NANOG 95

Darn you, Dr. Peter Shor.

The Basics of Quantum Computing and the Threat to Asymmetric Encryption.

Bill Nelson, Not a Doctor.

28 Oct 2025

What We're Doing Here

- The goal is to understand the threat posed by quantum computing by developing a better understanding of:
  - The problem statement of what's called a cryptographically relevant quantum computer (CRQC).
  - How quantum computers work.
  - The state of the art of quantum computing.
  - The future timeline of quantum computing.
  - The mitigation methods available to become quantum computing resistant.
  - But, first, a very little bit about me…

What I am - A curious engineer.

- 26 Year IT Professional working as a Network Engineer building and operating different parts of the internet.
- Have worked for:
  - Internet Service Providers
  - Data Center Providers
  - Manufacturing Companies
  - Different Size Enterprises
- Currently work in an enterprise environment for a Cleveland, Ohio bank, operating their network and firewall devices.

What I am not - A quantum anything.

- Not a quantum physicist
- Not a quantum information scientist
- Not a quantum computer scientist

- The feeling of being an imposter up here is ***strong***.

Why Build Quantum Computers?

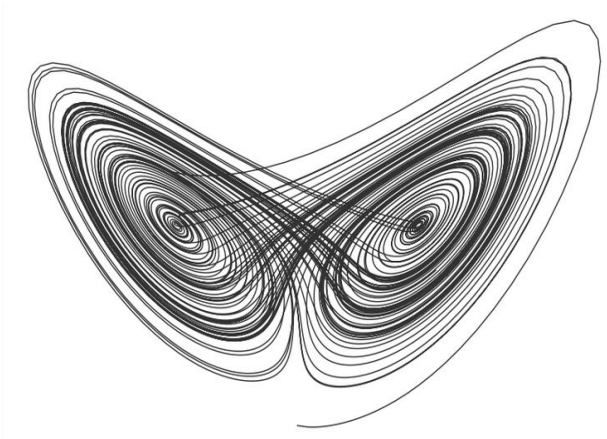
- Originally it was because classical computing hardware simply could not, and still cannot, keep up with the exponential growth simulating quantum mechanical systems takes.
- However, since 1994 it has also - and mostly - been a race to be able to decrypt data with them.

The Problem Statement of a Cryptographically Relevant Quantum Computer (CRQC.)

- All public-key (asymmetric) encryption security relies on the difficulty a classical computer has in solving two types of math problems:
  - Solving discrete logarithms over finite fields and elliptical curves.
  - Factoring large numbers into their prime components
- In 1994 Dr. Peter Shor from MIT discovered a quantum algorithm that excels at solving both of these problems.
- All widely used public-key cryptographic algorithms are then vulnerable to attacks based on Shor's algorithm, but the algorithm depends upon operations that can only be achieved by a large-scale quantum computer[1].

Quantum Concepts and Terms

- It's Weird
- It's Random but Probabilistic
- Wave-Particle Duality
- Wave Function/State Vector
- Measurement Collapse
- **Superposition**
- **Interference**
- **Entanglement**



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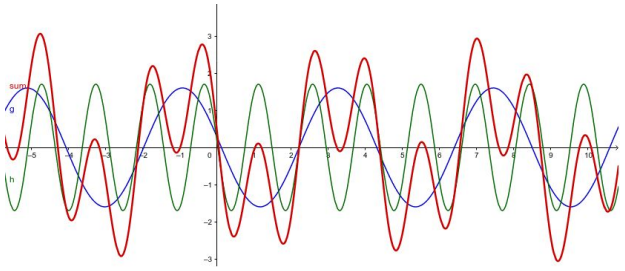
* This image is of the Lorentz Attractor and has **nothing** to do with quantum mechanics. Entanglement has no analogue in the classical world of physics. This is a surreal visual I thought might help imagine entanglement.

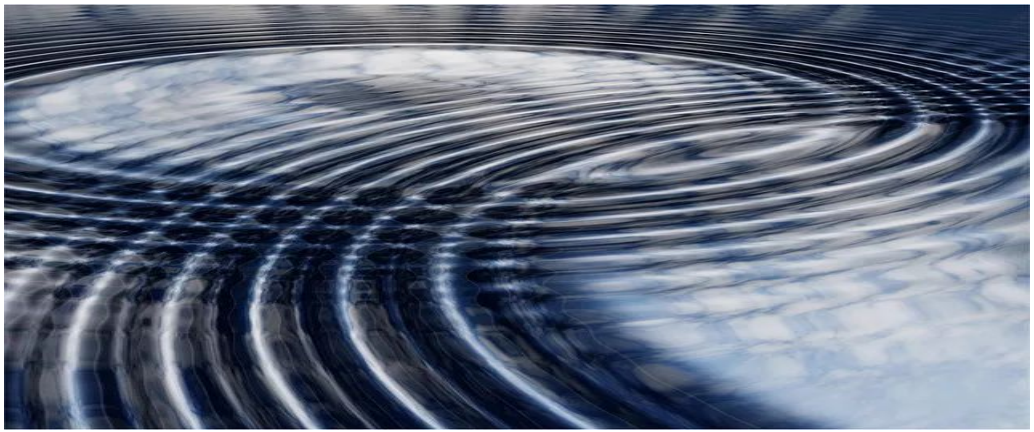
What Do We Need to Know About Quantum Mechanics?

- Classic physics defines the behavior for the large and quantum physics defines the behavior for the molecularly/atomically small.
- At quantum scale particles exist in multiple states at the same time as a probabilistic wave called a superposition.
- The particles will stay in a superposition of probabilistic states until they are measured, at which point the wave function “collapses” into a definite, classical state.

What Do We Need to Know About Quantum Mechanics? (2)

- Interference of Waves:
  - Constructive interference leads to a larger probability wave.
  - Destructive interference leads to a smaller probability wave.





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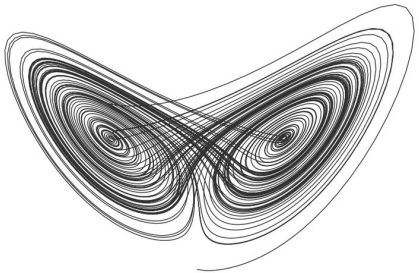
What Do We Need to Know About Quantum Mechanics? (3)

- Entanglement: When two quantum particles are entangled, the state of one particle cannot be described without describing the state of the other.
- No-Cloning Theorem: You cannot duplicate a qubit of an unknown quantum state.



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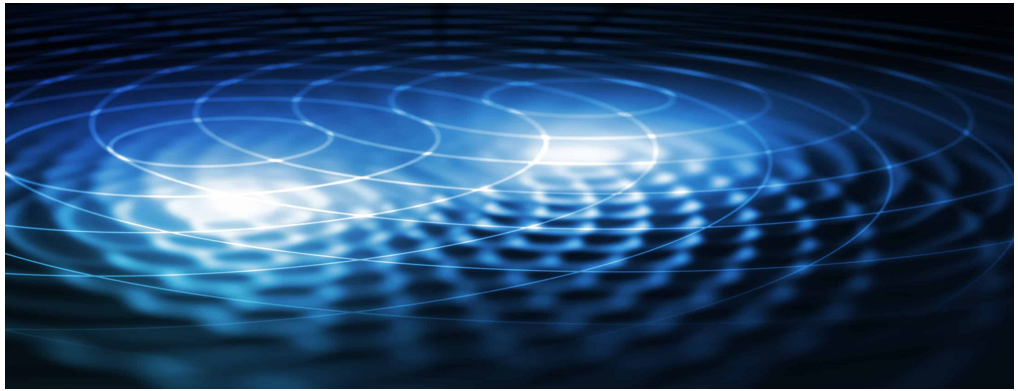
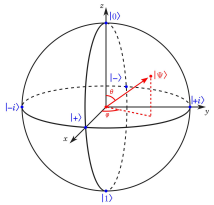


The Qubit



The qubit is the fundamental unit of quantum information.

- Physically, a qubit can be any two-state quantum system.
- Analogous to a classical bit, a qubit can also be in a state of superposition of both a 1 and a 0 at the same time.
- Qubits can be entangled with each other allowing quantum computers to perform ***certain*** calculations exponentially faster than classical computers.

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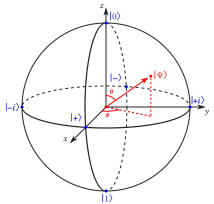
The Qubit (2)



- All qubit implementations are inherently unstable and noisy.
- Decoherence is the state where all of the quantum information has been lost due to noise.
- Types of noise
  - Thermal
  - Electromagnetic
  - Vibration
- Other sources of errors
  - Control signal errors
  - Measurement errors

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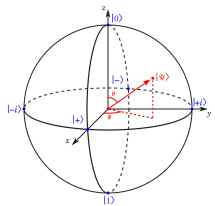
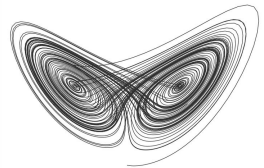
The Logical Qubit - From Many Comes One

- A logical qubit is a combination of physical qubits using special rules called quantum error correction codes.
- If one physical qubit makes a mistake, the others can help figure out what went wrong and fix it.
- The logical (also called an error-corrected) qubit stores quantum information more reliably than any single physical qubit alone.



The Entangled Qubit - Quantum Parallelism

- One qubit can represent 2^1 or 2 states at once.
- Two entangled qubits can represent 2^2 or 4 states at once.
- Three entangled qubits can represent 2^3 or 8 states at once.
- …
- 32 entangled qubits can represent 2^{32} or 4,294,967,296 states at once.
- N entangled qubits can represent 2^N states at once.



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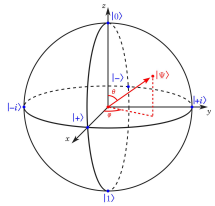
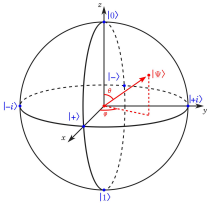
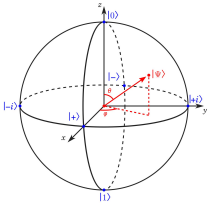


What is a Quantum Logic Gate?



- Quantum logic gates are the components that make up quantum circuits which are what implement quantum algorithms.
- A quantum logic gate performs calculations on qubits by altering:
  - The probabilities of measuring a 1 or a 0.
  - The relative phase between the qubits' interfering waves.

What is a Quantum Logic Gate? (2)



- Quantum logic gates are imposed on the qubits by way of different types of electromagnetic pulses.
- Quantum logic gates have worse error rates than logical qubits, which limits circuit depth which limits algorithm complexity.

A Three-Qubit Computer Computing Example

|000>

|001>

|010>

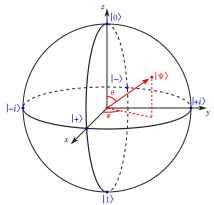
|011>

|100>

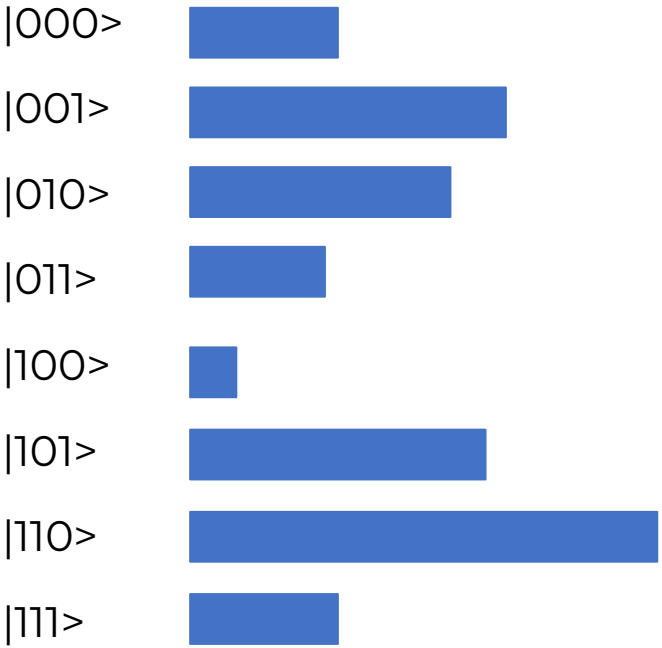
|101>

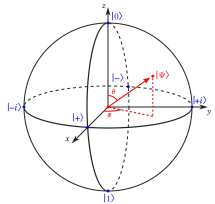
|110>

|111>



A Three-Qubit Computer Computing Example





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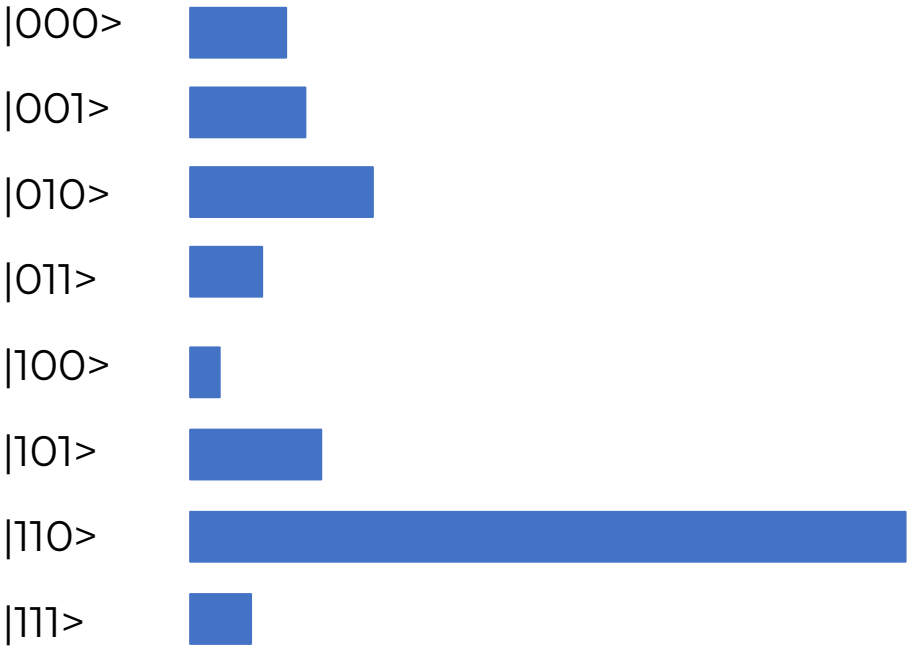
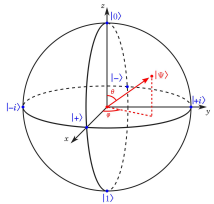
A Three-Qubit Computer Computing Example





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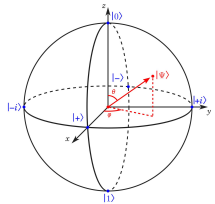
A Three-Qubit Computer Computed Example



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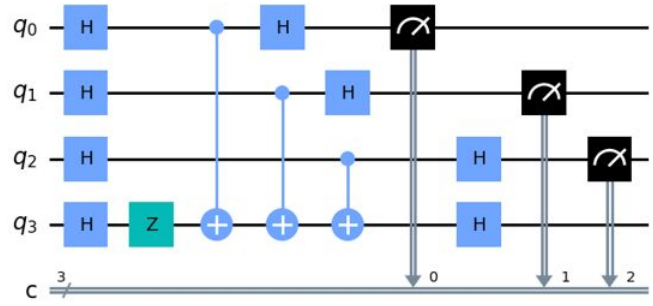
The State of the Art - What Variables to Track.

- The number of physical and logical qubits in a QPU.
- The error rate trends of logical qubits.
- The error rate trends of quantum logic gates.



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The State of the Art - A Theoretical Danger Zone

- It will take a minimum of 4,098 logical qubits to run Shor's algorithm to break an RSA-2048 bit key. [6]
- Using the math from [6] shows the number of gate operations required to break said key is 6.08×10^{14} operations.

The State of the Art

- Qubit Count
  - Oct 2023: Microsoft/Atom's QPU with 1,225 physical qubits [7]
  - Dec 2023: IBM's Condor QPU with 1,121 physical qubits making up 12 logical qubits. [8]
  - Dec 2023: IBM's Heron R1 QPU with 133 logical qubits. [9]
  - May 2024: Chinese Academy of Science's Ziahong 3.0 QPU with 105 logical qubits. [10]
  - July 2024: IBM's Heron R2 QPU with 156 logical qubits. [11]

The State of the Art (2)

- Qubit Count (cont'd)
  - Nov 2024: Microsoft/Atom's QPU with 24 entangled logical qubits. [12]
  - Dec 2024: Google's Willow QPU with 105 logical qubits and a 49:1 physical to logical qubit ratio [13]
  - Feb 2025: Microsoft's Majorana 1 QPU with 8 error resistant physical qubits that make up 8 "topological" logical qubits. [14] Very much under peer review.
  - Feb 2025: Amazon's Ocelot QPU with 5 error resistant, logical "cat" qubits. [15]

Post Quantum Cryptography (PQC) Mitigation

“If you really have sensitive data, do it now.”

– Vadim Lyubashevsky, IBM Cryptography Researcher

Quantum Computing Timeline

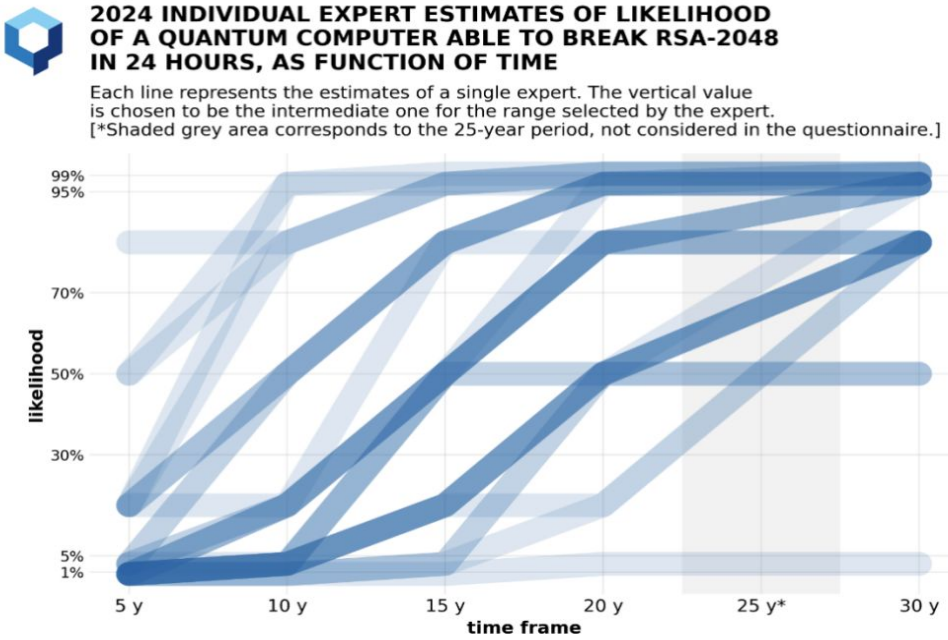
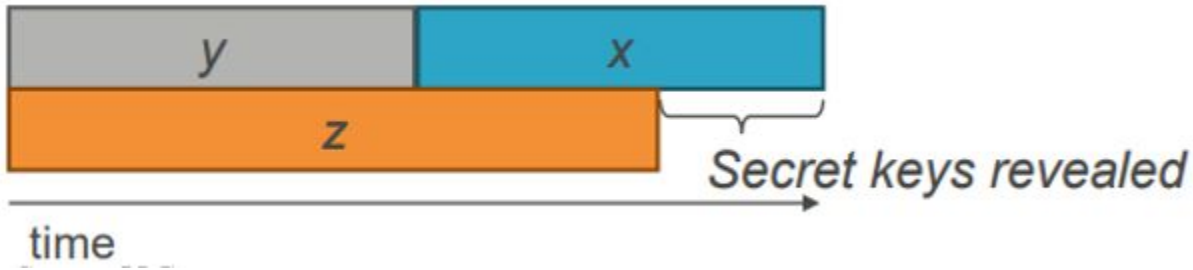


Image 1 - Variance in Expert Estimates [18]

Dr. Mosca's Inequality for Determining Risk

- If X + Y > Z then your data is at risk [21], where:
  - X is the amount of time that your data needs to remain secure.
  - Y is the amount of time it will take to transition your environment to post quantum cryptography (PQC) algorithms.
  - Z is the amount of time it will take to develop a CRQC capable of breaking existing asymmetric encryption algorithms.



PQC Mitigation: 10,000’ View

- You will find every piece of quantum broken/weakened encryption in your IT environment and replace it with standardized, quantum resistant encryption.
- You will document the work done and create centralized, operational documents in order to facilitate something called “crypto-agility.”
    - There is a good chance this work will need to be done more than once.
    - There should not be a reliance on institutional knowledge of individuals.

PQC Mitigation: Crypto-Agility Definition

- Crypto agility facilitates migrations between cryptographic algorithms without significant changes to the application that is using the algorithms. [20]
- Quantum computing is in its infancy and we need to be able to quickly adjust to newly developed/improved/broken algorithms.
- Example: SIKE was an algorithm that got broken late in the standardization process.
  - 4th and final-round NIST candidate
  - Broken in 62 minutes of compute time by a Belgian team using a single, legacy Intel Xeon core.[22]

PQC Mitigation: “New” Math

- NIST Post Quantum Cryptography:
  - **FIPS203**: Module-Lattice based key-encapsulation-method (ML-KEM) algorithm
  - **FIPS204**: Module-Lattice based digital signature standard (ML-DSA) algorithm
  - **FIPS205**: Stateless-Hash based digital signature standard (SLH-DSA) algorithm
  - **FIPS206**: FFT over NTRU-Lattice-Based digital signature standard (FN-DSA) algorithm.
  - **FIPS207**: Hamming-Quasi-Cyclic-Code based key-encapsulation-method (HQC-KEM) algorithm.

PQC Mitigation: IETF RFCs

- IETF RFCs:
  - RFC 8784: Mixing pre-shared keys in IKEv2
  - RFC 9242: IKE layer fragmentation
  - RFC 9370: Multiple key exchanges in IKEv2

PQC Mitigation: 1,000’ View

- Build awareness in the company
  - Senior Management, Legal and Risk Management will need to know
  - SMEs will want to chime in
- Build a team and assign responsibilities
- Develop a crypto inventory and data protection priority list
  - Crypto Bill of Materials/Crypto Agile Single Source of Truth?
- Evaluate solutions and implementation options
- **Experiment and test quantum resistant algorithms.**
  - **These are not drop in replacements for DH/RSA**
  - You’re going to need a real test environment. :-)
- Plan out the migration
- Execute the migration
- Review
- Stay up-to-date with quantum computing and PQC developments
- Repeat as needed
  - Use the crypto agile SSoT’s operational documents.

PQC Mitigation: Finding the Quantum Weak

- Investigate and develop a complete, end-to-end inventory of:
  - 3rd party application encryption
  - Source code encryption
  - OS/firmware/hardware encryption
  - Hardware Security Modules
  - Network encryption - data in flight
  - System encryption - data at rest
  - Cloud environment encryption
  - Vendor interaction encryption
  - Probably more I can’t think of…
  - Data flow diagrams and Visios will really help here…if they exist

PQC Mitigation: Crypto Inventory

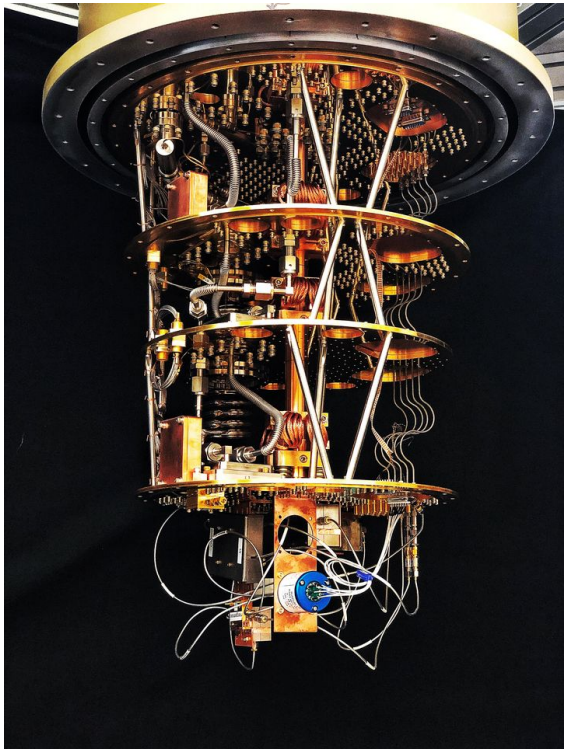
- Each item in the inventory should/could/may/must include:
  - Current key sizes and hardware/software limits on future key and signature sizes.
  - Latency and throughput thresholds
  - Processes and protocols used for crypto negotiation
  - Current key establishment handshake protocols
  - Where each cryptographic process is taking place in the stack.
  - How each cryptographic process is invoked (call to a crypto library, using a process embedded in the OS, calling an application, using cryptography as a service, etc)
  - Whether the implementation supports the notion of cryptographic agility.
  - Whether the implementation may be updated via software
  - Suppliers and owners of each cryptographic process
  - Sources of keys and certificates
  - Contractual and legal conditions imposed by and on the supplier
  - The support lifetime or expected end-of-life of the implementation
  - Sensitivity of the data being protected.
  - And probably some other things…

PQC Mitigation: Vendor/Change Management

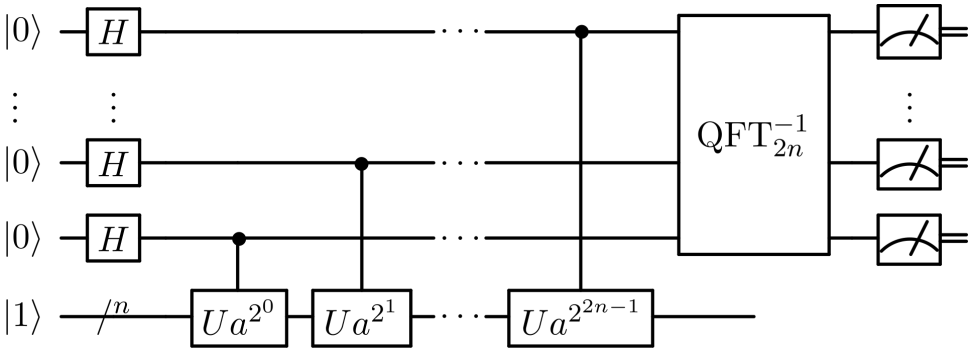
- From this point on, every vendor, architecture change, or hardware/software/firmware release needs to describe the encryption in detail so that PQC readiness is understood and PQC algorithms are implemented where able.

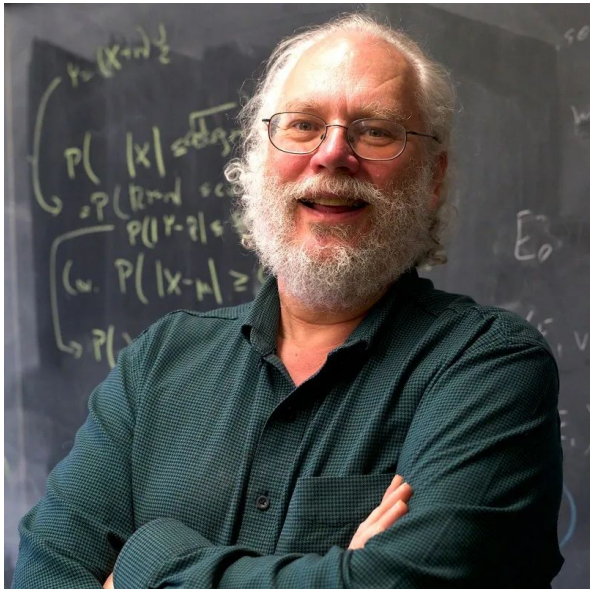
How to Roughly Go About “Quantuming.”

- We need a problem and a quantum algorithm to map it to.
- There are multiple languages to write an algorithm for a quantum computer, depending on the platform. But, mostly Python libraries.
- Choose the number or qubits needed as inputs for our algorithm.
- Compile the algorithm into a series of logic gates in a quantum circuit.
- Insert the QPU into its holder at the bottom of the dilution refrigerator.
- Connect the control cables to the QPU that manipulate one qubit per cable.
- Prep the refrigerator, turn it on and wait a few days or so for the final (lowest) stage to cool down to milliKelvin temperatures
- Specify the number of shots (runs) that need to be made.
- Load and execute the circuit on the quantum computer.
    - Each shot gives a bit string as output.
- Measure and acquire data.
- Interpret the results and validate.



The Quantum Circuit - Shor's Quantum Subroutine





Questions?

28 Oct 2025

Thank you.

28 Oct 2025

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PQC - Further Reading

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PQC - Further Reading

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https://www.ncsc.gov.uk/whitepaper/next-steps-preparing-for-post-quantum-cryptography

https://pixelplex.io/blog/post-quantum-cryptography/

PQC - Further Reading

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