4 Design

4.1 Design Context

4.1.1 Broader Context

Describe the broader context in which your design problem is situated. What communities are you designing for? What communities are affected by your design? What societal needs does your project address?

Area	**Description**
Public health, safety, and welfare	**Due to the purely theoretical and research-oriented nature of our design, it has minimal immediate impacts on public health, safety and welfare of people. The design is intended for students and faculty in the field of quantum computing / quantum physics, and stands to further the goals of the field. Down the line, it is our hope that quantum computers will be commercially viable and unlock a new paradigm of computing power for the general welfare. We believe we are doing our part in furthering this goal. Hopefully, our contributions to the field of quantum computing will enhance public welfare, as prior advancements in technology have.**
Global, cultural, and social	**The most significant impact of this project will be in global, cultural, and social areas. With this being a design of Iowa State origin, although our findings will be publicly available, the project stands to benefit Iowa State oriented individuals the most. Iowa State is very behind in the race for quantum computing power and the end goal of this project is to reduce that gap through further recognition of the school's efforts, increases in staff count and caliber in this department, and student engagement in the field. Doing so will increase the longstanding culture at Iowa State of ingenuity. As a team, we say "If the first digital computer was invented at Iowa State, why can't the first large-scale Quantum Computer?" While ambitious, there is a chance of global effects of our design. If our design works and performs as we intend it to, this could help the global field of quantum computing move forward. It could help open a door for the QC community into another school of design.**
Environmental	**Again, due to the purely theoretical and research-oriented nature of this design, the environmental impacts of it are negligible at the moment. A physical quantum computer of this specification would require a great amount of energy to run, similar to other Quantum Computers (QCs) of today. The power requirements and necessity of running the computer at 10 Kelvin would be significant relative to many other senior design projects. Our QC would utilize materials standard in other QCs, but procedures around obtaining such materials may still be harmful to society and the environment. This is not something we have much affect over, as we would not be constructing the computer, and as such, sourcing the materials.**

Economic	**Should this QC stay within the realm of a hypothetical design, the economic impact will be very minimal. We hope that our design will spur further ideation and design creation, further leading to the financial viability of quantum computers as a whole. If we begin to construct a physical QC, the economic impact will be more substantial, due to the requirement of designing such a cutting-edge machine. We couldn't do any sort of component production at Iowa State and would have to outsource it to a DoE lab. Even still, our computer would most likely not be financially viable, and as such, not have any large macroeconomic effects for us or associated parties.**

4.1.2 Prior Work/Solutions

Include relevant background/literature review for the project

– If similar products exist in the market, describe what has already been done

– If you are following previous work, cite that and discuss the **advantages/shortcomings**

– Note that while you are not expected to "compete" with other existing products / research groups, you should be able to differentiate your project from what is available. Thus, provide a list of pros and cons of your target solution compared to all other related products/systems.

Detail any similar products or research done on this topic previously. Please cite your sources and include them in your references. All figures must be captioned and referenced in your text.

The Honeywell and IonQ Quantum Computers have been built, but they have very few qubits, and are therefore limited. Our design will be similar in many regards, but designed for a great many qubits, around 1,000. We will do this by arranging multiple ion traps together into a cluster, and using a special memory-type ion trap that allows qubits to last longer.

Our design will be more like the Honeywell QC. Both use Ytterbium (Yb) ions for qubits, each use electrodes to keep them in an ion trap, and each use beams of lights/lasers to set, address, cool and manipulate them. The Honeywell QC cools its Yb ions using Barium (Ba), while the IonQ QC does not. The Honeywell QC physically moves its qubits around to have them interact with each other, whereas the IonQ computer transfers information using light and swap gates.

Works Cited

AVS Quantum Sci. 3, 044101 (2021); https://doi.org/10.1116/5.0065951

4.1.3 Technical Complexity

Provide evidence that your project is of sufficient technical complexity. Use the following metric or argue for one of your own. Justify your statements (e.g., list the components/subsystems and describe the applicable scientific, mathematical, or engineering principles)

1. The design consists of multiple components/subsystems that each utilize distinct scientific, mathematical, or engineering principles –AND–
2. The problem scope contains multiple challenging requirements that match or exceed current solutions or industry standards.

The complexity and scope of designing a quantum computer is apparent to us:

- **The physics and mathematics of the operations inside a quantum computer are so complex (literally, they have a large focus on complex numbers, e.g. (a+bi,c+di)) that we have largely neglected them for the purposes of the design. We are treating ion-traps, an extremely new and relatively unproven design, to be a single, solid entity within our computer. Our computer will consist of a number of these ion traps in a specific layout to facilitate computing on a larger-scale than other QCs currently known in the public domain.**
- **Our problem is fundamentally an engineering problem - the layout and rough construction of a Quantum Computer with particular attributes. This holistically encompasses many aspects of the engineering design process - including ideation (see below), tradeoff consideration (technical and otherwise), and rough prototyping.**
- **Our Quantum Computer will consist of ion-traps laid out in a novel design to accomplish basic computing responsibilities: mutilation and storage of data for multiple cycles. This is very similar to designing a traditional computer, but with an extra helping of mathematics and physics.**
- **The handoff of ions between traps relies heavily on particle physics**
- **The scope of our design problem hinges on the creation of a kilo-qubit scale quantum computer - a novel concept yet to be successfully created. Designs for QCs with 10s or low hundreds of qubits do exist, but haven't been implemented due to cost, material, or technology constraints. We intend on making this computer with current technologies and materials, which will definitely be a challenge. Pushing the boundaries of a new field with existing technology will prove to be a sufficient challenge.**

4.2 Design Exploration

4.2.1 Design Decisions

List key design decisions (at least three) that you have made or will need to make in relation to your proposed solution. These can include, but are not limited to, materials, subsystems, physical components, sensors/chips/devices, physical layout, features, etc. Describe why these decisions are important to project success.

Number of clusters in the computer

- **These are the largest layer of the QC. Depending on their role, the number of these may be important to not bottleneck the computer during operation. An adequate number of these is important to the "scale" aspect of our design, as multiplying these elements will quickly get oru computer to the size we'd like it to be.**

Number of nodes in a cluster

- **These are the intermediate layer of the QC. Depending on their role, the number of these may be important to not bottleneck the computer during operation. The number of each of these in each computing node will set the upper limit of computations the computer could perform.**

Number of traps per node

- **These are the base layer of the QC. They serve a fundamentally different role than the larger two layers due to their importance to the physical operations of the computer. The number of each of these in each computing node will set the upper limit of computations each node unit could perform.**

Function(s) of traps, nodes and/or clusters

- **The decision to use all computing components as duplicates which do any one or number of functions would sway the number of each type of component needed to effectively perform computing operations.**

Physical orientation of traps relative to other traps, nodes to other nodes, clusters to other clusters

- **The orientation of each component is of paramount importance with respect to the physical tradeoff of ions, ability to hold information for multiple machine cycles, and ability to use quantum computing effectively.**

4.2.2 Ideation

For at least one design decision, describe how you ideated or identified potential options (e.g., lotus blossom technique). Describe at least five options that you considered.

We must decide upon the physical orientation of traps relative to others. As previously mentioned, the orientation of the ion traps relative to other ones will be fundamental in the handoff of ions between traps, a crucial standpoint of our design and the driving force behind our scalable, modular design.

- **Square Grid design with upper and lower tracks**
    - **This was the design recommended by the advisors of our project. This type of design is supported by modern, 2-level wafer electronics printing and will most likely be what we moved forward with. Similar to a street-level grid used in many newer towns, a meeting point would consist of two, three, or four "roads" (ion traps) convergining in "intersections." This design calls for explicit usage oif the cardinal directions to maintain order**
- **Tree design**
    - **Two major factors permeate our design requirements. Firstly, the addition of ion traps at their intersections introduces additional noise and uncertainty, as a qubit traveling from one to another is less likely to go in the intended direction. Secondly, the movement of a qubit reduces its coherence time, and introduces error into the QC. Therefore, we would do good to minimize both the number of ion traps at each junction, and the distance between each qubit. A tree-like design, such as a binary tree, compromises between these constraints. It allows for each qubit to only need to travel O(log(n)) ion traps to get to any other qubit,as opposed to a line or circle, which requires O(n) ion traps to be traversed. It also requires less ion traps per junction between ion traps than a grid or wheel spoke. Even if the design is not strictly a tree, it can have aspects that are like one.**
- **Wheel and spoke design**
    - **This was a design thought of by a team member. It involves many ion traps converging at a central point, where ions could be handed off to any one of the number of "spoke" ion traps. Around the outside of these spoke traps, we could have a "wheel" of ion traps providing a potentially different function.**
- **Triangular grid design with upper and lower tracks**
    - **This is a slightly different iteration of the grid design. Instead of having squares, we could have a triangular grid, with each connection being a meeting point of three ion traps instead of two or four. This design would not use the cardinal directions, and all intersections would have exactly three connections (outside of those on the corners of the grid).**
- **Other 3+ Layer designs**
    - **This is a subset of thoughts that we came up with when considering the binary tree design. This school of design requires the practical capability of electronics manufacturing with 3+ layer wafer design. We did not look much into this option, as to our knowledge, such wafer design is not possible.**

4.2.3 Decision-Making and Trade-Off

Demonstrate the process you used to identify the pros and cons or trade-offs between each of your ideated options. **You may wish** to include a weighted decision matrix or other relevant tool. Describe the option you chose and why you chose it.

Physical Layout of computer

- **Grid design with upper and lower tracks**
  - **Pros:**
    - **Moderate junction density, at most 4 for a square grid**
  - **Cons:**
    - **Moderate-High O(n^(1/2)) distance between qubits**
- **Tree design**
  - **Pros:**
    - **Moderate-low O(logn) distance between qubits**
    - **Moderate-low junction density, at most 3 in the case of a binary tree.**
    - **Principles of the tree design may be applied to other designs.**
  - **Cons:**
    - **Leafs have the worst travel time, and they are the most prevalent.**
    - **Other designs have better qubits distance or junction density individually**
- **Wheel and spoke design**
  - **Pros:**
    - **Low distance between qubits**
    - **Low junction density on the wheel, 2 or 3 ion traps per junction.**
    - **Could support parallel computing in multiple "spoke" ion traps**
  - **Cons:**
    - **High junction density, particularly in the center of the wheel**
    - **Ions could get lost in the hub of the wheel, where the spokes all meet**
- **Triangular grid design**
  - **Pros:**
    - **Moderate-Low distance between qubits.**
    - **The structure would be most dense, and take up less space.**
  - **Cons:**
    - **High junction density, at most 6 for a triangular grid**
- **Other 3+ Layer Designs**
  - **Pros:**
    - **Denser, taking up less space.**
    - **Vertical traversal allows for shorter qubit traversal time.**
  - **Cons:**
    - **Likely high junction density**
    - **Probably not possible with current technology**

We have not yet made an official decision on this or other considerations yet, as knowledge acquisition is still underway to help more thoroughly inform our decisions.