Google AI Quantum

The quest for viable quantum algorithms and applications

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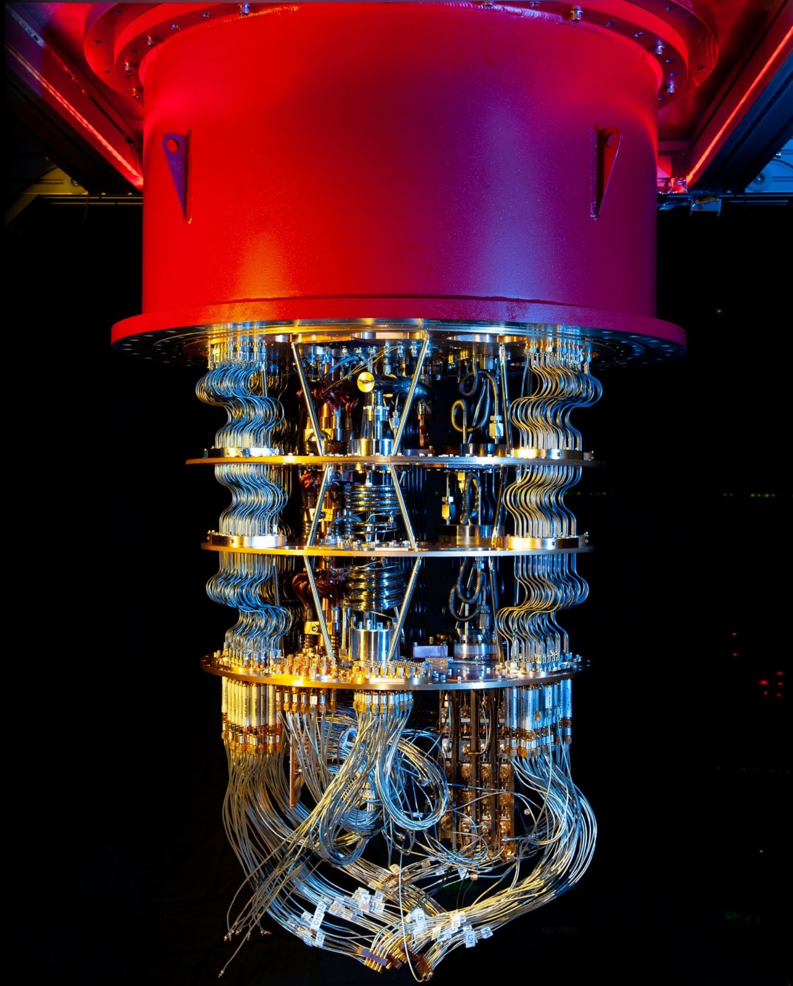
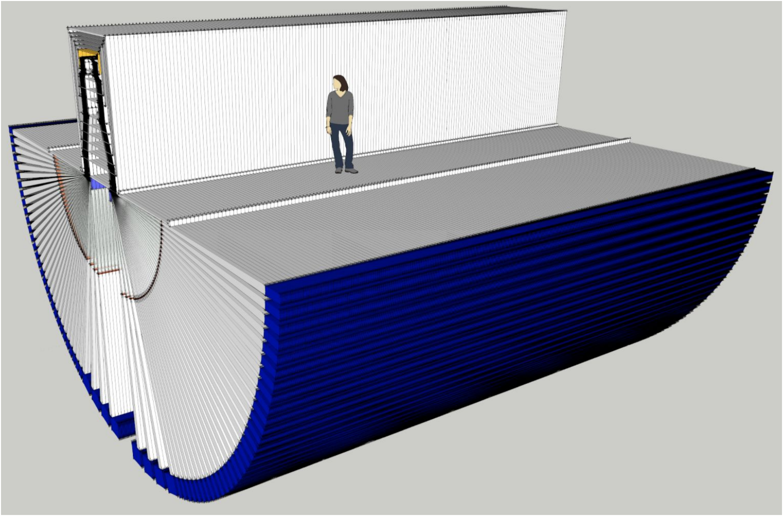
February 4
QIP 2021



Google's hardware team is dedicated to two goals

Deliver the world's best quantum computing service

Build an error-corrected quantum computer



We need your help figuring out what to do with these things!

Google's quantum computing service

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Chips from Google's 2019 "beyond classical" experiments, are now available via cloud
Small number of academic groups are already using it to implement experiments

Some early results from our cloud service:

- Chemistry (in *Science*) - arXiv:2004.04174
- QAOA (in *Nature Physics*) - arXiv:2004.04197
- Hubbard model simulation - arXiv:2010.07965
- High accuracy calibration methods - arXiv:2012.00921
- Out-of-time-order correlators - arXiv:2101.08870
- Machine learning - arXiv:2101.09581

Google's quantum computing service

Open source tooling

- OpenFermion
- TensorFlow Quantum
- ReCirq
- qsim on Cirq

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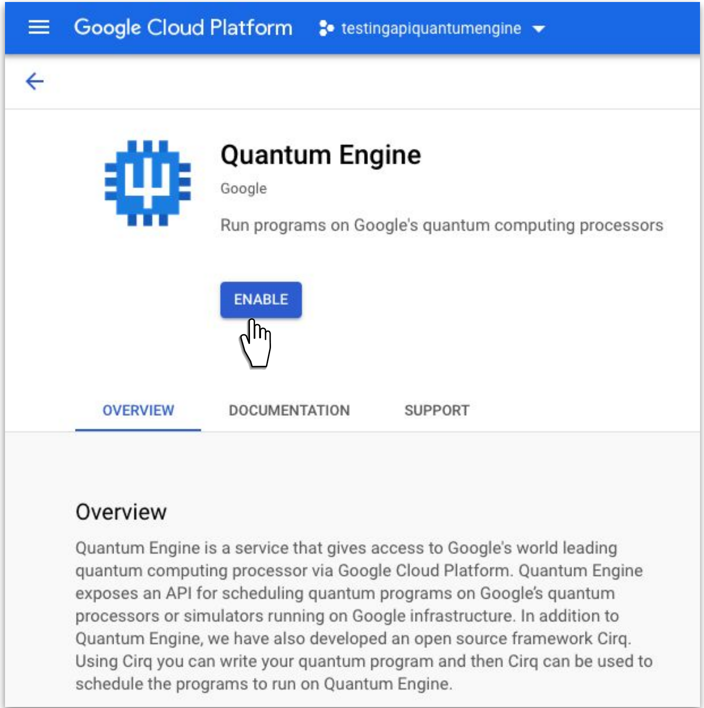
Cirq

Program in Cirq



Quantum Engine API

Quantum processors

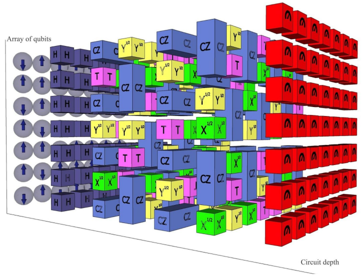
What are going to do with NISQ?

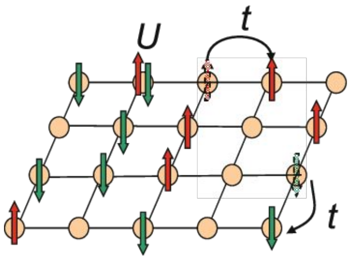
We're going to have NISQ devices on road to QEC, we might as well try to use them!

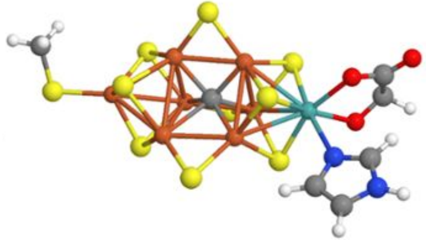
Most NISQ algorithms are heuristics with few performance guarantees and dubious prospects
Few papers estimate resources to exceed classical algorithms for a NISQ application

Quantum supremacy reveals we can sample extremely complex quantum states
Best known "application" is generating certifiable random numbers...

Likely that NISQ "physics" applications are possible, but how realistic?







Why provide a quantum computing service?

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Serving access to our devices diverts certain resources from error-correction effort...
... but the quantum computing industry will not survive without compelling applications

Hope is that cloud access to our chips will provide a tool for developing NISQ applications
Do you have an exciting idea? Get in touch!

The best experiments are those that teach us something we couldn't learn from numerics
Even small experiments can teach us about properties of noise and how to mitigate it

Error-mitigation and calibration techniques are essential to making NISQ work

- Decoding errors with subspace expansions - *Nature Comms* 11, 636 (2020)
- Density matrix purification - arXiv:2010.02538, arXiv:2011.07064, arXiv:2004.04174
- Rescaling experimental values by reference - arXiv:2010.07965, arXiv:2101.08870
- "Floquet calibration" - arXiv:2010.07965, arXiv:2012.00921

Our plan of record is to build a surface code quantum computer one million physical qubits

So what would you do with 1 million qubits?

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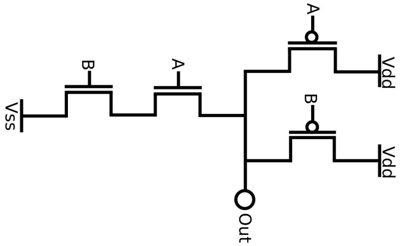
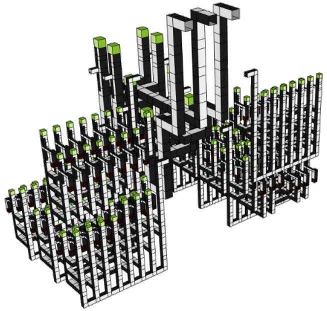
Error-corrected quadratic speedups are not promising

- There are massive constant-factor slowdowns associated with error-correction



classical NAND gate (CMOS)
$<10^{-9}$ “transistorseconds”



“quantum NAND” gate
(distillation of Toffoli state)
>10 “qubitseconds”

- MANY proposed applications of quantum computers (Monte Carlo, optimization, search, etc.) promise only quadratic speedups

- Classical algorithm scaling as C * N, quantum algorithm scaling as Q * sqrt(N)
  - If Q >>> C then we need very large N for quadratic speedup to win
  - In contrast, an exponential scaling advantage will quickly close the gap

- Many applications with quadratic speedup are classically embarrassingly parallel

Viability of error corrected quadratic speedups

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PRX Quantum 1, 020312 (2020) compiles quantum optimization heuristics (QAOA, Grover, adiabatic, quantum simulated annealing, etc.) to error-correcting code

How long must algorithm run until quadratic speedup overcomes constant factors?

polynomial of quantum speedup	classical parallelism	simulated annealing crossover time
quadratic	1 core	320 days
	10^3 cores	880 years
	10^6 cores	880 millennia

arXiv:2011.04149 argues for "lower bound" (best case) scenario on crossover time

Quartic speedups look viable

Conclusion for quadratic persists even if we speedup error-correction by 100x

Other prominent application areas

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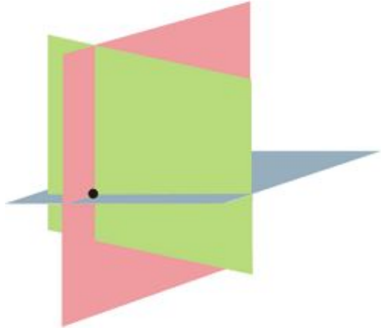
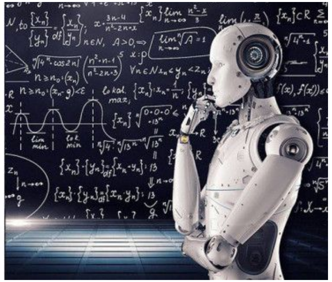
- Shor's algorithm has applications but viability of a business around that is unclear
    - breaking RSA encryption require 8 hours and 20M qubits - **arXiv:1905.09749**

- Quantum linear algebra (e.g., HHL) gives exponential speedup
    - A number of tricky conditions must be met to realize advantage
    - Differential equations seem promising if there is sign problem



- Machine learning
    - Quantum circuits can sample intractable probability distributions
    - What properties of data lead to quantum advantage?
        - see recent work from Google - **arXiv:2011.01938**



Quantum simulation to the rescue?

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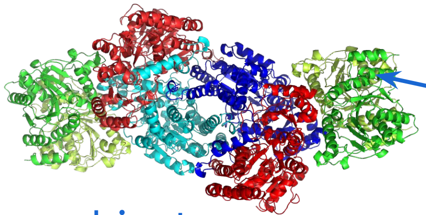
There are many exponential speedups available in simulating physical systems

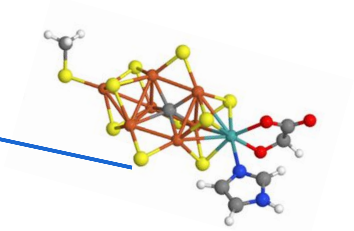
- But will there be a large enough market to justify the costs of error-correction?

$N_2 + 3\,H_2 \longrightarrow 2\,NH_3$

500°C, 20 MPa
2% of world energy



ambient pressure
and temperature



how does the
chemistry work???

- **arXiv:2011.03494** gives lowest scaling algorithm / best compilation for such problems
  - about 4M physical qubits and 4 days runtime required 99.9% fidelity gates

- Unclear how easily this tool will translate into development of valuable technologies

Outlook on error-corrected applications

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- Need to do better than the broadly applicable quadratic speedup algorithms
  - e.g., reason to doubt options pricing application based on Monte Carlo
- Machine learning and optimization have broad appeal but most hope for large speedup is to find instances with very specific structure
- Quantum algorithms for linear systems can be studied formally, give exponential speedup but need to find a problem that is perfect fit
- There are industrial applications of quantum simulating chemistry, materials
  - Important to refine how these simulations will advance technologies
- Surely there must be other applications!

Google academic programs

Direct grants (to fund your team to collaborate with Google)

Sponsored research agreements (combination of grant funding and personal compensation for collaborating with Google)

Visiting academic researcher positions (1 day / week or full time)

PhD fellowships and internships (for excellent students)

Chip access (for those with excellent experiment proposals)

Google Quantum AI is hiring! (+150% by 2023)

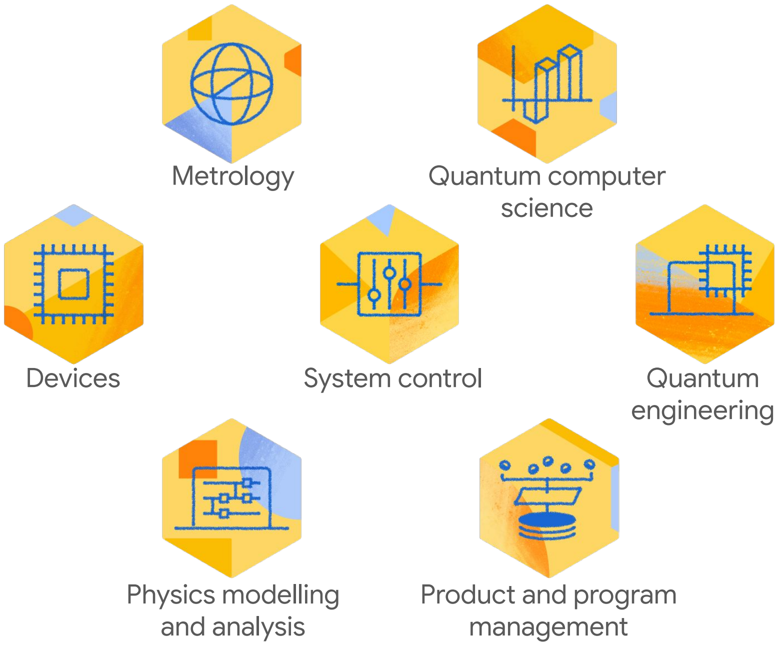
Apply for an active role at

- quantumai.google/team/careers

Or send our team your resume!

We're continually searching for:

- Research Scientists
- Hardware Engineers
- Software Engineers
- Interns



Thank you!

Solid-state material calculations

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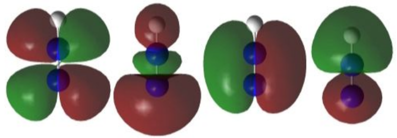
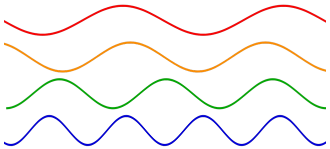
- Different representations of quantum chemistry involve simpler (cheaper) basis

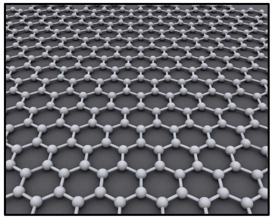


precise but expensive
100 qubits industrially relevant
good for molecules

vs



cheap but less precise
100 qubits scientifically interesting
good for materials



- Plane waves are good for solid-state (materials science) calculations

- **PRX 8, 041015 (2018)** and **Quantum 4, 296 (2020)** optimize error-corrected algorithms
  - ~300k qubits, ~1 hour for classically intractable calculations at 99.9% fidelity
  - ~60k qubits, ~30 minutes for classically intractable calculations at 99.99% fidelity

- For more accurate solid-state calculations use **Nature QI 5, 92 (2019)**
  - Still working to fully compile algorithm to error-correction, assess use cases

Algorithms have rapidly improved

Year	arXiv	First/Last Affiliations	Basis Set	Space Complexity	T Gate Complexity	T Gates for $N \approx 100$
2005	0604193	Berkeley	Arbitrary	$\mathcal{O}(N)$	$\mathcal{O}(\text{poly}(N/\epsilon))$	Unknown
2010	1001.3855	Harvard	Arbitrary	$\mathcal{O}(N)$	$\widetilde{\mathcal{O}}(N^{11}/\epsilon^{3/2})$	Unknown
2012	1208.5986	Haverford	Arbitrary	$\mathcal{O}(N)$	$\widetilde{\mathcal{O}}(N^{10}/\epsilon^{3/2})$	Unknown
2013	1312.1695	Microsoft / ETH Zurich	Arbitrary	$\mathcal{O}(N)$	$\widetilde{\mathcal{O}}(N^{9}/\epsilon^{3/2})$	$\sim 10^{20}$
2013	1312.2579	Haverford	Arbitrary	$\mathcal{O}(\eta \log N)$	$\mathcal{O}(\eta^2 N^{8}/\epsilon^{3/2})$	Unknown
2014	1403.1539	Microsoft / ETH Zurich	Arbitrary	$\mathcal{O}(N)$	$\widetilde{\mathcal{O}}(N^{8}/\epsilon^{3/2})$	Unknown
2014	1406.4920	Sherbrooke / Microsoft	Arbitrary	$\mathcal{O}(N)$	$\widetilde{\mathcal{O}}(N^{7}/\epsilon^{3/2})$	Unknown
2014	1410.8159	Harvard / Microsoft	Arbitrary	$\mathcal{O}(N)$	$\widetilde{\mathcal{O}}(N^{6}/\epsilon^{3/2})$	Unknown
2015	1506.01020	Harvard	Arbitrary	$\mathcal{O}(N)$	$\widetilde{\mathcal{O}}(N^{5}/\epsilon)$	Unknown
2015	1506.01029	Harvard	Arbitrary	$\mathcal{O}(\eta \log N)$	$\widetilde{\mathcal{O}}(\eta^2 N^{3}/\epsilon)$	Unknown
2016	1605.03590	ETH Zurich / Microsoft	Arbitrary	$\mathcal{O}(N)$	$\widetilde{\mathcal{O}}(N^{6}/\epsilon^{3/2})$	$\sim 10^{15}$
2018	1808.02625	Caltech / Google	Arbitrary	$\mathcal{O}(N)$	$\widetilde{\mathcal{O}}(N^{9/2}/\epsilon^{3/2})$	Unknown
2019	1902.02134	Macquarie / Google	Arbitrary	$\widetilde{\mathcal{O}}(N^{3/2})$	$\widetilde{\mathcal{O}}(N^{4}/\epsilon)$	$\sim 10^{11}$
2020	2007.14460	ETH Zurich / Microsoft	Arbitrary	$\widetilde{\mathcal{O}}(N^{3/2})$	$\widetilde{\mathcal{O}}(N^{7/2}/\epsilon)$	$\sim 10^{10}$
2020	2011.03494	Columbia / Google	Arbitrary	$\widetilde{\mathcal{O}}(N)$	$\widetilde{\mathcal{O}}(N^{3}/\epsilon)$	$\sim 10^{9}$

TABLE I. Best fault-tolerant algorithms for phase estimating chemistry in an arbitrary (e.g., molecular orbital) basis. N is number of basis functions, $\eta < N$ is number of electrons and ϵ is target precision. Gate counts here are for FeMoCo.

Year	arXiv	First/Last Affiliations	Basis Set	Space Complexity	T Gate Complexity	T Gates for $N \approx 100$
2017	1706.00023	Google / Caltech	Plane Waves	$\mathcal{O}(N)$	$\widetilde{\mathcal{O}}(N^{11/3}/\epsilon)$	Unknown
2018	1805.00675	Microsoft	Plane Waves	$\mathcal{O}(N \log(N/\epsilon))$	$\widetilde{\mathcal{O}}(N^{2}/\epsilon)$	Unknown
2018	1805.03662	Google	Plane Waves	$\mathcal{O}(N)$	$\mathcal{O}(N^{3}/\epsilon)$	$\sim 10^{9}$
2018	1807.09802	Google	Plane Waves	$\mathcal{O}(\eta \log N)$	$\widetilde{\mathcal{O}}(\eta^{8/3} N^{1/3}/\epsilon)$	Unknown
2019	1902.10673	Google	Plane Waves	$\mathcal{O}(N)$	$\widetilde{\mathcal{O}}(N^{5/2}/\epsilon^{3/2})$	$\sim 10^{7}$
2019	1912.08854	Maryland	Plane Waves	$\mathcal{O}(N)$	$\widetilde{\mathcal{O}}(N^{2}/\epsilon)$	Unknown

TABLE II. Best fault-tolerant algorithms for phase estimating chemistry in a plane wave basis. N is number of basis functions, $\eta < N$ is number of electrons and ϵ is target precision.