On the application of quantum computers for Quantum Optimisation

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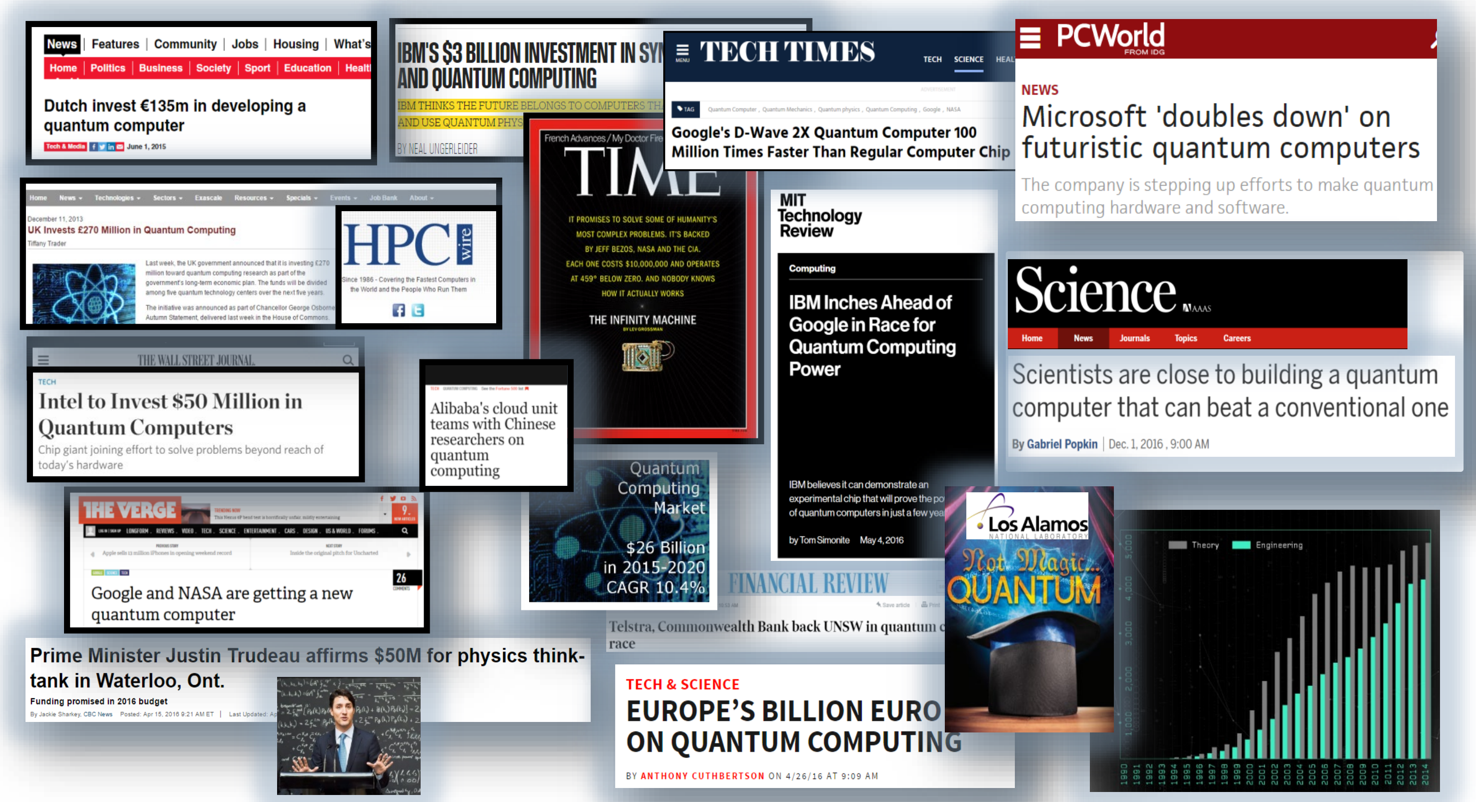
CAPD CENTER

Disclaimer: personal opinions

Outline of my talk



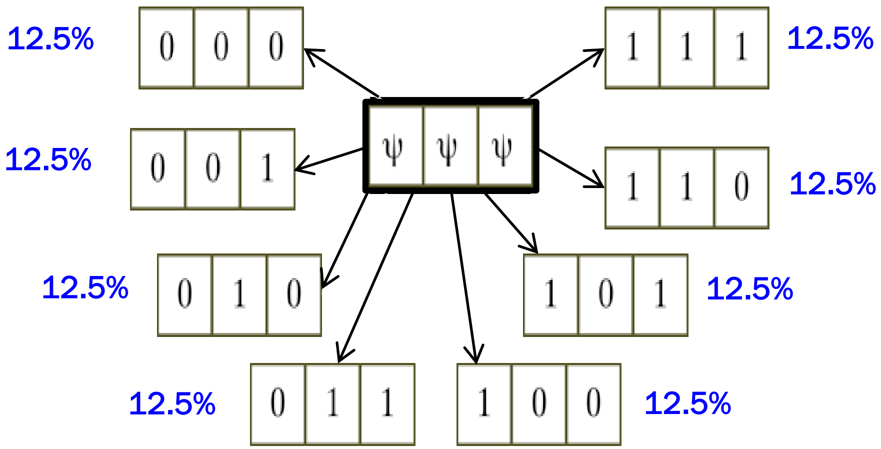
- Introduce quantum algorithms
- Quantum Advantage and Supremacy
- Quantum Optimization landscape
- Quantum Annealing and QAOA
- Recent Results in Quantum Optimization
- Resources to watch

A Quantum Computer in a nutshell

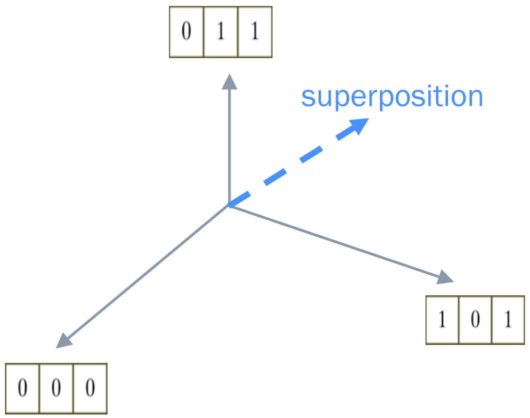
Take all possible 2^N solutions of your problem and represent them as bitstrings:

Sol1 = 000
Sol2 = 001
Sol3 = 010
...

Quantum initialization



Imagine each bistring is a direction in a 2^N dimension vector space. Your initial quantum state is a vector that has an equal component in all directions.



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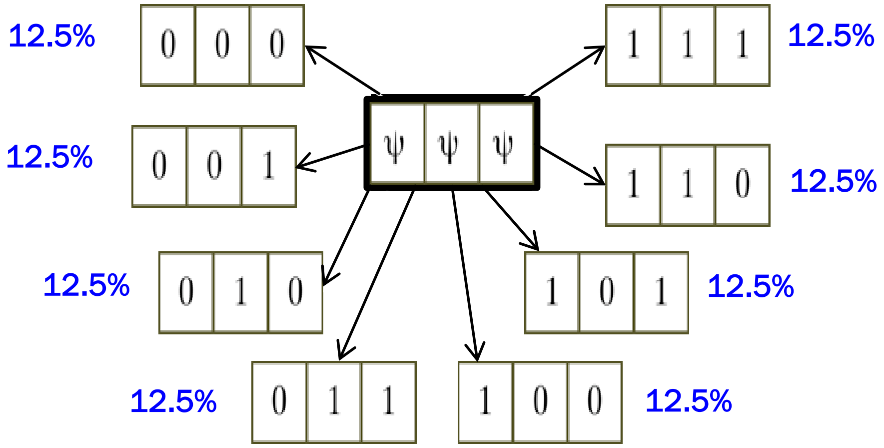

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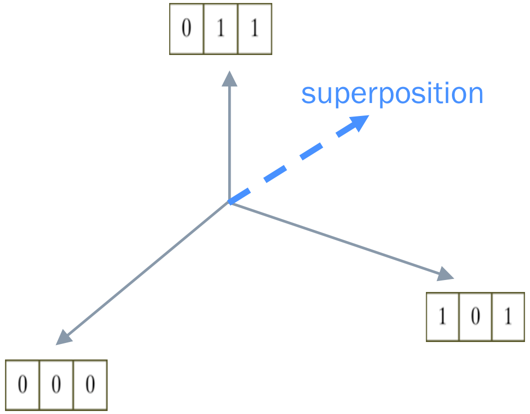
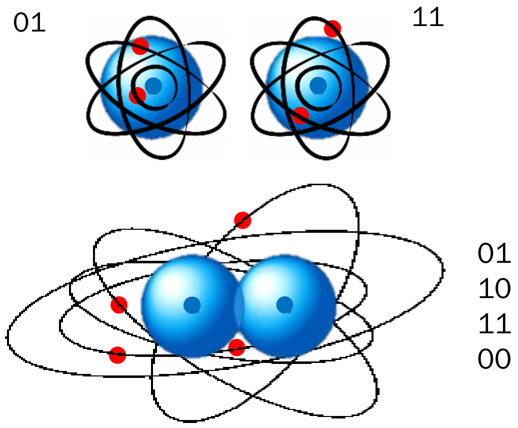
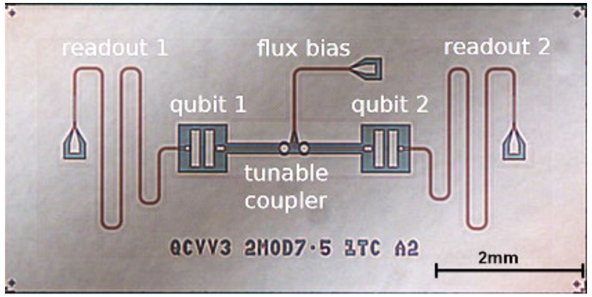


Analogy in Chemistry

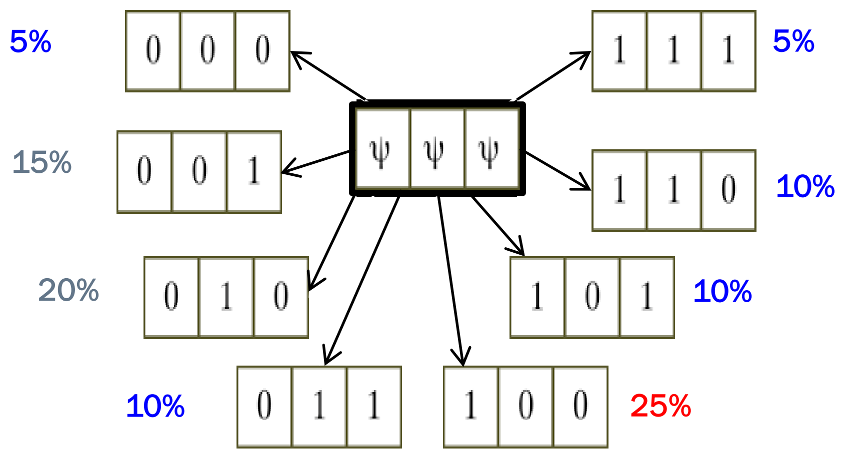




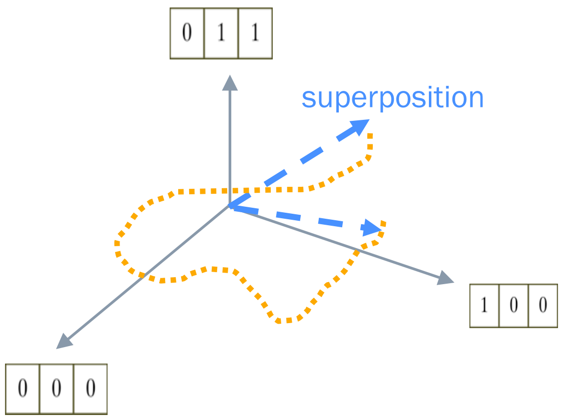
A Quantum Computer in a nutshell

Quantum algorithm

The algorithm moves the vector changing the components and arrives «closer» to the classical solution that we want, almost aligned



When measured, the state is aligned («collapsed») to a given component axis with a probability proportional to the projection of the final quantum state.



A Quantum Computer in a nutshell

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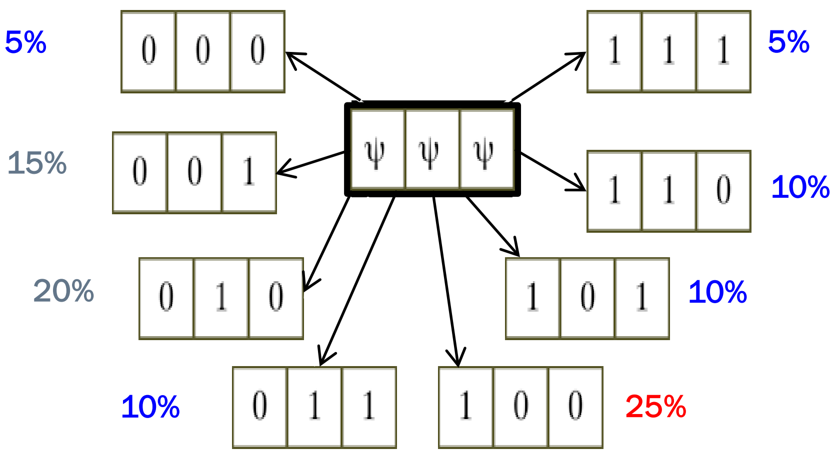
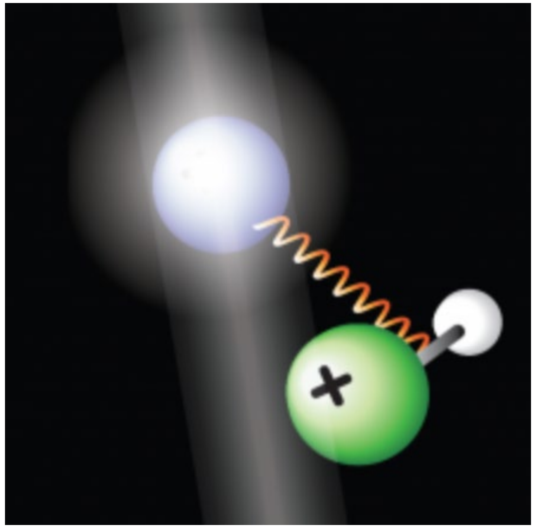
Quantum algorithm





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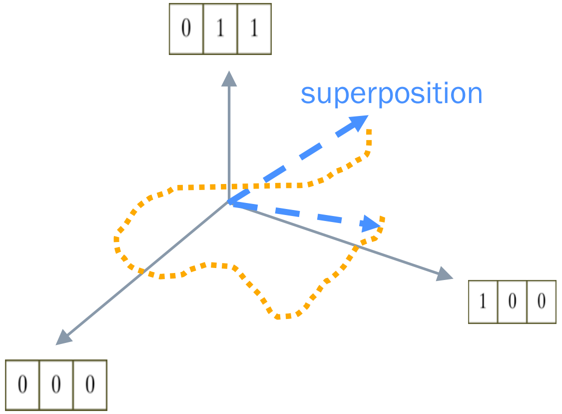
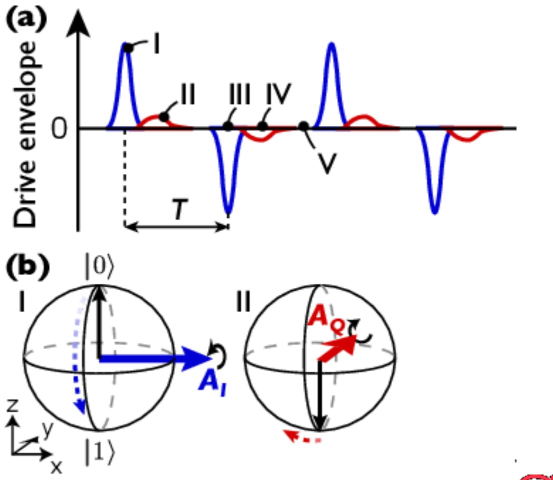
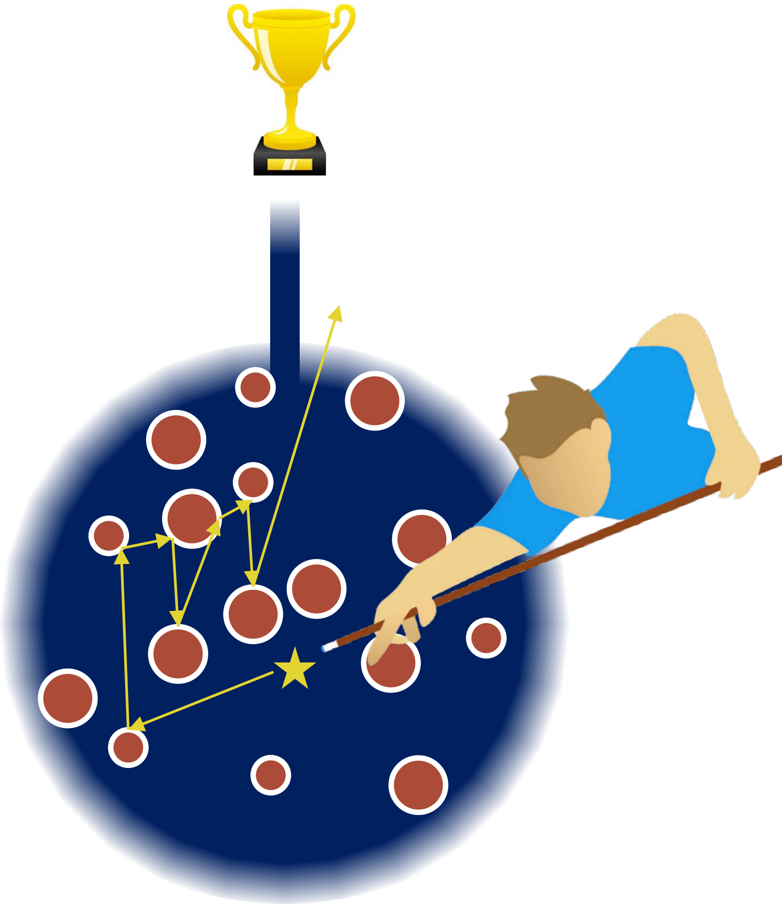




Driving an exponentially large field with an exponentially large vehicle

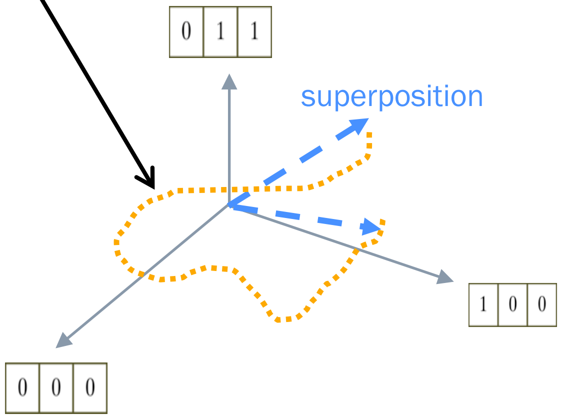
Quantum optimization:
Driving the evolution of a state in an exponential number of dimensions, trying to avoid an exponential number of wrong ways, to target a very small final number of locations.



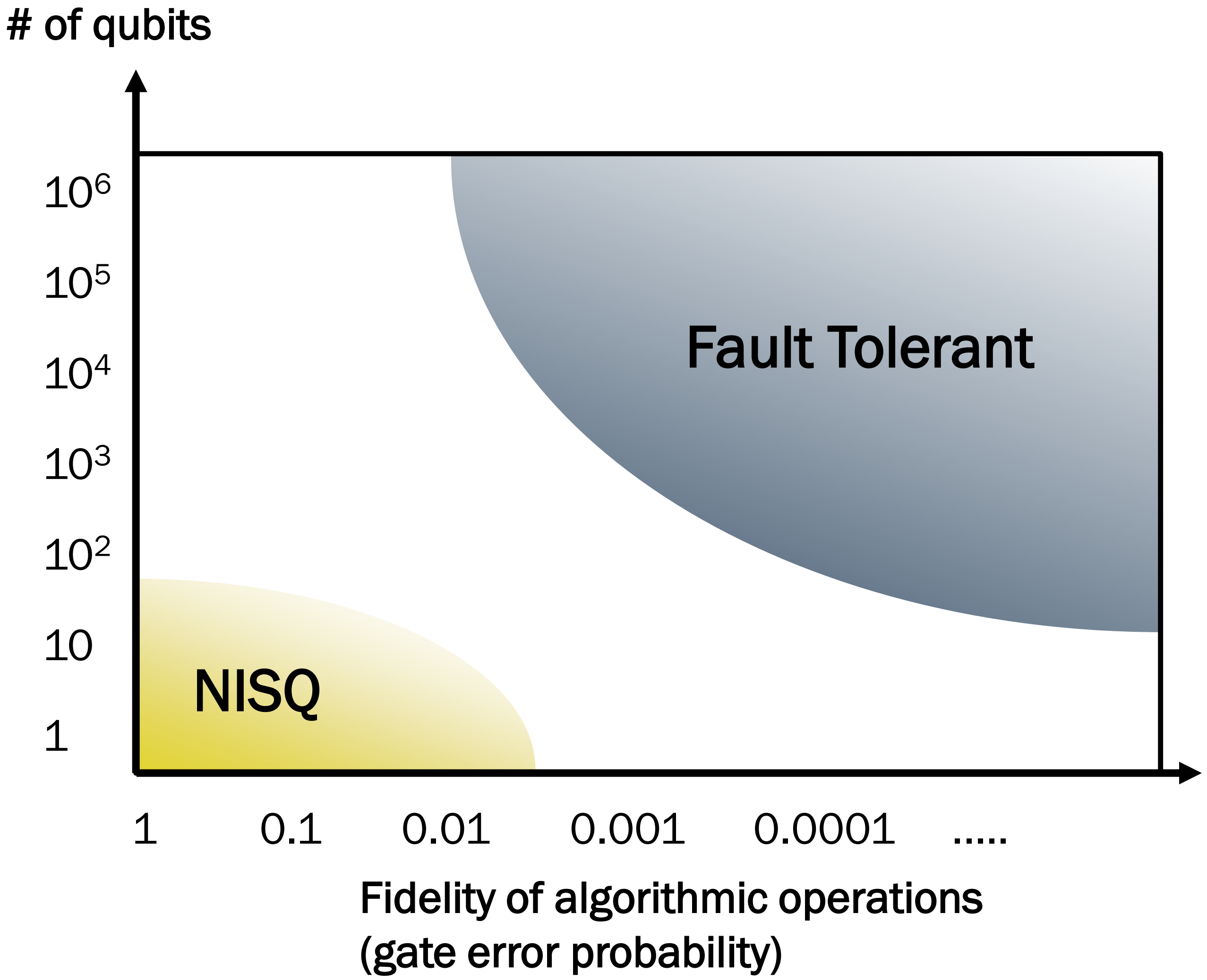
Typ. Search Space : $O(2^N)$
Typ. Target Solution set : $\leq O(N^k)$

Classical state description: $O(N)$
Quantum state description: $O(2^N)$

Can complexity shortcut complexity?



NISQ Quantum Computing



Quantum Computing in the NISQ era and beyond

John Preskill

Institute for Quantum Information and Matter and Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena CA 91125, USA

30 July 2018

Noisy Intermediate-Scale Quantum (NISQ) technology will be available in the near future. Quantum computers with 50-100 qubits may be able to perform tasks which surpass the capabilities of today's classical digital computers, but noise in quantum gates will limit the size of quantum circuits that can be executed reliably. NISQ devices will be useful tools for exploring many-body quantum physics, and may have other useful applications, but the 100-qubit quantum computer will not change the world right away — we should regard it as a significant step toward the more powerful quantum technologies of the future. Quantum technologists should continue to strive for more accurate quantum gates and, eventually, fully fault-tolerant quantum computing.

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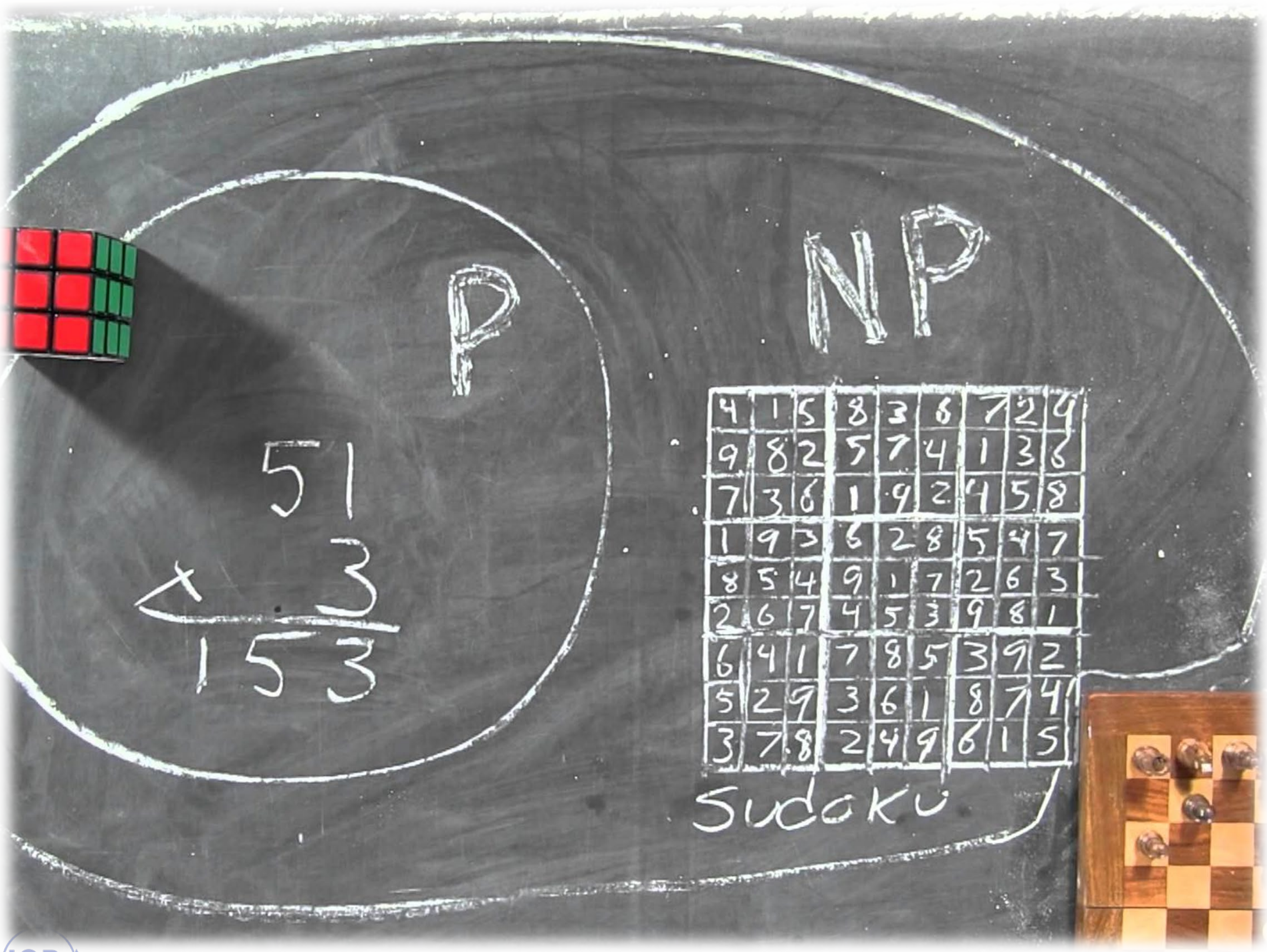
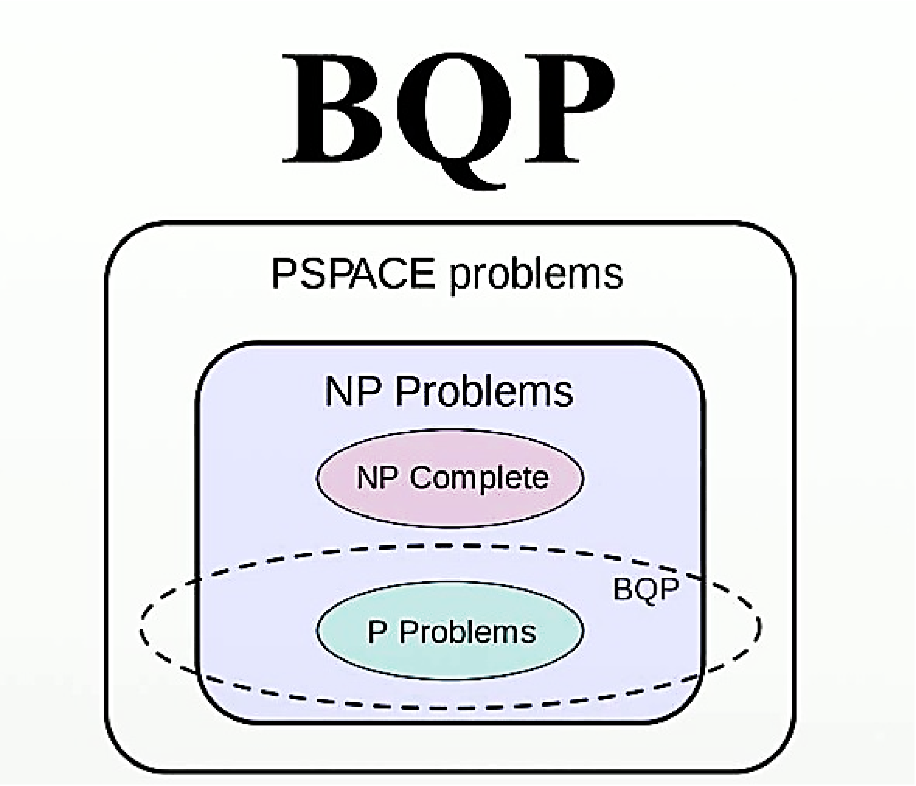
The theoretical power of FT Quantum Computing



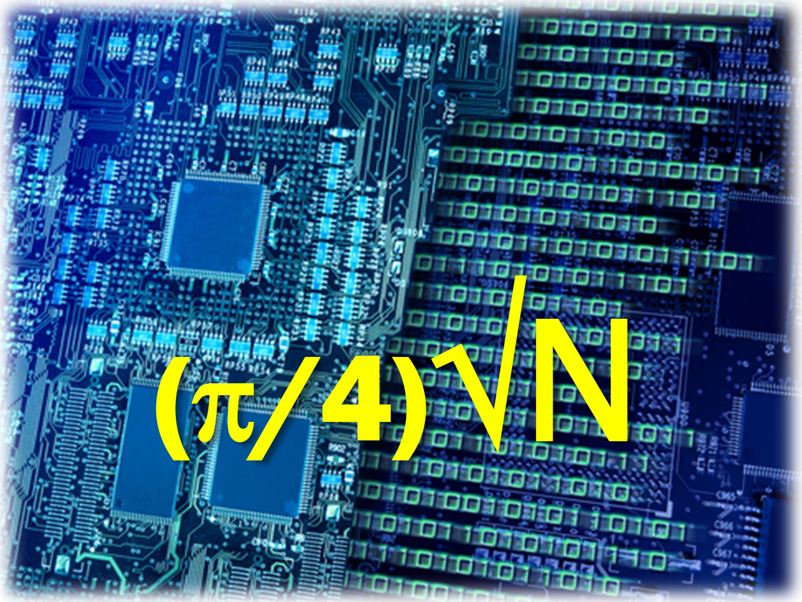


Fault Tolerant Quantum Computing: Estimates

Linear search Complexity N

Quantum Search

$N \rightarrow \sqrt{N}$



Applying quantum algorithms to constraint satisfaction problems

Earl Campbell,[1] Ankur Khurana,[2,3] and Ashley Montanaro[4]

[…] when one takes into account the cost of classical processing using current techniques, the speedup disappears. Also, the space usage of the algorithms is extremely high (sometimes over 10^{13} physical qubits) […]

Compilation of Fault-Tolerant Quantum Heuristics for Combinatorial Optimization

Yuval R. Sanders,[1,2] Dominic W. Berry,[1,*] Pedro C. S. Costa,[1] Nathan Wiebe,[3,4,5] Craig Gidney,[5] Hartmut Neven,[5] and Ryan Babbush[5,†]

[…] "Our results discourage the notion that any quantum optimization heuristic realizing only a quadratic speedup will achieve an advantage over classical algorithms on modest superconducting qubit surface code processors without significant improvements in the implementation of the surface code. For instance, under quantum-favorable assumptions (e.g., that the quantum algorithm requires exactly quadratically fewer steps), our analysis suggests that quantum accelerated simulated annealing would require roughly a day and a million physical qubits to optimize spin glasses that could be solved by classical simulated annealing in about four CPU-minutes."

One hope: NISQ heuristics!

What are the chances that the only compelling speedup we can get out of QC is the one we can prove ab-initio?

(E.g. We did not understand the power of deep learning until we could actually run deep neural networks in practice. We still don't really understand the power of deep learning on theoretical grounds.)

How we measure quantum heuristics

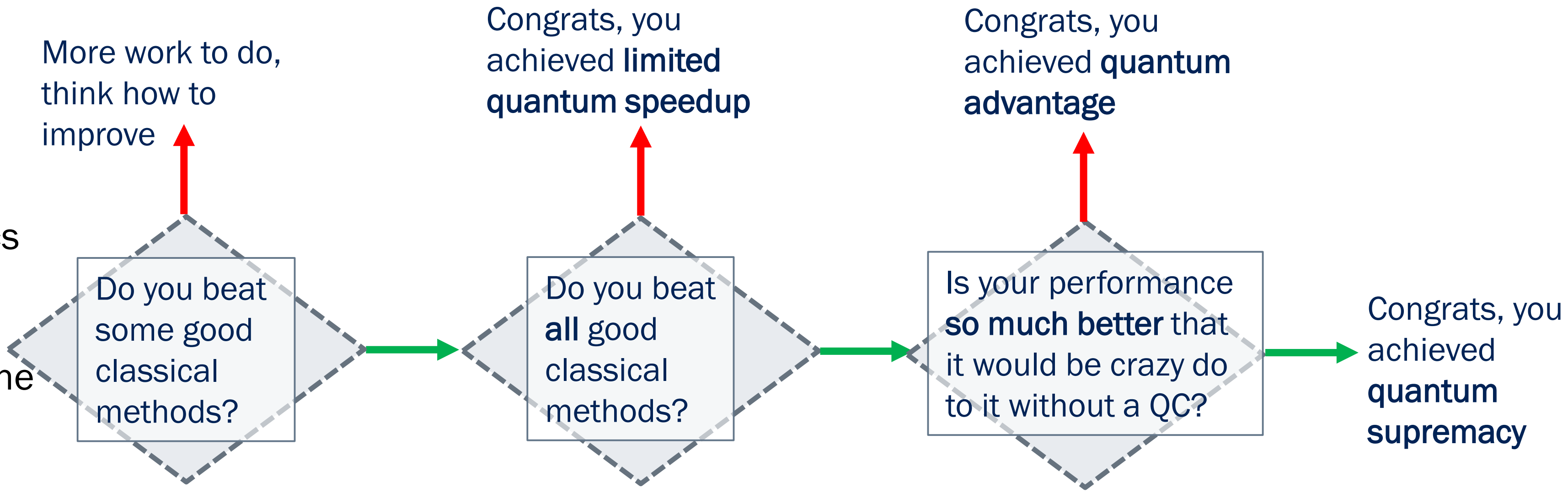
1. Set up the quantum algorithm on the QPU with some initial parameters

2. Run it a number of times and process the performance collecting the statistics of distribution

3. If performance is not acceptable, use the distribution to choose new parameters (might involve processing)
   → Repeat 1-3 until satisfaction

4. Process final result and measure resource used (time, energy)
   → Repeat 1-4 for many benchmarking instances and collect distribution of performance.

5. Compare against best classical method on available hardware (time, energy)

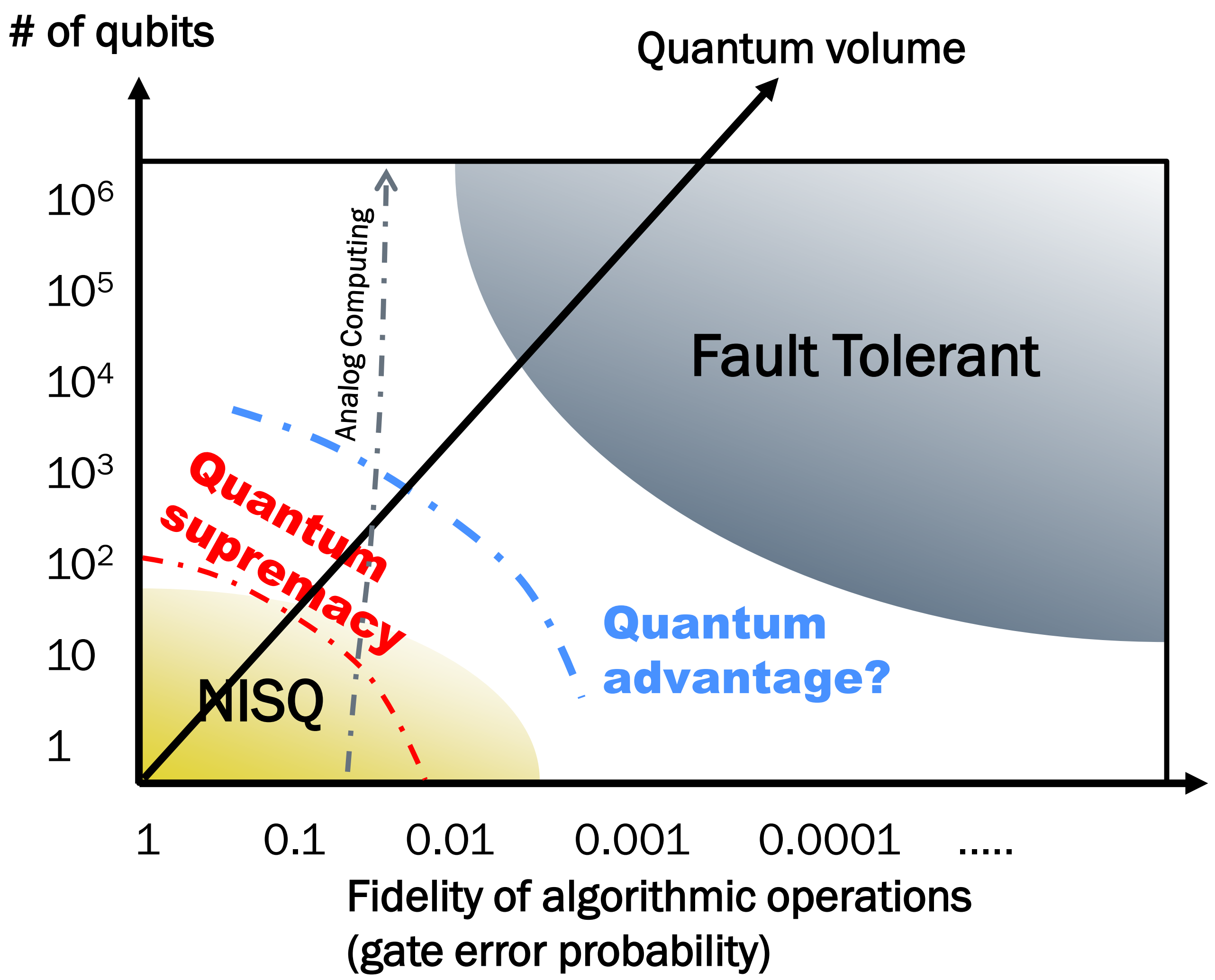


As of 8/30/2020:

- Few limited quantum speedup demos achieved with quantum annealing (both application and tailored).
- No quantum advantage for application problems.
- One quantum supremacy demo on «self-simulation»

WORLD QUEST :
Discover an interesting, useful application where we see quantum advantage

Quantum Supremacy and Quantum Advantage



Article | Published: 23 October 2019

Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, [...] John M. Martinis

Nature **574**, 505–510(2019) | Cite this article

720k Accesses | **113** Citations | **6062** Altmetric | Metrics

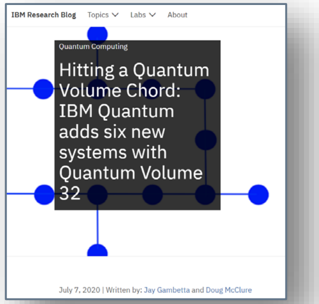
- Sep19 Paper Leaks
  Oct19 IBM pre-announce counter-test estimate (days)
- Oct19 Google announce (10k years)
- May 15 2020 Alibaba announce counter-test estimate (20 days)
- Followup works seem to bring the number down to days

Number of qubits
X
Length of an algo

at fixed error probability
≈ **quantum volume**

1,260 views | Aug 20, 2020, 08:30am EDT

IBM Announces It Doubled Quantum Volume From 32 To 64



techradar pro IT INSIGHTS FOR BUSINESS

Honeywell delivers the largest quantum volume yet

Honeywell has developed a quantum computer with a quantum volume of 64

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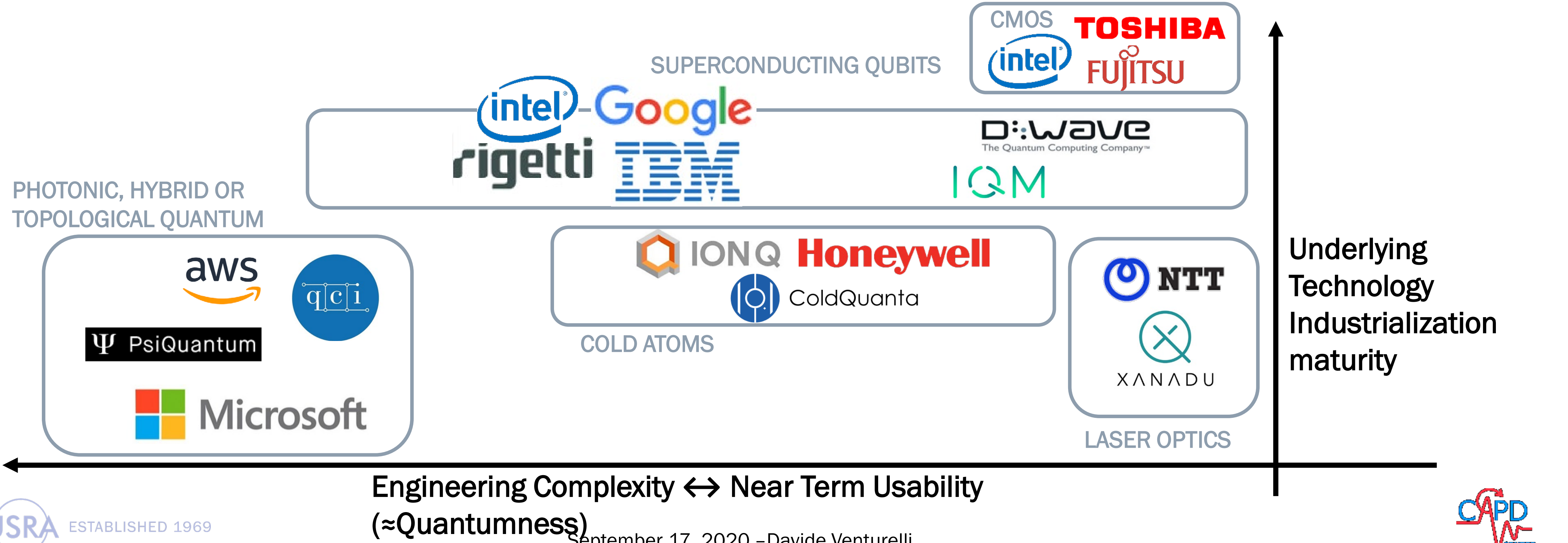
Strategies, Technologies (as 9/2020)

Disclaimer: personal opinions,
Non-exhaustive list

FAULT-TOLERANT QUANTUM:
- Phase Estimation
- Amplitude Amplification/Estim.
- Sampling

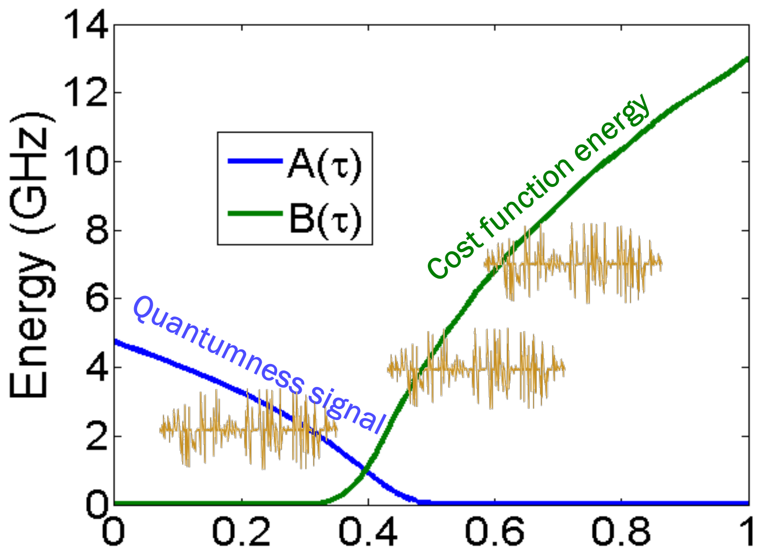
GATE-MODEL NISQ:
- Quantum Approximate Optimization
- Quantum Alternate Operator Ansatz
- Variational Quantum Eigensover
- Quantum Neural Networks

ANALOG:
- Quantum Annealing
- Coherent (Optical) Ising Machines
- Oscillator-based Computing
- Quantum-Inspired Digital Annealers



First contender for quantum optimization: quantum annealing

QUANTUM ANNEALING



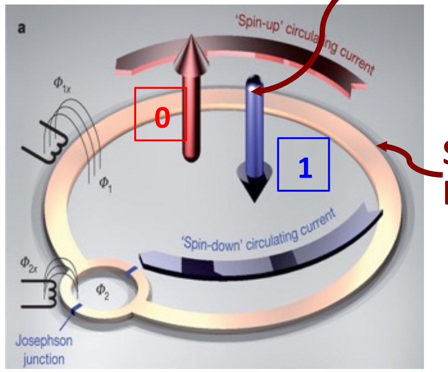
The Ising Model in a Transverse Field

Minimum of $\sum_{ij} Q_{ij}\, x_i\, x_j$

$$B(t)\left(\sum_{ij} J_{ij}\, \sigma^z_i\, \sigma^z_j + \sum_i h_i\, \sigma^z_i\right)$$

$$+\, A(t) \sum_i \sigma^x_i$$

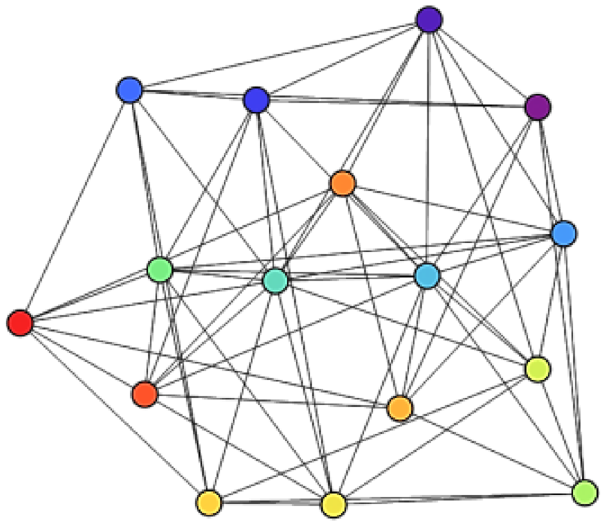
Magnetic Flux



Superconducting Loop

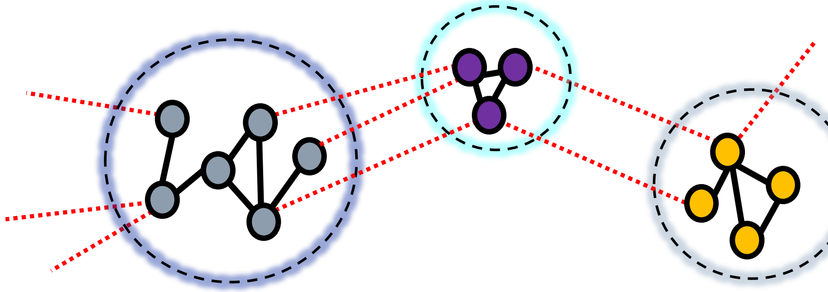
Programming a Quantum Annealer: Embedding

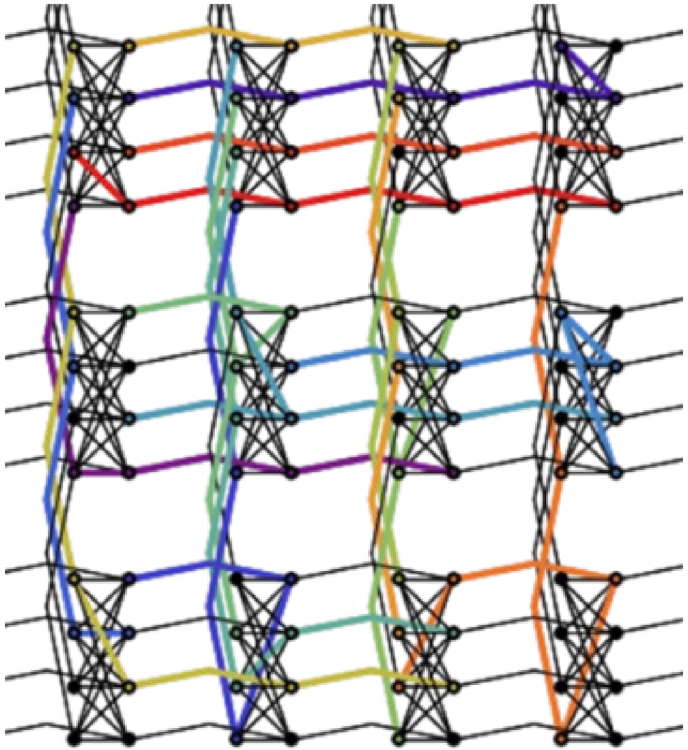
$B(t)\left(\sum_{ij} J_{ij}\,\sigma^z_i\,\sigma^z_j + \sum_i h_i\,\sigma^z_i\right)$



$$\mathcal{E}(i) : \{1, \ldots, n_L\} \rightarrow 2^{\{1,\ldots,n_P\}}$$

Assign "colors" to connected sets of qubits

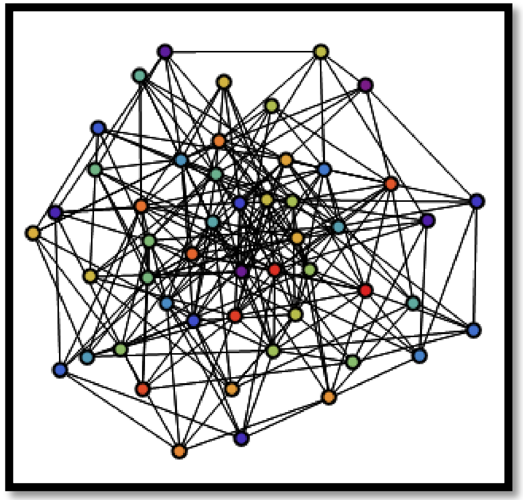




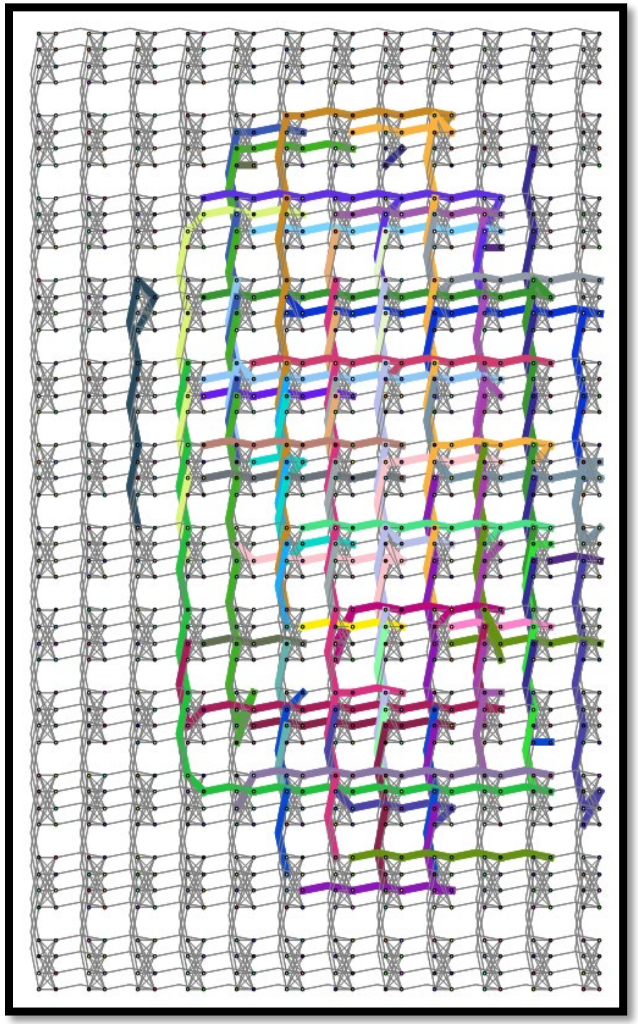
(n_P logical bits)

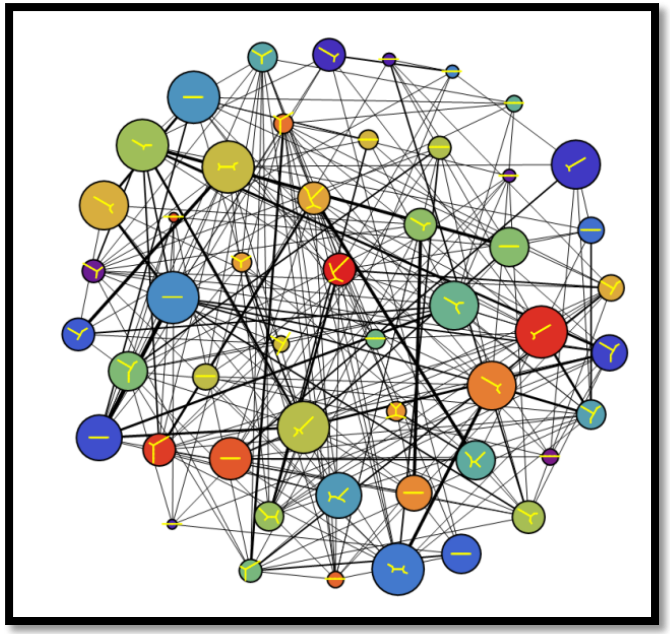
(n_H hardware qubits)

Programming a Quantum Annealer: Embedding



A practical heuristic for finding graph minors
Jun Cai, Bill Macready, Aidan Roy D-Wave Systems Inc.
ArXiv:1406.2741 (2014)





Integer programming techniques for minor-embedding in quantum annealers
David Bernal, Kyle Booth, Raouf Dridi, Hedayat Alghassi, Sridhar Tayur and Davide Venturelli ArXiv:1912.08314 (2020)

Frontiers in quantum annealing: embrace dissipation

Power of Pausing: Advancing Understanding of Thermalization in Experimental Quantum Annealers

Jeffrey Marshall,[1,2,3] Davide Venturelli,[1,4] Itay Hen,[3,5] and Eleanor G. Rieffel[4]

Why and when is pausing beneficial in quantum annealing?

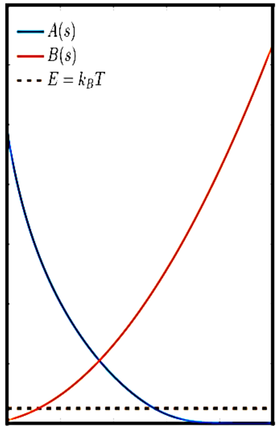
Huo Chen[1,2] and Daniel A. Lidar[1,2,3,4]

Ferromagnetically shifting the power of pausing

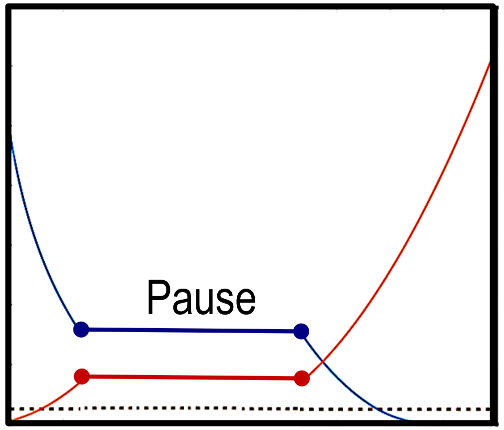
Zoe Gonzalez Izquierdo,[1,2,3] Shon Grabbe,[2] Stuart Hadfield,[2,3] Jeffrey Marshall,[2,3] Zhihui Wang,[2,3] and Eleanor Rieffel[2]

This establishes that the observed success probability enhancement can be attributed to incomplete quantum relaxation, i.e., is a form of beneficial non-equilibrium coupling to the environment.

a) Forward Annealing



annealing time τ



Reverse Annealing:

Search range in experimental quantum annealing

Nicholas Chancellor and Viv Kendon
Department of Physics; Joint Quantum Centre (JQC) Durham-Newcastle
Durham University, South Road, Durham, DH1 3LE, UK
(Dated: August 26, 2020)

Reverse Quantum Annealing Approach to Portfolio Optimization Problems

Davide Venturelli[1] Alexei Kondratyev[2]
[1] *USRA Research Institute for Advanced Computer Science, Mountain View, CA 94035, USA*
[2] *Data Analytics Group, Financial Markets, Standard Chartered Bank, London EC2V 5DD, UK*

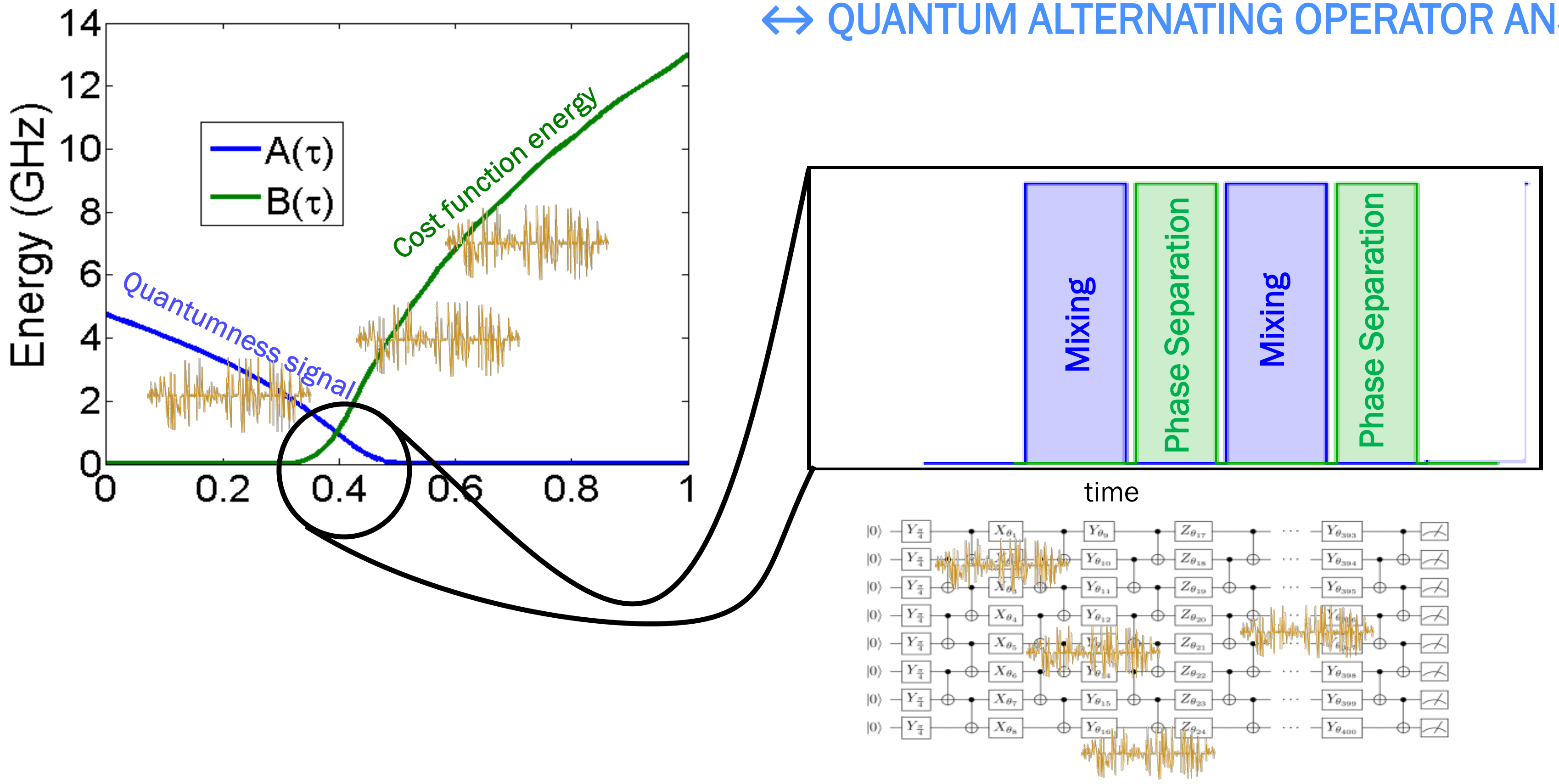
Towards Hybrid Classical-Quantum Computation Structures in Wirelessly-Networked Systems

Minsung Kim[1,2,3], Davide Venturelli[2,3], and Kyle Jamieson[1]
[1] *Princeton University*
[2] *USRA Research Institute for Advanced Computer Science*
[3] *NASA Ames Research Center, Quantum Artificial Intelligence Laboratory*

Second condented for quantum optimization: QAOA

QUANTUM ANNEALING

QUANTUM APPROXIMATE OPTIMIZATION ALGORITHM (QAOA) ↔ QUANTUM ALTERNATING OPERATOR ANSATZ



The programming paradigm: quantum circuits

IDEALIZED QUANTUM CIRCUIT

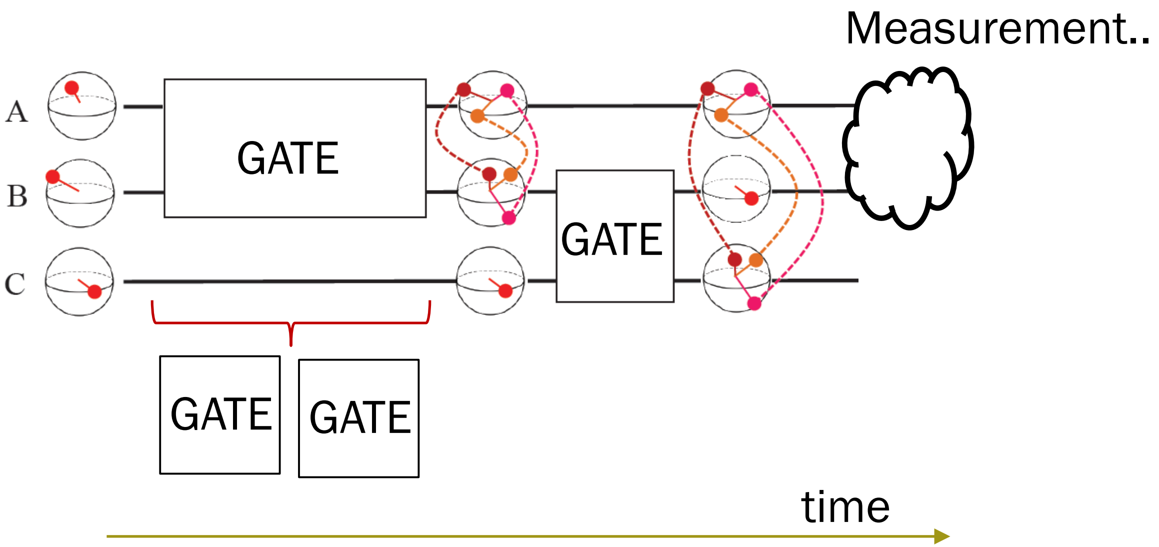
What is the best way to express the unitary transformation that implements the algorithms?
(you cannot write the matrix)

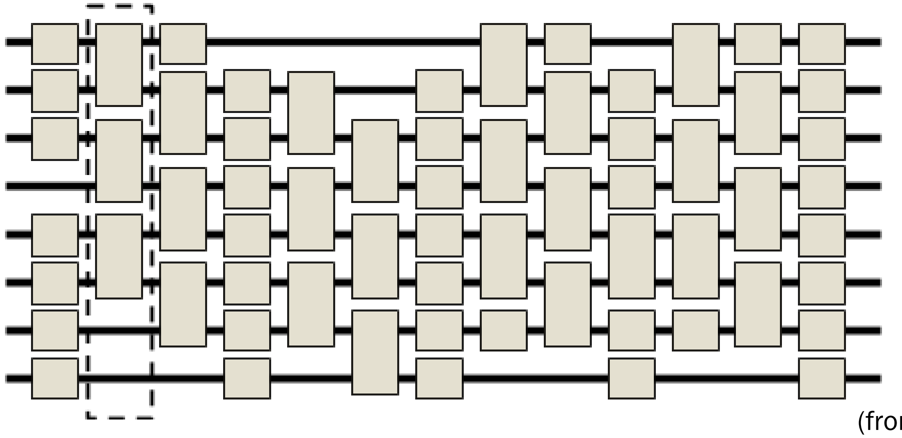
SYNTHESIS

... in term of the natively implementable gates?

COMPILATION (PARALLELIZATION)

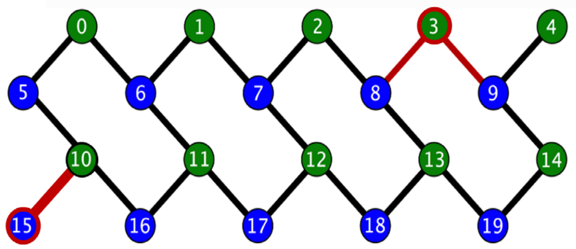
... minimizing the duration of the execution of the circuit?

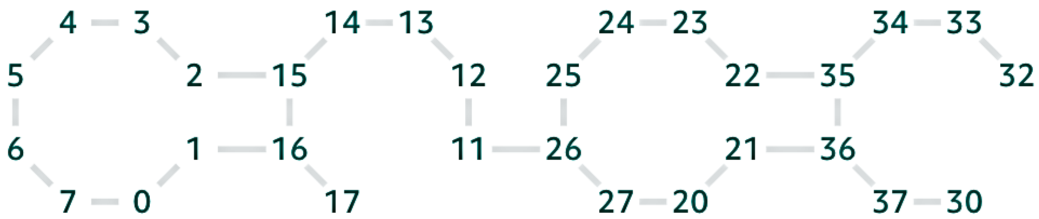


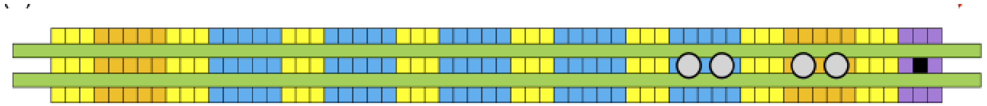


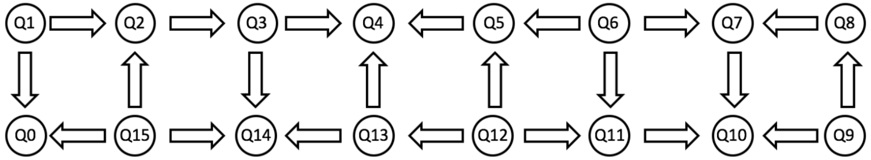
(from Cirq)

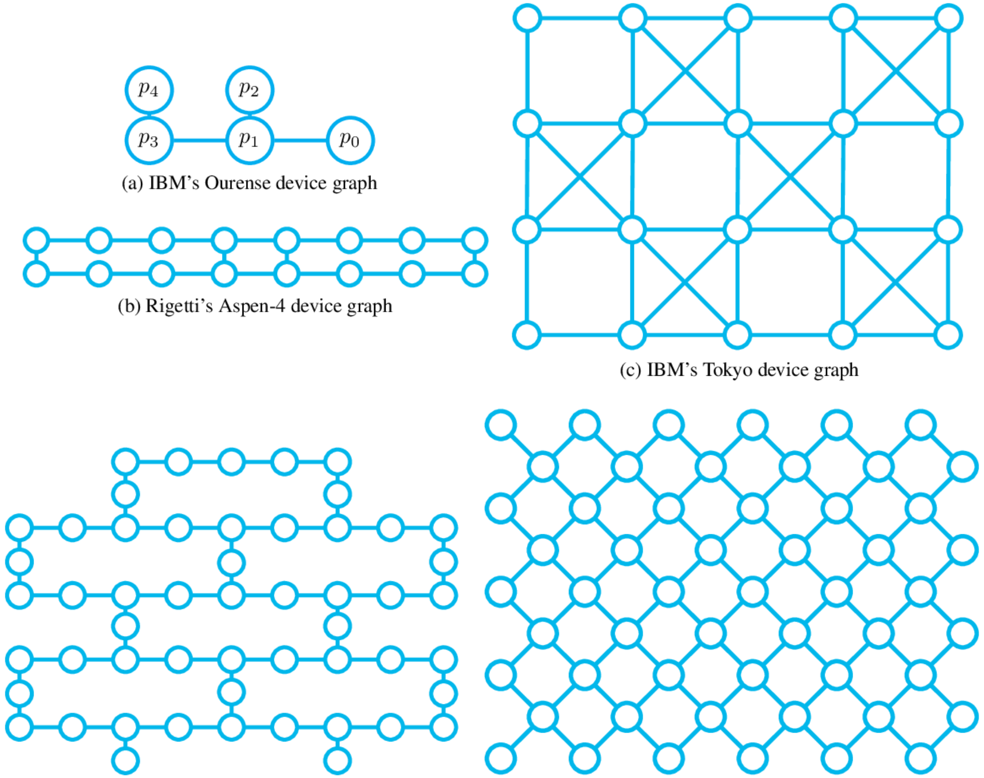
Compilation and overhead











(a) IBM's Ourense device graph

(b) Rigetti's Aspen-4 device graph

(c) IBM's Tokyo device graph

(d) IBM's Rochester device graph

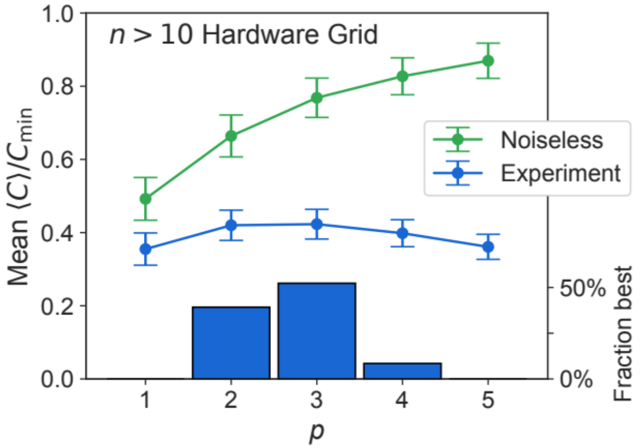
(e) Google's Sycamore device graph

Frontiers in QAOA: empirical advances and noise theory

Reference	Date	Problem topology	$\Delta(G)$	n	p	Optimization
Otterbach *et al.* [22]	2017-12	Hardware	3	19	1	Yes
Qiang *et al.* [27]	2018-08	Hardware	1	2	1	No
Pagano *et al.* [26]	2019-06	Hardware[1] (system 1)	n	12, 20	1	Yes
		Hardware[1] (system 2)	n	20–40	1–2[(2)]	No
Willsch *et al.* [23]	2019-07	Hardware	3	8	1	No
Abrams *et al.* [24]	2019-12	Ring	2	4	1	No
		Fully-connected	n			No
Bengtsson *et al.* [25]	2019-12	Hardware	1	2	1, 2	Yes
This work		Hardware	4	2–23	1–5	Yes
		3-regular	3	4–22	1–3	Yes
		Fully-connected	n	3–17	1–3	Yes

Quantum Approximate Optimization of Non-Planar Graph Problems on a Planar Superconducting Processor

Google AI Quantum and Collaborators*
(Dated: April 10, 2020)



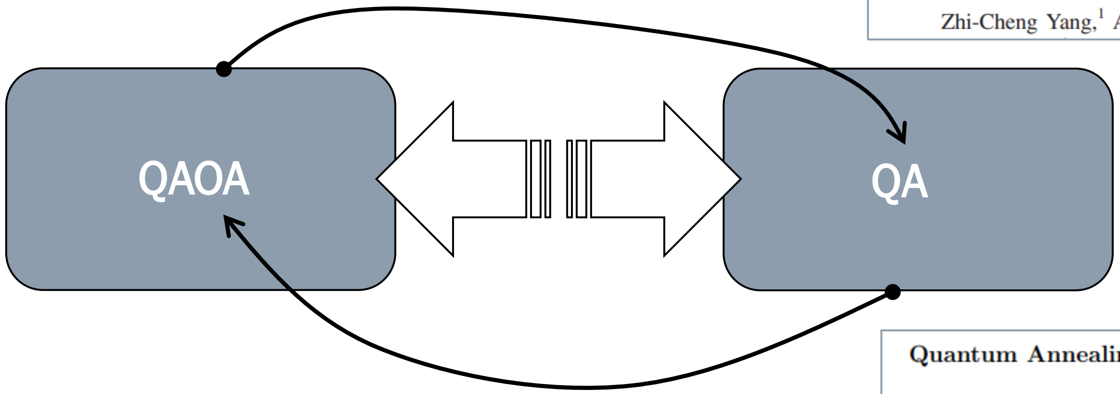
Characterizing local noise in QAOA circuits

Jeffrey Marshall,[1,2] Filip Wudarski,[1,2] Stuart Hadfield,[1,2] and Tad Hogg[1,2]

QA ↔ QAOA

Optimizing Variational Quantum Algorithms Using Pontryagin's Minimum Principle

Zhi-Cheng Yang,[1] Armin Rahmani,[2,3] Alireza Shabani,[4] Hartmut Neven,[4] and Claudio Chamon[1]



Quantum Annealing: a journey through Digitalization, Control, and hybrid Quantum Variational schemes

Glen Bigan Mbeng
SISSA, Via Bonomea 265, I-34136 Trieste, Italy and INFN, Sezione di Trieste, I-34136 Trieste, Italy

Rosario Fazio
Abdus Salam ICTP, Strada Costiera 11, 34151 Trieste, Italy and Dipartimento di Fisica, Università di Napoli "Federico II", Monte S. Angelo, I-80126 Napoli, Italy

Giuseppe E. Santoro
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Abdus Salam ICTP, Strada Costiera 11, 34151 Trieste, Italy and
CNR-IOM Democritos National Simulation Center, Via Bonomea 265, I-34136 Trieste, Italy

Approximating the Quantum Approximate Optimisation Algorithm

David Headley,[1,2,*] Thorge Müller,[3,2,†] Ana Martin,[4] Enrique Solano,[4,5,6] Mikel Sanz,[4] and Frank K. Wilhelm[2]

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(Dated: May 20, 2020)

Quantum Approximate Optimization Algorithm: Performance, Mechanism, and Implementation on Near-Term Devices

Leo Zhou,[1,*] Sheng-Tao Wang,[1,†] Soonwon Choi,[1,2] Hannes Pichler,[3,1] and Mikhail D. Lukin[1]

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(Dated: November 12, 2019)

Low depth mechanisms for quantum optimization

Jarrod R. McClean,[1,*] Matthew P. Harrigan,[1] Masoud Mohseni,[1] Nicholas C. Rubin,[1] Zhang Jiang,[1] Sergio Boixo,[1] Vadim N. Smelyanskiy,[1] Ryan Babbush,[1] and Hartmut Neven[1]

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(Dated: August 21, 2020)

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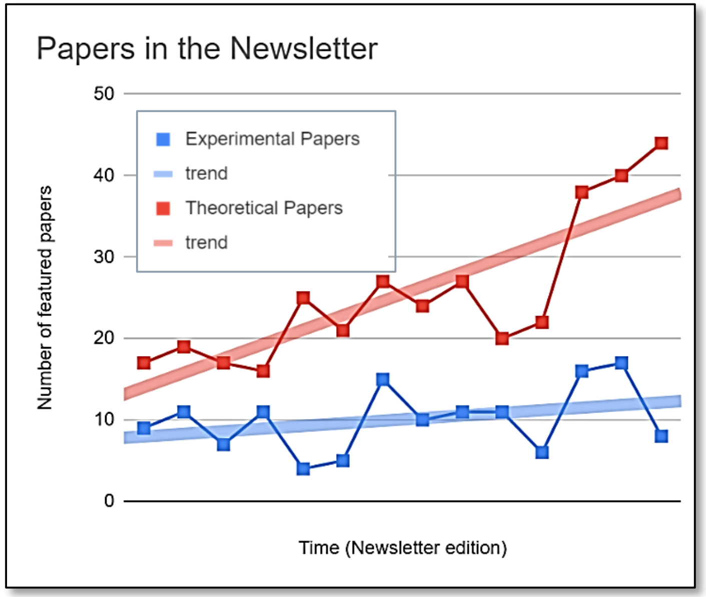

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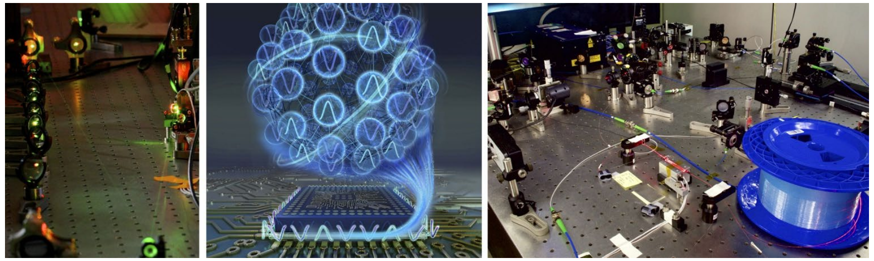

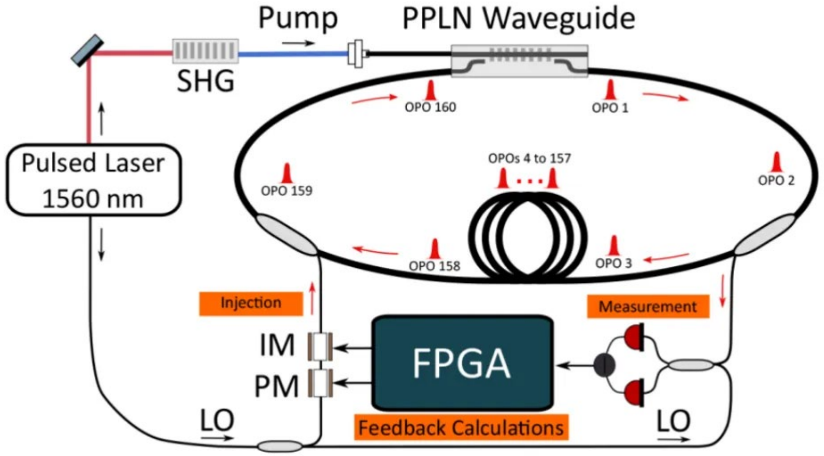

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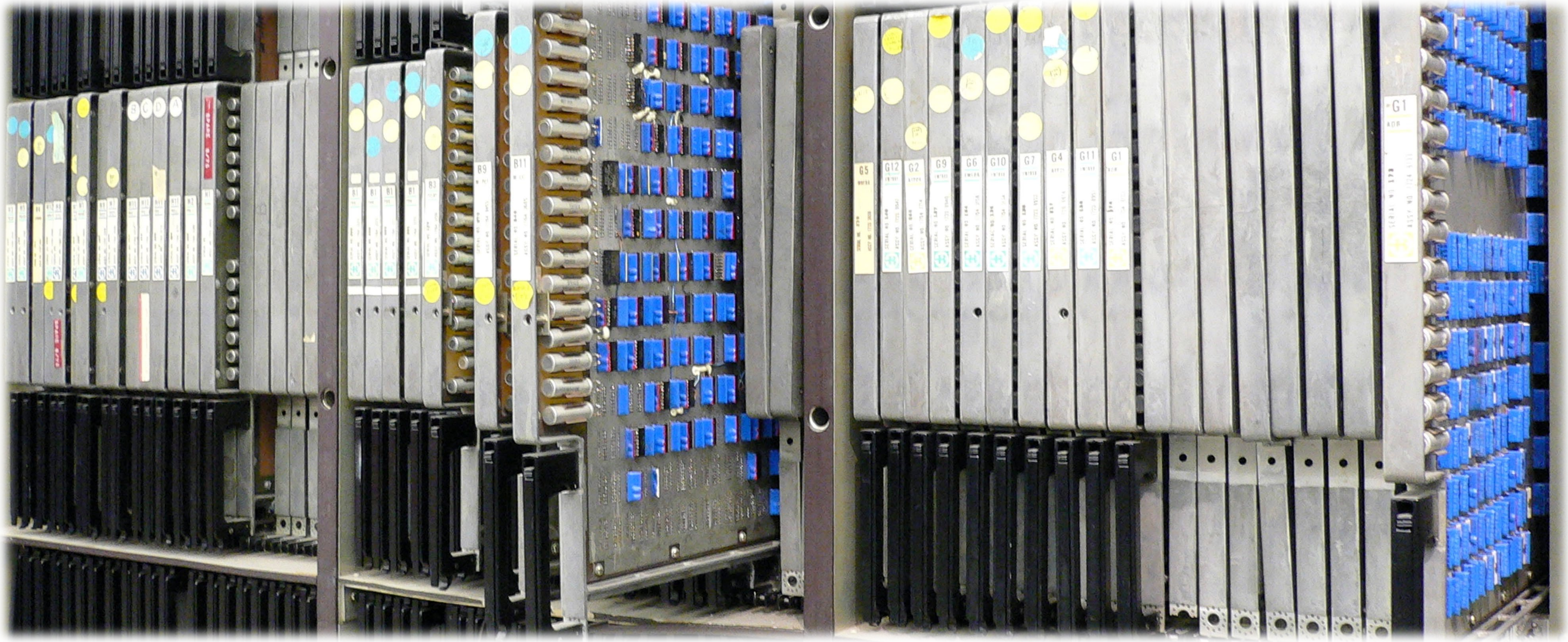

ILLIAC IV – first massively parallel computer, installed at NASA Ames 1972, first network-available supercomputer

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