consider multiple outcomes at once
        - Distributing tasks on top of that is still possible, so it has the potential to be even more powerful

Implications from a Computing Point of View

- FLOPs doesn't mean much for measuring a quantum computer's success
- Quantum computing cares about:
    - The fidelity (how reliable is the answer)
    - The scale (the resources required to run a circuit)
    - The speed (the speed of executing the layers of the circuit)
- But how do you determine the performance of a quantum computer / qubit? Some ways:
    - **Quantum Volume**: a benchmark that measures how well a quantum computer can execute complex, random circuits of increasing size
        - Helps quantify "depth", the number of layers of quantum gates that plan to be executed
    - **CLOPs**: "circuit layer operations per second", how fast you can execute the layers of a circuit
    - **Number of Qubits**: measures the scale

Noise

- All of quantum computing is affected by difference sources of “noise” (aka “error”)
    - Noise affects the final outcome of your system
- “Inherent randomness” / “Statistical Noise”: The fact that you’re flipping a coin
- External noise: noise imposed from the environment
- Qubit-centric noise: qubit coherence (how long it’s able to hold quantum information)
- Ways to deal with noise
    - Error Suppression: account for known errors ahead of time (typically the hardware level)
    - Error Mitigation: based on results, account for the inaccuracies you’re seeing in the outcomes
        - Noise cancelling headphones
    - Error Correction: creating redundancy to explicitly make errors disappear (i.e, “**fault-tolerant**”)
        - Encoding multiple physical qubits to form “logical” qubits
        - Maybe leverage a classical computer to algorithmically correct things in real-time?

Coin equivalent: Noise in the coin example is not flipping it the same way every time, or maybe the wind is blowing

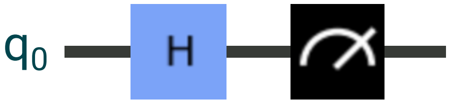
“Visualizing” Noise

- To get a better estimate of outcomes, circuits are run for multiple “**shots**” (i.e., running the same thing multiple times)
- You can see “noise” when inspecting the final results (e.g., the “**counts**”)
  - Running the same experiment again for the same amount of shots doesn’t guarantee the counts will be the same (noise!)

Let’s say we run this for 100 shots, 3 different times

Our coin:

$$|\psi\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

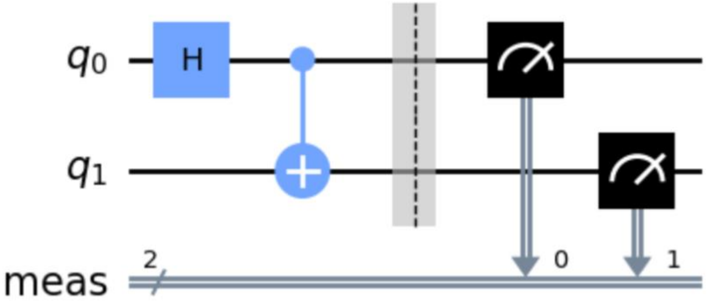


$|0\rangle$ 50 counts, $|1\rangle$ 50 counts

$|0\rangle$ 48 counts, $|1\rangle$ 52 counts

$|0\rangle$ 41 counts, $|1\rangle$ 59 counts

Slightly more complex case of noise:



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

$|00\rangle$ 48 counts, $|11\rangle$ 50 counts, $|01\rangle$ 1 count, $|10\rangle$ 1 count

Options to run Quantum Computations

Backend	Mechanism	Functionality
Simulator	Classical	Classical program modeling a quantum system in an ideal scenario
Emulator	Classical	Classical program modeling actual behavior of a quantum system
Real	Quantum	Physical hardware performing real quantum computations

For the challenges, we’ll be using Odo (classical) and IQM (real quantum hardware)

Conclusions

- Info dump over!
- Goal was not to make you an expert, but to open the door to this world and to give context
- Having a place to refer back to
- Way to think about quantum computing:
    - The goal isn’t to completely replace classical computers with quantum computers
    - Classical computers still will be much better at certain things
    - Goal is to find how to leverage both to form a complete ecosystem
- For some more context (and a great intro!) checkout this OLCF User Call on QC/HPC Integration: https://www.olcf.ornl.gov/wp-content/uploads/olcf_user_call_talk_2025_04.pdf
- Another way to visualize the Bloch sphere with gates. By IQM: https://www.iqmacademy.com/curriculum/foundations06.html

Oak Ridge National Laboratory | Leadership Computing Facility