Turning atoms and lasers into a quantum computer: an inside look with University of Chicago physicists-

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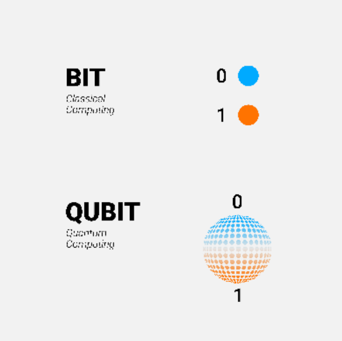
In the Bernien lab at the University of Chicago, we build quantum computers out of individual atoms. Quantum computing might sound like something out of science fiction, but small-scale quantum computers have existed in some form since the late 90's. Today, quantum computers are growing exponentially more advanced, and researchers all over the world are trying out new ideas to advance this exciting technology. We probably shouldn't expect household quantum computers any time soon, but the practicality of quantum computing has grown to the point where dozens of startup companies, and even multiple big-name corporations, are building their own quantum computers. Many of them even allow you to rent time on their computers to run your own quantum programs! However, quantum computing is still very much an in-development technology, on account of the small sizes and large error rates of these systems. As such, it is often said that we are in the Noisy Intermediate-Scale Quantum (NISQ) era. Getting out of this era will require many technological advancements, and our lab is actively working on solving some of the issues which are hindering atom-based quantum computing systems.

What is quantum computing?

Before talking about how the Bernien lab is working to progress quantum computing hardware, it is helpful to have an idea of why people are interested in quantum computing in the first place. Quantum computers, just like regular computers, possess data stored in registers, and perform operations between these data to make a calculation or execute an algorithm. However, the important difference is in what form this data takes.



Qubits can store significantly more information than a classical bit.

Regular (or 'classical') computers store data as 'bits', which can each be either a 0 or a 1. On the other hand, quantum computers use 'qubits'. Qubits also have a 0 and a 1, but what makes them special is that they aren't restricted to *either* a 0 *or* a 1; instead, we can think of qubits as a continuously adjustable vector, which can attain any combination of 0 and 1, potentially with a complex-valued phase between the two. In quantum mechanics, we call this special combination of two or more states a 'superposition'.

Furthermore, qubits can make use of the quantum mechanical principle of entanglement. If you imagine flipping two normal coins, we intuitively understand that the outcome of each coin flip is independent of the other. So, if we flip the first coin, we will have gained no additional information about the other coin's outcome. However, this independence is not the case for an entangled state. If we have two qubits entangled in a particular way, it may be the case that neither qubit is fully-0 or fully-1 (thanks to superposition!), but by measuring one of the qubits, we cause the quantum state to collapse, and we will subsequently find that the second qubit is always in the same state the first one was found to be in.

It is superposition and entanglement which give qubits the edge over bits, and quantum computers the edge over classical computers. Essentially, because qubits can be continuously adjusted instead of just a binary 0 or 1, they contain much more information. And when you have many qubits, which can be entangled with each other in a huge number of ways, the amount of information contained by a set of qubits is exponentially larger than a comparable number of bits.

The analog nature of qubits also means there are more operations you can do between them. Whereas a computer can perform any operation using combinations of a single gate (e.g. a NAND gate), quantum computers need at least one two-qubit gate (e.g. CNOT), as well as the ability to rotate each individual qubit along at least two of its X, Y, and Z axes. Quantum computers seek to implement these operations in a discrete and controlled manner, but there is another paradigm, called quantum simulation, which instead tasks the user with programming a specific interaction equation (or 'Hamiltonian') between the qubits, and then letting the qubits evolve naturally to a state which represents a solution to some encoded problem. This can be used as a way of modeling more complicated systems, and could therefore serve as an efficient testbench for investigating problems in fundamental physics, materials research, energy research, and more.

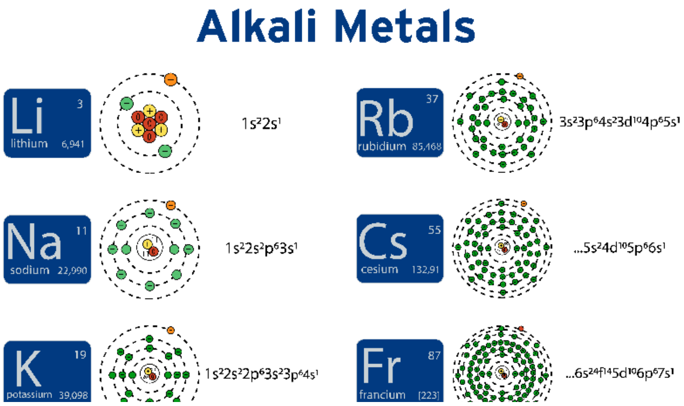
So if qubits are so much more powerful than bits, does that mean a quantum computer should be better than a classical computer at everything? Not exactly. Physicists have shown that there are certain problems which an ideal quantum computer would be able to solve, that could likely never be reasonably solved by a normal computer. For example, a commonly used data encryption scheme derives its security from the fact that classical computers struggle with finding the prime factorization of very large numbers. However, in 1994 Peter Shor formulated what is now known as Shor's Algorithm; this algorithm is a fast, efficient way for quantum computers to factorize numbers, which would in turn break encryption schemes based on prime factorization. While this is a very nice example of a way that quantum computers could surpass classical computers, there is no need to use complicated quantum mechanics on a problem that already has good classical algorithms. Many theorists are actively investigating how broadly useful quantum computers might be, but generally it is believed that their raw computational power will be useful for speeding up a wide variety of problems.

Unfortunately, the same features that make quantum computing so great are also the challenges that are limiting devices to the NISQ era. The continuous nature of qubits means that it is much easier for your data to be slightly incorrect, and the complex gate operations present a controls challenge that can only be solved up to finite accuracy. These problems may be solved with Quantum Error Correction (QEC), which uses additional qubits to redundantly encode the state of the system, protecting against common sources of error. Implementing a quantum computer with QEC and a reasonable memory size will require at least many thousands of qubits, with high fidelity gate operations between them. Scientists and companies around the world are actively investigating how to reach these goals, across a varied selection of quantum computing platforms.

How do you make a quantum computer out of atoms?

Quantum computers have been made from several different systems, such as photons, electrons, superconducting circuits, and individual atoms. Different systems have different advantages and challenges, so it is not necessarily the case that there is a “best” way to build a quantum computer, at least at this point in time. These platforms can look very different from one another, but ultimately, they are all about controlling qubits, which are defined from two (or more) quantum states in each system.

In the case of neutral atoms, these quantum states are the electronic and nuclear states of the atom. In chemistry class, we are taught that electrons fill orbital levels of an atom up until the number of electrons equals the number of protons. The atoms in the outermost orbital level of an atom are the valence electrons, but there’s nothing stopping us from moving these valence electrons up to even higher energy levels, as long as we pay the energy difference by applying laser light of the right color to the atom. These are what we mean by “electronic states of an atom”; these discrete energy levels could serve as the quantum states for our qubits. Experiments typically use alkali metals for the atoms because they only have one valence electron, which greatly simplifies the



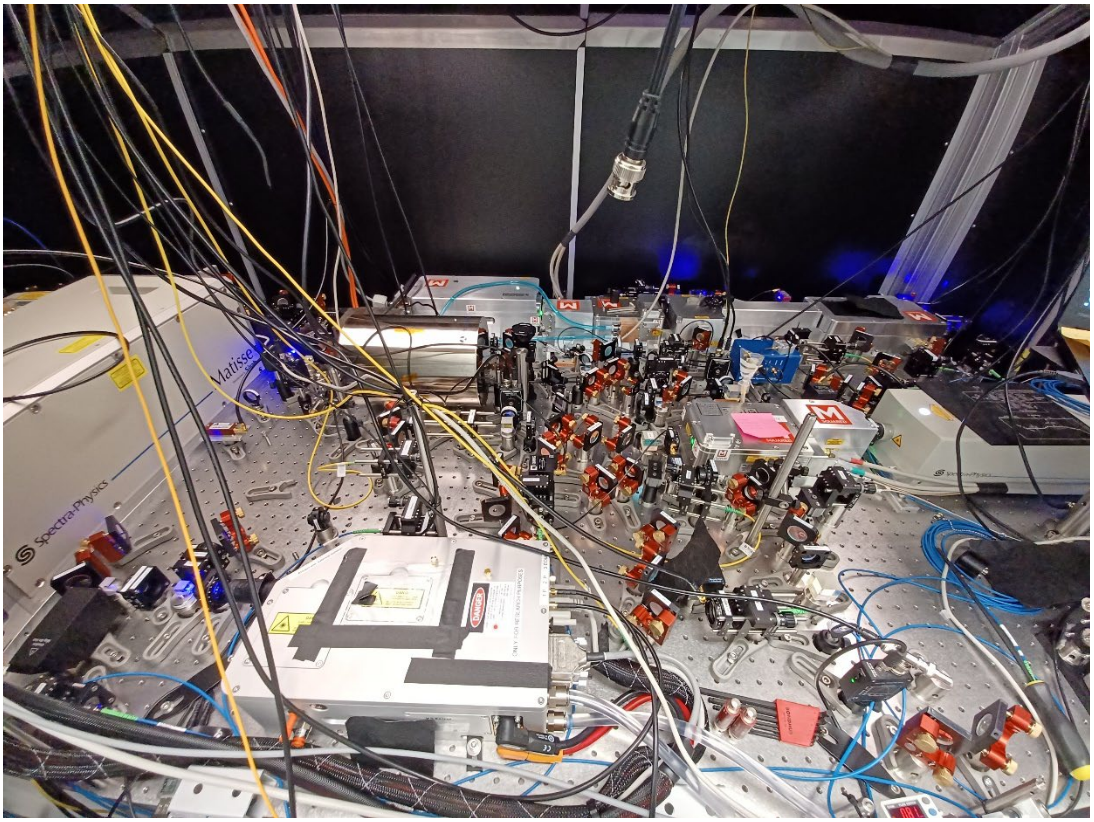
Alkali metals all have a single valence electron electronic structure of the atoms. Some experiments prefer alkaline earth atoms, which have a richer level structure, and others are actively investigating how more complicated atoms might be controlled.

As it turns out, these electronic states usually aren't super long-lived, so they make poor qubits — although they are useful for other functions, such as taking pictures of the atoms or getting the atoms to interact with each other. Fortunately, atoms have another degree of freedom: the nuclear spin. Spin is a fundamental property of particles, just like charge or mass. The protons and neutrons in the nucleus have an effective total spin, and this spin can even interact with the electron's orbit, introducing new discrete energy levels (so-called 'hyperfine' levels) which can be used as a long-lived qubit. To control this qubit, we must apply electromagnetic radiation of the appropriate frequency. In the case of hyperfine qubits, this is typically a microwave frequency (~1-10 GHz), which can be addressed using either a microwave horn or a two-frequency 'Raman' laser system.

We've picked our qubit states for our atoms, but in order to use these states properly we need to be able to keep track of where all of our atoms are, i.e. we need to cool them down and hold them in place. The first step in this process is the Magneto-Optical Trap, or MOT. A MOT uses a magnetic field gradient to split the energy levels of the atoms, and this splitting is positive on one side of the MOT, negative on the other. Next, we apply off-resonant laser light to the atoms from all 6 directions: up/down, left/right, and forward/backward. Because the light is off-resonant, it is more likely to be absorbed by the atoms when the magnetic field splitting is sufficiently large, i.e. further from the middle of the MOT. Absorbing a photon also transfers momentum, so after enough photons are absorbed, the atoms will be pushed towards the middle of the MOT, and their temperature will be reduced to just tens of millikelvin above absolute zero. From this point, more advanced cooling techniques can bring the atoms to tens of microkelvin above zero, making these atoms some of the coldest things in the universe. It turns out that temperature is a common concern: the atoms must be cooled so they can be controlled accurately, the room must be at a stable temperature so the optics don't drift, and the lasers must be cooled with chillers like the PolyScience DuraChill Benchtop in order to mitigate noise, as we'll discuss soon.

A MOT contains tens of millions of atoms, but they're still all jumbled together, which makes them impossible to work with as qubits. But now, since they're so cold, we can try to pick out individual atoms using lasers. If you focus a laser beam down to a tight spot, the atoms will be attracted to the point of high intensity, and if this spot is sufficiently small, it only has enough room for one atom. These focused laser beams are called optical 'tweezers', and we can generate potentially thousands of them at a time by manipulating the laser in particular ways (specifically, using optical devices such as an acousto-optic deflector and/or spatial light modulator). We use these optical tweezers to grab onto hundreds of individual atoms, then we get rid of the MOT, so we are left with nothing but our individual cold atoms which can be used as qubits.

The final ingredient for our neutral atom quantum computer is a two-qubit gate. Such a gate requires an interaction between different qubits, but since our atoms are neutral (i.e. no net charge), we shouldn’t expect them to interact. However, there’s a trick we can play: if we excite the valence electron to a high energy level (known as a ‘Rydberg’ level), then it will be much further away from the nucleus, and the electron-nucleus charge separation makes the atom highly polarizable. Place two Rydberg atoms within short range (~5 microns) of each other, and they will feel a strong van der Waals interaction, which we can use to create a two-qubit gate.


High-powered lasers are at the heart of Bernien's quantum experiments

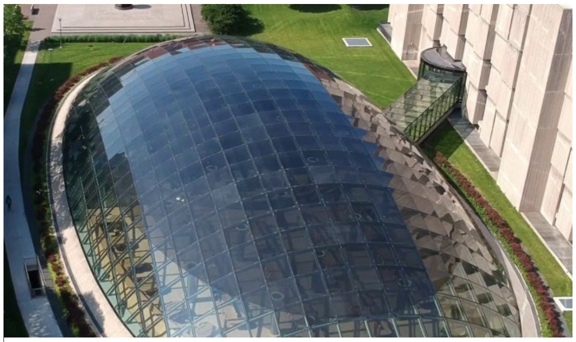
Accessing these Rydberg states is done with, of course, more lasers. Most experiments use two lasers as part of a two-photon excitation process, because this gives a more convenient selection of which Rydberg states are accessible. Much of the error associated with two-qubit gates on neutral atoms arises from technical limitations in these two lasers. If the frequency or intensity of the laser is unstable, the gate process will be slightly off-target. To combat this, the frequency is stabilized by locking the laser to a highfinesse optical cavity, and the intensity is stabilized by sampling the beam power and feeding back to an acousto-optic modulator. The laser technology also has an impact on these noise profiles: a regular diode laser tends to be very noisy, whereas a well-thermally-regulated fiber laser or titanium-sapphire (Ti:sapph) laser has much lower frequency and intensity noise. Because of this, our lab prioritizes using Ti:sapph lasers like the Sirah Matisse, kept at a steady temperature with chillers such as PolyScience's DuraChill Benchtop. Even if this is all done correctly, there will be errors because of atomic decay and photon scattering events. The only way to mitigate this is to spend less time doing Rydberg operations, which is achieved with higher-power lasers. Nowadays, groups are using blue lasers with >1 W optical power, and infrared lasers with nearly 100 W optical power. As scientific lasers get more and more powerful, we must make sure they don't start burning the experiment or themselves; the former is mitigated by safe laser operating practices, and the latter is accomplished with laser chiller technology such as the DuraChill Benchtop chiller.

Lasers require exceptional temperature control. The PolyScience DuraChill Benchtop fills this critical role perfectly.

Neutral atom quantum computers are at the point where all the ingredients are present, and research groups are trying to figure out how to do it all bigger and better. Some challenges that are still being addressed are how to get even more qubits, how to make the gates even more error-free, how to control which qubits are being addressed by a gate, and how to measure specific qubits without disrupting the others. It will be some time before we see large-scale quantum computation with neutral atoms (or any other platform), but in the meantime many groups are still putting out very impressive small-scale calculations and simulations, showcasing the power and promise of this technology.

What's the Bernien lab up to?

Our research in the Bernien lab is all about exploring new ways to make neutral atom quantum computing more powerful. There are two main experiments in the lab: the 'network' experiment, which investigates using atoms as a node in a network of quantum computers, and the 'dual-species' experiment, which uses two



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different kinds of atomic qubits to do things that single-species experiments struggle with.

Quantum networking is based on the idea that individual quantum computers will struggle with scalability and computational power, but if you have a bunch of quantum computers connected together, you can share the workload, and even do things like share encrypted messages in a way that cannot be intercepted. The nodes of a quantum network need to be able to exchange quantum information between each other, and the most straightforward way to do this is by exchanging photons through fiber optic cables. For particular wavelength ranges (i.e. 'telecom' wavelengths), these fibers are very low-loss, making them ideal for long-distance networking.

It turns out that none of the ground state transitions in neutral atoms are within the telecom range. So, our network experiment is doing a trick: make the atoms absorb two photons, then decay from an excited state to release a telecom photon, before being brought back to the ground state. We have recently demonstrated that this trick works, and enables us to significantly reduce background light when imaging the atoms (https://arxiv.org/abs/2311.02153). We've also shown first steps toward coupling these atoms to nanophotonic devices, which is necessary for collecting these telecom photons into a fiber, and sending them out into a quantum network.

Another project that's closely tied to this experiment is our so-called 'hybrid' experiment. There are many kinds of quantum platforms out there, and sometimes we would like to leverage the advantages of a different system. This is a challenge, because two different systems are unlikely to be able to directly share quantum information, e.g. if they involve photons of different wavelengths. But we have found a candidate system, composed of rare earth atoms embedded in a crystal, which should be able to share photons directly with a neutral atom system. This would enable us to use the long-lived qubit state of a crystal system, without sacrificing the computational power of a neutral atom system.

Instead of connecting to other remote quantum systems, the dual-species experiment is essentially using two systems inside the same experiment. A major challenge with neutral atom quantum computers is that the atoms are measured by fluorescing the atoms, but this ends up measuring the atoms all at once. Sometimes, you only want to measure a few qubits, and keep working with the rest. But if you have two different qubit types, e.g. rubidium and cesium, you can measure one element without disrupting the other, since the wavelengths are very different between the two. We have demonstrated that this idea works, and we can do these measurements fast enough to even perform feed-forward operations (https://www.science.org/doi/10.1126/science.ade5337).

When you place atoms of different elements close to each other, one should expect that the Rydberg gates still work as usual, since it's ultimately just a van der Waals interaction between polarizable atoms. However, a dual-species system has the added benefit that you can find pairs of Rydberg states between the two species that enhance the van der Waals interaction into a much stronger dipole-dipole interaction. We have found such a pair of states, and used them to demonstrate the first inter-species entanglement in a neutral atom system (https://arxiv.org/abs/2401.10325). We think this enhanced interaction can be useful for many tasks, such as creating larger entangled states, or for using one of the species as an auxiliary qubit to assist with quantum error correction.

The work being done in our lab is just one example of a global scientific effort to develop quantum computing technology. We are very much still in the NISQ era, so there is lots of research to be done before we will see a quantum computer doing things like cracking encryption algorithms. It's not yet clear to what extent quantum computers will revolutionize the way we do computations, but every day they are getting a little bit more powerful, and I do not think it is a stretch to believe that someday they will be finding solutions to problems we could not conceive of solving otherwise.