



Quantum Computing at Fermilab

Adam Lyon (Fermilab Scientific Computing Division, Muon g-2, Fermilab Quantum Institute)

3rd Rucio Community Workshop

10 March 2020



Quantum Data Handling with Qurucio

You?

13th Rucio Community Workshop

March 2030

THE WALL STREET JOURNAL.

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How Google's Quantum Computer Could Change the World

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TECHNOLOGY 19 DECEMBER 2017

How quantum computing will change the world

We are on the cusp of a new era of computing, with Google, IBM and other tech companies using a theory launched by Einstein to build machines capable of solving seemingly impossible tasks.

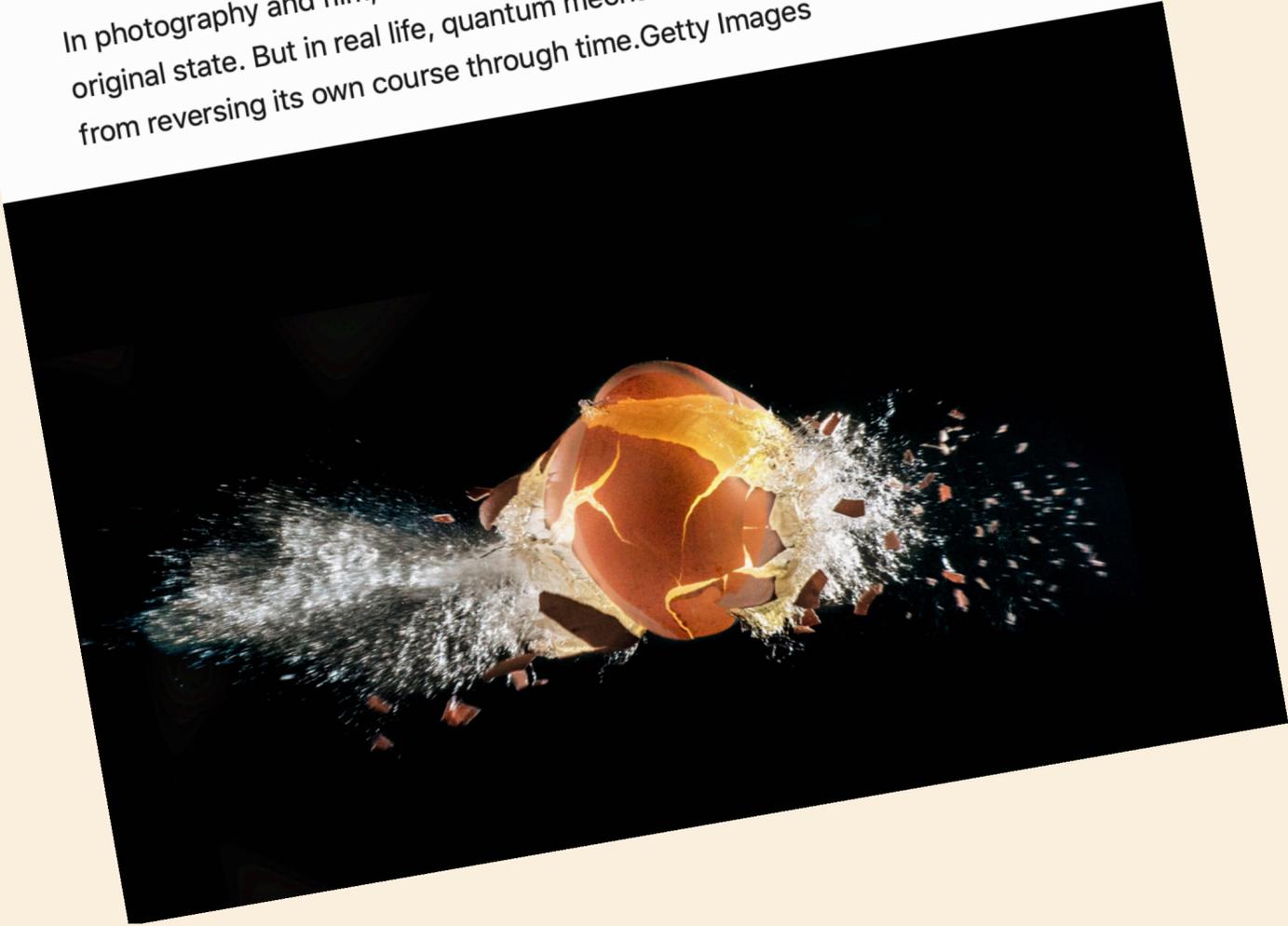
Hyper hype

The New York Times

For a Split Second, a Quantum Computer Made History Go Backward

By Dennis Overbye • May 8, 2019

In photography and film, a broken egg can be perfectly unscrambled to its original state. But in real life, quantum mechanics prevent even a single particle from reversing its own course through time. Getty Images



Sci Rep 9, 4396 (2019). <https://doi.org/10.1038/s41598-019-40765-6>

Scientists just turned back time and it's like Back To The Future is coming true

WTF.



by CATRIONA HARVEY-JENNER MAR 13, 2019

COSMOPOLITAN

The Atlantic Popular Latest Sections Magazine

TECHNOLOGY
Could Quantum Computing Be the End of Free Will?
On the fear that too much processing power will make us cease to be human

RACHEL GUTMAN JUN 30, 2018

YUSUF AHMAD / REUTERS

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Super-hyper hype

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Mathematicians Are Studying Planet-Sized Quantum Computers With God-Like Powers

New research has exploded the space of problems that quantum computers can efficiently verify, simultaneously knocking down milestone problems in quantum physics and math.

By **Mordechai Rorvig**
Feb 11 2020, 7:00am [Share](#) [Tweet](#) [Snap](#)

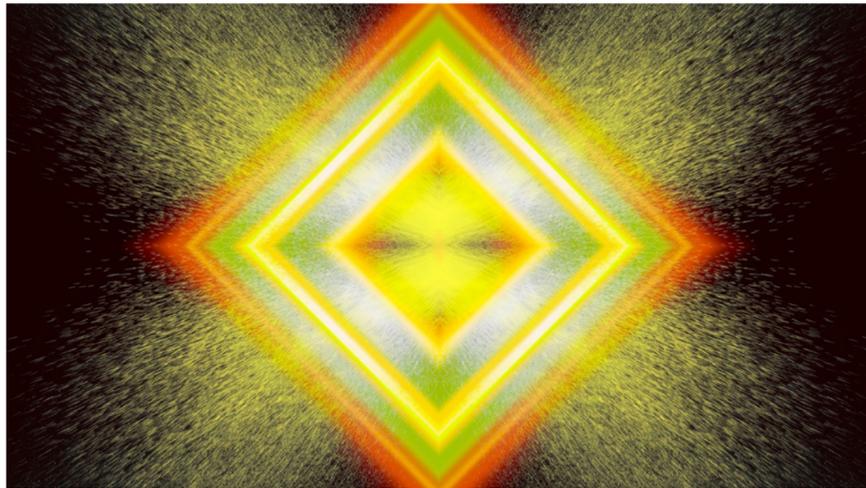


IMAGE: GETTY IMAGES

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[arXiv:2001.04383 MIP*=RE](#)
We show that the class MIP^* of languages that can be decided by a classical verifier interacting with multiple all-powerful quantum provers sharing entanglement is equal to the class RE of recursively enumerable languages. ... An immediate byproduct of our result is that there is an efficient reduction from the Halting Problem to the problem of deciding whether a two-player nonlocal game has entangled value 1 or at most $1/2$.

GIZMODO | We come from the future

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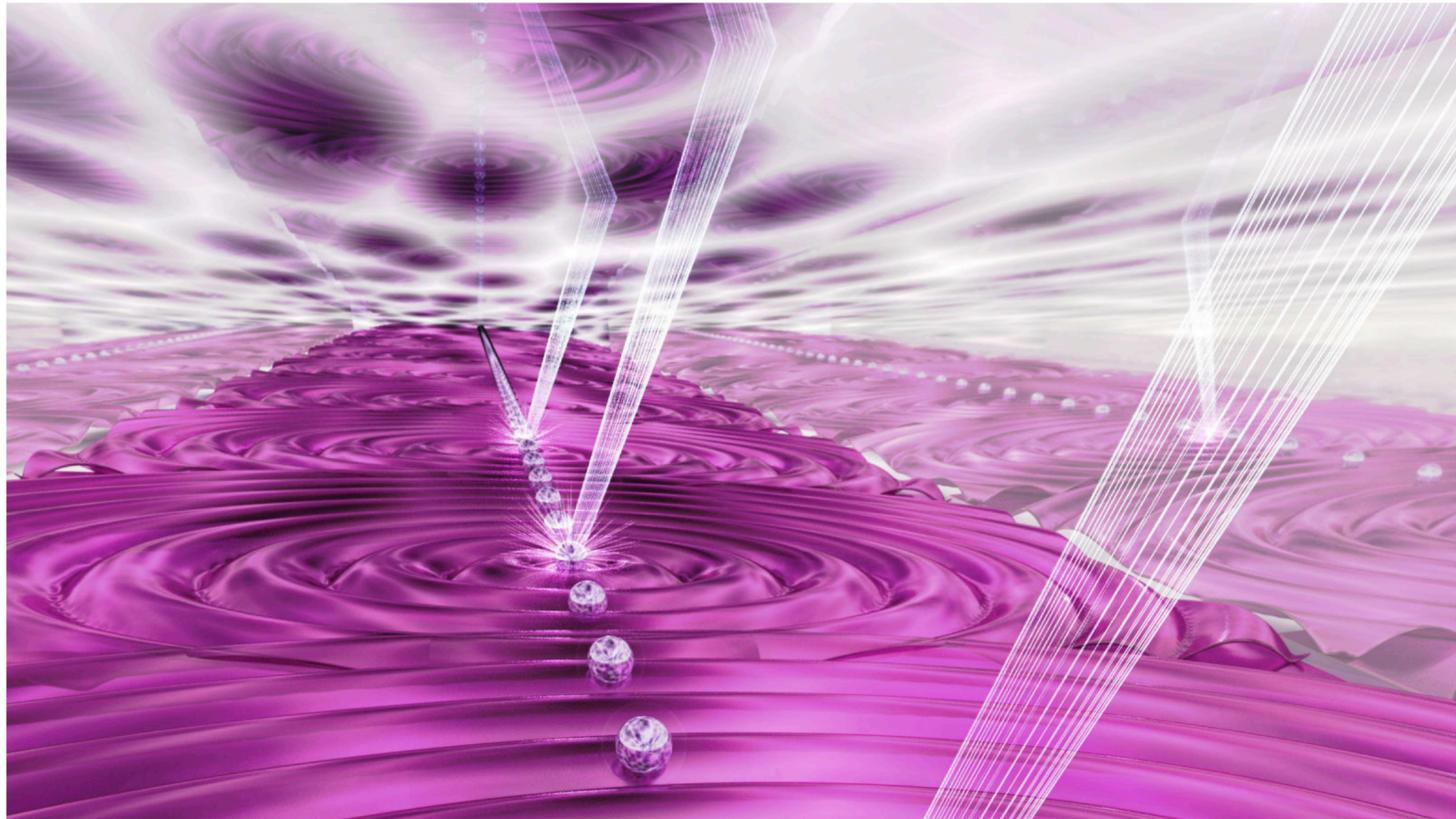
PHYSICS

It's Time to Plan for How Quantum Computing Could Go Wrong, Say Entrepreneurs and Physicists

Ryan F. Mandelbaum
12/13/18 6:00pm • Filed to: ETHICS

29.1K 19 4

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More of that weird quantum art that always comes with quantum computing press releases.
Illustration: E. Edwards/JQI (NIST)

Weird Quantum Art

We do it too!



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Useful links

- Symmetry magazine
- Interactions

Department of Energy awards Fermilab \$3.5 million for quantum science

August 27, 2019 | edited by Leah Hesla

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The U.S. Department of Energy has awarded researchers at its Fermi National Accelerator Laboratory more than \$3.5 million to boost research in the fast-emerging field of Quantum Information Science.

“Few pursuits have the revolutionary potential that quantum science presents,” said Fermilab Chief Research Officer Joe Lykken. “Fermilab’s expertise in quantum physics and cryogenic engineering is world-class, and combined with our experience in conventional computing and networks, we can advance quantum science in directions that not many other places can.”

As part of a number of grants to national laboratories and universities offered through its Quantum Information Science-Enabled Discovery (QuantISED) program, DOE’s recent round of funding to Fermilab covers three initiatives related to quantum science. It also funds Fermilab’s participation in a fourth initiative led by Argonne National Laboratory.



The DOE QuantISED grants will fund initiatives related to quantum computing. These include the simulation of advanced quantum devices that will improve quantum computing simulations and the development of novel electronics to work with large arrays of ultracold qubits.

6



The real question I'll try to answer



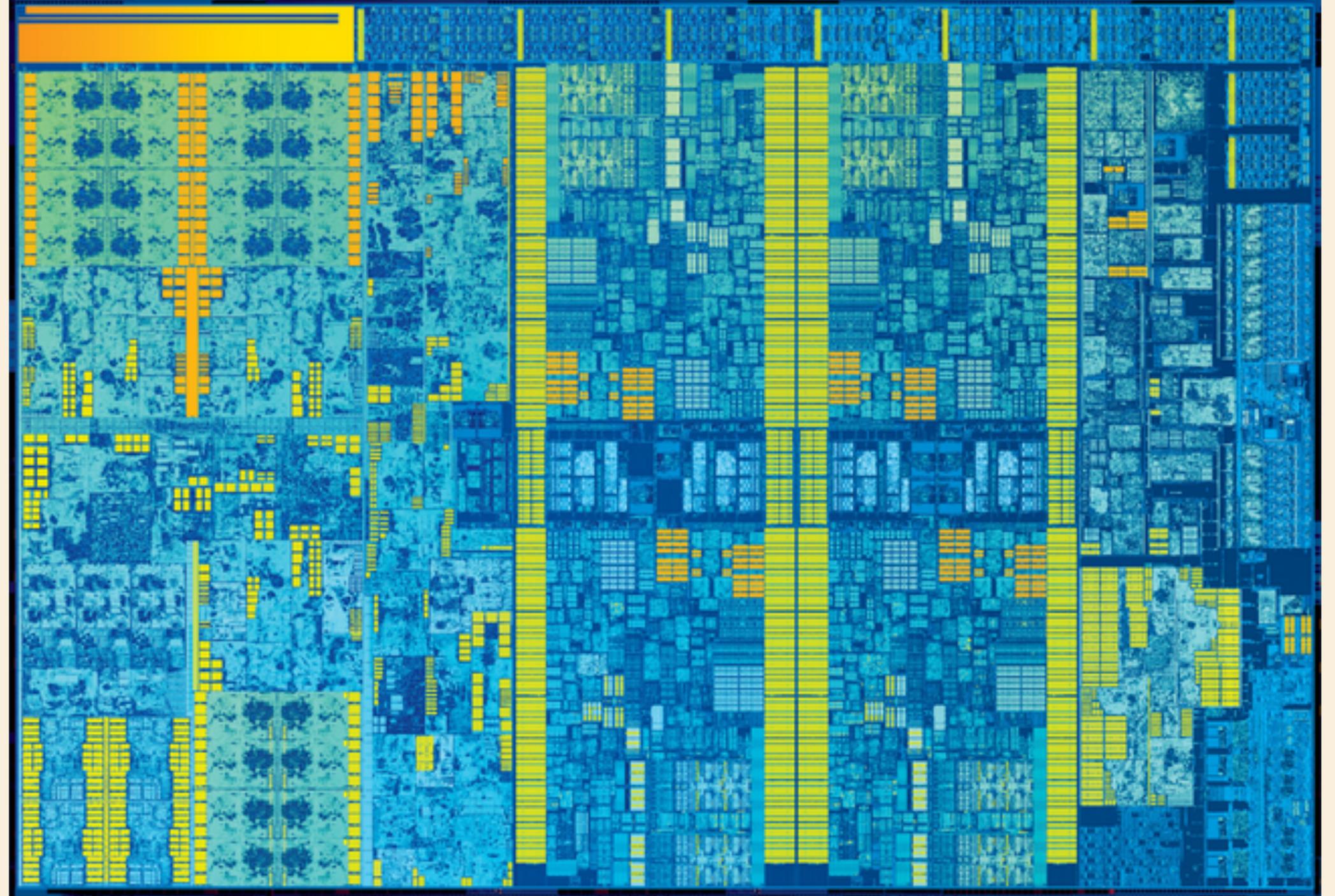
Overview

- **Motivate the need for a new kind of computing...**
 - Learn about computational complexity
 - Traditional (Classical) computers are good at certain kinds of problems and bad at others
- **Learn just enough quantum mechanics**
 - “I think I can safely say that nobody understands quantum mechanics” — Richard Feynman
- **Learn the very basics of how Quantum Computers work**
- **Show Fermilab’s involvement in Quantum Computing and why its important**

Note: All computers today need Quantum Mechanics

- Intel Skylake Processor
- 28 cores
- 8 BILLION transistors
- Quantum mechanics governs construction and limitations
- The materials science is based on QM

- BUT - operation is not “quantum”
- Manipulate bits: (0 or 1)
- Classical Digital Machine



Motivation: How do we compare algorithms? Complexity

- Insertion

```
6 5 3 1 8 7 2 4
```

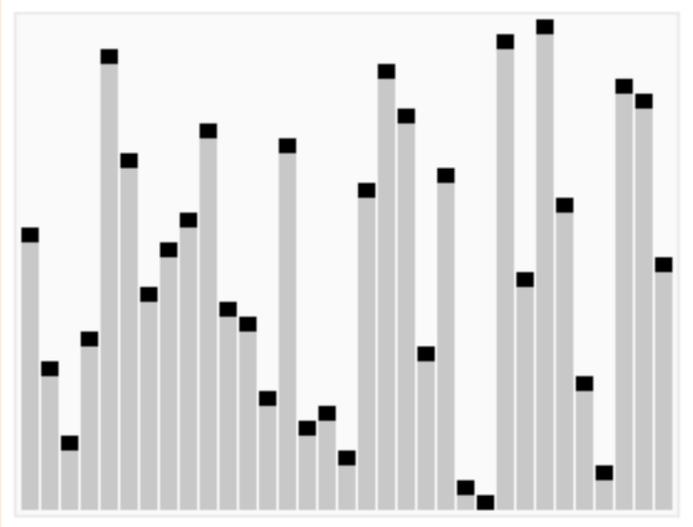
- Merged

```
6 5 3 1 8 7 2 4
```

- Selection

	8
	5
	2
	6
	9
	3
	1
	4
	0
	7

- QuickSort



- Bubble

```
6 5 3 1 8 7 2 4
```

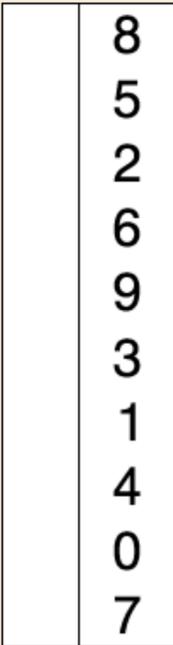
<https://github.com/gibsjose/cpp-cheat-sheet>

How do we compare algorithms? Complexity (asymptotic)

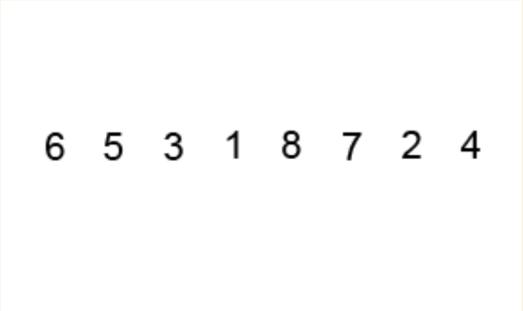
- **Insertion**
 $O(n^2)$



- **Selection**
 $O(n^2)$



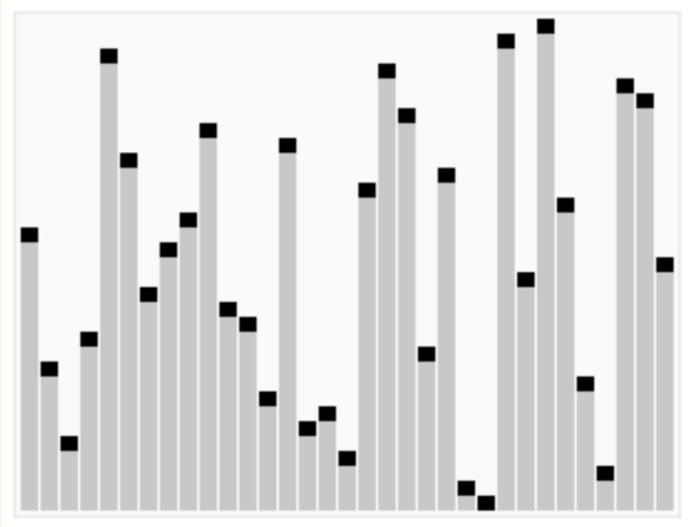
- **Bubble**
 $O(n^2)$



- **Merged**
 $O(n \log n)$



- **QuickSort**
 $O(n \log n)$



Asymptotic number of operations

<https://github.com/gibsjose/cpp-cheat-sheet>

Complexity (C++ Standard Template Library)

Data Structures

Data Structure	Time Complexity								Space Complexity
	Average				Worst				Worst
	Indexing	Search	Insertion	Deletion	Indexing	Search	Insertion	Deletion	
Basic Array	$O(1)$	$O(n)$	-	-	$O(1)$	$O(n)$	-	-	$O(n)$
Dynamic Array	$O(1)$	$O(n)$	$O(n)$	$O(n)$	$O(1)$	$O(n)$	$O(n)$	$O(n)$	$O(n)$
Singly-Linked List	$O(n)$	$O(n)$	$O(1)$	$O(1)$	$O(n)$	$O(n)$	$O(1)$	$O(1)$	$O(n)$
Doubly-Linked List	$O(n)$	$O(n)$	$O(1)$	$O(1)$	$O(n)$	$O(n)$	$O(1)$	$O(1)$	$O(n)$
Skip List	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(n)$	$O(n)$	$O(n)$	$O(n)$	$O(n \log(n))$
Hash Table	-	$O(1)$	$O(1)$	$O(1)$	-	$O(n)$	$O(n)$	$O(n)$	$O(n)$
Binary Search Tree	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(n)$	$O(n)$	$O(n)$	$O(n)$	$O(n)$
Cartresian Tree	-	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	-	$O(n)$	$O(n)$	$O(n)$	$O(n)$
B-Tree	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(n)$
Red-Black Tree	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(n)$
Splay Tree	-	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	-	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(n)$
AVL Tree	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(\log(n))$	$O(n)$

<https://github.com/gibsjose/cpp-cheat-sheet>

An NP problem - factorizing numbers

$$15 = 5 \times 3$$

$$91 = 13 \times 7$$

$$4095 = 45 \times 91 = 13 \times 7 \times 5 \times 3 \times 3$$

RSA Encryption (Rivest, Shamir, Adleman)

You want send your credit card information to a web-store securely

The store sends you a **public key** (a big number) that the algorithm uses to encrypt your message.

The store uses the corresponding top secret **private key** they hold to decrypt your message.

The public key is not usable for decrypting messages, only encrypting

How does this work?

The private key is two large prime numbers.

The public key is their *product*

So long as the public key is hard to factor, anyone can **encrypt** but only the store can **decrypt**

https:// uses this technique. So long as the public key is big, you can't figure out the private key

RSA Encryption and Factorization

- Factorization is an NP problem (very hard to solve, but efficient to check)
- Best algorithm is “General Number Field Sieve” $O\left(e^{\sqrt[3]{b(\log b)^2}}\right)$, basically like $O(2^n)$
- Largest integer factorized is RSA-768 (768 bits, 232 decimal digits) in 2009
 - 100s of machines running for over two years - equivalent to 2000 CPU years

- RSA-2048 is the current standard (617 decimal digits)

~6 quadrillion years to break on a desktop
~6 billion years on a million processor supercomputer
Expected to remain unbroken until after 2030
Then we'll use RSA-4096 !
Note that RSA-1024 was expected to be broken before 2010 and it hasn't yet

```
RSA-768 = 12301866845301177551304949583849627207728535695953347921973224521517264005
07263657518745202199786469389956474942774063845925192557326303453731548268
50791702612214291346167042921431160222124047927473779408066535141959745985
6902143413

RSA-768 = 33478071698956898786044169848212690817704794983713768568912431388982883793
878002287614711652531743087737814467999489
× 36746043666799590428244633799627952632279158164343087642676032283815739666
511279233373417143396810270092798736308917
```

<https://www.digicert.com/TimeTravel/math.htm>
https://en.wikipedia.org/wiki/Integer_factorization
https://en.wikipedia.org/wiki/RSA_numbers#RSA-768



And now for something completely different

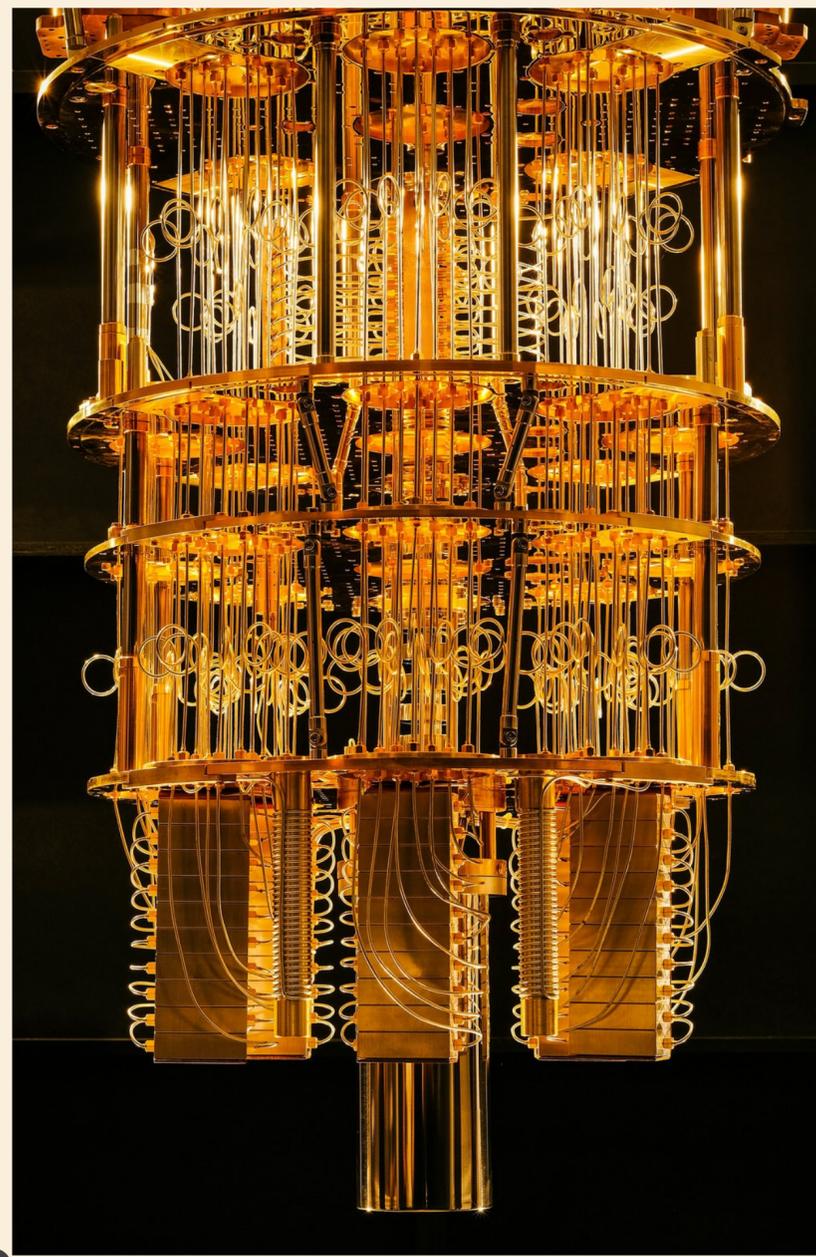
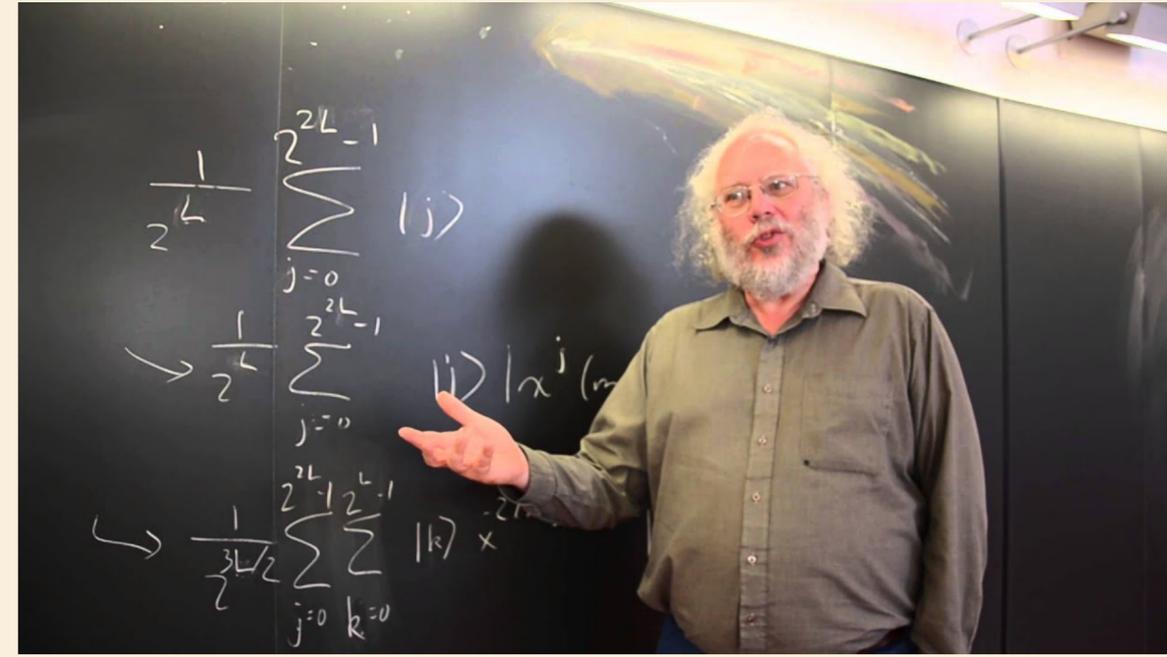
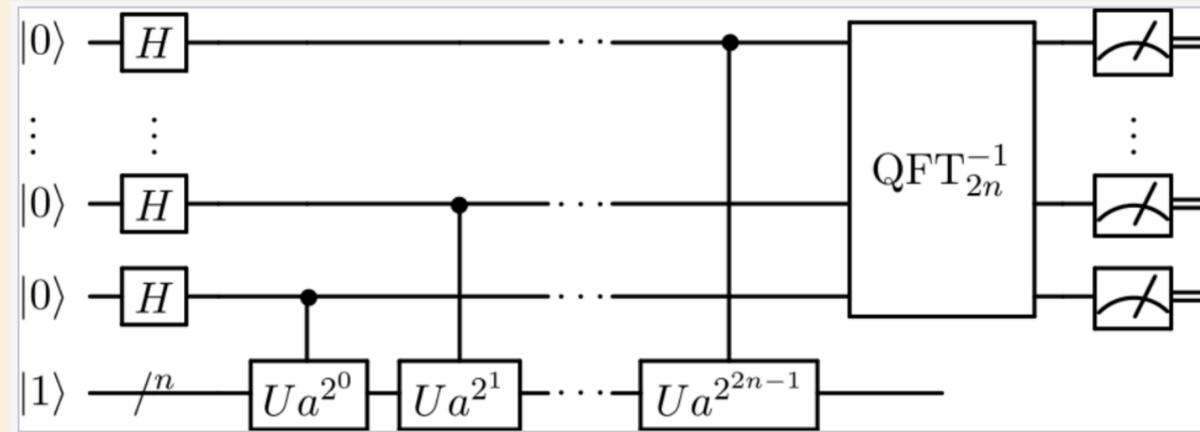
Think about a completely different type of computer... a Quantum Computer

Shor's Algorithm invented in 1994 by Peter Shor (MIT) can factor numbers on a Quantum Computer with **polynomial scaling**

$$O(b^2 \log b \log \log b) \sim O(b^3)$$

The largest number factored with Shor's algorithm is **21 = 7 x 3 (wow!)**

Largest number factored by a later algorithm is **56,153 = 241 x 233**
 Could potentially factor very large numbers in a short amount of time

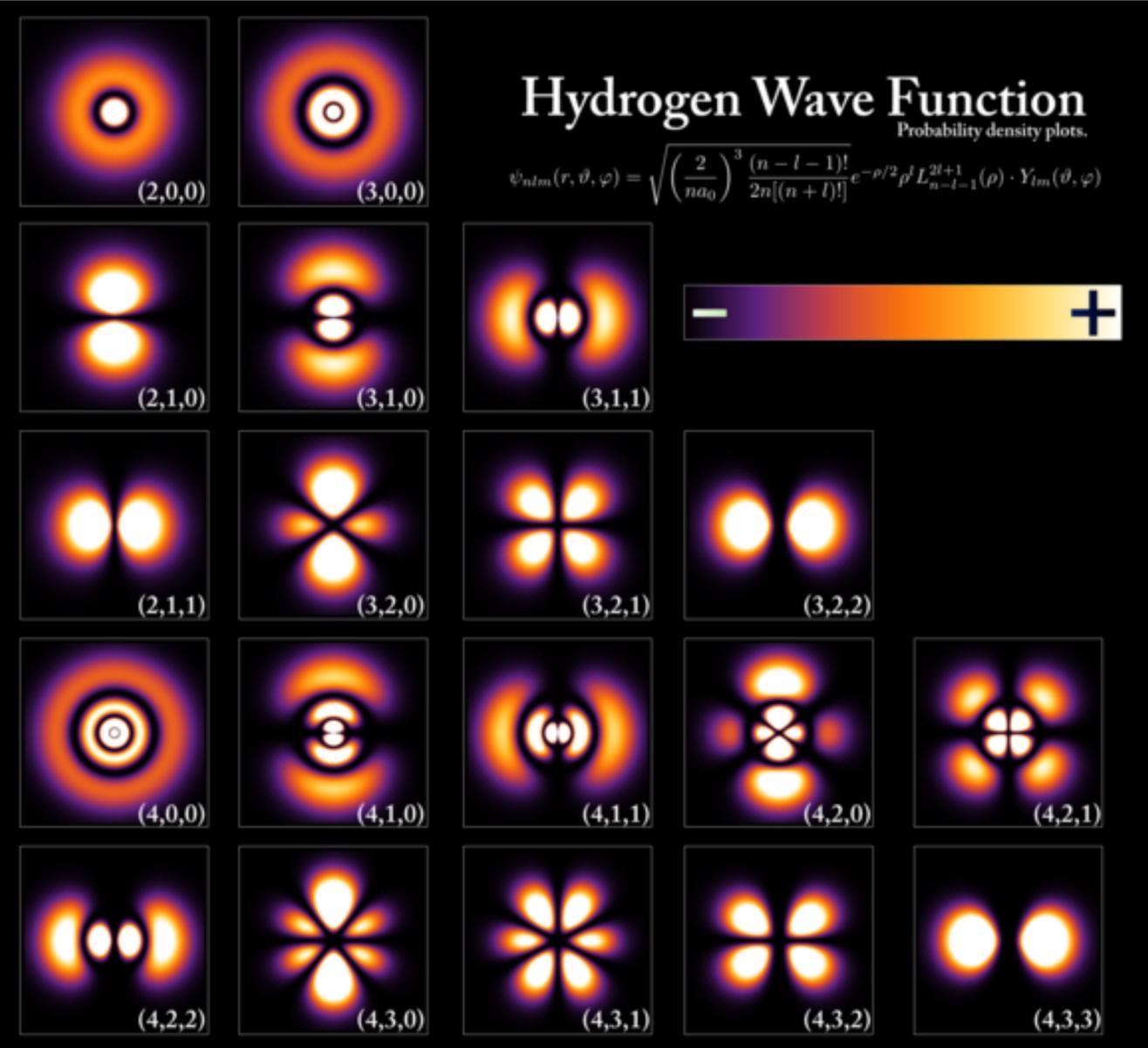


Quantum Computing

Potential for Quantum Computing to ruin RSA, but not any time soon.

This isn't the thing that drives Quantum Computing now, but allows us to introduce it...

A Quantum Computer OPERATES exploiting the strange world of Quantum Mechanics

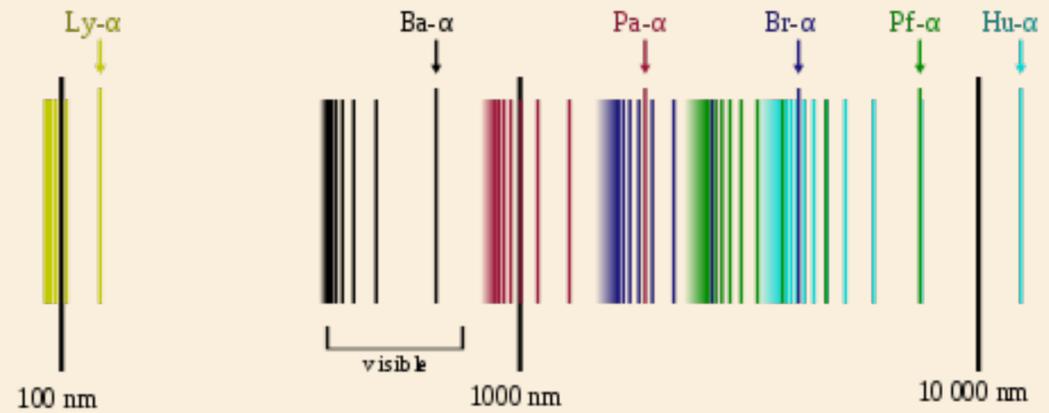
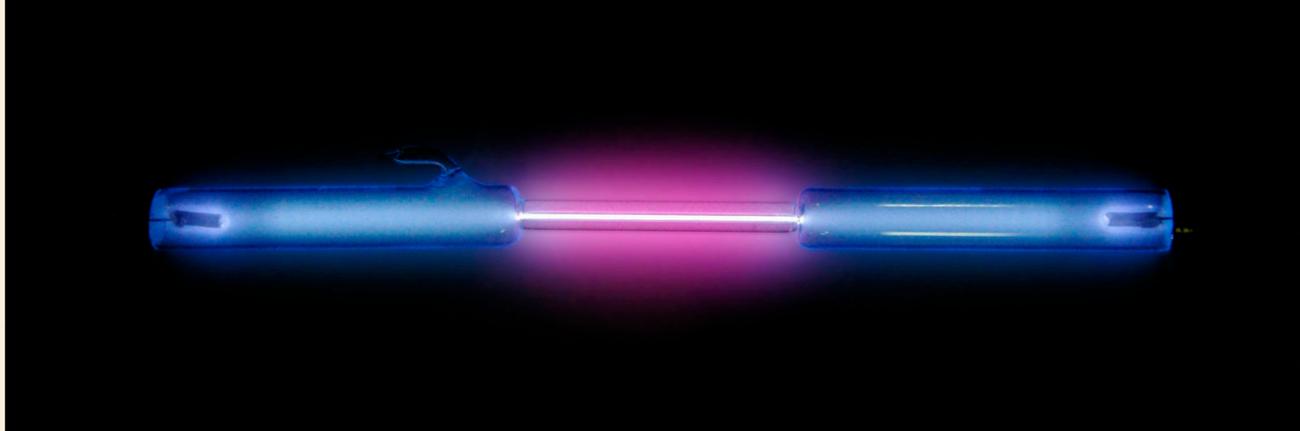
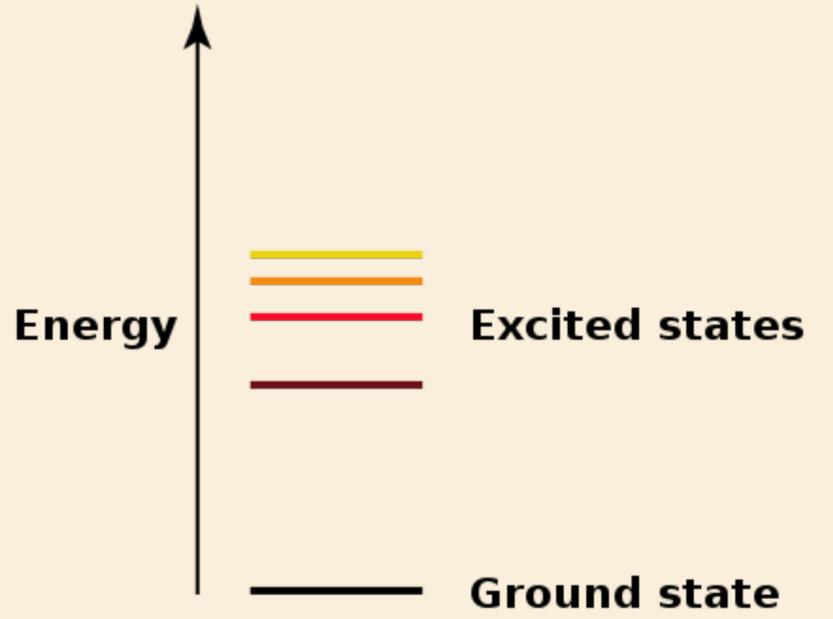


<http://bit.ly/2JWA1GM>

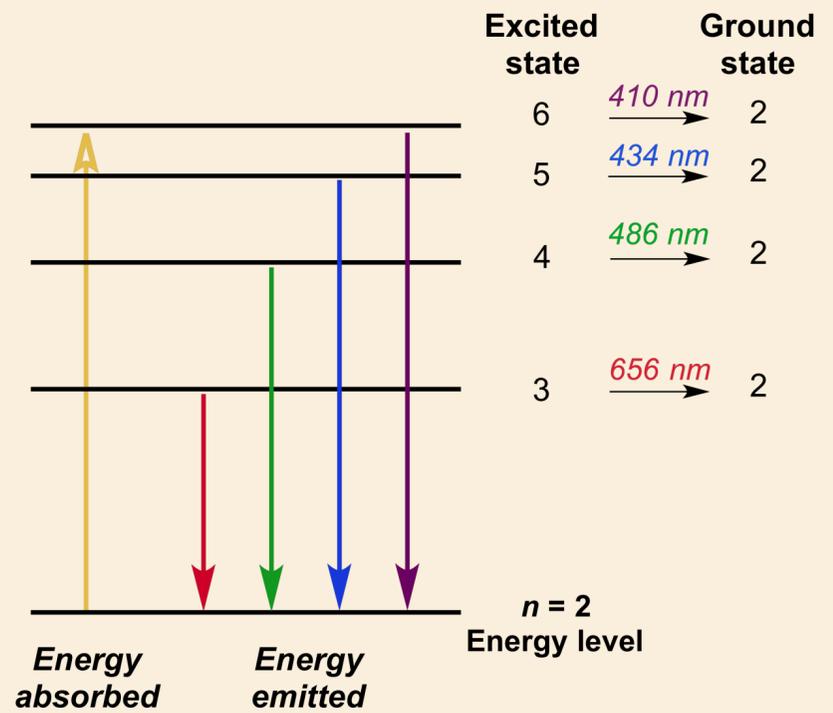
Quick Introduction to just enough Quantum Mechanics (QC Algorithms are very involved - so we'll learn the basics)

Important concepts of Quantum Mechanics

- States - A system is in a state with an energy. The ground state is the state with the lowest energy. Changing states requires absorbing or emitting a specific amount of energy.
- For example, electron levels in a Hydrogen atom



<http://bit.ly/2YpBQVV>

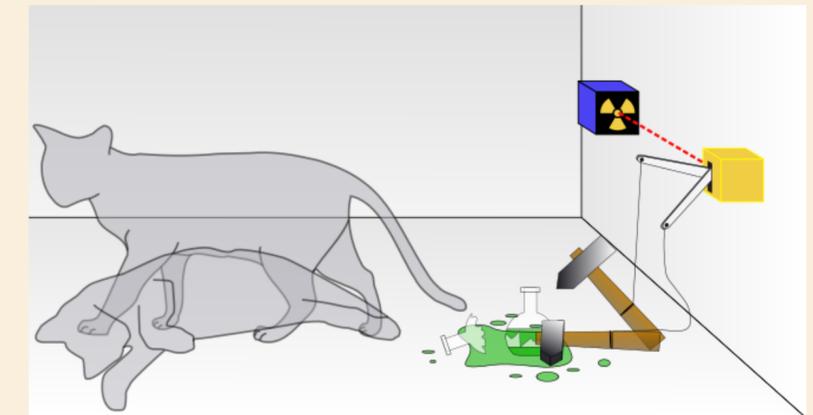
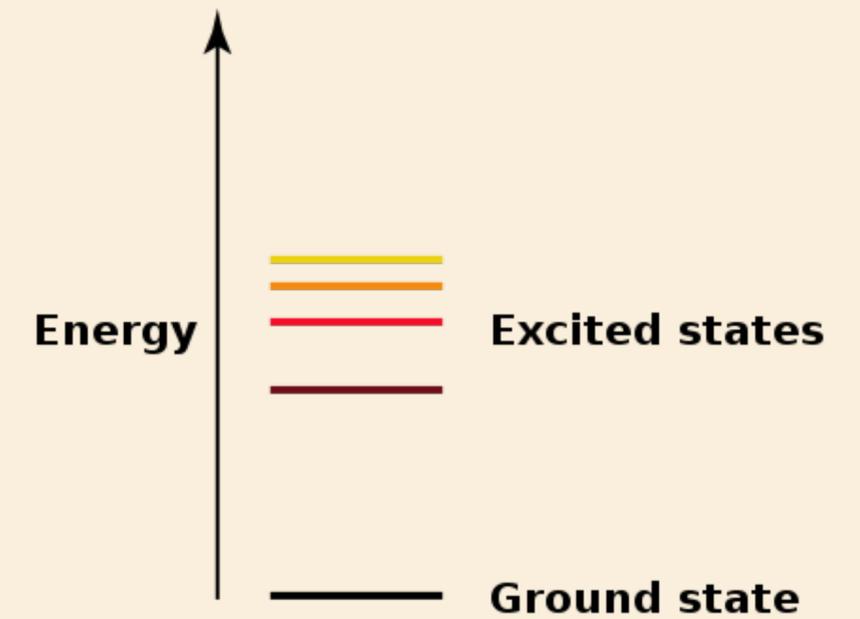


<http://bit.ly/2YkKyoh>

<http://bit.ly/2JZzgwX>

Important concepts of Quantum Mechanics

- **States** - A system is in a state with an energy. The ground state is the state with the lowest energy. Changing states requires absorbing or emitting a specific amount of energy.
- **Superposition of states** - A system can be in more than one state **AT THE SAME TIME** [strange!] Each possible state has an associated amplitude
- The sum of all the possible states is the *wave function* $|\psi\rangle = \alpha |\mathbf{dead}\rangle + \beta |\mathbf{alive}\rangle$
- Upon measurement, you will observe **ONE** state. QM can tell us its probability e.g. Open the box and you'll see the cat alive with probability β^2



<http://bit.ly/2K2NLzD>

Quantum Mechanics

- The probability of *observing* a system in a particular state is that state's **|amplitude|²**

- Note: Probabilities follow certain rules...**

$P(\text{rain}) \geq 0, P(\text{no rain}) \geq 0$ Negative makes no sense

$P(\text{rain}) + P(\text{no rain}) = 1$ Something must happen

- The only rule amplitudes must follow is**

$|\alpha|^2 + |\beta|^2 = 1$ Something must happen

Miami, FL 5 Day Weather
11:30 pm EDT [Print](#)

DAY	DESCRIPTION	HIGH / LOW	PRECIP
TONIGHT JUL 23	 Partly Cloudy	--/78°	↓ 20%
WED JUL 24	 PM Thunderstorms	91°/78°	↓ 50%
THU JUL 25	 PM Thunderstorms	89°/78°	↓ 80%
FRI JUL 26	 PM Thunderstorms	89°/80°	↓ 40%
SAT JUL 27	 Scattered Thunderstorms	88°/80°	↓ 40%
SUN JUL 28	 Scattered Thunderstorms	88°/79°	↓ 40%

- Amplitudes can be positive or negative. They can be real or complex**

This is valid... $|\psi\rangle = \frac{1}{2}|0\rangle - \frac{i\sqrt{3}}{2}|1\rangle$ **if measure we'll see** $P(0) = \frac{1}{4}; P(1) = \frac{3}{4}$

Quantum Interference

The fact that amplitudes can be positive or negative and real or complex means that states can interfere. Famous example is the double slit experiment

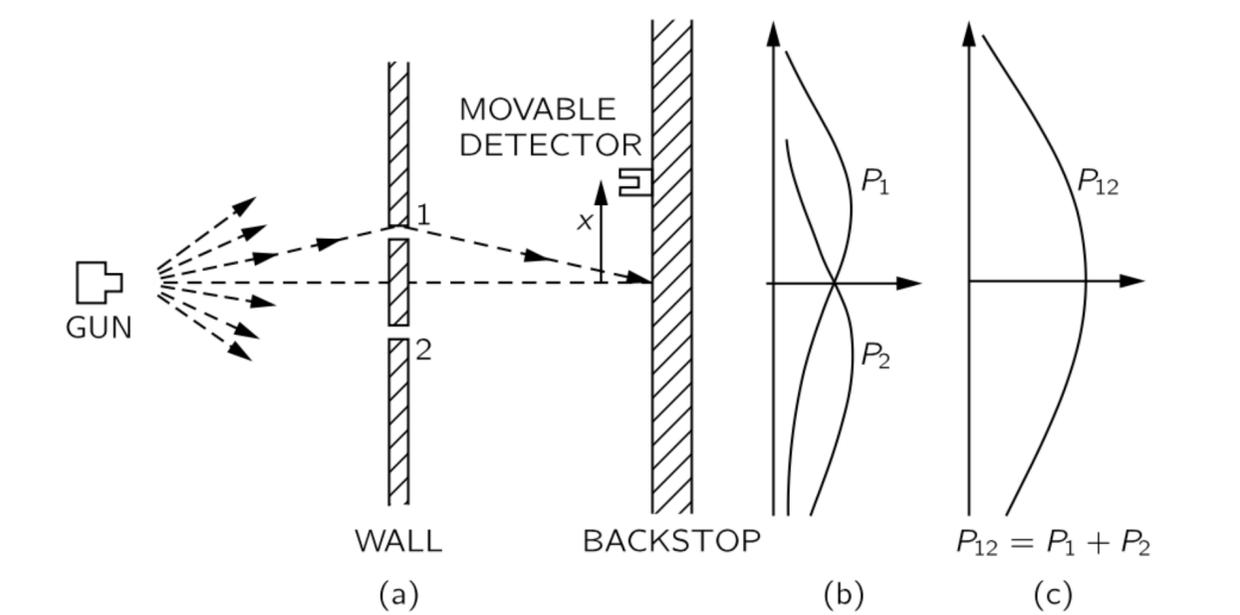


Fig. 1-1. Interference experiment with pellets.

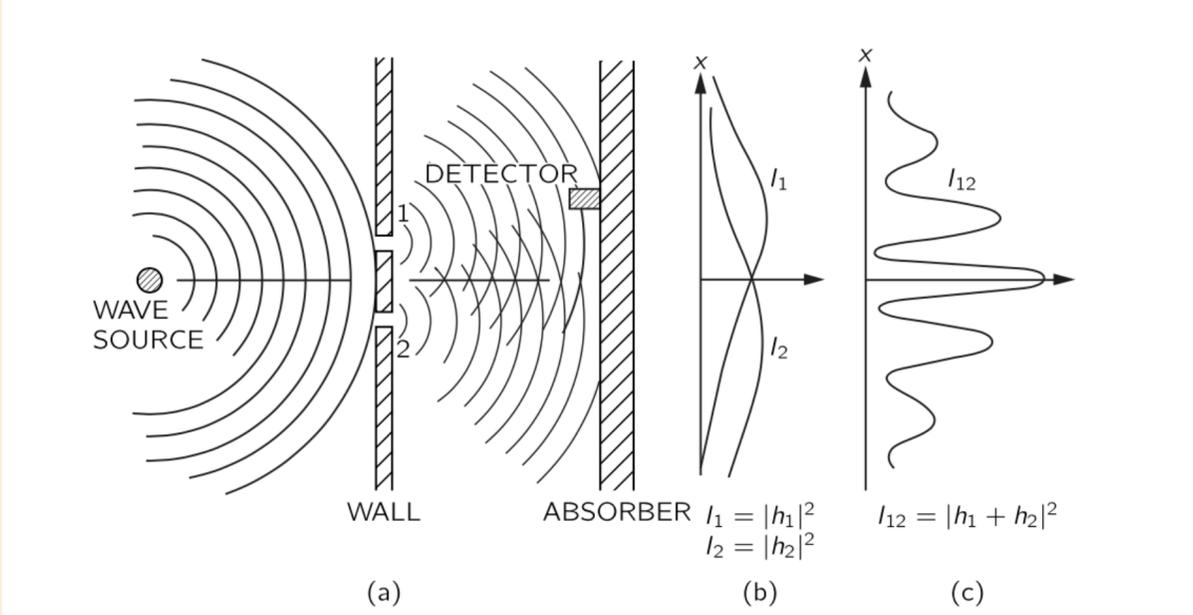


Fig. 1-2. Interference experiment with water waves.

http://www.feynmanlectures.caltech.edu/III_01.html#Ch1-S1

Qubit

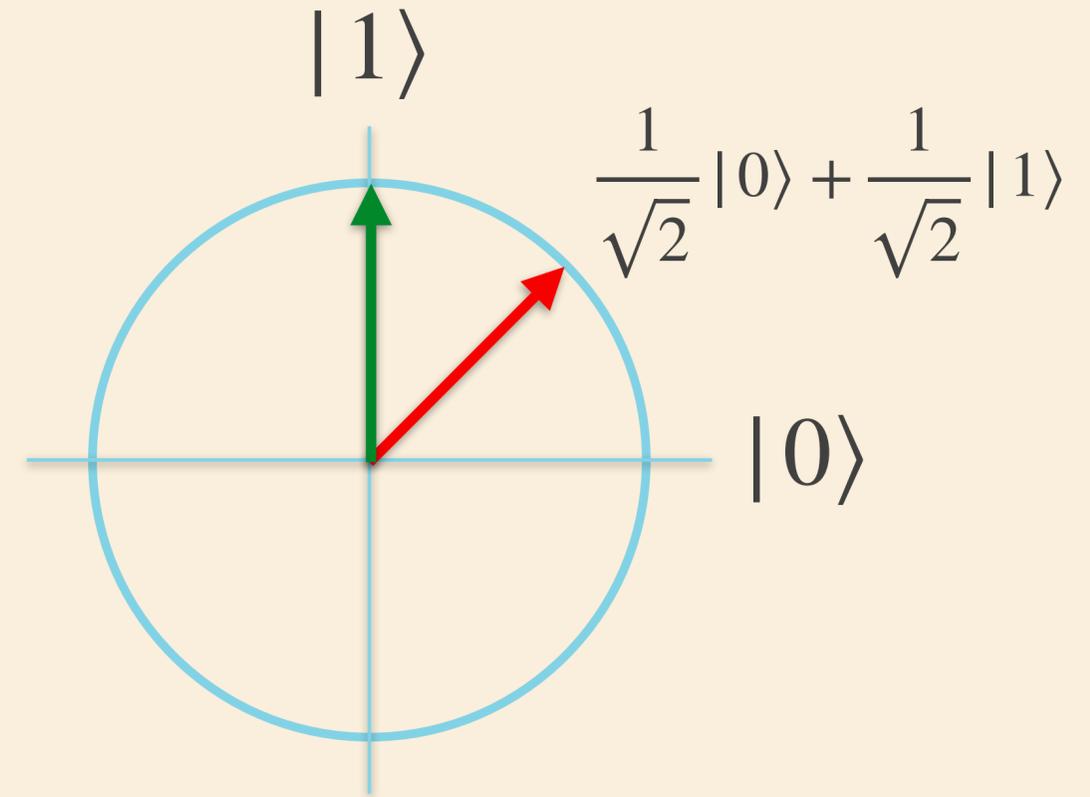
Unlike a classical bit (0/1), a qubit can be in a **SUPERPOSITION** of $|0\rangle$ and $|1\rangle$

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

When we observe (or measure) the qubit, we see it in either $|0\rangle$ or $|1\rangle$ with probability given by the amplitudes

e.g. For green, we will always observe $|1\rangle$

e.g. For red, we'll see $|0\rangle$ with 50% prob and $|1\rangle$ with 50% prob



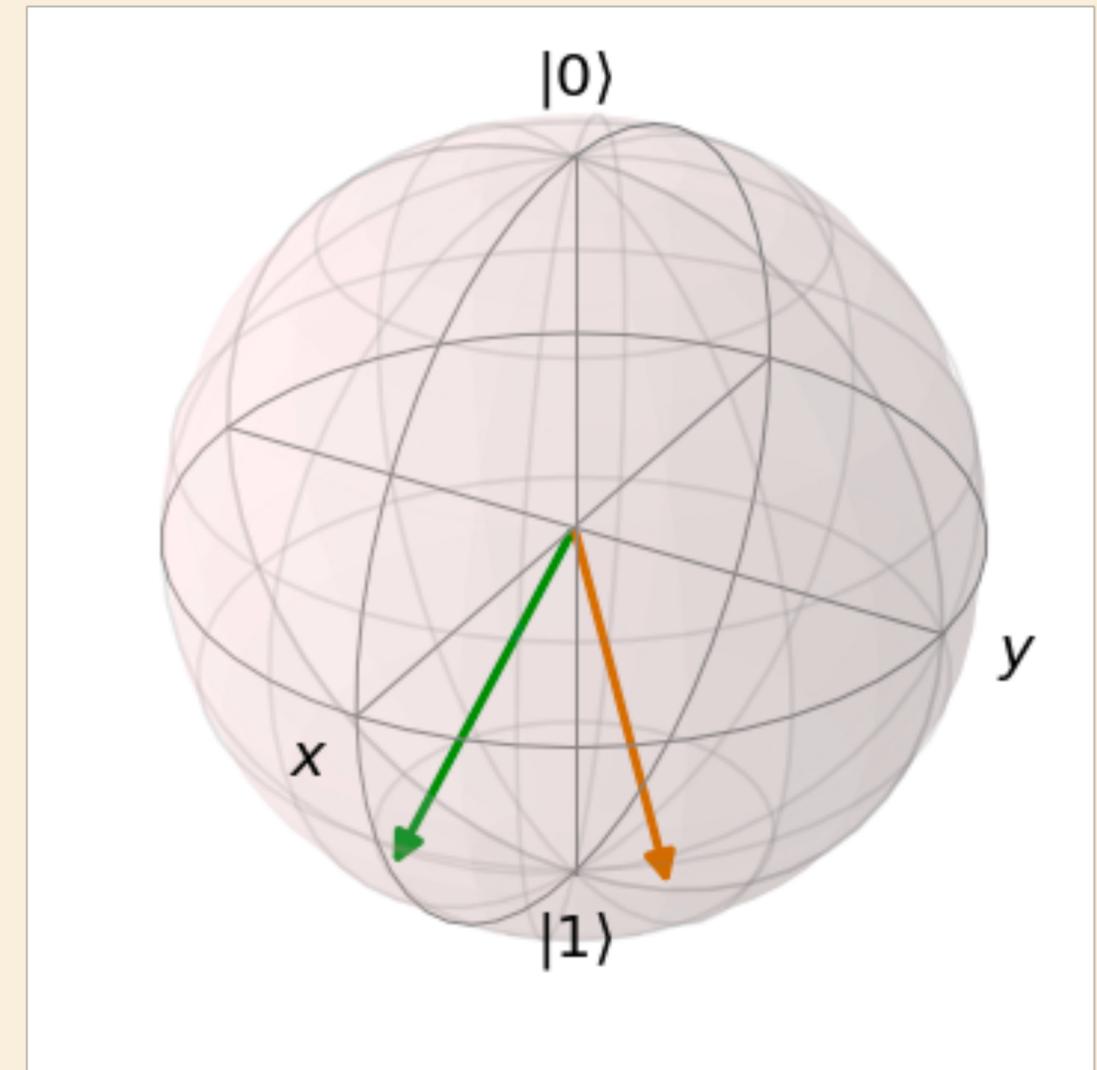
For red, if we do this “experiment” many times, we’ll see $|0\rangle$ half the time and $|1\rangle$ half the time

Bloch spheres

Actually, the circle representation is simplistic. Since amplitudes can be complex, there's another dimension... we use a "Bloch" sphere

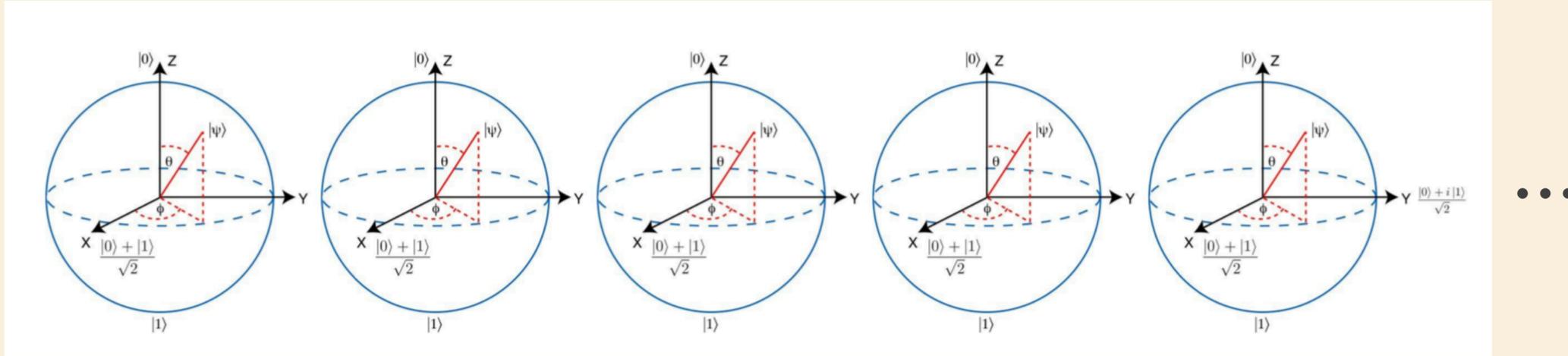
$$|\psi\rangle = \frac{1}{2}|0\rangle + \frac{\sqrt{3}}{2}|1\rangle; \quad P(0) = \frac{1}{4}; P(1) = \frac{3}{4}$$

$$|\psi\rangle = \frac{1}{2}|0\rangle + \sqrt{\frac{3}{8}}(1+i)|1\rangle; \quad P(0) = \frac{1}{4}; P(1) = \frac{3}{4}$$



Quantum Information

You can have many qubits (IBM has a 53 qubit machine; Google has a 53 qubit)



Wave function is the sum of all states each with an amplitude

$$|\psi\rangle = a_0 |0\dots 00\rangle + a_1 |0\dots 01\rangle + a_2 |0\dots 10\rangle + \dots + a_k |1\dots 11\rangle$$

e.g. Three qubits $|\psi\rangle = \alpha_0 |000\rangle + \alpha_1 |001\rangle + \alpha_2 |010\rangle + \alpha_3 |011\rangle + \alpha_4 |100\rangle + \alpha_5 |101\rangle + \alpha_6 |110\rangle + \alpha_7 |111\rangle$

For n qubits, there are 2^n amplitudes (so $k = 2^n$)

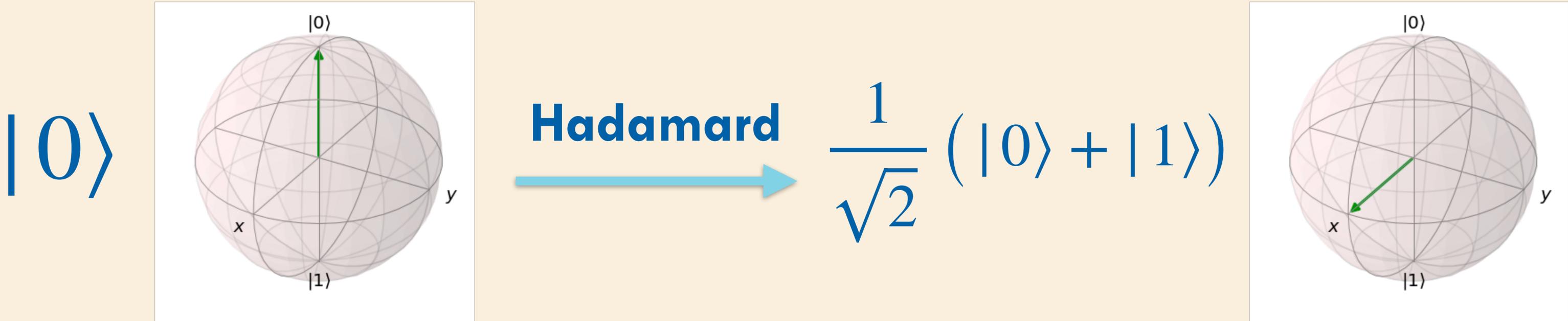
To write down the wave function for a 49 qubit computer, you need

$$2^{49} = 562,949,953,421,312 \text{ complex numbers (memory of a supercomputer)}$$

Quantum Computer Operations

Qubits can evolve and be manipulated without measuring them (**gate** operations):

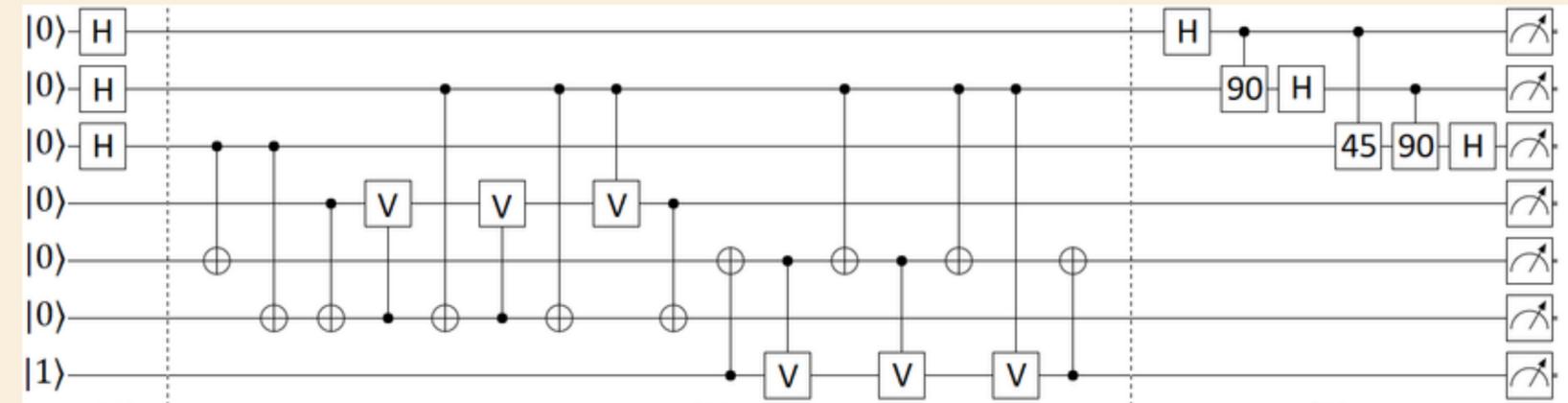
- Rotate state in the Bloch sphere ... for example put qubit in a superposition



- Entangle 2 or 3 qubits (e.g. make them dependent on each other)
- Measure one, some, or all of the qubits in the computer

How quantum algorithms work — General principals

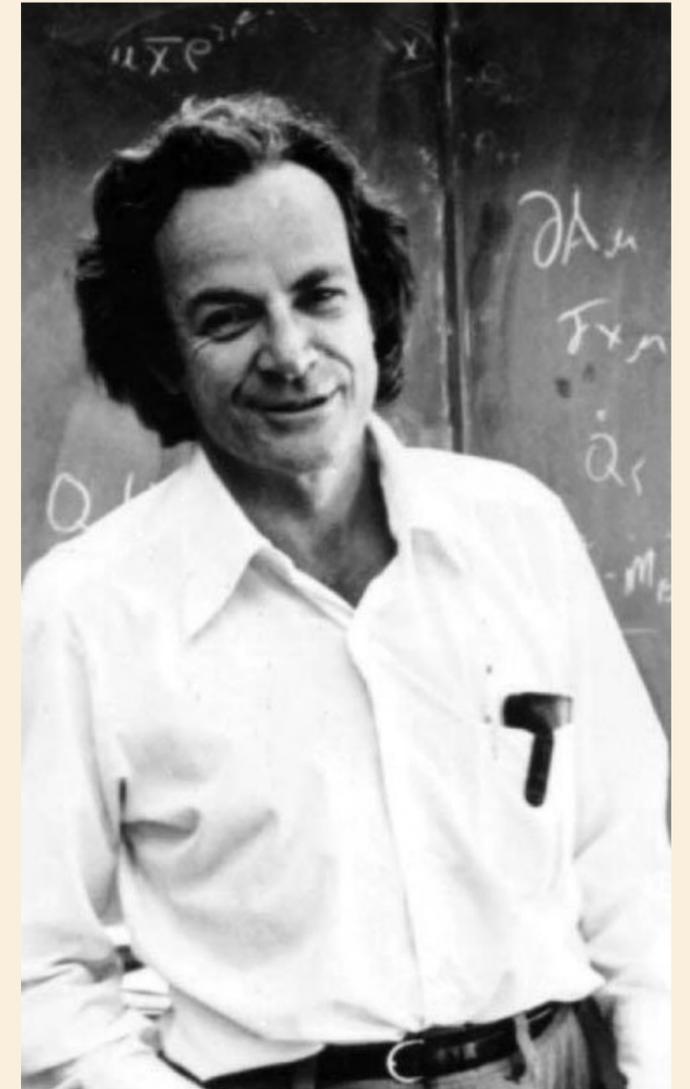
- Put the qubits in a superposition representing all the answers (right answers and wrong answers)



- If you measured the qubits now, you would randomly get a right answer or a wrong answer ... that doesn't help! [Parallel computing in multiple universes is a misconception]
- Exploit Quantum **Interference**: Manipulate the qubits to “choreograph the amplitudes” [Scott Aaronson] so that paths to the wrongs answers cancel out and paths to the right answers reinforce
- Hopefully, when you measure the qubits, the probability of observing the right answer is high and probability of observing a wrong answer is low
- In practice this is very difficult and algorithms are very complicated — almost always named after the inventor — if you want to try an algorithm, go to <https://github.com/lyon-fnal/qc-tutorial-fnal>

So what's all this good for?

- This is all crazy ... but it's how Nature WORKS!
- But aside from factoring numbers, what can you do with it?
- Richard Feynman (1981) was one of the originators of QC:
“...because nature isn't classical, ..., and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy”
- Qubits are like artificial atoms that can be controlled.
Simulate nature in a quantum mechanical way



Example application

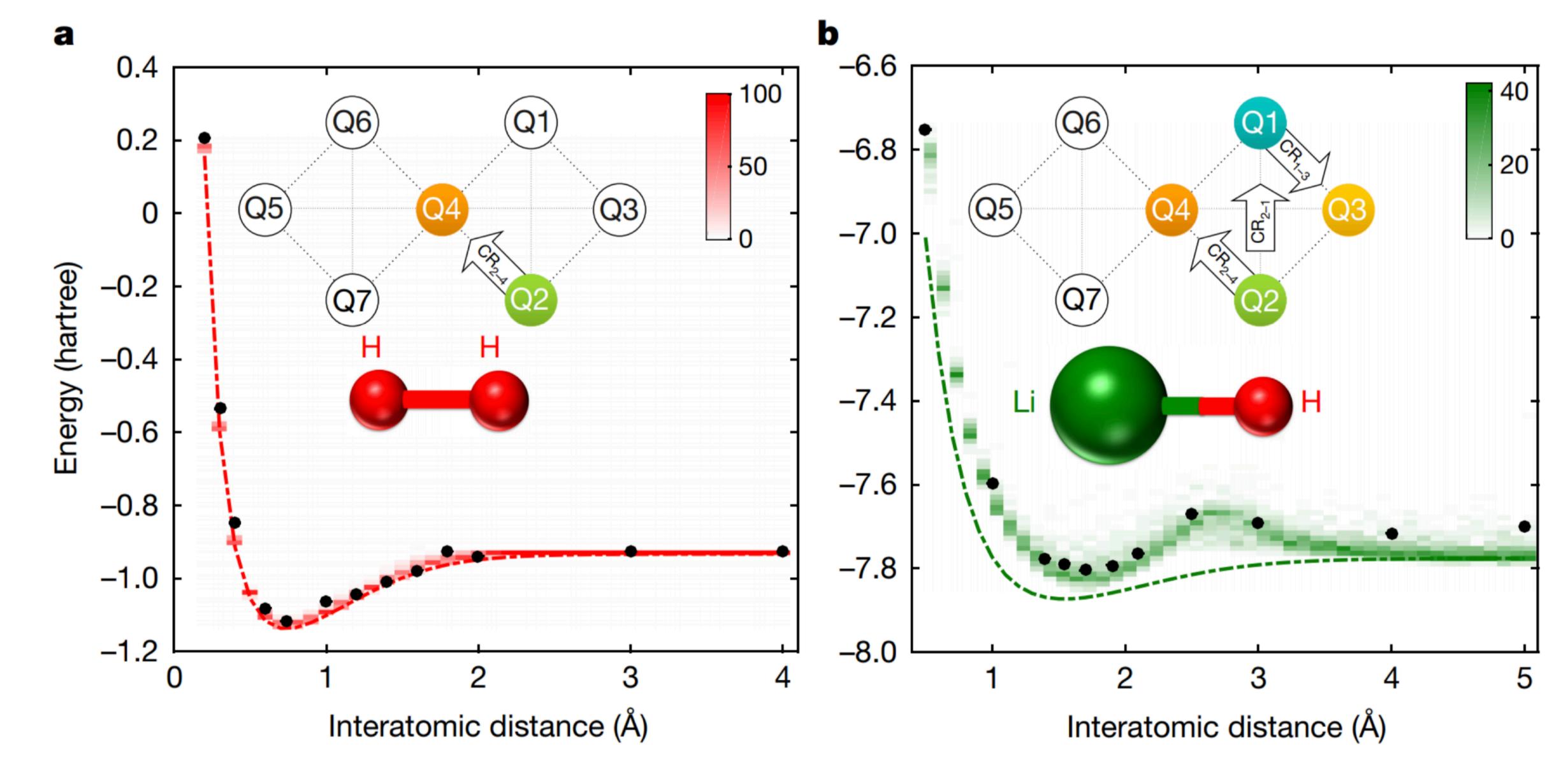
Nature 549.7671 (2017) 242.

IBM 6 Qubit Device

Find ground state energy vs. interatomic distance

$$H|\Phi\rangle = E_G|\Phi\rangle$$

Hard to solve on classical Computers



Variational Quantum Eigensolver (VQE) - hybrid classical/quantum algorithm

Mismatch and kink in Li-H due to noise and low circuit depth

Why is Fermilab Involved?

- **Fermi National Accelerator Laboratory**
- **America's particle physics and accelerator laboratory**
- **A single purpose lab for High Energy Physics**

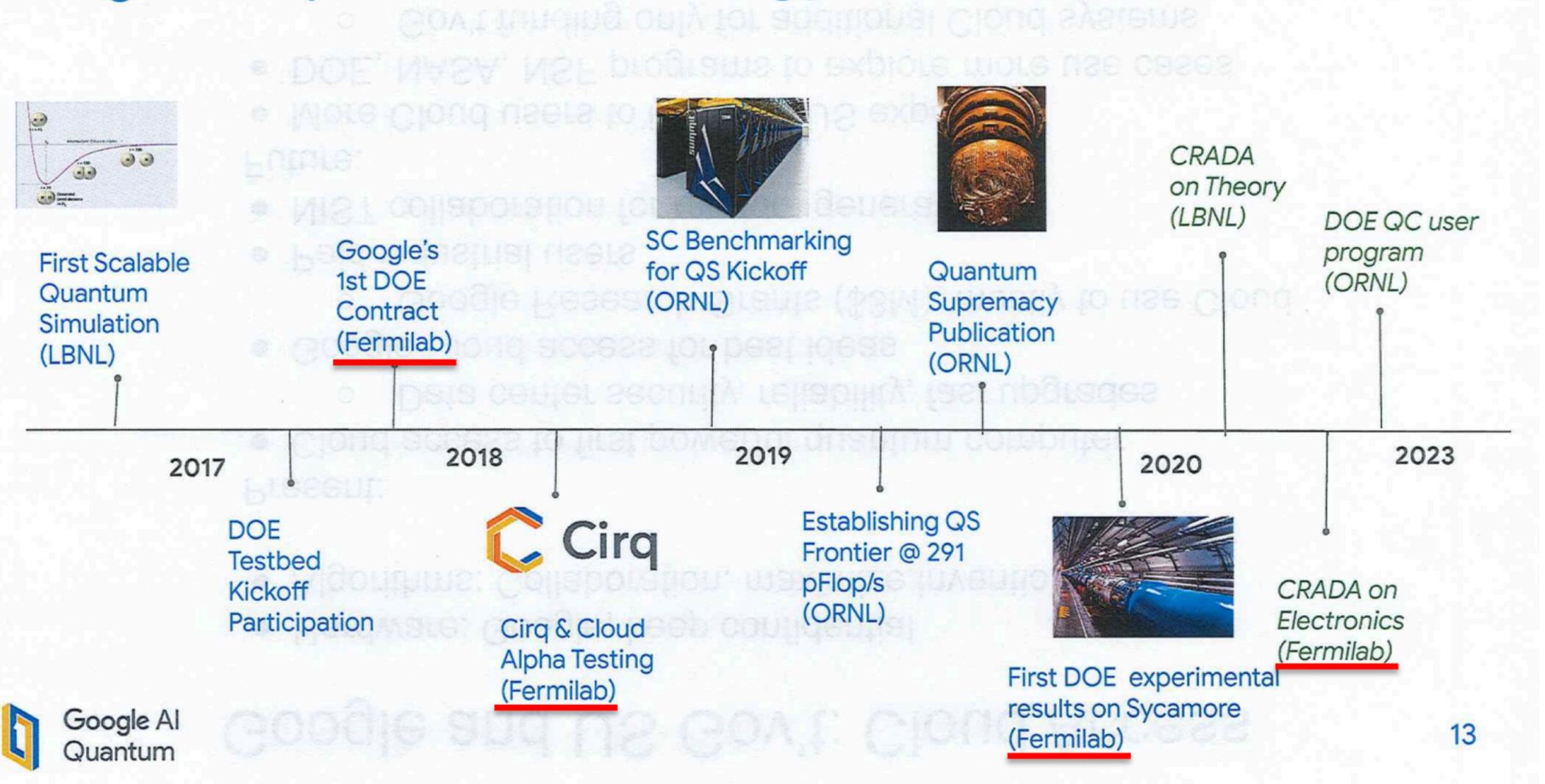


- **We've learned that Quantum Information Science (QIS) can impact HEP and HEP can impact QIS**
- **Guiding Principle: Focus on the science**
- **Quantum program aligns with HEP program needs. Fermilab has 16 funded QIS projects**

We also have strong relationships with industry

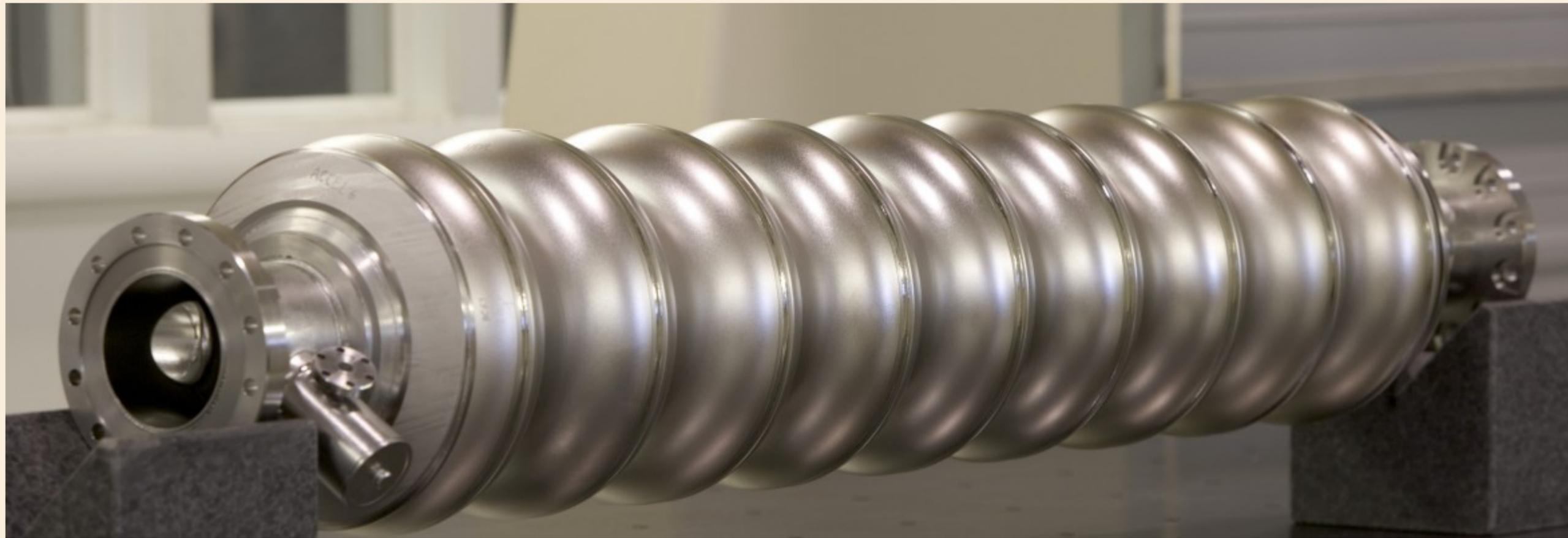
White House briefing on Google quantum supremacy result 10/22/19

Google / Department of Energy Collaboration Timeline



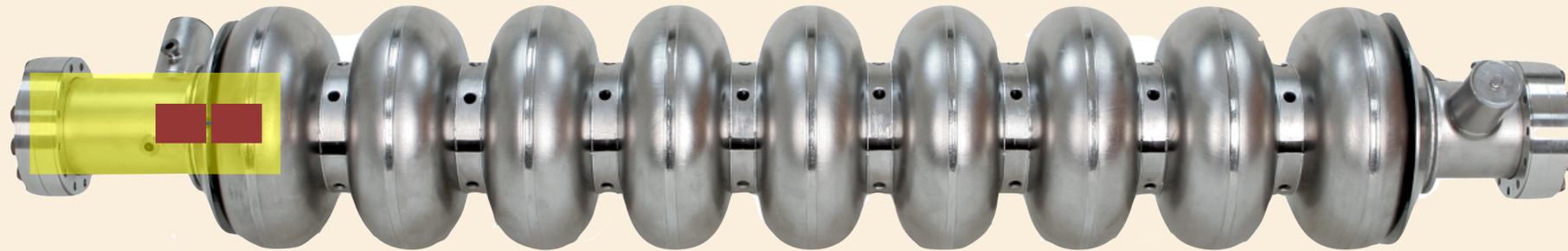
1 Superconducting Technology for Quantum

- Fermilab is a world leader in superconducting RF (SRF) cavities for particle accelerators; LCLS-II (X-ray Laser at SLAC); PIP-II (New LINAC at Fermilab)
- Reached unprecedented “Q” factor based on our SRF R&D program

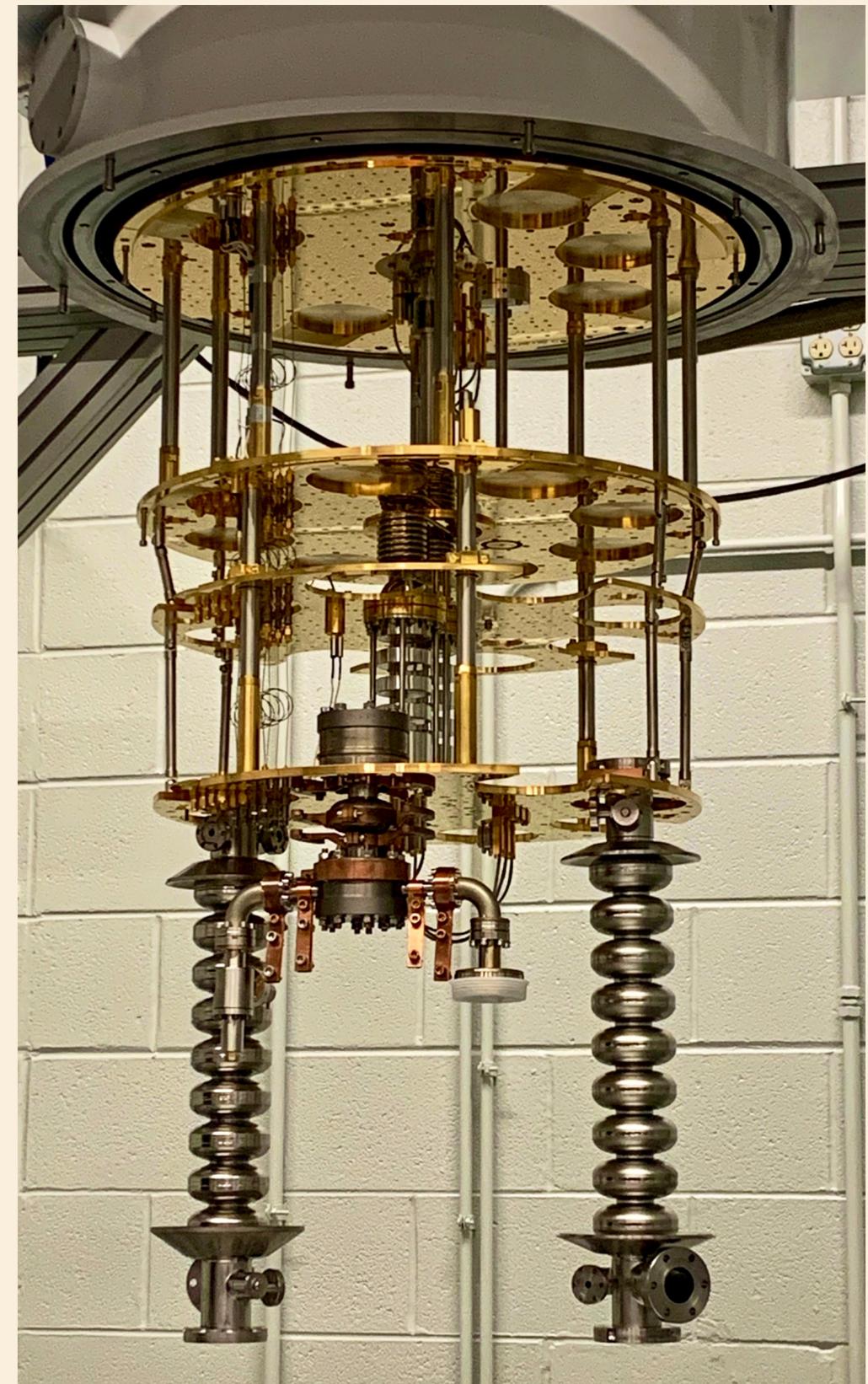


1 Superconducting Technology for Quantum

- SRF Cavity technology may be used for quantum computing devices



- Very high Q leads to very long coherence time - unique to Fermilab
- Multi-level nature of 3D cavities (qudits) effectively act as many qubits
- Many cavities (e.g. in a string) may be entangled
- This would be a very special Quantum Computer
Under experiment now! I'm leading a small project with Argonne to do classical simulations of this device - will need a supercomputer



2 Quantum Computing Applications

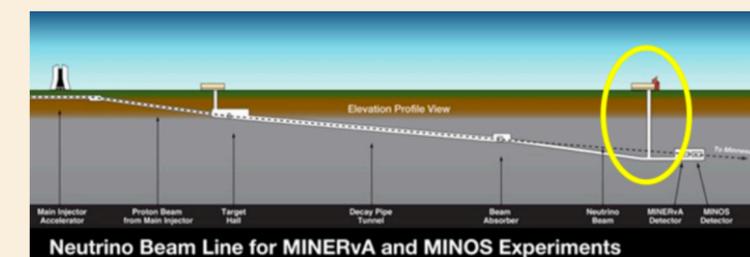
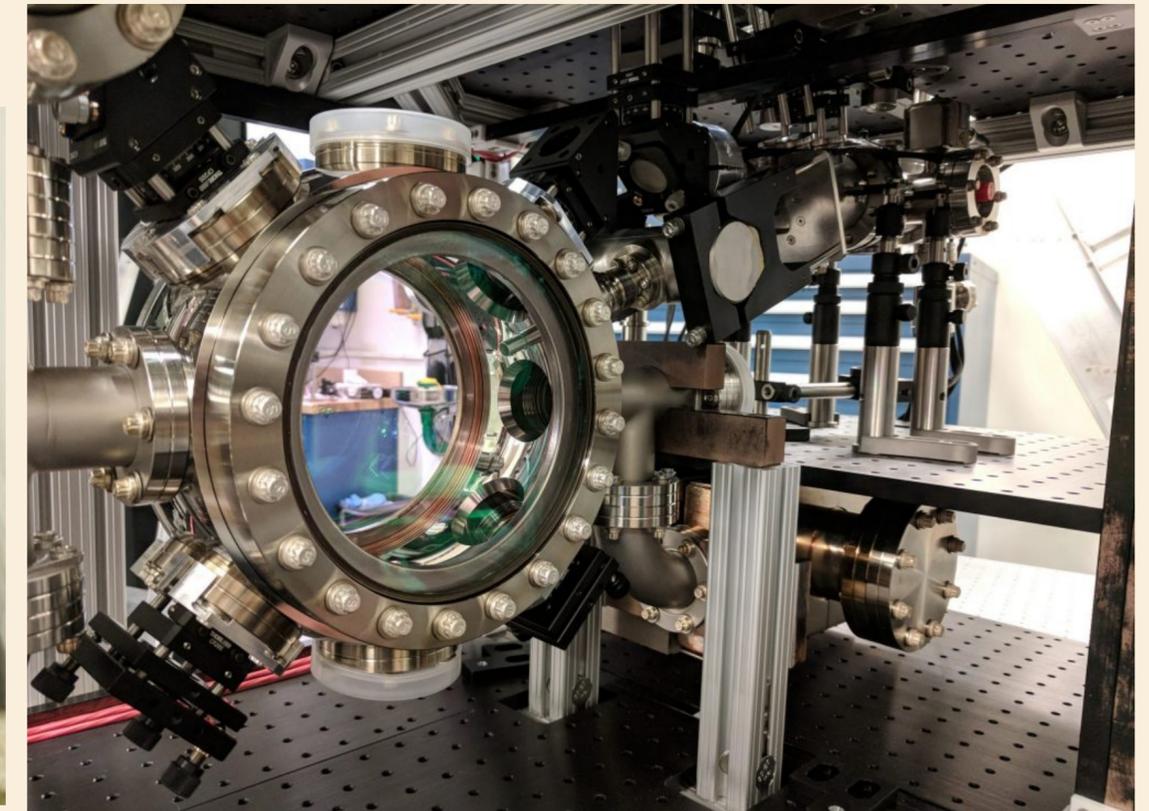
- **Quantum Optimization and Machine Learning**
 - Solve optimization problems (one day: fitting, pattern matching, etc)
 - Improve hadronization in LHC physics simulations
- **Theory advances**
 - Directly simulate processes in Quantum Field Theory
 - Simulate aspects of early universe physics
 - Simulation Boson interactions (hard)
- **Algorithm and “coding” advances**
 - Hybrid classical/quantum algorithms
 - Novel gate designs
 - Optimal control of a quantum computing device



3 Quantum Sensing

- Axion searches (ADMX) - big magnet to convert dark matter into photons inside an ultra-cold microwave cavity. Photons oscillate at a particular energy based on axion mass. Tune cavity frequency to match - read it out

- **MAGIS-100**
Drop cold atoms down a 100' shaft (MINOS) at vacuum to make an interferometer. (World's largest) Essentially, turns atoms into very spatially long quantum states sensitive to disturbances perhaps from gravitational waves and dark matter



4 Quantum Networking

Teleport quantum states with worlds first long range, high fidelity, high rate quantum communications system

Illinois Express Quantum Network (IEQNET) -
Fermilab, Argonne, Caltech, Northwestern

Leading up to a
Quantum Internet!

A huge national effort!





NATIONAL STRATEGIC OVERVIEW FOR QUANTUM INFORMATION SCIENCE

Product of the
SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE
under the
COMMITTEE ON SCIENCE
of the
NATIONAL SCIENCE & TECHNOLOGY COUNCIL
SEPTEMBER 2018

DEPARTMENT OF ENERGY
OFFICE OF SCIENCE



NATIONAL QUANTUM INFORMATION SCIENCE
RESEARCH CENTERS

FUNDING OPPORTUNITY ANNOUNCEMENT (FOA) NUMBER:
DE-FOA-0002253

- **\$25M/yr for 5 years for 2-5 DOE office of Science QIS centers**
- **To be funded this fiscal year!**
- **Proposals due in April!**

Summary

- **The potential for Quantum Computing has generated enormous hype**
- **Quantum computers offer a different approach to computation**
- **There are problems that are hard for classical computers but may be easy for quantum computers**
- **Fermilab is leveraging its HEP program to contribute to QIS and leveraging QIS to enhance its HEP program**
- **Quantum Computing devices that kinda do stuff (only useful to learn more about Quantum Computing) are only the beginning. It will take A LOT OF work to get to QC that's useful for the greater world. But this effort is underway with much support!**

Backup Backup Backup Backup Backup Backup Backup Backup Backup



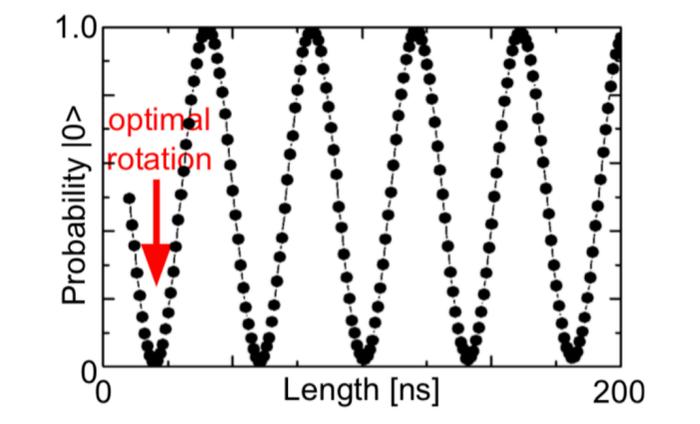
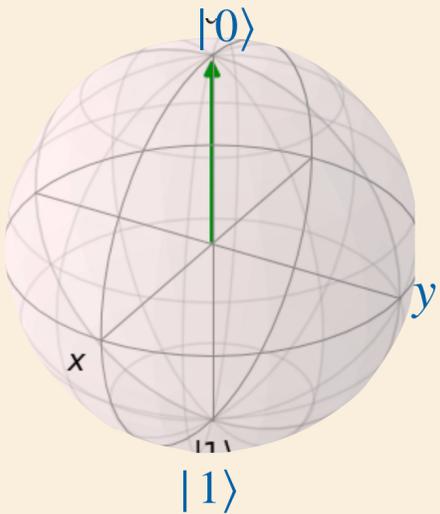
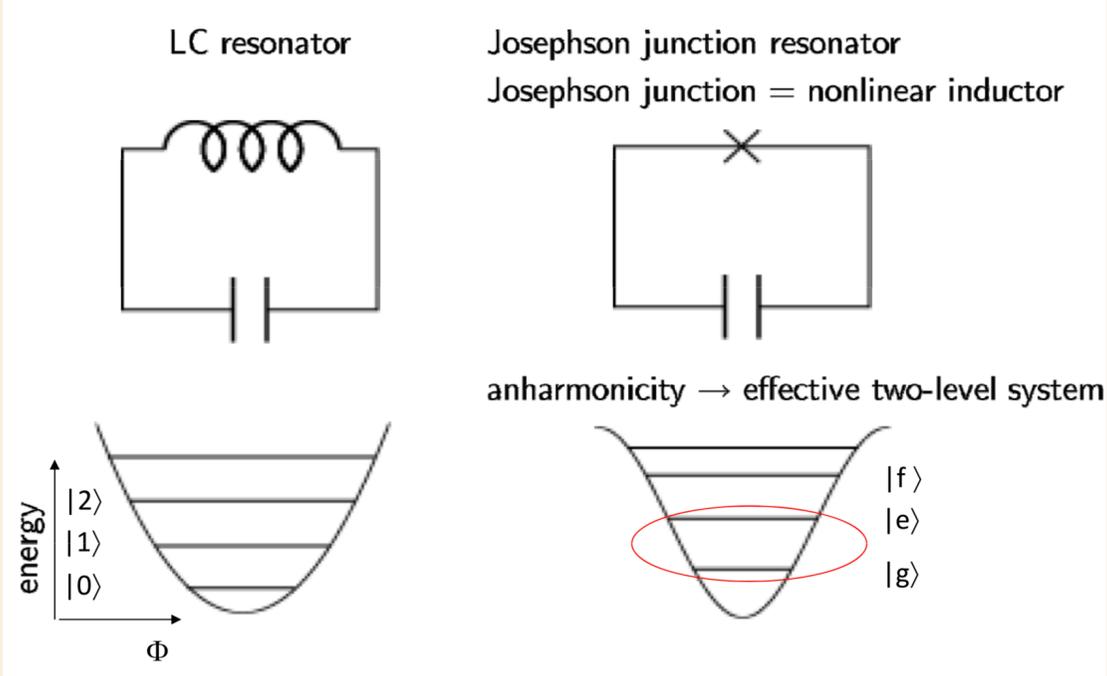
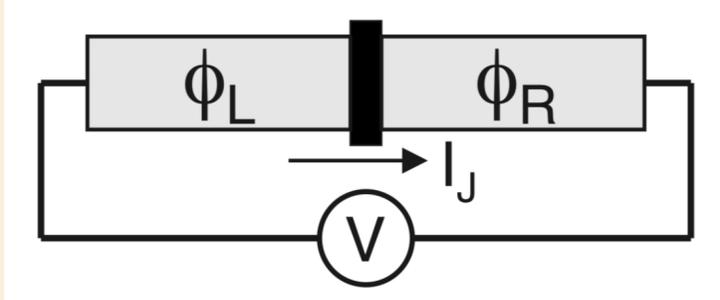
How do we make a quantum computer?

- **Requirements**

- Qubits need some kind of physical representation and maintain quantum properties
- We must be able to manipulate their quantum evolution (e.g. a transistor works by QM, but isn't a qubit)
- We must be able to prepare their initial states and measure their final states

- **Superconducting Qubits (artificial atoms)**

- Super-current tunnels through barrier between two superconductors
- Combined with a capacitor — make a resonator
- Josephson junction provides non-linearity to make anharmonic oscillator — usable 2 level system!
- Microwave pulses rotate qubit about the Bloch Sphere:
 - Frequency is energy level difference, Axis selected by amplitude modulation, Angle set by pulse duration

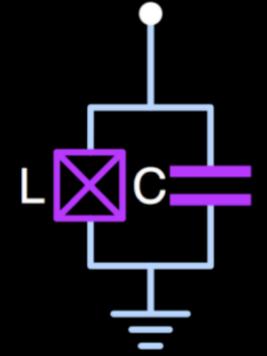
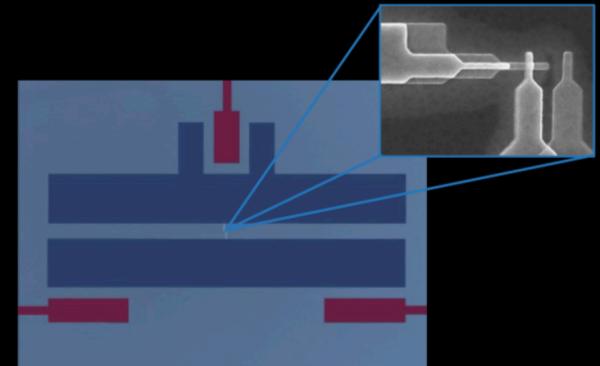


What do they look like (deep on the inside)?



Superconducting qubit

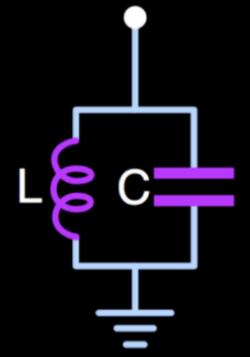
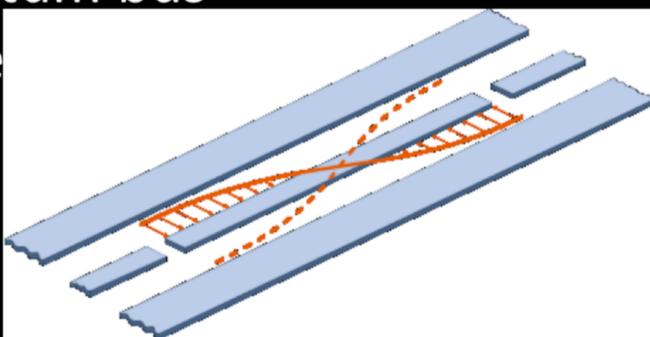
- quantum information carrier



$$E_{01} \approx 5 \text{ GHz} \approx 240 \text{ mK}$$

Microwave resonator:

- read-out of qubit states
- quantum bus
- noise



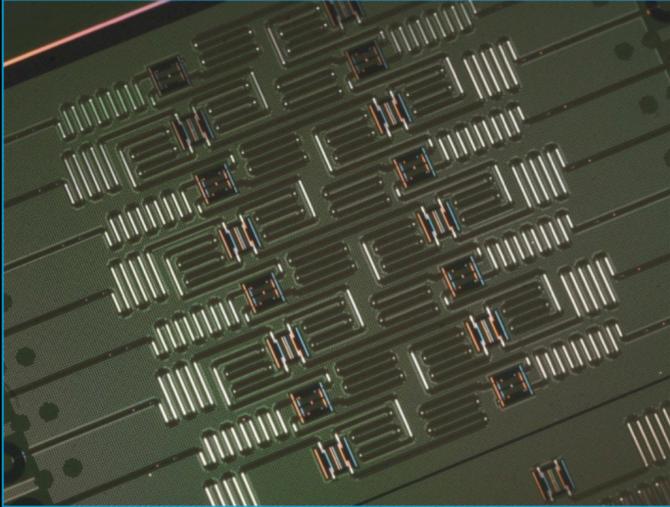
© 2018 International Business Machines Corporation – Stefan Filipp – sfi@zurich.ibm.com

What do they look like (deep on the inside)?

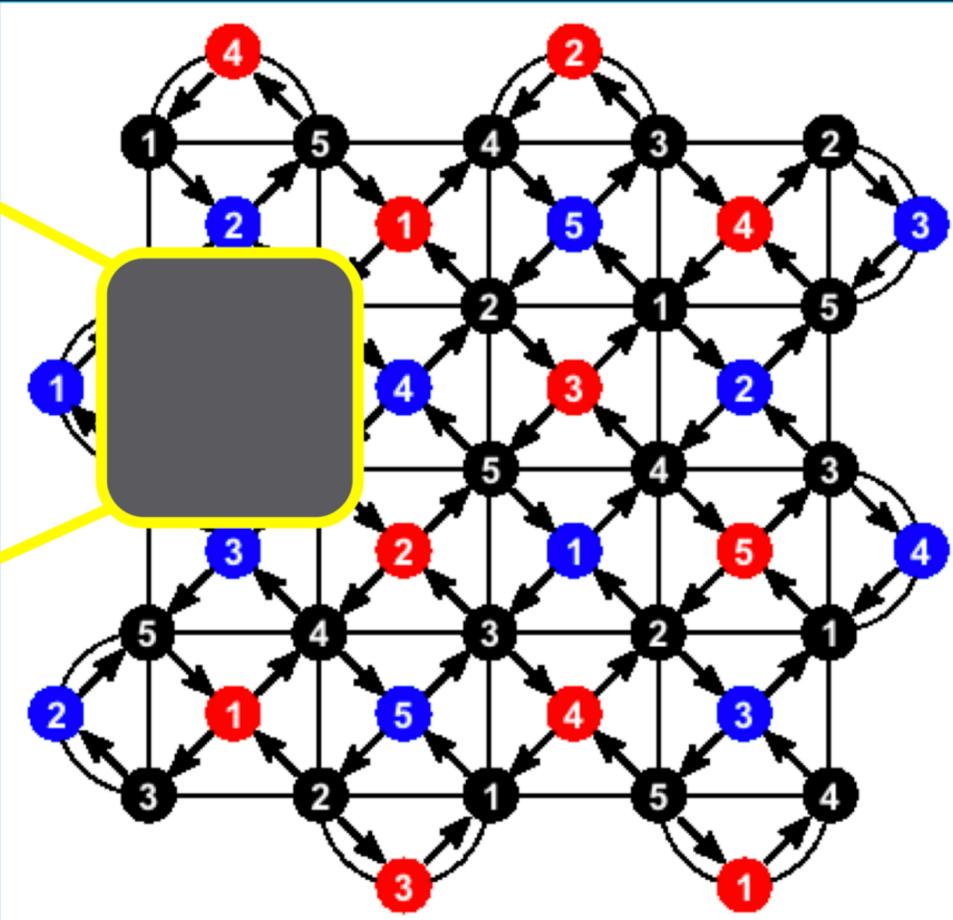
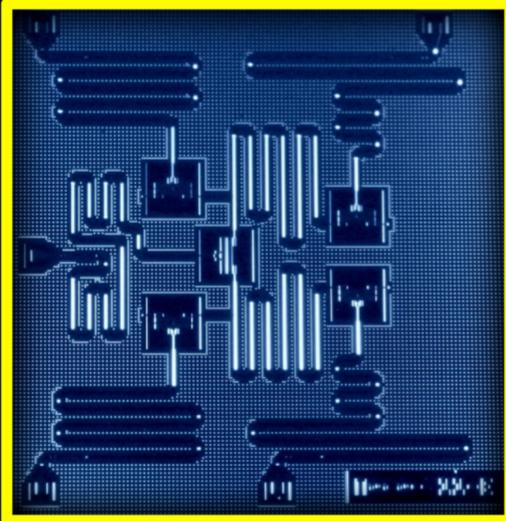
IBM qubit processor architectures

IBM Q experience (publicly accessible)

16 Qubits (2017)



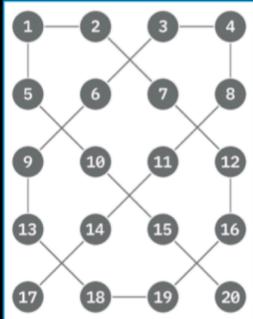
5 Qubits (2016)



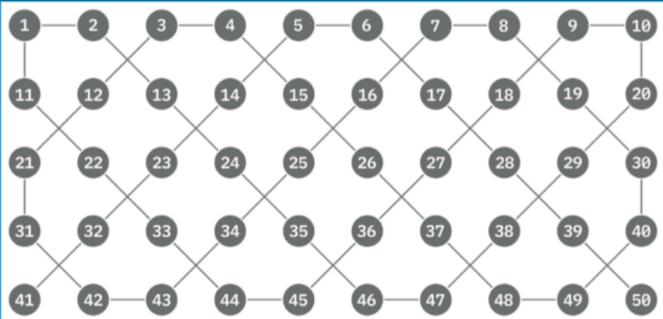
Latticed arrangement for scaling

IBM Q commercial

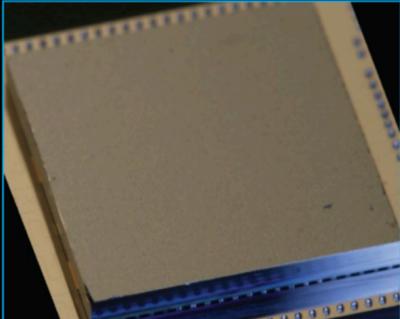
20 Qubits



50 Qubit architecture (2017)

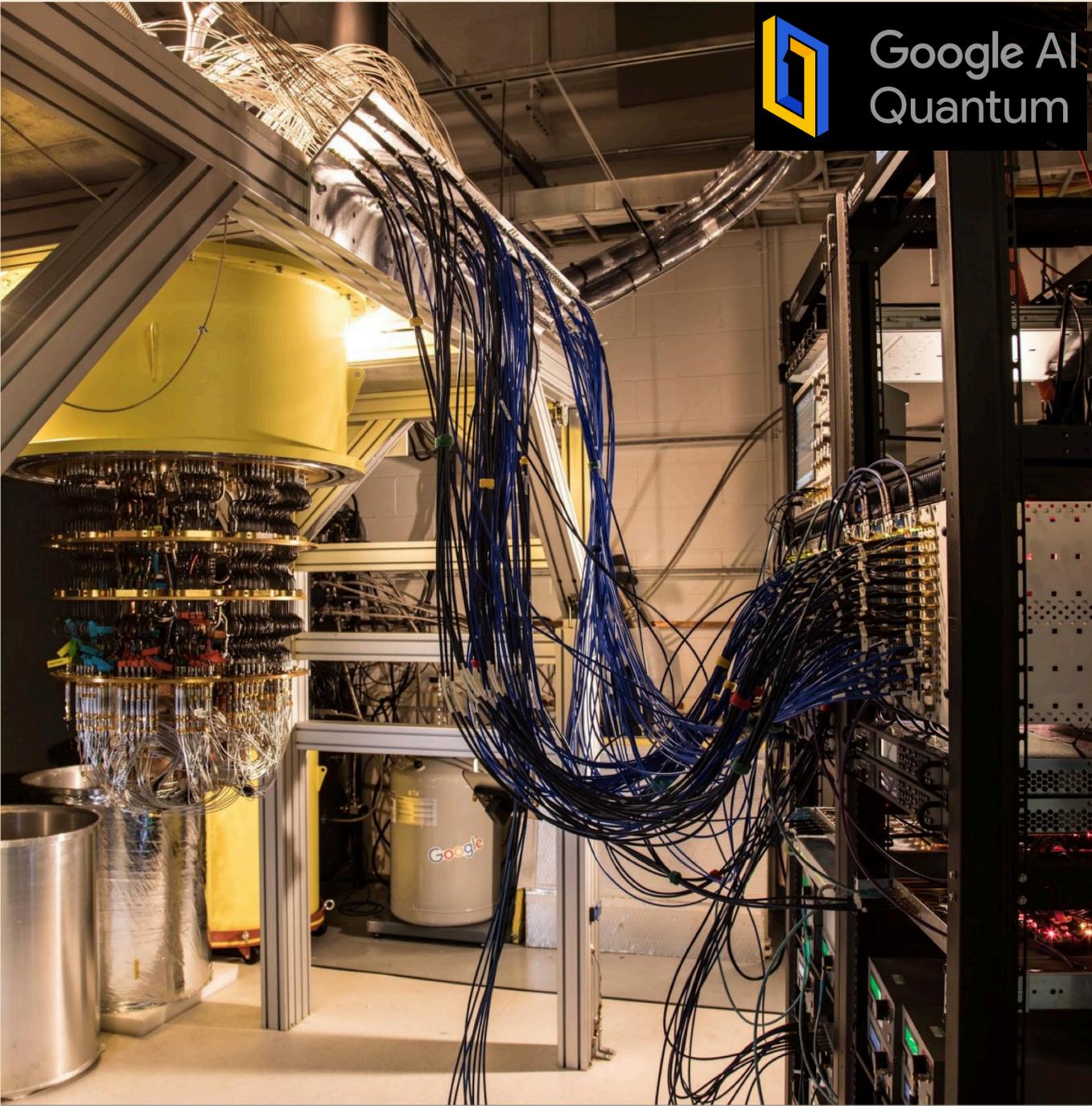


Package

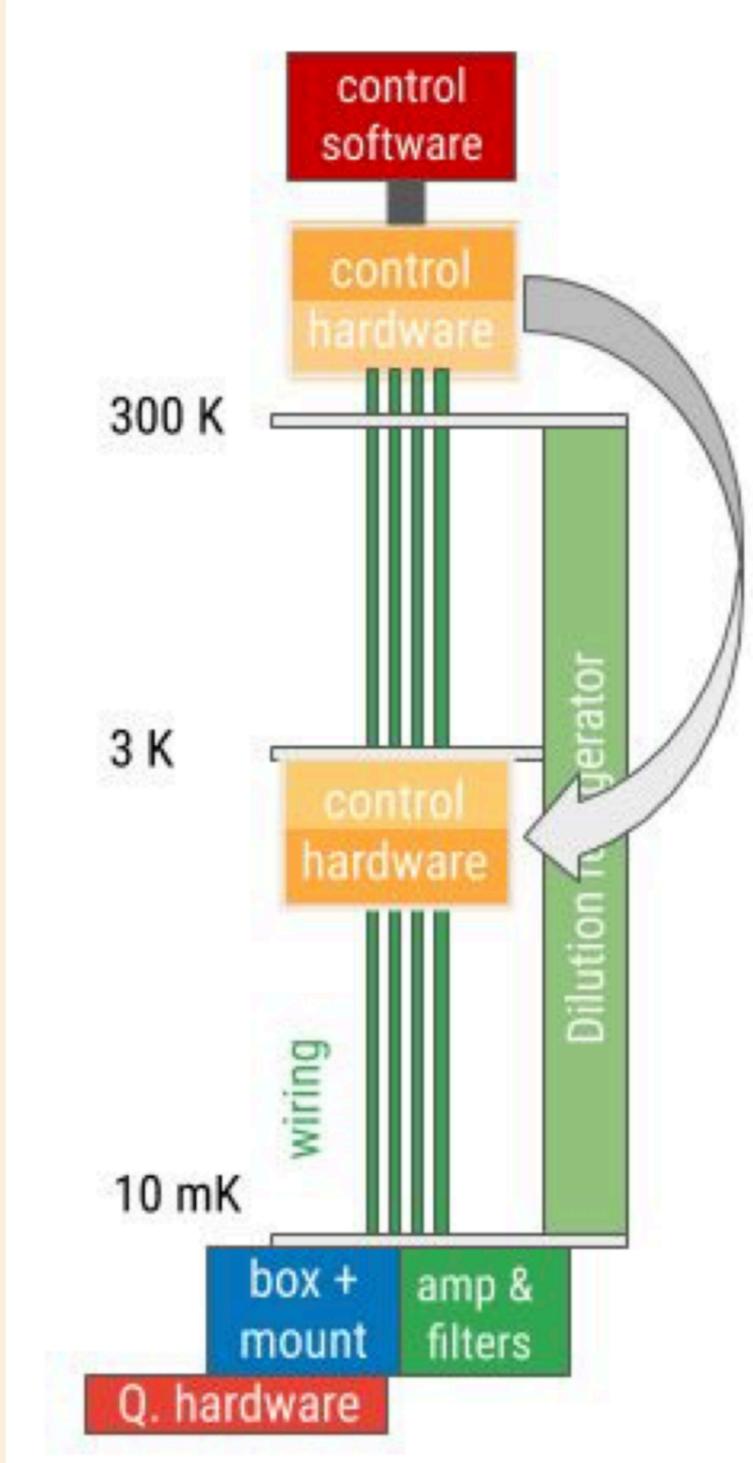


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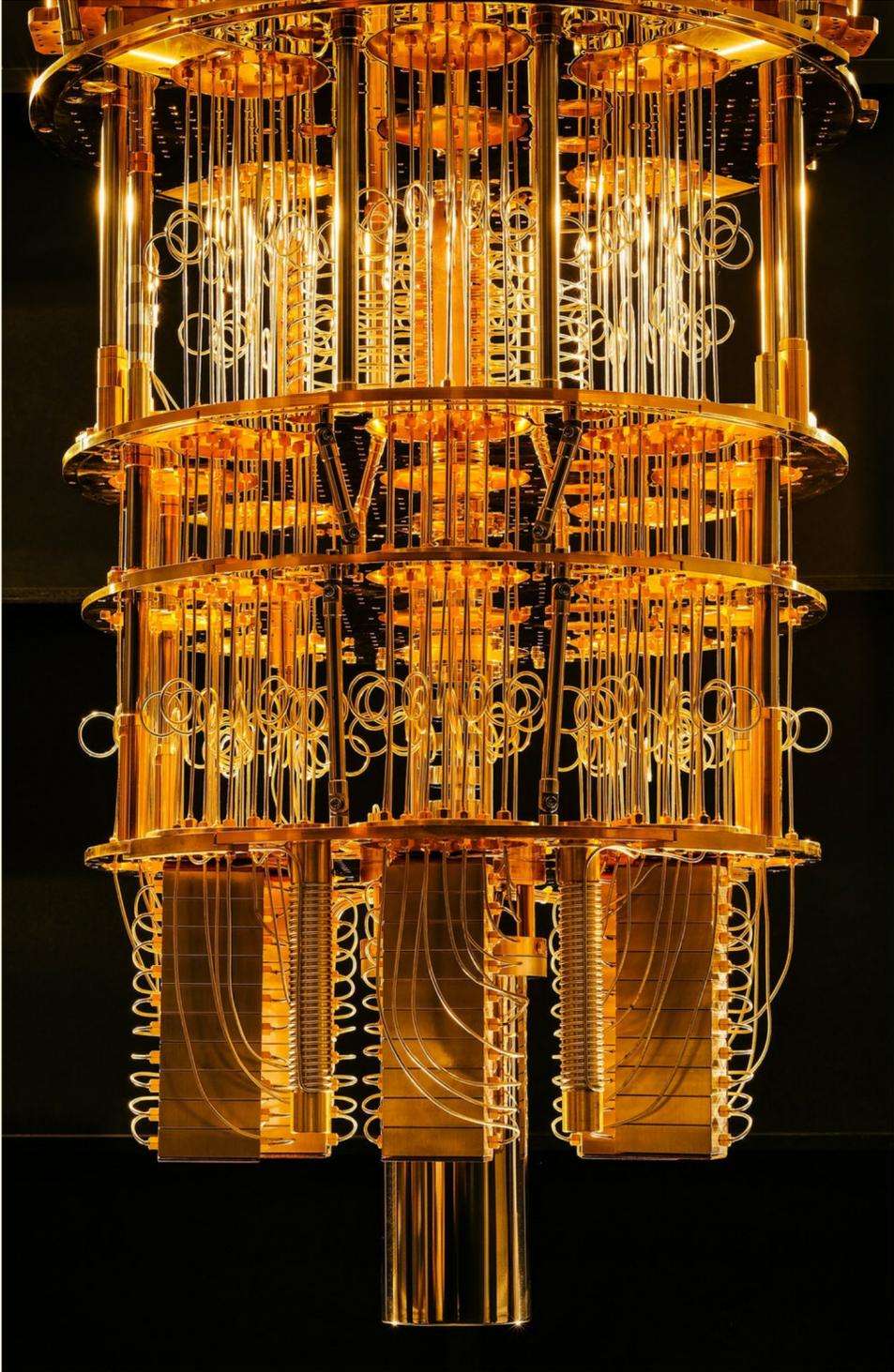
What do they look like (on the outside)?



What do they look like (under the hood)?



Credit: Google AI Quantum

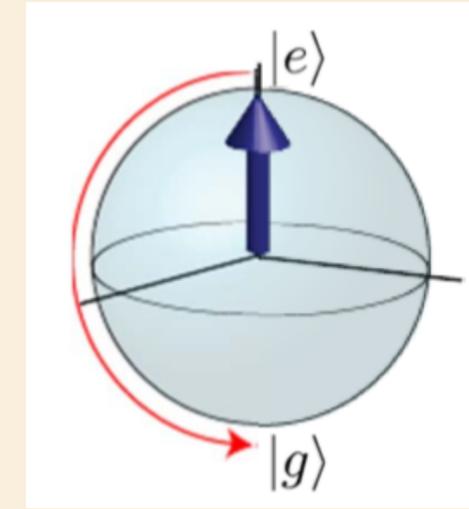


Limitations of Quantum Computers

All qubits have limitations:

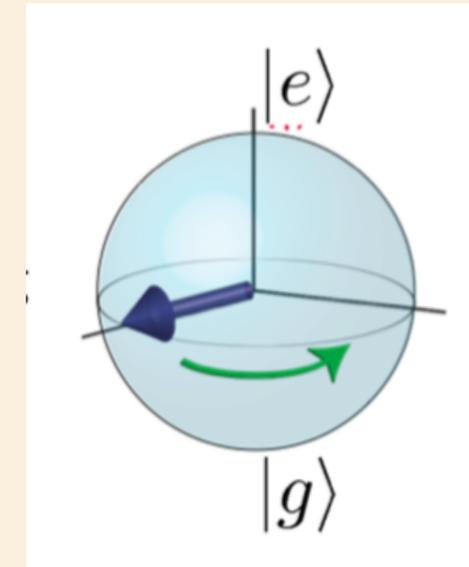
Qubit “relaxes” to the lower energy state

~ 60 micro-seconds



Any contact with the outside world (e.g. heat) “dephases”

~ 100 micro-seconds



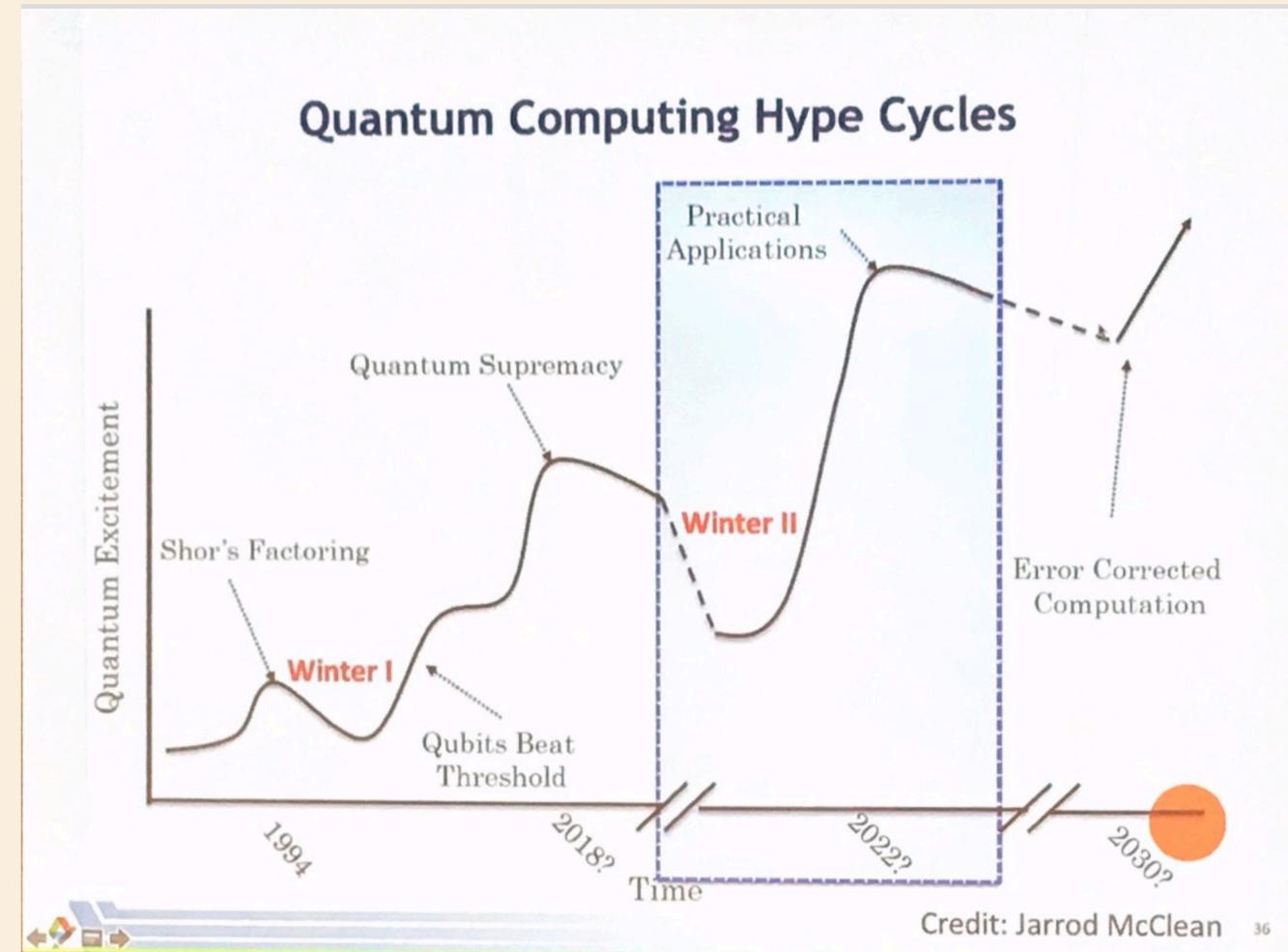
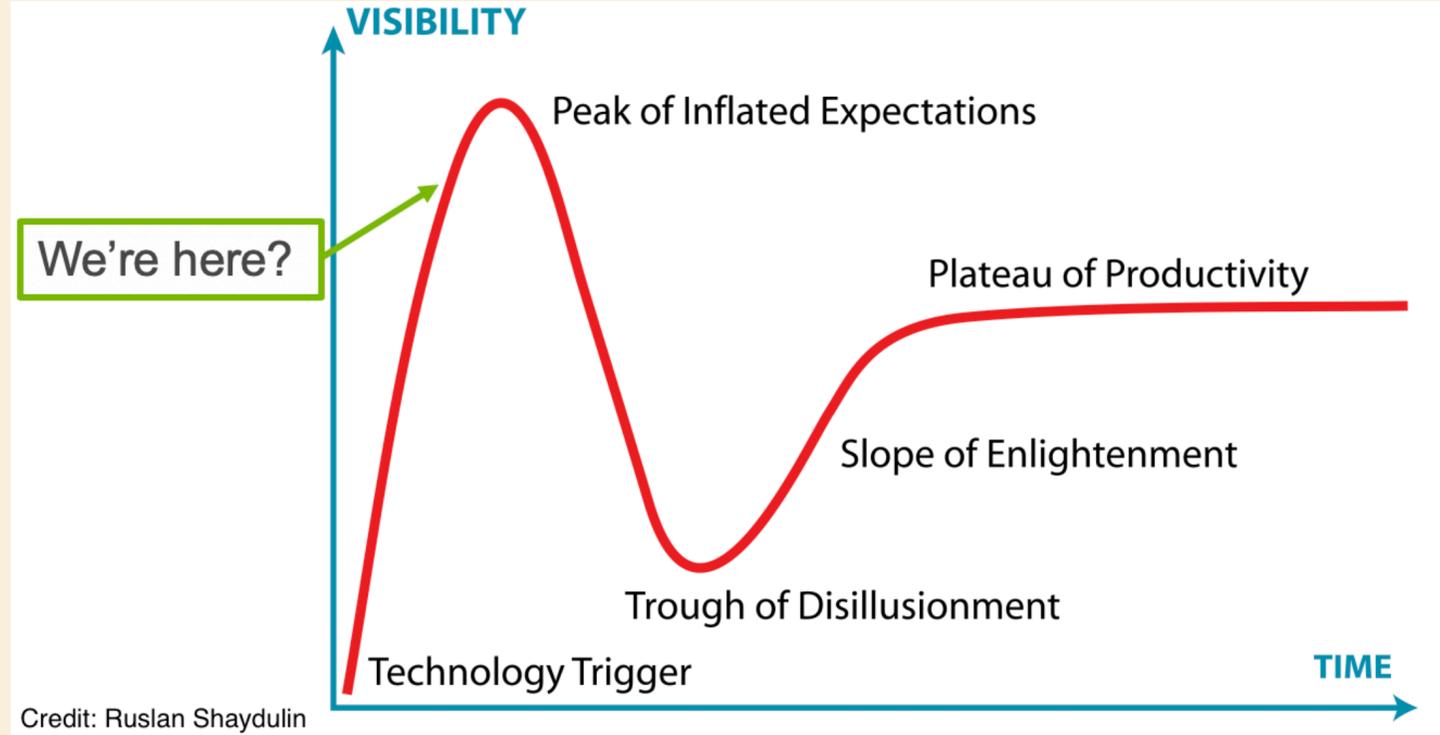
Fidelities (errors)

The qubits don't always do what you tell them to (e.g. 99.8% gate fidelity)

These limitations impact how much an algorithm can do!

Looking for error corrections, fault tolerance, and ways to increase times above

Where are we now?



- **We're in the Noisy Intermediate-Scale Quantum (NISQ) era**
Current state: IBM has 49 qubits, Google has 72 qubits
- **Other technologies are in development (ion traps, silicon spin, topological)**
- **Usefulness of quantum computers is to learn more about quantum computing**
- **Future will require millions of qubits ... scaling and fault tolerance!**

QC Applications

- **Quantum Supremacy - may reach soon?**
- **Destroying encryption (it turns out there are Quantum-proof means of encryption)**
- **Optimization problems (scheduling, routing, operations) [Car & Aerospace Industry]**
- **Finance, Quantum Chemistry, Forecasting, **Machine Learning** [Pharmaceutical, Cosmetics]**
- **Learning more about Quantum Mechanics, Quantum Gravity, Blackholes, Wormholes**

These applications are a long way away!

We just now have “baby” NISQ Computers that kinda do stuff. They need to scale up dramatically to be useful. Real applications will take $\sim 1M$ qubits

Summary

Quantum Computers are a completely different type of computing machine

You won't use them to balance your checkbook or surf the web

(Just like you wouldn't light your dining room with lasers)

QC exploits properties of Quantum Mechanics

Seems amazing and magical, but this is how nature works and we know it!

QC is just getting started

While the field has been around for decades, technology is catching up and we now have real quantum computing machines. But it is still early days and useful QC is likely at least a decade or more away.

Research has reached the point where it needs the management, organization, and resources of the national laboratories, so DOE, Fermilab, Argonne, and other national labs are getting involved

Why Fermilab? Particle Physics is built on Quantum!

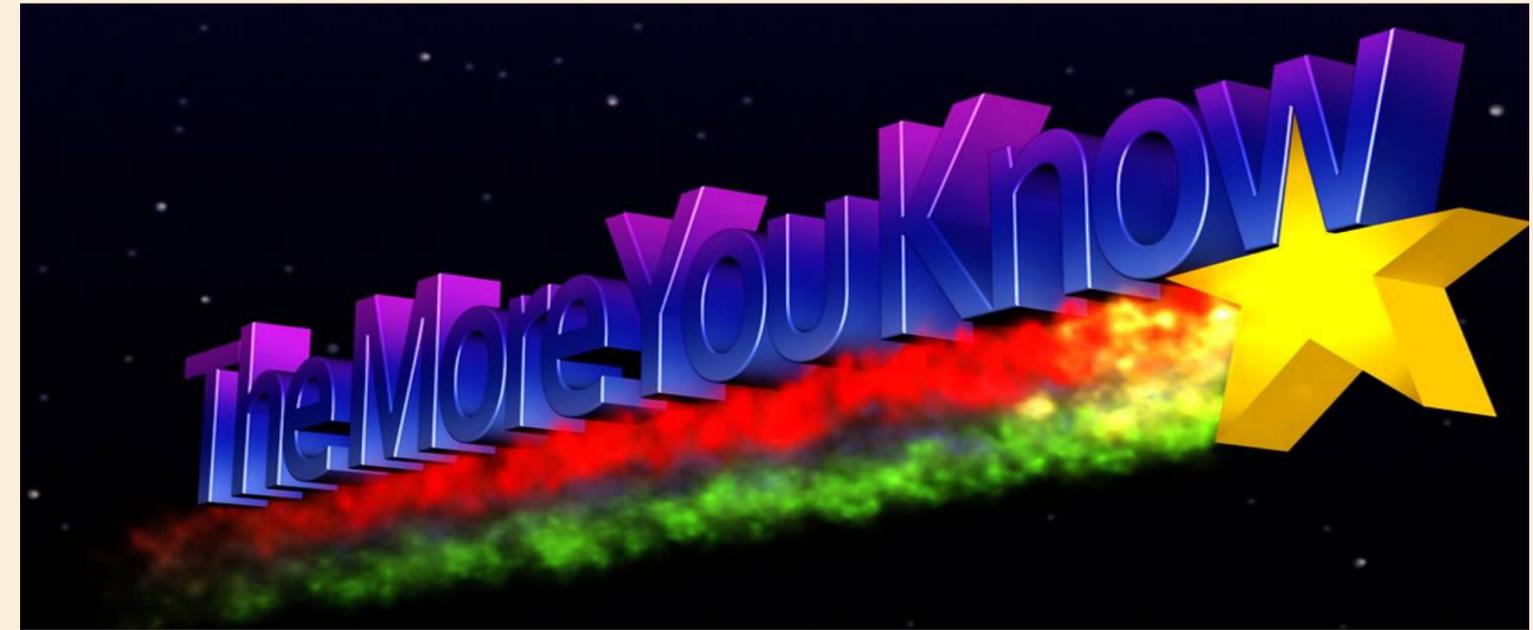
Fermilab is contributing to Quantum Science with Superconducting Cavity Qubits, Microwave control electronics, particle detectors with qubit cavities, and classical computing expertise like analysis and simulations

Learning more

We've barely scratched the surface

Places to go to learn more:

- Wikipedia articles on QC are quite good
- **Scott Aaronson (UTA professor)**
<https://www.scottaaronson.com> and his talks on YouTube
- **IBM Quantum Experience (actually play with a Quantum Computer in the cloud)**
<https://www.research.ibm.com/ibm-q/>
- If you can code in Python then see SDKs from Google, IBM, and Microsoft ... they have lots of examples to play with (use simulations or real Quantum Computers in the cloud)
- **Shor's algorithm is very complicated. Learn about it at "Minute Physics" videos at**
<https://www.youtube.com/watch?v=lvTqbM5Dq4Q> and <https://www.youtube.com/watch?v=FRZQ-efABeQ>



And you?

Quantum Information Science is an exploding multi-disciplinary field

- **Physics (Theory, Particle, Nuclear, Condensed Matter)**
- **Computer Science (including theoretical)**
- **Engineering (Electrical, RF, Microwave, Mechanical)**
- **Materials science**

What places do Quantum Computing?

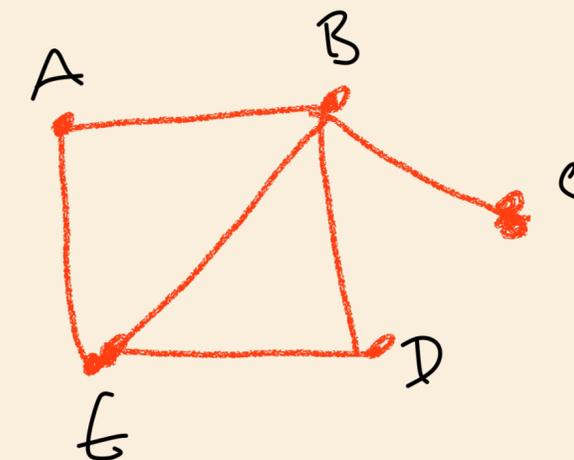
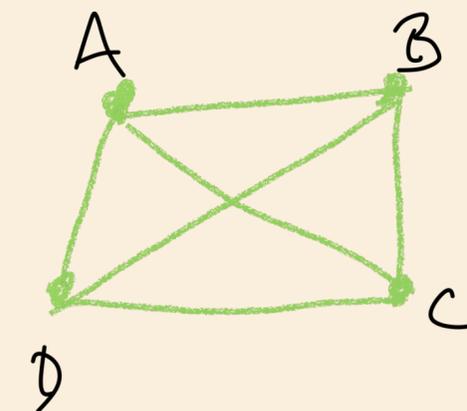
- **Universities (many are starting Quantum Information Science/Engineering groups/departments)**
- **National Laboratories (all the labs are getting into this) ... US is funding \$1.2B with NQI**
- **Industry**
 - **Building Quantum Computers ... IBM, Google, Microsoft, Intel, Regetti**
 - **Using Quantum Computers ... Ford, Mercedes, VW, Boeing, Airbus, Amazon, ...**

A fun time to get in ... rapid advances are perhaps coming soon ... a LOT of money is being spent

An NP problem - Traveling Salesman

- Can you make a closed loop, following connections (lines), visiting each node (dot) exactly once? (yes or no)
- E.g. 15 fully connected nodes has 43,589,145,600 possible routes. # of routes for 50 nodes is a 63 digit number
- Imagine millions of fully connected nodes
- Hard to solve, but efficient to verify
- Note - Finding the *shortest* route is *not* NP!
 - It is hard to solve and *not-efficient* to verify
 - NP-hard
- Optimization problem - industrial processes, scheduling, etc

<https://eklitzke.org/the-traveling-salesman-problem-is-not-np-complete>



<http://www.math.uwaterloo.ca/tsp/usa50/index.html>

Note: Theoretical Computer Science is a thing

- You can make a career thinking deeply about algorithms mathematically (and not actually running them)

- Huge question: Does $P = NP$?
That is, for every NP problem, does a P solution exist?

- Computer Science Theorists are not willing to eliminate that possibility, despite reality

