LECTURE 1: QUANTUM COMPUTING HARDWARE LANDSCAPE AND INTRODUCTION

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RIACS USRA Universities Space Research Association

INTELLIGENT SYSTEMS DIVISION

OUTLINE:

- Brief history, International stakeholders, research communities, buzzwords
- Recap of quantum computing concepts
- Presentation of hardware architectures, main relevant results, roadmaps
  - Superconducting transmons and cQED systems
  - Neutral atoms analog mode
  - Ion traps
  - Others
- Resources and Snapshot of the rest of the course

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The second industrial revolution in quantum Tech

First quantum revolution:
Understanding quantum mechanics

Birth of **quantum information science:**
Theoretical framework and foundational experiments for algorithms, communication, metrology

Second quantum revolution:
Applied use of quantum mechanics: information processing, acquisition, transmission and transduction

1930

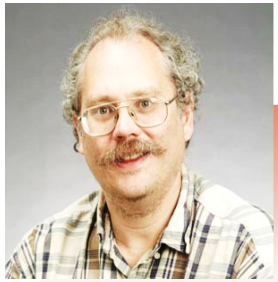
1980

2020

2030

Fault-Tolerant Quantum Computing

Physics of Computation Conference Endicott House MIT May 6-8, 1981

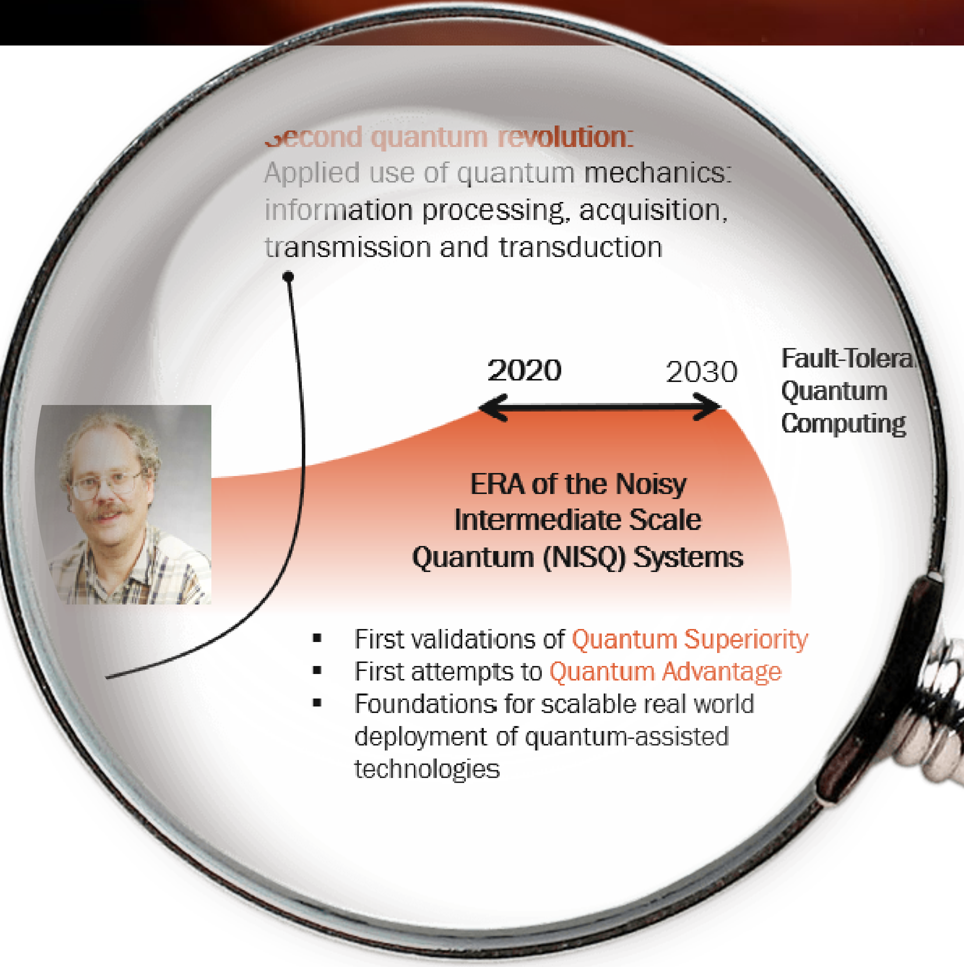


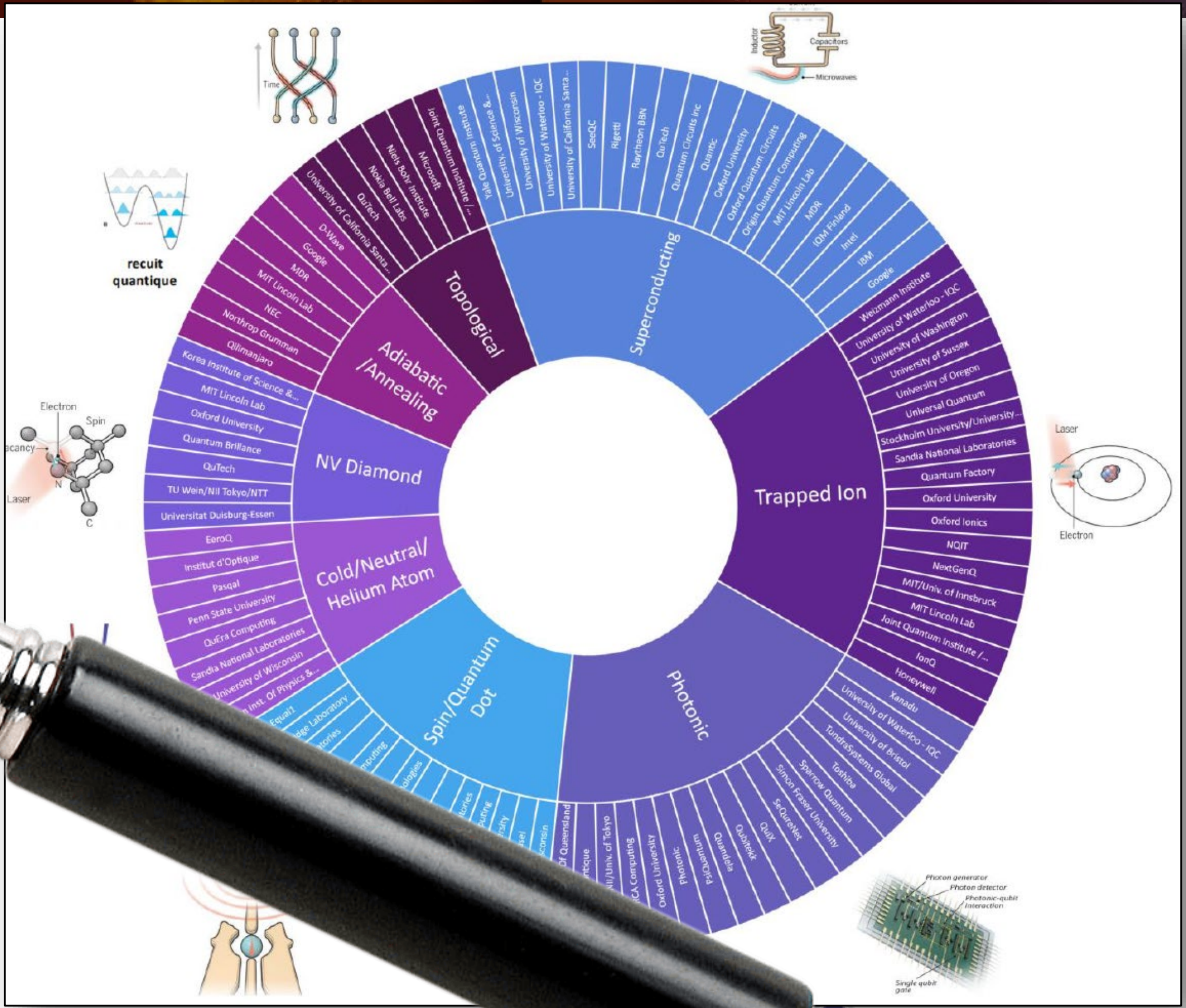
ERA of the Noisy Intermediate Scale Quantum (NISQ) Systems

- First validations of Quantum Superiority
- First attempts to Quantum Advantage
- Foundations for scalable real world deployment of quantum-assisted technologies

2007:
First not-so-bad **qubit** @ Yale

A Zoom in the NISQ Era: hardware players





Anything could be a qubit – but can we build a computer around it?

A Zoom in the NISQ Era: hardware players

NISQ Era Applications

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Most Algorithmic Activity in NISQ Era

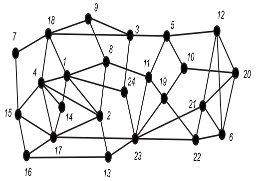
Quantum Simulation

Can we use a QPU as a programmable quantum experiment and measure what we want faster than simulating it on HPC?

Quantum Machine Learning

Can we run a quantum neural network that is capable to learn patterns or distributions better than classical deep learning?

Quantum Optimization



Can we run a quantum algorithm that maps its final result to a good solution of an optimization problem?

- QE … aria…

- Boltzm … Machines
- Kernel M…

- QAOA and variations
- Quantum Annealing

Unclear the fidelity required.
Hardware-efficiency and keep noise under control.

Other algorithms

- Randomness
- Linear Algebra
- Non-linear ODE/PDEs
- Data Structures
- Quantum Tests

Worldwide Investment in Quantum Computing (focus on EU/Italy)

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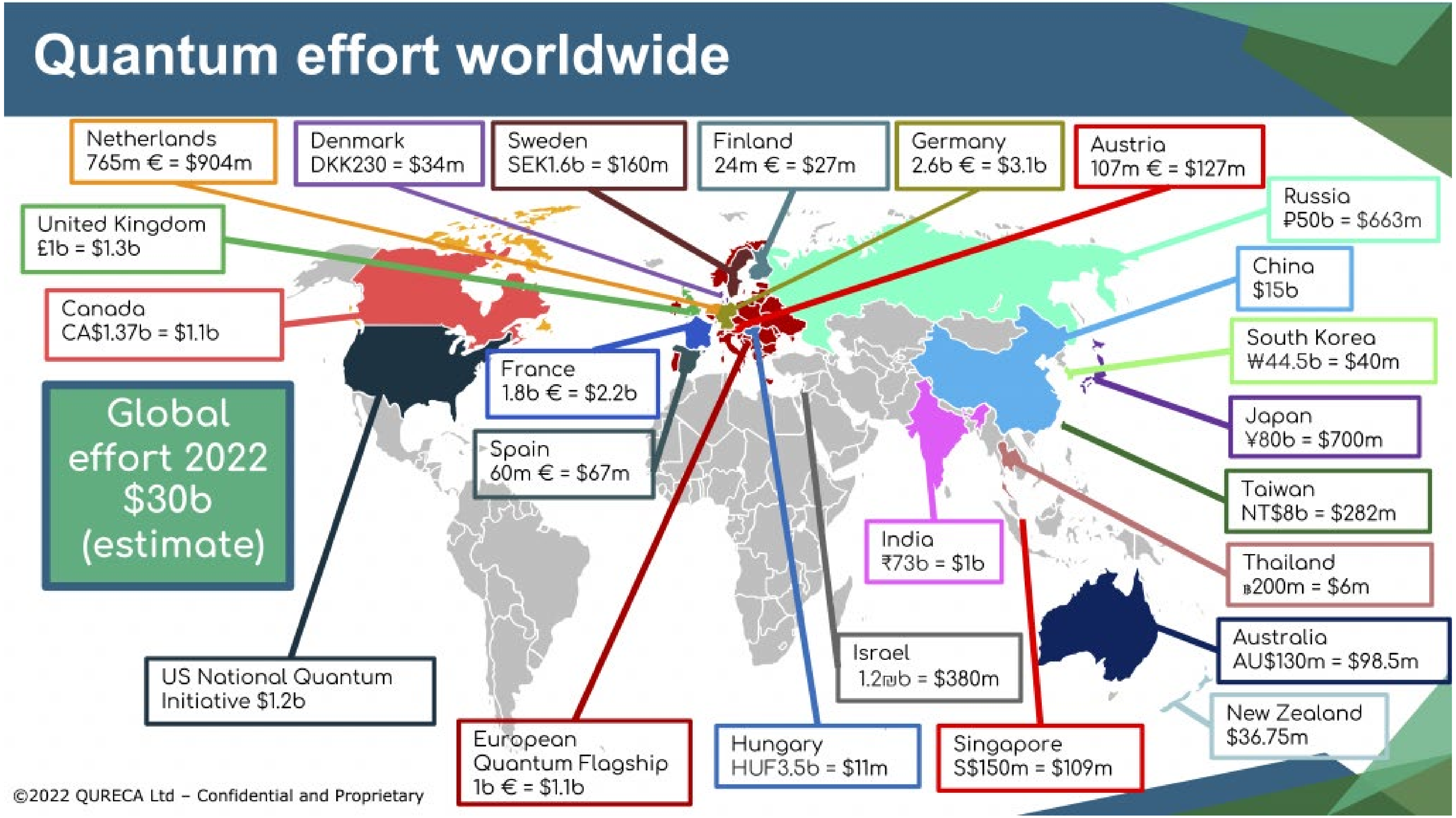


QUANTUM FLAGSHIP

QuIC European Quantum Industry Consortium

European Innovation Council

SUPERCALCOLO

Quantum computing, nasce il centro nazionale: 320 milioni dal Pnrr

Home › Tech Zone

Condividi questo articolo

Obiettivo dell'iniziativa è realizzare una nuova rete con capacità di oltre un terabit al secondo. Garr tra i 51 partner di tutta Italia. L'hub è stato individuato al Tecnopolo di Bologna. L'infrastruttura trasversale supporterà i principali settori strategici per il Paese

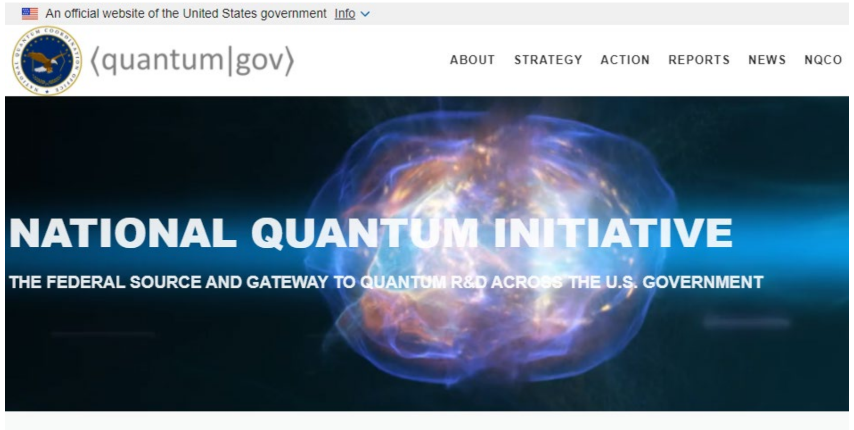
19 Lug 2022

USRA Universities Space Research Association

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

U.S. Investment in Quantum Computing: big picture

INTELLIGENT SYSTEMS DIVISION



DARPA · U.S. DEPARTMENT OF ENERGY · NSF · IARPA BE THE FUTURE

Funding ≈$1B in Quantum

NASA · AFRL THE AIR FORCE RESEARCH LABORATORY LEAD | DISCOVER | DEVELOP | DELIVER · U.S. NAVAL RESEARCH LABORATORY

QED-C

Purposes

- Enable and support a robust U.S. quantum ecosystem and quantum industry supply chain
- Provide a collective industry voice to inform and guide Federal R&D investment priorities, standards and regulation, and quantum workforce education and development
- Facilitate and coordinate industry interaction and partnerships with Government agencies
- Foster sharing of intellectual property, efficient supply chains, technology forecasting and quantum literacy
- Communicate potential economic impact of quantum technologies

NIST National Institute of Standards and Technology U.S. Department of Commerce

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U.S. Investment in Quantum Computing: NQI

Quantum Leap Challenge Institutes

CIQC Challenge Institute for Quantum Computation

Berkeley UNIVERSITY OF CALIFORNIA

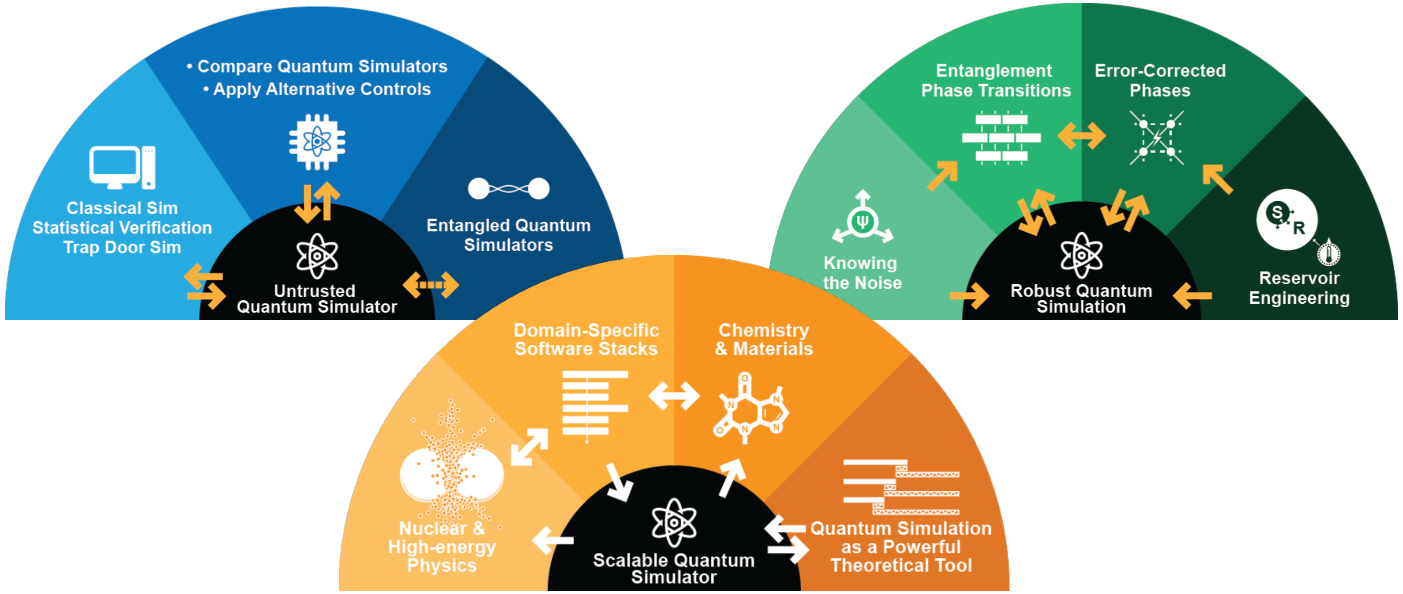
Institute for Robust Quantum Simulation

UNIVERSITY OF MARYLAND

Algorithms Our specific aims are (1) to develop novel quantum algorithms for future fault-tolerant hardware, (2) to develop alternative quantum computing paradigms that are suited to more limited computing resources, and (3) to extend the impact of quantum computation on classical computer science.

Verifiable Quantum Advantage Our specific aims in addressing this challenge are (1) to develop protocols for rigorously verifiable quantum advantage, (2) to refine the connection between noise and error models and computational capacity, and (3) to exploit one of the most valuable applications of NISQ computing, which is the advancement of physical science through quantum simulation.

Scaling Atom-Based Computers the specific aim of utilizing AMO research on the scaling quantum systems challenge has the specific aim of utilizing AMO-based quantum technologies, including advances in optical engineering, to realize improved modularity, high-fidelity operation and classical control within quantum systems of increasing size and complexity, deriving generalized approaches to scaling up quantum information processors.



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Focus on Quantum Computing:
5 DOE Centers in Quantum Information Sciences ($25M/year for 5 years)

C²QA
Co-design Center for Quantum Advantage

Q-NEXT
NEXT GENERATION QUANTUM SCIENCE AND ENGINEERING

QUANTUM℠ SCIENCE CENTER

QUANTUM SYSTEMS ACCELERATOR
Catalyzing the Quantum Ecosystem

Fermilab
SQMS
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

The center will (1) study the problem of decoherence in superconductors and (2) build a new type of quantum computer at Fermilab and develop new quantum sensors based on superconducting technology.

Asking the good questions, DARPA challenging programs

DARPA Approach: HARD Challenges, well funded, milestone based, with a Test and Evaluation Team

Optimization with Noisy Intermediate-Scale Quantum devices (ONISQ)
- exploit quantum information processing before fully fault-tolerant quantum computers
- demonstrate the quantitative advantage

Reversible Quantum Machine Learning and Simulation (RQMLS)
- explore the fundamental limits and utility of reversible quantum annealers
- design experimental tests that can be carried out on small-scale systems

Quantum Benchmarking (QB)
- estimate the long-term utility of quantum computers
- estimate the hardware-specific resources required to achieve levels of performance

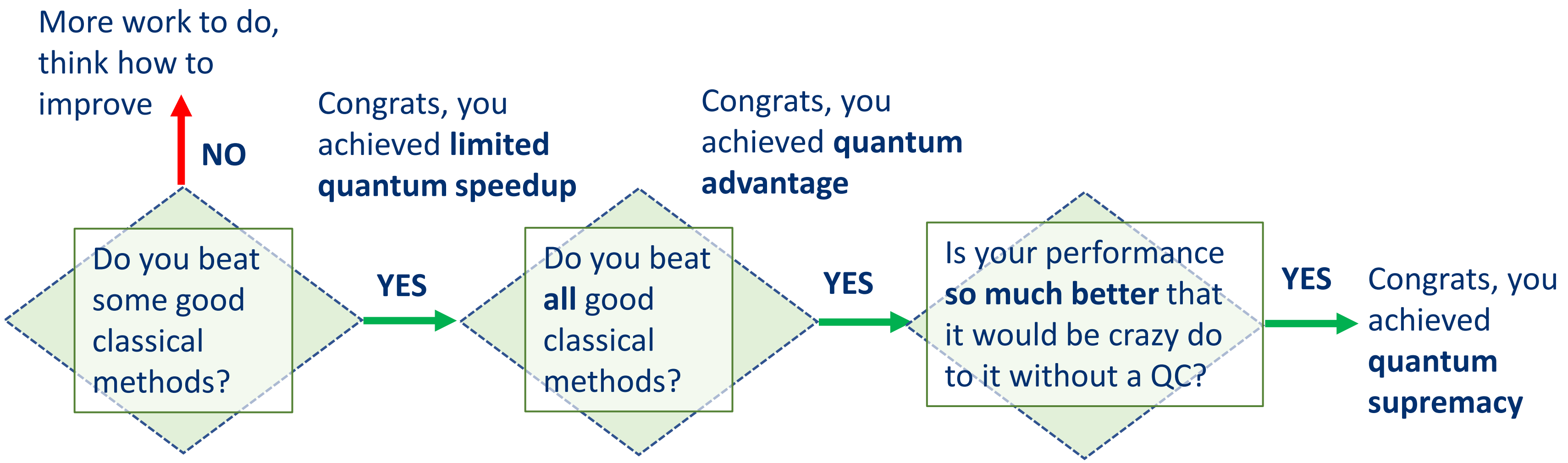
Underexplored Systems for Utility-Scale Quantum Computing (US2QC)
- determine if an underexplored approach is capable of achieving utility-scale operation

Quantum-Inspired Classical Computing (QuICC)
- develop quantum-inspired solvers for a range of complex DOD optimization problems
- reducing the required energy by at least 100x over existing techniques.

What we hope during NISQ era

A NISQ Hope: **Speedup and Quantum Advantage will be determined empirically rather than be identified theoretically beforehand**

(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 performance estimates of deep learning on theoretical grounds.)



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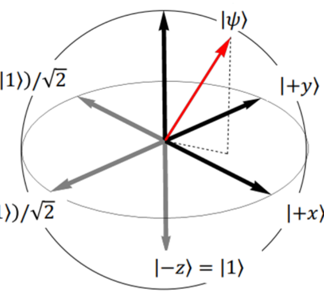
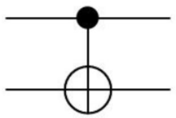
What we assume you kinda know

$$\psi_{00}|00\rangle + \psi_{01}|01\rangle + \psi_{10}|10\rangle + \psi_{11}|11\rangle$$



$$R_x(\theta) \equiv e^{-i\frac{\theta}{2}X} = \cos\frac{\theta}{2}I - i\sin\frac{\theta}{2}X = \begin{bmatrix} \cos\frac{\theta}{2} & -i\sin\frac{\theta}{2} \\ -i\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$



$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\left(\frac{\gamma}{2}\right) & i\sin\left(\frac{\gamma}{2}\right) & 0 \\ 0 & i\sin\left(\frac{\gamma}{2}\right) & \cos\left(\frac{\gamma}{2}\right) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\sum_{pq} h_{pq}\hat{a}_p^\dagger \hat{a}_q + \sum_{pqrs} g_{pq,rs}\hat{a}_p^\dagger \hat{a}_q^\dagger \hat{a}_r \hat{a}_s$$

$$|\psi^I(\Delta t)\rangle = T\exp\left(-\frac{i}{\hbar}\int_0^{\Delta t} \hat{H}_c^I(t)\,dt'\right)|\psi^I(0)\rangle$$

$$\rho_A = \mathrm{Tr}_B(\rho_{AB})$$

Quantum Mechanics gives us two operations: evolution and measurements

A quantum program is a classically controlled execution of sequence of quantum circuits and measurement.

(every quantum computation is hybrid)

A quantum circuit is an ordered sequence of quantum gates*

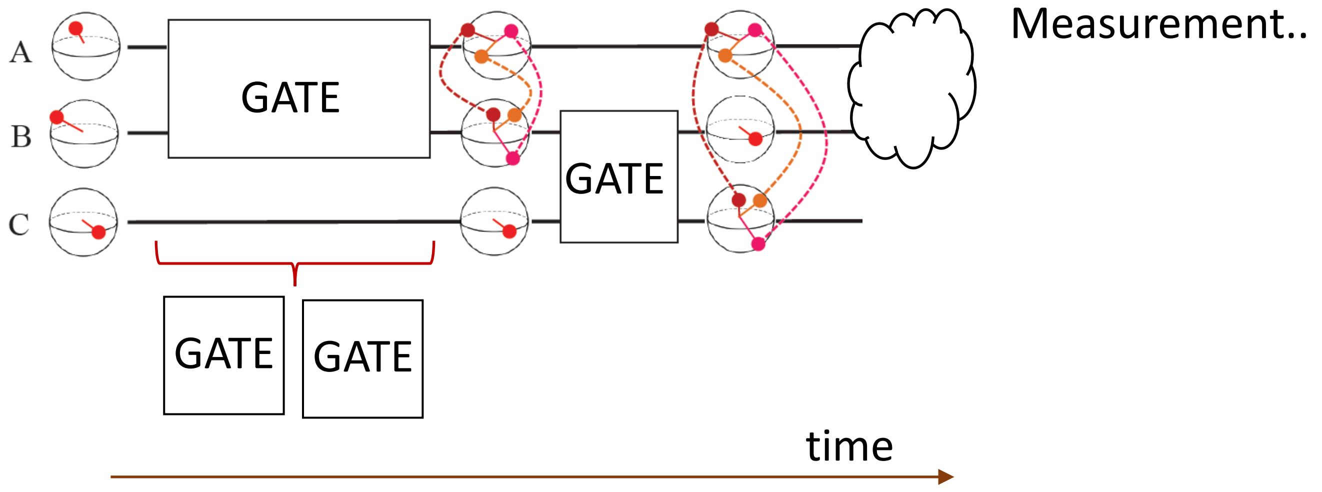
A quantum gate is a unitary operation.

* It could be also a single N-qubit gate, such as in analog quantum computing / quantum annealing, although that is usually not discussed in the circuit/gate model framework

(see also next lecture!)

IDEALIZED QUANTUM CIRCUIT

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

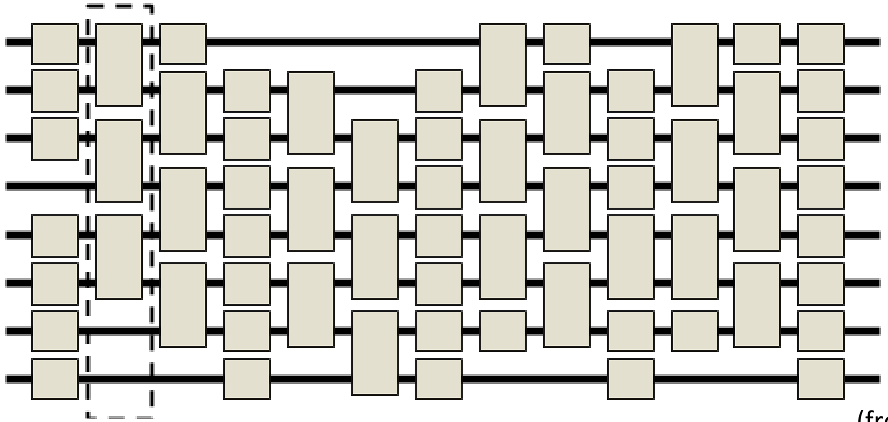


SYNTHESIS

… in term of the natively implementable gates?

COMPILATION (PARALLELIZATION)

… minimizing the duration of the execution of the circuit? Or the total infidelity of the computation?


(from Cirq)

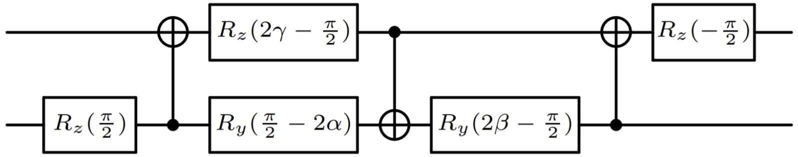
Example: Synthesis

$$R_x(\theta) \equiv e^{-i\frac{\theta}{2}X} = \cos\frac{\theta}{2}I - i\sin\frac{\theta}{2}X = \begin{bmatrix} \cos\frac{\theta}{2} & -i\sin\frac{\theta}{2} \\ -i\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{bmatrix}$$

$$R_y(\theta) \equiv e^{-i\frac{\theta}{2}Y} = \cos\frac{\theta}{2}I - i\sin\frac{\theta}{2}Y = \begin{bmatrix} \cos\frac{\theta}{2} & -\sin\frac{\theta}{2} \\ \sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{bmatrix}$$

$$R_z(\theta) \equiv e^{-i\frac{\theta}{2}Z} = \cos\frac{\theta}{2}I - i\sin\frac{\theta}{2}Z = \begin{bmatrix} e^{-i\theta/2} & 0 \\ 0 & e^{i\theta/2} \end{bmatrix}$$

$$N(\alpha,\beta,\gamma) = \left[\exp\left(i(\alpha\,\sigma_x\otimes\sigma_x + \beta\,\sigma_y\otimes\sigma_y + \gamma\,\sigma_z\otimes\sigma_z)\right)\right]$$



Maximum number of elementary 1-qubit gates: **15**
Maximum number of CNOTs: **3**
Maximum depth assuming R_Y, R_Z and simplifications: **11**

Quantum Circuits can be composed by single and two-qubit gates of universal set*
CNOT, $R_y(\theta)$ and $R_z(\alpha)$

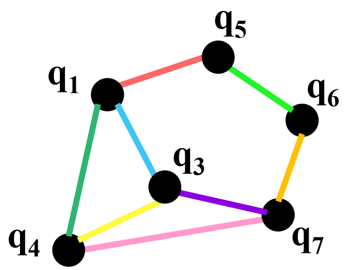
Each single qubit gate can be decomposed by single qubit rotations.
U1= $R_z(\alpha)$ $R_y(\beta)$ $R_z(\gamma)$ $e^{i\phi}$

Each two qubit gate is reversible and it is representable by a Unitary Matrix.

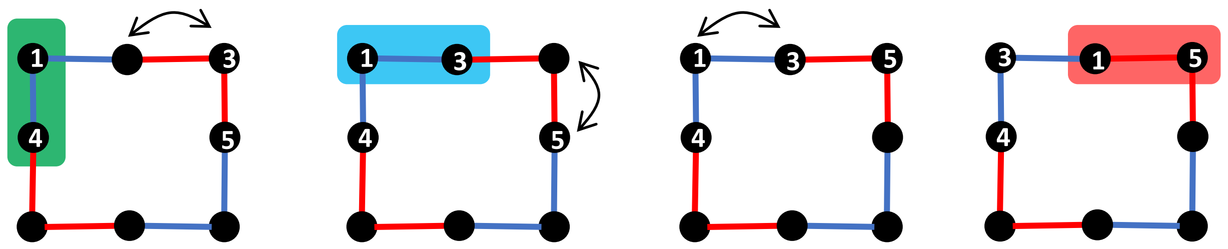
Barenco et al. (1995)
Kraus, Cirac (2001)
Vatan, Williams (2003)

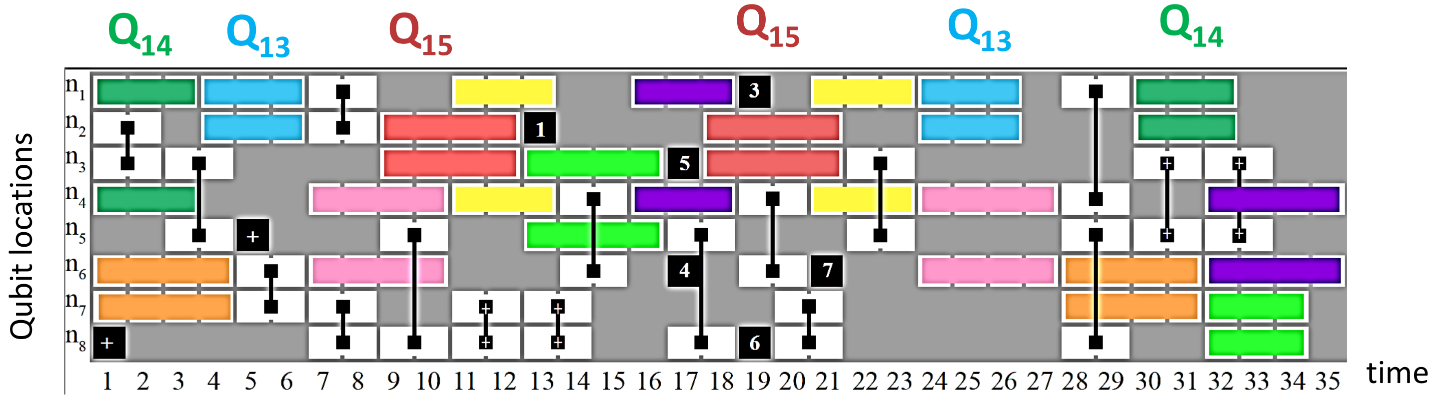
Example: Compilation

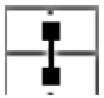
Example Interaction Graph of gates



First few operations involving qubit 1

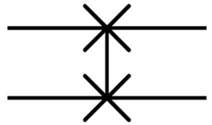






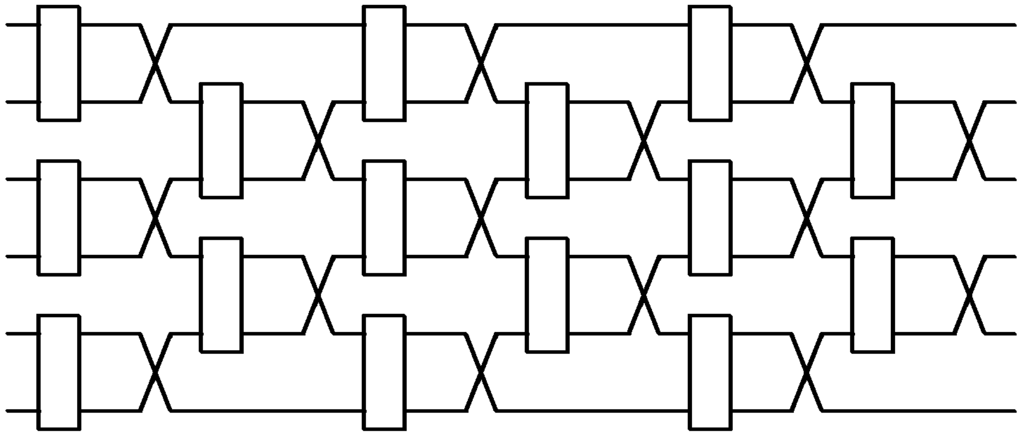
SWAP Operation

$$\mathrm{SWAP} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



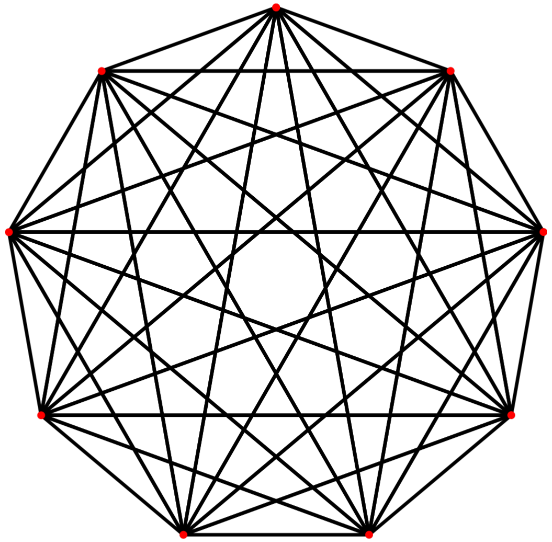
From D Venturelli, M Do, E Rieffel, J Frank Quantum Science and Technology 3 (2), 025004 (2017)

Example: Compilation, SWAP networks



Swap network depth N with N(N-1)/2 gates

See Kivlichan Phys.Rev.Lett 120, 110501 (2018) and O'Gorman et al. ArXiv:1905.05118 (2019)



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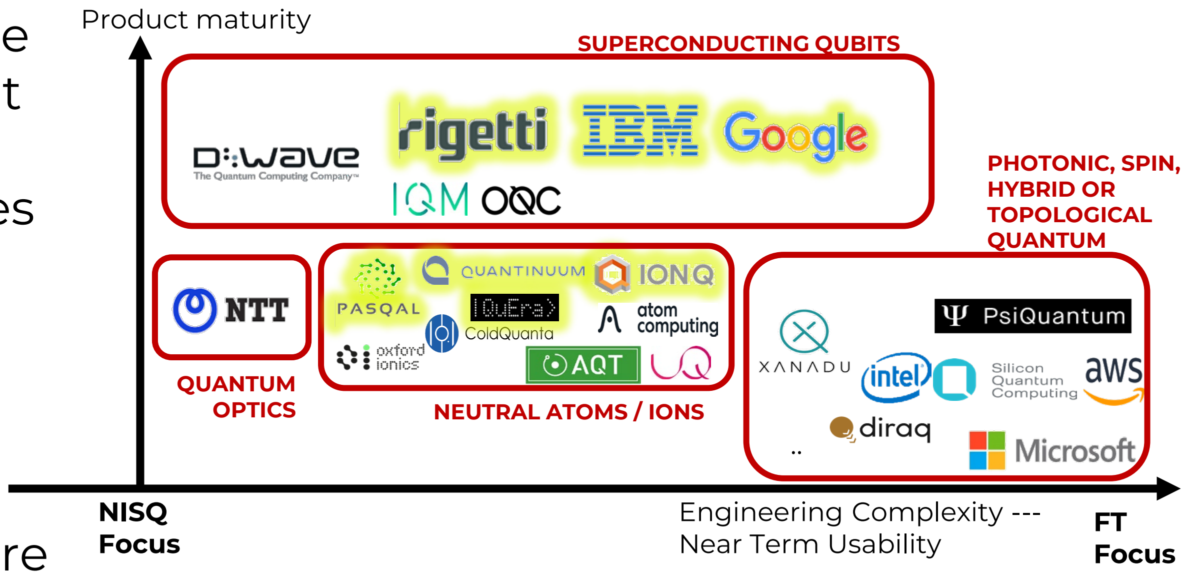
Quantum NISQ Architectures

DISCLAIMER

We are going to look at what are computers that research group can use today (if you pay!) for non-fault-tolerant <u>universal</u> quantum computing, not considering non-universal architectures (e.g. gaussian boson sampling, limited quantum annealers), or other architectures that are not as industrialized but are possibly better suited for quantum simulations. These are not necessarily the best future quantum computers, and there are others that are non-commercial!



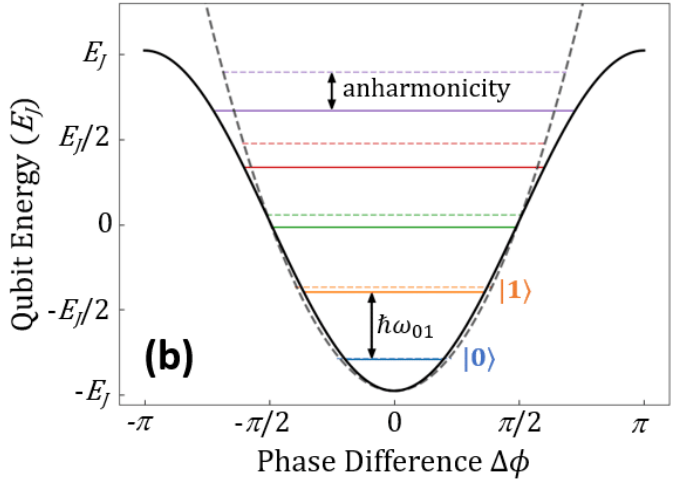
Superconducting: Transmons

A Quantum Engineer's Guide to Superconducting Qubits
P. Krantz[1,2,†], M. Kjaergaard[1], F. Yan[1], T.P. Orlando[1], S. Gustavsson[1], and W. D. Oliver[1,3,‡]

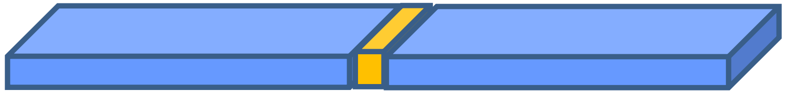
https://arxiv.org/pdf/1904.06560.pdf

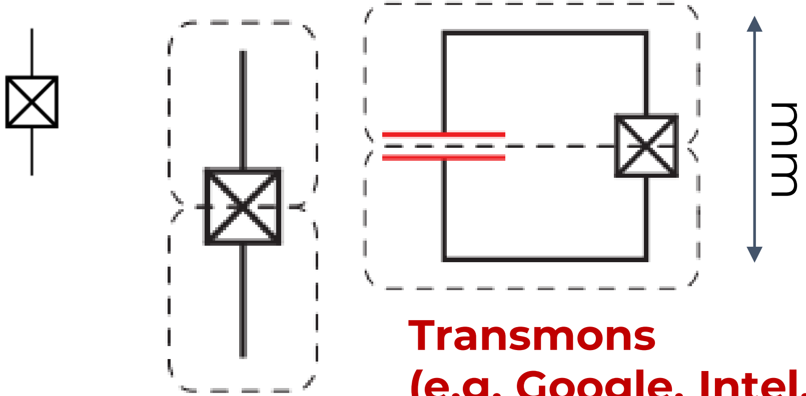
Tutorial: Gate-based superconducting quantum computing
Sangil Kwon,[1,a)] Akiyoshi Tomonaga,[1,2] Gopika Lakshmi Bhai,[1,2] Simon J. Devitt,[3] and Jaw-Shen Tsai[1,2]

https://arxiv.org/pdf/2009.08021.pdf



If two superconductors are separated by a thin barrier, their wavefunction communicates and creates a tunneling current with non-linear properties
(Josephson Effect; Josephson Junctions – Phys. Lett. 1. 251 - 1962)





Transmons (e.g. Google, Intel, IBM, Rigetti)

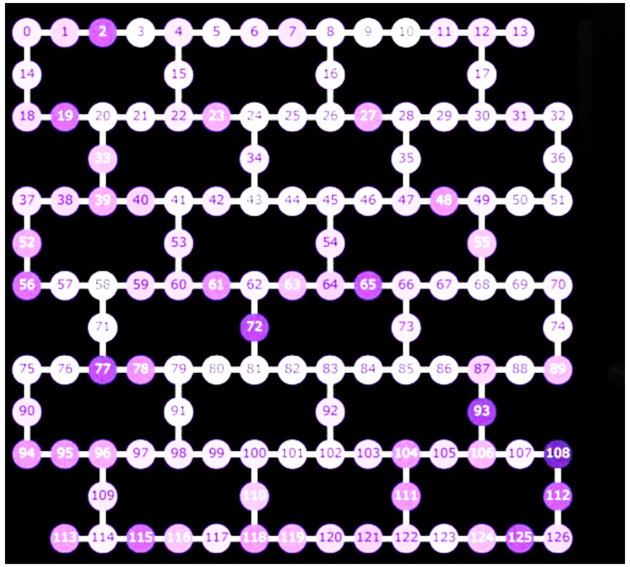
LEADING QUBITS DESIGN

- High quality factor
- Ability to be coupled to other transmons.
- Absorb/Emit in microwave region (Ghz)

Superconducting: Vendors

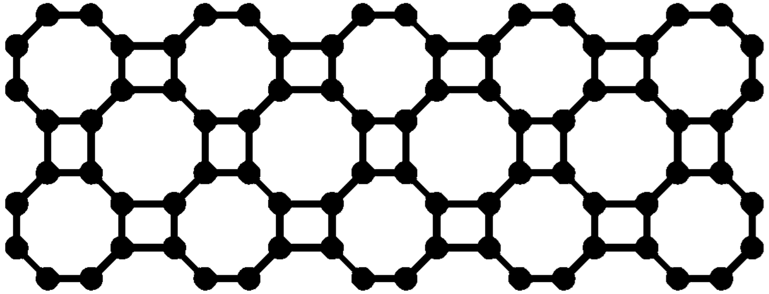
IBM

Current: 127 IBM Eagle
Roadmap: 433 (2022); 1121 (2023)
Basis gates: CX, ID, RZ, SX, X



rigetti

Current: 80 M-1
Roadmap: 336 (2023) 1000+ (2025)
Basis gates: RX, RY, RZ, CPHASE, XY



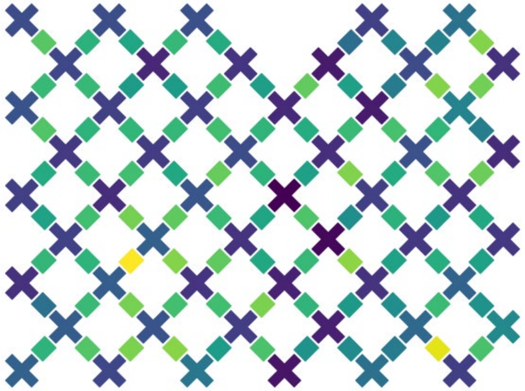
CPHASE

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & e^{i\theta} \end{pmatrix}$$

$$\mathrm{XY}(\beta,\theta) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\frac{\theta}{2}) & i\sin(\frac{\theta}{2})e^{i\beta} & 0 \\ 0 & i\sin(\frac{\theta}{2})e^{-i\beta} & \cos(\frac{\theta}{2}) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Google

Current: 72(53)
Roadmap: 1 logical qubit! Undisclosed
Basis gates: RX, RY, RZ, fSim



$$\mathrm{fSim}(\theta,\phi) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -i\sin\theta & 0 \\ 0 & -i\sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & e^{-i\phi} \end{pmatrix}$$

Superconducting: Recent Quantum Simulation Results

nature

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Article | Open Access | Published: 30 November 2021

Time-crystalline eigenstate order on a quantum processor

Article | Published: 23 June 2021

Accurately computing the electronic properties of a quantum ring

Article | Open Access | Published: 16 March 2022

Unbiasing fermionic quantum Monte Carlo with a quantum computer

arXiv > quant-ph > arXiv:2206.05254

Quantum Physics

[Submitted on 10 Jun 2022 (v1), last revised 29 Jun 2022 (this version, v2)]

Formation of robust bound states of interacting photons

arXiv > quant-ph > arXiv:2203.08905

Quantum Physics

[Submitted on 16 Mar 2022]

Probing confinement in a $\mathbb{Z}_2$ lattice gauge theory on a quantum computer

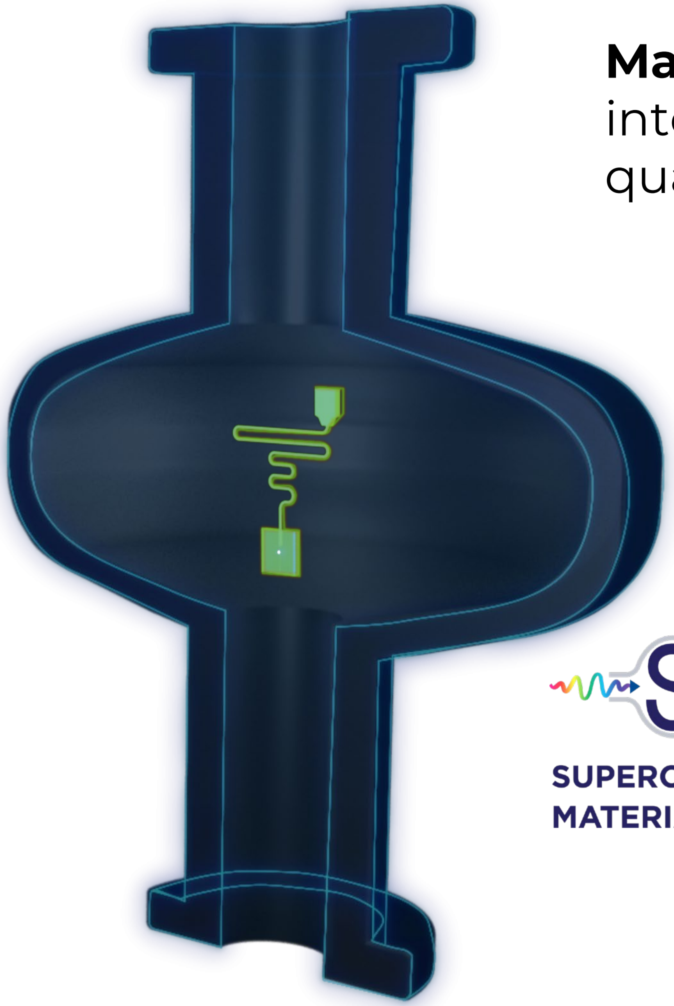
arXiv > quant-ph > arXiv:2108.13375

Quantum Physics

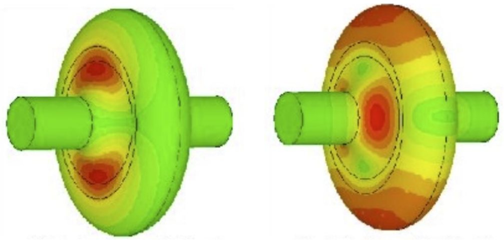
[Submitted on 30 Aug 2021 (v1), last revised 8 Sep 2021 (this version, v2)]

Benchmarking variational quantum eigensolvers for the square-octagon-lattice Kitaev model

Superconducting: cQED



Main idea: use the transmons as non-linear element mediating interactions between electromagnetic modes inside a 3D cavity or quantized in a 2D resonator



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(see Wed Lecture)

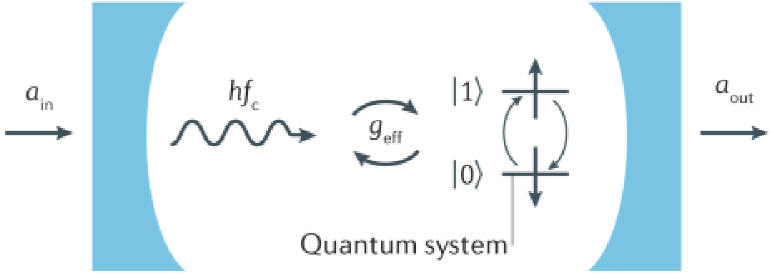
Quantum Computation and Sensing

Online Event

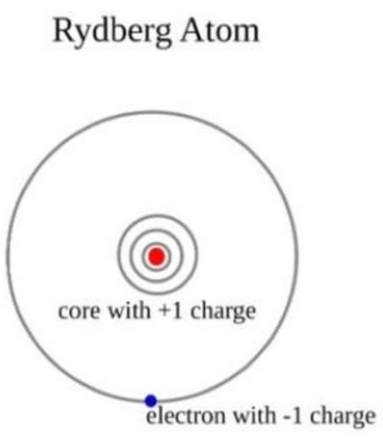
Jun 21, 2021 - Jul 02, 2021

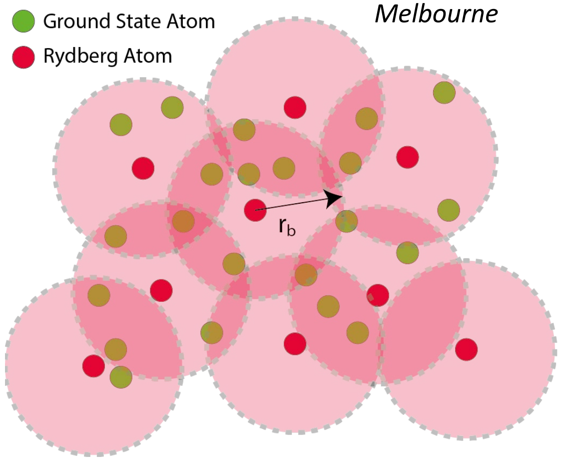
https://www.ggi.infn.it/showevent.pl?id=402

See the four lectures by J.Koch (SQMS) !



Neutral Atoms: analog simulators





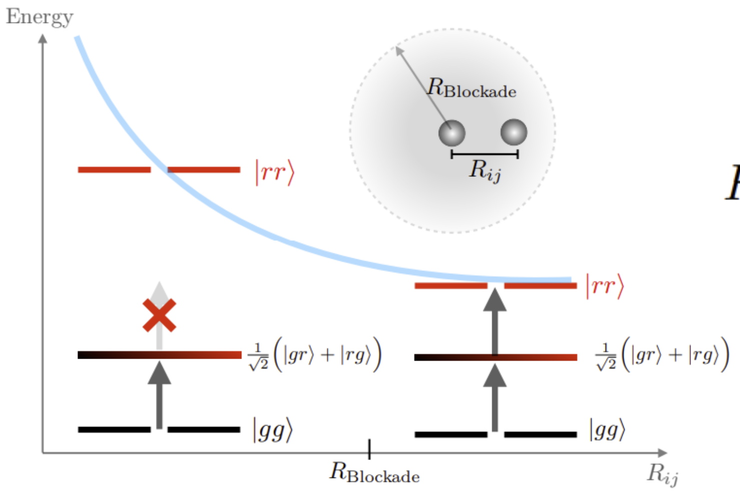
From: *University of Melbourne*

$$\mathcal{H}(t) = \sum_i \left(\frac{\hbar\Omega(t)}{2}\sigma_i^x - \hbar\delta(t)\hat{n}_i + \sum_{j<i} \frac{C_6}{(R_{ij})^6}\hat{n}_i\hat{n}_j \right)$$

$$\hat{n}_i = (1 + \sigma_i^z)/2$$ Ising Hamiltonian

$$\mathcal{H}_{int} = 2\sum_{i\neq j} \frac{C_3}{R_{ij}^3}\left(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y\right)$$ XY Hamiltonian

Atoms that allow high-orbital occupation (Rydberg), interacting through Van-Der-Waals electrostatic interaction, are effectively implementing "Ising" or "XY" between two computational states.



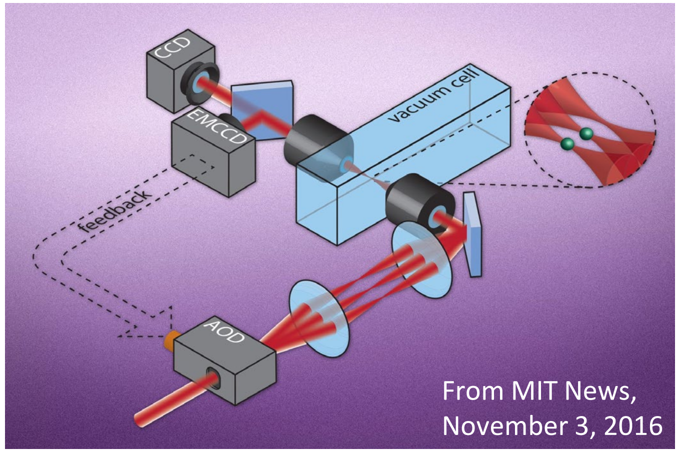
$$R_b = \left(\frac{C_6}{\hbar\Omega}\right)^{1/6}$$

Pulser: An open-source package for the design of pulse sequences in programmable neutral-atom arrays

Henrique Silvério[1,*], Sebastián Grijalva[1,*], Constantin Dalyac[1], Lucas Leclerc[1], Peter J. Karalekas[2], Nathan Shammah[2], Mourad Beji[1], Louis-Paul Henry[1], and Loïc Henriet[1]

Unitary Fund

Neutral Atoms: processor architectures, vendors and results



From MIT News, November 3, 2016

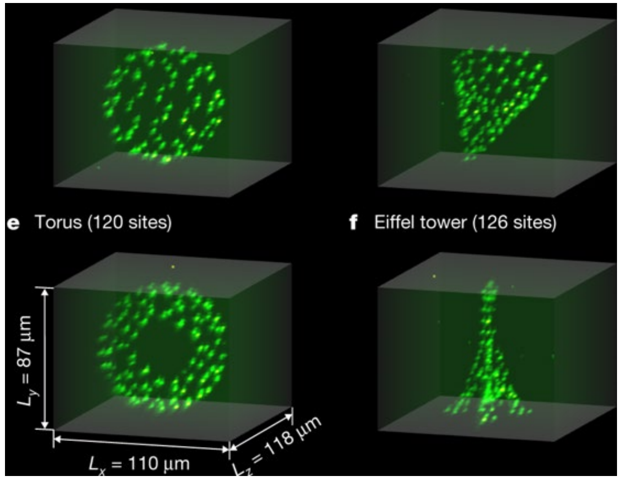
Current technology allows to place atoms in arbitrary 3D structures – but the laser excitation triggering dipole interaction is still "global" on a large part of the processor.

|QuEra> Computing Inc.

Current: 256 quantum analog (rubidium) soon on AWS
Roadmap: 1024 QPU by 2024

PASQAL

Current:: 100 qubits (rubidium) available now on CINECA, 300 qubit in dev (Microsoft Azure)
Roadmap: 1000 qubits in 2023



Barredo, D., Lienhard, V., de Léséleuc, S., Lahaye, T. & Browaeys, A. Nature 561, 79–82 (2018).

nature — Article | Published: 07 July 2021
Quantum phases of matter on a 256-atom programmable quantum simulator

Science — Vol. 374, No. 6572 — Research Article — Topological Matter
Probing topological spin liquids on a programmable quantum simulator

nature — Article | Published: 07 July 2021
Quantum simulation of 2D antiferromagnets with hundreds of Rydberg atoms

Science — Vol. 374, No. 6572 — Research Article — Topological Matter
Probing topological spin liquids on a programmable quantum simulator

Physical Review X — Open Access
Emerging Two-Dimensional Gauge Theories in Rydberg Configurable Arrays

Cornell University — arXiv:2107.14459 (quant-ph) — Quantum Physics
[Submitted on 30 Jul 2021 (v1), last revised 1 Mar 2022 (this version, v2)]
Microwave-engineering of programmable XXZ Hamiltonians in arrays of Rydberg atoms

Note: Coldquanta and Atom Computing are focusing on digital quantum computing with Rydberg (cesium, strontium) – no product yet.

Ion Trap Processors: 1D dipole-dipole architecture

IONQ

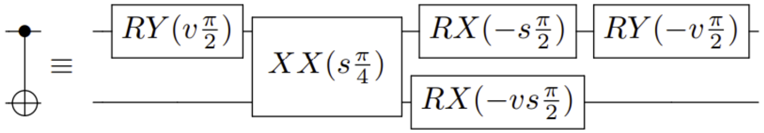
Native Gates:

$$GPI(\phi) = \begin{bmatrix} 0 & e^{-i\phi} \\ e^{-i\phi} & 0 \end{bmatrix}$$

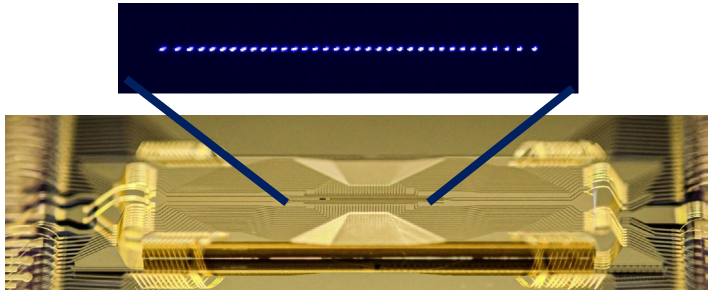
$$GPI2(\phi) = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -ie^{-i\phi} \\ -ie^{i\phi} & 1 \end{bmatrix}$$

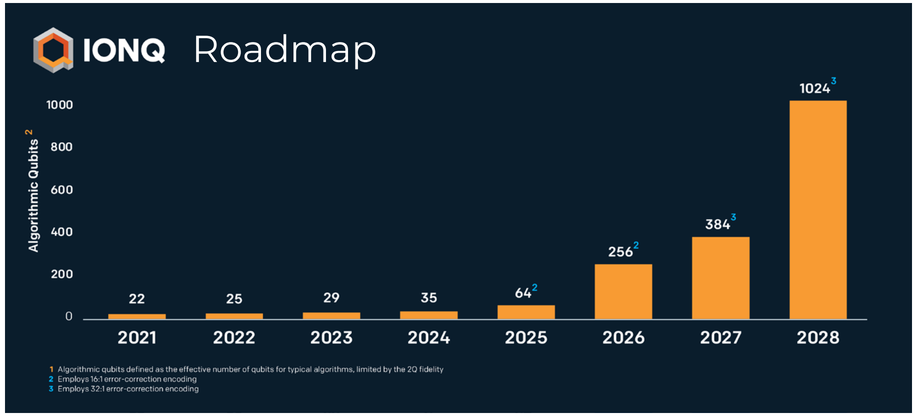
$$Virtual\ Z(\theta) = \begin{bmatrix} e^{-i\theta/2} & 0 \\ 0 & e^{i\theta/2} \end{bmatrix}$$

$$XX(\chi) = \begin{pmatrix} \cos(\chi) & 0 & 0 & -i\sin(\chi) \\ 0 & \cos(\chi) & -i\sin(\chi) & 0 \\ 0 & -i\sin(\chi) & \cos(\chi) & 0 \\ -i\sin(\chi) & 0 & 0 & \cos(\chi) \end{pmatrix}$$



- Linear trap holds the ions (ytterbium) in place via oscillating fields (paul trap) – only 1D, currently 32 (max ≈100 ions) separated few microns.
- Lasers displace atoms ≈nm induce dipole-dipole interaction in arbitrary pairs of qubits. Gate time 10-100 us; Fidelity ≈99+% - full connectivity but parallelization is difficult from the quantum control point of view.



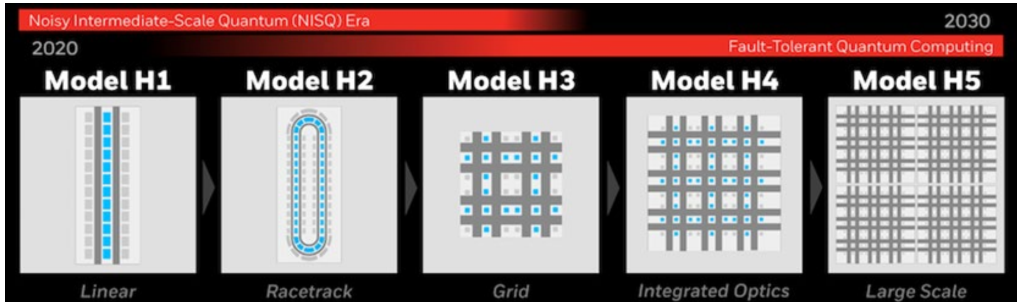


Ion Trap Processors: Quantum Charge Coupled Device (QCCD)

QUANTINUUM

Same as ion-Q but the traps are designed to have regions of movement of ions, and regions of interactions. Motional mode are not exploited except by a small number of ions when closeby with the others separatged.

≈512 qubits by 2025



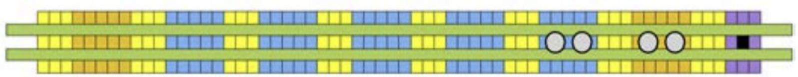
Native Gates

$$U_{1q}(\theta,\varphi) = e^{-i\,(\cos\varphi\hat{X}+\sin\varphi\hat{Y})\,\theta/2} = \begin{pmatrix} \cos\frac{\theta}{2} & -ie^{-i\varphi}\sin\frac{\theta}{2} \\ -ie^{i\varphi}\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{pmatrix}$$

$$R_z(\lambda) = e^{-i\,\hat{Z}\,\lambda/2} = \begin{pmatrix} e^{-i\,\lambda/2} & 0 \\ 0 & e^{i\,\lambda/2} \end{pmatrix}$$

$$ZZ() = e^{-i\,\pi/4\,\hat{Z}\otimes\hat{Z}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & i & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Operation	Duration(μs)
Qubit initialization	10
Qubit measurement (high-fidelity)	120
Qubit measurement (low crosstalk)	60
Cooling stage 1 (Doppler)	550
Cooling stage 2 (Axial and Radial SB)	850
Cooling stage 3 (Axial SB)	650
SQ $\pi/2$ time	5
TQ gate	25



Linear Transport (physical shuttling)
SWAP Operation (physical out-of-plane swaps)

Operation	Duration (μs)
Intrazone shift	58
Interzone shift	283
Split/combine	128
Swap	200

System Fundamentals	H1-1			H1-2		
Parameters	**min**	**typ**	**max**	**min**	**typ**	**max**
General						
Qubits		20			12	
Average depth-1 circuit time[1]		28 ms			27 ms	
Connectivity		All-to-all			All-to-all	
Parallel two-qubit operations		5			3	
Errors						
Single-qubit gate infidelity	2×10^{-5}	5×10^{-5}	3×10^{-4}	2×10^{-5}	5×10^{-5}	3×10^{-4}
Two-qubit gate infidelity	2×10^{-3}	3×10^{-3}	5×10^{-3}	2×10^{-3}	3×10^{-3}	5×10^{-3}
State preparation and measurement (SPAM) error	2×10^{-3}	3×10^{-3}	5×10^{-3}	2×10^{-3}	3.5×10^{-3}	6×10^{-3}
Memory error per qubit at average depth-1 circuit	1×10^{-4}	4×10^{-4}	1×10^{-3}	1×10^{-4}	4×10^{-4}	1×10^{-3}
Mid-circuit measurement cross-talk error	5×10^{-5}	1×10^{-4}	5×10^{-4}	5×10^{-5}	1×10^{-4}	5×10^{-4}

Recap of NISQ top contenders

Highest Speed of Operations: Superconductors *≈10ns*

Highest Fidelity of Operations: Ions *≈99.9%*

Highest Scalability of qubits: Rydberg (analog) *≈300*

Other Emerging Architectures, what we did not discuss

Photonic Architectures: not currently NISQ capable of quantum simulations. Important for interconnects (transduction) and for fault-tolerant quantum computing.

Quantum Annealers: they are capable of simulation of thermodynamic properties of spin materials at scale but are limited in programmability and coherence.

Electron Spin in 2DEGs / Quantum Dots / Silicon / Electron on Helium qubits: still to early stage to have products of more than few qubits (although 10 qubits planted in silicon published June 2022, Nature volume 606, p. 694–699 (2022))

Topological Quantum Computing: only one qubit kind of demonstrated, not relevant in the NISQ era.

THE QUANTUM INSIDER

OUTLINE:

- Brief history, International stakeholders, research communities, buzzwords
- Recap of quantum computing concepts
- Presentation of hardware architectures, main relevant results, roadmaps
  - Superconducting transmons and cQED systems
  - Neutral atoms analog mode
  - Ion traps
  - Others
- Resources and Snapshot of the rest of the course

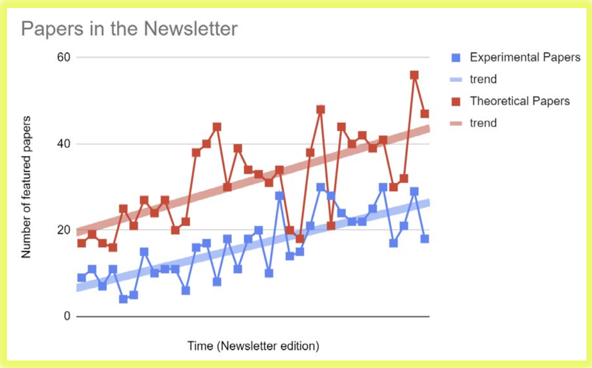
Resources: NISQ Computing ArXiv Digest & SQMS ArXiv Digest

Monthly Newsletter on NISQ Applied Quantum Computing
https://riacs.usra.edu/quantum/nisqc-nl

- 1000+ subscribers
- ArXiv Digest ~70 papers a month
- Interfaced with http://metriq.info

metriq

- **NISQ Experiments**
  - Analog / Quantum Annealing
  - Atom Based
  - Photonic
  - Superconducting
  - Other
- **NISQ Algorithms**
  - Benchmarking; Software Tools; Compilation
  - Machine Learning
  - Optimization
  - Simulation
  - Other



SQMS PREPRINT DIGEST

http://sqms-preprint-digest.usra.edu/

- Coherence in Superconducting Devices and Materials; SRF Cavity Physics circuit Quantum Electro Dynamics (cQED); Generalized Jaynes-Cummings Physics
- Quantum Simulation for HEP; BES and NP Applications
- Software; Theory; New Application of Quantum Optimal Control; Pulse Engineering
- Techniques for Computing with Qudits
- Other relevant for SQMS (e.g. Quantum Sensing for Dark Matter Search)

Recap of the rest of the course

Monday

1030 Valter Bonvicini, Stefania de Curtis: **Welcome and introduction to the school**
1045 Davide Venturelli: **The Quantum Computing landscape**
1330 Hank Lamm and Dorota Grabowska: **Field Theory 1**
1515 Giacomo de Palma and Sohaib Alam: **Quantum Algorithms 1**
1700 **Q&A Session with all the day's speakers**

Tuesday

0900 Giacomo de Palma and Sohaib Alam: **Quantum Algorithms 2**
1045 Leonardo Banchi and Peter Orth: **Quantum Variational Methods 1**
1330 **Student presentations** (chairman Davide Venturelli)
1515 Norm Tubman: **Lab 1: Quantum Computing**
1700 **Q&A Session with all the day's speakers**

Wednesday

0900 Leonardo Banchi and Peter Orth: **Quantum Variational Methods 2**
1045 Hank Lamm and Dorota Grabowska: **Field Theory 2**
1330 Pietro Silvi: **Numerical Simulations**
1515 Anna Grasllino, Alex Romanenko, Silvia Zorzetti: **SQMS and INFN**
1700 Visit to Galileo's house

Thursday

0900 Nathan Shammah, Andrea Mari: **Quantum Error Mitigation 1**
1045 Ryan LaRose: **Error Correction and Error Mitigation 2**
1330 Paolo Perinotti: **Advanced topics in Quantum Simulations**
1515 Nathan Shammah, Andrea Mari: Lab 2: **Error Mitigation Techniques**
1700 **Q&A Session with all the day's speakers**

Friday

0900 Andrea Delgado: **Quantum Machine Learning**
1045 Lorenzo Maccone: **Quantum Foundations, time and Field theory**

Student Presentations Instructions

- **Objective:** get to know each other!

- We have 34 participants in person and 90 minutes for the session: **2 minutes per person**!

- **Format:**
  1. Who are you and where you come from, what is your study path so far
  2. What are you researching/studying right now
  3. Why you wanted to attend this school and what you hope to get out of this training
  4. One hobby or interesting adventure you had