# Quantum Memory & qRAM

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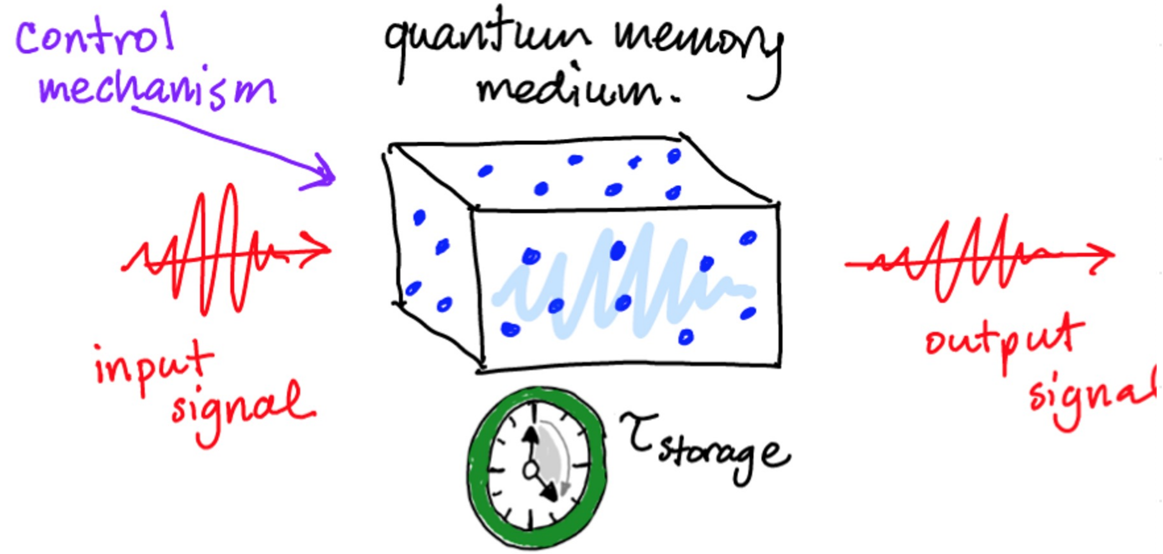
# Quantum Memory – Overview

1. What does the memory imply in quantum computation?
2. Benefits
3. Challenges
4. Physical realization

# What is Quantum Memory?

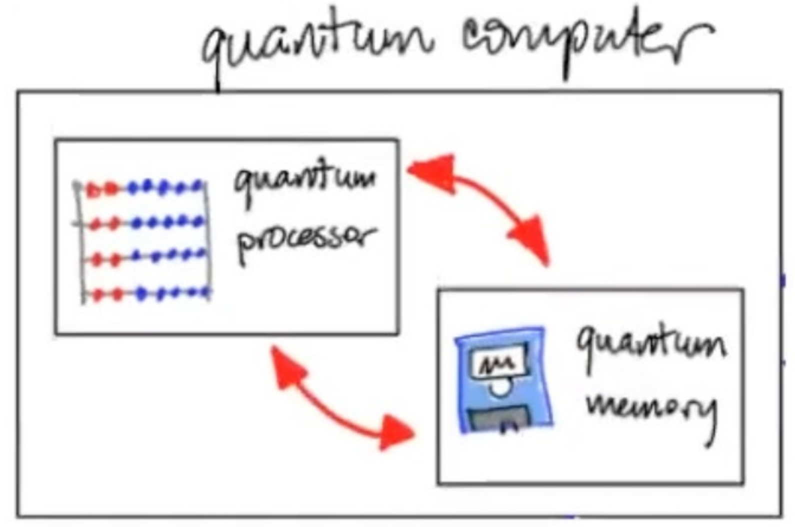
- A system or medium that stores and retrieves fragile quantum states
- Stores an input signal, typically quantum information
- Released after some time based on a control mechanism
- Example medium: Rubidium atom [1]




*Ref: https://sites.google.com/ualberta.ca/ultracold/research/quantum-memory*

# Quantum Memory – Applications

- Future of quantum networks and communication
  - Quantum repeaters for long distance communication
  - Popular research topic on arxiv!
- Quantum random access memory
  - Quantum analog of classical RAM
  - memory access and manipulation to quantum computer
  - *Focused in this presentation*
- In general, stores any intermediate $|\Psi>$
  - Quantum Algorithms

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# Quantum Memory – Challenges

- Must not be observed. Obvious! : )
- Decoherence: loss of information from a system into the environment
  - Isolated and well-controlled environment
  - Tiny disturbances can make it lose quantum state
  - Errors during measurement
- Exotic hardware
  - Example: [2] Refrigerators that go to absolute zero (~ -460 F)
- Scalability
  - Growing number of qubits!

# Quantum Memory – Realizations

- Active research area! Based on decoherence times
- Fundamental representations
  - Spin, charge and photon
- Paper on optical quantum memory [3]
  - Lists some photon-based memory implementations
- Single-qubit quantum memory exceeding 10-minute coherence time [4]
  - Trapped ion implementation
    - uses individual ions that are trapped and manipulated using electromagnetic fields

| System | $\tau_Q$ |
|---|---|
| Nuclear spin | $10^{-2} - 10^{8}$ |
| Electron spin | $10^{-3}$ |
| Ion trap ($In^{+}$) | $10^{-1}$ |
| Electron – Au | $10^{-8}$ |
| Electron – GaAs | $10^{-10}$ |
| Quantum dot | $10^{-6}$ |
| Optical cavity | $10^{-5}$ |
| Microwave cavity | $10^{0}$ |

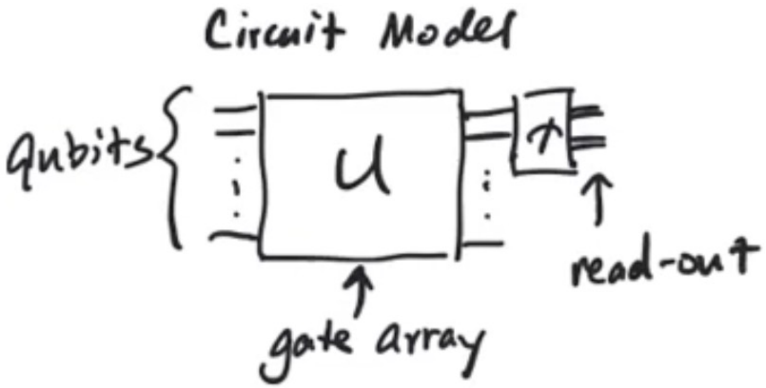
decoherence times τQ (seconds)

# qRAM - Contents

# qRAM – Idea & Current State

- Paper from late 2000's
- Quantum memory is a really old Idea!
- Bucket Brigade Architecture
- Current State
  - Only on paper!
  - Quantum memory is often cited as being essential to achieving quantum computational advantage
  - Technological ability does not yet exist, and we cannot store any quantum states for any practical length of time.

*Gate based quantum architecture*



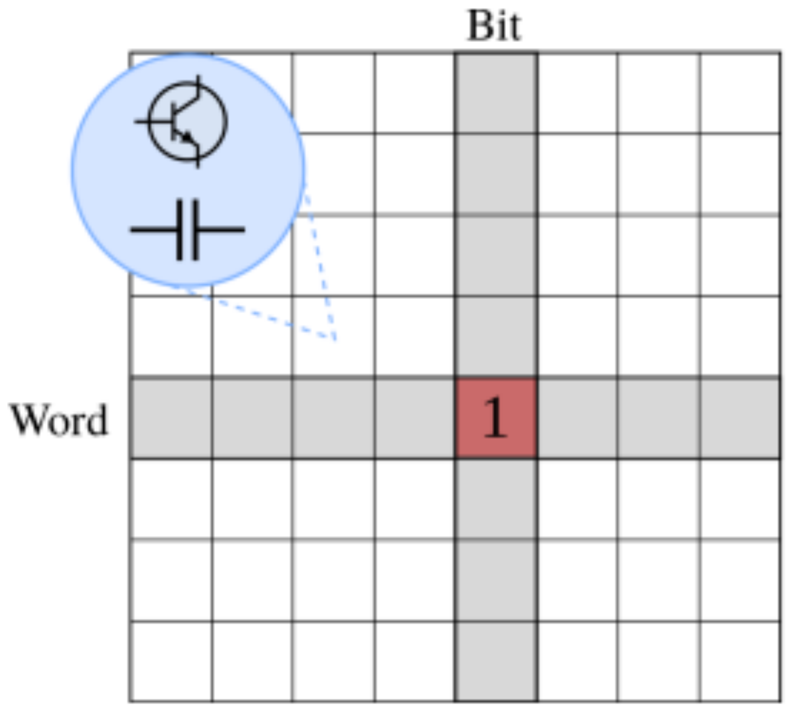

# Why qRAM?

- Can we shift classical computing elements to quantum
  - Ex: Fault tolerance, Memory
- Quantum analog of classical RAM
- Few QML algorithms and quantum algorithms need QRAM to load classical data.
- Provided QRAM, few algorithms proposed an exponential speed up.
  - Q-Means [5]
  - A quantum active learning algorithm [6]

- *An algorithmic speedup on paper may not translate to a speedup in hardware if it is not efficient to load the data in the first place! – Dr. Olivia Di Matteo*

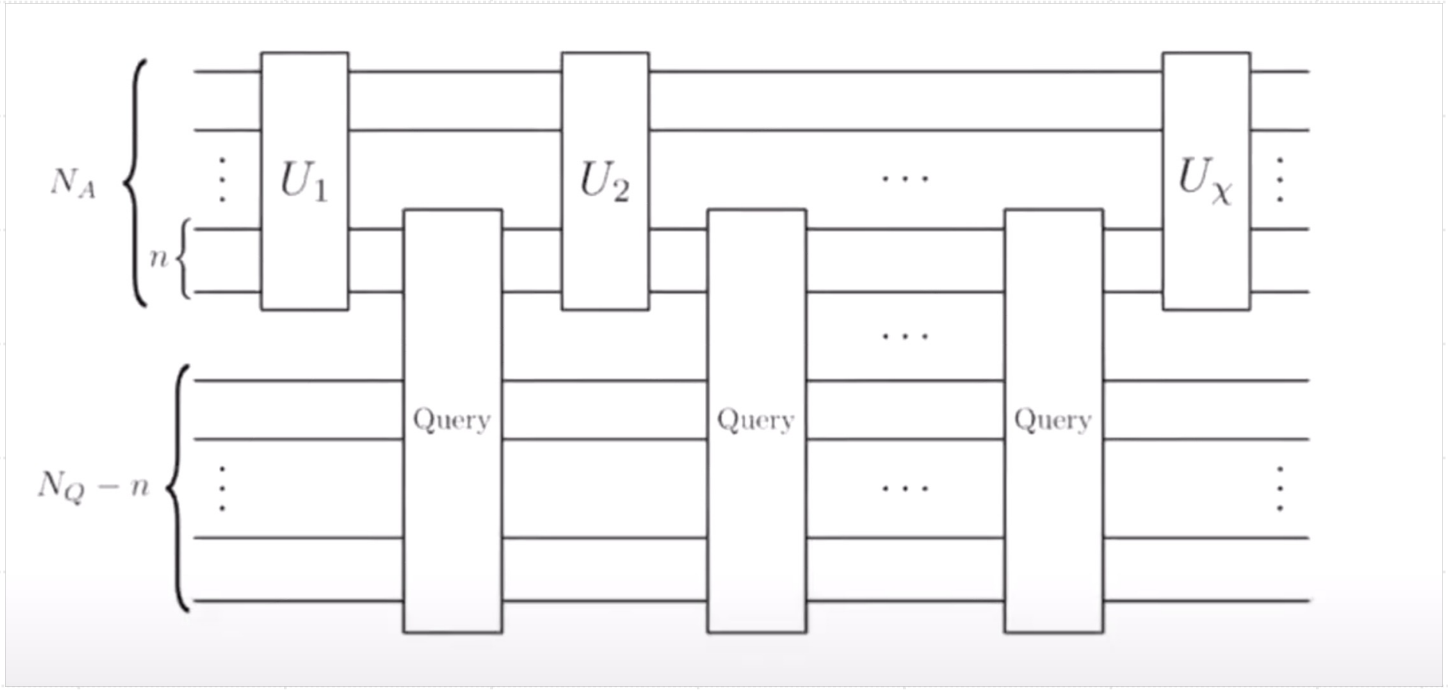
# Classical RAM

- 2D Array of transistor and capacitor pairs
- Store and retrieve classical data from any arbitrary cell
- Rows are represented as word lines. Columns are represented as Bit lines
- Charge is leaked in the capacitors over time and is often refreshed
- Fast, cheap and abundant!!



# qRAM– Generalized Circuit

- Like an oracle
- Algorithm with unitary
- Makes a query to QRAM

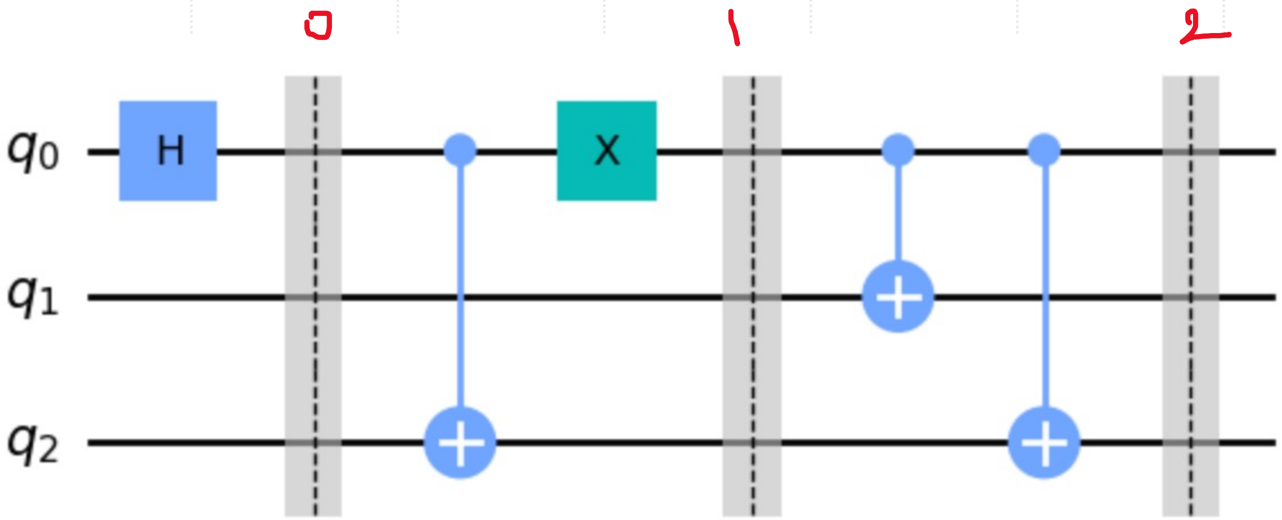


# qRAM – Simple Circuit

- $\sum_x \alpha_x |x\rangle |0\rangle^{\otimes m} \longrightarrow \sum_x \alpha_x |x\rangle \,|b_x\rangle$
- $|0\rangle\ |0\rangle\ |0\rangle$
- $\frac{1}{\sqrt{2}}(|0\rangle|0\rangle|0\rangle + |1\rangle|0\rangle|0\rangle)$ 0
- $\frac{1}{\sqrt{2}}(|1\rangle|0\rangle|0\rangle + |0\rangle|0\rangle|1\rangle)$ 1
- $\frac{1}{\sqrt{2}}(|0\rangle|0\rangle|1\rangle + |1\rangle|1\rangle|1\rangle)$ 2

address data

| $\|x\rangle$ | $\|bx\rangle$ |
|---|---|
| 0 | 01 |
| 1 | 11 |



# qRAM – Query

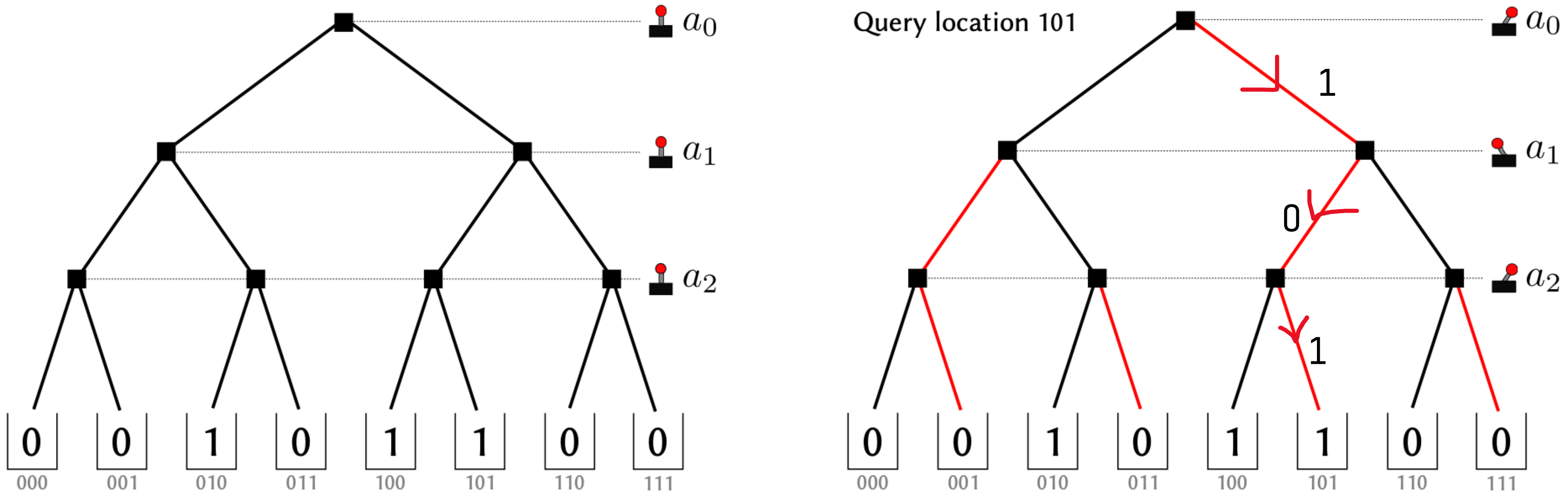
- Types
  - Reading the query output to the phase information
    - $\sum_x |x\rangle \longrightarrow \sum_x (-1)^{b_x} |x\rangle$
    - Reads the bit values into the phase of a state
    - Ex: Grover's search
  - Reading the query output into the state of a qubit
    - $\sum_x \alpha_x |x\rangle |0\rangle^{\otimes m} \longrightarrow \sum_x \alpha_x |x\rangle \left|b_x\right\rangle$
    - Ex: $(|00\rangle + |01\rangle + |10\rangle + |11\rangle) \otimes |0000\rangle \longrightarrow |00\rangle|0110\rangle + |00\rangle\,|1100\rangle + |00\rangle\,|0101\rangle + |00\rangle\,|1111\rangle$

| ADDRESS (X) | DATA (BX) |
|---|---|
| 00 | 0110 |
| 01 | 1100 |
| 10 | 0101 |
| 11 | 1111 |

# qRAM Motivation – Fanout RAM

- Go left for zero, go right for one
- Leaves are memory locations
- For an n-bit address, an n-level binary tree stores the memory contents at its leaves
- Each level is associated with address bits
- Exponential number of transistors have to be turned on

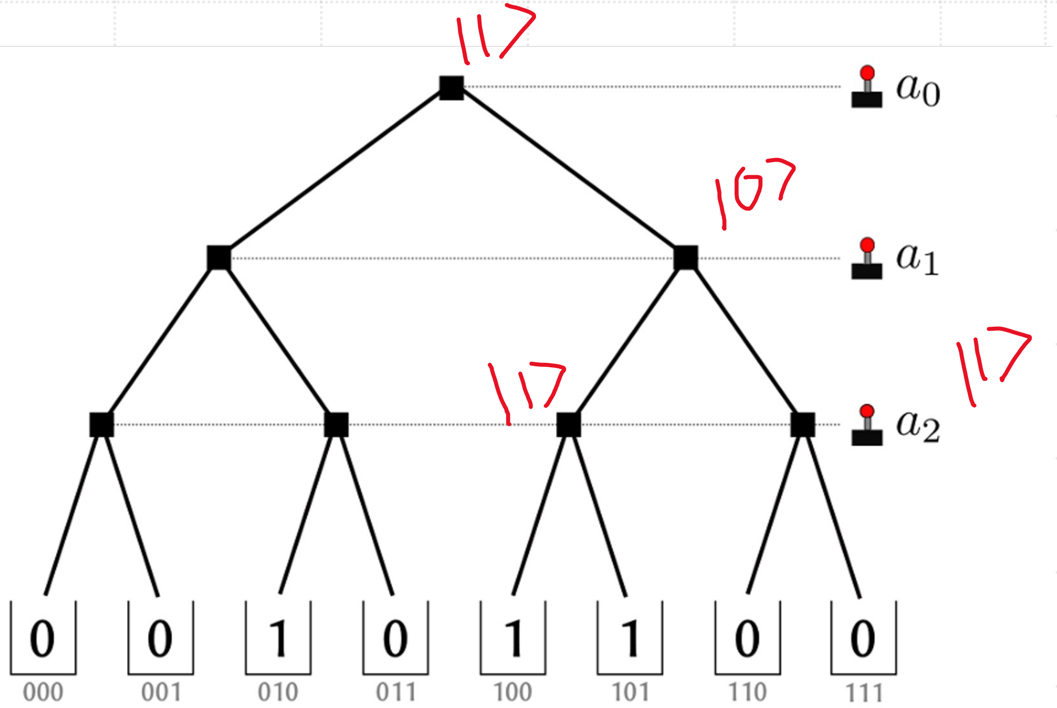
Bifurcation Tree




[8] Source: https://github.com/qsharp-community/qram

# qRAM – Direct Translation

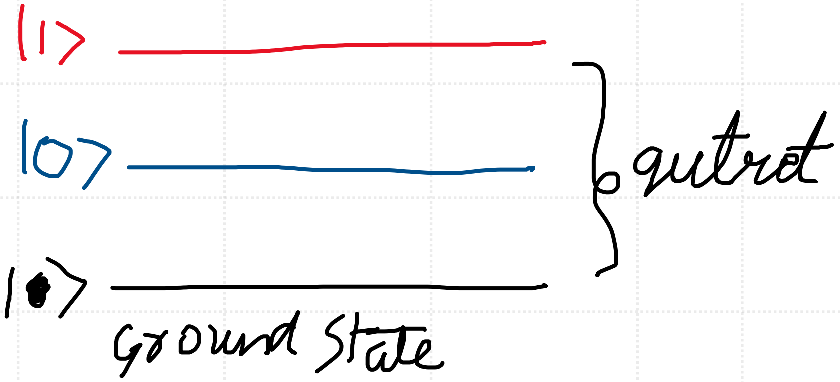
- Direct translation of classical bifurcation tree
  Is this feasible?
- Address qubits are in general entangled with O(N) quantum gates
- $k^{th}$ address qubit is coupled with $2^k$ qubits in $k^{th}$ row
- Results in precarious superposition
  - Hard to keep the coherence
  - High error rates!
  - $\sum_j \alpha_j |j_0 j_1 .. j_{n-1}\rangle \otimes \ |j_0\rangle_{k_0} |j_1\rangle_{k_1}^{\otimes 2} .. |j_{n-1}\rangle_{k_{n-1}}^{\otimes 2^{n-1}}$




[8] Source: https://github.com/qsharp-community/qram

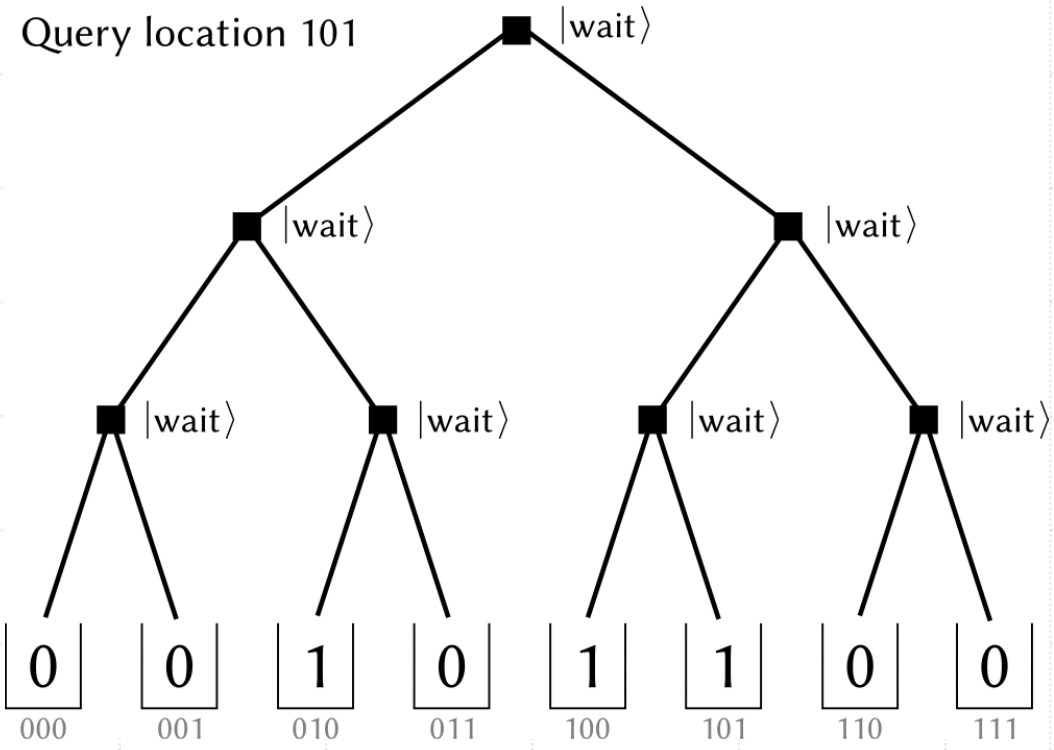
# qRAM – Bucket Brigade

- Introduced in the paper QRAM [17] by Giovannetti et al.
- Qutrits are used instead of qubits.
  - States: $|wait\rangle, |left\rangle$ *and* $|right\rangle$
- A quantum bus is used to read the contents of memory
- Every node is initialized with $|wait\rangle$ state
- Unitary transformation of qutrits
  - $U|0\rangle|wait\rangle \rightarrow |f\rangle|left\rangle$
  - $U|1\rangle|wait\rangle \rightarrow |f\rangle|right\rangle$



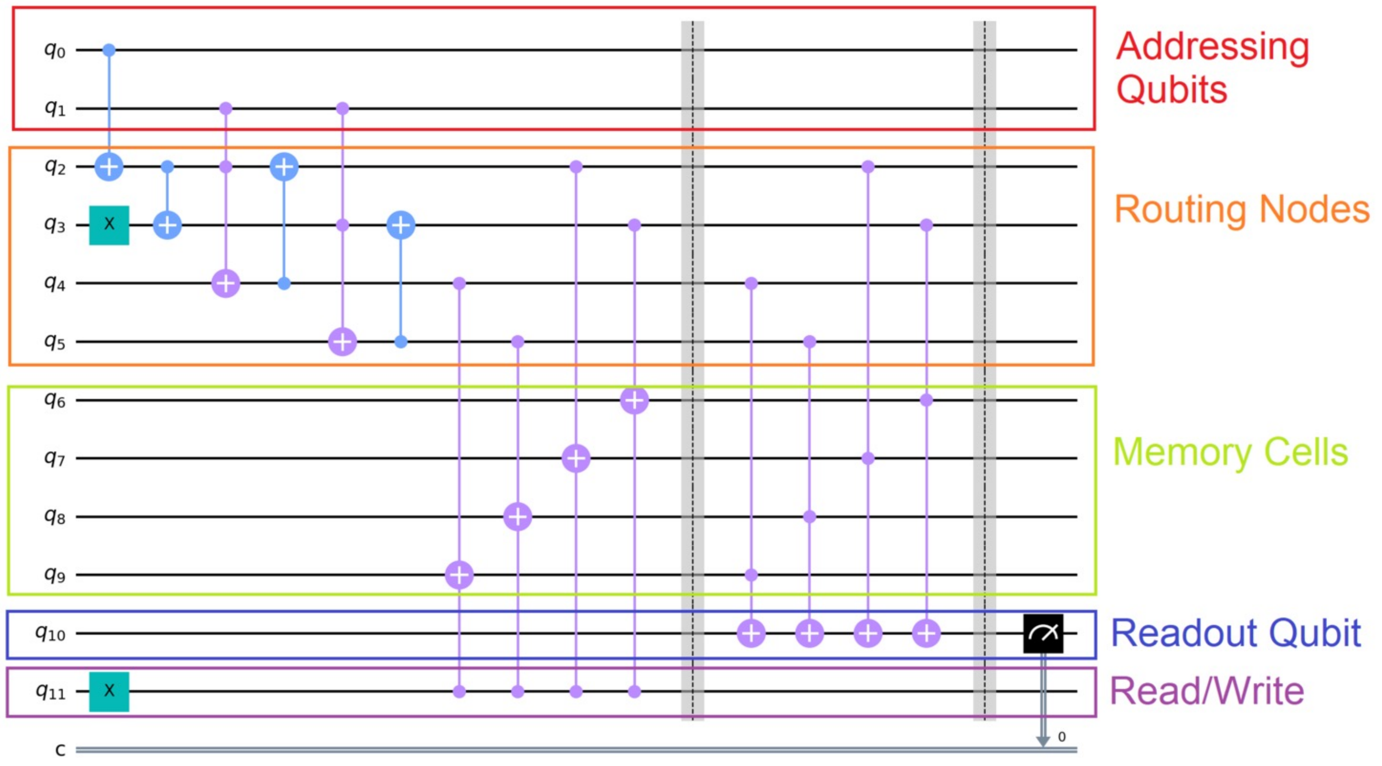
# qRAM – Bucket Brigade

- $O(n^2)$ operations instead of exponential
  - 1st qubit performs 1, 2nd performs 2 ….
  - n(n+1)/2 operations
- Claimed worst case error rate $O(1/n^2)$
- Leaves idle qutrits uncorrected.




[8] Source: https://github.com/qsharp-community/qram

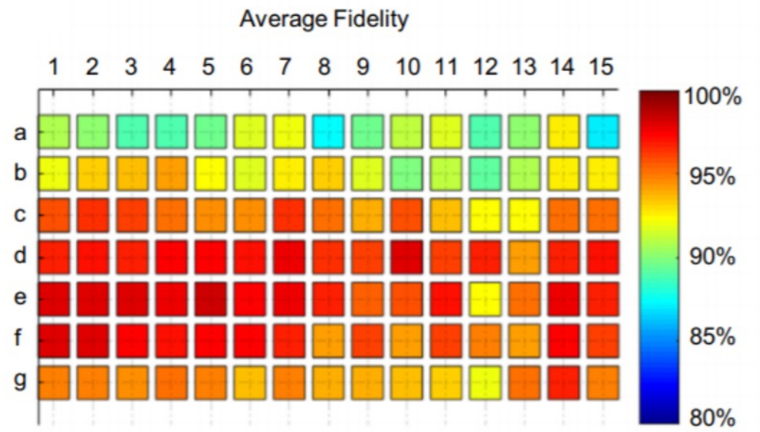
# qRAM – Circuit




https://quantumcomputinguk.org/tutorials/implementing-qram-in-qiskit-with-code

# qRAM – Current State & Experiments

- Scalable and High-Fidelity Quantum Random Access Memory in Spin-Photon Networks [9] [2021]
  - Uses photons, theoretical analysis of the qRAM efficiency and query fidelity
  - *Our numerical simulations show that our architecture can achieve > 0.99 fidelity with > kHz success rate for a qRAM containing 102 memory cells [9]*
- Experimental realization of 105-qubit random access quantum memory [10] [2019]
  - Photonic pulses as bus qubits and atomic spin states as memory qubits
  - 105 qubit random access memory using 210 memory cells
  - Different architecture. Experiment storage time of 1.38 µs.




Measured state fidelities of the retrieved optical qubits after storage in the 210-cell quantum memory. [10]

# Conclusion & Questions

- Quantum Memory is a highly active research area
  - Lot of experiments on physical realizations
- qRAM is vital in future of quantum computing and networking!
- Theoretical architectures
- Few recent experiments shed a light on how qRAM might look like!

# References


[1] *Ultracold@UAlberta - Quantum Memory*. (n.d.). https://sites.google.com/ualberta.ca/ultracold/research/quantum-memory

[2] https://quantumcomputing.stackexchange.com/questions/117/why-do-optical-quantum-computers-not-have-to-be-kept-near-absolute-zero-while-su

[3] Lvovsky, A. I., Sanders, B. C., & Tittel, W. (2009). Optical quantum memory. *Nature Photonics*, *3*(12), 706–714. https://doi.org/10.1038/nphoton.2009.231

[4] Wang, Y., Um, M., Zhang, J., An, S., Lyu, M., Zhang, J., Duan, L., Yum, D., & Kim, K. (2017). Single-qubit quantum memory exceeding ten-minute coherence time. *Nature Photonics*, *11*(10), 646–650. https://doi.org/10.1038/s41566-017-0007-1

[5] Kerenidis, I. (2018, December 10). *q-means: A quantum algorithm for unsupervised machine learning*. arXiv.org. https://arxiv.org/abs/1812.03584

[6] Casares, P. a. M., & Martin-Delgado, M. A. (2020). A quantum active learning algorithm for sampling against adversarial attacks. *New Journal of Physics*, *22*(7), 073026. https://doi.org/10.1088/1367-2630/ab976f

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