Quantum Algorithms: Where We've Been, Where We Are, and Where We're Going

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EST. 1943

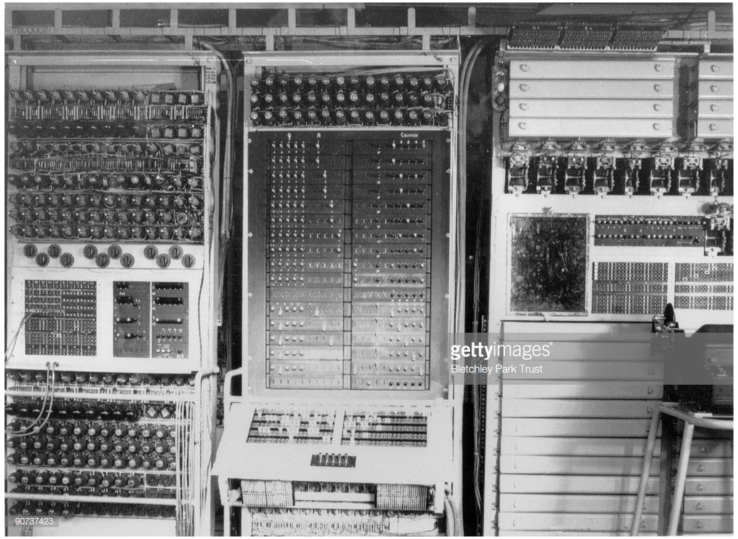
IEEE Quantum Computing Summit, August 30, 2018

LA-UR-18-28184

Los Alamos NATIONAL LABORATORY EST. 1943

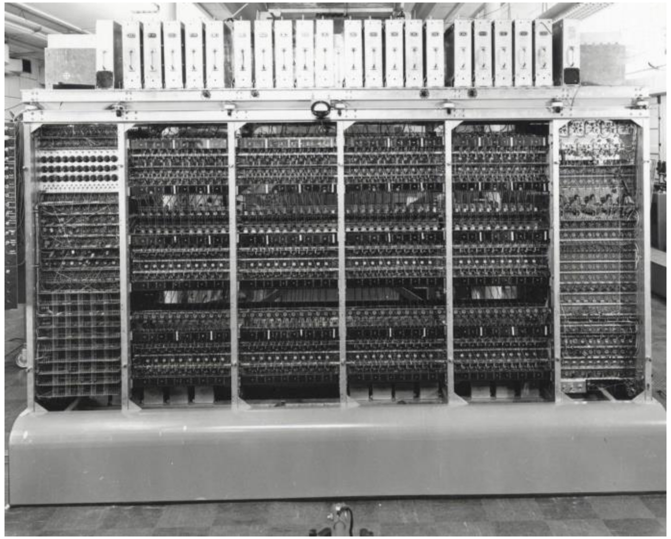
Evolution of Classical Computers

Colossus



https://www.gettyimages.com/detail/news-photo/this-shows-control-panels-of-colossus-the-worlds-first-news-photo/90737423#/this-shows-control-panels-of-colossus-the-worlds-first-electronic-picture-id90737423

Maniac



https://twitter.com/LosAlamosNatLab/status/1025033591712112640

Evolution of Classical Computers

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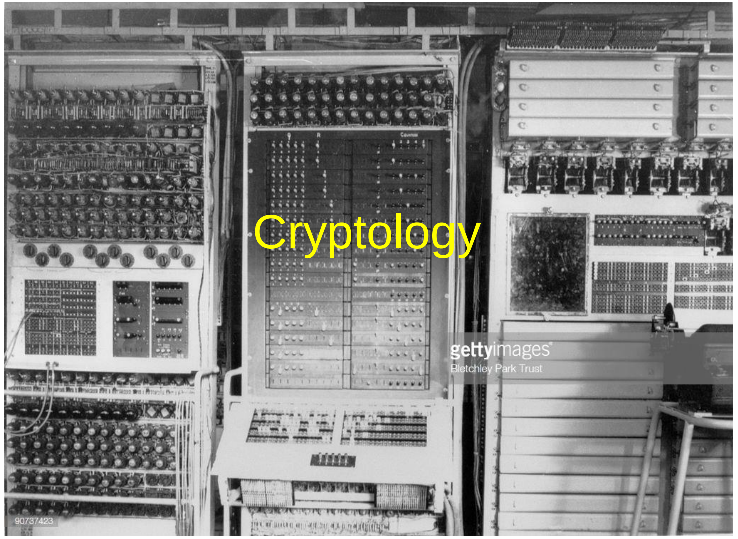

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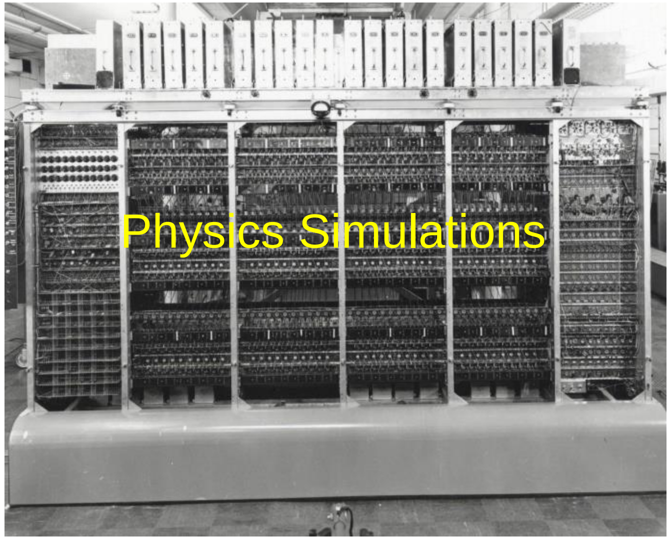
Maniac



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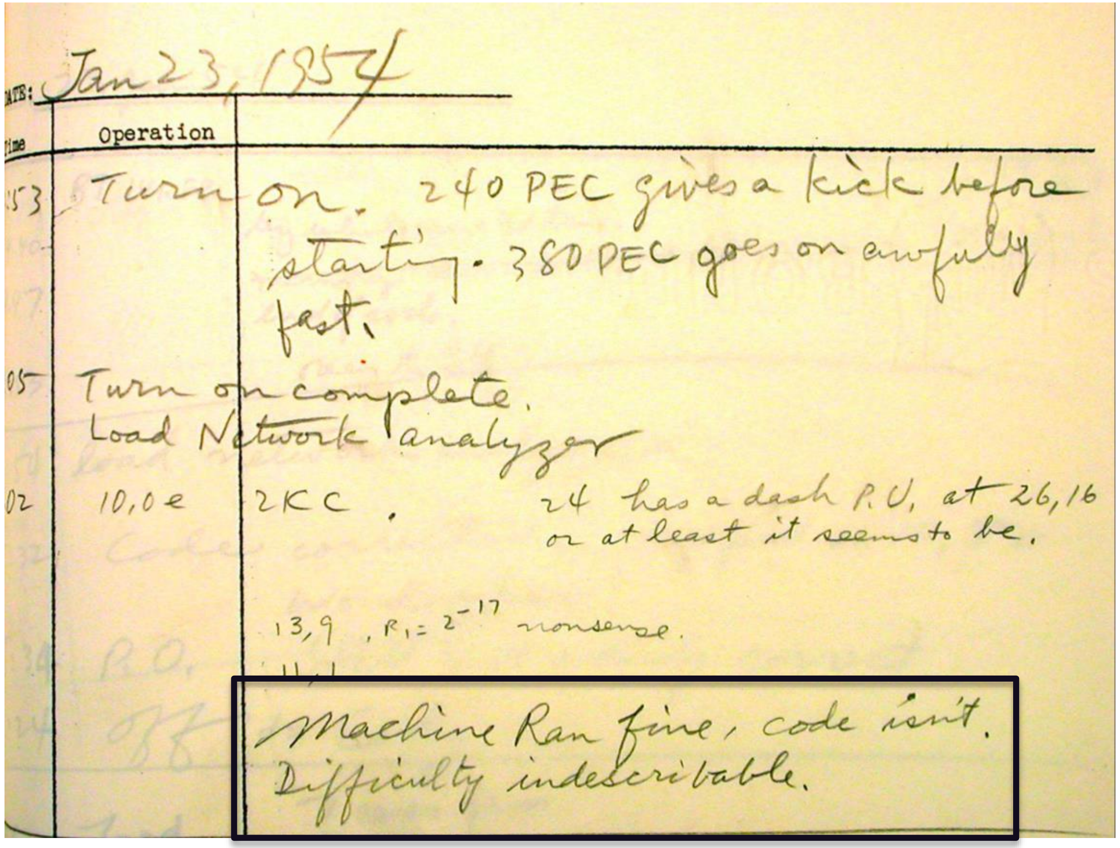
Evolution of Classical Computers


ATE: Jan 23, 1954

Time | Operation

53 Turn on. 240 PEC gives a kick before starting. 380 PEC goes on awfully fast.

05 Turn on complete.
Load Network analyzer

02 10,0e 2KC. 24 has a dash P.U. at 26,16 or at least it seems to be.

13,9 , $R_1 = 2^{-17}$ nonsense.

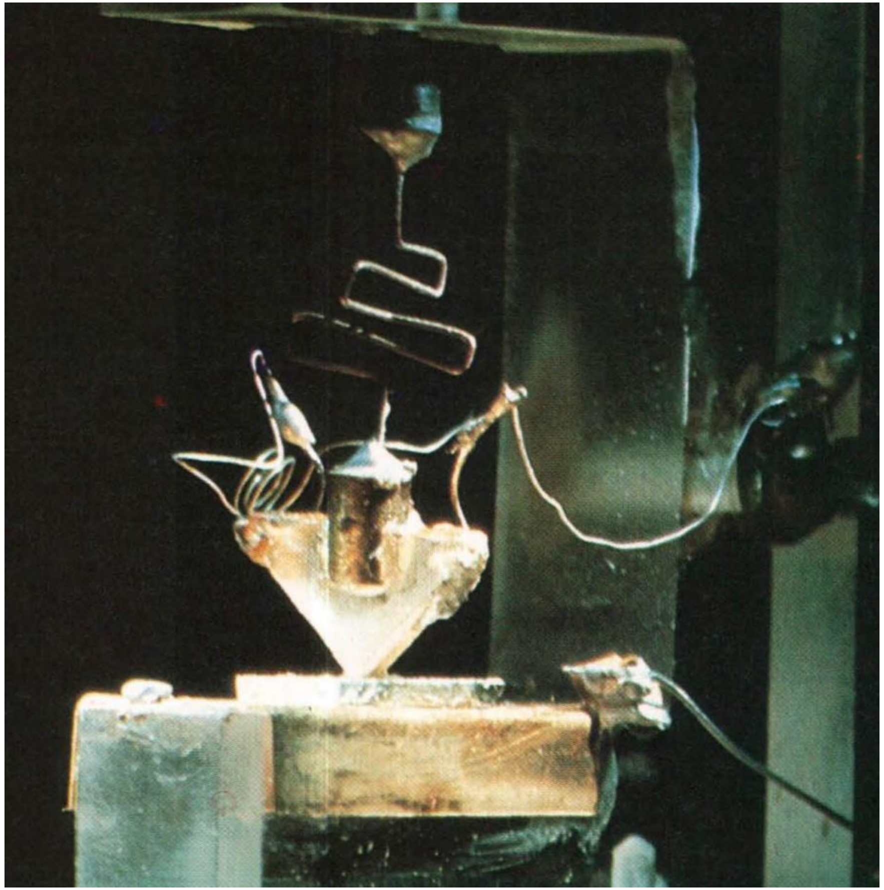
Machine Ran fine, code isn't.
Difficulty indescribable.

Page from Maniac’s machine log.

See George Dyson, “Turing’s Cathedral”

http://www.ranum.com/security/computer_security/papers/ur-syslogs/

Evolution of Classical Computers

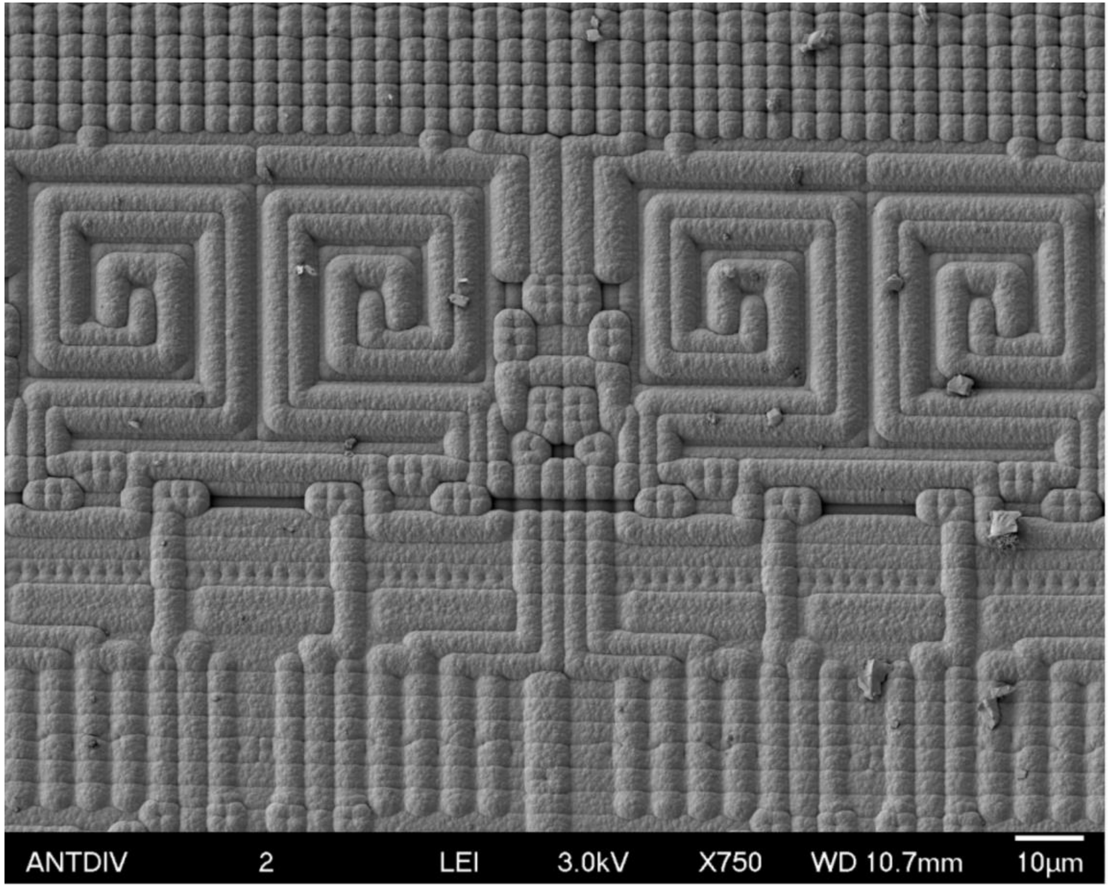


Point-contact transistor, 1951

http://ds-wordpress.haverford.edu/bitbybit/bit-by-bit-contents/chapter-eight/8-2-the-point-contact-transistor/

Evolution of Classical Computers

70 years on



14 nm
integrated
circuit

http://www.antarctica.gov.au/science/laboratory-facilities/kingston-laboratories/electron-microscope/images/man-made

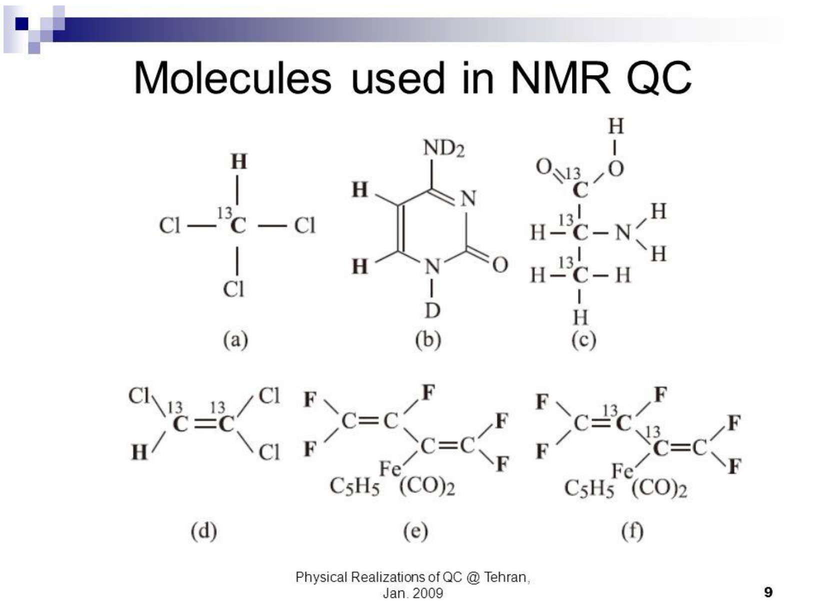
Moore’s Law is Dead, Long Live Moore’s Law

With the demise of Moore’s Law as relates to transistor size, we are investigating ways to, nonetheless, keep it going.

Quantum: Adding one qubit every two years will keep up with Moore’s law w.r.t. quantum simulations. A single qubit doubles the size of the Hilbert space of the quantum simulation.

Evolution of Quantum Computers

NMR QC at IBM with Isaac Chuang and Costantino Yannoni

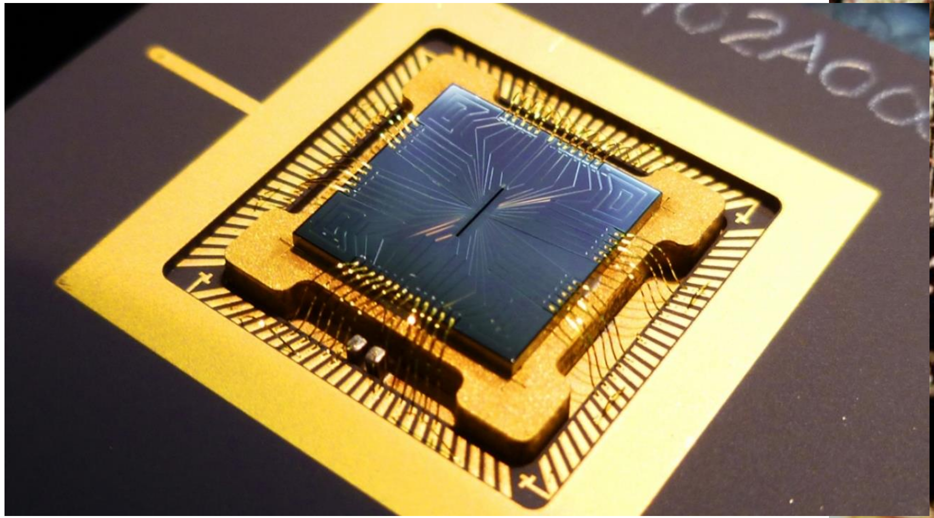


IBM Almaden photo

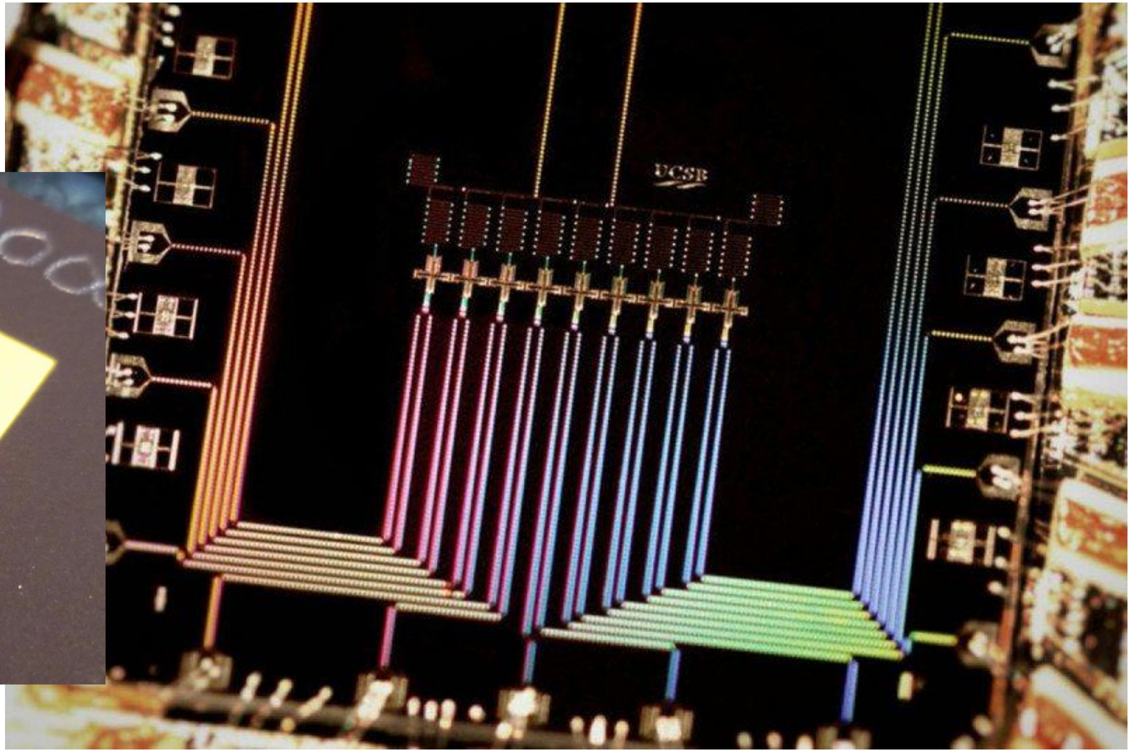
http://pubs.acs.org/cen/coverstory/7845/7845scit.html

Evolution of Quantum Computers

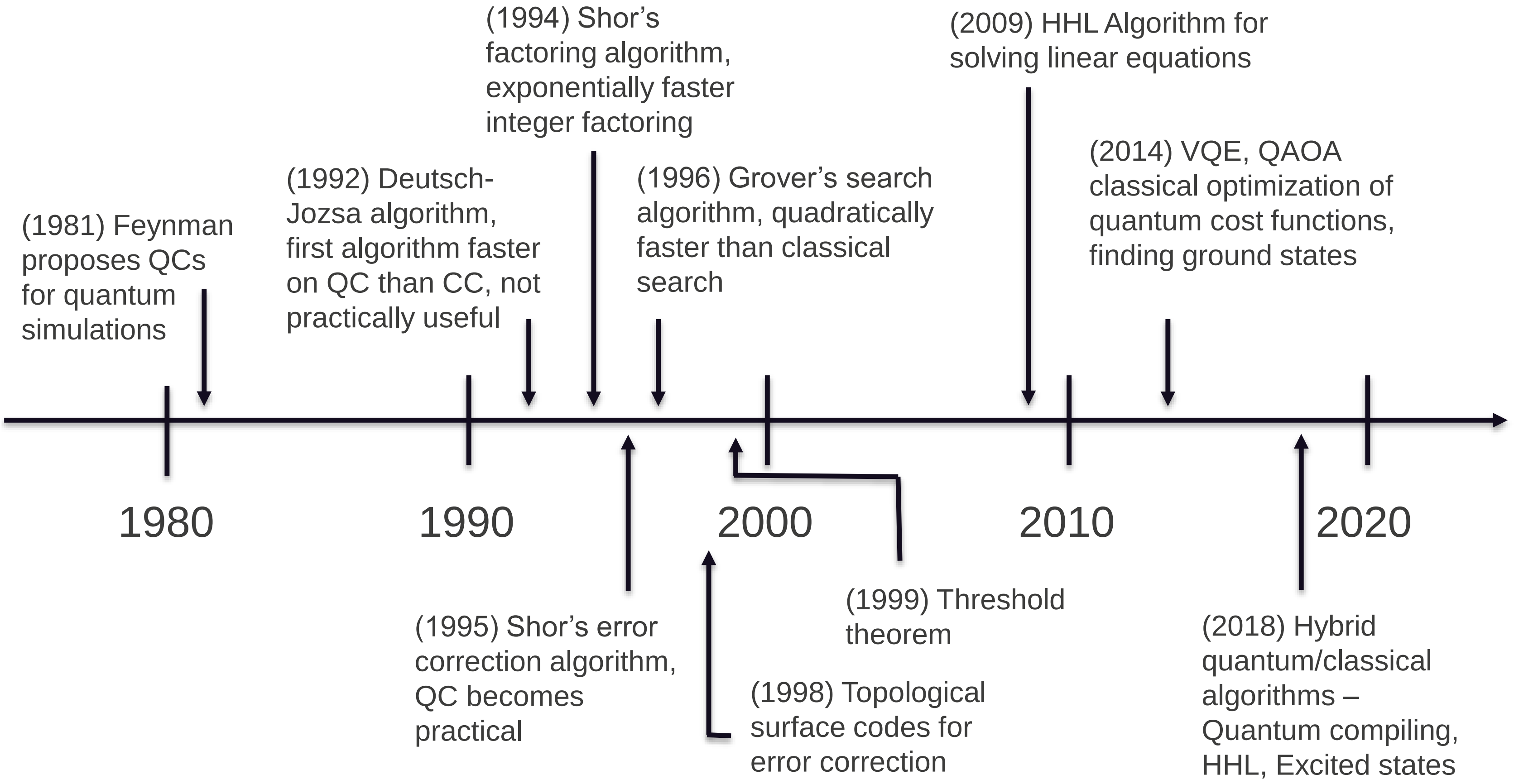
Sandia Ion Trap QC - IT QCs are being targeted at implementing error correcting codes



One of Google’s superconducting QC chips – for flipping 9 qubits



Evolution of Quantum Algorithms



Evolution of Quantum Algorithms

Killer Apps: Quantum Simulation, Integer Factoring

Physical Simulation, Cryptology

Quantum Machine Learning

The research presented below is a combination of ASC and lab-funded work done by Patrick Coles' group, with members Lukasz Cincio, Yigit Subasi, and Andrew Sornborger. Coles and Sornborger (both recent hires) are funded by the ASC Beyond Moore's Law program at LANL. Cincio is an Oppenheimer Fellow and Subasi is funded by the Center for Nonlinear Systems and LDRD funds.

Motivation, Background, Where can QML make a difference?

- Current, noisy, intermediate-scale quantum (NISQ) computers are not yet capable of outperforming classical computers.
- However, indications are that soon ‘quantum supremacy’ will be demonstrated on QCs with ~100 qubits, with algorithms *designed solely for that purpose*.
- Getting QCs to perform useful computations will be yet harder to demonstrate.
- **At LANL, we are working to optimize algorithms for implementation on available (noisy) hardware and are using machine learning methods to make this possible.**

Current and Near Future Research: Using Noisy Intermediate-Scale Quantum (NISQ) Devices

- Available hardware
- D-Wave quantum annealer (at LANL)
- Gate-based architectures
- Superconducting qubits – IBM (Cloud), Rigetti (Cloud), Google (soon to be Cloud?)
- Trapped ions – (IonQ, Sandia)

Current and Near Future Research: Using Noisy Intermediate-Scale Quantum (NISQ) Devices

Need to combat decoherence

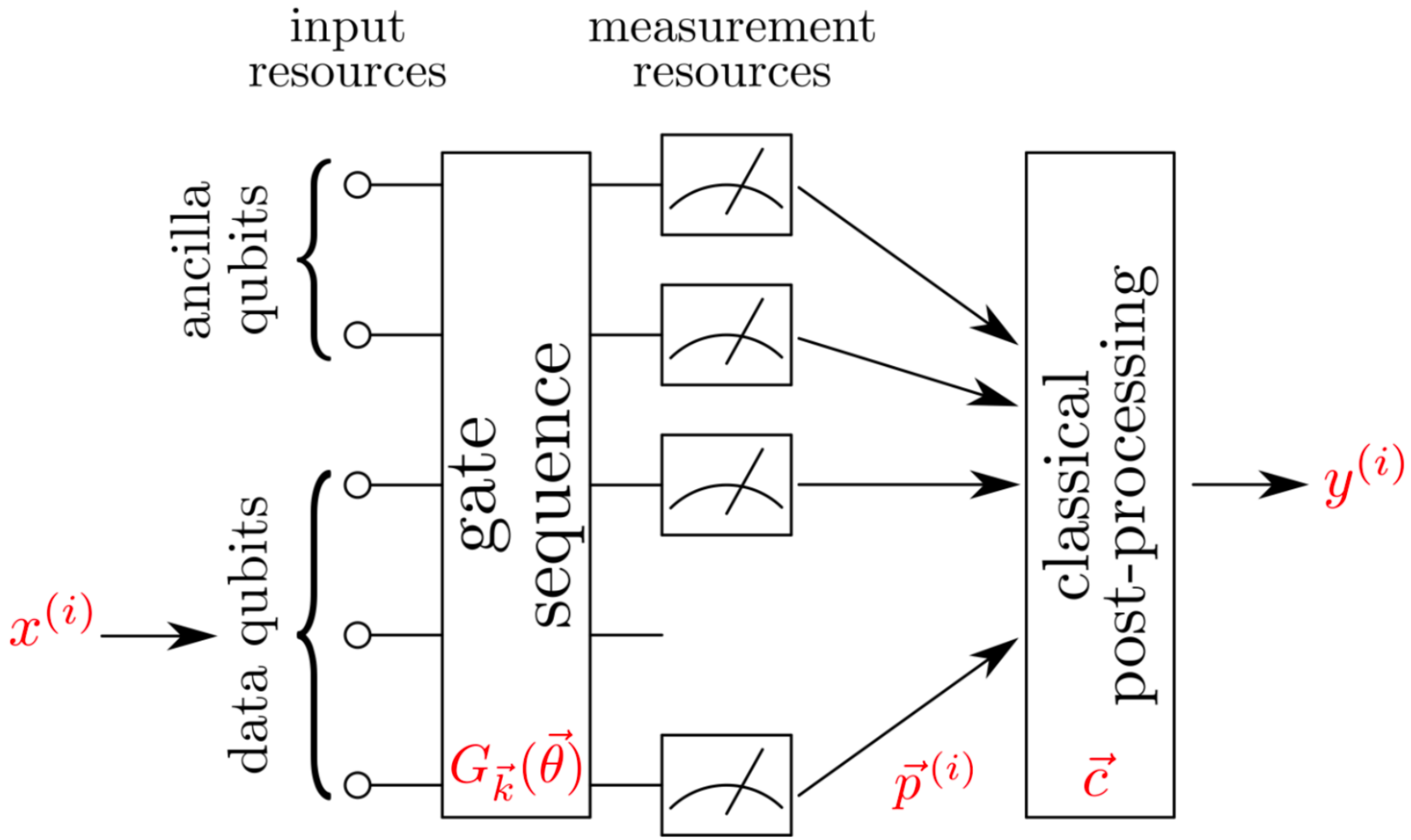
- Short gate sequences/annealing schedules
- As few controlled gates as possible (induce cross-talk between qubits and hence decoherence)
- Offload as much compute as possible to classical pre- and post-processing

Be realistic

- Annealing may not be very quantum
- Gate-based algorithms cannot involve too many qubits or too many gates

Computations on quantum processors are largely proof-of-principle, but advantages found today are likely to be useful in the intermediate term if coherence trends continue.

Using Noisy Intermediate-Scale Quantum (NISQ) Devices

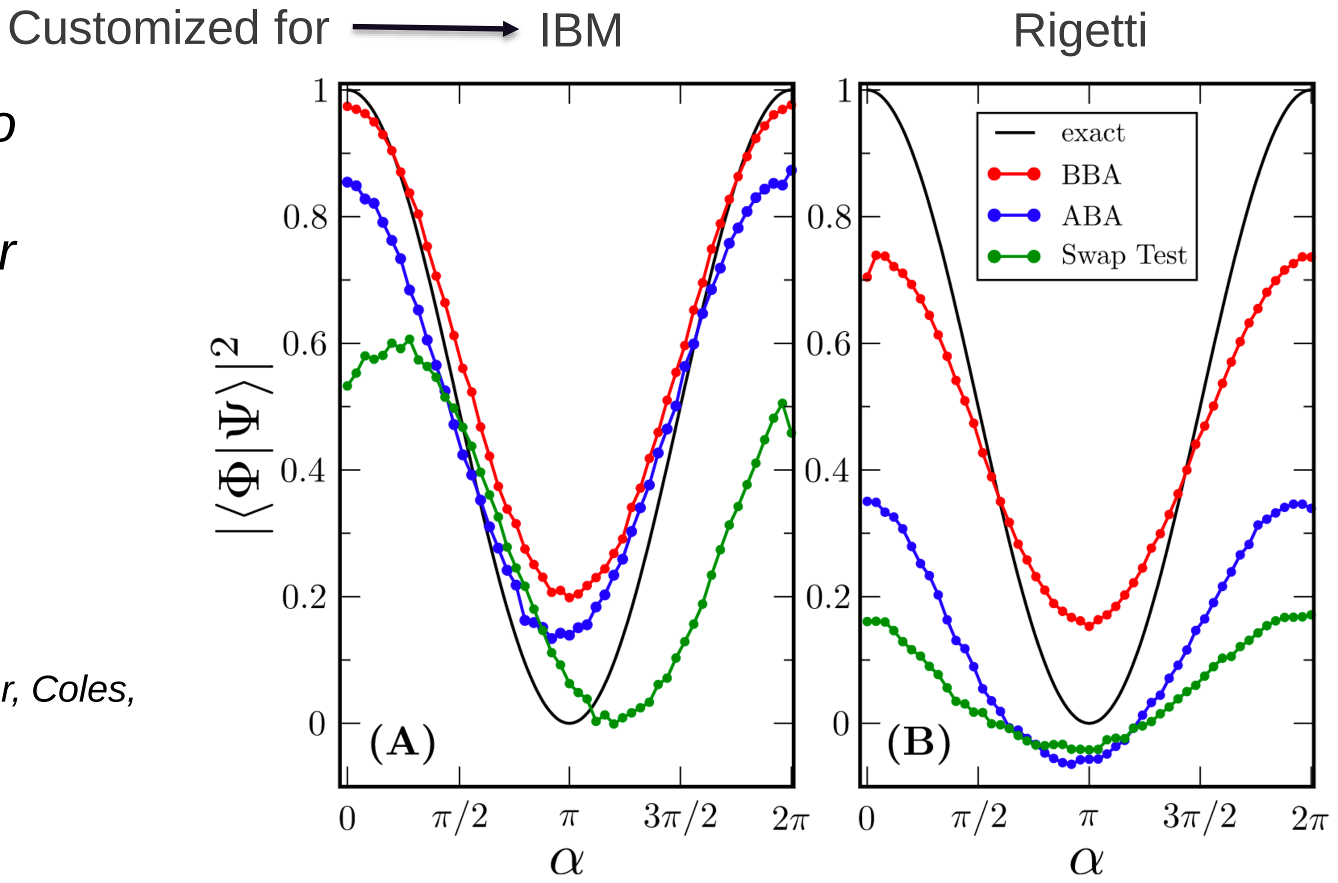


Enabling Quantum Cost Function Evaluation on NISQ Devices

Used classical machine learning to find short-depth, quantum circuits for measuring inner products (i.e. a circuit to perform quantum machine learning).

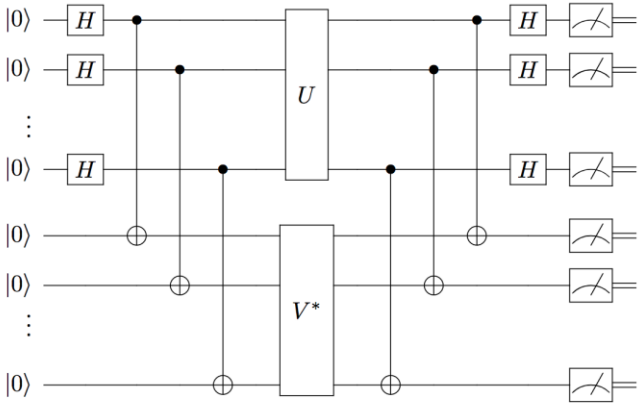
Cincio, Subasi, Sornborger, Coles, LANL, 2018

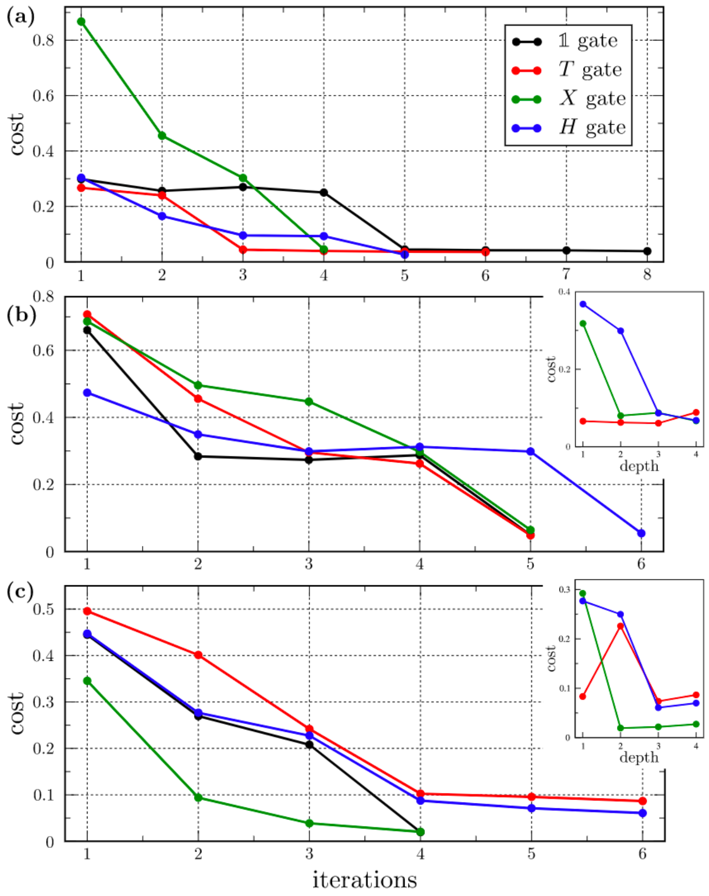
Cincio, Subasi, Coles, LANL, 2018



Exponential Speedup for Learning Arbitrary Quantum Circuits

Quantum machine learning using our classically-learned quantum circuit





Khatri et al., LANL, 2018

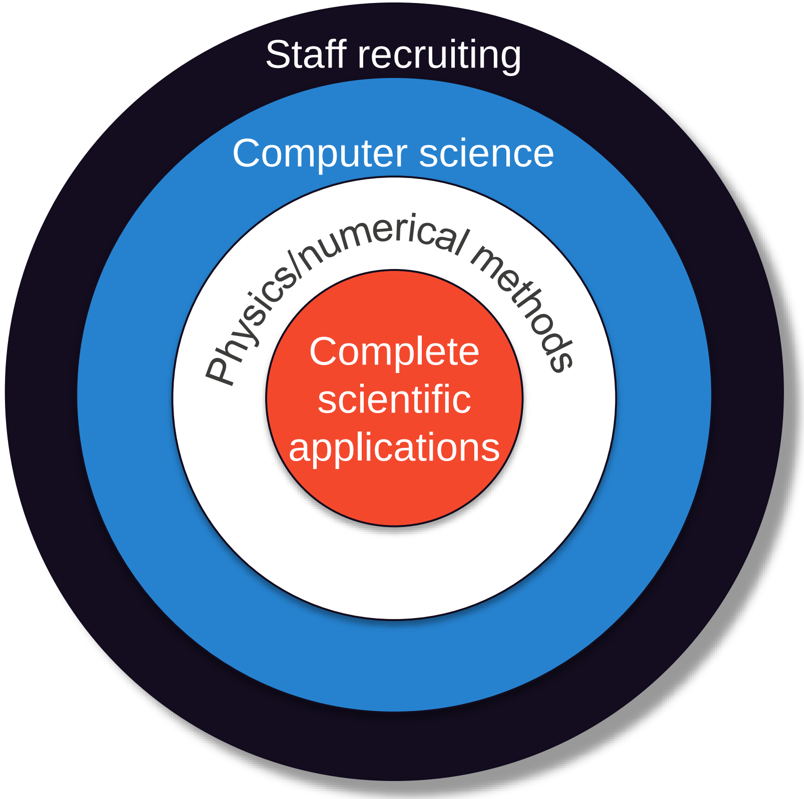
Where We’re Going - What is the Ultimate Killer App

Combine quantum simulation with machine learning to find room-temperature superconductor

- Exponential speedup simulating quantum effects using quantum simulation
- Search parameter space to find low resistance materials using quantum machine learning

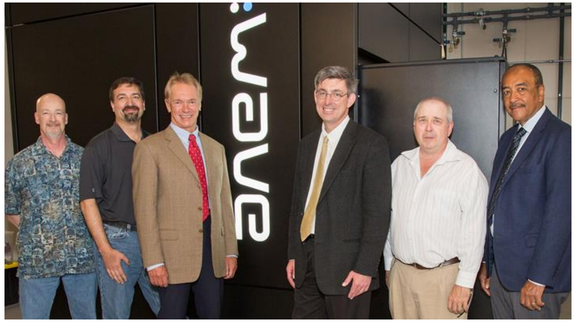
Can IEEE learn from LANL's approach to QC's future

- **"Circles of influence"**
  - Outer to inner = more desirable but more challenging and less likely to achieve soon
- **Forward-thinking approach**
  - Invest in new technologies now, before the situation becomes dire
  - Perhaps even influence the development of these new technologies
  - Even though qubit counts, error properties, and other limitations curtail the utility of current quantum computers, we want to be ready for future generations that can deliver useful results
- **Interplay of science and mission**
  - Need fundamental science to deliver to mission
  - Need mission to identify goals for fundamental science



Equipment

- **D-Wave quantum annealer**
- **Shared resource usage model on open network**
  - Focus is to develop collaborative network of people and ideas
  - External users/collaborators welcome
  - Makes LANL the world's first "quantum user facility"
- **Reaping benefits of local access**
  - Unmetered access encourages experimentation



LANL and D-Wave executives in front of Ising, LANL's D-Wave quantum annealer

  - Have had a D-Wave staff member on-site at LANL since 2016 giving technical advice and assistance
  - LANL-developed open-source software for the D-Wave includes bqpjson, bqpsolvers, D-WIG, D-WISC, edif2qmasm, find-frustration, Go-SAPI, hsapi, inverse_ising, Origami.jl, QMASM, quantum-sociology, ThreeQ.jl
- **Usage stats (Nov 2016–May 2018)**
  - Jobs executed: 291,847,888 (9,629 QPU hours)
  - Average utilization: 70%

Equipment (cont.)

- **Emerging collaborations with other quantum computing vendors (gate model)**
  - Rigetti, IBM
- **Considering role of gate-model hardware in addressing LANL's computational needs**
  - Machine learning
  - Optimization
  - Quantum simulation

Rigetti Computing's QC facility

Educating the LANL Workforce

- **Want quantum computers to be a practical tool**
  - …not just an apparatus for physics experiments
- **How to get people up to speed?**
  - Especially people who know absolutely nothing about quantum computing—or even quantum mechanics
- **Initial experience gained in the context of D-Wave**
- **Internal D-Wave info Web site**
  - Software, examples, docs, …
- **Public mailing list for D-Wave discussions**
  - To join, send a message *body* of "subscribe dwave-users" to listmanager@lanl.gov

Attendees of the first hands-on D-Wave tutorial given at LANL (December 2016)

- **On-site D-Wave tutorials**
  - Presented by D-Wave staff
  - Beginner, intermediate, advanced
  - Mostly hands-on but did one in a large auditorium, broadcast it over the Internet, and recorded it for offline viewing

“Rapid Response” Projects

- **Managed by LANL’s Information Science and Technology Institute (ISTI)**
- **Goal is to familiarize technical staff with a strategic topic (e.g., QC)**
  - Grow a community
  - Shepherding provided by ISTI and senior domain experts
- **Agile, small, short funding cycles**
  - Staff are given ~10 days to write a 1-page proposal with decisions made in ~2 weeks
  - Funding covers about one person-month of effort spread over 2–6 months
- **Sharing of experiences to help performers learn from each other**
  - Performers give brief public presentations and produce short written reports
  - A compilation of IBM Q-related RR reports, “Quantum Algorithm Implementations for Beginners” (arXiv:1804.03719 [cs.ET]), is heavily Scited on SciRate.com

Quantum Computing Summer School

- **LANL has run summer schools since 2011 in areas of strategic interest**
  - QCSS first introduced summer 2018
- **Goals**
  - Educate next-generation workforce in QC
  - Establish new staff pipeline for LANL
  - Educate students in translating algorithms into applications on QCs
  - Develop students' intuition for exponential speedup on QCs
  - Familiarize students with software interfaces for current QCs
- **Structure**
  - 2 weeks of lectures—multiple per day, given by both external visitors and by LANL staff and postdocs
  - 8 weeks of supervised research projects
- **Students**
  - Very competitive application process: 10 selected out of 90 applicants
  - All 10 offers were accepted
  - Each student had some prior exposure to QC
  - Education ranges from 3rd year undergraduate to 3rd year graduate
  - 7 students from US universities: MIT, Michigan State, Oregon State, Louisiana State, Univ. of Southern California (2), Northern Arizona
  - 3 students from universities abroad: Imperial College London (2), Univ. of Heidelberg

Quantum Computing Summer School (cont.)

- **Visiting lecturers**
  - Peter Shor (MIT)
  - Matthias Troyer (Microsoft)
  - Sergio Boixo (Google)
  - Eleanor Rieffel (NASA)
  - Susan Coppersmith (U. Wisconsin)
  - Daniel Lidar (USC)
  - Ivan Deutsch (U. New Mexico)
  - Will Zeng (Rigetti)
  - Jungsang Kim (Duke/IonQ)
  - Denny Dahl (D-Wave)
  - Doug McClure (IBM)

- **Student projects**
  - Quantum-assisted quantum compiling
  - Novel variational hybrid quantum-classical algorithms
  - Motif recognition in quantum algorithms
  - Machine-learning of noise-tolerant quantum algorithms
  - Fermionic embeddings on QCs
  - Efficient quantum tomography

From the QCSS Web site:

"Developing new leaders in the theory, application, and programming of quantum computers"