Critique request:

The link below asks for your comments on Professor Peter H. Fisher's Alumni Forum talk. Your responses are for Professor Fisher's use only. https://bit.ly/3ulCCVo

Quantum: The Hope, the Hype, and the Glory

Peter Fisher

Nov. 15, 2023

This talk is about quantum mechanics and how it may make a new kind of computing possible.

Section 1. We will start with a brief (2 slides) examination of current computing technology, its scale – in terms of total capacity – and ultimate limitations. This points to the need for a new way of carrying out complex calculations.

Section 2. The following three slides introduce the quantum storage unit – the qubit -- and shows that a single qubit stages vastly more information that the bit. We understand this in terms of superposition – the ability of a particle in the quantum mechanical regime to separate into two parts. The wave nature of particles in quantum mechanics makes the separation possible.

Section 3. With the idea of superpostion in hand, the following two slides shows how two qubits in close proximity may store and process information quantum mechanically. We show how, in a quantum mechanical system, the addition of a qubit double the storage and processing capacity of a system as a whole. This section concludes with the calculation showing 60 qubits can store and process as much information as the largest data center in the world.

Section 4. This section shows how the ideas developed so far may be used to sense very small magnetic, electric, gravitational, and positions.

Section 5. Sections 1-4 presents the Hope of quantum information science. This section describes the difficulty and Hype of the field -- the challenge of error correction.

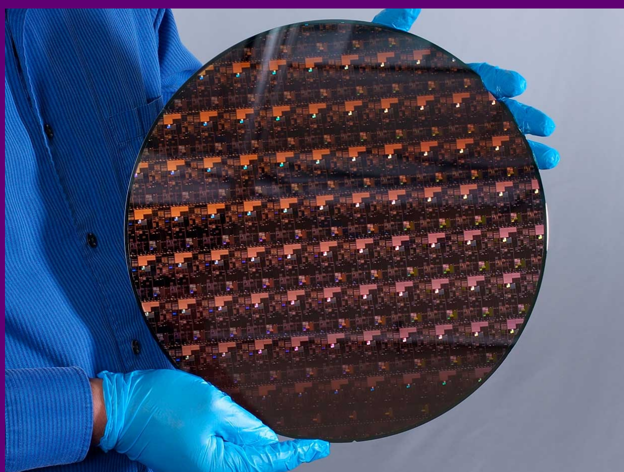
Section 6. The Glory – the outlook for the field area-by-area

Appendix

A. Measurement – 1 slides

B. Quantum commuincation

Why we need quantum - Small



Moore’s law is not forever

The picture shows a 12” or 300 mm wafter with integrated circuit patterned on it. Electrical elements - mostly transistors, capacitors, and resisters make up the CPUs patterned on the wafer, connected by “wires” in the silicon measuring 2 nm across – about four atoms wide. The wafer has about 140 CPUs on it, each with about 2 trillion circuit elements per square inch.

Moore’s law says silicon technology causes a doubling of circuit density every 18 months, which has driven the computer industry for about four decades. Making the wires as circuit elements smaller than atomic dimensions will prove challenging and designers have started using the third dimension to increase the density of circuit elements on a chip. I guess that Moore’s law will remain intact for at least a decade, but after that will begin to flatten. Our demand for compute will not.

Why we need quantum - Large

China Telecom – Inner Mongolia Information Park

Exascale – 1,000,000,000,000,000,000 bytes

https://www.greenergydatacenters.com/eng/blog/where-is-the-worlds-largest-data-center https://www.racksolutions.com/news/data-center-news/top-10-largest-data-centers-world/#:~:text=Located%20in%20the%20Inner%20Mongolia,building%20of%20720%2C000%20square%20meters.

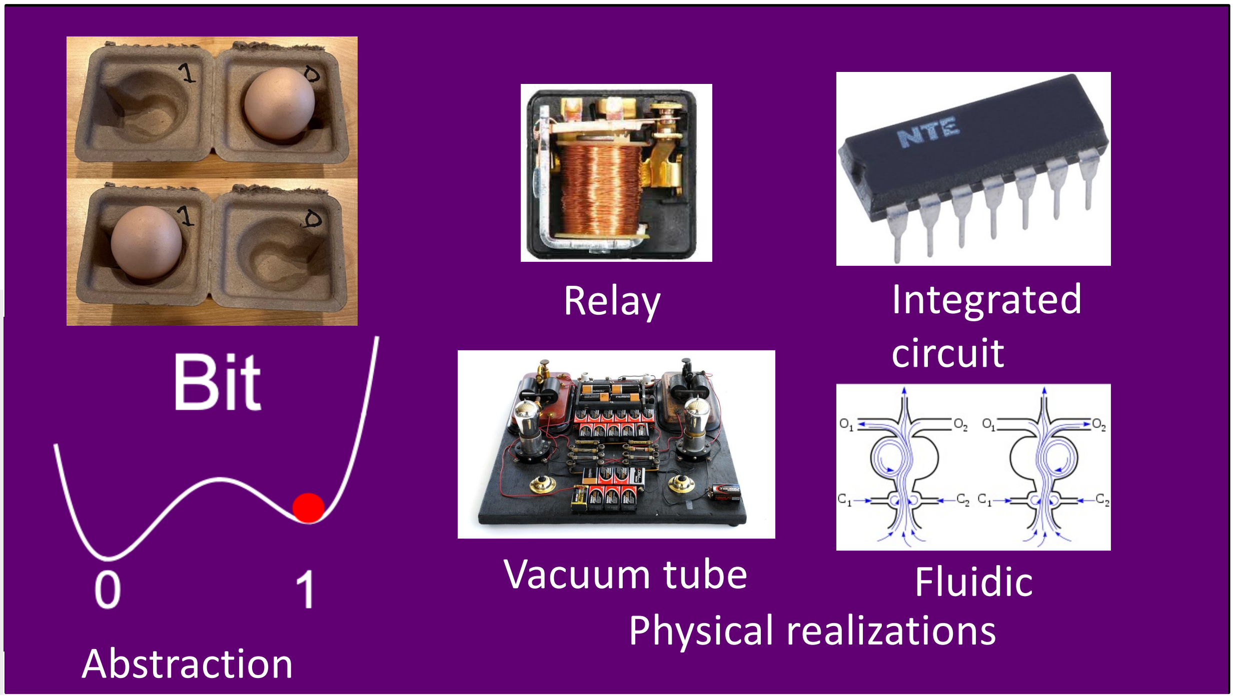
We consolidate computing into data centers to maximize the lifetime of the hardware, provide cyber security, and enable cluster of machines to carry out large calculations. The China Telecom Inner Mongolia Information Park consumes 100 MW of electrical power. This center holds a few hundred thousand servers. Wind and hydroelectric provide most of the power. 8,000 data centers this size would consume nearly 30% of the world's energy consumption. I doubt we will reach that level for a few decades, but we cannot build more indefinitely.

About an exabyte of data, a billion, billion bytes, resides in a data center of this size.

The lower bound on compute density and the upper bound on the size and number of data centers the human race can build will become important in the coming decade or two.

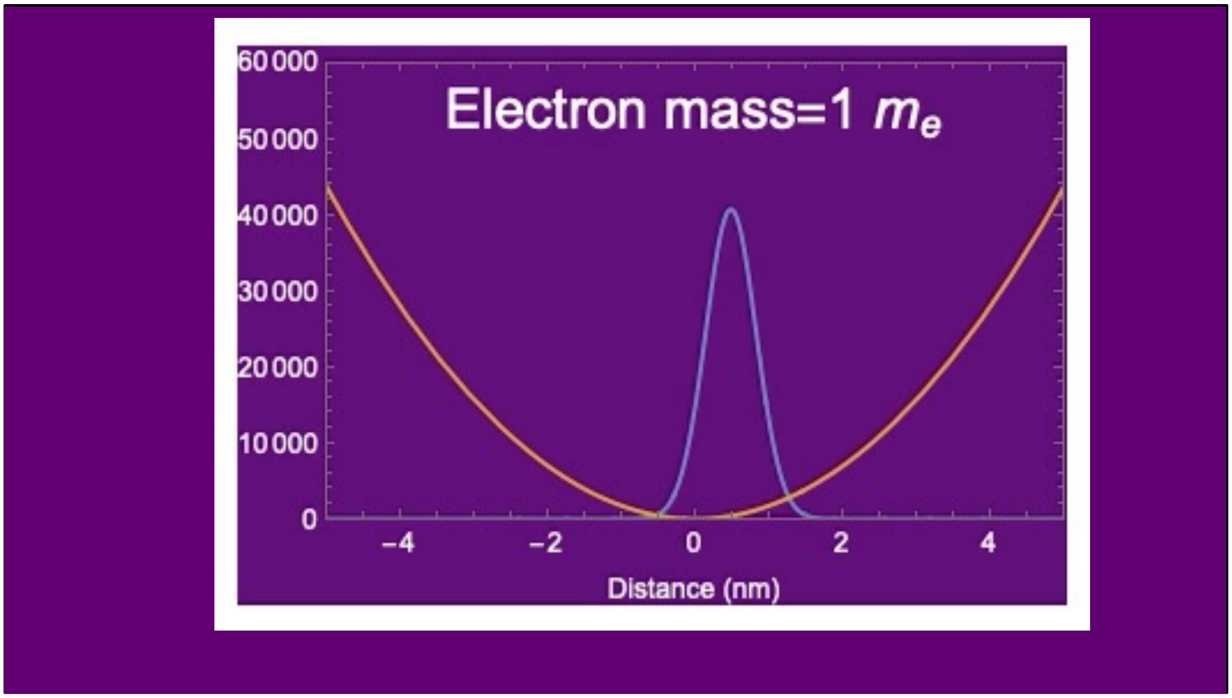
Quantum computing may offer to overcome these barriers, but will take a decade or two to develop.

https://www.researchgate.net/figure/Computing-power-has-been-growing-exponentially-which-is-reflected-in-Moores-Law_fig1_260686521



We'll start with the smallest unit of storage in a computer – the bit. A bit storage a one or zero and we string them together in base to to make larger numbers?: 111 in base 2 represents 7, 1000000000000 in base 2 is 1,024 and so one. We can think of the bit as an egg carton with two wells. A marble in one well signifies 1, in the other it represents 0. The left shows the *abstraction* – the simplest representation of all the properties of a bit. We think of this when working out how to program and how to storage information. The idea of abstraction allows us to separate the function of a bit from the physical realizations, shown on the right. These become important when building the computer. Integrated circuits provide most bits these days.

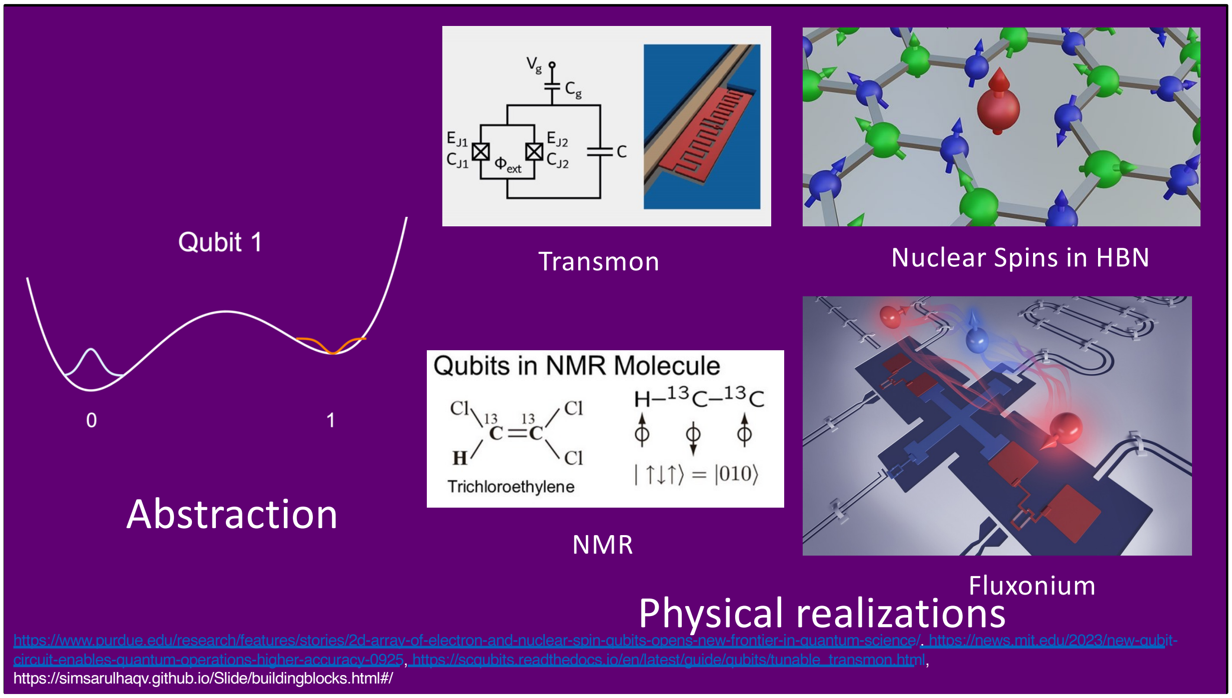
1. ADD EGG CARTON PICTURE
2. SHOW A WORD FOR BITS



Now we zoom in on the bottom of the well and the particle “sitting” in it to see what happens in the quantum world. The well of the egg carton measures a centimeter and this animations shows what happens when we zoom in. Quantum mechanics becomes important when at the 1 nm – 1 billionth of a cm – scale. If the particle wieghes 100 times as much as an electron, you can see it move a little back and forth around then center of th ewell, from quantum mechanical energy.

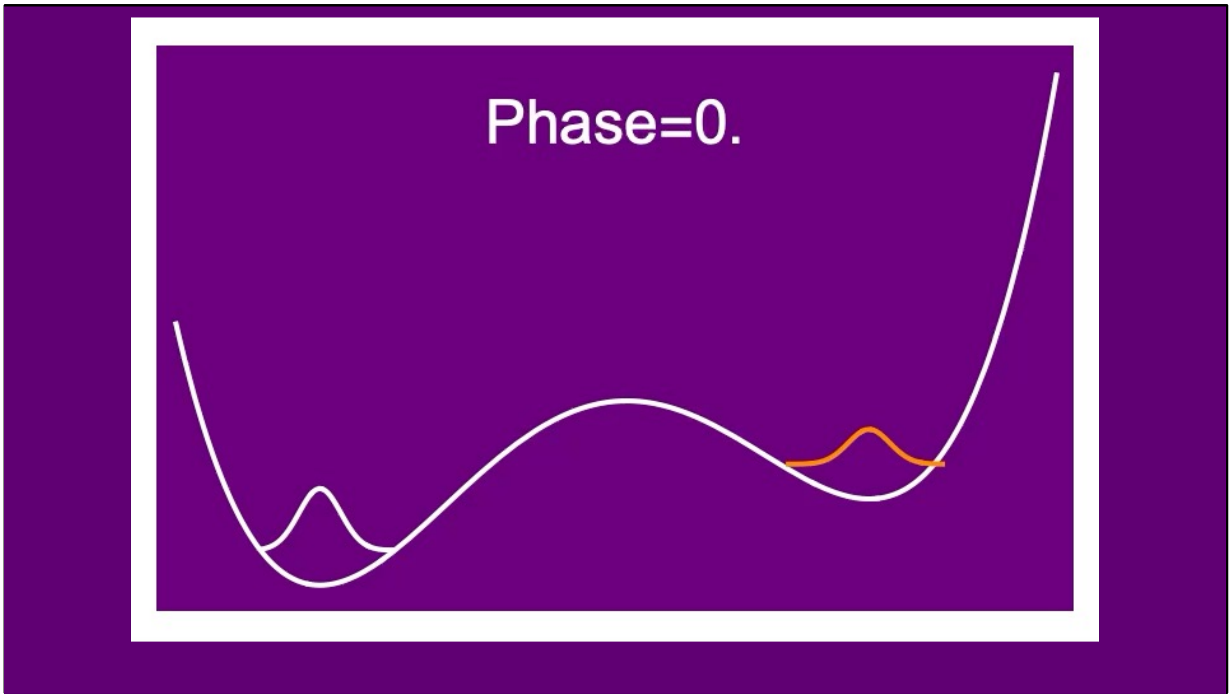
The blue curve represents the particle’s wave. In quantum mechanics, the particle has a size and the curve represents the probability that the particle lies at a particular place. As we think about lighter and lighter particles, the wave becomes wider and oscillates from side to side more quickly. This happens because quantum mechanics requires the particle to have a little bit of energy, related to its velocity. This lighter the particle, the high the velocity. Again, from quantum mechanics, a higher velocity particle spreads out more.

In the next slide, we see of we can use the quantum mechanical spreading to make a qubit.



On the left, we see a double well – our egg carton – but this time very small, a few billionths of a meter. Trapped in the two wells is one electron, with a piece in each well. I show each piece as a wave that oscillates up and down with time – which is what waves do. As in the video, the height of the wave tells us the probability that the electron is locating in one of the other well. Unlike a qubit that stores 0 or 1, qubit can store a range of values. We'll go into this more in the next slide.

The double well trapping part of an electron in each trough gives the abstraction – those essential things we need to think about conceptually. The right shows several physical realizations qubits. Like bits, many different physical systems can serve as a qubit, including chemicals (lower left), electronic circuit (upper left and lower right), and ions trapped in material (upper right). Our next speaker, Prof. Paola Capallero, researchers the trapped ions.



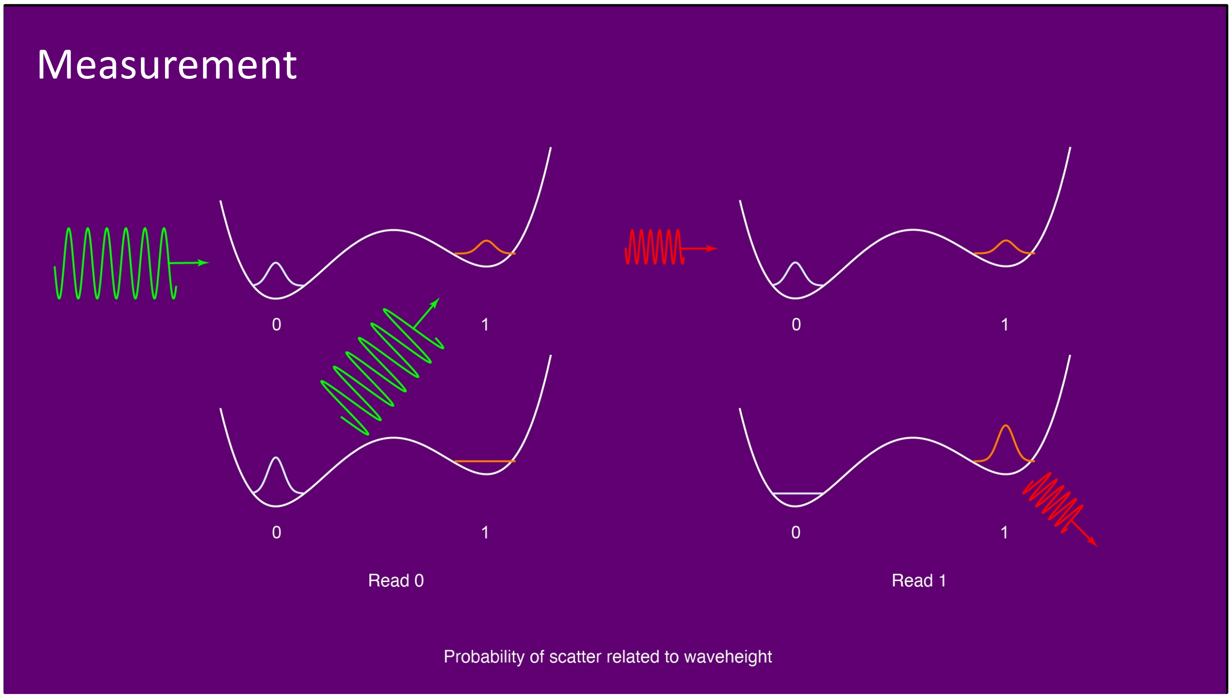
This animation shows the double well with part of an electron in each side. This graphic shows how the qubit stores two real numbers at the same time.

First, the relative heights on each side stores one real number. The probability comes from the height of each part of the wave and must sum to one – the electron sets in one side or the other – but the wave can divide between the sides in an infinite number of waves.

The animation shows the electron oscillating up and down and these relative oscillations store the second real number. If the oscillation of each wave reaches the maximum at the same time, we say they are *in phase*, if the left reaches its maximum when the right reach its minimum, the oscillations lie *out of phase*. The relationship between the oscillations may lie anywhere in between, allowing the encoding of a second real number in the qubit.

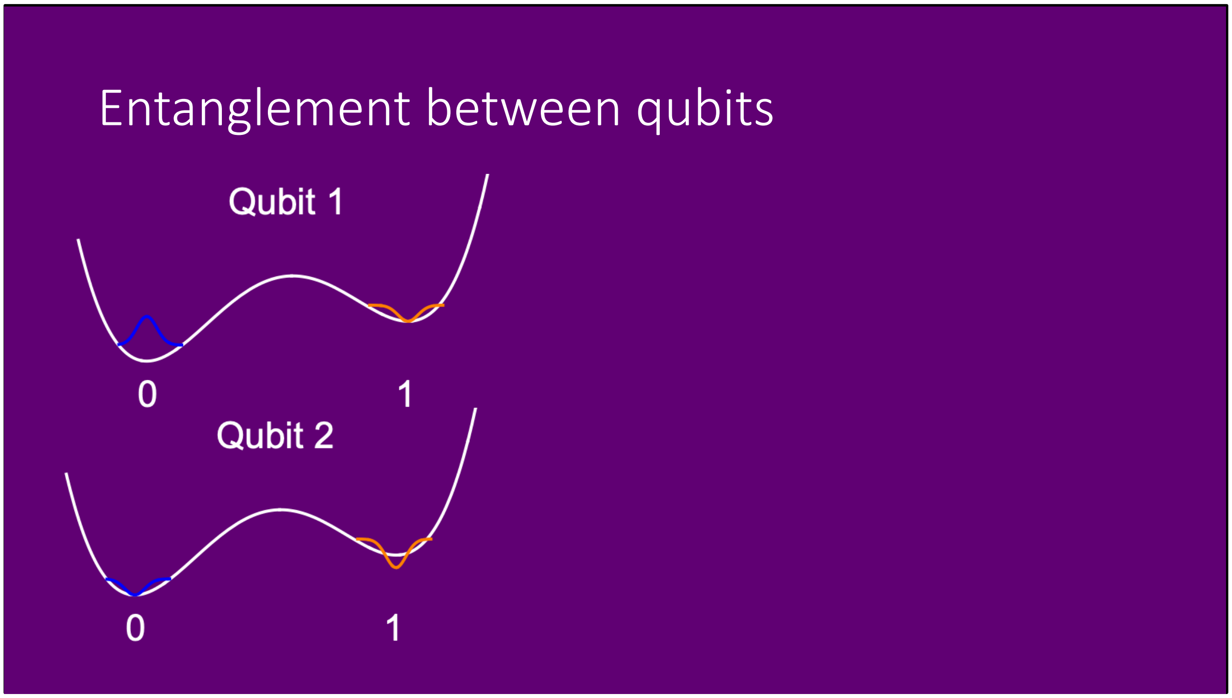
Sometimes, the height of the wave lies below zero, so how can the wave give the probability the electron sits on one side or the other? The slide before last gives the answer – the probability comes from squaring the wave – multiplying the wave by itself. Quantum mechanics refers to these waves as amplitudes and has a rule that the probability comes from squaring the amplitude, which always gives a positive value.

We call The splitting of a particle between two wells *superposition* and superposition presents the cornerstone of quantum mechanics. Superposition seems to say that a particle can exisit in two places at the same time, but the next slide on measurement will shows how quantum mechhnics really works.



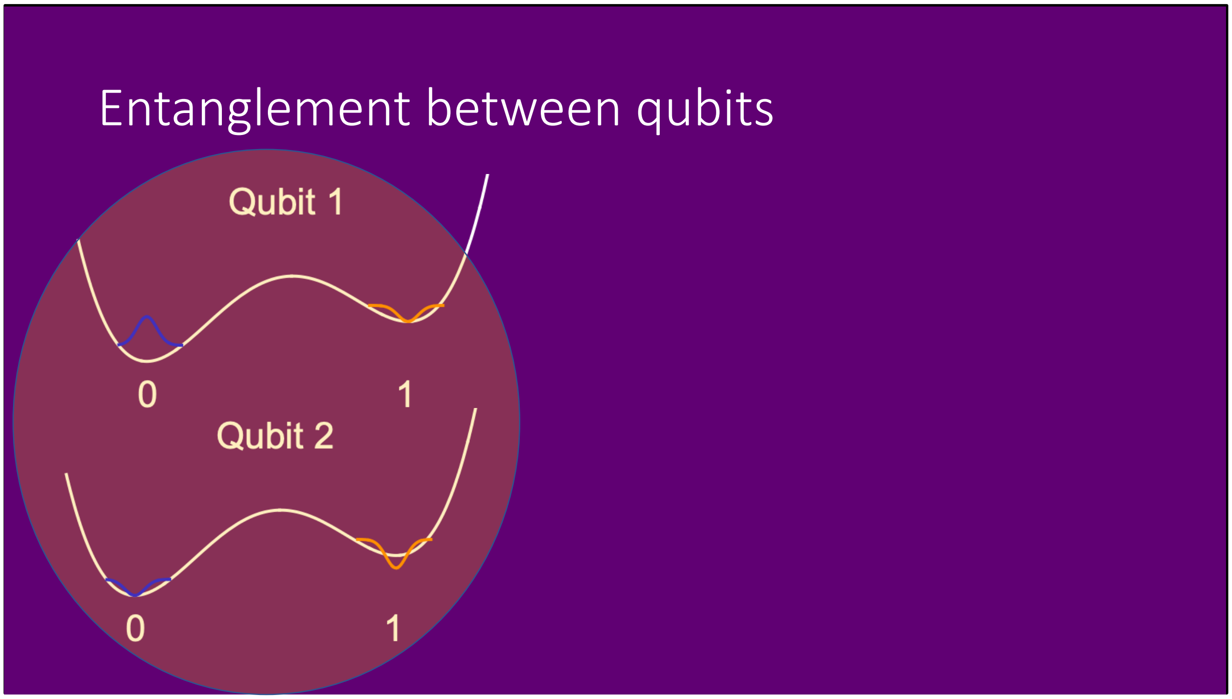
Measuring quantum system consists of *interrogating* the system using a light tuned to the system. On the left, a green light bean, a *photon*, enters the system tuned to the energy of the well on the left, the 0 well. Its energy matches the well depth (the distance from the hump in the middle to the bottom of the left-hand well. The photon will "bounce" off the electron with a probability related to the height of the wave in the left well. If the green photon does not bounce of the electron, it will continue in a straight line. We can interrogate the right well in the same way with a red photon tuned to the well depth.

In both cases, if scattering happens, we know which well holds the electron, and the wave function must all reside in the well. Sometimes called *wavefunction collapse*, this encodes our new knowledge of the system. Interrogating the system again should produce the same result.



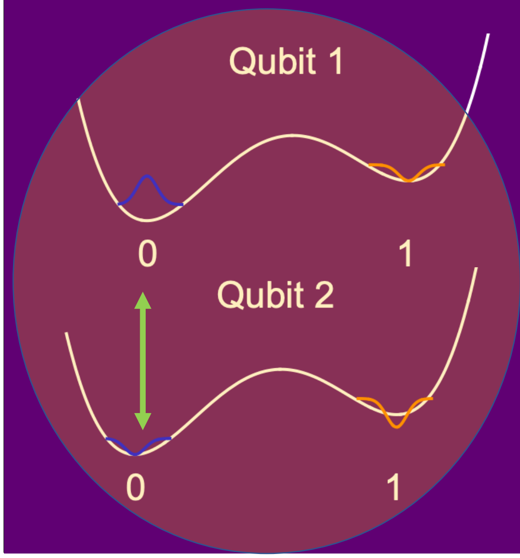
Now we want to think about how quantum mechanics processes information. Storing information serves a useful purpose, but computing means processing information, usually to reduce vast quantities of hard-to-understand information into a few easy-to-understand pieces.

Let's start with two qubits, each with on electron split between the two wells we want to combine the information in the two qubits in some way and for this they need to interact with each other. By interact, I mean that the two electrons exert a programmed influence on each other. In this example, the electrons both carry electrical charges, so they push or pull on each other – the detail are not important.

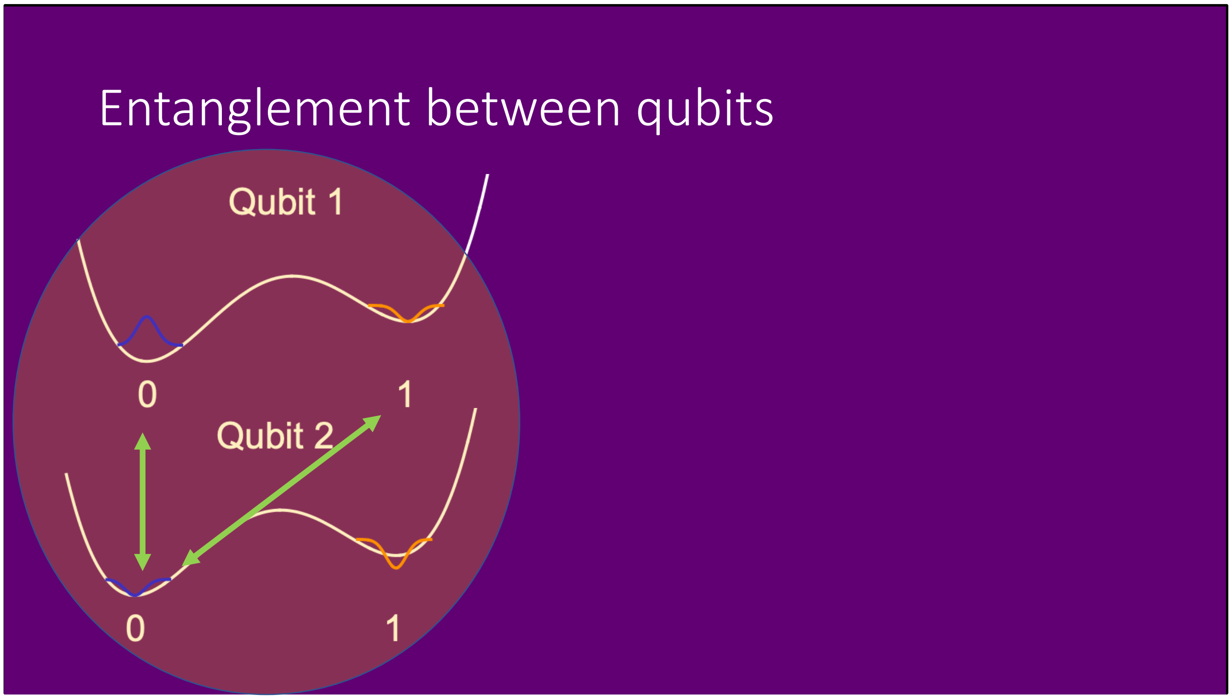


The brown oval indicates the close proximity between the qubits. Next, we will count the interactions.

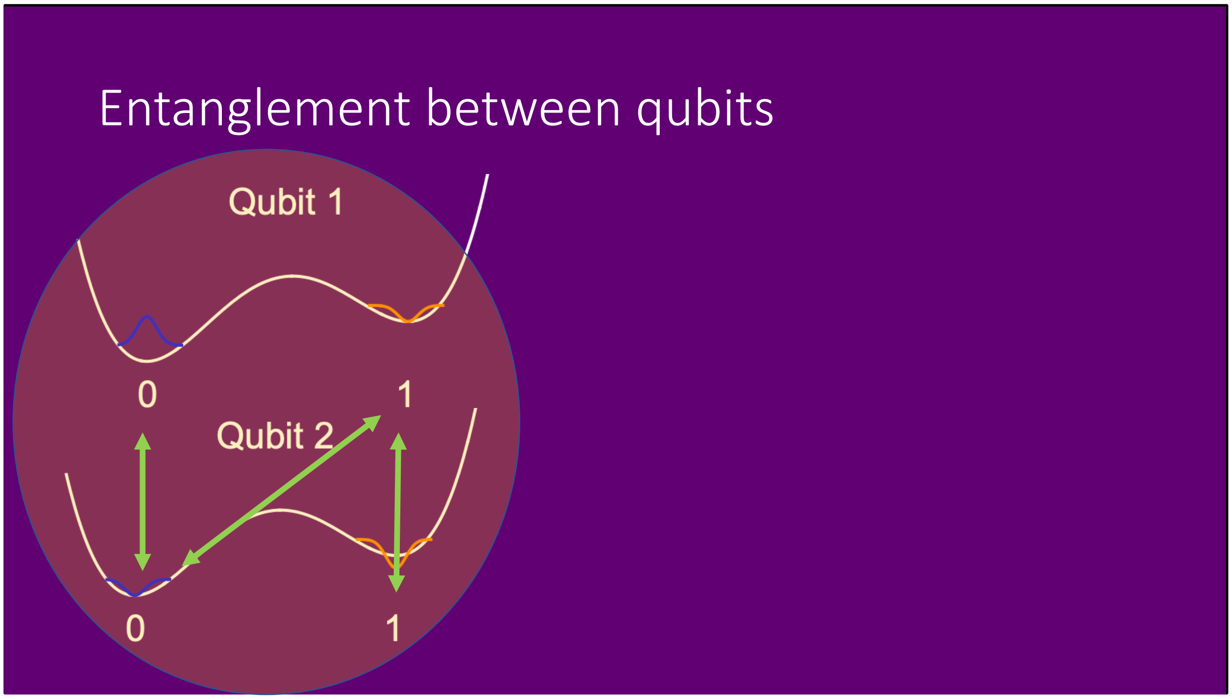
Entanglement between qubits



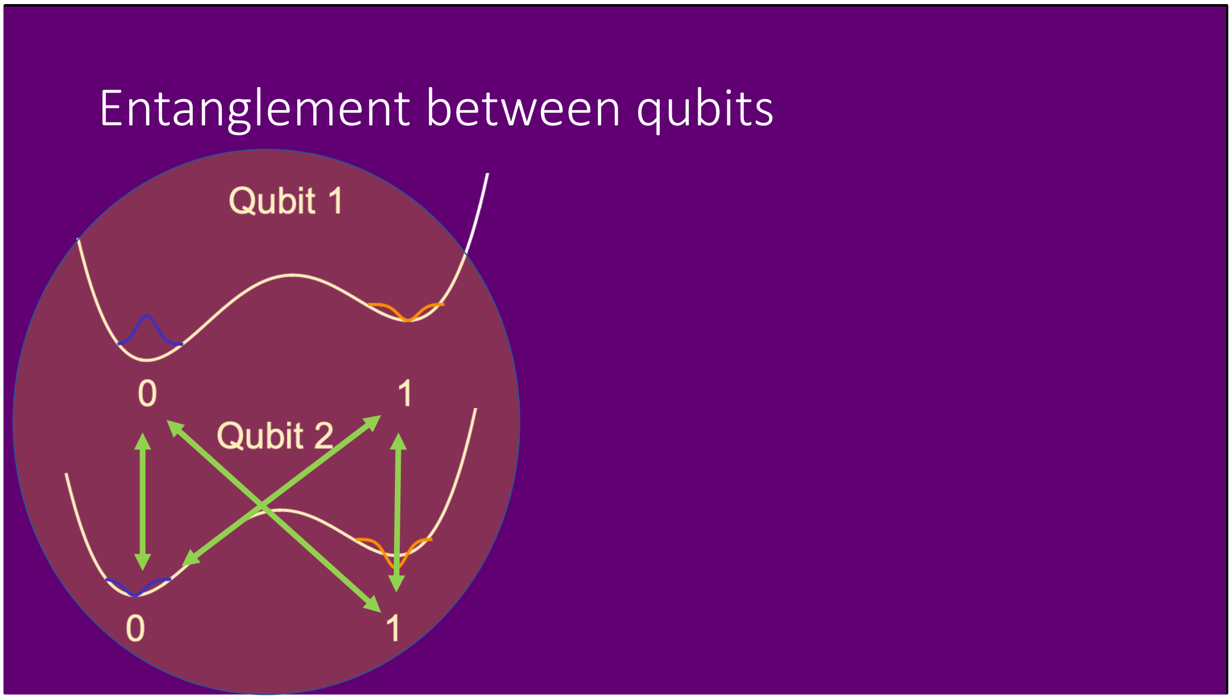
Interaction between zero wells.



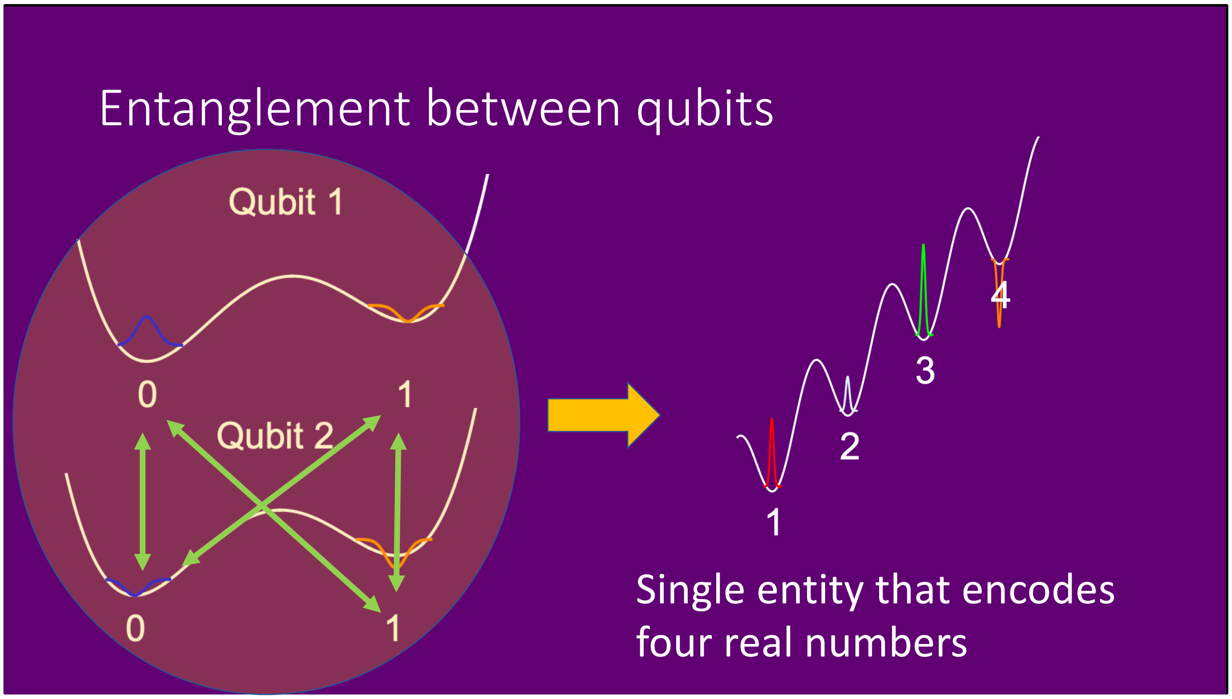
Interaction between 1 and 0



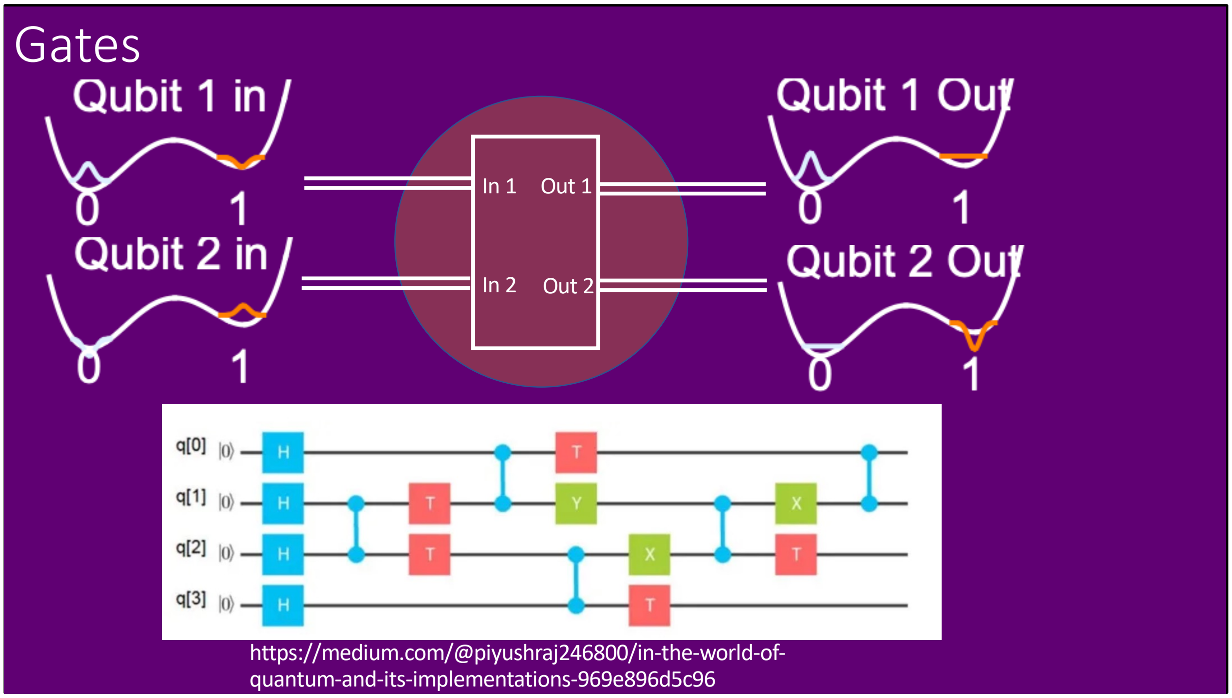
Interaction between 1 wells



Interaction between 0 and 1



The two qubits form a single system with four wells, encoding four real numbers encoded in the phases and amplitudes. You might think the sytem can encode eight numbers, but keep in mind the amplitudes describe two electrons spread over the four wells, so there are four amplitude and phase relations. From this we can sumerize that adding a qubit to the system doubles the number of real numbers the system can hold. Adding one qubit to these two would would store eight numbers, and so on.



The top shows a gate – a set of interactions that take place for a time between two qubits. The calculation takes place in the qubit, in contrast to a classical computer where data moves in and out of memory to a central processing unit where calculations take place.

The Lower panel shows another view of quantum computation. This shows the qubits arranged in parallel with gates between them. Calculations happen left to right and, again, the calculations take place in the qubits. Not every qubit connects directly with every other qubit, but information form one qubit may propagate to any other qubit through qubits in between.

The lower panel shows one way of arranging qubits, called the *topology* of the quantum computer. Unlike classical computers, quantum computers do not yet have a standard topology.

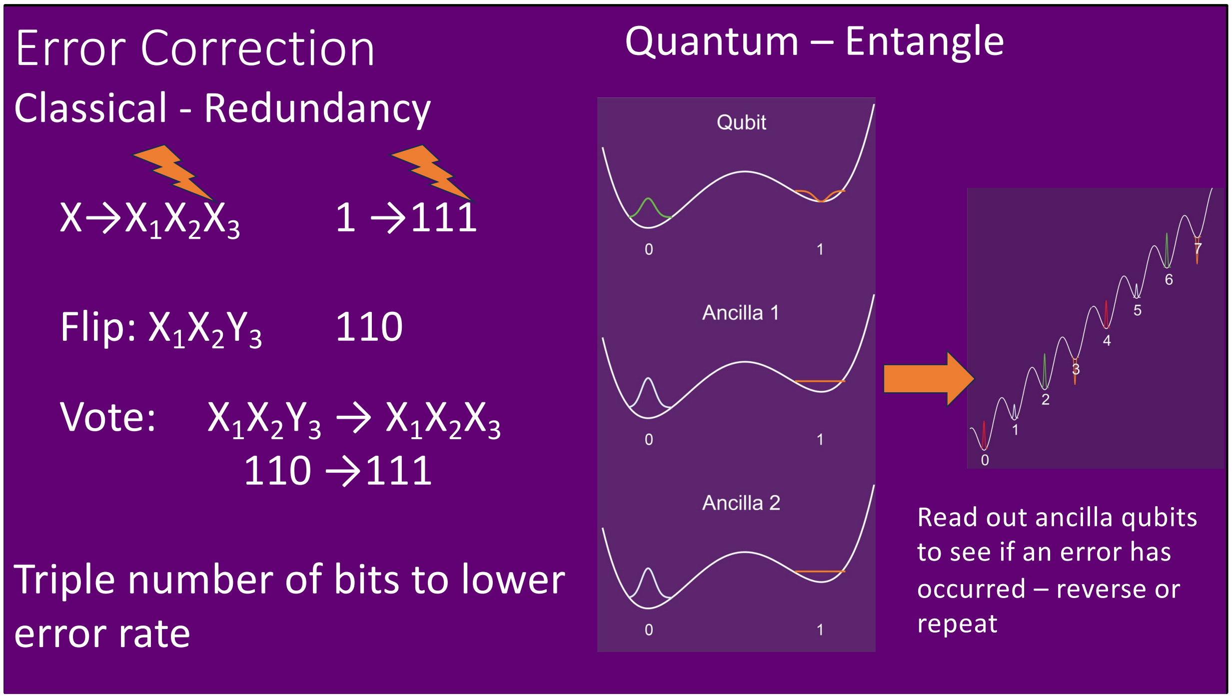
Scaling the number of Qubits

Each additional qubit doubles the number of real numbers under computation

No. Qubits	No. quantities	
1	2	
2	4	
3	8	
10	1,024	1 kb
20	1,048,576	1 Mb
40	1,099,511,627,776	1 Tb
60	1,152,921,504,606,846,976	Exascale

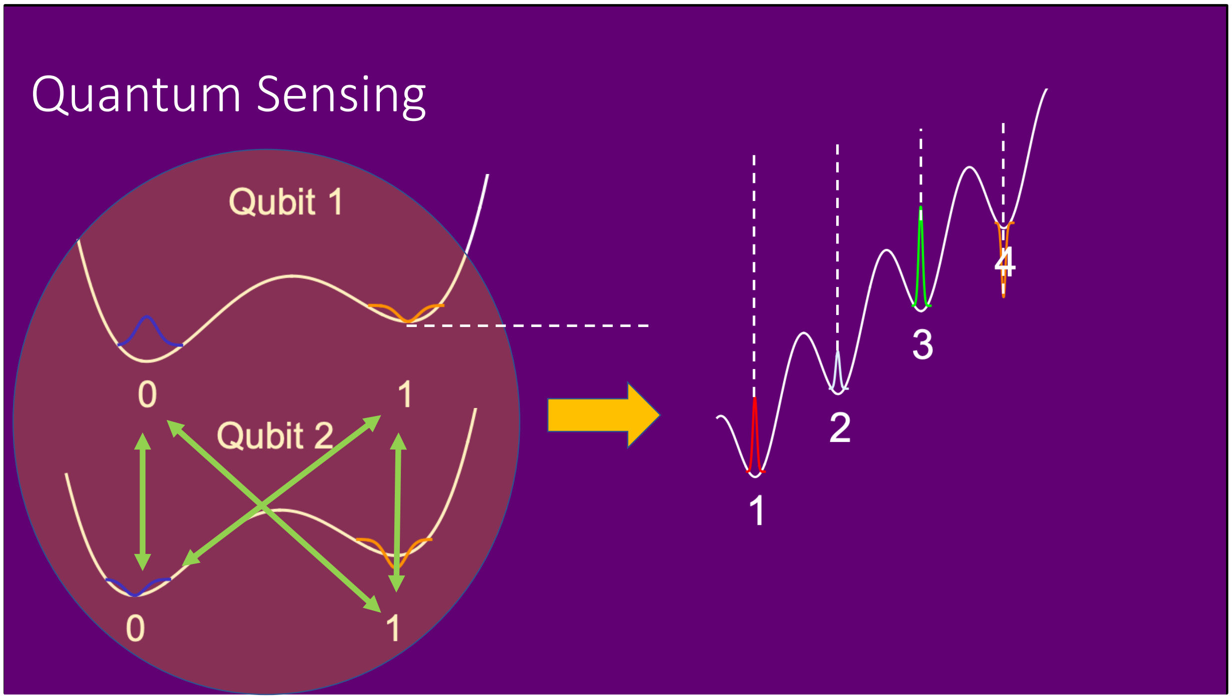
IN the last slide, we learned that adding a qubit to a computer doubles the number of quantities the computer can process. This table shows the progression up to 60 qubits that constitutes the exascale or a billion numbers.

This is the HYPE of quantum computing – the possibility of such a computer. The numbers work out, but we will learn on the next slide about the delicacy of quantum states and the need for error correction to make good on this idea.

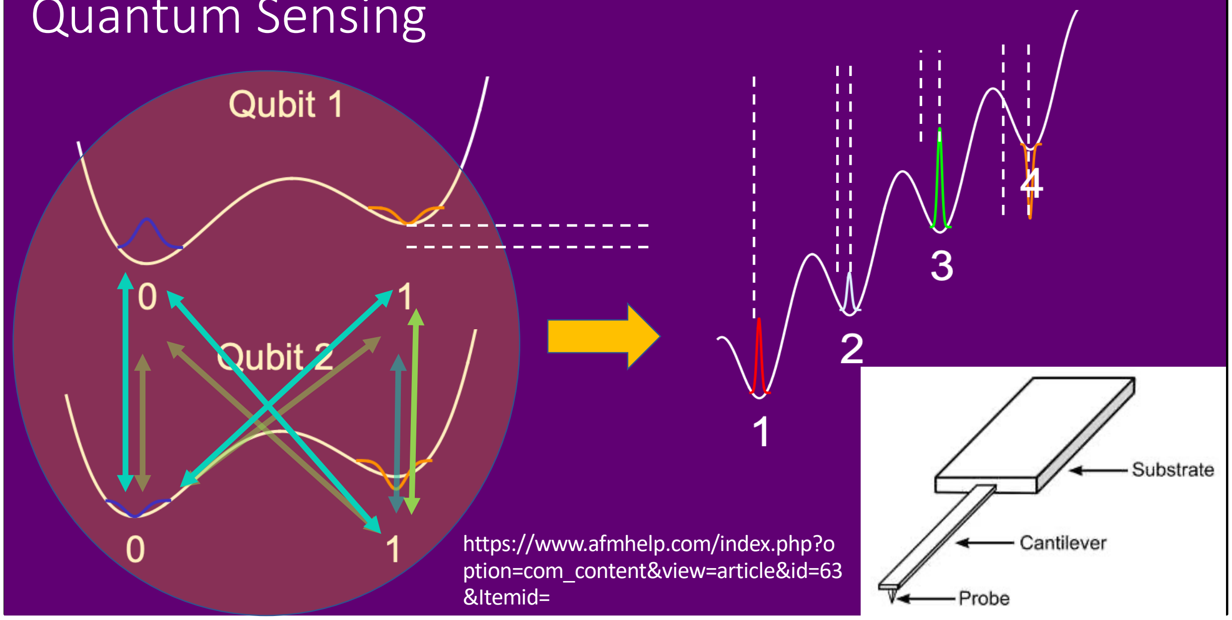


From the beginning, designers had to contend with "bit flips" from electrical noise or cosmic rays. Much of the most sophisticated electronics in our computers today contend with error correction. Majority voting provides the simplest method, shown here. Our computers use much more eifficient error correction schemes.

In a quntum computing circuit, a "measueremnt" can force the qubit into a well and we would not know it and the quantum mechanical "No cloning" theorem says we cannot copy a qubit. In this scheme, entangling the qubit with two "ancilla" qubits that start in known states allows reading out one ancilla to check that it resides in the right state. If not,


Quantum Sensing
Qubit 1
0
1
Qubit 2
0
1
1
2
3
4

Quantum Sensing



https://www.afmhelp.com/index.php?option=com_content&view=article&id=63&Itemid=

Next..

Prof. Cappallero leads quantum@mit, a new organization that will start soon.

She will tell you how these ideas have led to exciting new projects at MIT Campus and Lincoln Labs.

Prof. Cappallero holds appointments in Nuclear Science and Engineering and Physics at MIT. She just became a Fellow of the American Physical Society.

Massachusetts Institute of Technology

Quantum@MIT
Where small meets big challenges

Paola Cappellaro, Ph.D.'06
Ford Professor of Engineering

November 17th, 2023

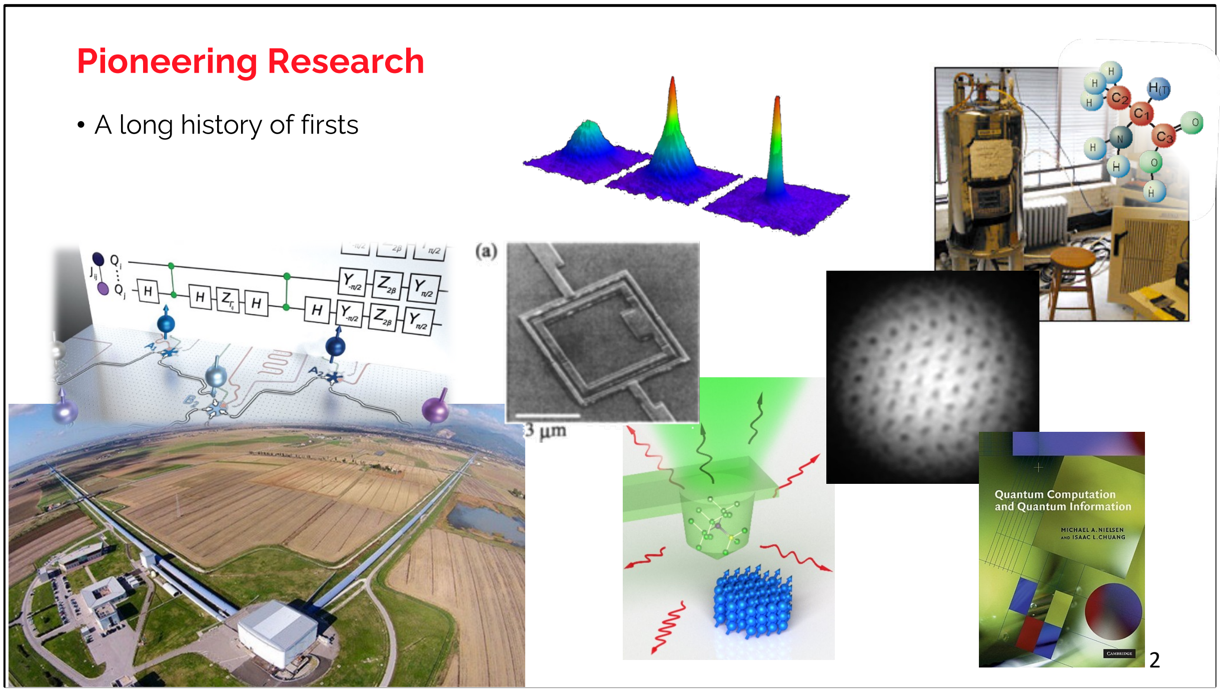
Quantum Science and engineering is a new paradigm where genuinely quantum phenomena are exploited to offer major breakthroughs in how we measure & understand nature, in how we store, process, and transfer information.

I will first describe MIT's contributions and how we plan to multiply our impact by creating a more cohesive Quantum@MIT center to foster collaborations, fundamental research and entrepeneurship. (Slides 2-7)

I will then focus on two directions where MIT is leading:

Quantum sensing (slides 8-11)

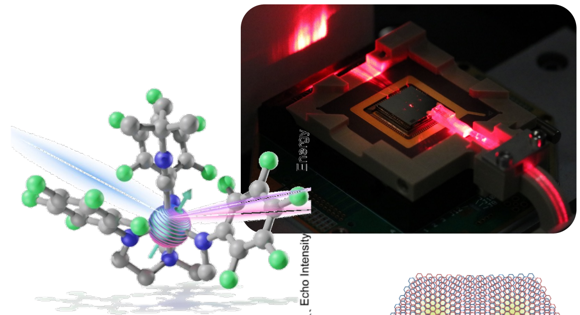
Quantum computing with atoms (slides 12-15)

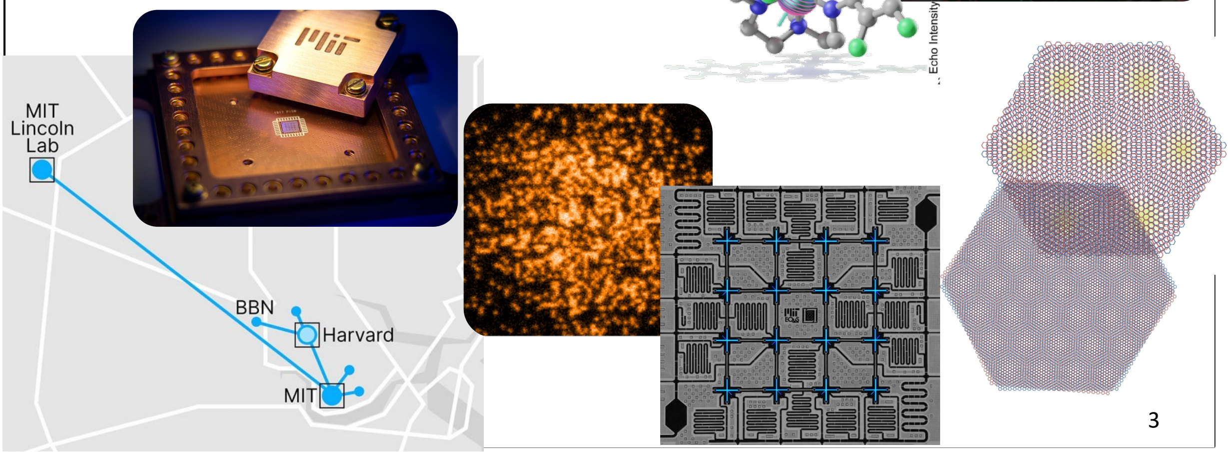


MIT has made foundational contributions to Quantum Science and Engineering, from one of the first superconducting qubit to the first spin qubit, to cold atoms condensation and superfluidity, to sensing at the nanoscale and at the cosmic scale with LIGO.
In addition, ,many of the quantum algorithms that are now pushing for the quantum computational advantage have been introduced by MIT faculty and THE textbook for quantum information has also been developed by MIT faculty.

Pioneering Research

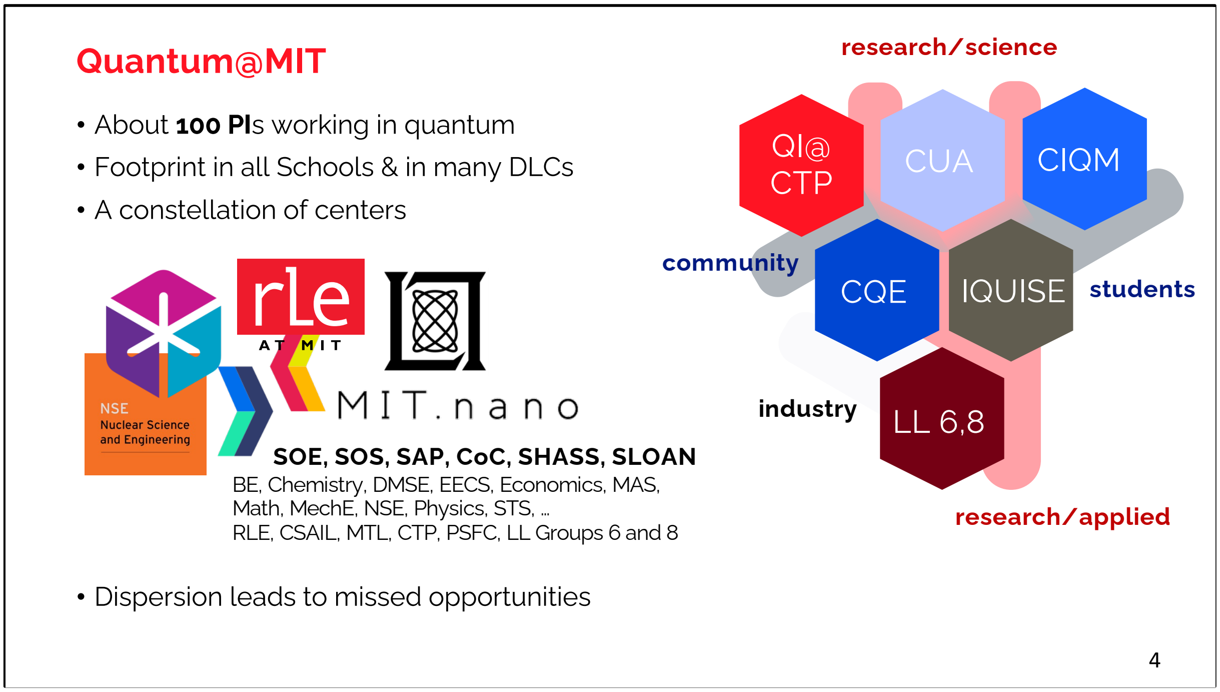
- A long history of firsts
- Leaders in science and engineering and education



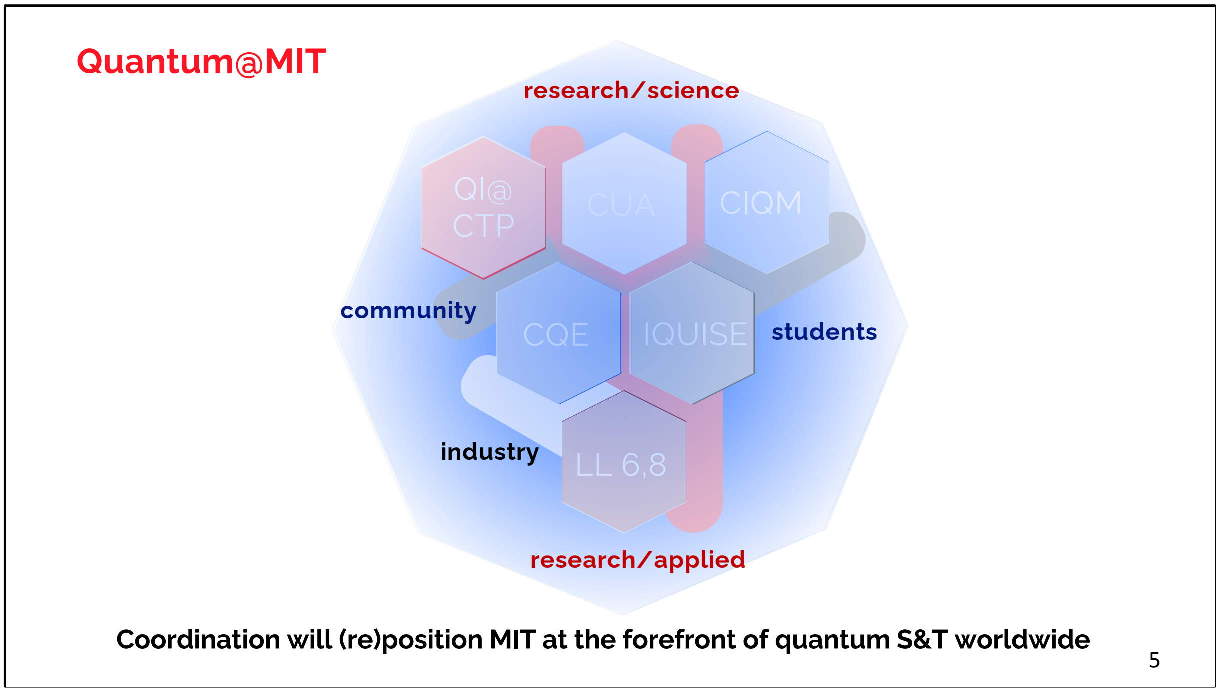


3

The progress continues today, with a strong emphasis on intentional complexity (larger systems, more precise control and engineering). This results in larger-scale quantum networks, more powerful quantum chips based on superconducting, atomic, ions and photonic systems, and engineered simulation platforms such as molecules and twisted bilayer graphene



Research and education in quantum happens in all schools and many departments and centers at MIT, we are now bringing everybody together under a single umbrella of Quantum@MIT to keep our forefront position in quantum research.



Maintain our leadership role – mention that most other universities already have institute-wide quantum initiatives

Quantum@MIT is the hub for MIT's quantum research, education, and outreach, spanning science and engineering.

The mission of Quantum@MIT is to foster exploration and application of quantum systems, bridging fundamental discovery and impactful technology.

Quantum@MIT will accelerate the translation of quantum innovations at MIT to important world challenges in science and society.

Quantum@MIT: where small meets big challenges

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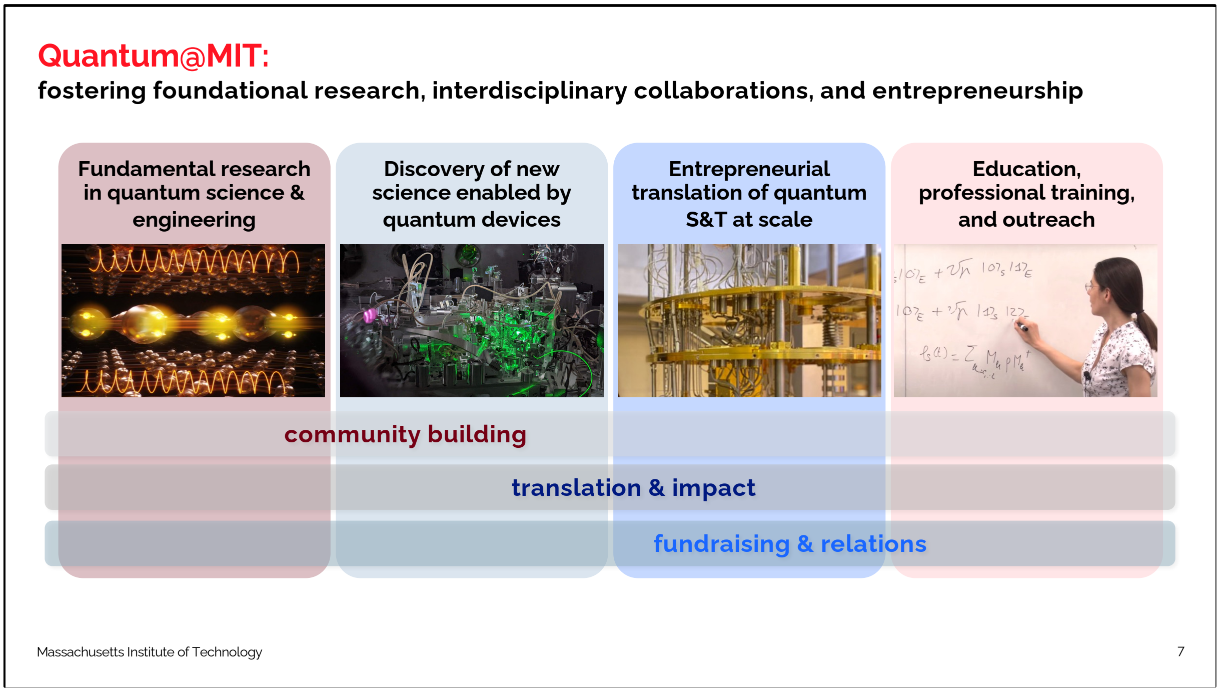
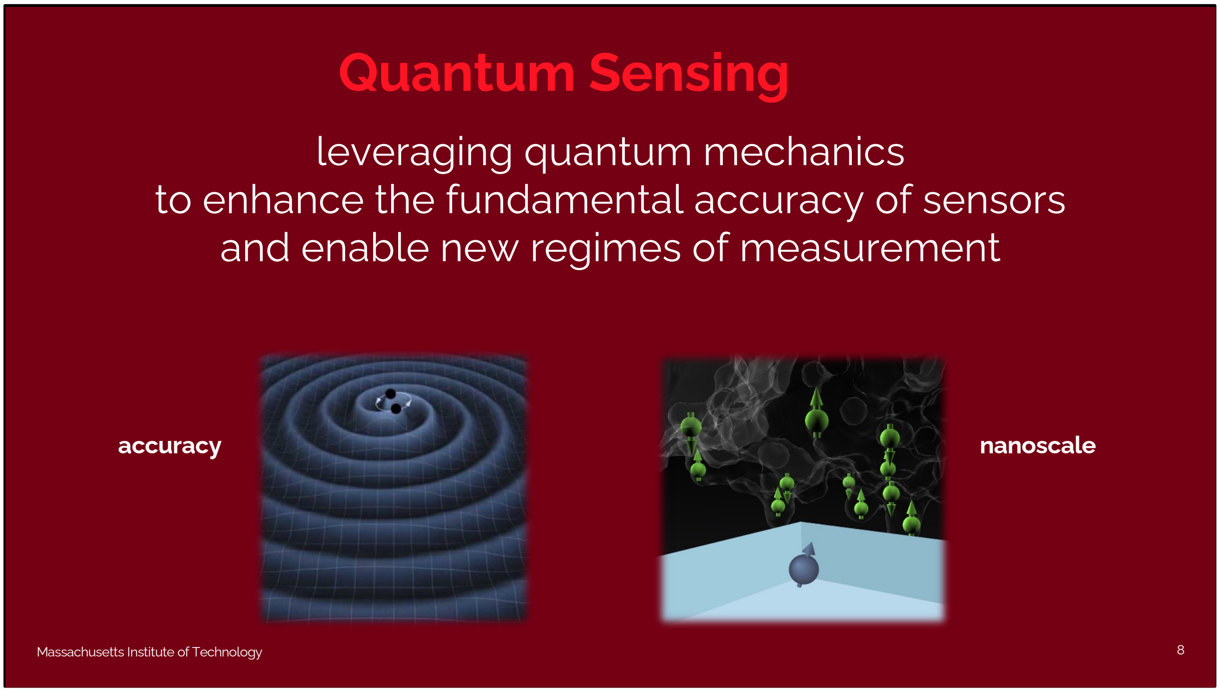


Quantum@MIT is organized around 4 pillars

- **Fundamental research in quantum science & engineering**
- **Discovery of new science enabled by quantum devices**
- **Entrepreneurial translation of quantum S&T at scale**
- **Education, professional training, and outreach**

I'd like to illustrate the impact that quantum research can have by combining these 4 pillars with two examples, from quantum sensing and quantum computing.



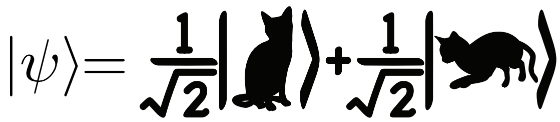
Quantum sensing aims at leveraging quantum mechanics

For example, many quantum sensors are at the atomic scale, thus allowing nanoscale measurements.

Why quantum sensing?

- Quantum systems are "fragile"
  because very sensitive to external perturbations

Great sensors!



- Signal-to-Noise Ratio for N classical sensors SNR ~ √N
- Signal-to-Noise Ratio for N entangled sensors SNR ~ N : quantum advantage

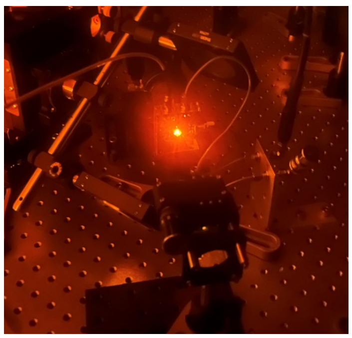
9

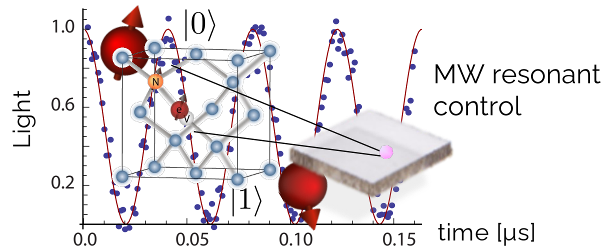
The power of quantum sensing stems from the fragility of quantum systems to external perturbation (think of the Schroedinger's cat!)
This is a challenge for quantum computing but can be leveraged for sensing. Finding a good compromise between noise and preserving the quantumness of the sensor can lead to a quantum advantage in SNR, similar to the advantage in computation.

My favorite quantum sensor: NV center in diamond

Nanoscale, sensitive, biocompatible, …

- Isolated spin defect ⟶ nanoscale resolution
- Color center ⟶ ultra-sensitive with optical detection



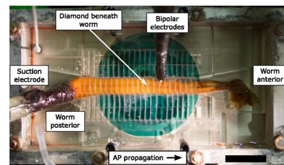


10

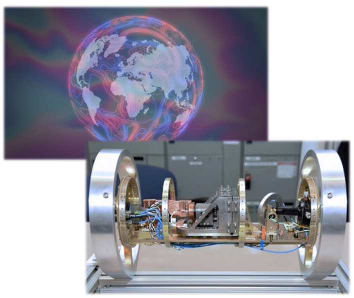
What are practical sensors? You might already be familiar with atomic clocks. Other modalities include for example spin defects in diamond. These emit red light, that we can see by masking the green laser excitation. Like the needle of a compass, the spins orient themselves with external magnetic field, and their rotation from up to down (and superpositions, that we detect optically) indicate the strength of external magnetic fields.

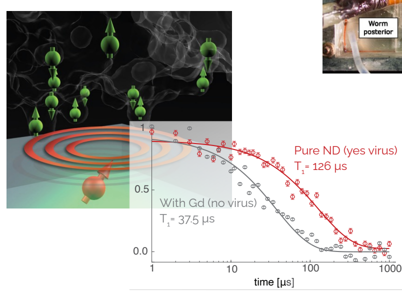
Application: navigation, imaging, health

- Excellent sensitivity, vectorial and broadband sensors & imagers
  - Navigation (magnetic, gyroscopes)
  - Bioimaging (RNA sensor, single molecule,...)
  - Materials (magnetism, batteries, chips, ...)

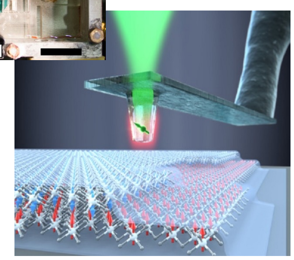


Harvard University





Cappellaro

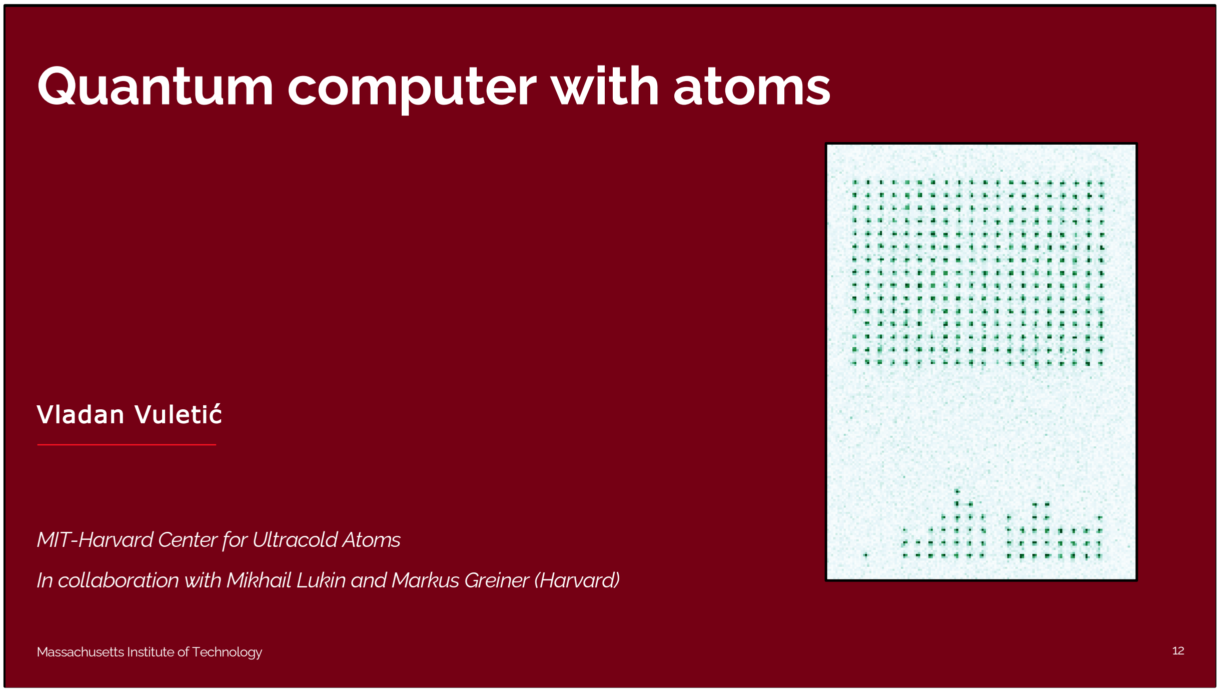


Basel University

11

https://www.gpsworld.com/quantum-magnetometer-senses-its-place

The applications of magnetic field sensing are numerous and they already find practical implementations.

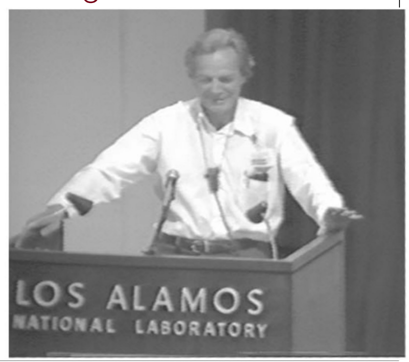


I want now to give you a glimpse of a quantum computing architecture that have come late to the fold, but is making leaps beyond other technologies. These slides are courtesy of my colleague Vladan Vuletić who is a pioneer in Rydberg atom quantum computers

Now, we can, in principle make a computing device in which the numbers are represented by a row of atoms with each atom in either of the two states. That's our input.
The Hamiltonian starts [evolving] the wave function. . .
The ones move around, the zeros move around . . .
Finally, a particular bunch of atoms […] represent the answer.
Nothing could be made smaller. Nothing could be more elegant …
But can we do it?

Richard Feynman

1983. Tiny Computers Obeying Quantum Mechanical Laws.
Talk delivered at Los Alamos National Laboratory

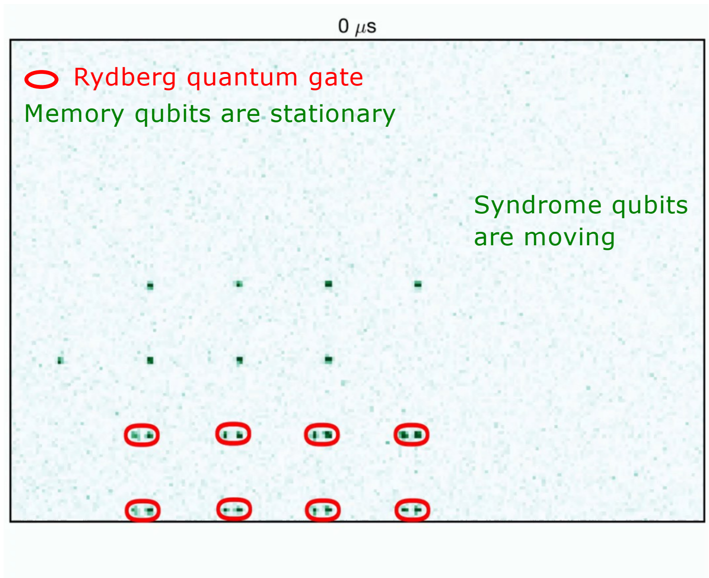


Massachusetts Institute of Technology

I'm starting with a quote from Richard Feynman, which has been both visionary but for a long time even appeared impractical (people thought the vision was right but the technology would need to develop differently…)

Array of atoms, the ones move around, … Nothing can be more elegant.

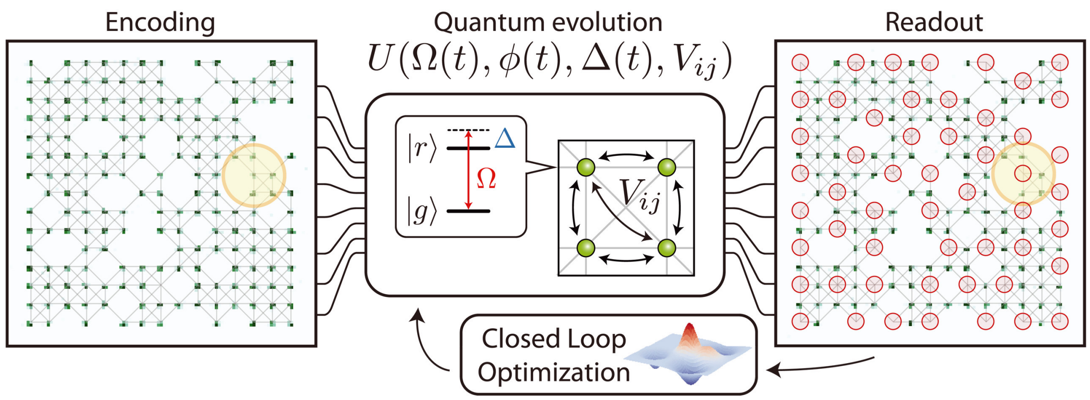
Implementation of Toric code for error correction



This is exactly what is being implemented in Rydberg atom arrays!!

Maximally independent set

(optimization problem)



SCIENCE 376, 1209-1215 (2022)

This platform is quickly moving ahead, performing simulations beyond what possible classically, implementing variational algorithms that combine quantum and classical machine, and working on the development of QEC.

Quantum: State of Play

Seeds for discussion!

- Q. Computing – IBM (433 qubits), Google (70), Atom Computing (1,180), D-Wave (#k?). Much hype about quantum advantage, but needs practical demonstration. Huge progress, error correction, power consumption, and other technical challenges remain. Probably 5 years to improve on classical capabilities
- Q. Communications – Secure networks are okay for now (post-quantum cryptography). Applications to distributed computing, sensing. 5-10 years for clock synchronization.
- Q. Sensing – already here, steady improvements. New atomic clocks are so good we do not know what to do with them. Exciting NOW.
- Q. Simulators – simulating materials, black holes, other quantum many-body problems. Recently IBM has produced results that cannot be obtained classically, exciting NOW.
- Q. Business – Quantum Entrepreneur Subject (Oliver, Cusumano), MIT xPro subjects. Substantial business activity NOW.
- Q. Education – Physics Grad/Undergrad sequences, EECS, MechE, NSE, Sloan….
  Opportunity for interdisciplinary and innovation

The future is very promising and there's already a lot to be done and to be gained now. Happy to answer any questions!