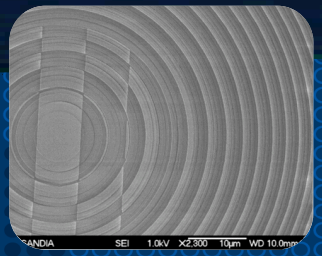
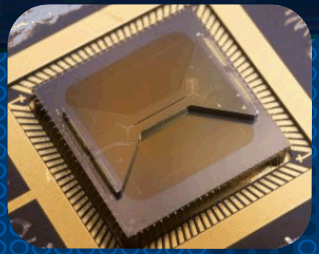
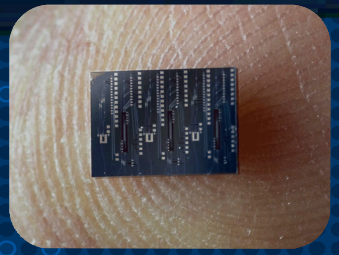
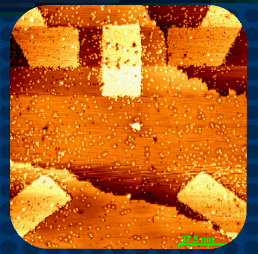
Salishan Conference on High-Speed Computing

Perspectives on HPC's Current *Cambrian Explosion*

SAND2017-4454C



Quantum Computing: Cladogenesis Beyond Exascale HPC

Andrew J. Landahl
Sandia National Laboratories

27 April 2017

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

Cladogenesis

n. The genesis of a complete subtree of higher taxonomy clades

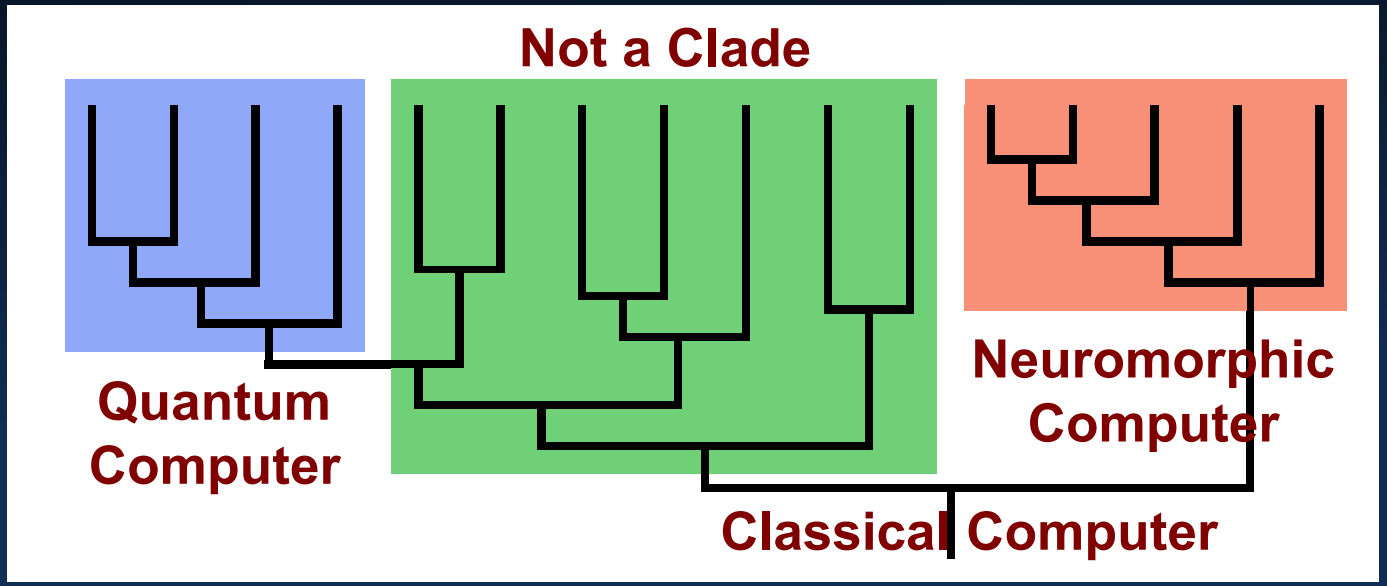


Image: Wikimedia, "Clade"

Cladogenesis

Quantum Computer

Classical Computer

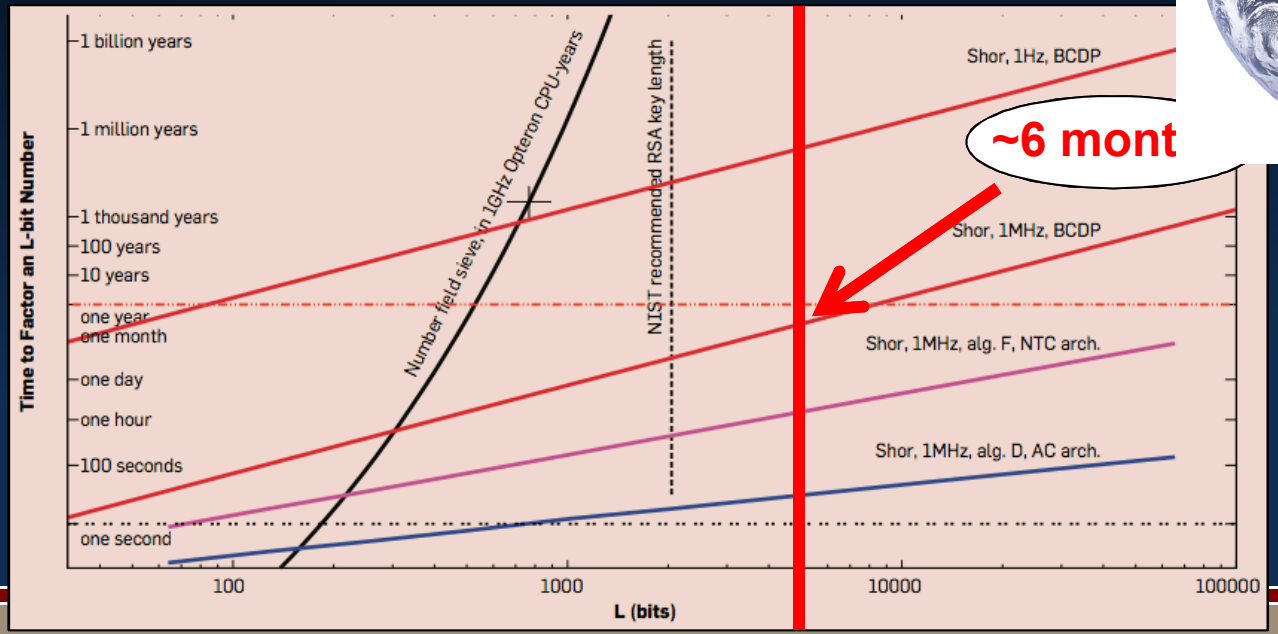
Photos: Wikipedia, KMJ, "Incandescent Lightbulb," Jan Pavelka, "Fluorescence in Calcite"

Quantum is Different

The laws of computation are not what you think they are

Quantum Cryptanalysis

If all the silicon in the world's crust were converted to Pentium chips, it would take the ag of the universe to factor a 5,000-bit number.



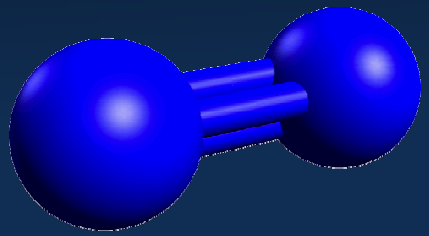
A blueprint for building a quantum computer, R. van Meter & C. Horsman, *Comm. ACM*, (2013) doi:10.1145/2494568

limage: NASA "Blue Marble," Apollo 17

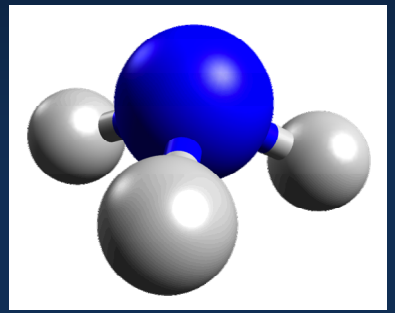
Quantum Simulation

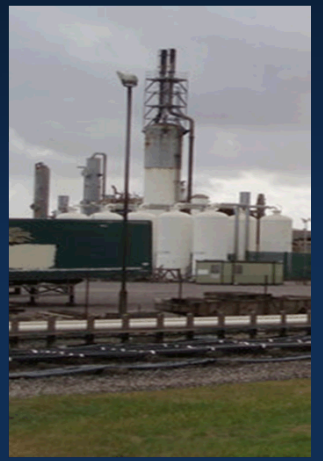
With only 200 error-free qubits, a quantum computer could unravel biological nitrogen fixation [1]. Currently, the Haber-Bosch process consumes 2% of the world's annual energy supply.

Nitrogen



Ammonia





Images: Andrew Baczewski/Sandia
Wikipedia, Rabel, "Pear Leaf," Sharon Loxton "Haber Process."

Quantum Algorithms

Cryptanalysis

- RSA, Diffie-Hellman, elliptic-curve cryptography

Simulation

- Explosives, fuels, armor, batteries, nanomedicine

Pattern-finding

- Social networks, data analytics, radar signatures

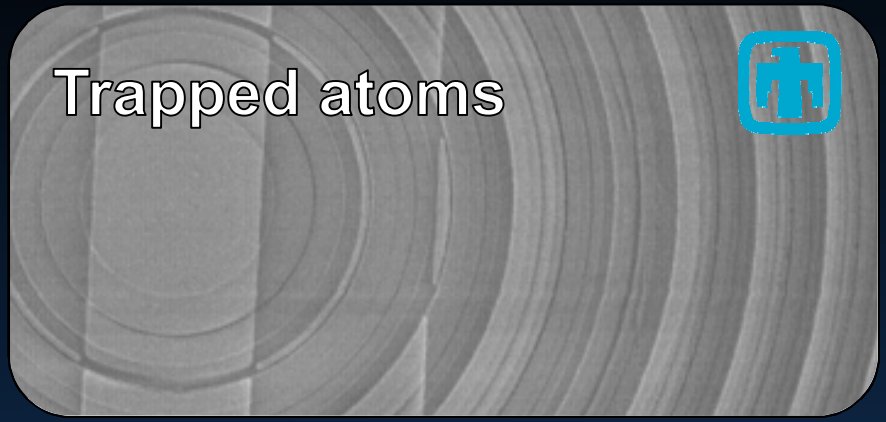
Machine learning

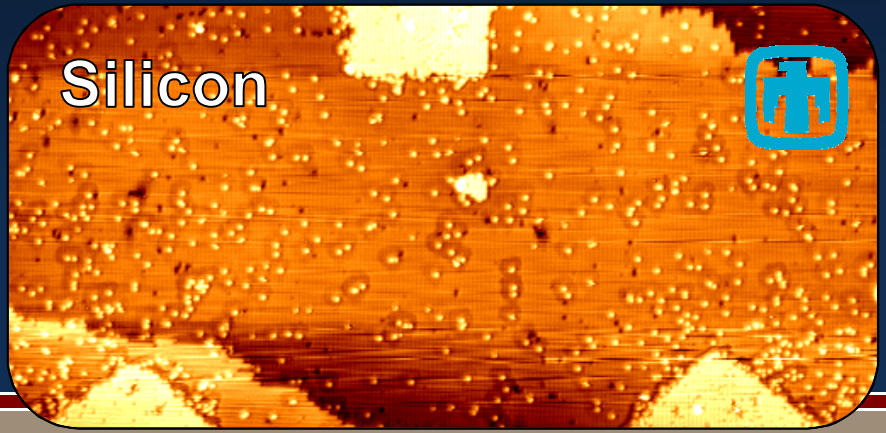
- Financial fraud detection, computer vision, speech recognition

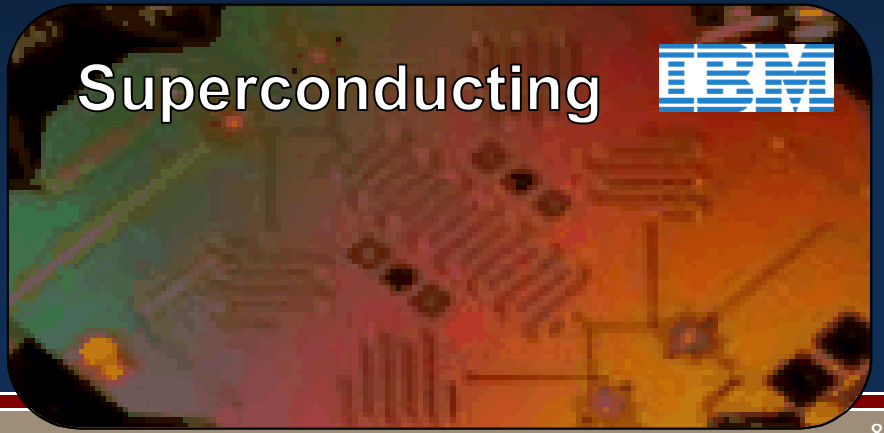
Over 50 more @ http://math.nist.gov/quantum/zoo

Images: Andrew Landahl/Sandia

Quantum Chips



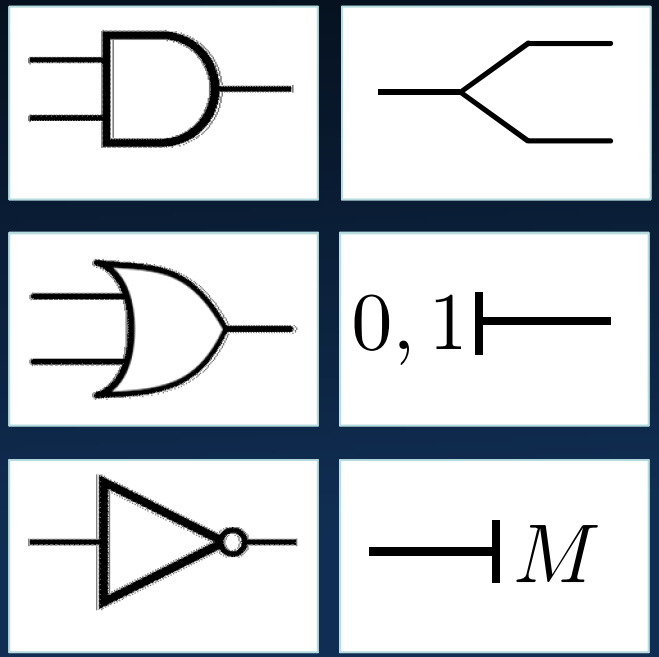




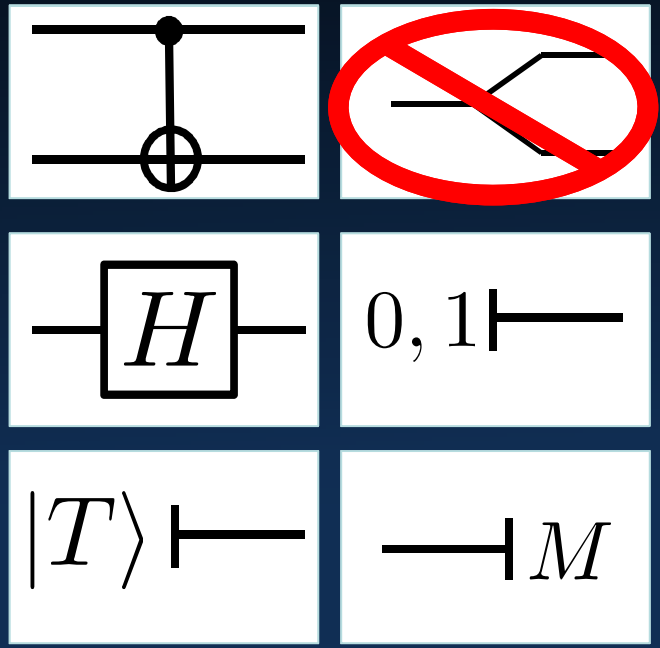
Images: Sandia, IBM

Quantum Logic

Classical gates



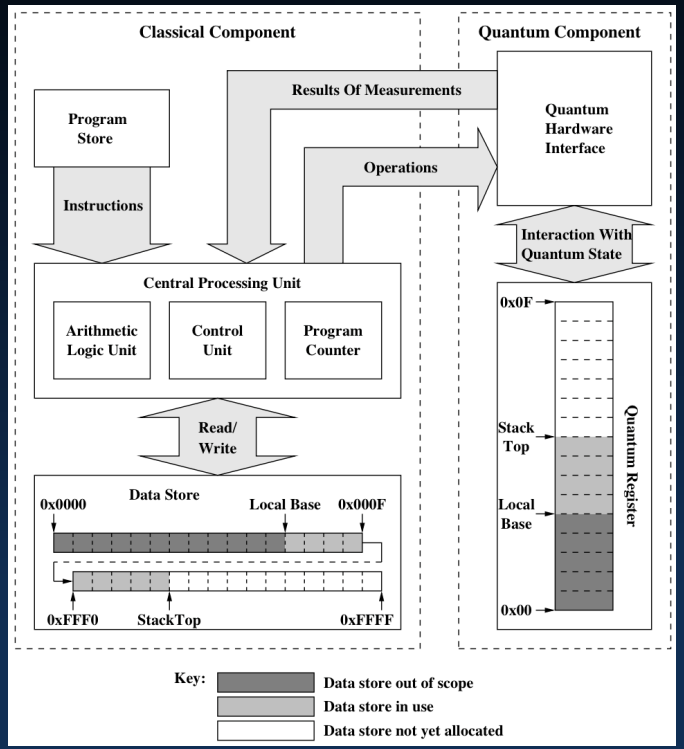
Quantum gates



Images: Andrew Landahl/Sandia

Programming

QRAM ISA [1, 2]



Languages

- Assembly: QASM, Quil
- Imperative: QCL, Scaffold
- Functional: QML, Quipper
- Hybrid: LIQUi|>
- Framework: ProjectQ

Noteworthy Features

- JIT Compiling
- ILP: Superscalar? VLIW? EPIC?

image: Reference [2]

[1] Knill, Tech. Rpt. LAUR-96-2724 (1996). [2] Nagarajan *et al.*, Electronic Notes in Theoretical Computer Science **170**, 101 (2007).

Example QC Specs [1]

Trapped-ion (UMD)

- **Qubits:** 5
- **Interconnect:** Laser
  - All 12.642821 GHz
- **1-qubit gates:** 20 μs, 99.1%
- **2-qubit gates:** 250 μs, 97.0%
- **Prep/readout:** X μs, 99.4%

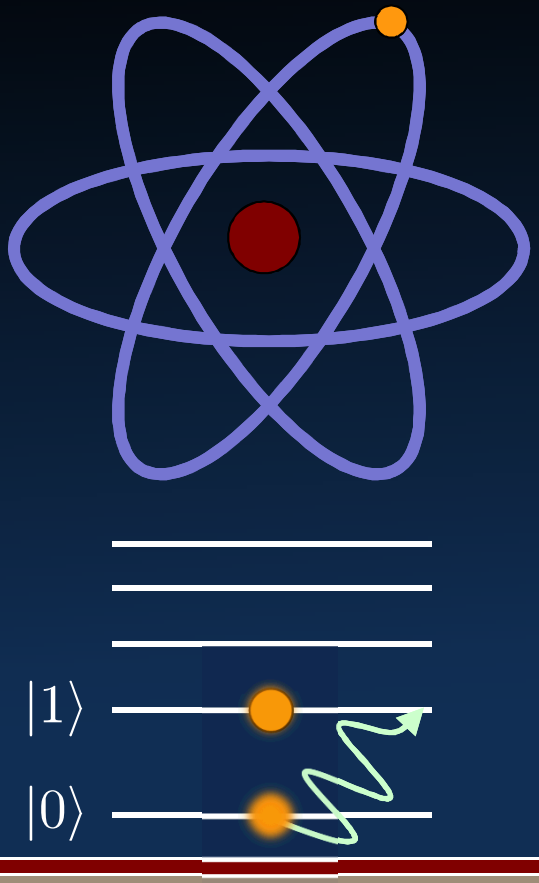
Superconducting (IBM)

- **Qubits:** 5
- **Interconnect:** Microwave
  - 5 – 5.4 GHz; drifts daily
- **1-qubit gates:** 130 ns, 99.7%
- **2-qubit gates:** 450 ns, 96.5%
- **Prep/readout:** X ms, 96%

Images: Andrew Ladnah/Sandia

[1] Linke *et al.*, Proc. Natl. Acad. Sci. **114**, 3305 (2017).

Quantum Fragility



$$|0\rangle \longleftrightarrow |1\rangle$$

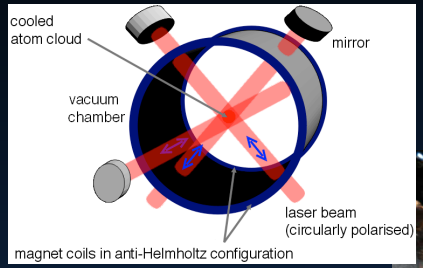
$$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

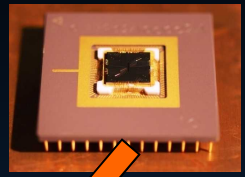
$$\updownarrow$$

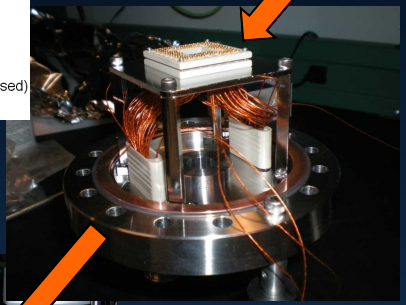
$$\frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

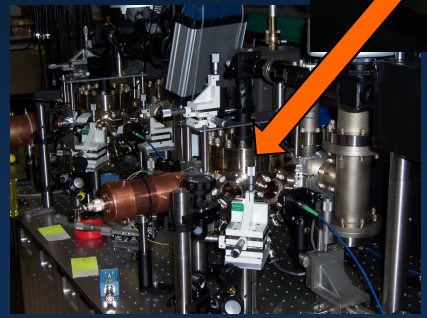
Image: Andrew Landahl/Sandia

Quantum Isolation









Dilution refrigerator: 10 mK

Laser cooling: 10 μK

Images: Wikipedia, "Magneto-optical trap;" Sandia

Fault tolerance

ENIAC, 1946

PROBABILISTIC LOGICS AND THE SYNTHESIS OF RELIABLE ORGANISMS FROM UNRELIABLE COMPONENTS

J. von Neumann

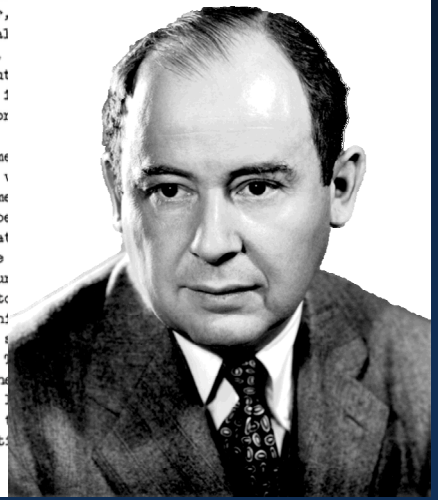
1. INTRODUCTION

The paper that follows is based on notes taken by Dr. R. S. Pierce on five lectures given by the author at the California Institute of Technology in January 1952. They have been revised by the author but they reflect, apart from minor chs

The subject-matter, in logics, or in the physical synthesis. Error is viewed, or misdirecting accident, but sideration — its importance parable to that of the factor correct logical structure.

Our present treatme is the author's conviction, treated by thermodynamical me theory, as information has be [Cf. 5.2]. The present treat assembles, it is hoped, some enter into the final structu

The author wants to M. Gell-Mann, then at the Uni 1951 he owes some important the California Institute of position is based; and to the invitation to deliver these by the audience, caused him whose cooperation in connect appreciated.



von Neumann, 1956

Images: Wikipedia, "ENIAC," "John von Neumann"

Cost of redundancy

Assumed Machine: 100 MHz quops

Factoring a 2000-bit number in 2.7 h [1]:

- 10^{-3} error: 500 qB (logical), 120 MqB (physical).
- 10^{-4} error: 500 qB (logical), 16.5 MqB (physical).

Quantitatively accurate simulation of FeMoCo in 15 d [2]:

- 10^{-3} error: 14 qB (logical), 5.1 GqB (physical)
- 10^{-6} error: 14 qB (logical), 3.75 MqB (physical)

[1] Fowler *et al.*, Phys. Rev. A **86**, 032324 (2012). [2] Reiher *et al.*, arXiv:1605.03590 (2016).

Testbed QCs

Google: 49-qubit goal by December 2017.

NSF: $3M/yr Ideas Lab: Practical Fully-Connected Quantum Computer Challenge (PFCQC), November 2017

DOE: $5M/yr Quantum Testbed User Facility (pending Congressional budget action)

IBM: Open-Access "Quantum Experience" online since 5/16: 40k users, 270k experiments, 15 published papers

image: IBM

ETH Zurich: 45 *simulated* qubits on Cori II (#5) (4/17) [1]

[1] Haener and Steiger, arXiv:1704.01127 (2017).

How to use a testbed

School of thought 1: "Quantum Supremacists"

- **Let's run algorithms on it and benchmark it**
- **Maybe we can demonstrate "quantum supremacy"**

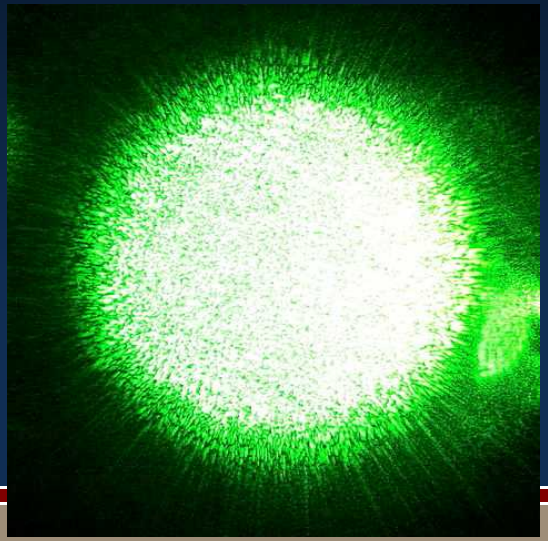


Image: Degir6328, Wikipedia "Laser Speckle"

How to use a testbed

School of thought 2: "Quantum Visionaries"

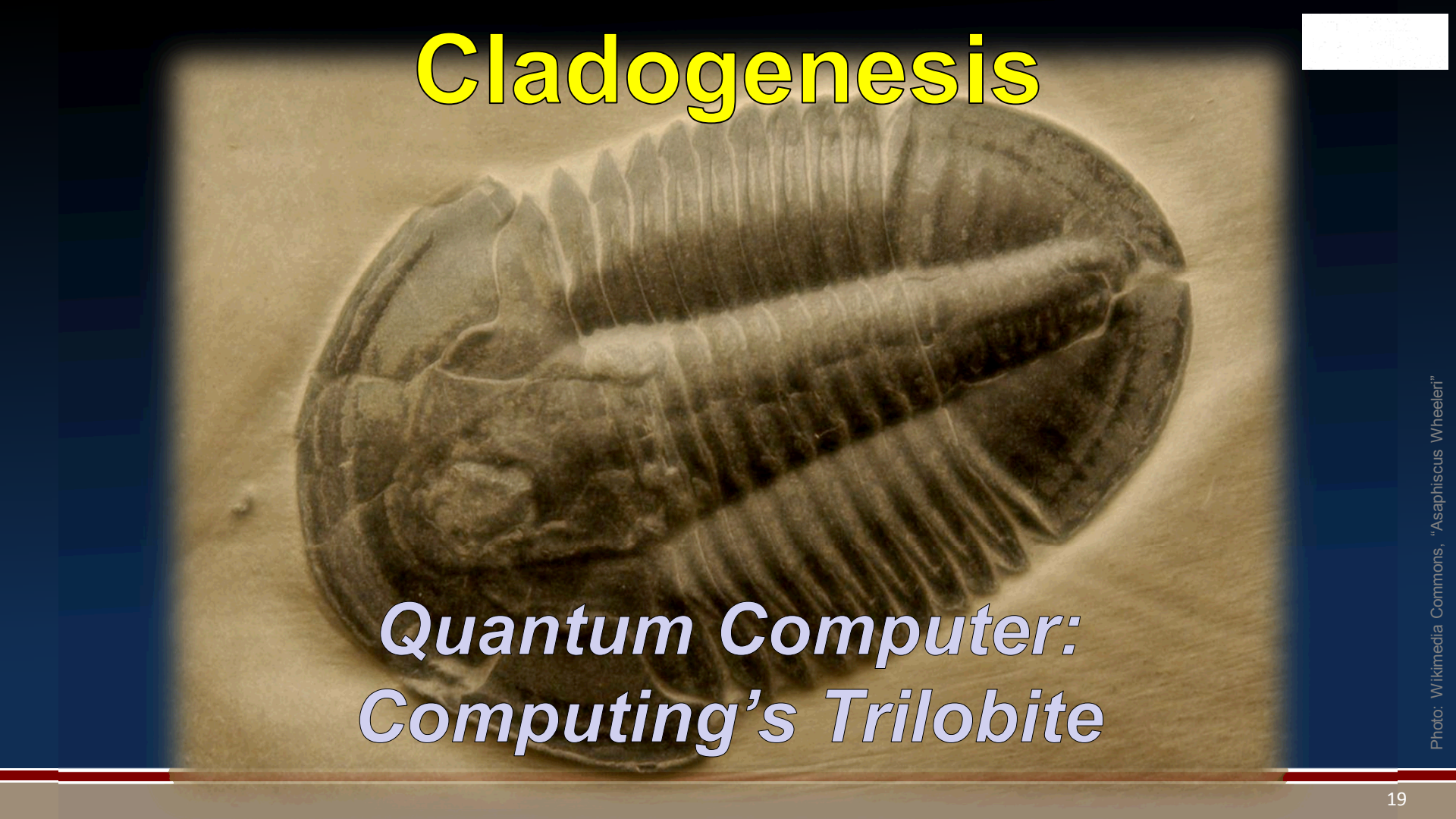
- **Let's use it to learn how to build bigger, better machines**
- **Maybe we can validate theoretical error models**

"The Child is the Father of the Man"

—William Wordsworth, 1770 – 1880

My Heart Leaps Up

Cladogenesis

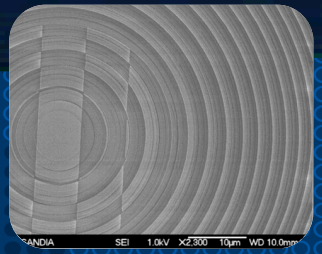


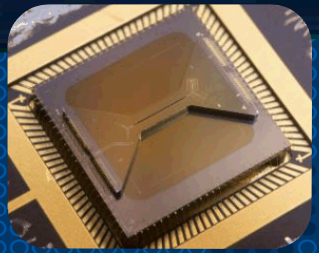
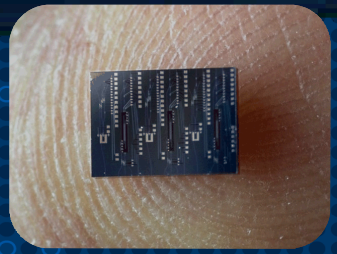
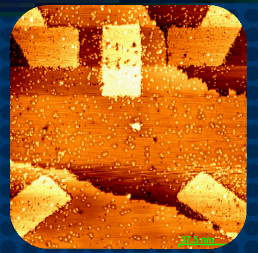
Quantum Computer: Computing's Trilobite

Photo: Wikimedia Commons, "Asaphiscus Wheeleri"

Salishan Conference on High-Speed Computing

Perspectives on HPC's Current *Cambrian Explosion*



Quantum Computing: Cladogenesis Beyond Exascale HPC

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27 April 2017

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