Computer Architecture

Rev.12-30-24

Quantum Computing

Vol. 2

by

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Dr Jeff Software
Lecturer, CSUN

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QC

Quantum
Technical Background

Quantum Dots

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MicroCloud Hologram Inc. Develops Semiconductor Quantum Dot Hole Spin Qubit Technology, Advancing the Frontiers of Quantum Computing

MicroCloud Hologram Inc.
Mon, Dec 30, 2024 at 09:00 AM

SHENZHEN, China, Dec. 30, 2024 /PRNewswire -- MicroCloud Hologram Inc. (NASDAQ: HOLO), they have pioneered an advanced technological solution: using a fast adiabatic driving protocol to achieve coherent control of two heavy hole spin qubits in a double quantum dot (QD) system. In traditional quantum experimental protocols, conventional methods such as linear ramps, π-pulses, or Landau-Zener channels have contributed to the incremental development of quantum control techniques. However, due to their inherent physical limitations, these methods struggle to meet the current stringent demands for high fidelity in quantum information processing. In contrast, the fast

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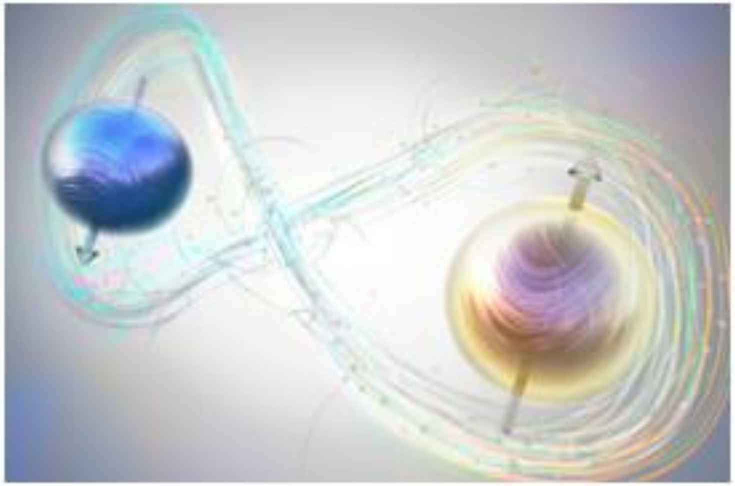
QC News

July 2020



UC to lead Group Awarded $25M by NSF to Launch Quantum Computing Institute

The National Science Foundation announced a five-year, $25 million award to UC Berkeley, UCLA and other universities to create an institute to study quantum computation. Computer science professor Jens Palsberg is part of the team.

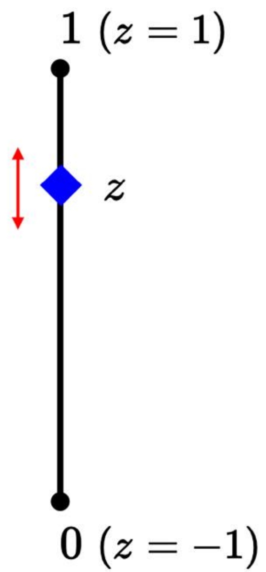
QC's & Qubits

Probabilistic Bits vs. Quantum Bits

Classical Bit

Only 2 *definite* states: 0 or 1

z-axis connecting them is *indefinite*, or probabilistic



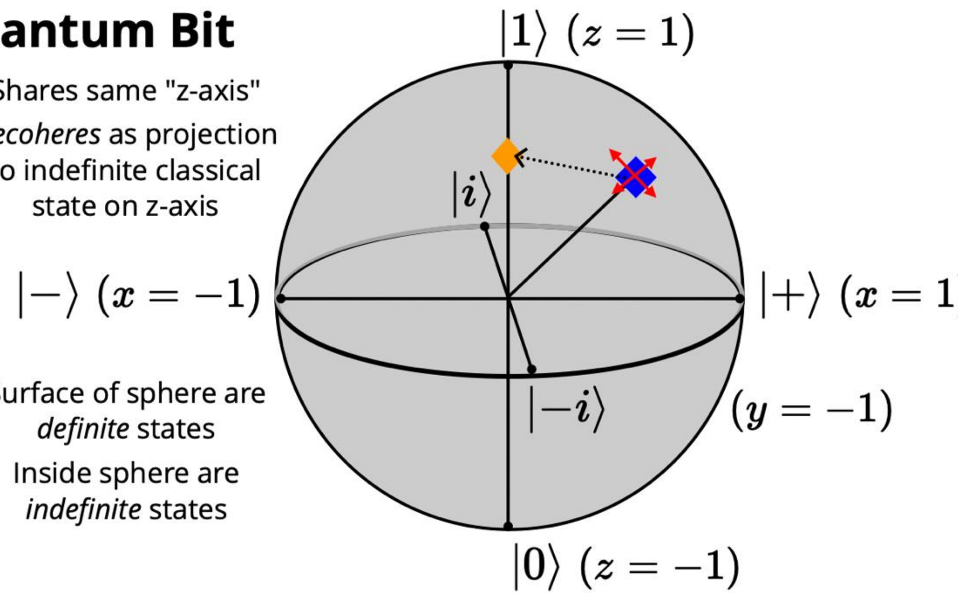
Quantum Bit

Shares same "z-axis"

Decoheres as projection to indefinite classical state on z-axis

Surface of sphere are *definite* states

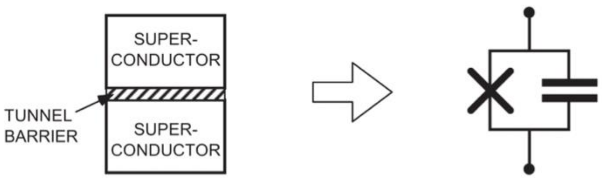
Inside sphere are *indefinite* states

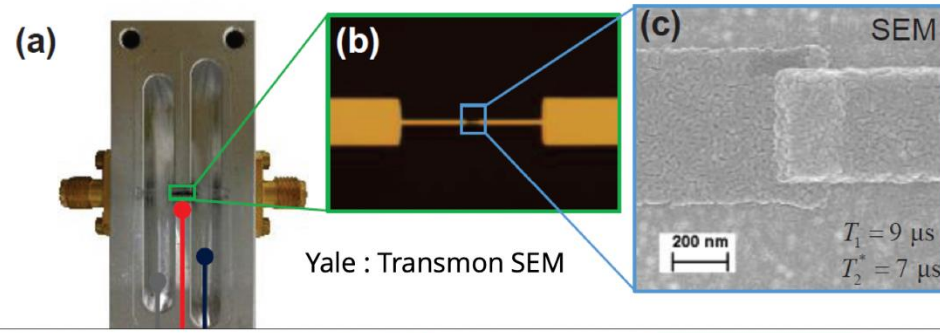


QC's & Qubits

Technology 2 : Superconducting Qubits

A superconducting (transmon) qubit is a superposition of the lowest two energy levels of a charge oscillation (an "artificial atom") across a nonlinear inductive tunnel barrier attached to a capacitive antenna

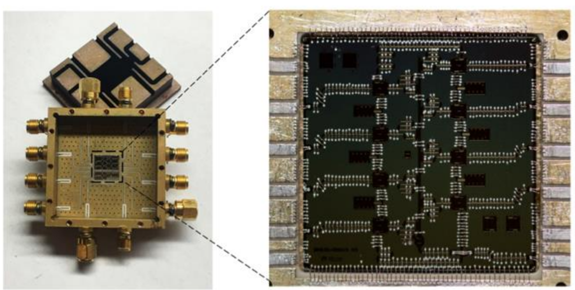




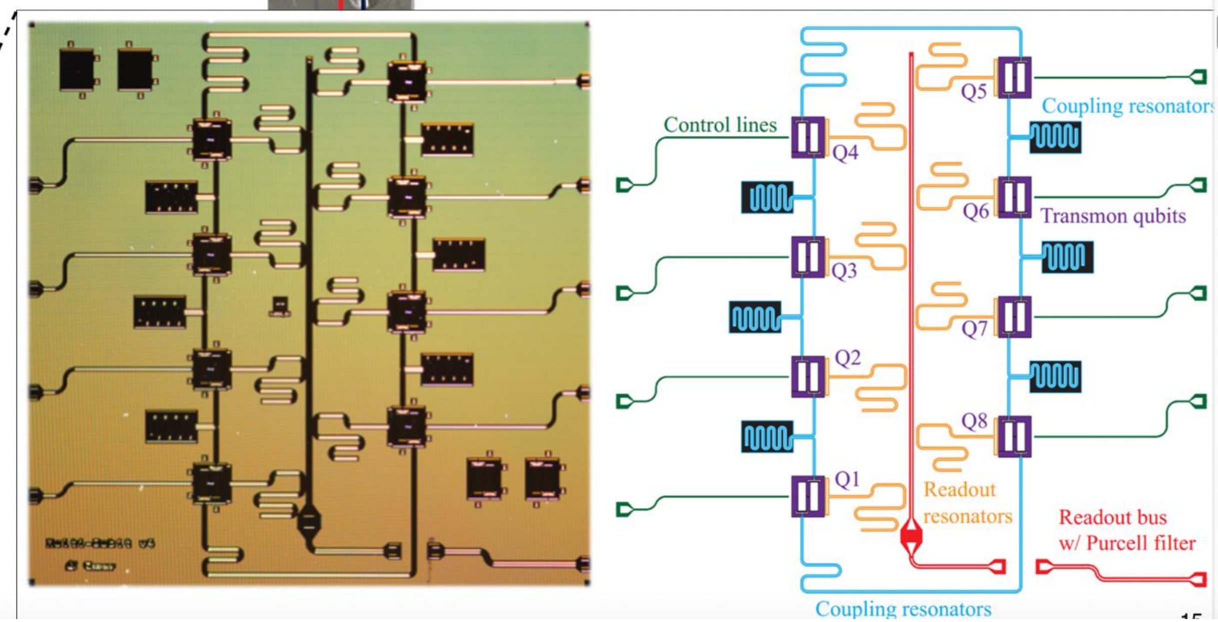
Yale : Transmon SEM

Controlled with all electrical AC signals at microwave frequencies

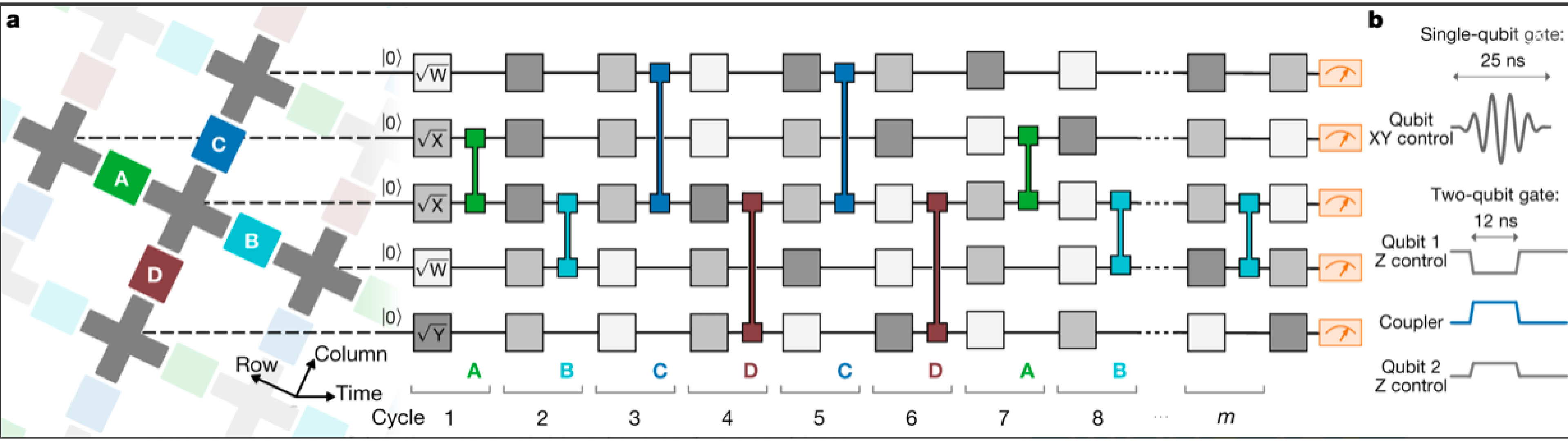
Cooled to mK temperatures



UC Berkeley : 8 qubit chip

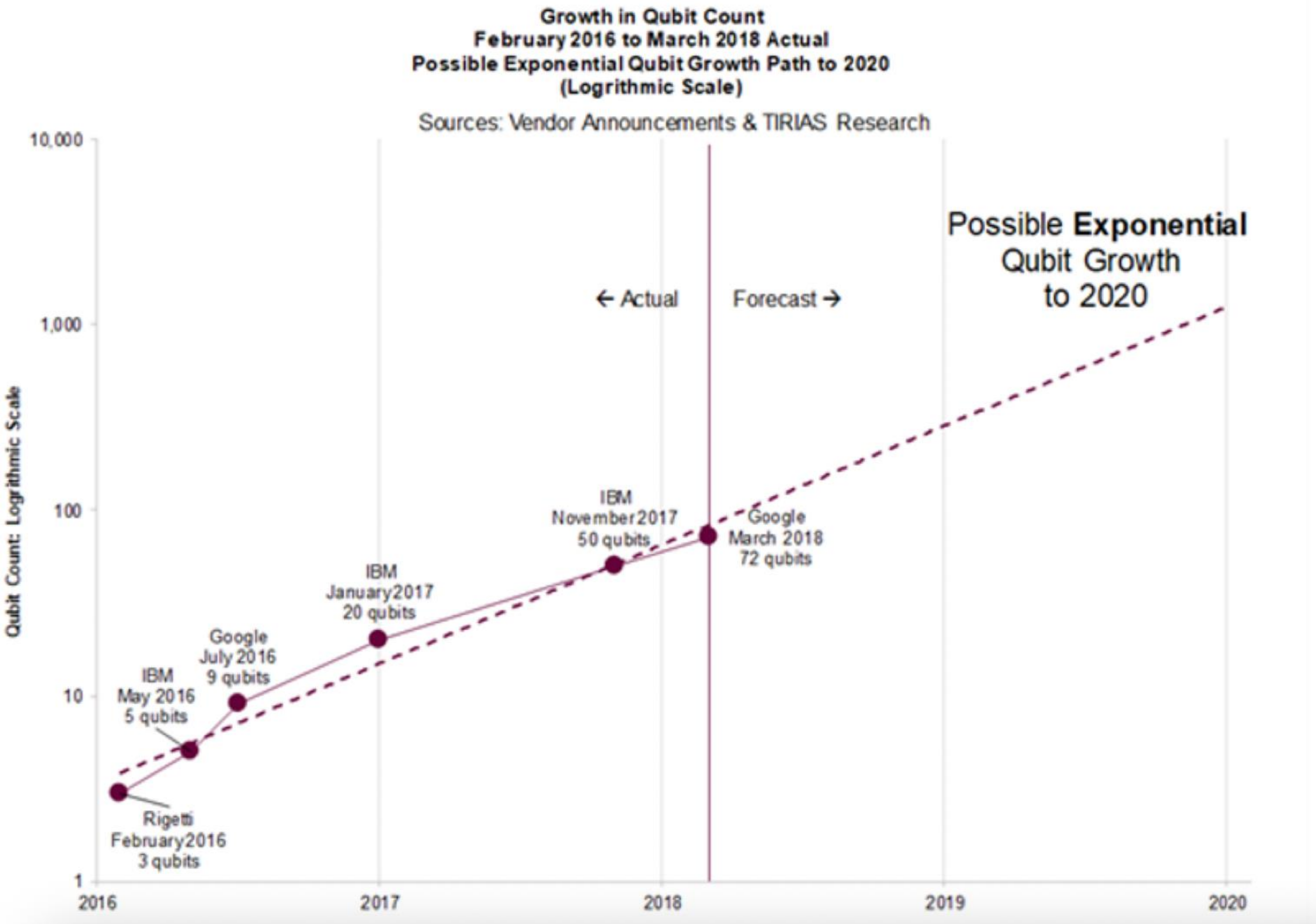


Qubits


a
C
A
B
D
Row
Column
Time
|0⟩
√W
√X
√Y
A
B
C
D
Cycle 1 2 3 4 5 6 7 8 ... m
b
Single-qubit gate:
25 ns
Qubit
XY control
Two-qubit gate:
12 ns
Qubit 1
Z control
Coupler
Qubit 2
Z control

QC's & Qubits

How Long Until A Billion Qubits?



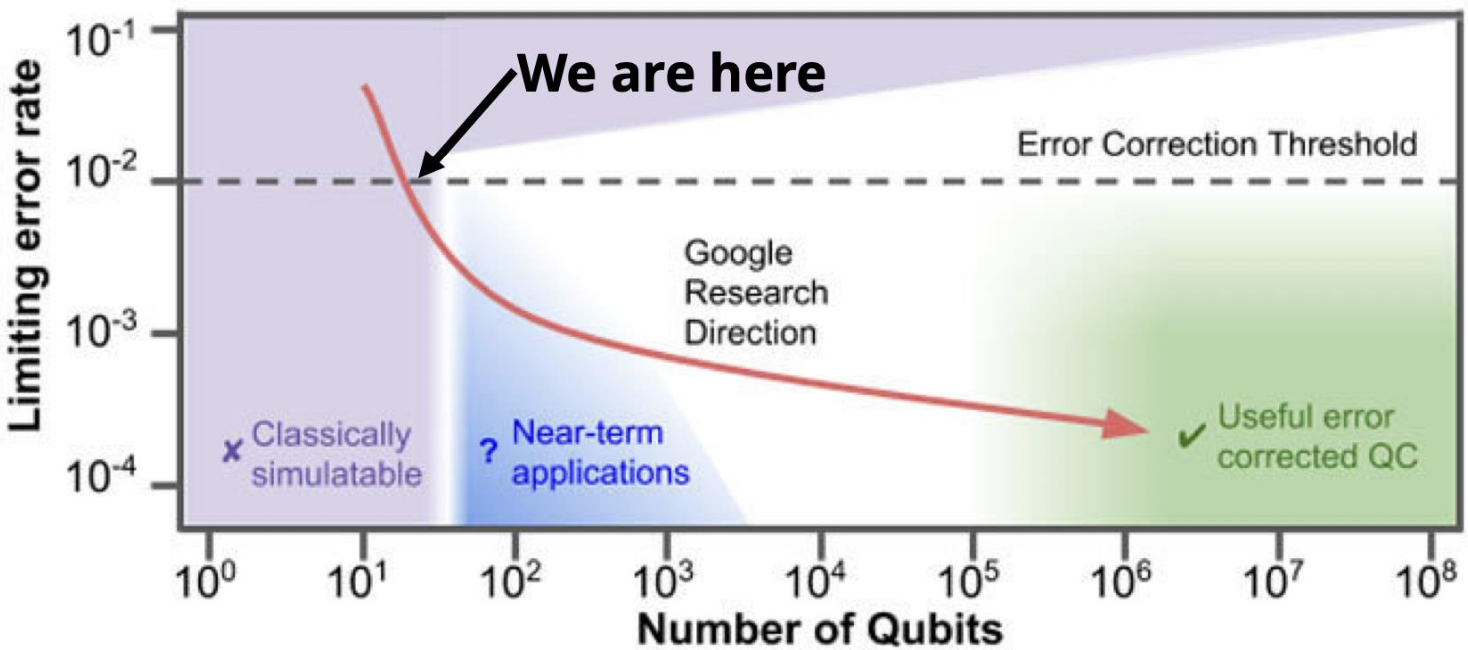
Growth in qubit number is currently **exponential**

If growth continues exponentially (with both fidelity and technical substrate scaling favorably) then we can expect chips with one billion qubits in:

~10-15 years

QC's & Qubits

What can we do until then?



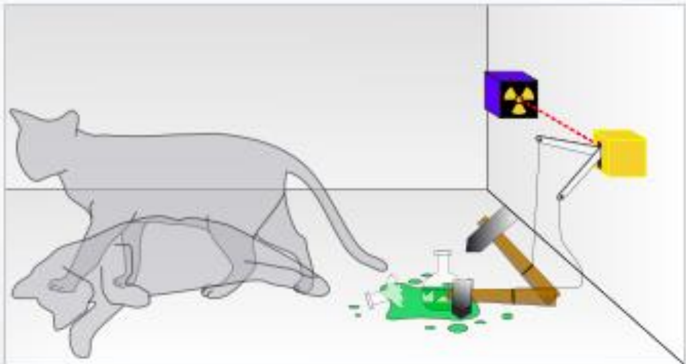
We are now reaching the scale that is no longer possible to simulate using classical supercomputers.

The current challenge is to find "near-term" applications for the existing quantum devices.

QC: Quantum Mechanics

Schrödinger's cat

From Wikipedia, the free encyclopedia

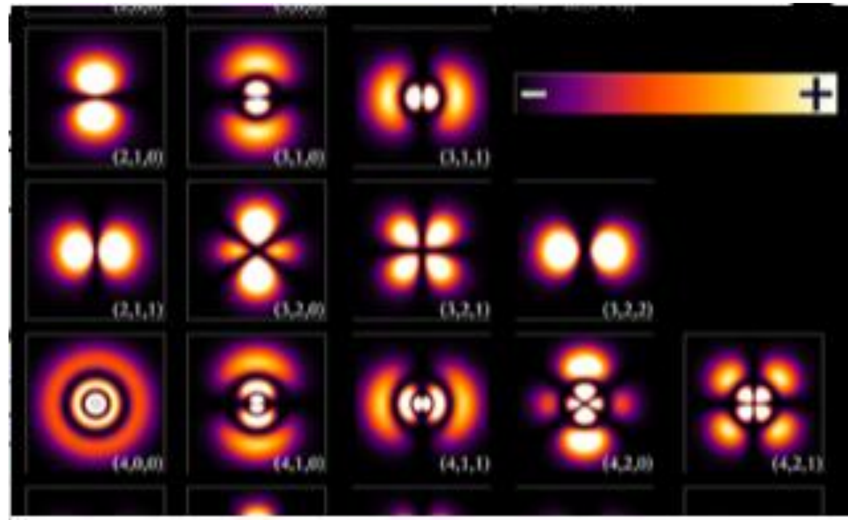


Schrödinger's cat: a cat, a flask of poison, and a radioactive source are placed in a sealed box. If an internal monitor (e.g. Geiger counter) detects radioactivity (i.e. a single atom decaying), the flask is shattered, releasing the poison, which kills the cat. The Copenhagen interpretation of quantum mechanics implies that after a while, the cat is *simultaneously* alive *and* dead. Yet, when one looks in the box, one sees the cat *either* alive *or* dead, not both alive *and* dead. This poses the question of when exactly quantum superposition ends and reality collapses into one possibility or the other.

Quantum mechanics

$$i\hbar \frac{\partial}{\partial t}|\psi(t)\rangle = \hat{H}|\psi(t)\rangle$$

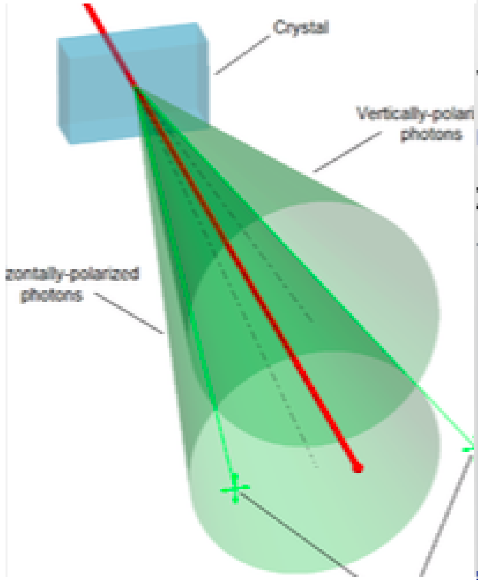
Schrödinger equation



Quantum mechanics is a fundamental theory in physics that describes the physical properties of nature at small scales, of the order of atoms and subatomic particles. It is the foundation of all quantum physics including quantum chemistry, quantum field theory, quantum technology, and quantu

QC: Quantum Mechanics

Quantum entanglement is a physical phenomenon that occurs when a pair or group of particles is generated, interact, or share spatial proximity in a way such that the quantum state of each particle of the pair or group cannot be described independently of the state of the others, including



Quantum superposition is a fundamental principle of quantum mechanics. It states that, much like waves in classical physics, any two quantum states can be added together ("superposed") and the result will be another valid quantum state; and conversely, that every quantum state can be represente

QC: Spinions & Chargons

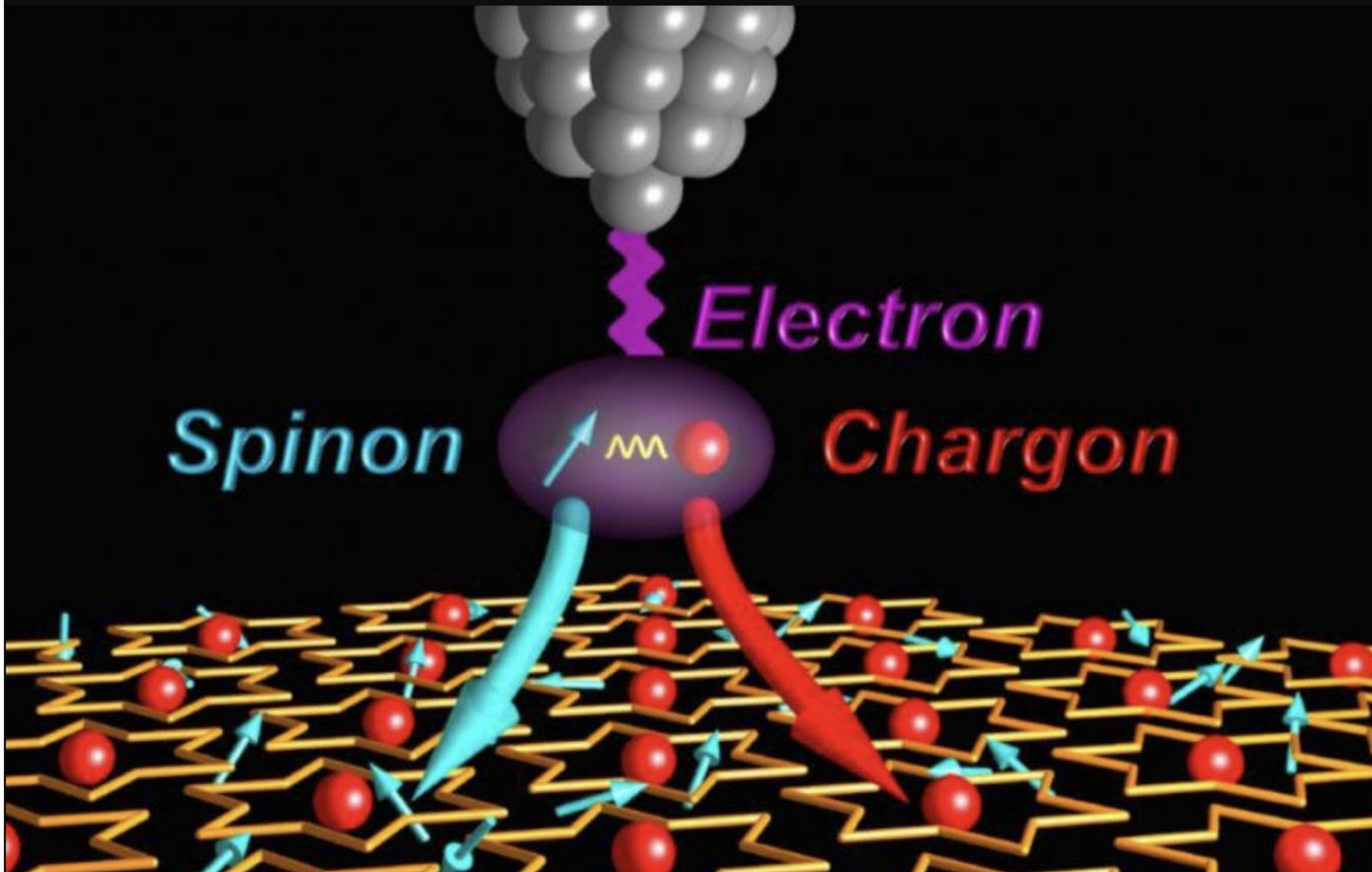


Illustration of an electron breaking apart into spinon ghost particles and chargons inside a quantum spin liquid — Image Credit: Mike Crommie et al./Berkeley Lab

The next step involved the UC Berkeley team injecting electrons from a metal needle into the tantalum diselenide TMDC sample — using a

QC's

Quora   206   720   Search Quora

anywhere and stay connected to your team. If your team—like (Continue reading in feed

Jake Van Wagoner, Been playing video games since 1992
Answered 1h ago

No.

Quantum computers aren't computers the way we think of them. They're not Turing Complete — that is, they don't perform arbitrary operations. They operate on a probabilistic basis. They're ***absolutely brilliant*** for certain categories of extremely difficult algorithms, known as a Quantum algorithm — one in which the solution is a superposition of every possible solution. Examples include:

- Querying a data set for a specific thing. Every input is tested simultaneously against the algorithm and only the correct one survives.
- Performing anything based on a Fourier transform, which at best is an O(N log(N)) algorithm on a traditional computer, but constant time O(1) on a quantum computer.
- Computing something where every possible path must be searched, because the quantum computer can search them all simultaneously.

Video games might have some algorithms that could be sped up on a quantum computer, *maybe*, but the QC will never be in the "driver's seat." At best, it'd be an accelerator for specific things.

QC's

Quora

John Bailey, Trying to transfer experience with binary logic design into the domain of qubits

Answered Wed

Non-abelian anyons | Topological QC

Microsoft, among others saw quantum computing would be limited by the physical limits of storing qubits. They placed their hopes on the existence and tractability of particles that might not even exist. Now they have been found!

> Microsoft is hoping to encode its qubits in a kind of quasiparticle: a particle-like object that emerges from the interactions inside matter. Some physicists are not even sure that the particular quasiparticles Microsoft are working with — called non-abelian anyons — actually exist. But the firm hopes to exploit their topological properties, which make quantum states extremely robust to outside interference, to build what are called topological quantum computers. Early theoretical work on topological states of matter won three physicists the Nobel Prize in Physics on 4 October. (Inside Microsoft's quest for a topological quantum computer)
>
> David Thouless, Duncan Haldane and Michael Kosterlitz won the 2016 Nobel Prize in Physics for their theoretical explanations of strange states of matter in two-dimensional materials, known as topological phases. (Physics of 2D exotic matter wins Nobel)

QC’s

Quora

Now at the same institutions:

Topological Superconductor

> University of Kent and the STFC Rutherford Appleton Laboratory researchers have discovered a new rare topological superconductor, LaPt3P, which could be used in the future of quantum computing. This discovery was made through muon spin relaxation experiments, and solves the issue of elementary units of quantum computers (qubits) losing their quantum properties from electromagnetic fields. Topological superconductors host protected metallic states on their surfaces.

HEBI

LaPt3P, a New Rare Topological Superconductor, Could be Used in Quantum Computing

University of Kent and the STFC Rutherford Appleton Laboratory...

https://www.techeblog.com/lapt3p-rare-topological-superconductor-qu...

Hardware

Time Crystals

Time Crystals

QUANTUM TIME CRYSTAL

Google researchers create a time crystal in a quantum computer

Scientists at the search engine giant claim to have observed a genuine time crystal, using a quantum processor

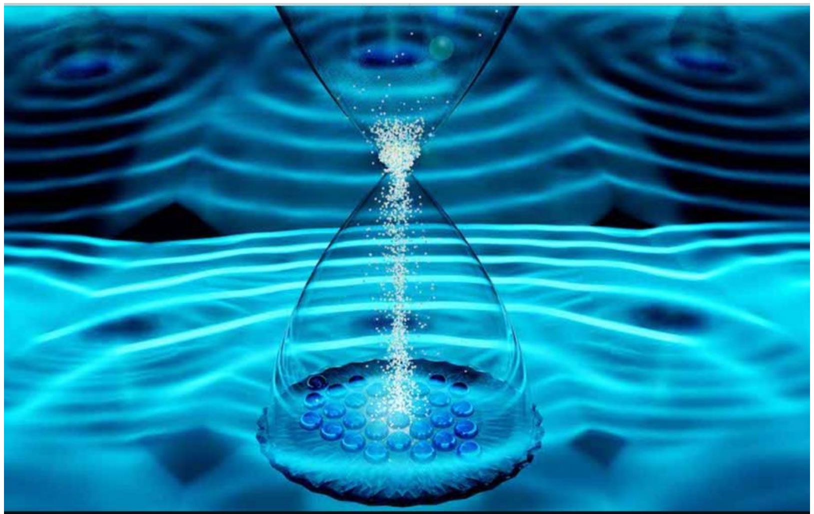


Image Credit: E. Edwards/JQI

Faisal Khan

A devout futurist keeping a keen eye on the latest in Emerging Tech, Global Economy, Space, Science, Cryptocurrencies & more

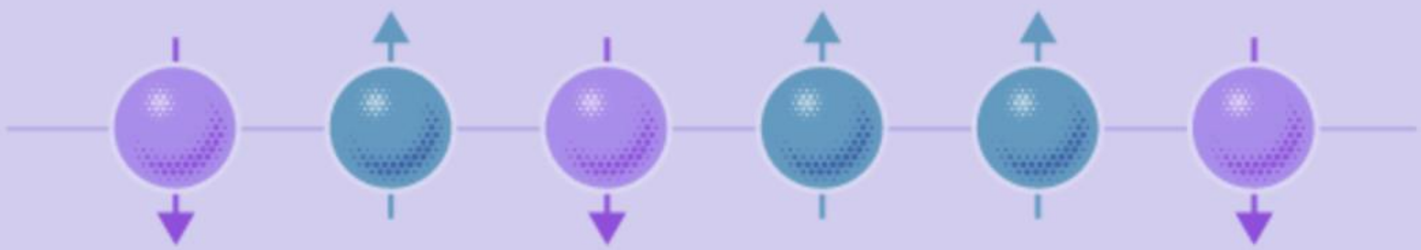
Time Crystals

Recipe for a Time Crystal

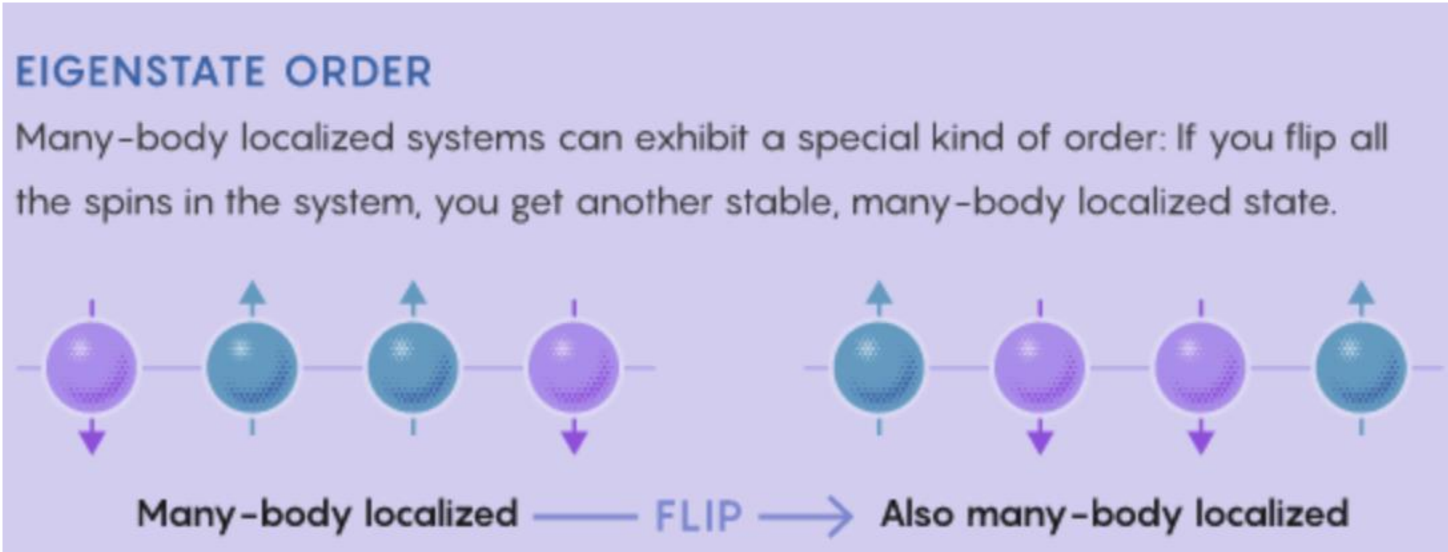
A time crystal is a newly realized phase of matter in which particles move in a regular, repeating cycle without burning any energy. The phase arises through a combination of three special ingredients.

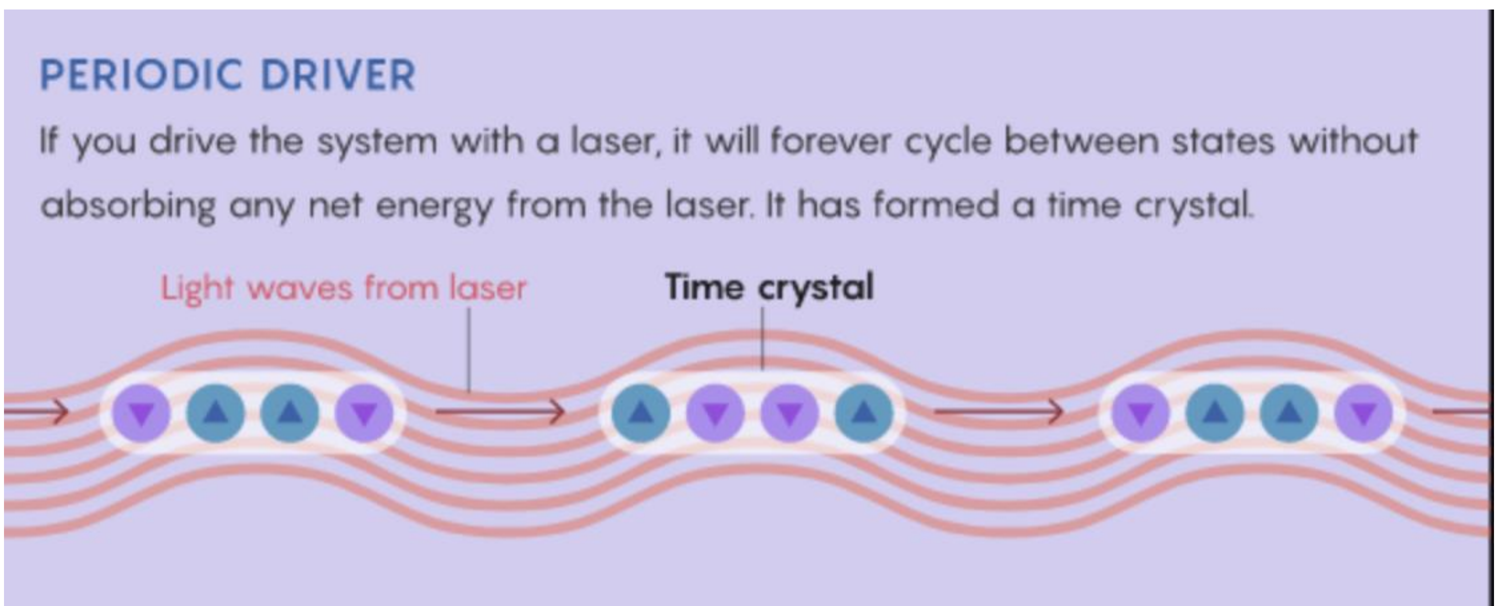
MANY-BODY LOCALIZATION

A row of particles, each with a magnetic orientation, or "spin," will ordinarily settle into an arrangement with the lowest possible energy. But random interference can make the particles get stuck in a higher-energy configuration. The effect is called **many-body localization**.



Time Crystals





Software

Applications

QC's

Quora

John Schlesinger, MA Physics & Philosophy, University of Oxford (1977)

Answered March 25, 2020

Quantum computers have transitioned from an experimental technology to what is called NISQ - noisy intermediate-scale quantum computing - see Quantum Computing in the NISQ era and beyond. They still need a roomful of cooling equipment to get the noise to a reasonable level. And it is still not possible to build logical qubits that use error correction to eliminate the noise, hence the name. The belief is that a logical qubit may require 10,000 physical qubits and currently the largest QC is about 53 qubits. If noise can be reduced to a low enough level then the quantum threshold theorem kicks in and it becomes feasible to build large scale QCs. It is still possible that it will be shown impossible to beat the noise threshold. This is what this phase of research is about.

QC's

Quora

Hunter Johnson · Follow

Associate Professor at John Jay College of Criminal Justice (2008–present) ·

QC is primarily a danger to public key signature algorithms that are based on discrete logs or integer factorization. As it currently stands, bitcoin does depend on the discrete log problem in an elliptic curve group. This is part of the ECDSA signature algorithm. If quantum computing comes to fruition, it would be unwise not to replace this module.

In fact, just to be conservative, this should be changed in a few years with a soft fork which will probably go through with very little opposition. (Assuming that someone hasn't found a way to make millions off the vulnerability and also runs a major mining cabal.)

There are plans to change in the near future from ECDSA to a Schnorr signature - Wikipedia. However this scheme is also based on the discrete log problem — it just happens to use less space. As things stand, storing the signature data is the most expensive part of a transaction, and people are eager to reduce the storage cost.

QC's

Quora

Hunter Johnson · Follow
Associate Professor at John Jay College of Criminal Justice (2008–present) ·

Some answers have claimed that QC will destroy all of cryptography. This is not true. We already have QC resistant encryption public key crypto, for example NTRU Quantum-Resistant High Performance Cryptography. This system is based on integer lattices rather than discrete logs or factoring, and no one seems to know how to use QC to simplify

Other answers have claimed that QC can be used to recover a private key from a bitcoin address. This is most definitely not true for the most common form of address, namely pay to public key hash. As you can see from this diagram (File:PubKeyToAddr.png - Bitcoin Wiki) the public key is hashed on its way to becoming an address. Addresses are not naked public keys (anymore).

QC's: Shor's Alg

Quora

Dave Bacon · Follow
Quantum ninja · 11y

Related **How useful will Shor's algorithm be for quantum computers?**

If a large and fast enough quantum computer is built, Shor's algorithm will break many (but not all) public key cryptosystems. Is this "useful?" Well if you're the NSA or the CIA, I suppose you would say yes. Is it going to change how everyday computers work? Certainly it would require a reworking of many cryptographic algorithms currently in widespread use. This is in some sense the opposite of useful: it will cause a lot of pain to do this update. Plus Shor's algorithm would render a ton of prior communication that was secure insecure, which could cause a lot of damage. But I don't think these are really "useful."

Most likely the most "useful" application of a quantum computer will not be Shor's algorithm, but will be as a simulator of quantum systems. The billion dollar question for this type of software is how important quantum theory is in, say, biological systems, material systems, chemistry, etc. There are other places where quantum computers might be useful, but the field is really still in its infancy with respect to algorithms (The number of people who work on actually coming up with new quantum algorithms is very small, probably less than a hundred, though there are many researchers who don't work directly on this but whose work could contribute to this endeavor.)

QC's: Shor's Alg

Quora

Guy Garnett · Follow
Information Security Professional · 3h

You asked "*Will the IBM Condor quantum computer be ready to implement Shor's algorhirithm? How performant will it be at breaking cryptography?*"

Since IBM has demonstrated Shor's algorithm on previous quantum computers (for example, IBM factored the number 21 using solid-state qubits in 2012), I'm would be surprised if they didn't implement it on their new quantum processors. While this means that current algorithms (based on integer factorization, discrete logarithms, or elliptic-curve logarithms) have a foreseeable demise, it isn't imminent, for two reasons:

First, IBM failed to factor the number 35 on a Q System One in 2019 due to accumulated errors, meaning that they still have a long way to go before quantum computing can be relied on to factor the very large numbers used in cryptography. I'm sure that reducing errors and improving reliability and repeatability are key focus areas for their research.

QC's: Shor's Alg

Quora

Guy Garnett · Follow
Information Security Professional

Second, the current best estimates are that more than 2k qubits will be needed for meaningful attacks on today's cryptography, with possibly more than 16k needed for longer keys in some algorithms. The goal of IBM's current research is to produce a quantum processor with about 1k qubits, so processors with enough capacity to break current encryption are still one or more generations in the future.

Organizations that establish cryptography standards are looking at post-quantum cryptography now, with the intent that there will be workable algorithms that remain secure even against quantum computers when we need them.

Finally, Shor's algorithm is named for mathmetician Peter Shor; it is a proper name (not an acronym) and should be capitalized like other proper names.

Software

Programming

QC's

Quantum Computing

How do you program a quantum computer?

The most basic operations performed on qubits are defined by quantum gates, similar to logical gates used in classic computers. Using **quantum gates** one can build complex algorithms, usually ending in a measurement operation, which obtains a classical value of qubits (either 0 or 1, but not a superposition). The state of a quantum computer, a set of qubits called quantum register, can be visualized in a **number of ways**, typically as a 2D or 3D graph, on which points or bars represent superpositions of qubits, while their color or bar height represent amplitude and phase of a given superposition. An interesting property of quantum gates is their reversibility, allowing for program execution both forward and in reverse without any side-effects.

Where can I buy a real quantum computer?

As of today the only company selling quantum computers is **D-Wave**, but unfortunately their architecture does not perform arbitrary quantum gate operations on sequences of qubits (which is what Quantum Computing Playground simulates at this time). The proof-of-concepts for capabilities of quantum computing have been demonstrated in multiple laboratories around the world though, so there is a chance that quantum computers will become one day everyday's reality. For now, you can experience the technology of tomorrow today, inside our Playground.

Quantum Computing

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Quantum Computing Playground

http://www.quantumplayground.net/#/home

```
// This is a simple example.
//
VectorSize 8

SigmaX 2
Hadamard 2
Hadamard 1
Hadamard 0
QFT 0, 8

SetViewMode 2

Delay 10

for i = 0; i < 360; i += 5
  SetViewAngle Math.PI * i / 180
endfor

```

Quantum Computing Playground

Quantum Computing Playground is a browser-based WebGL Chrome Experiment. It features a GPU-accelerated quantum computer with a simple IDE interface, and its own scripting language with debugging and 3D quantum state visualization features. Quantum Computing Playground can efficiently simulate quantum registers up to 22 qubits, run Grover's and Shor's algorithms, and has a variety of quantum gates built into the scripting language itself.

Quantum Computing

Quantum Computing Playground

http://www.quantumplayground.net/#/home

```
// This example demonstrates properties of Hadamard [redacted]
//
VectorSize 8

Delay 500

for i = 0; i < 8; i++
  Display "Creating superposition of all states, bit " + i
  Hadamard i
endfor

Delay 2000
Delay 500

for i = 0; i < 8; i++
  Display "Applying Hadamard gates in the same order, bit " +
  Hadamard i
endfor

Delay 2000
Delay 1
```

Quantum Computing

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```
// Based on C++ code from libquantum library.

proc FindFactors N
  x = 0

  if N < 15
    Print "Invalid number!"
    Breakpoint
  endif

  width = QMath.getWidth(N)
  twidth = 2 * width + 3

  for x; (QMath.gcd(N, x) > 1) || (x < 2); x
    x = Math.floor(Math.random() * 10000) % N
  endfor

  Print "Random seed: " + x

  for i = 0; i < twidth; i++
    Hadamard i
  endfor

  ExpModN x, N, twidth

  for i = 0; i < width; i++
    MeasureBit twidth + i
  endfor

  InvQFT 0, twidth
```

Quantum Computing Playground

http://www.quantumplayground.net/#/home

Software

Other Algorithms

Lab Experiments in QC

By a PhD researcher: **Patrick Banner** Physics PhD student

In my experiment, rubidium atoms are loaded into a magneto-optical trap (MOT), cooled using optical molasses, and then trapped finally in an optical dipole trap (ODT); we then run our experiment, which usually means sending a probe laser and a control laser through our cloud of about 10,000 atoms, and measuring in one way or another the probe light that exits the cloud. All of this happens in a fraction of a second, with the interesting part happening in tens of milliseconds or less. The time period of an experiment happening is audibly defined by laser shutters in our lab clicking on and off within a second. An entire experimental cycle is called a "shot," and gives effectively one data point for every parameter.

QC Algorithms

Quantum Algorithm Zoo

This is a comprehensive catalog of quantum algorithms. If you notice any errors or omissions, please email me at stephen.jordan@microsoft.com. (Alternatively, you may submit a pull request to the repository on github.) Your help is appreciated and will be acknowledged.

Algebraic and Number Theoretic Algorithms

Algorithm: Factoring
Speedup: Superpolynomial
Description: Given an *n*-bit integer, find the prime factorization. The quantum algorithm of Peter Shor solves this in $\widetilde{O}(n^3)$ time [82,125]. The fastest known classical algorithm for integer factorization is the general number field sieve, which is believed to run in time $2^{\widetilde{O}(n^{1/3})}$. The best rigorously proven upper bound on the classical complexity of factoring is $O(2^{n/4+o(1)})$ via the Pollard-Strassen algorithm [252, 362]. Shor's factoring algorithm breaks RSA public-key encryption and the closely related quantum algorithms for discrete logarithms break the DSA and ECDSA digital signature schemes and the Diffie-Hellman key-exchange protocol. A quantum algorithm even faster than Shor's for the special case of factoring "semiprimes", which are widely used in cryptography, is given in [271]. If small factors exist, Shor's algorithm can be beaten by a quantum algorithm using Grover search to speed up the elliptic curve factorization method [366]. Additional optimized versions of Shor's algorithm are given in [384, 386]. There are proposed classical public-key cryptosystems not believed to be broken by quantum algorithms, *cf.* [248]. At the core of Shor's factoring algorithm is order finding, which can be reduced to the Abelian hidden subgroup problem, which is solved using the quantum Fourier transform. A number of other problems are known to reduce to integer factorization including the membership problem for matrix groups over fields of odd order [253], and certain diophantine problems relevant to the synthesis of quantum circuits [254].

QC Algorithms-Primality

Algorithm: Primality Proving
Speedup: Polynomial
Description: Given an *n*-bit number, return a proof of its primality. The fastest classical algorithms are AKS, the best versions of which [393, 394] have essentially-quartic complexity, and ECPP, where the heuristic complexity of the fastest version [395] is also essentially quartic. The fastest known quantum algorithm for this problem is the method of Donis-Vela and Garcia-Escartin [396], with complexity $O(n^2(\log n)^3 \log \log n)$. This improves upon a prior factoring-based quantum algorithm for primality proving [397] that has complexity $O(n^3 \log n \log \log n)$. A recent result of Harvey and Van Der Hoeven [398] can be used to improve the complexity of the factoring-based quantum algorithm for primality proving to $O(n^3 \log n)$ and it may be possible to similarly reduce the complexity of the Donis-Vela-Garcia-Escartin algorithm to $O(n^2(\log n)^3)$ [399].

Grover's Algorithm

Grover's algorithm

From Wikipedia, the free encyclopedia

Grover's algorithm is a quantum algorithm that finds with high probability the unique input to a black box function that produces a particular output value, using just $O(\sqrt{N})$ evaluations of the function, where N is the size of the function's domain. It was devised by Lov Grover in 1996.

The analogous problem in classical computation cannot be solved in fewer than $O(N)$ evaluations (because, in the worst case, the N-th member of the domain might be the correct member). At roughly the same time that Grover published his algorithm, Bennett, Bernstein, Brassard, and Vazirani proved that any quantum solution to the problem needs to evaluate the function $\Omega(\sqrt{N})$ times, so Grover's algorithm is asymptotically optimal.[1]

It has been shown that a non-local hidden variable quantum computer could implement a search of an N-item database in at most $O(\sqrt[3]{N})$ steps. This is faster than the $O(\sqrt{N})$ steps taken by Grover's algorithm. Neither search method will allow quantum computers to solve NP-Complete problems in polynomial time.[2]

Unlike other quantum algorithms, which may provide exponential speedup over their classical counterparts, Grover's algorithm provides only a quadratic speedup. However, even quadratic speedup is considerable when N is large. Grover's algorithm could brute-force a 128-bit symmetric cryptographic key in roughly 2^{64} iterations, or a 256-bit key in roughly 2^{128} iterations. As a result, it is sometimes suggested[3] that symmetric key lengths be doubled to protect against future quantum attacks.

Like many quantum algorithms, Grover's algorithm is probabilistic in the sense that it gives the correct answer with a probability of less than 1. Though there is technically no upper bound on the number of repetitions that might be needed before the correct answer is obtained, the expected number of repetitions is a constant factor that does not grow with N. Grover's original paper described the algorithm as a database search algorithm, and this description is still common. The database in this analogy is a table of all of the function's outputs, indexed by the corresponding input.

Performance

Quantum

Supremacy

Quantum Supremacy

Scott Aaronson

Q1. What is quantum computational supremacy?

Often abbreviated to just "quantum supremacy," the term refers to the use of a quantum computer to solve *some* well-defined set of problems that would take orders of magnitude longer to solve with any currently known algorithms running on existing classical computers—and not for incidental reasons, but for reasons of asymptotic quantum complexity. The emphasis here is on being as sure as possible that the problem *really was* solved quantumly and *really is* classically intractable, and ideally achieving the speedup *soon* (with the noisy, non-universal QCs of the present or very near future). If the problem is also *useful* for something, then so much the better, but that's not at all necessary. The Wright Flyer and the Fermi pile weren't useful in themselves.

Quantum Supremacy

Scott Aaronson

Q2. If Google has indeed achieved quantum supremacy, does that mean that now "no code is uncrackable", as Democratic presidential candidate Andrew Yang recently tweeted?

No, it doesn't. (But I still like Yang's candidacy.)

There are two issues here. First, the devices currently being built by Google, IBM, and others have 50-100 qubits and no error-correction. Running Shor's algorithm to break the RSA cryptosystem would require several thousand logical qubits. With known error-correction methods, that could easily translate into *millions* of physical qubits, and those probably of a higher quality than any that exist today. I don't think anyone is close to that, and we have no idea how long it will take.

But the second issue is that, even in a hypothetical future with scalable, error-corrected QCs, on our current understanding they'll only be able to crack *some* codes, not all of them. By an unfortunate coincidence, the public-key codes that they can crack include *most* of what we currently use to secure the Internet: RSA, Diffie-Hellman, elliptic curve crypto, etc. But symmetric-key crypto should only be minimally affected. And there are even candidates for public-key cryptosystems (for example, based on lattices) that no one knows how to break quantumly after 20+ years of trying, and some efforts underway now to start migrating to those systems. For more, see for example my letter to Rebecca Goldstein.

Quantum Supremacy

Scott Aaronson

Q13. Did you (Scott Aaronson) invent the concept of quantum supremacy?

No. I did play some role in developing it, which led to Sabine Hossenfelder among others generously overcrediting me for the whole idea. The term "quantum supremacy" was coined by John Preskill in 2012, though in some sense the core concept goes back to the beginnings of quantum computing itself in the early 1980s. In 1993, Bernstein and Vazirani explicitly pointed out the severe apparent tension between quantum mechanics and the Extended Church-Turing Thesis of classical computer science. Then, in 1994, the use of Shor's algorithm to factor a huge number became the quantum supremacy experiment *par excellence*—albeit, one that's still (in 2019) much too hard to perform.

The key idea of instead demonstrating quantum supremacy using a *sampling problem* was, as far as I know, first suggested by Barbara Terhal and David DiVincenzo, in a farsighted paper from 2002. The "modern" push for sampling-based supremacy experiments started around 2011, when Alex Arkhipov and I published our paper on BosonSampling, and (independently of us) Bremner, Jozsa, and Shepherd published their paper on the commuting Hamiltonians model. These papers showed, not only that "simple," non-universal quantum systems can solve apparently-hard sampling problems, but also that an efficient classical algorithm for the same sampling problems would imply a collapse of the polynomial hierarchy. Arkhipov and I also made a start toward arguing that even the *approximate* versions of quantum sampling problems can be classically hard.

Quantum Supr.: Random Sampling

Scott Aaronson

As far as I know, the idea of "Random Circuit Sampling"—that is, generating your hard sampling problem by just picking a random sequence of 2-qubit gates in (say) a superconducting architecture—originated in an email thread that I started in December 2015, which also included John Martinis, Hartmut Neven, Sergio Boixo, Ashley Montanaro, Michael Bremner, Richard Jozsa, Aram Harrow, Greg Kuperberg, and others. The thread was entitled "Hard sampling problems with 40 qubits," and my email began "Sorry for the spam." I then discussed some advantages and disadvantages of three options for demonstrating sampling-based quantum supremacy: (1) random circuits, (2) commuting Hamiltonians, and (3) BosonSampling. After Greg Kuperberg chimed in to support option (1), a consensus quickly formed among the participants that (1) was indeed the best option from an engineering

Quantum Supr.: Random Sampling

Scott Aaronson

The Randomness Protocol

"Born from complexity theory. Somehow became first planned application for Bristlecone / Sycamore…"

Goal: By interacting with a NISQ QC remotely, force it to generate fresh random bits, which no one (not even the QC) knew beforehand. **Place no trust in the QC!**

"Proof of Sampling." Modest quantum speedups, not for their own sake, but as proof of some other property

Quantum Supr.: Random Sampling

Scott Aaronson

The Protocol

1. The classical client generates n-qubit quantum circuits $C_1,\ldots,C_T$ pseudorandomly (mimicking a random ensemble)

2. For each t, the client sends C_t to the server, then demands a response S_t within a very short time

   In the "honest" case, the response is a list of k samples from the output distribution of $C_t|0\rangle^{\otimes n}$

3. The client picks a few random iterations t, and for each one, applies a "HOG" (Heavy Output Generation) test

4. If the tests pass, then the client feeds $S=\langle S_1,\ldots,S_T\rangle$ into a classical **randomness extractor**, such as GUV (Guruswami-Umans-Vadhan), to get nearly pure random bits

Quantum Computing

DR JEFF SOFTWARE
INDIE APP DEVELOPER

QC Presentation

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Quantum Computing:

State of Play

Justin Dressel, Ph.D.
Institute for Quantum Studies, Chapman University

OC ACM Chapter Meeting, May 16th, 2018

How close are we to practical quantum computers?

We already have them! ... sort of

2 main competing implementations (others in development):

1. Trapped ions
   UMD : 53 qubits

2. Superconducting circuits
   Google : 72 qubits
   IBM : 50 qubits
   Rigetti Computing : 19 qubits
   UC Berkeley : 10 qubits

But these numbers do not tell the complete story

Is a quantum computer more powerful?

- The answer to this is ***unknown***. However there are ***strong indications it is***.
- Rough logic of why it *likely* to be more powerful:
  - ***(+) Parallelization*** of computations over superpositions
    - This parallelization can *exponentially speed up* a single computation
  - ***(-) Randomness*** of measurement kills the parallelization speedup
    - Computations generally are *exponentially repeated* due to uncertainty
  - **(+) *Destructive interference*** can eliminate most uncertainty
    - Prior to measurement, *interference can reduce most outcomes to zero probability*, leaving only a few information-dense possibilities
    - This can at least partially restore the speedup expected from parallelism

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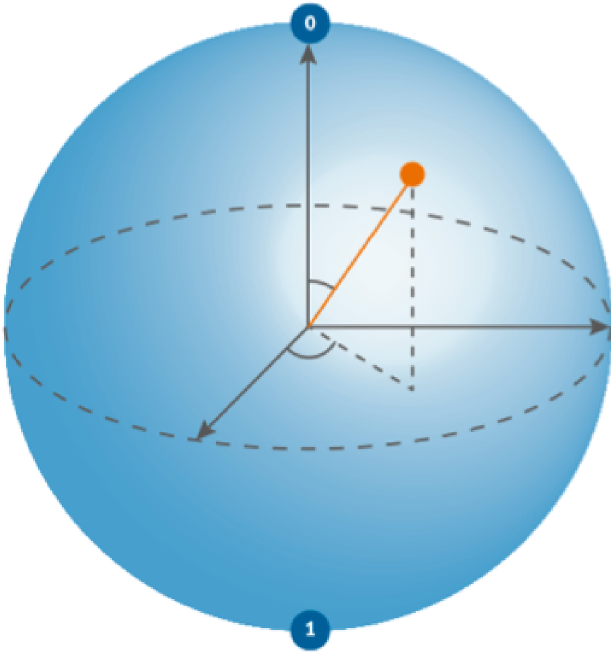
Quantum Physics and Qubits

New "coherent" features for quantum bits (qubits)



- ***Superpositions*** of 0 and 1 can also be *definite*
  - A bit has two possible definite states.
  - A qubit has a definite state for each point on the surface of a unit sphere.
- ***Entanglement*** breaks modularity : *More is different*
  - 1 qubit requires 2 continuous angles to cover its spherical state space
  - N qubits require 2^N continuous angles to cover their state space (not 2N)
  - *Exponential scaling* of parameters with qubit number, not linear!
- ***Time-symmetry*** : logic gates must be *reversible*
  - Qubit states follow *smooth continuous orbits* on the unit sphere
- ***Measurement*** forces *probabilistic* description
  - When measured, qubit *randomly* collapses to 0 or 1 based on state proximity

These coherent features wash out (or "decohere") on the macro-scale to produce the classical picture

Classical Bit Error Correction

$$0 \mapsto 000 \qquad 1 \mapsto 111$$

If one bit flips, can detect and correct via majority-voting

Qubit Error Correction

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \mapsto \alpha|000\rangle + \beta|111\rangle$$

Same basic idea, but now applied to *superpositions*

Main problem: cannot "look" at the bits directly due to measurement collapse

Resolution: measure *parities* of bits instead

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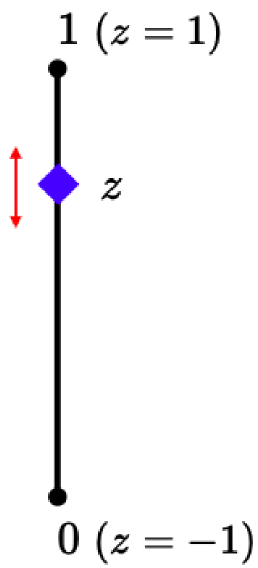
Probabilistic Bits vs. Quantum Bits

Classical Bit

Only 2 *definite* states: 0 or 1

z-axis connecting them is *indefinite*, or probabilistic



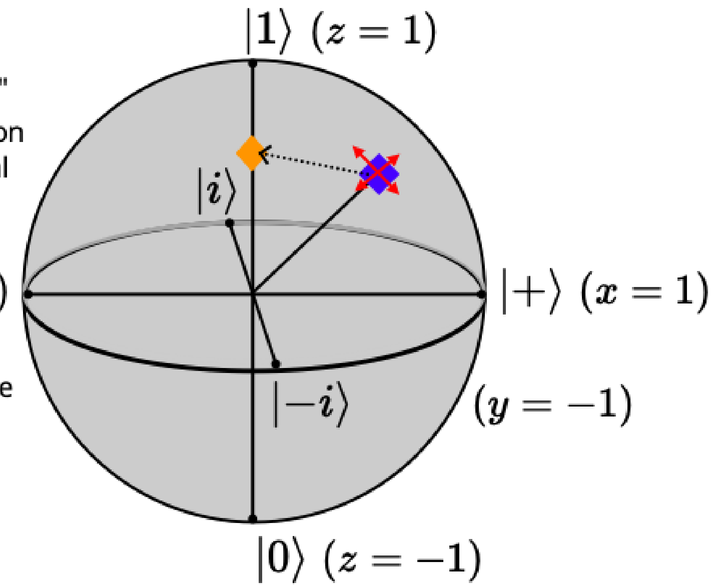
Quantum Bit

Shares same "z-axis"

Decoheres as projection to indefinite classical state on z-axis

Surface of sphere are *definite* states

Inside sphere are *indefinite* states



- Probabilistic *state*: 1 parameter

$$z = P(1) - P(0) \in [-1,1], \quad (P(1)+P(0)=1)$$

- Evolution can only flip: $0 \leftrightarrow 1,\ (z \to -z)$
- Measurement obeys Bayes' rule:

$$P(1|r) = \frac{P(r|1)P(1)}{P(r|1)P(1)+P(r|0)P(0)}$$

- Probabilistic *state*: 3 parameters

$$\vec{\rho} = (x,y,z) \in [-1,1]^{\times 3}, \quad (x^2+y^2+z^2 \leq 1)$$

$$x + iy = e^{-(i\phi+d)/2}\, 2\sqrt{P(1)P(0)}$$

- Evolution precesses in circle: $\partial_t \vec{\rho} = \vec{\Omega} \times \vec{\rho}$
- Measurement obeys Bayes' rule

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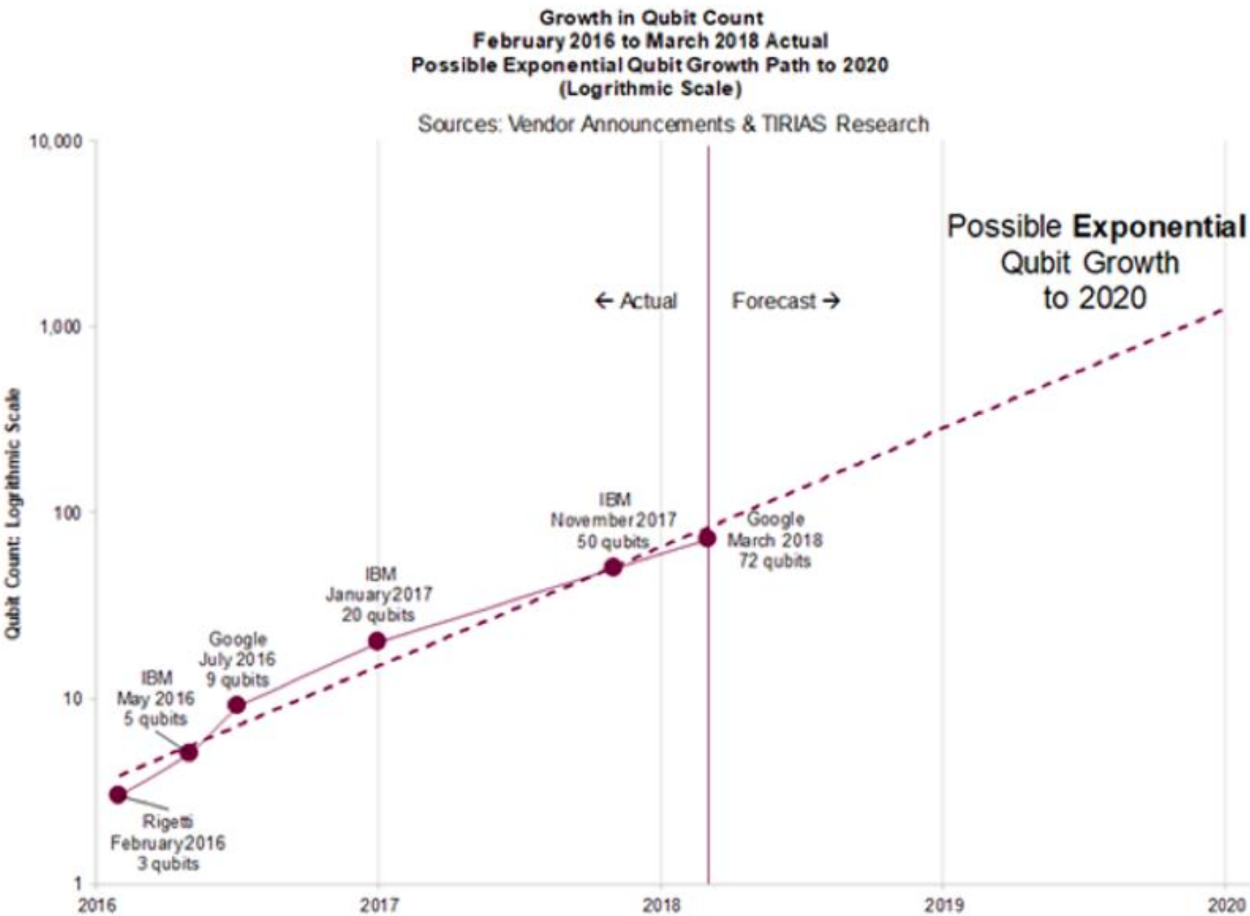
How Long Until A Billion Qubits?



Growth in qubit number is currently **exponential**

If growth continues exponentially (with both fidelity and technical substrate scaling favorably) then we can expect chips with one billion qubits in:

~10-15 years

How Many Qubits is "Enough"?

- Suppose our goal is to implement **Shor's Algorithm** to factor an **n-bit** integer. For example, strong RSA encryption uses 2048-bit keys.
  - Need: **2n** qubits minimum to implement algorithm
    - RSA needs 4096 qubits - about 2 orders of magnitude more than state-of-the-art quantum computing hardware (a few years away)
  - **Caveat: qubits need to be perfect - no laboratory qubit is perfect**

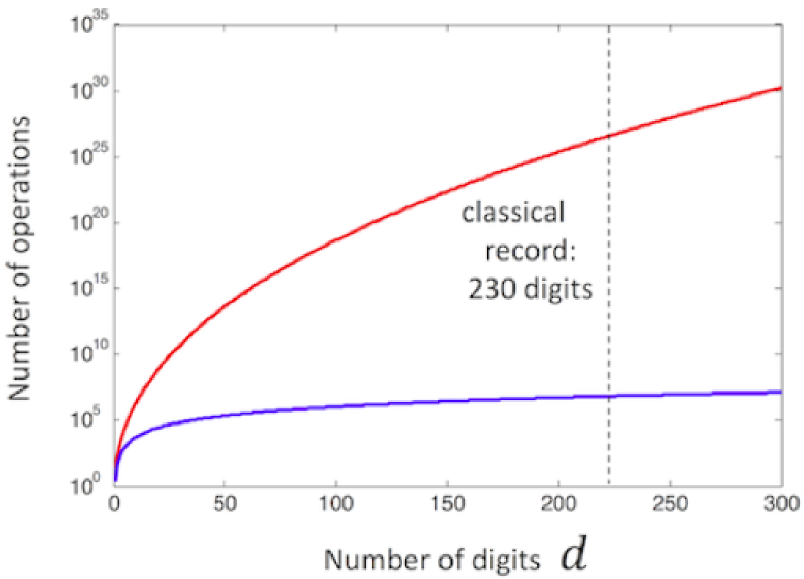
- Hidden resource cost : **Quantum Error Correction**
  - **Quantum coherence is very sensitive**
  - To protect against decoherence, **need to encode quantum information redundantly**

  - **Idea : compose "Logical" qubits out of many "Physical" qubits**

Example: Shor's Algorithm

To **factorize an n-bit integer**, reduce the problem to a period-finding problem, then apply the quantum Fourier transform to exponentially speed it up. Since the resulting superpositions are periodic by construction, the main caveat of the QFT is mitigated.

$$O(e^{1.7(\log n)^{1/3}(\log\log n)^{2/3}})\ \text{(number sieve)} \longrightarrow O((\log n)^2(\log\log n)(\log\log\log n))\ \text{(Shor)}$$

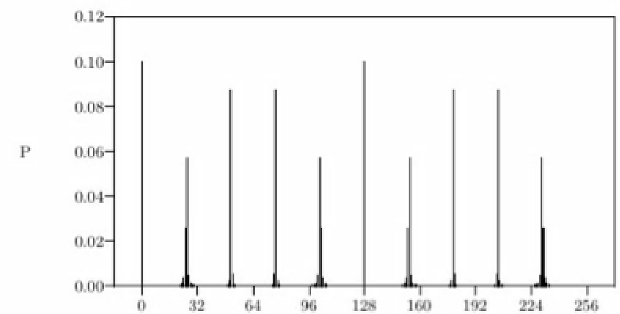


$\exp(\text{const} \times d^{1/3})$

best classical algorithm (number field sieve)

$\text{const} \times d^{3}$

Shor's algorithm



Measured output : sparse, easy to sample

Useful for breaking encryption!

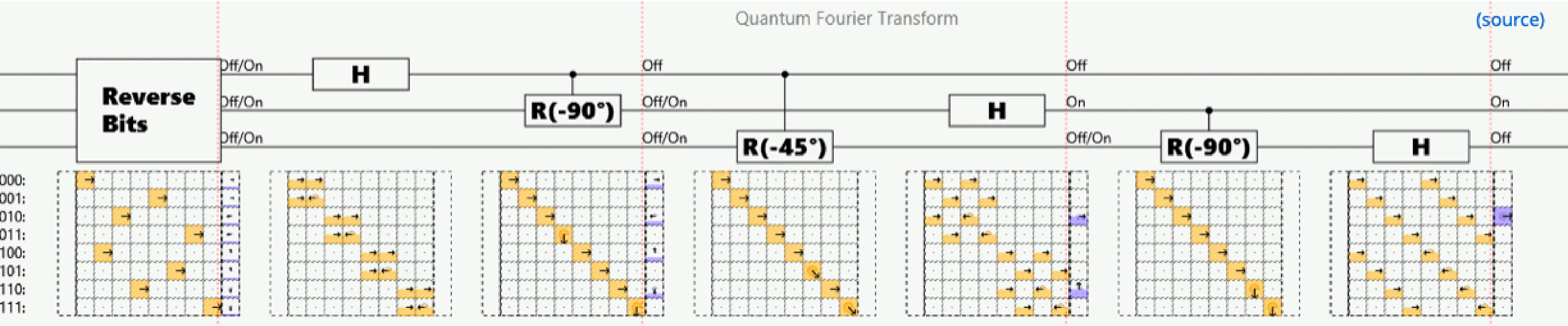
Public key encryption (RSA) relies on the factoring of integers to be difficult

Example: Quantum (Fast) Fourier Transform

Suppose a periodic sequence can be encoded as the amplitudes of a superposition

The quantum Fourier transform (QFT) finds periodicity in polynomial operations

steps per n bits: $2^n(2^{n+1} - 1)\ (\mathrm{DFT}) \longrightarrow 3n2^n\ (\mathrm{FFT}) \longrightarrow (n^2+n)/2\ (\mathrm{QFT})$



$$|\psi\rangle = |000\rangle + i|001\rangle - |010\rangle - i|011\rangle + |100\rangle + i|101\rangle - |110\rangle - i|111\rangle$$

$\Rightarrow \hat{F}|\psi\rangle = |010\rangle$ Detects that each successive phase factor is: $(e^{2\pi i/8})^2$

Caveat: Answer stored as *superposition*. Must *randomly sample outputs* to measure.

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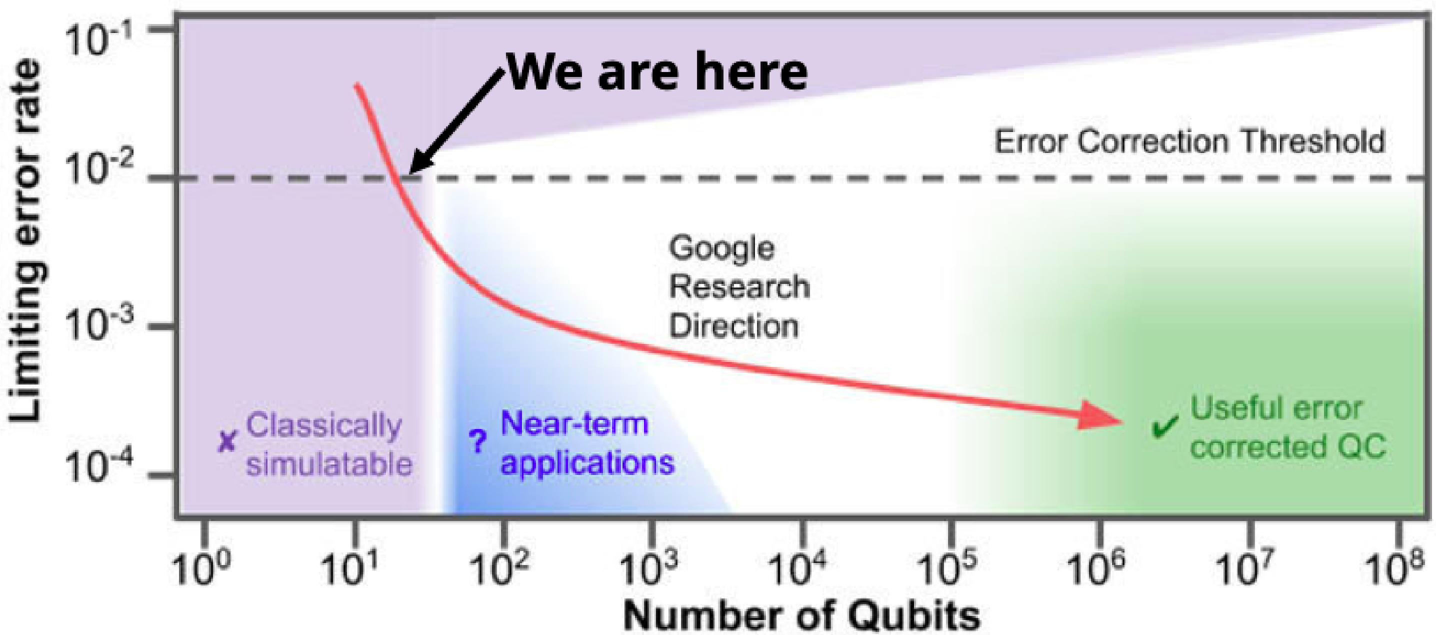
What can we do until then?



Google Slides

We are now reaching the scale that is no longer possible to simulate using classical supercomputers.

The current challenge is to find "near-term" applications for the existing quantum devices.

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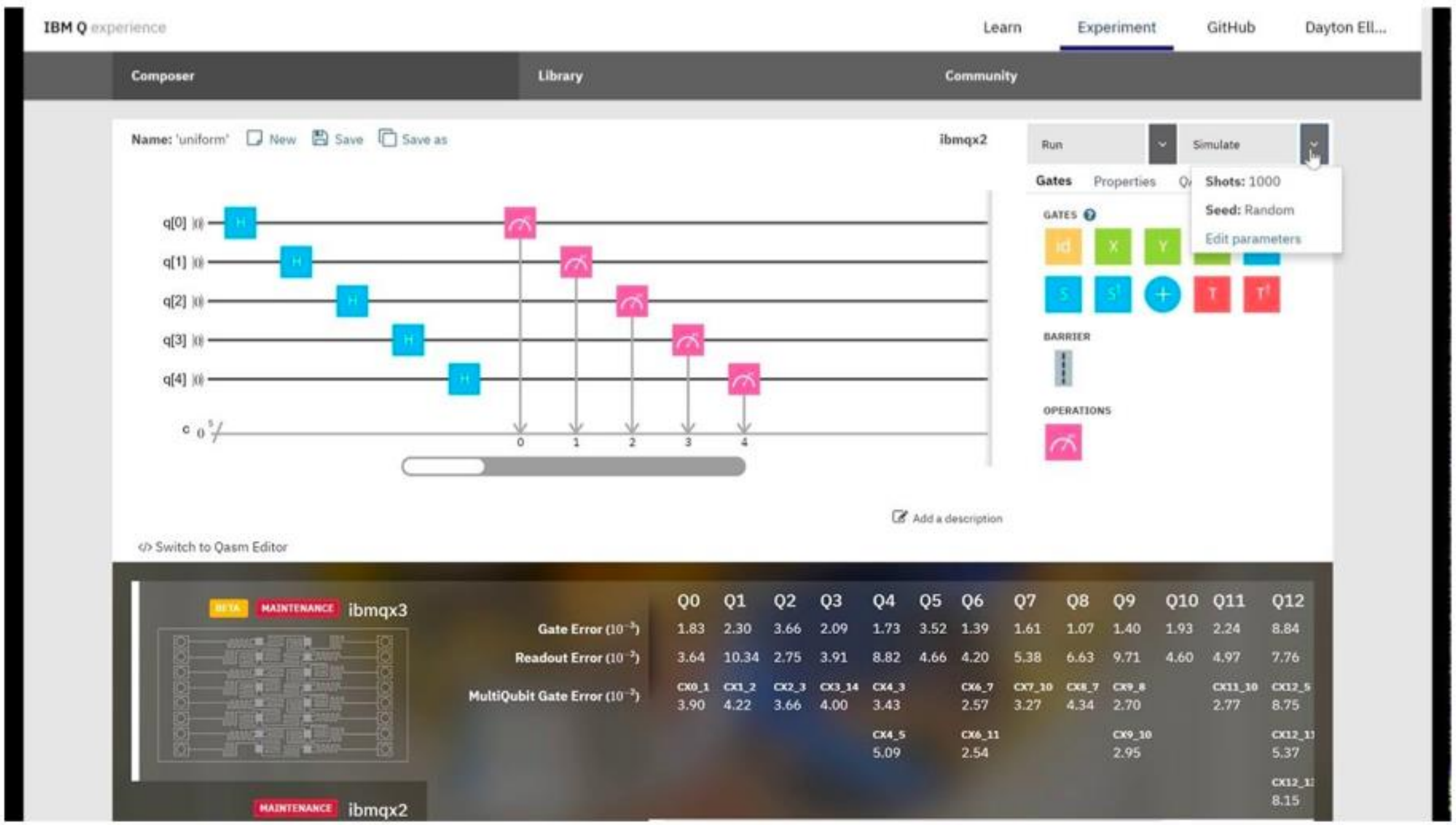
Program a Quantum Computer Now



IBM Quantum Experience : Cloud Computer (16 qubits free, 20+ paid)

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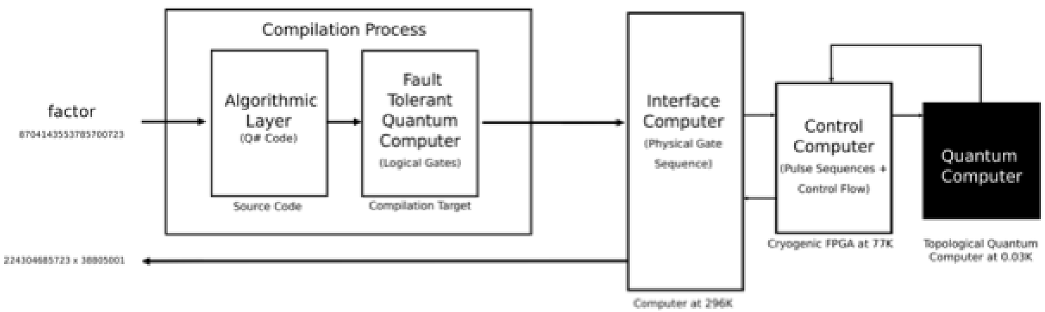
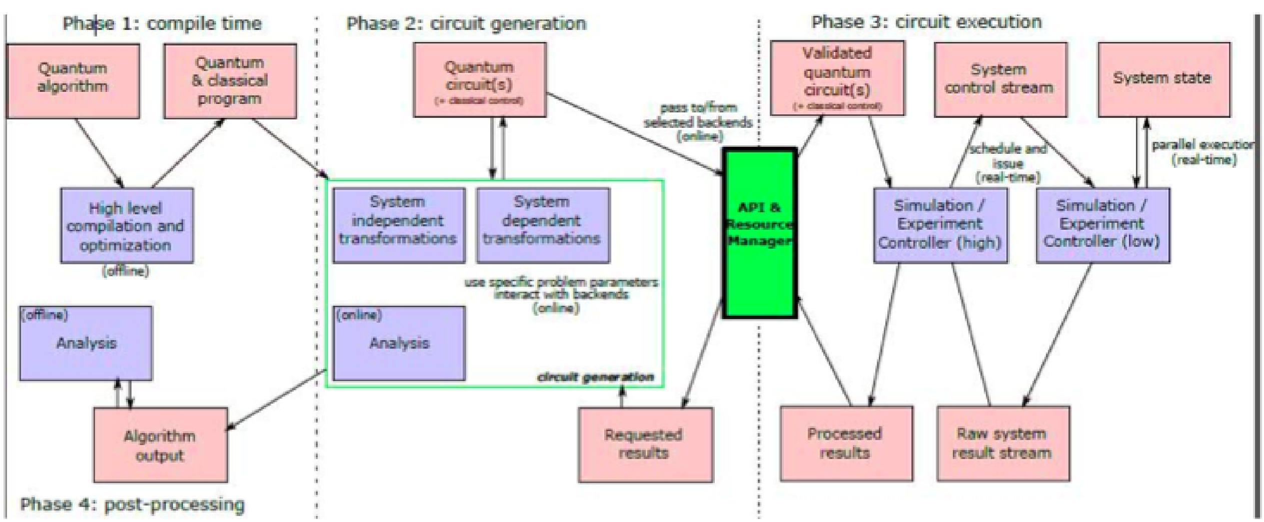
Quantum Software Stacks

Microsoft : Q#, Quantum Dev Kit, LiQui|>




```
operation Teleport(msg : Qubit, there : Qubit) : (
    body {
        using (register = Qubit[1]) {
            let here = register[0];
            H(here);
            CNOT(here, there);
            CNOT(msg, here);
            H(msg);
            // Measure out the entanglement.
            if (M(msg) == One)  { Z(there); }
            if (M(here) == One) { X(there); }
        }
    }
}
```

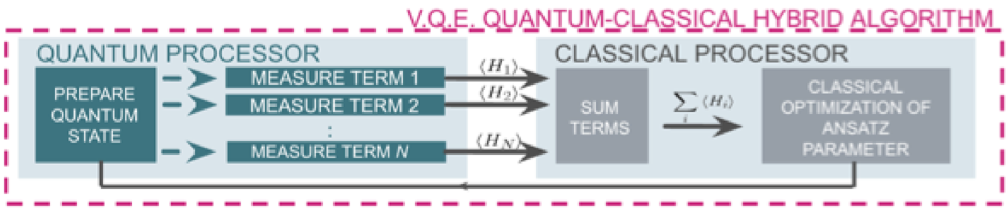
IBM : QISKit SDK




```
from qiskit import ClassicalRegister, QuantumRegiste
from qiskit import QuantumCircuit, execute
from qiskit.tools.visualization import plot_histogra

# set up registers and program
qr = QuantumRegister(16)
cr = ClassicalRegister(16)
qc = QuantumCircuit(qr, cr)

# rightmost eight (qu)bits have ')' = 00101001
qc.x(qr[0])
qc.x(qr[3])
qc.x(qr[5])

# second eight (qu)bits have superposition of
# '8' = 00111000
# ';' = 00111011
# these differ only on the rightmost two bits
qc.h(qr[9]) # create superposition on 9
qc.cx(qr[9],qr[8]) # spread it to 8 with a CNOT
qc.x(qr[11])
qc.x(qr[12])
qc.x(qr[13])

# measure
for j in range(16):
    qc.measure(qr[j], cr[j])
```

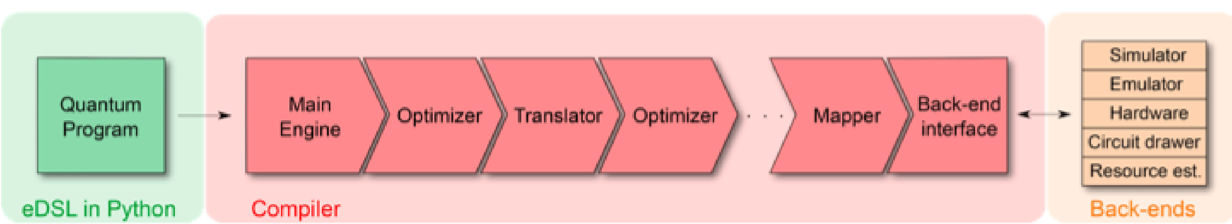
More Quantum Software Stacks

Rigetti Computing : Forest, Quil, PyQuil




```
from math import pi

def qft3(q0, q1, q2):
    p = Program()
    p.inst( H(q2),
            CPHASE(pi/2.0, q1, q2),
            H(q1),
            CPHASE(pi/4.0, q0, q2),
            CPHASE(pi/2.0, q0, q1),
            H(q0),
            SWAP(q0, q2) )
    return p
```

Opensource : ProjectQ




```
from projectq import MainEngine
from projectq.backends import CircuitDraw
from teleport import create_bell_pair

# create a main compiler engine
drawing_engine = CircuitDrawer()
eng = MainEngine(drawing_engine)

create_bell_pair(eng)

eng.flush()
print(drawing_engine.get_latex())
```

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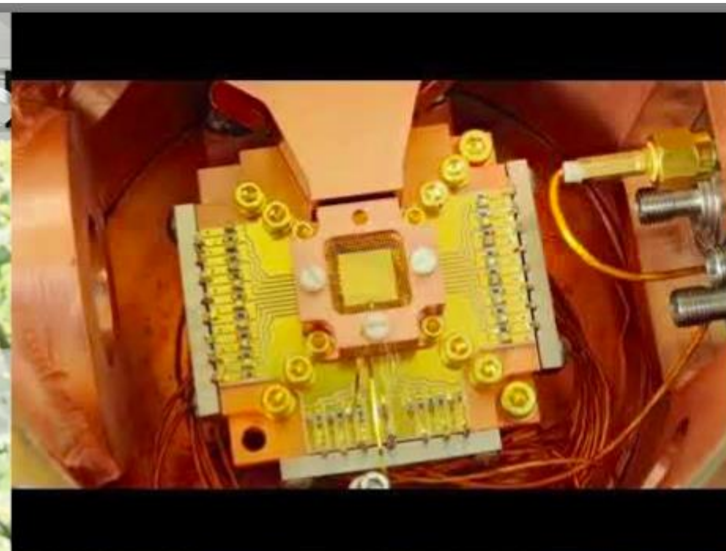

Jay Gambetta, Jerry Chow

IBM Q

IBM Q Prototype 50 qubits

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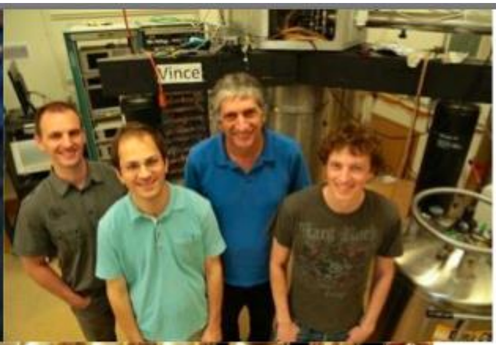

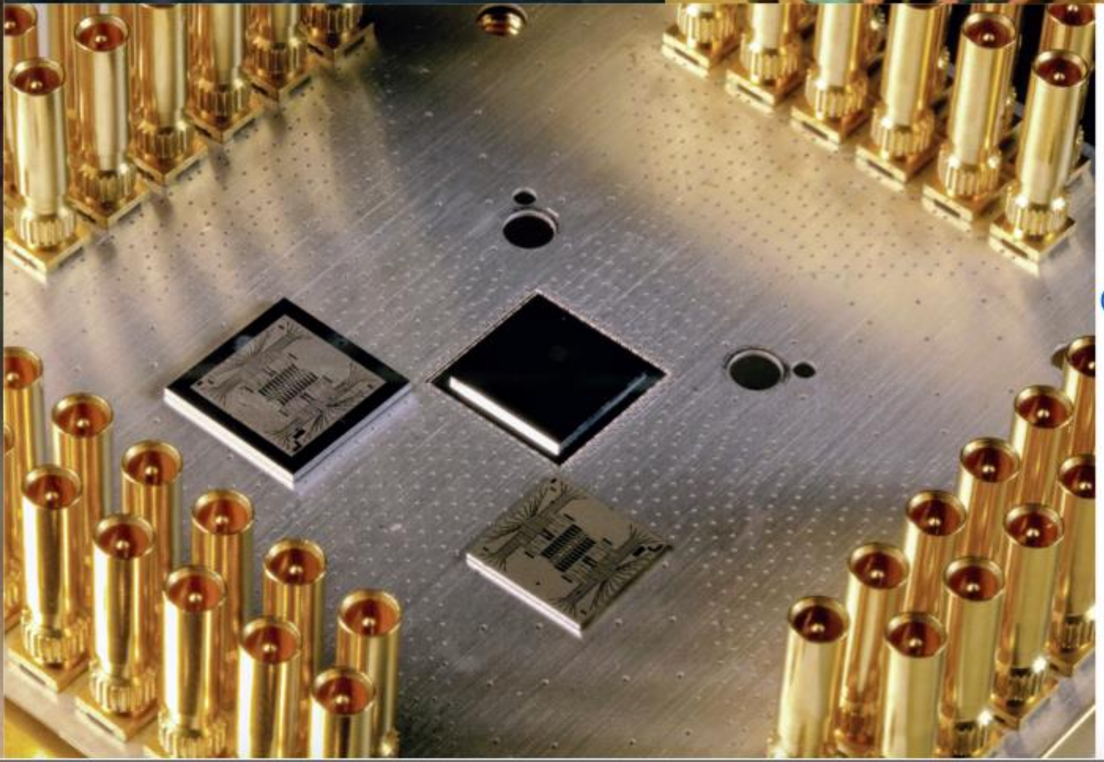

Hartmut Neven, John Martinis,

Google Quantum AI Lab

Bristlecone Chip
72 qubits

18

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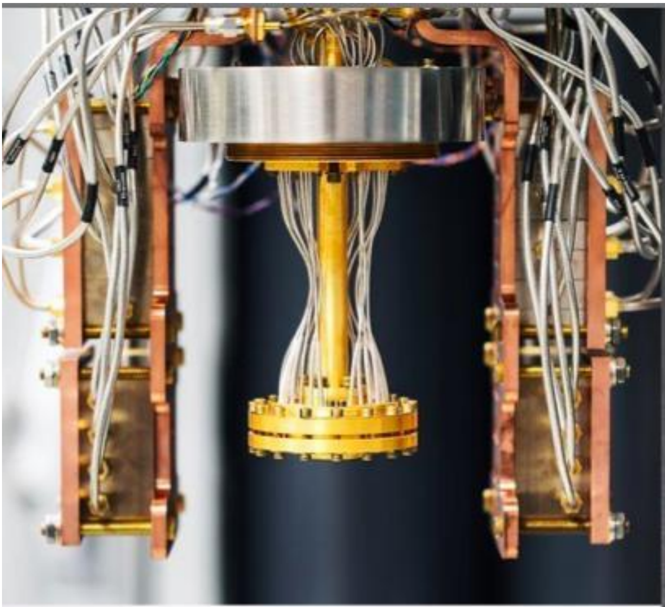

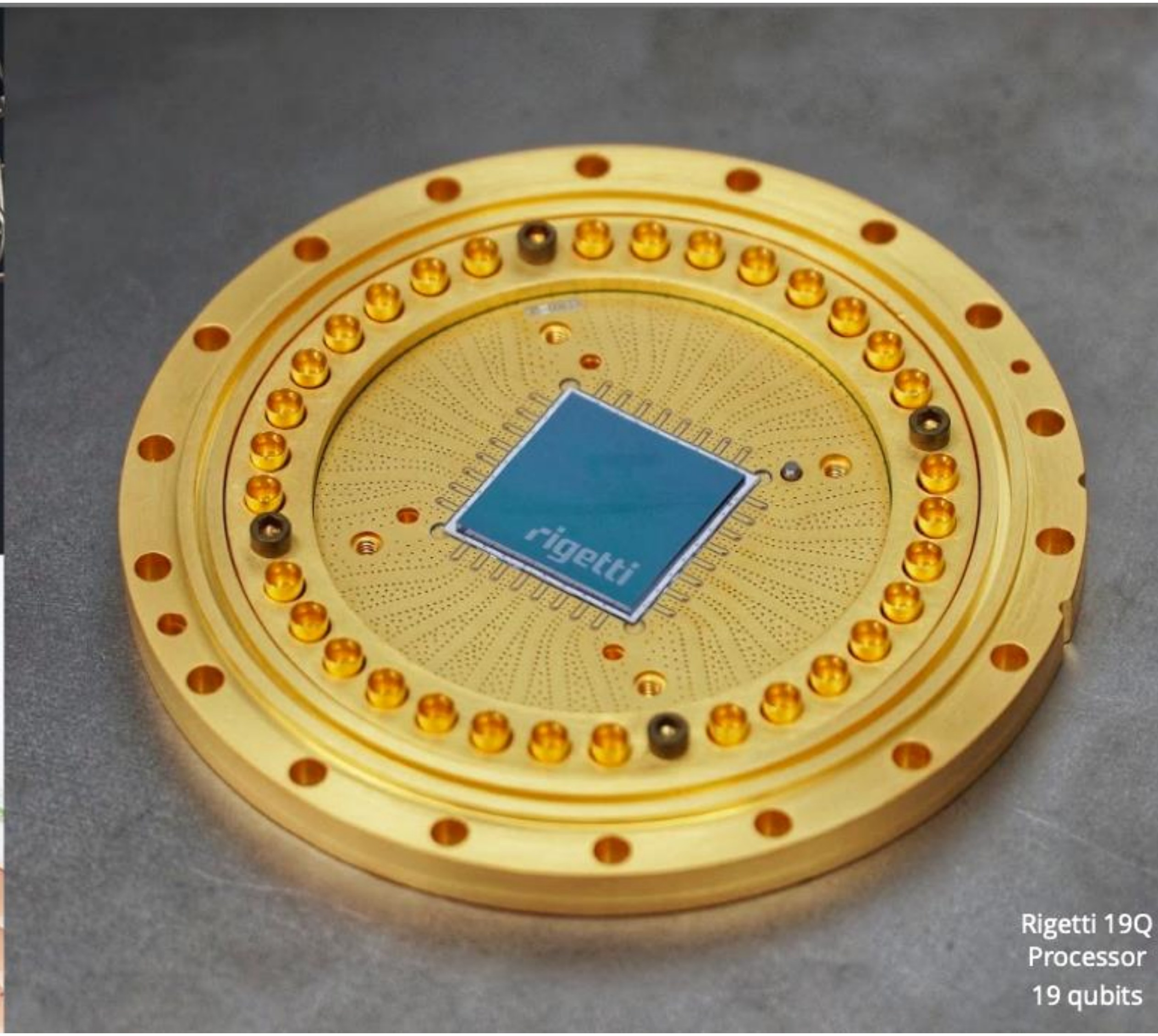

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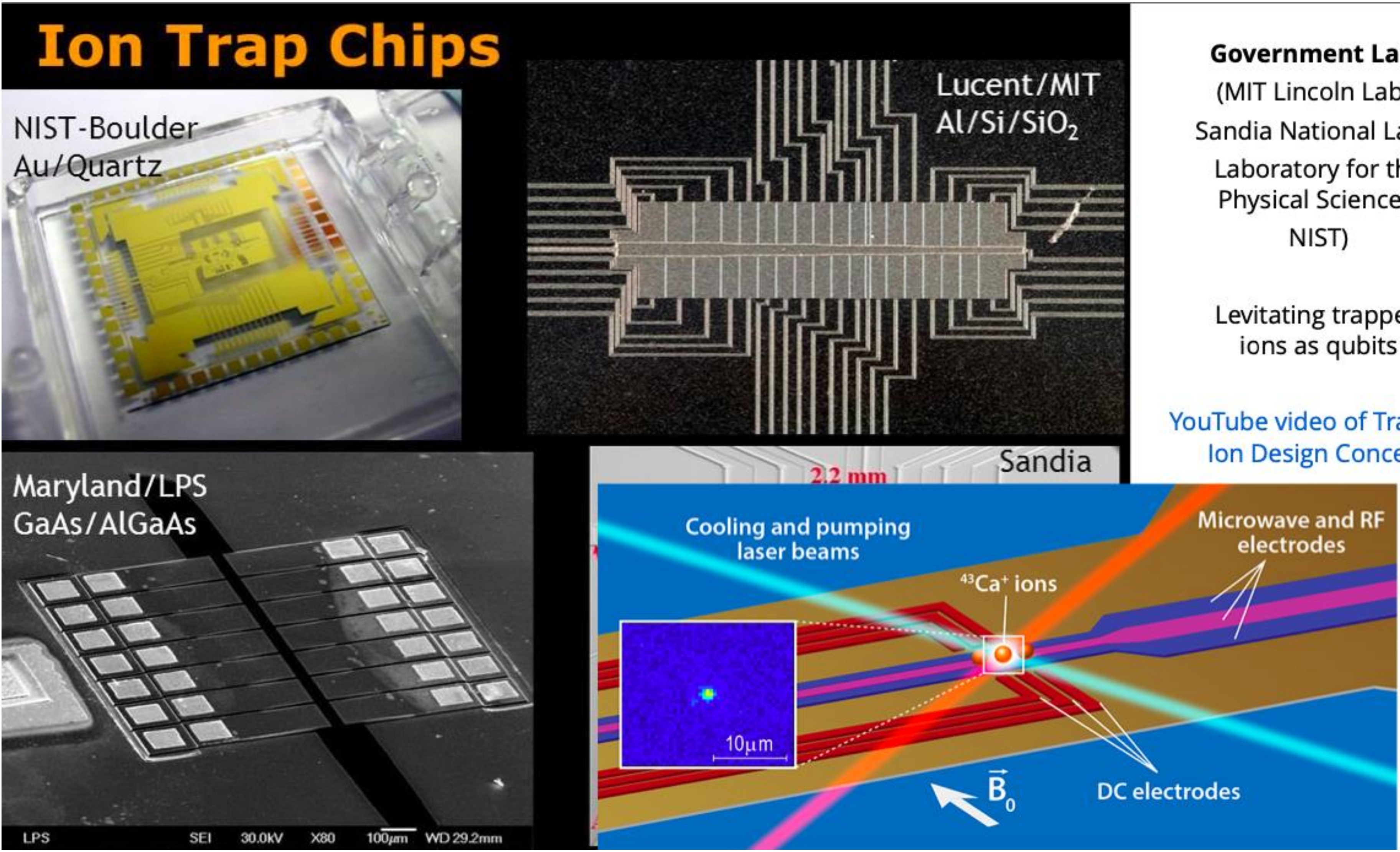

Government Labs
(MIT Lincoln Labs,
Sandia National Labs,
Laboratory for the Physical Sciences,
NIST)

Levitating trapped ions as qubits

YouTube video of Trapped Ion Design Concept

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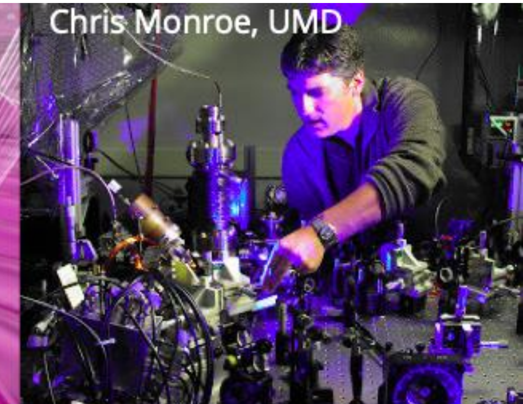
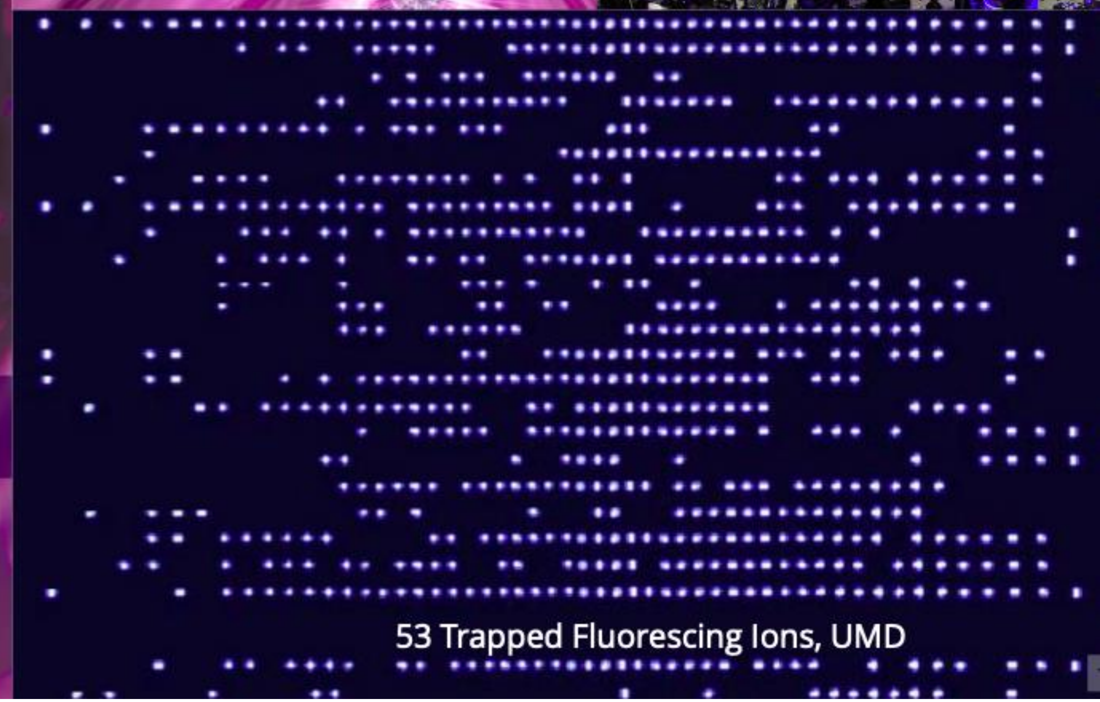
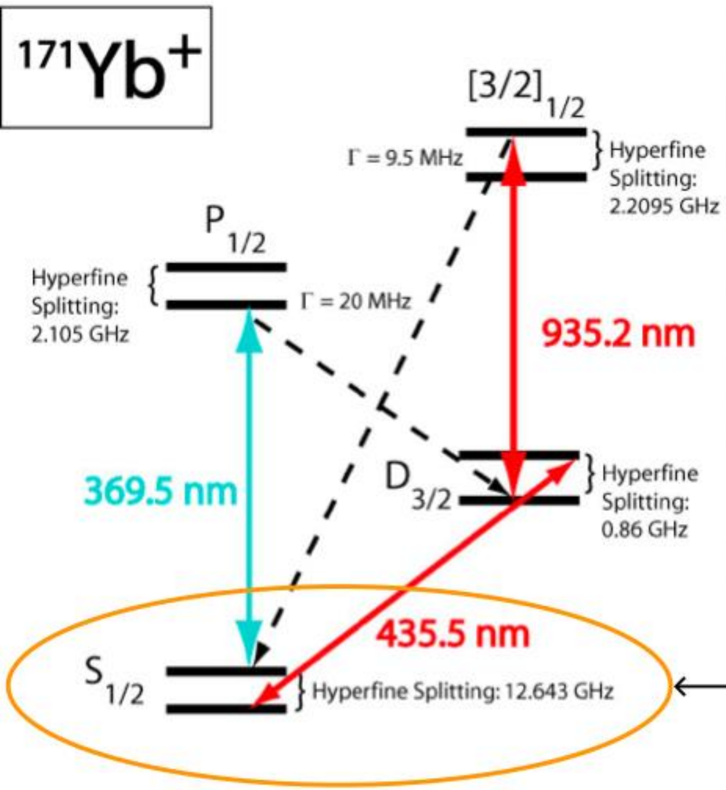
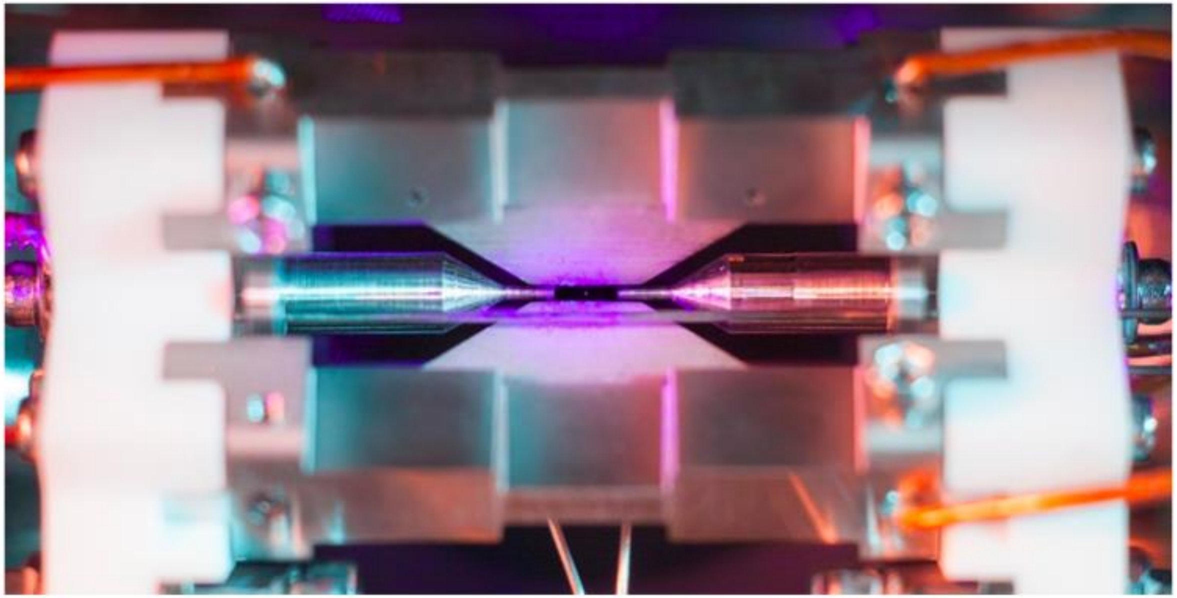




Technology 1 : Trapped Ions





A trapped ion qubit is a superposition of the lowest two magnetic hyperfine energy levels of an ion (like Ytterbium or Calcium)

Such ions are trapped and cooled with lasers, then manipulated with more lasers

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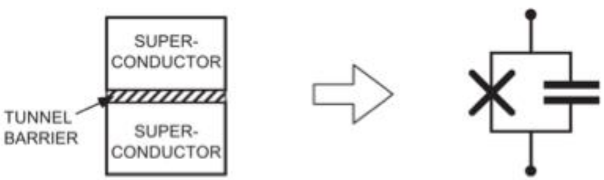
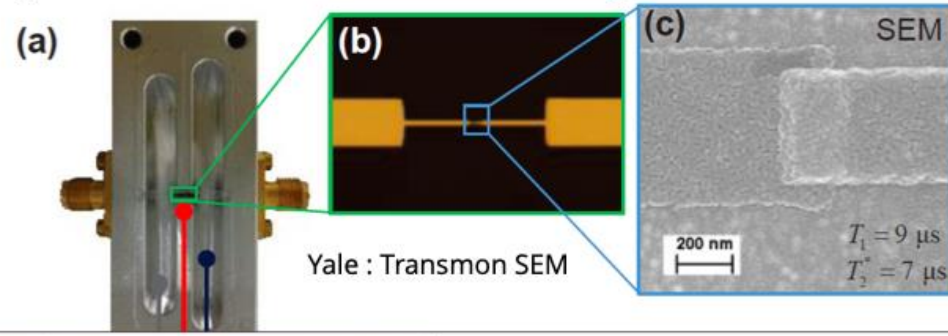
Technology 2 : Superconducting Qubits

A superconducting (transmon) qubit is a superposition of the lowest two energy levels of a charge oscillation (an "artificial atom") across a nonlinear inductive tunnel barrier attached to a capacitive antenna

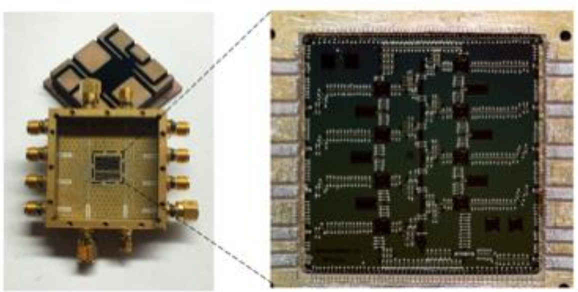




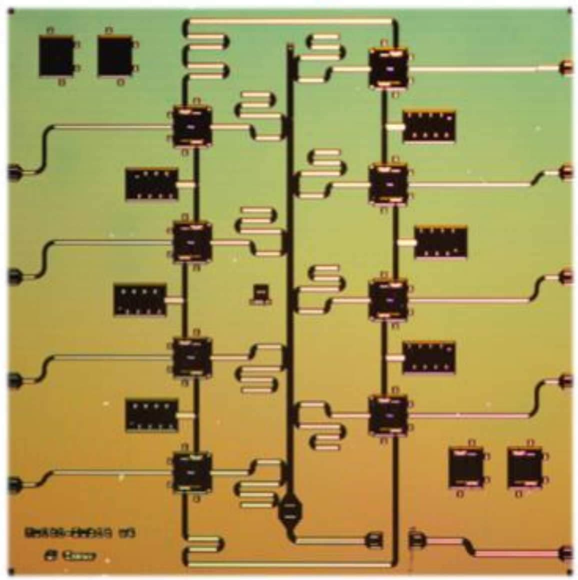
Yale : Transmon SEM

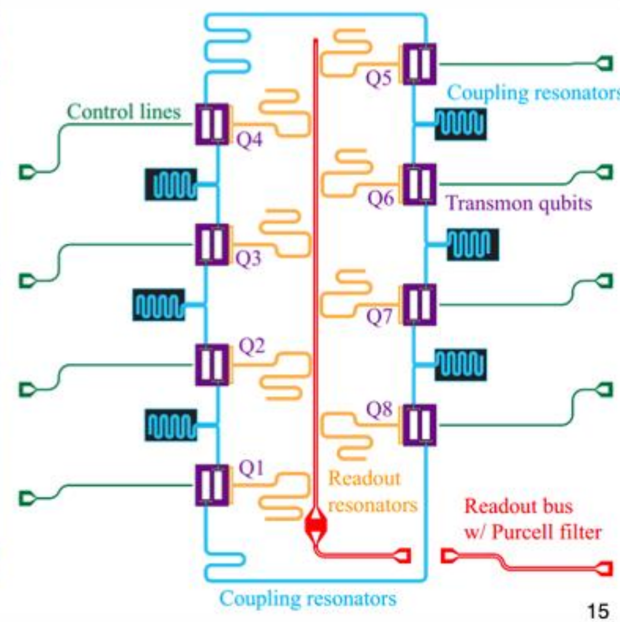
Controlled with all electrical AC signals at microwave frequencies

Cooled to mK temperatures



UC Berkeley : 8 qubit chip





ACM Tech Talk

Quantum Computing

Seismic Shifts: Challenges and Opportunities in the 'Post-ISA' Era of Computer Systems Design

Education
ACM Learning Center

Compiled by Dr Jeff Drobman

- Focus on a hybrid *classical – quantum* distributed architecture

SPEAKER

Margaret Martonosi @Professor of Computer Science, Princeton University

Margaret Martonosi is the Hugh Trumbull Adams '35 Professor of Computer Science at Princeton University. Dr. Martonosi's research interests are in computer architecture and hardware-software interface issues in both classical and quantum computing systems. Dr. Martonosi is a member of the U.S. National Academy of Engineering and the American Academy of Arts and Sciences. She is a Fellow of ACM and IEEE. She was the 2021 recipient of the ACM/IEEE Eckert-Mauchly Award.

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Professional Ethics: https://ethics.acm.org

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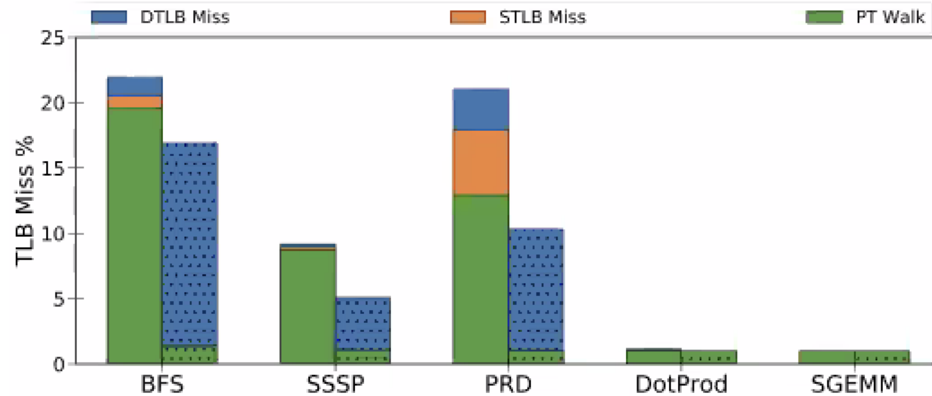
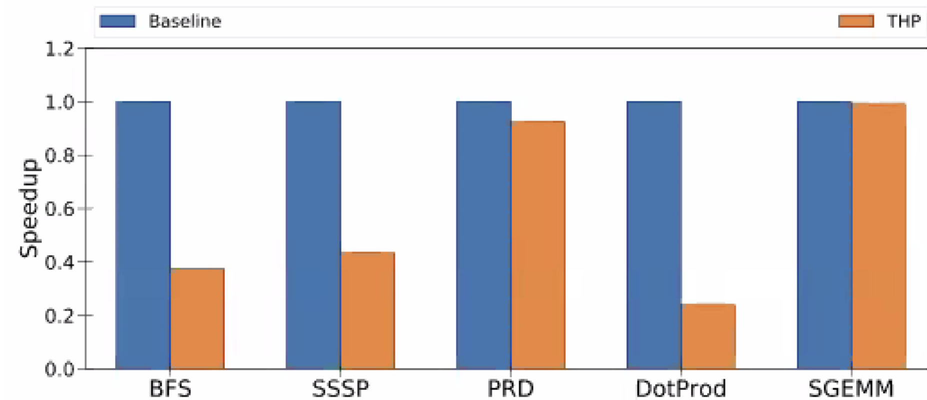
Page Size

Example 1: OS Page Size Management Tailored Graph Analytics

- Graph analytics have high TLB miss rates that cause address translation overheads
- Huge pages (2MB on x86) can alleviate such overheads with increased TLB reach
- Modern OS policies greedily (over)allocate huge pages due to lack of app knowledge
- Need: OS techniques to intelligently manage huge pages tailored for graph analytics



TLB miss rates without (left) and with (right) THPs; graph analytics have high miss rates compared to dense apps



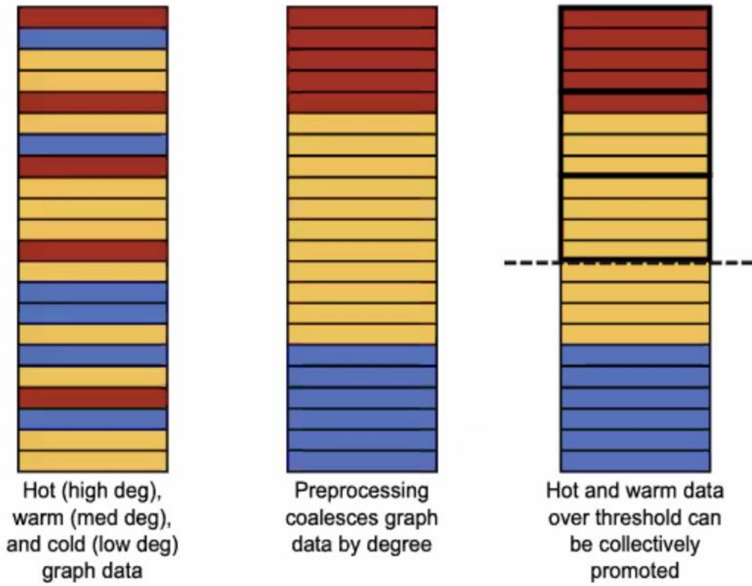
Runtime speedups without (left) and with (right) THPs; Linux THP causes slowdown when memory is constrained

Page Size

Intelligent Page Size Management

- Objective: utilize huge pages in an intelligent, application-aware manner where they will bring most benefit (lower TLB miss rate)

- Graph-tailored huge page management:
  - **Preprocess** dataset to coalesce hot pages worth of (high-degree vertex) data
  - Dynamically **promote** hot data based on amount of memory fragmentation
- Promote irregularly accessed data that has highest access frequency

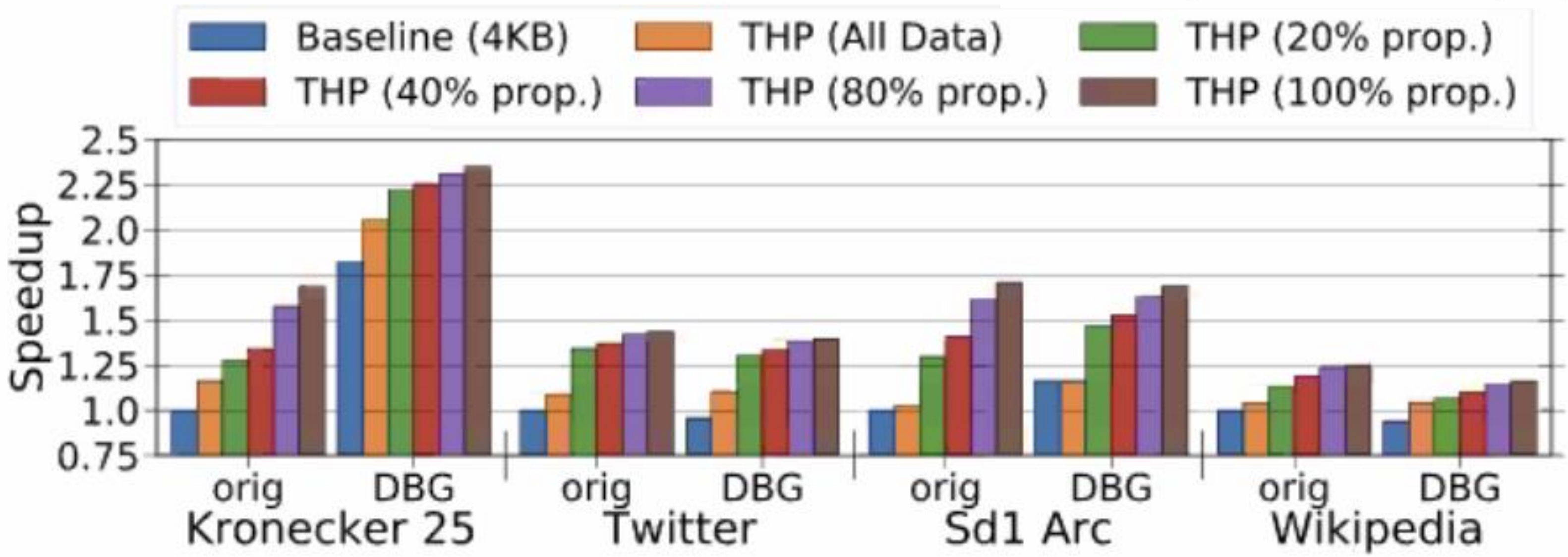


1947 2022 Association for Computing Machinery

Page Size

Results and Takeaways

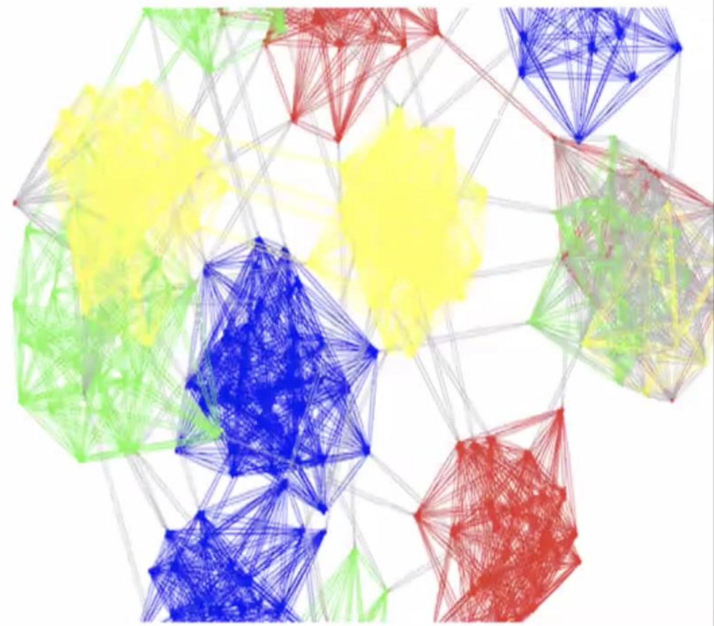
- Leveraging application knowledge for huge page allocation and placement best optimizes performance improvements from huge pages in real systems
- For graph analytics, utilize huge pages selectively for hottest percentage of **property array** (frequently and irregularly accessed data)
  - **1.26-1.57x** speedup over 4KB pages
    - **77.3-96.3%** of ideal THP performance
    - Requires only **0.58-2.52%** of application footprint to be backed by huge pages



Runtime speedups comparing THPs applied system-wide vs. selectively to percentage of preprocessed TLB-sensitive prop. array

Example 2: Hardware and Programming Models for Sparse/Graph Applications

- Graph analytics and memory bottlenecks
- Challenges:
  - Little compute per loaded cache line
  - Little data reuse
  - >50% of accesses go to main memory
  - >95% of total energy spent on memory operations
- Prior work mitigates the memory latency, but bandwidth and synchronization remains a problem when scaling to high core counts



Orenes-Vera, Tureci, Wentzlaff, Martonosi. Dalorex: A Data-Local Program Execution and Architecture for Memory-Bound Applications". ArXiv July 2022

Dalorex

Dalorex: A Data-Local Program Execution and Architecture for Memory-bound Applications

- **Data local program execution model**:
  - Data arrays are distributed in equal chunks across tiles
  - Only one core has access to a given data (no copies)

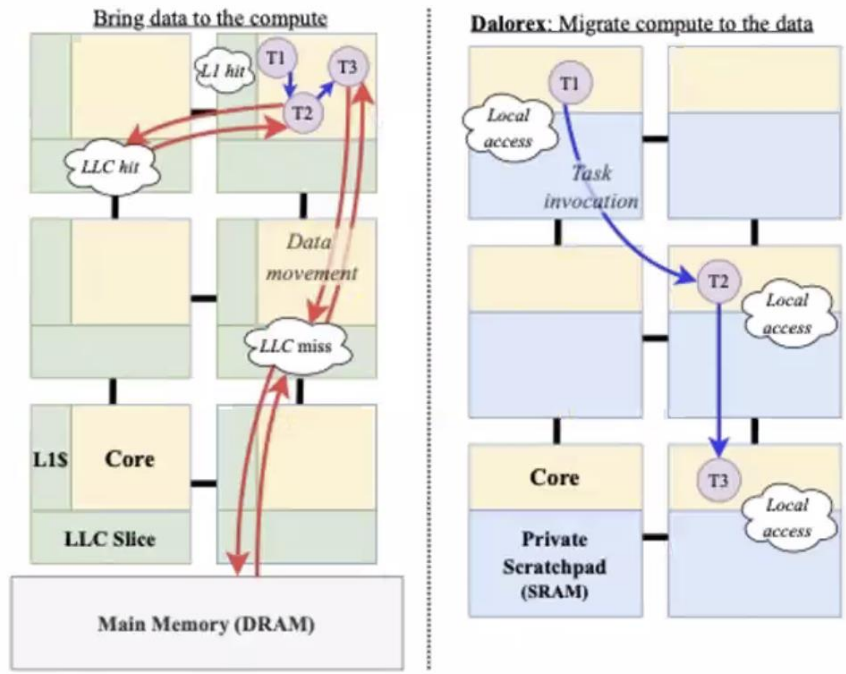
Edge-sized array tuple: chunked among all tiles

Tile 1	Tile 2	Tile 3	Tile 4

Vertex-sized array tuple

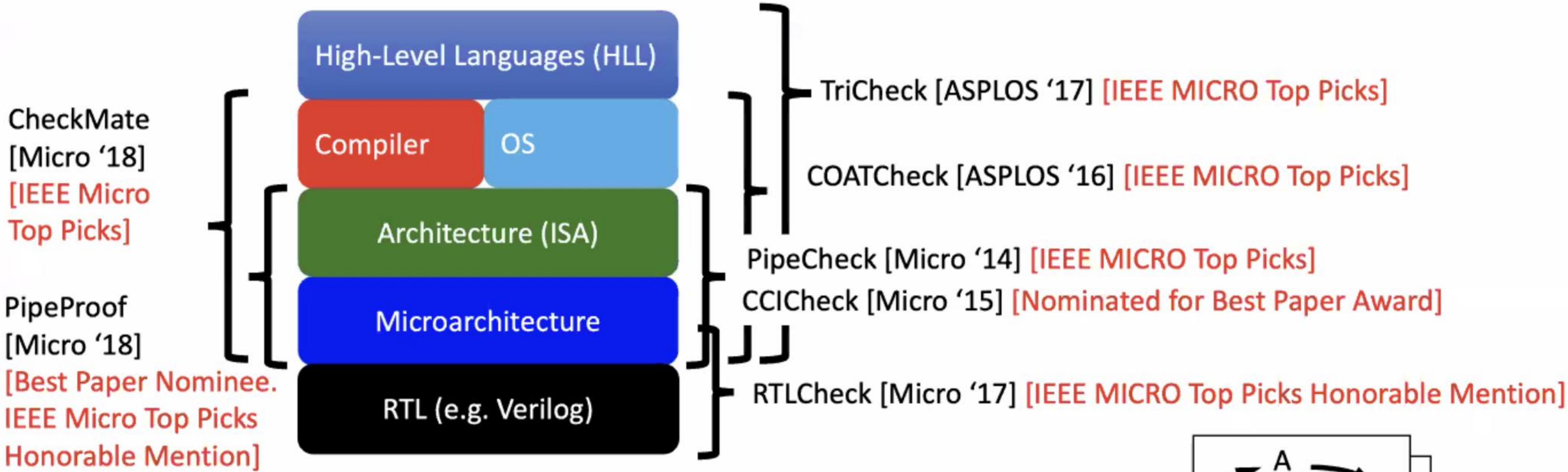
Tile 1	Tile 2	Tile 3	Tile 4

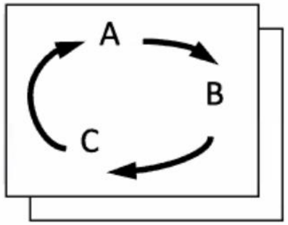
- **Program is sliced at each pointer indirection** resulting in multiple program slices (tasks)
  - All tiles are homogeneous, they can perform any task
  - A task is performed in the core where data is local
  - Tasks can invoke other tasks by placing the tasks parameters in the on-chip network.
  - The first parameter is an index to the distributed array
- **Dalorex** provides a new programming model and architecture to support task invocations natively
  - Plus optimizations in task scheduling and work-balance!



A **tile** in Dalorex is composed of a local SRAM memory, a stripdown sw-programmable core (no cache) and a route

Example 3: The Check Suite: An Ecosystem of Tools For Early-Stage Verification and Example Synthesis





Our Approach

- Axiomatic specifications -> Happens-before graphs
- Check Happens-Before Graphs via Efficient SMT solvers
  - Cyclic => A->B->C->A... Can't happen

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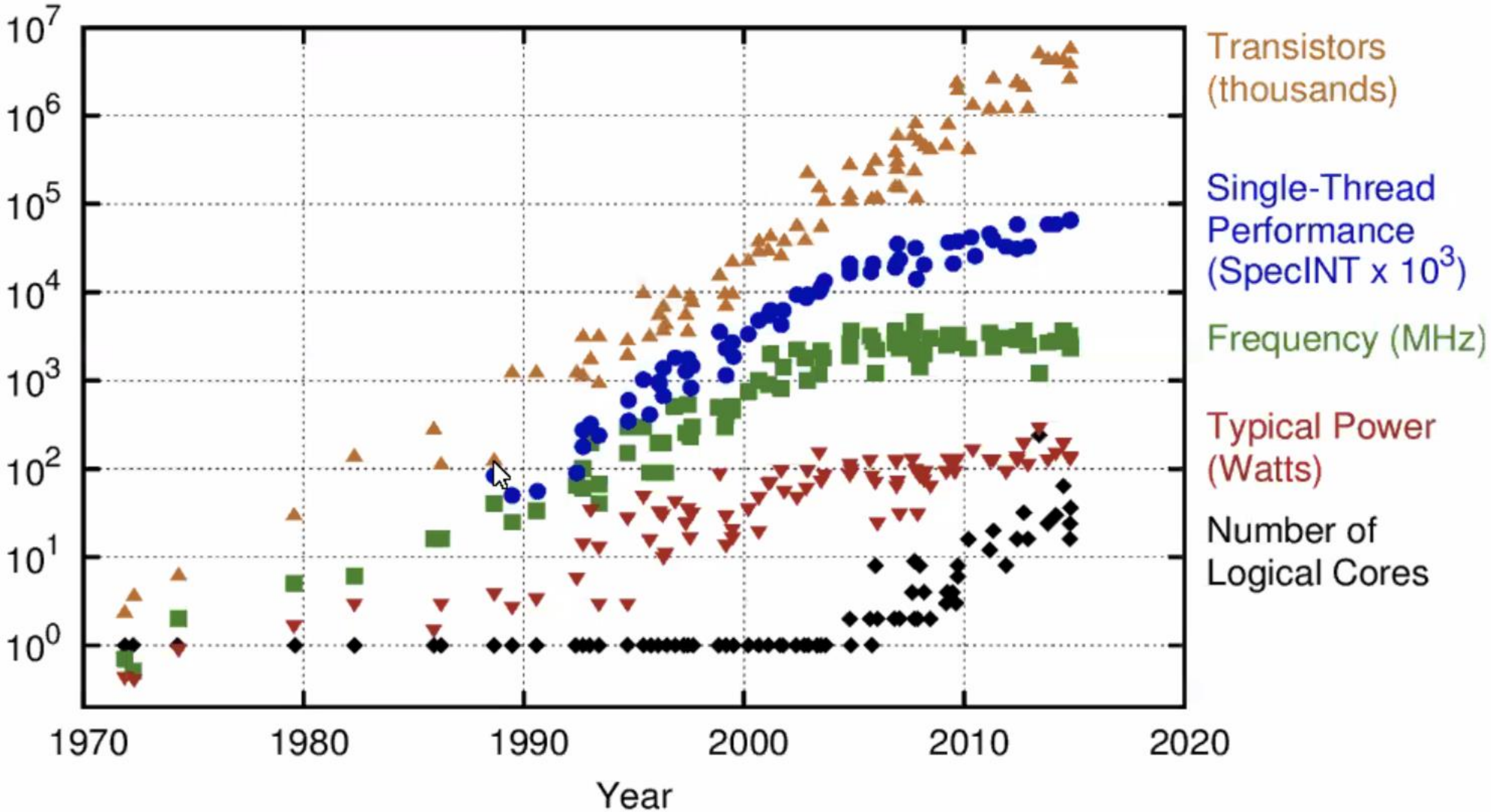
Moore's Law

Decades of Moore's Law scaling

40 Years of Microprocessor Trend Data



Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2015 by K. Rupp

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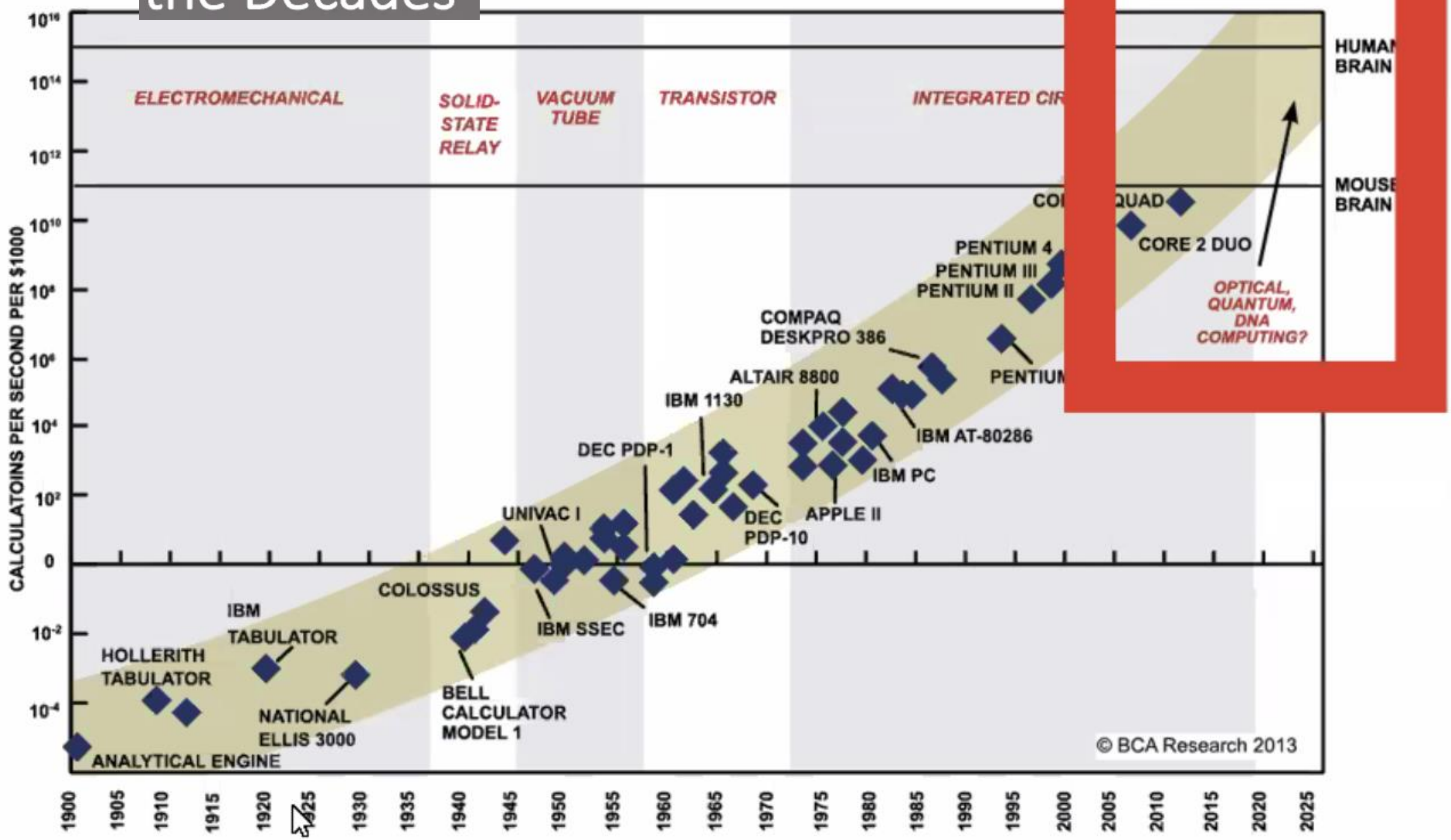
Performance Scaling over the Decades



SOURCE: RAY KURZWEIL, "THE SINGULARITY IS NEAR: WHEN HUMANS TRANSCEND BIOLOGY", P.67, *THE VIKING PRESS*, 2006. DATAPOINTS BETWEEN 2000 AND 2012 REPRESENT BCA ESTIMATES.

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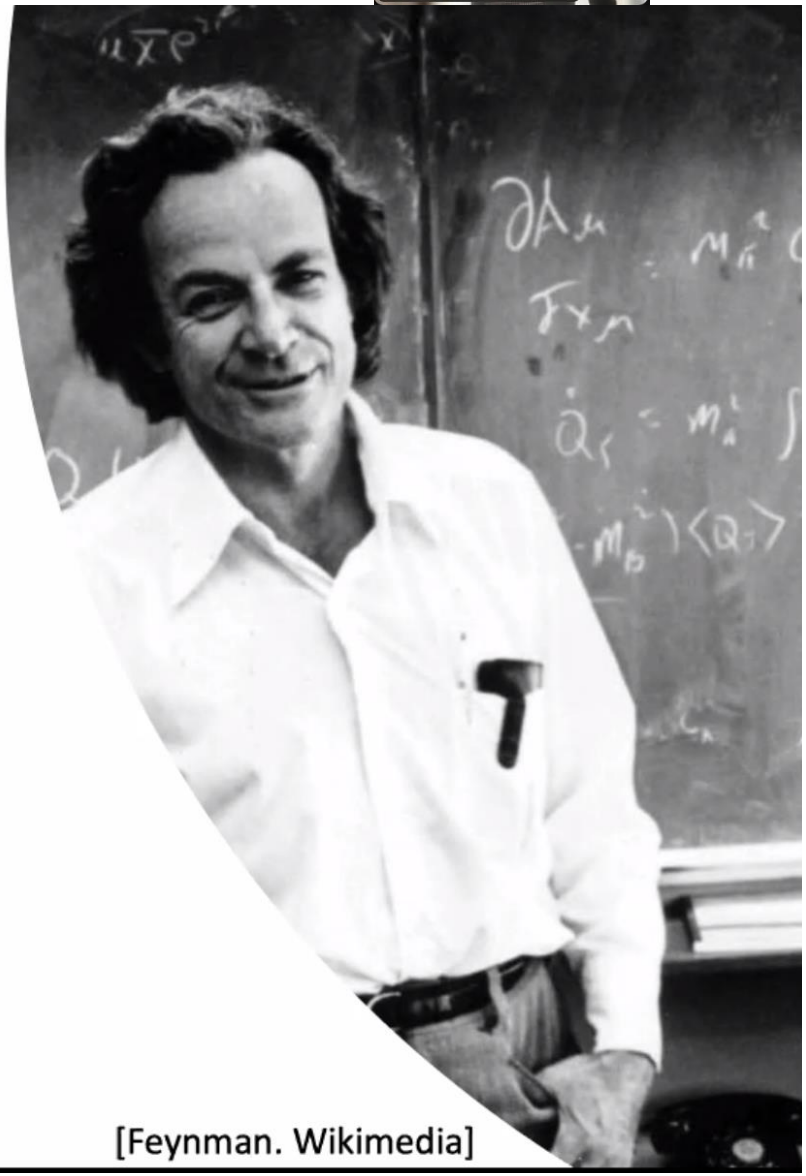
Feynman: Simulating the Physical World

"The full description of quantum mechanics for a large system with R particles … has too many variables, it cannot be simulated with a normal computer with a number of elements proportional to R or proportional to N…

And therefore, the problem is, how can we simulate the quantum mechanics? …. We can give up on our rule about what the computer was, we can say:

Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws. "



[Feynman. Wikimedia]

Key Enablers of Quantum Speedups

- Superposition of states within a quantum bit (qubit)
  - Large and probabilistic representation of possibilities
- Entanglement of states between qubits
  - Correlations between qubit states, once entangled.
  - Einstein: ”Spooky action at a distance”

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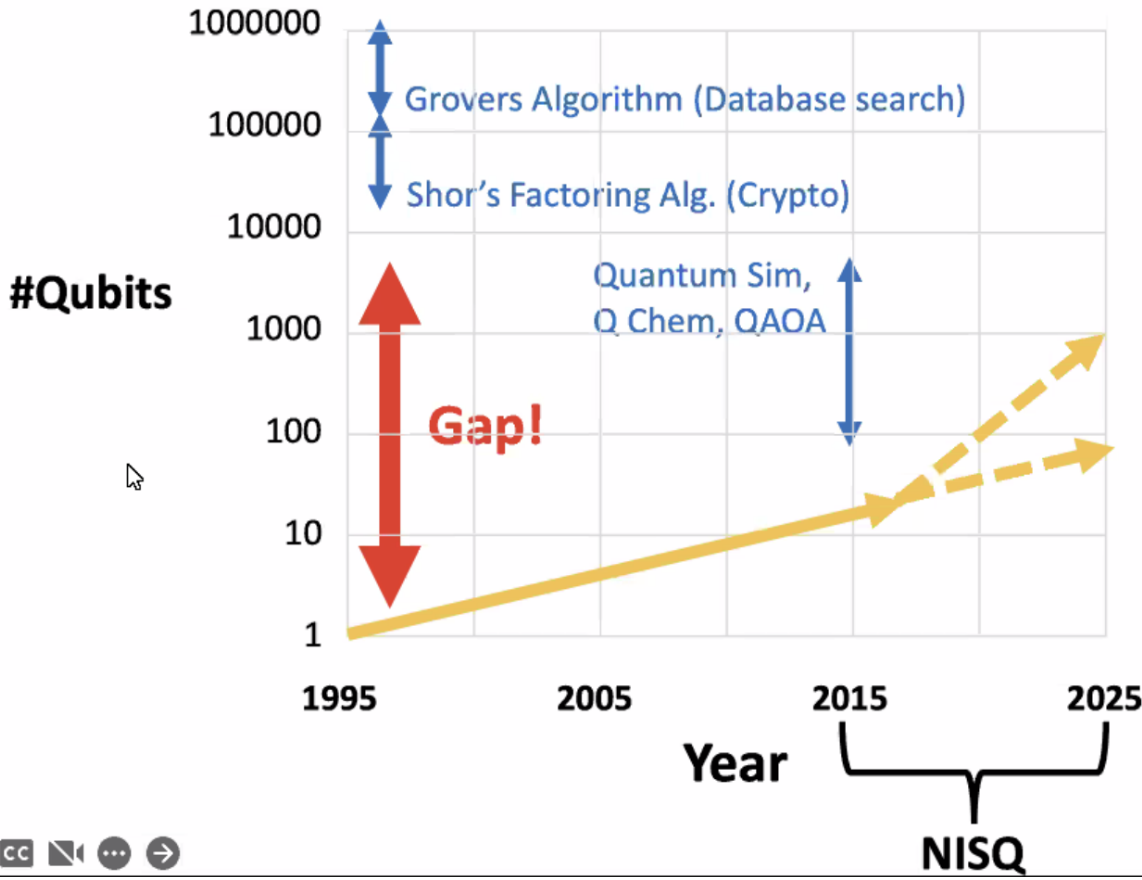
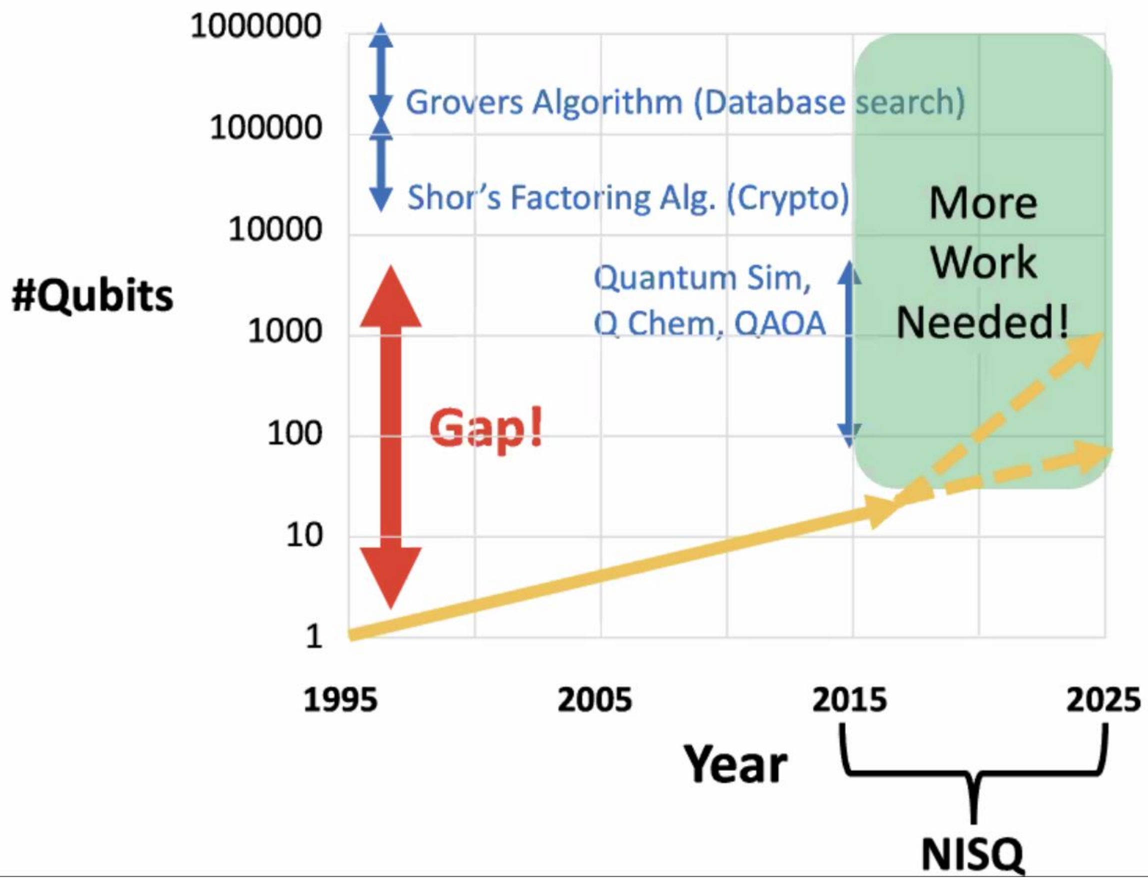
QC Algorithms to Machines Gap: The NISQ Era



- Noisy Intermediate-Scale Quantum (NISQ)
  - Preskill, Jan 2018
  - 10-1000 qubits
- Too small for known algorithms with exponential speedup
- Too small for ECC
- Large enough to support interesting experiments!

QC Algorithms to Machines Gap: Opportunity

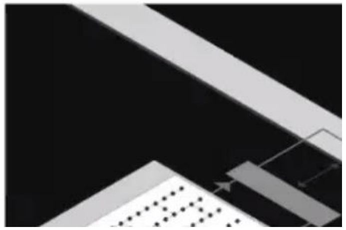


QC programming and design tools that shrink the gap can move the feasibility point years sooner!

- Reduce algorithm qubit requirements
- Improve effectiveness of hardware qubits

Scaling Quantum Systems: Mind the Gap!

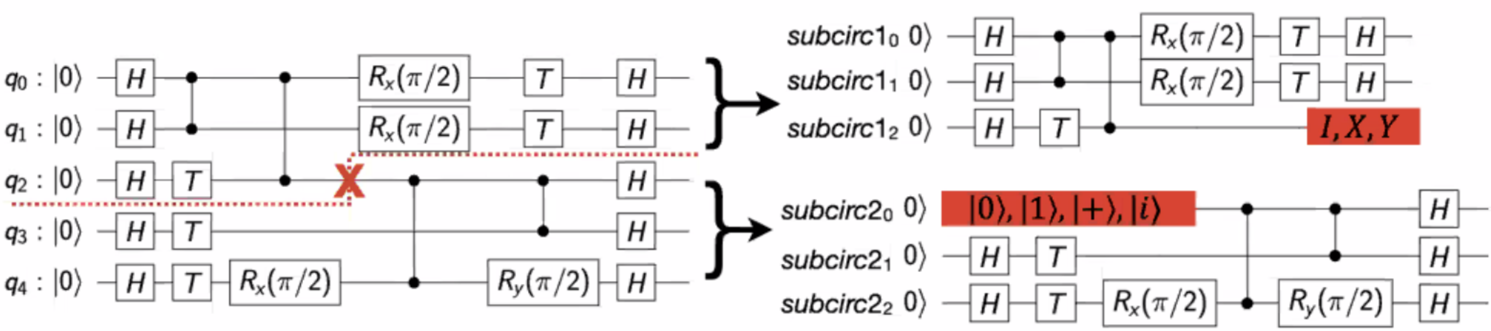
- Today: Small NISQ QC Systems available for use
- For quantum advantage, most algorithms require a large and reliable QPU. But, building such monolithic QPUs is challenging.
  - E.g., 27-qubit IBM Kolkata has 2X the “quantum volume” (capability) of 127-qubit IBM Washington, despite many fewer qubits
- Still much easier to build multiple smaller QPUs.
- How do we make use of the multiple small QPUs to run large target applications?



Example 4: CutQC: Combining Classical and Quantum Computation to Run QC algorithms at Larger Scale

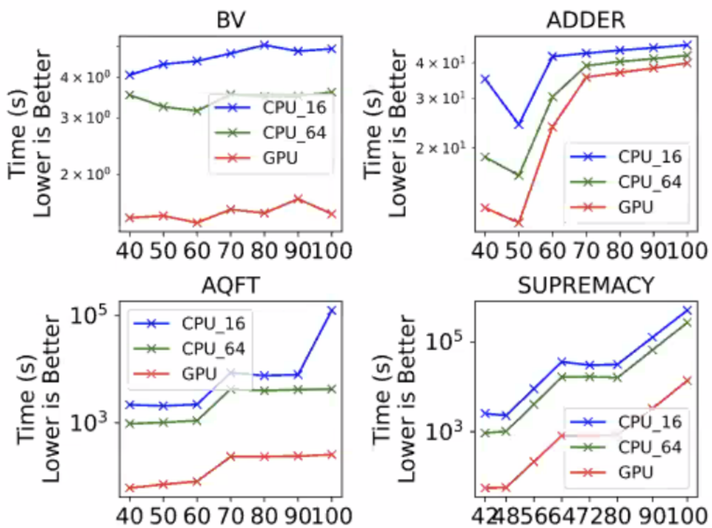
- Approach: Cut quantum circuits into smaller subcircuits that fit and reconstruct the results classically afterward.
- Challenge: Classical reconstruction scales exponentially!
- Solution: parallel processing[1] and GPU[2].

Example: Cut one edge to split a 5-qubit circuit into two smaller (3-qubit each) subcircuits.

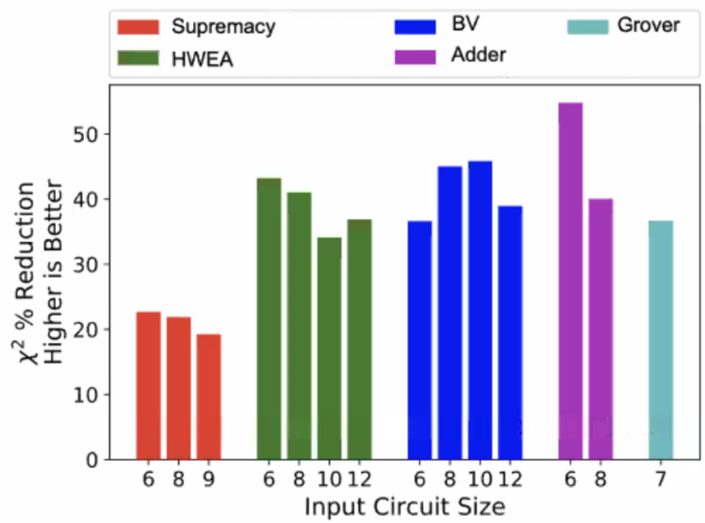


[1]Tang, Wei, Teague Tomesh, Martin Suchara, Jeffrey Larson, and Margaret Martonosi. "Cutqc: using small quantum computers for large quantum circuit evaluations." In *Proceedings of the 26th ACM International conference on architectural support for programming languages and operating systems*, pp. 473-486. 2021.
[2]Tang, Wei, and Margaret Martonosi. "Cutting Quantum Circuits to Run on Quantum and Classical Platforms." *arXiv preprint arXiv:2205.05836* (2022).

Result: Runtime and Fidelity Improvements



Faster than classical.



Higher fidelity than large monolithic QPUs.

- Cut and run benchmarks with up to 75% of number of qubits in input circuits.
- Runtime shows the reconstruction of 2^{30} bins. GPU is the fastest backend as expected.
- CutQC achieves an average of 21% to 47% fidelity improvement

Quantum Systems Today: An Analogy

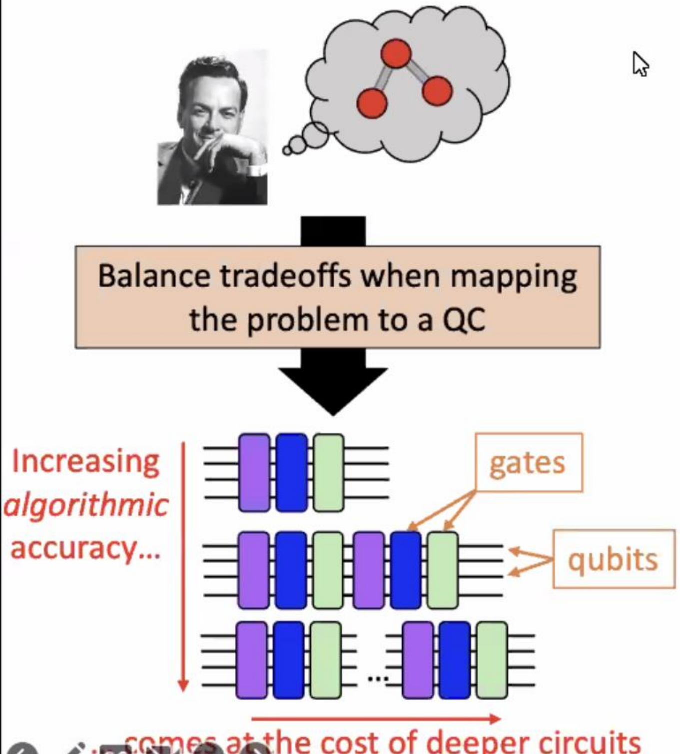
~1950's Classical Computing
- Algorithms
- Assembly Language
- Vacuum Tubes, Relay Circuits

Today's Classical Computing
- Algorithms
- High-Level Languages
- Compiler | OS
- Architecture
- Modular hardware blocks: Gates, registers
- VLSI Circuits
- Semiconductor transistors

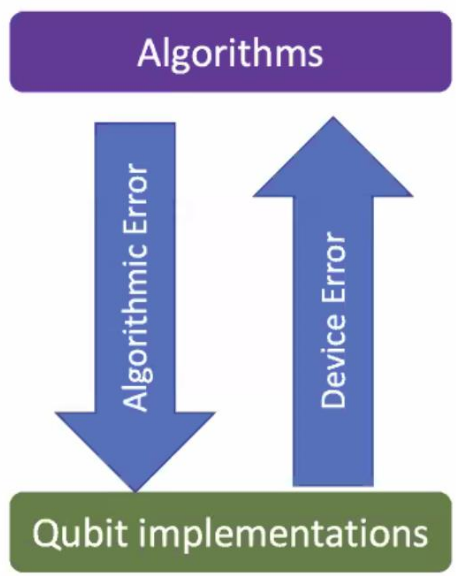
Quantum Toolflows
- Algorithms
- Qubit implementations

Example 5: Using Codesign to optimize Hamiltonian Simulation

1. Hamiltonian Simulation

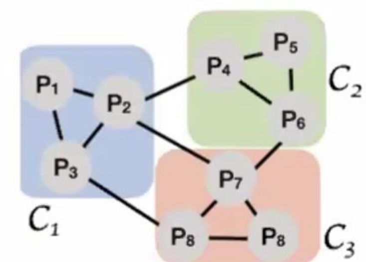


2. Cross-layer Codesign

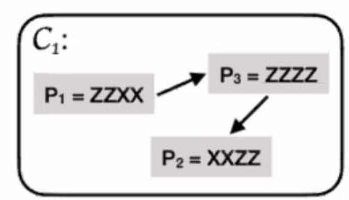


3. Max-commute-tsp

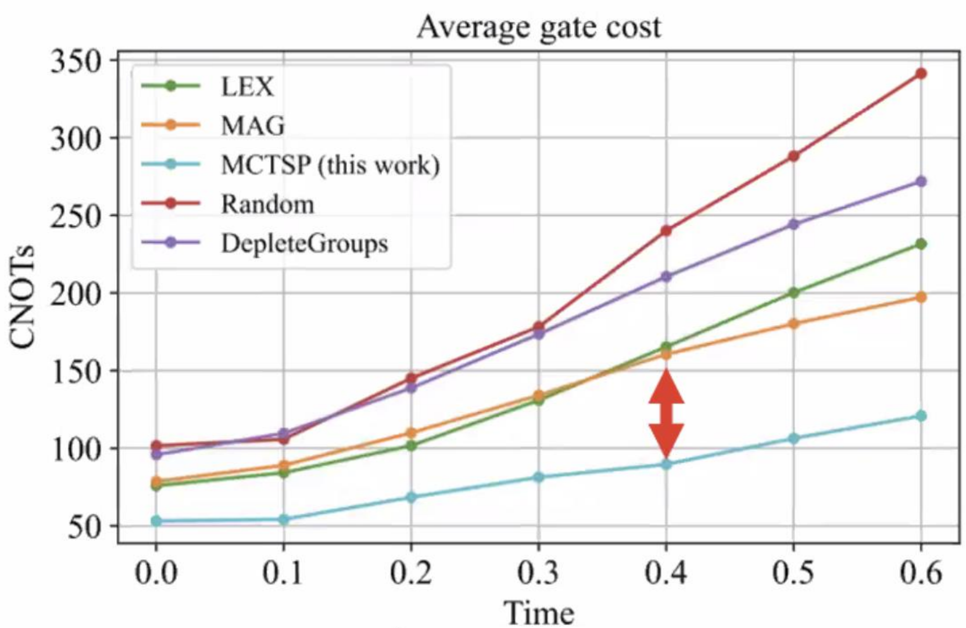
- Mitigate algorithmic errors
  - Group commuting terms together



- Mitigate physical errors
  - Sort terms using TSP



Simultaneous optimization results in 40% fewer CNOT gates in equal accuracy comparisons



- Simultaneously mitigate *both* algorithmic and physical errors
- Codesign optimizations useful now and into the future when NISQ transitions to fault-tolerant approaches

Tomesh, Gui, Gokhale, Shi, Chong, Martonosi, Suchara.
"Optimized Quantum Program Execution Ordering to Mitigate Errors in Simulations of Quantum Systems."
In *2021 Intl. Conf. on Rebooting Computing (ICRC)* **Best Paper Award**

Other QC Examples

- Tolerating long computation (ie gate) latencies:
  - SIMD operating zones to parallelize many qubit operations [Chi, ISCA 2006]
  - Multi-SIMD approaches allow different gate types to be executed in same cycle [Javadi-Abhari, CF 2014, Best paper]
- Arch and App tradeoffs for ECC: [Javadi-Abhari, MICRO-50]
- Accounting for communication latency
  - Achieving high Multi-SIMD parallelism requires properly accounting for qubit movement times. [Heckey, ASPLOS 2015]
- Scaffold programming language and ScaffCC Compiler [Javadi-Abhari, CF 2014, Best paper]
- Proposing and evaluating QC PL assertions for debuggable QC code [Huang, Plateau, 2018]
- Recurring theme: Full-stack knowledge from Apps to HW characteristics is important, and will be even more so in NISQ devices.

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Quantum Systems: Layering Options

Classical Layering

- Algorithms
- High-Level Languages
- Compiler | OS
- Architecture
- Modular hardware blocks: Gates, registers
- VLSI Circuits
- Semiconductor transistors

Quantum Toolflows

- Algorithms
- High-level QC Languages. Compilers. Optimization. Error Correcting Codes Orchestrate classical gate control, Orchestrate qubit motion and manipulation.
- Qubit implementations

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Conclusions & What's next?

Quantum Toolflows

- Algorithms
- High-level QC Languages. Compilers. Optimization. Error Correcting Codes Orchestrate classical gate control, Orchestrate qubit motion and manipulation.
- Qubit implementations

- QC is NOT a Moore's Law replacement
  - Unique, special-purpose hardware
  - Focused applications
- But potentially game-changing
  - Make intractable tractable
  - Lessons learned (algs, systems, devices) drive innovation on classical side as well
- Full CS ecosystem needed to shift QC from theoretical to commercial