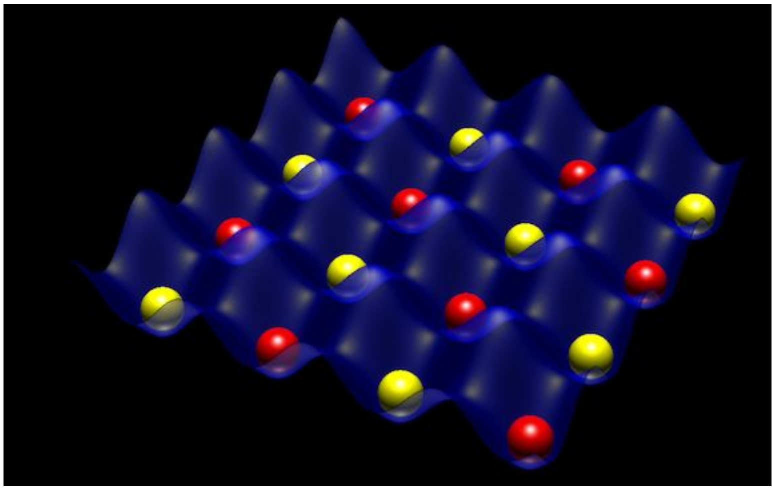
Which modality do you think would be the first to support a functional quantum computer? Why do you think your chosen modality will be the first one in supporting a functional quantum computer? Compare at least three modalities. Think about the second modality that might be also a good candidate and answer the same as above.

1.1 Three leading qubit modalities leading today

1.1.1 Neutral Atoms

Neutral atoms qubits are based on the internal states of atoms. The qubit states are hyperfine states, resulting from an interaction between the electron spin and the nuclear spin. Such hyperfine transitions are driven at very well-defined microwave frequencies, commonly used for atomic clocks.



Neutral atoms can be trapped by cross propagating optical beams, which combine to form an egg carton like potential.

- *Advantages*
  1. Highly stable qubits
  2. Their coherence times are very long
  3. Gate fidelity in neutral atoms is limited by control errors
  4. The ability to trap these neutral atoms in two and even three-dimensional arrays.
  5. Arrays with up to 49 qubits have been demonstrated
  6. Their weak interactions with the environment may help to reduce computing errors.
- *Challenges*
  1. Large laser power required to trap and control neutral atoms

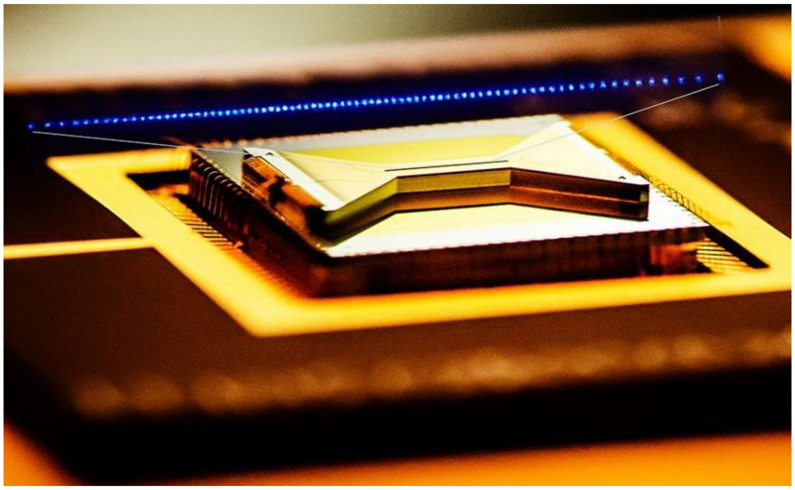
2. Loading the trap is stochastic process
3. Neutral atoms will require integrated optics to ultimately be scalable (something that's not yet been implemented)

- *Outreach articles*
    1. https://academic.oup.com/nsr/article/6/1/24/5094563
    2. https://physics.aps.org/articles/v12/s120
    3. https://jila.colorado.edu/dzanderson/research-area-description/neutral-atom-quantum-computing

1.1.2 Trapped Ions

Ion qubits generally start as atoms with two electrons in their outermost shell. And then one of those electrons is removed through ionization. The qubit is realized as either an optical transition between orbital states of this outermost electron, or a microwave transition between hyperfine states. Because the ion is charged, it can be trapped, or held in place using oscillatory electromagnetic field. Although these fields used to be applied using large electrodes arranged in three-dimensional configuration today, they're implemented using surface traps-electrodes manufactured on silicon wafers that hold the ions just above the wafer surface.

To date, arrays of 10 to 20 trapped ion qubits have been demonstrated, and surface traps in silicon are now being developed and used to both capture and control these ions in a scalable manner.



Linear computation: montage of a photo of the chip containing the trapped ions and an image of the ions in a 1D array (Courtesy: Christopher Monroe)

- *Advantages*

Trapped ions were the first qubit technology, and this is primarily due to their historical use in atomic clocks and precision measurements.

1. Stable and very well-characterized
2. Many of the DiVincenzo criteria are satisfied for trapped ion qubits

- *Challenges*
  1. The primary challenge is the 3D integration of optical and electrical technologies into the surface traps to make them scalable.
- *Business perspectives of trapped ions*

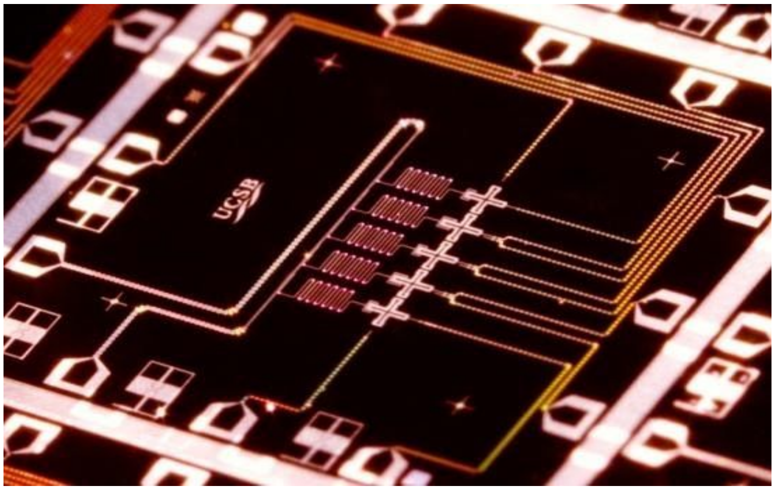
  Trapped ions are attractive for the following reasons:

  1. They leverage a substantial existing technology base
  2. Trapped ions today are fundamentally a silicon-based technology
  3. All of the key control and readout circuitry can be integrated with existing CMOS electronics, and, in this sense, they are scalable to large numbers of qubits
  4. Today, there are growing number of commercial efforts pursing or supporting the development of trapped ion qubits
- *Outreach articles*
  1. https://www.techspot.com/news/77887-new-type-quantum-computer-has-smashed-every-record.html
  2. https://phys.org/news/2020-04-speeding-up-quantum-giant-atomic-ions.html
  3. https://physicsworld.com/a/ion-based-commercial-quantum-computer-is-a-first/

1.1.3 Superconductors

Superconducting qubits are manufactured, artificial atoms. Superconducting qubits are electrical circuits that behave like atoms. Circuits with a huge number of electrons can be used, and quantum errors are prevented with superconductivity. When certain metals are cooled down, their electrons join together in a single unit. The individual electrons no longer scatter and the rate of quantum errors drops. Our quantum bits are just electoral oscillators built from aluminum, which become superconducting when cooled to below 1-degree Kelvin. The oscillators store tiny amount of electrical energy. When the oscillator is in the 0 state, it has 0 energy. When it is in the 1 state, it has single quantum energy. These are the logical states of our qubit.

To date, arrays of 10 to 20 qubits have been demonstrated, including cloud-based quantum processors.



- *Advantages*
    1. The gates are fast compared with the other qubits
    2. They are manufactured on silicon wafers using materials and tools common to CMOS foundries
    3. Superconductivity greatly reduces errors
- *Challenges*
    1. The main challenge is the integration of control and readout technologies that maintain qubit coherence, even at mK temperatures.
    2. Superconductivity greatly reduces errors, but there are still some
- *Business perspectives of superconducting qubits*

    Superconducting qubits are attractive for the following reasons:

    1. They leverage a substantial existing technology base
    2. They are lithographically scalable to large numbers of qubits
- *Outreach articles*
    1. https://www.techspot.com/community/topics/intel-is-one-step-closer-to-mass-production-of-quantum-processors.241429/
    2. https://physicsworld.com/a/ten-superconducting-qubits-entangled-by-physicists-in-china/
    3. https://www.news.ucsb.edu/2014/014074/superconducting-qubit-array-points-way-quantum-computers

4. https://www.techspot.com/news/71832-ibm-announces-20-qubit-quantum-cloud-computer-public.html
5. https://epiq.physique.usherbrooke.ca/data/files/publications/zagoskin2007.pdf

1.2 Comparing the leading qubit modalities

Hundreds if not thousands of companies and research groups race towards constructing the first quantum computer that can outperform traditional supercomputers. However, the competition is not just between organizations, it is also between competing methods of quantum computing. I do believe that the three leading qubit modalities are trapped ions, superconducting qubits and neutral atoms.

Leading qubit modalities	D1	D2	D3	D4	D5	D6	D7
Neutral atoms							
Trapped ions							
Superconducting qubits							

D1	Scalable system
D2	Initialization
D3	Measurement
D4	Universal gates
D5	Coherence
D6	Interconversion
D7	Communication

	Sufficient demonstrations exist to proceed to the 100-qubit level
	Concepts for first demonstrations exist
	In-between the first and the second

In terms of scalability, neutral atoms, trapped ions, and superconducting qubits are more mature comparing to other modalities. In terms of initialization, most technologies are doing pretty well. For measurement, the measurement of neutral atoms is extremely slow and would certainly limit the ultimate clock speed of an error-corrected system. In terms of universal gates, neutral atoms, although their two qubit gates have been demonstrated, they still have a relatively low fidelity, around 80%. In terms of coherence other modalities are better compared to superconducting qubits.

Here are some articles about improvements on superconducting qubit coherence:

1. https://arxiv.org/abs/1303.4071
2. https://phys.org/news/2016-04-autonomous-quantum-error-method-greatly.html

3. https://analyticalscience.wiley.com/do/10.1002/gitlab.16901/full/

Let's turn now to the gate fidelity and gate speed of these modalities.

Trapped ions		Superconducting qubits	
Single-qubit fidelity	2-quibit fidelity	Single-qubit fidelity	2-quibit fidelity
Highest fidelity	Almost the same as superconducting qubits	Lower than trapped ions	Almost the same as superconducting qubits
Single-qubit speed	2-qubit speed	Single-qubit speed	2-qubit speed
500 times slower	1,000 times slower	500 times faster	1,000 times faster

As you can see both trapped ions and superconducting qubits have made significant progress and they are viewed as leading candidates. In my opinion, superconducting qubits will be the first to support fictional quantum computer for the following reasons:

1. They are comparatively easy to connect to each other and they have become stable enough to potentially meet fidelity thresholds required for quantum error correction. (https://arxiv.org/abs/1905.13641)
2. They leverage existing technologies
3. I believe speed is one of the most features of quantum computers, and according to our comparison superconducting qubits are much faster than other qubit modalities
4. High-Fidelity Quantum Operations on Superconducting
5. And today, there are a large number of major corporations pursing superconducting qubits, including Google, IBM, and Inter as well as startup companies like D-Wave and Rigatti

I think the second modality which is a great candidate to support fictional quantum computer is trapped ions. There have been some awesome experiments done using these systems showing their suitability as well as proof of concept experiments demonstrating aspects of quantum error corrections. There's a general impression that these systems will be harder to scale up to larger number of qubits than superconducting circuits given their experimental complexity, but that certainly won't stop researchers from trying.

The following are the main advantages of trapped ions which makes them attractive:

1. High fidelity
2. Low error rates
3. Easy to entangle many qubits
4. Can be operated at room temperature

When do you think the first functional quantum computer will be created? Why do you think it will take the time that you chose to create the first functional quantum computer? Argue at least two reasons. Think about the time frame of the second modality that might also be a good candidate. Argue at least two reasons.

I believe it takes around 30 – 60 but definitely less than 100 years to build the first functional quantum computer. Similar to the trajectory of non-quantum communications, which took more than 100 years from discovery to mass use, quantum computers are now maturing very quickly. I think that quantum computers will advance faster than classical computers since now we have a better and more sophisticated technology to support its journey. In addition, today many players are engaged in a battle over who can build the first powerful quantum computer. Huge corporations, including Google, and IBM have invested hundreds of millions to develop quantum computer. Moreover, national governments have also committed themselves to quantum growth and there's growing push among politicians in the U.S government to devote more money to the technology – out of fear that China's scientist and national efforts have outpaced American advances in the field. Financing a company that can achieve a quantum breakthrough is one of those moonshot investments where the return on a successful investment is basically unlimited. There's so much potential in the technology, and so little viable commercial business, that the first to break through the noise could be a real win and it can undeniably influence the economy of the countries. In my opinion, this battle can have a huge effect on the pace of the development of quantum computers. Today, sufficient demonstrations exist to proceed to the 100-qubit level for some of the leading qubit modalities, which are the core component in quantum computing and one of its milestones involve packing ever more qubits onto a processor chip. Of course, a quantum computer is more than just its processor. These next generation systems will also need new algorithms, software, interconnects and number of other yet-to-be-invented technologies. For these reasons, I strongly believe quantum computers are likely more two decades away. They are so fragile and that's why they are taking so long.

I believe the first qubit modality that will be used to create the first quantum computer is superconducting qubits. Their compatibility with microwave control electronics, ability to operate at nanosecond time scales, continually improving coherence times and potential to leverage lithographic scaling, all converge to place superconducting qubits among the forefront of the qubit modalities being considered for both digital quantum computation and quantum annealing. The current approach, using room temperature control and measurement planes, with multiple wires per qubit, should scale around 1,000 physical qubits, but still many factors will limit the size of machine that can be achieved by simply scaling up the number of qubits placed on a single integrated circuit. Such as maintaining qubit quality while scaling up the number of bits, refrigeration, wring, and packaging and control and measurement. For these reasons, I think it takes at least a decade to reach many hundreds of superconducting qubits.

The second modality that might also be a good candidate is trapped ion modality. The jury is still out," Chiaverini reflects. "In this instance, we are thinking about what might be most advantageous to scaling up a system. These ions are very amenable to that." It is likely that some early, small-scale quantum computer based on ion traps will become available by the early 2020s. However, many conceptual and technical challenges remain toward a creating a truly scalable, fault-tolerant ion trap quantum computer. For instance, difficulty of isolating individual ion motions as chain length increases, the number of ions one can individually address with gate laser beams, and measuring individual qubits. Moreover, it will require strategies beyond the single ion chain approach. Ion trapping for quantum information processing is technically challenging. For these reasons, I believe it takes at least 15 – 20 years to reach many hundreds of trapped ions qubits. However, no one actually knows what kind of architecture will enable quantum computation first.

Outreach articles:

1. https://www.statista.com/chart/17896/quantum-computing-developments/
2. https://www.weforum.org/agenda/2019/10/quantum-computers-next-frontier-classical-google-ibm-nasa-supremacy/
3. https://disruptionhub.com/5-advances-in-quantum-computing/
4. https://www.nap.edu/read/25196/chapter/7#123
5. https://www.quantumoptics.at/images/publications/dissertation/MH_diss.pdf