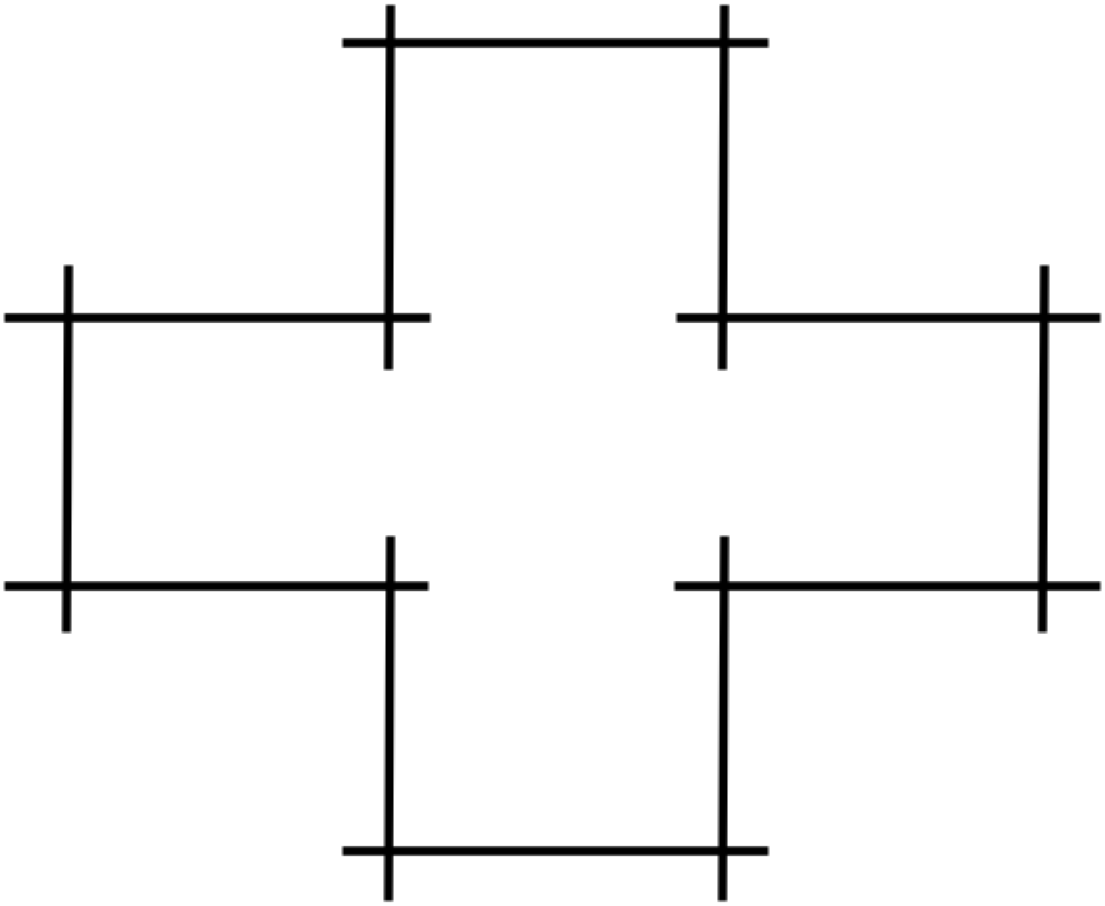
4.3 Proposed Design

4.3.1 Overview

Provide a high-level description of your current design. This description should be understandable to non-engineers (i.e., the general public). Describe key components or sub-systems and how they contribute to the overall design. You may wish to include a basic block diagram, infographic, or other visual to help communicate the overall design.



We are designing a quantum computer schematic. Pictured above is our design for a node of this computer. This node will be composed of 12 ion traps, and each will hold 5-10 ions, each ion acting as a quantum bit ("qubit"). Each of these nodes will operate in the same fashion, and will connect to each other. To transfer information within a node, these qubits will continuously move between ion traps at junction points near their ends. Due to the state of current technology, it is best to implement junctions between two ion traps with a right angle. The part of each ion trap that extends past this junction helps to guide the qubit to its destination. Additionally, the ends of each ion trap contain a DC voltage stop - a wall that stops ions from flying off the ion trap. The cross design is composed of only right angle junctions, and is, to some degree, symmetric, so forces from electrodes may cancel each other out (which is desired).

4.3.2 Detailed Design and Visual(s)

Provide a detailed, technical description of your design, aided by visualizations. This description should be understandable to peer engineers. In other words, it should be clearly written and sufficiently detail such that another senior design team can look through it and implement it.

The description should include a high-level overview written for peer engineers. This should list all sub-systems or components, their role in the whole system, and how they will be integrated or interconnected. A visual should accompany this description. Typically, a detailed block diagram will suffice, but other visual forms can be acceptable.

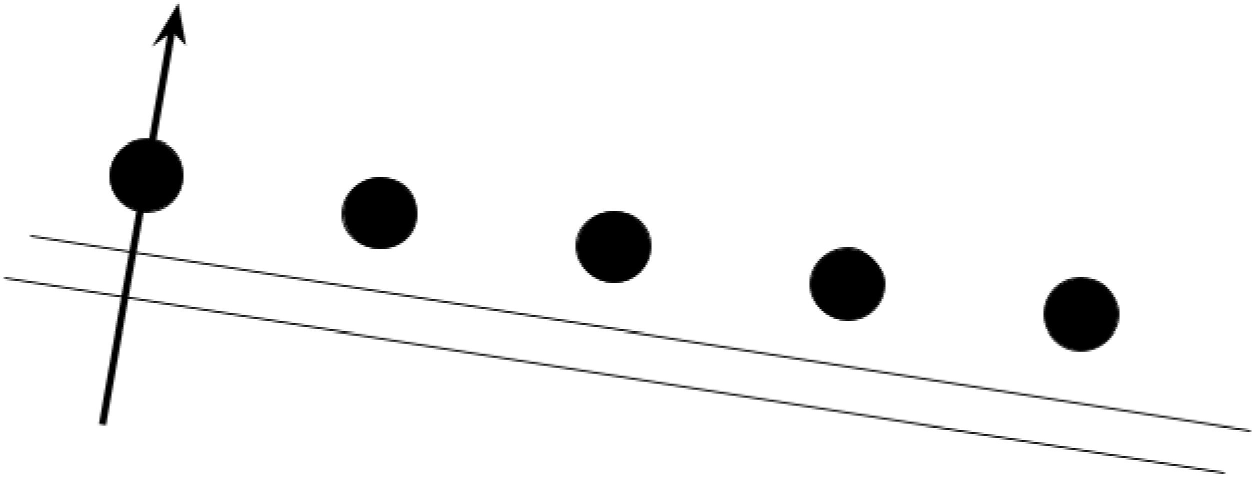
The description should also include more specific descriptions of sub-systems and components (e.g., their internal operations). Once again, a good rule of thumb is: could another engineer with similar expertise build the component/sub-system based on your description? Use visualizations to support your descriptions. Different visual types may be relevant to different types of projects, components, or subsystems. You may include, but are not limited to: block diagrams, circuit diagrams, sketches/pictures of physical components and their operation, wireframes, etc.

We are designing a quantum computer schematic. The central part of the computer is a node, which itself is a quantum computer holding a number of qubits on the order of ~100. The node will be used in clusters to build a quantum computer of many clusters, which in total can hold on the order of 1000 qubits.

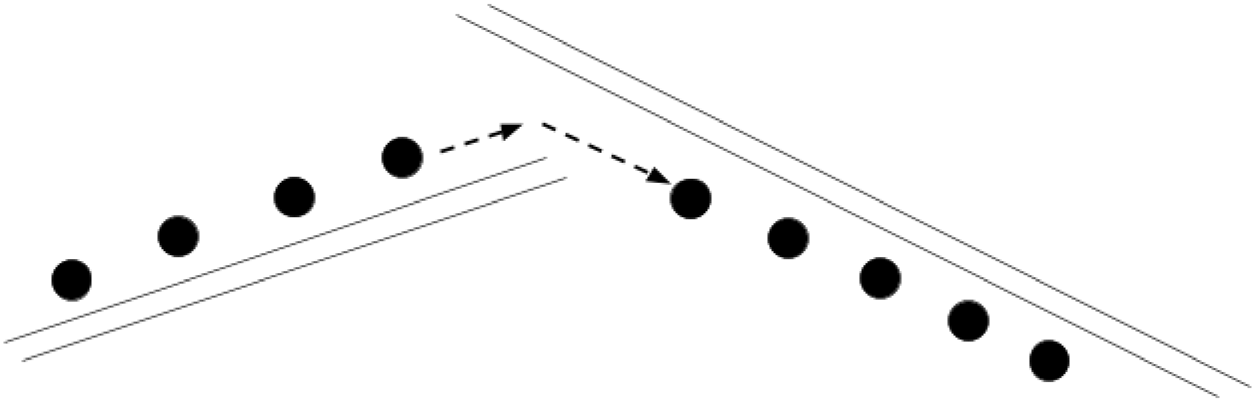
A "qubit" is a quantum bit in a superposition between 0 and 1. A single qubit may be represented as a vector of two complex numbers, the magnitudes of each are the probabilities that the qubit will be either 0 or 1 once it is measured, so the magnitude of the magnitudes of the elements of the vector is always 1. Qubits may be manipulated by quantum gates, which may be thought of as unary matrices, that is, any matrix when multiplied to its conjugate transpose becomes the identity matrix. This allows the probabilities of a qubit being 0 or 1 to be flipped, or for the polarity of one of the aforementioned complex numbers to be flipped, or for a qubit to gain an equal probability of yielding 0 or 1, from a state of exactly 0 or 1, but do nothing when applied twice. There are also two-qubit gates, such as the controlled not gate, which flips one qubit's value if and only if the other will yield 1 when measured. This allows for quantum entanglement, a situation where one qubit will not yield a different result than another qubit will when the same outside stimuli are applied to both. Complex quantum algorithms take advantage of these qualities to perform tasks faster than on digital computers. Though the complex numbers cannot be measured directly, their magnitudes can be measured by running the same algorithms multiple times, and measuring average responses.

As stated prior, qubit information is stored in Ytterbium cations, which are called "physical qubits." The last valence electron in the Ytterbium cation exists in a superposition between its usual orbital, and an excited state, allowing for us to use the ion (electron) as a qubit. Multiple physical qubits may be used together to model a single qubit with greater accuracy, called a logical qubit. We use lasers to emit photons, which then impart the Ytterbium atom with energy depending on the wavelength, as the last electron can absorb the incoming light, and jump to a higher state. Depending on the frequency of light provided, the electron could jump to a specific unstable state, and then go back down to its usual position. This allows us to set specific qubits to be either 0 or 1. Furthermore, we can measure the orbit of the electron by sending light to it, and then measuring what we get, because some light may be absorbed by the ion and will not go through it. Using these lasers, we can set and access the qubits.

In order for the qubits to be useful, the ions must exist at a very low temperature; otherwise, there will be too much noise, and the physical qubits we do have will retain information for less time. This temperature will be around 10 - 12 Kelvin. Therefore, we will employ multiple methods of cooling, including doppler cooling and passive Barium cooling. In doppler cooling, we emit light at a specific frequency to cause the Ytterbium ion to lose energy and slow down. In passive Barium cooling, we place Barium ions between the Ytterbium ions, and then cool the barium ions more aggressively, which then cool the Ytterbium ions. The image below depicts an ion gate with ions, and a beam of light going from the top to the bottom.



Useful quantum algorithms are complex, and require many qubits to execute. Therefore, we aim to create a machine with a great many qubits, on the order of 1000, to advance the field of quantum computing. The primary challenge to accomplishing this feat is that qubits are very unstable, and exist for only a short amount of time. Usually, the addition of more qubits in a quantum computer introduces noise, and reduces the amount of time a qubit can hold accurate information. Therefore, we will use special memory-specific ion traps that are designed to only store qubits without doing gate operations on them. This is a key point where our design diverges from existing designs.



In addition to using memory specific ion traps, we will also use a vertical transfer, shown above. In this, qubits will transfer from one ion trap to another vertically, just hovering across. We expect that this will limit the noise that a qubit encounters while traversing ion traps.

4.3.3 Functionality

Describe how your design is intended to operate in its user and/or real-world context. What would a user do? How would the device/system/etc. respond? This description can be supplemented by a visual, such as a timeline, storyboard, or sketch.

The goal of this project is to produce a viable quantum computer *design* that can achieve on the order of 1,000 qubits (referred to previously as "kilo-qubit"). Since the goal is a viable design, our client should expect to be able to apply tests or simulations against it to assess aspects of its functionality. Our guiding concern at the moment is the layout configuration of electrode rails called ion traps on top of which is where the qubits of the machine are located.

> **-Ion trap configuration testing: we will offer a proposed ion trap layout. While our current design is a result of our own thoughts, our final design may be generated by currently undetermined means. Our project will include a means to determine if ions configured in this layout behave as necessary for function in quantum computation**

Additionally this *design* is meant to be viable for computation. We will have to make certain allowances for scale, but the computational capacity of our design will also need to be testable in some way, with respect to the trap configuration, since that's what's novel about our design.

> **-Computation testing: our design will need to provide computational viability against testing and simulation that pay respect to decoherence factors such as transport interference, laser addressal, etc.**

4.3.4 Areas of Concern and Development

How well does/will the current design satisfy requirements and meet user needs?

Based on your current design, what are your primary concerns for delivering a product/system that addresses requirements and meets user and client needs?

What are your immediate plans for developing the solution to address those concerns? What questions do you have for clients, TAs, and faculty advisers?

We are still very early in the pre-design phase, lots of unknowns. Some of the most important factors of our design thus far may not even work, which we refer to later in 4.5 Design Analysis. Further development on our design will be largely dependent on access to high-grade electro-dynamic simulations. With our existing simulation software, we can not be sure that the results of our simulations accurately represent a real world outcome. We must be certain that under scrutiny from more well-endowed individuals and institutions with access to more advanced modeling software, our design holds up.

We have numerous concerns regarding our client needs. Our ion-trap topology will need to be sufficiently well simulated and highly optimized to achieve the client's desired volume of qubits in a feasible configuration (i.e. without decoherence factors rendering the system useless). All the while, we must maintain a topology that can address the numerous functional requirements for ion-trap quantum computer design, e.g. laser cooling and addressal, loading, etc. The largest concern at the moment is trap topology and the accurate simulation thereof. Until we have

determined feasible topologies, the other requirements are difficult or meaningless to attempt to address.

We must continue our dialogue with advisors and look into functionality of existing technologies to see if our existing design is even worth testing.

4.4 Technology Considerations

Describe the distinct technologies you are using in your design. Highlight the strengths, weakness, and trade-offs made in technology available. Discuss possible solutions and design alternatives.

We will be making a quantum computer out of one modular component - a Ytterbium ion-trap. While a fairly recent development within the broader scope of computing, this is a tested way of performing computational operations. These ion traps have two segmented RF electrodes with DC voltage steps that create a "tube" above the trap that the ion sits in.

One of the most important parts of our project is that we will use existing technology, materials and methodologies. We are not in the place to create new and advanced materials or technologies, financially and educationally. The pro of doing this is that we don't have to invent something new, but the con is that utilizing existing technologies to come up with a design that outperforms existing ones in many respects will be a challenge. We believe that the continuous transference of the ion between traps could be a game changer, if it works.

We are using Ytterbium ion-trap design for our quantum computer because the current existing king, the Honeywell H1, has been continuously breaking records in terms of quantum volume - a metric introduced by IBM to show the computational power of a quantum computer. The H1 has set the last three records of quantum volume, and has 10x'd their quantum volume annually. Other types of quantum computers, such as those utilizing supervodnuctiong ions or use material defects to trap ions, are either too unsophisticated at this point in time or have had their recent progress slow.

4.5 Design Analysis

Discuss what you have done so far, i.e., what have you built, implemented, or tested? Did your proposed design from 4.3 work? Why or why not? Based on what has worked or not worked (e.g., what you have or haven't been able to build, what functioned as expected or not), what plans do you have for future design and implementation work? For example, are there implications for the overall feasibility of your design or have you just experienced build issues?

We have not built or implemented any components. Due to the fact that our project simply calls for a non-physical design, there will be no construction or physical implementation of the design. As of last week, we began rudimentary mathematical simulations of an ion trap. By the end of the next week, we should have uncovered whether continuous exchange of an ion between ion traps without degradation would be possible. We currently believe it to be possible, and our overlapping-ion-trap design hinges on it being so. For this reason, there are serious implications for the overall feasibility of our design.

As previously mentioned, the difficult part of this assignment is the creation of the design. There is a high likelihood that some of our sub-systems or entire design may not 1. Be functional 2. Push the boundaries of quantum computing or 3. Be feasible with current technology. Put another way, we are not only working in the paradigm of "Will this be good or change the game?" but also "Is this even possible?"

Our plans for future design and non-physical implementation include more extensive testing of the continuous handoff of ions, hopefully getting access to a more thorough (and expensive) modeling software with which to test larger sub-systems of our design, and continuous refinement of our sub-systems in a way that contributes to our overall goal of a kilo-qubit scale quantum computer. These items are in chronological order, and we do not expect to move on to the last item until next semester.