Design of Ion Trap Junctions For Quantum Computing at Kilo-Qubit Scale

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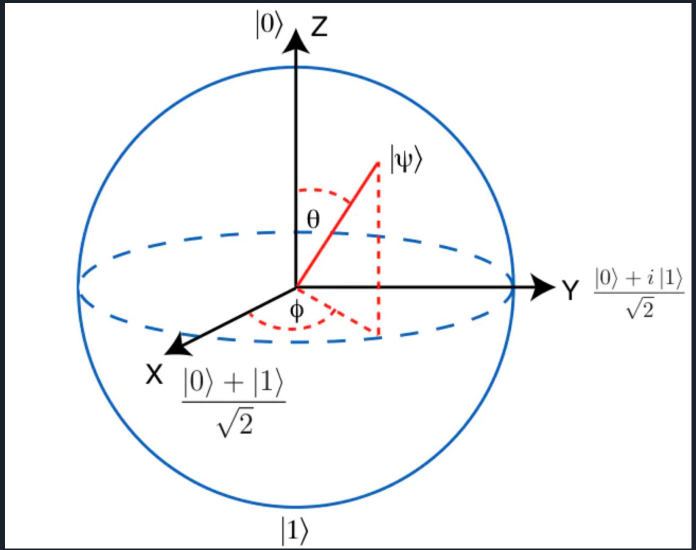
Problem We Are Addressing

- Iowa State's current Quantum Computing program
  - One researcher was recently granted $470,000 to work with quantum simulation
- We will create a novel design for a quantum computer
  - Make a novel improvement on quantum computers scalability, stability, and speed
  - Design will be used to create a quantum computer in the future
  - Contribute to Iowa State's prestige and programs

Quantum Computing Background

- Foundation: Quantum Bits
  - Superposition of 0 & 1; measures out probabilistically
  - Implemented by physical units with quantum behavior (e.g. electrons in certain ions, superconductors, etc.)
  - Physical vs Logical
- Motivation: Quantum Algorithms
  - Integer-number factoring : exponentially faster
  - Unordered searching: quadratically faster
  - Super-dense encoding: 2 Cbits per Qubit

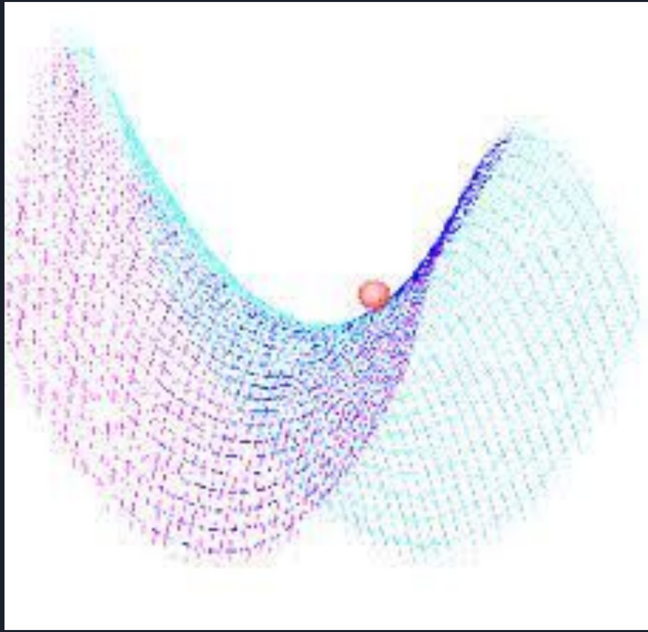
Quantum Computing Background Cont.



- Coherence Time
  - T1 is relaxation time (time it takes to go from |1> to |0>)
    - Otherwise known as longitudinal
  - T2 is more of the traditional "coherence" time.
  - It measures how long we can deduce any sort of probability ("phase information of the superposition state") from the qubit
    - Otherwise known as transverse or "phase coherence time"
- Noise / Quantum Fidelity / Error Correction
  - "Noise" is a big issue in quantum computing
  - The technical way of measuring is Quantum Fidelity - measure of how closely you can expect a qubit to behave compared to its Quantum Coding counterpart
  - Error Correction codes are the main way to combat noise

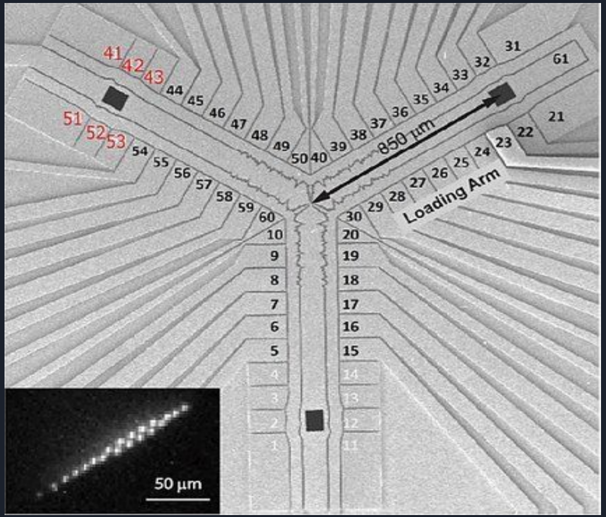
Quantum Computing Background Cont. 2

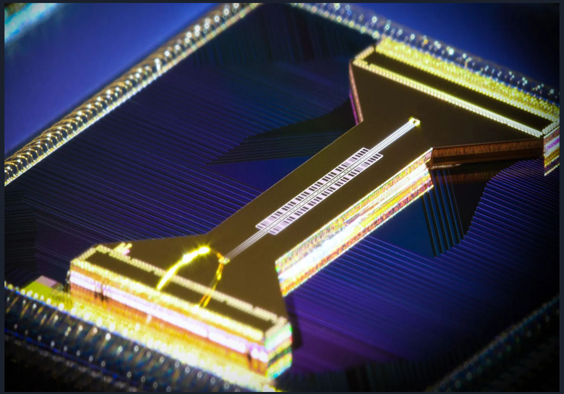
- Superconducting Qubits
  - Fast gate speed
  - Limited scaling
  - Near absolute zero cooling
- Ion Trap
  - Most accurate logic
  - Relatively slower gate speeds
  - Modular scaling
  - Laser crowding
- Photonic Coupling
- Ion Trap specifications
  - Single vs. multiple connected clusters
  - Calcium vs. Ytterbium ions
  - Utilization of Doppler Cooling
    - Barium vs. Strontium ions
  - RF (Paul) Traps
    - Y-intersection, T-intersection, or parallel pathways



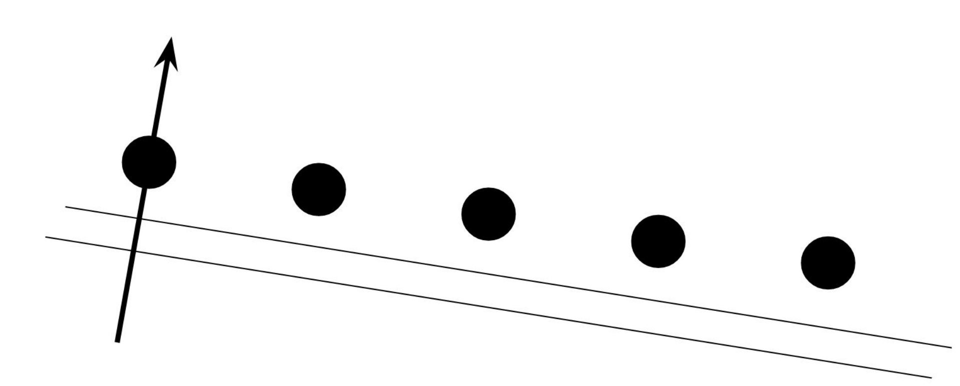
Current Design 1

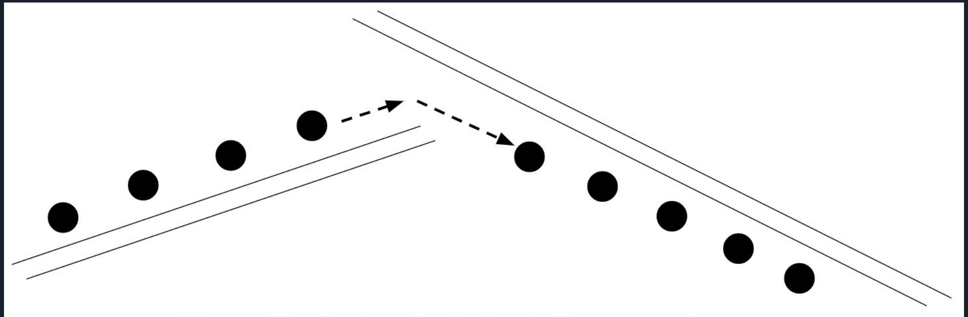
- Current leading model:
  - Y intersection
  - All electrodes facing "up"
  - At the intersection, surface area is minimized
    This could cause problems with conflicting qubits
- How can we improve the leading design?
  - Designated quantum memory hardware (Computation/Memory)
  - Increase stability of Qubits
  - Maximize efficiency of our RF electrode intersections
  - Modular -> Scalable





Current Design 2

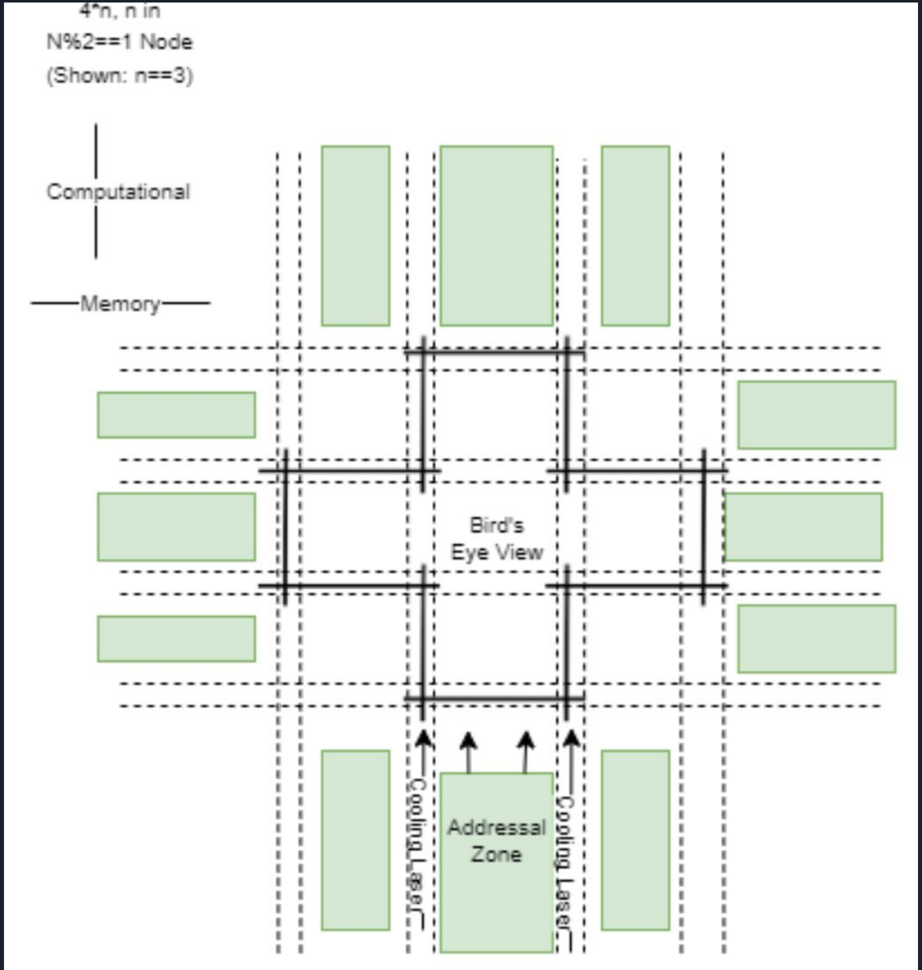




- We will use an ion trap **similar to** the Honeywell H1
- We will use multiple ion traps
  - Storage
  - Computing
  - ~10 ions per trap
- Ions will be handed off between traps
  - Hold the ion in place at the end
  - Turn RF trap #1 off while turning #2 on
- Design will be modular

Current Design 3

- Modular design
  - 12 traps in one node,
    - Half computing
    - Half storage
  - Nine nodes in a cluster (3x3 square)
  - Addressal from side (shown), in line, or possible integrated with the ion trap
    - Honeywell H1's trap has this
- Communication between nodes
  - Quantum using repeaters
  - Classical



Short Term Plan

- ❑ Continue testing
  - ❑ Ion Trap simulation code
- ❑ More complex testing
  - ❑ More robust modelling of single ion handoffs
  - ❑ Multiple ion handoffs
  - ❑ Viability of the storage of ions
- ❑ Confirm lasers for addressal and cooling fit in the design
  - ❑ Two separate lasers per ion trap
  - ❑ “If we can’t cool the ions, we’re dead in the water”

ion_trap_sim.cpp 9+

```cpp
//I'm generating this with mathematica code rn
//This should be first the mins, then the maxes in x y z order
//x is the axis for the ions, z is perpindicular to the trap surface
//so Controlm31 is in the -y direction
std::multimap<std::string, std::array<float, 6>> trapGeom{
  {"RF1", {{-800.0f, 245.0f, -2.0f, 800.0f, 500.0f, 0.0f}}},
  {"RF1", {{-800.0f, -500.0f, -2.0f, 800.0f, -245.0f, 0.0f}}},
  {"RFouter1", {{-800.0f, 150.0f, -2.0f, 800.0f, 245.0f, 0.0f}}},
  {"RFouter1", {{-800.0f, -245.0f, -2.0f, 800.0f, -150.0f, 0.0f}}},
  {"Ground1", {{-800.0f, 55.0f, -2.0f, 800.0f, 150.0f, 0.0f}}},
  {"Ground1", {{-800.0f, -150.0f, -2.0f, 800.0f, -55.0f, 0.0f}}},
  {"Controlm11", {{-100.0f, 30.0f, -14.0f, 0.0f, 55.0f, -12.0f}}},
  {"Controlm11", {{-100.0f, -55.0f, -14.0f, 0.0f, -30.0f, -12.0f}}},
  {"Controlm21", {{-200.0f, 30.0f, -14.0f, -100.0f, 55.0f, -12.0f}}},
  {"Controlm21", {{-200.0f, -55.0f, -14.0f, -100.0f, -30.0f, -12.0f}}},
  {"Controlm31", {{-300.0f, 30.0f, -14.0f, -200.0f, 55.0f, -12.0f}}},
  {"Controlm31", {{-300.0f, -55.0f, -14.0f, -200.0f, -30.0f, -12.0f}}},
  {"Control11", {{0.0f, 30.0f, -14.0f, 100.0f, 55.0f, -12.0f}}},
  {"Control11", {{0.0f, -55.0f, -14.0f, 100.0f, -30.0f, -12.0f}}},
  {"Control21", {{100.0f, 30.0f, -14.0f, 200.0f, 55.0f, -12.0f}}},
  {"Control21", {{100.0f, -55.0f, -14.0f, 200.0f, -30.0f, -12.0f}}},
  {"Control31", {{200.0f, 30.0f, -14.0f, 300.0f, 55.0f, -12.0f}}},
  {"Control31", {{200.0f, -55.0f, -14.0f, 300.0f, -30.0f, -12.0f}}},
  {"RF2", {{-245.0f, 800.0f, 122.0f, -500.0f, -800.0f, 120.0f}}},
  {"RF2", {{245.0f, 800.0f, 122.0f, 500.0f, -800.0f, 120.0f}}},
  {"RFouter2", {{-150.0f, 800.0f, 122.0f, -245.0f, -800.0f, 120.0f}}},
  {"RFouter2", {{150.0f, 800.0f, 122.0f, 245.0f, -800.0f, 120.0f}}},
  {"Ground2", {{-55.0f, 800.0f, 122.0f, -150.0f, -800.0f, 120.0f}}},
  {"Ground2", {{55.0f, 800.0f, 122.0f, 150.0f, -800.0f, 120.0f}}},
  {"Controlm12", {{-30.0f, 100.0f, 134.0f, -55.0f, 0.0f, 132.0f}}},
  {"Controlm12", {{55.0f, 100.0f, 134.0f, 30.0f, 0.0f, 132.0f}}},
  {"Controlm22", {{-30.0f, 200.0f, 134.0f, -55.0f, 100.0f, 132.0f}}},
  {"Controlm22", {{55.0f, 200.0f, 134.0f, 30.0f, 100.0f, 132.0f}}},
  {"Controlm32", {{-30.0f, 300.0f, 134.0f, -55.0f, 200.0f, 132.0f}}},
  {"Controlm32", {{55.0f, 300.0f, 134.0f, 30.0f, 200.0f, 132.0f}}},
  {"Control12", {{-30.0f, 0.0f, 134.0f, -55.0f, -100.0f, 132.0f}}},
  {"Control12", {{55.0f, 0.0f, 134.0f, 30.0f, -100.0f, 132.0f}}},
  {"Control22", {{-30.0f, -100.0f, 134.0f, -55.0f, -200.0f, 132.0f}}},
  {"Control22", {{55.0f, -100.0f, 134.0f, 30.0f, -200.0f, 132.0f}}},
  {"Control32", {{-30.0f, -200.0f, 134.0f, -55.0f, -300.0f, 132.0f}}},
  {"Control32", {{55.0f, -200.0f, 134.0f, 30.0f, -300.0f, 132.0f}}} };
```

Code for testing the ion traps

Where We See This Project Ending Up

- By the end of 492
  - Paper detailing how our design works and improves over existing designs
  - Potential (provisional) patent of our design
- Beyond 492
  - The project will continue with existing and new faculty
  - The design will be finalized, patented, and manufactured
- How Iowa State will benefit
  - Grants
  - Professors who specialize in this field