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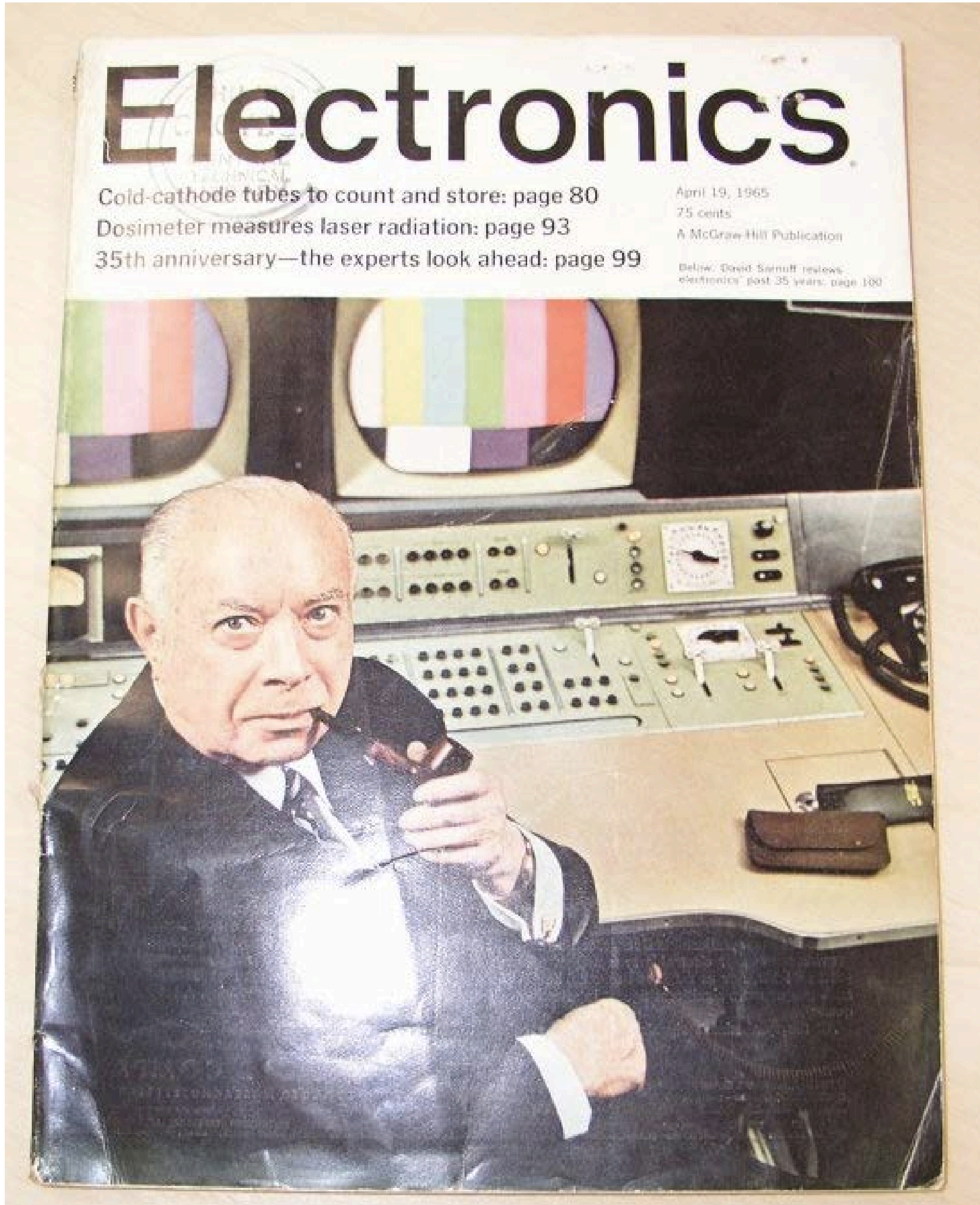
# An Introduction to Quantum Computing, D-Wave Style

QuAASI'16 Workshop

July 2016

# *Electronics* April 19, 1965

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# Moore's Law

The experts look ahead

## Cramming more components onto integrated circuits

**With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip**

By Gordon E. Moore

Director, Research and Development Laboratories, Fairchild Semiconductor division of Fairchild Camera and Instrument Corp.

**The future of integrated electronics** is the future of electronics itself. The advantages of integration will bring about a proliferation of electronics, pushing this science into many new areas.

Integrated circuits will lead to such wonders as home computers—or at least terminals connected to a central computer—automatic controls for automobiles, and personal portable communications equipment. The electronic wristwatch needs only a display to be feasible today.

But the biggest potential lies in the production of large systems. In telephone communications, integrated circuits in digital filters will separate channels on multiplex equipment. Integrated circuits will also switch telephone circuits and perform data processing.

Computers will be more powerful, and will be organized in completely different ways. For example, memories built of integrated electronics may be distributed throughout the machine instead of being concentrated in a central unit. In addition, the improved reliability made possible by integrated circuits will allow the construction of larger processing units. Machines similar to those in existence today will be built at lower costs and with faster turn-around.

**The author**

Dr. Gordon E. Moore is one of the new breed of electronic engineers, schooled in the physical sciences rather than in electronics. He earned a B.S. degree in chemistry from the University of California and a Ph.D. degree in physical chemistry from the California Institute of Technology. He was one of the founders of Fairchild Semiconductor and has been director of the research and development laboratories since 1959.

**Present and future**

By integrated electronics, I mean all the various technologies which are referred to as microelectronics today as well as any additional ones that result in electronics functions supplied to the user as irreducible units. These technologies were first investigated in the late 1950's. The object was to miniaturize electronics equipment to include increasingly complex electronic functions in limited space with minimum weight. Several approaches evolved, including microassembly techniques for individual components, thin-film structures and semiconductor integrated circuits.

Each approach evolved rapidly and converged so that each borrowed techniques from another. Many researchers believe the way of the future to be a combination of the various approaches.

The advocates of semiconductor integrated circuitry are already using the improved characteristics of thin-film resistors by applying such films directly to an active semiconductor substrate. Those advocating a technology based upon films are developing sophisticated techniques for the attachment of active semiconductor devices to the passive film arrays.

Both approaches have worked well and are being used in equipment today.

Electronics, Volume 38, Number 8, April 19, 1965

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# But, Moore's Law Seems to be Slowing Down

www.economist.com/technology-quarterly/2016-03-12/after-moores-law


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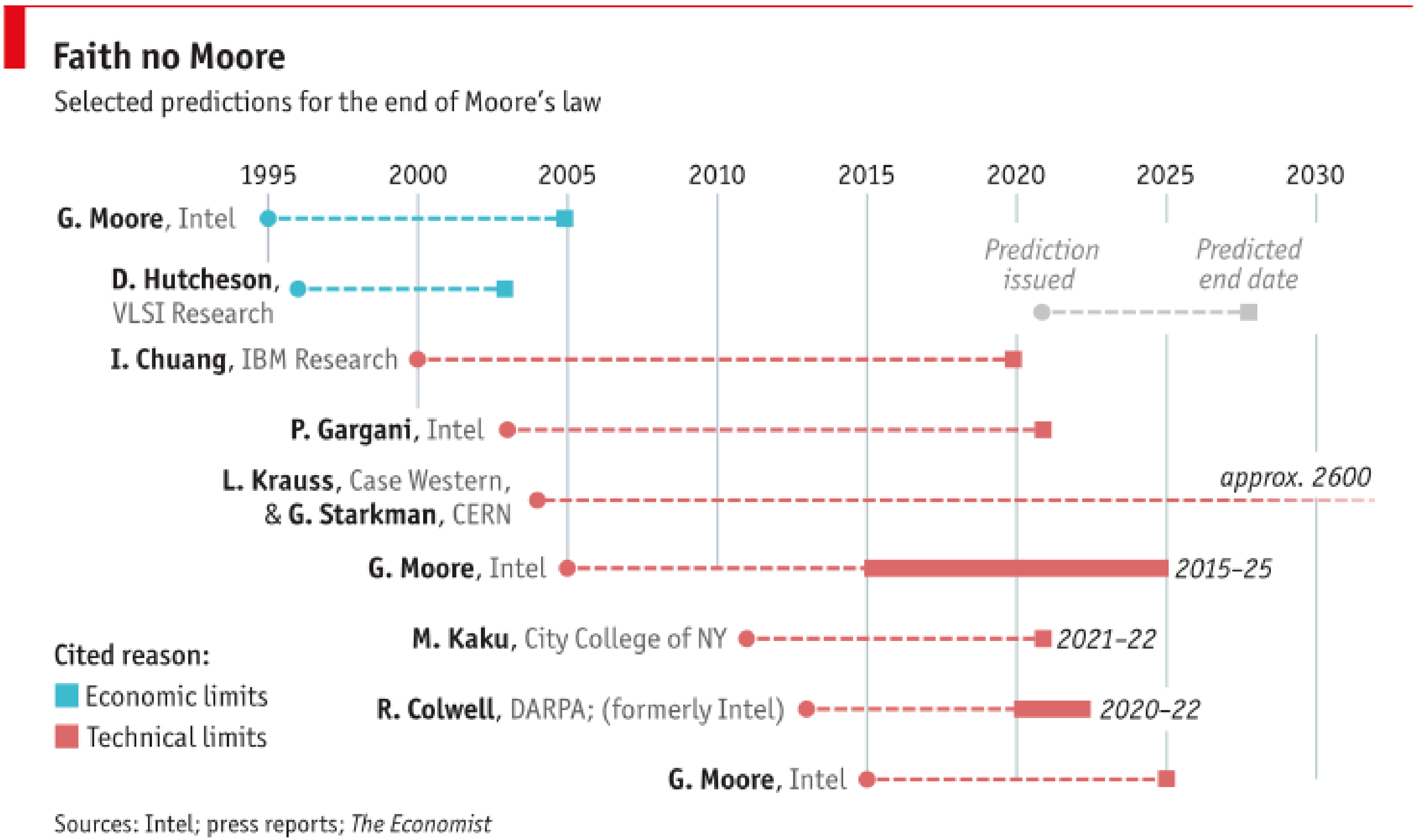
# Predictions for the End of Moore's Law





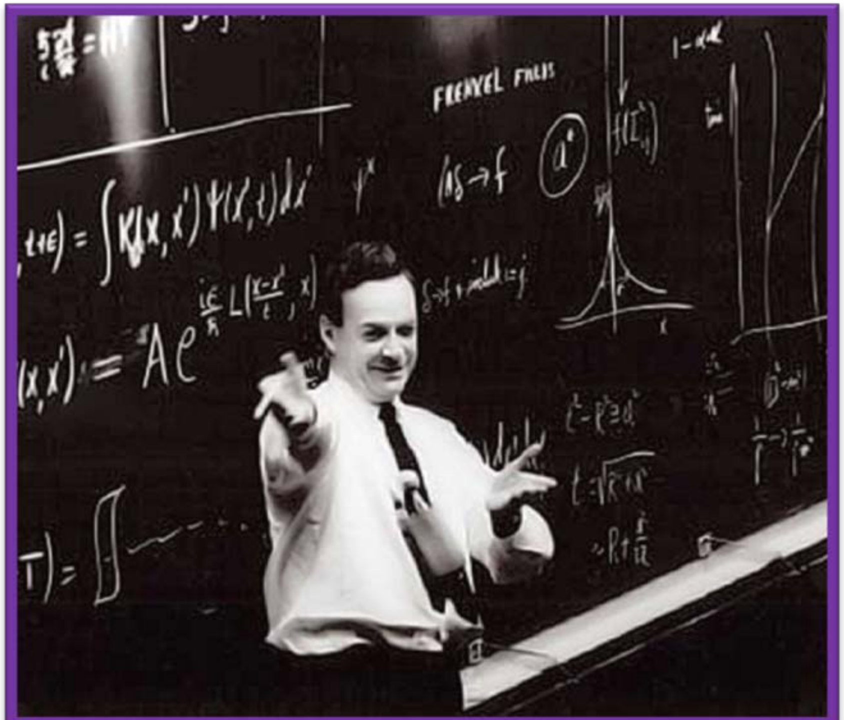
# Moore’s Law’s Law

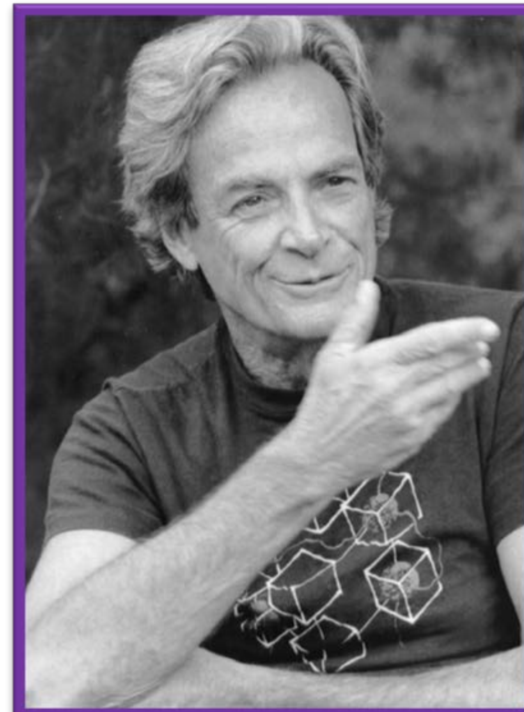
“The number of people predicting the death of Moore’s law doubles every two years.”

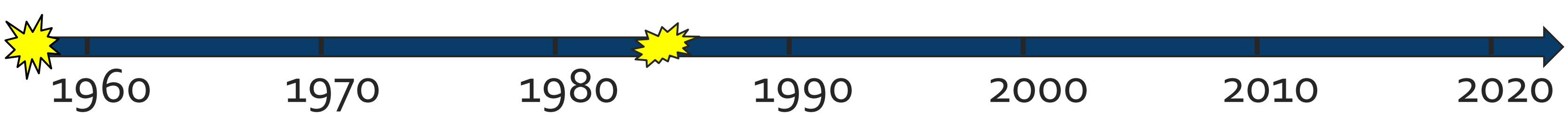
Peter Lee, a vice-president at Microsoft Research


FEBRUARY 17, 2014
French Advances / My Doctor Fired Me / Love App-tually
TIME
IT PROMISES TO SOLVE SOME OF HUMANITY'S MOST COMPLEX PROBLEMS. IT'S BACKED BY JEFF BEZOS, NASA AND THE CIA. EACH ONE COSTS $10,000,000 AND OPERATES AT 459° BELOW ZERO. AND NOBODY KNOWS HOW IT ACTUALLY WORKS
THE INFINITY MACHINE
BY LEV GROSSMAN
$4.99US $5.99CAN
time.com

# Richard Feynman









# April 1983 – Richard Feynman's talk

LOS ALAMOS NATIONAL LABORATORY
40th ANNIVERSARY CONFERENCE
NEW DIRECTIONS IN PHYSICS AND CHEMISTRY
April 13–15, 1983

*Wednesday, April 13*

6:00–8:00 P.M.—Informal Reception at Fuller Lodge

*Thursday, April 14*

Main Auditorium, Administration Building

8:45 A.M. Welcome—Donald M. Kerr, Director
Los Alamos National Laboratory

*Session I*—Robert Serber, Chairman

9:00 A.M. Richard Feynman
"Tiny Computers Obeying Quantum-Mechanical Laws"

10:00 A.M. I. I. Rabi
"How Well We Meant"

11:00–11:15 A.M.—Intermission

*Session II*—Donald W. Kerst, Chairman

11:15 A.M. Owen Chamberlain
"Tuning Up the Time Projection Chamber"

12:15–1:15 P.M.—Lunch

1:15 P.M. Felix Bloch
"Past, Present and Future of Nuclear Magnetic Resonance"

2:15–2.30 P.M.—Intermission

*Session III*—Edwin McMillan, Chairman

2:30 P.M. Robert R. Wilson
"Early Los Alamos Accelerators and New Accelerators"

3:30 P.M. Norman Ramsey
"Experiments on Time-Reversal Symmetry and Parity"

4:30 P.M. Ernest Titterton
"Physics with Heavy Ion Accelerators"

Title: Los Alamos Experience
Author: Phyllis K Fisher
Page 247

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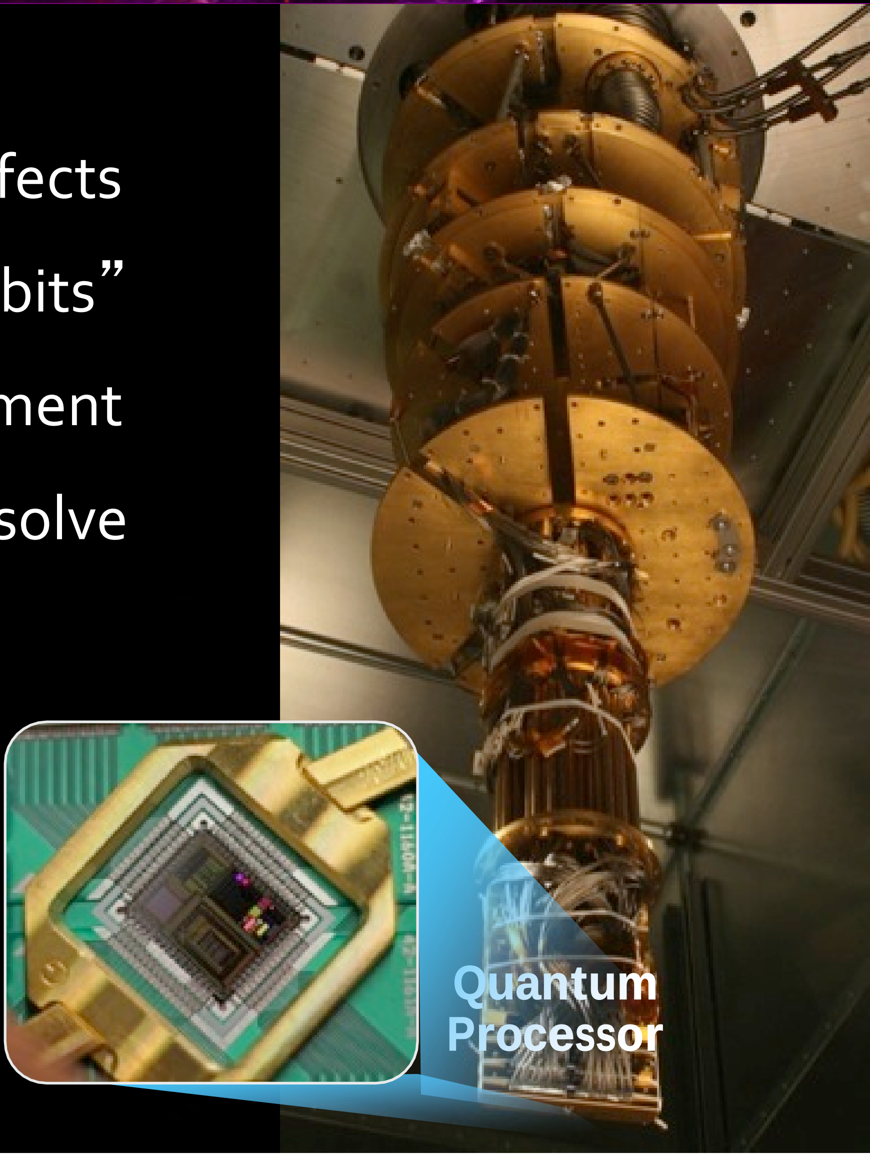
# What is a Quantum Computer?

- Exploits quantum mechanical effects
- Built with “qubits” rather than “bits”
- Operates in an extreme environment
- Enables quantum algorithms to solve very hard problems

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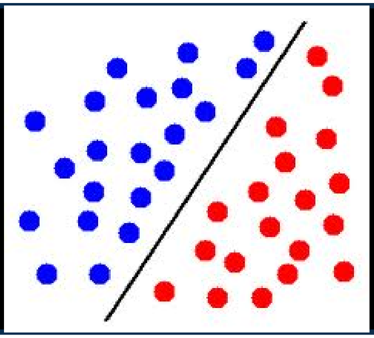
 | 

# Characteristics of Classical Digital Systems

Binary

0100011101110
1010111001001
1101010010000
0010000100111

Separable



Barriers

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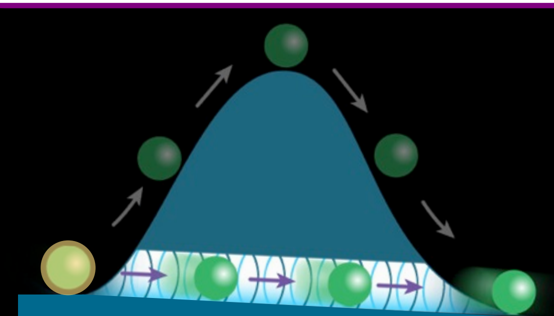
# Quantum Effects on D-Wave Systems

Superposition


Entanglement

Quantum Tunneling





# Quantum Turing Machine

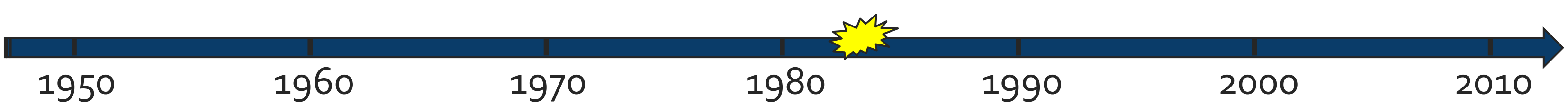
*Proc. R. Soc. Lond.* A **400**, 97–117 (1985)
*Printed in Great Britain*

## Quantum theory, the Church–Turing principle and the universal quantum computer

By D. Deutsch
*Department of Astrophysics, South Parks Road, Oxford OX1 3RQ, U.K.*

(*Communicated by R. Penrose, F.R.S. – Received* 13 *July* 1984)

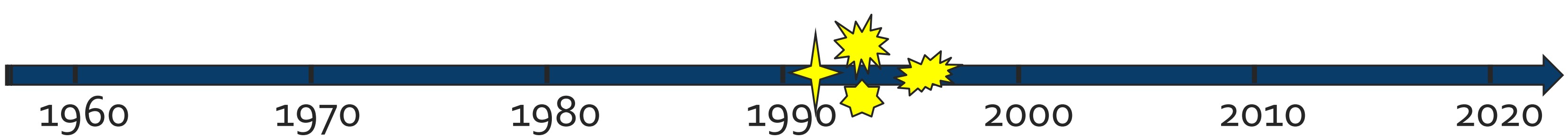
It is argued that underlying the Church–Turing hypothesis there is an implicit physical assertion. Here, this assertion is presented explicitly as a physical principle: 'every finitely realizible physical system can be perfectly simulated by a universal model computing machine operating by finite means'. Classical physics and the universal Turing machine, because the former is continuous and the latter discrete, do not obey the principle, at least in the strong form above. A class of model computing machines that is the quantum generalization of the class of Turing



# Algorithms

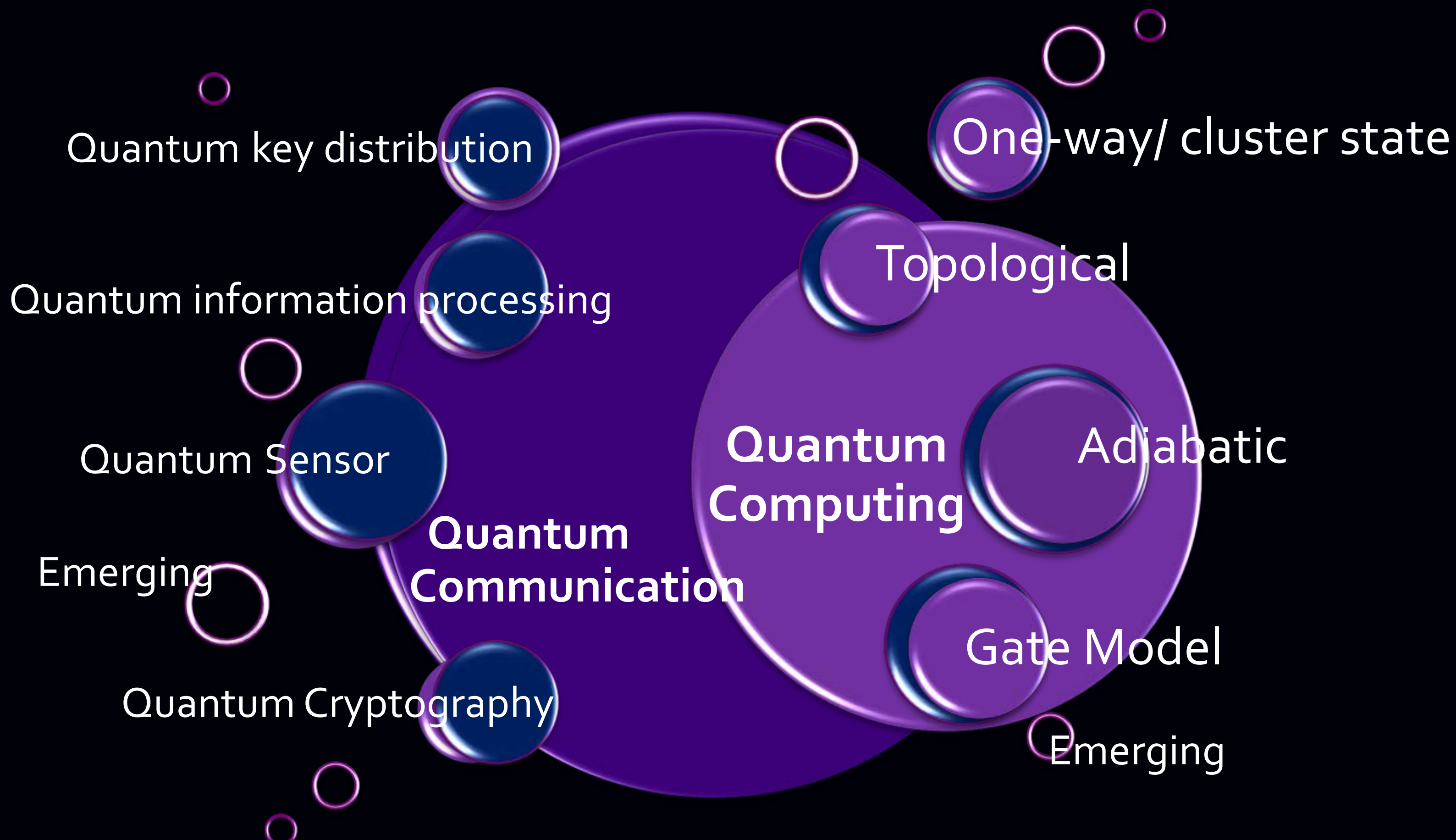
- **David Deutsch (1992)**: Determine whether f: $\{0,1\}^n \longrightarrow \{0,1\}$ is constant or balanced using a quantum computer
- **Daniel Simon (1994):** Special case of the abelian hidden subgroup problem
- **Peter Shor (1994):** Given an integer N, find its prime factors
- **Lov Grover (1996):** Search an unsorted database with N entries in $O(N^{1/2})$ time





# Quantum Information Science

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# Original Simulated Annealing Paper

THE JOURNAL OF CHEMICAL PHYSICS VOLUME 21, NUMBER 6 JUNE, 1953

## Equation of State Calculations by Fast Computing Machines

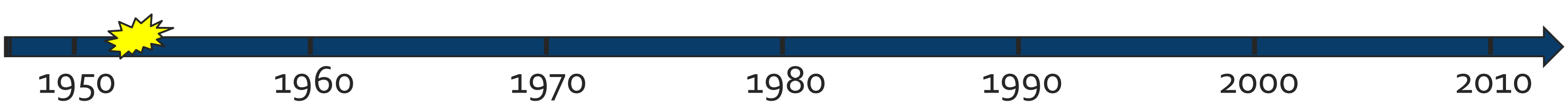
NICHOLAS METROPOLIS, ARIANNA W. ROSENBLUTH, MARSHALL N. ROSENBLUTH, AND AUGUSTA H. TELLER,
*Los Alamos Scientific Laboratory, Los Alamos, New Mexico*

AND

EDWARD TELLER,* *Department of Physics, University of Chicago, Chicago, Illinois*

(Received March 6, 1953)

A general method, suitable for fast computing machines, for investigating such properties as equations of state for substances consisting of interacting individual molecules is described. The method consists of a modified Monte Carlo integration over configuration space. Results for the two-dimensional rigid-sphere system have been obtained on the Los Alamos MANIAC and are presented here. These results are compared to the free volume equation of state and to a four-term virial coefficient expansion.





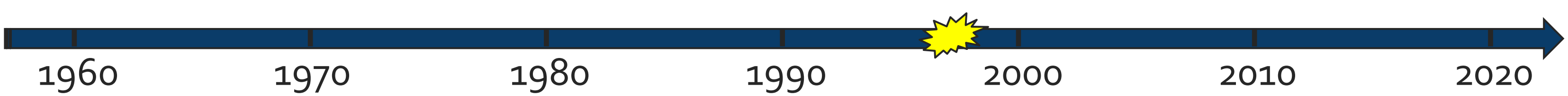
# Quantum Annealing Outlined by Tokyo Tech

PHYSICAL REVIEW E VOLUME 58, NUMBER 5 NOVEMBER 1998

## Quantum annealing in the transverse Ising model

Tadashi Kadowaki and Hidetoshi Nishimori
Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro-ku, Tokyo 152-8551, Japan
(Received 30 April 1998)

We introduce quantum fluctuations into the simulated annealing process of optimization problems, aiming at faster convergence to the optimal state. Quantum fluctuations cause transitions between states and thus play the same role as thermal fluctuations in the conventional approach. The idea is tested by the transverse Ising model, in which the transverse field is a function of time similar to the temperature in the conventional method. The goal is to find the ground state of the diagonal part of the Hamiltonian with high accuracy as quickly as possible. We have solved the time-dependent Schrödinger equation numerically for small size systems with various exchange interactions. Comparison with the results of the corresponding classical (thermal) method reveals that the quantum annealing leads to the ground state with much larger probability in almost all cases if we use the same annealing schedule.
[S1063-651X~98!02910-9]





# MIT Group Proposes Adiabatic QC



## Quantum Computation by Adiabatic Evolution

Edward Farhi, Jeffrey Goldstone*
Center for Theoretical Physics
Massachusetts Institute of Technology
Cambridge, MA 02139

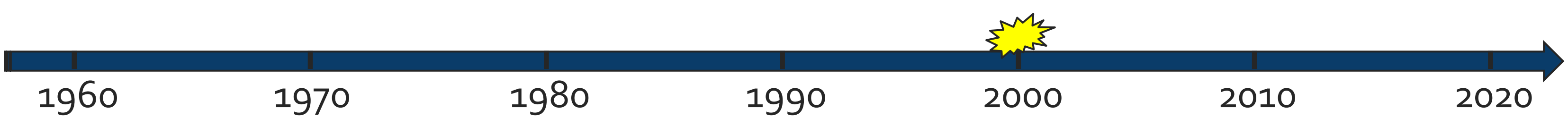
Sam Gutmann†
Department of Mathematics
Northeastern University
Boston, MA 02115

Michael Sipser‡
Department of Mathematics
Massachusetts Institute of Technology
Cambridge, MA 02139

MIT CTP # 2936 quant-ph/0001106

**Abstract**

We give a quantum algorithm for solving instances of the satisfiability problem, based on adiabatic evolution. The evolution of the quantum state is governed by a time-dependent Hamiltonian that interpolates between an initial Hamiltonian, whose ground state is easy to construct, and a final Hamiltonian, whose ground state encodes the satisfying assignment. To ensure that the system evolves to the desired final ground state, the evolution time must be big enough. The time required depends on the minimum energy difference between the two lowest states of the interpolating Hamiltonian. We are unable to estimate this gap in general. We give some special symmetric cases of the satisfiability problem where the symmetry allows us to estimate the gap and we show that, in these cases, our algorithm runs in polynomial time.

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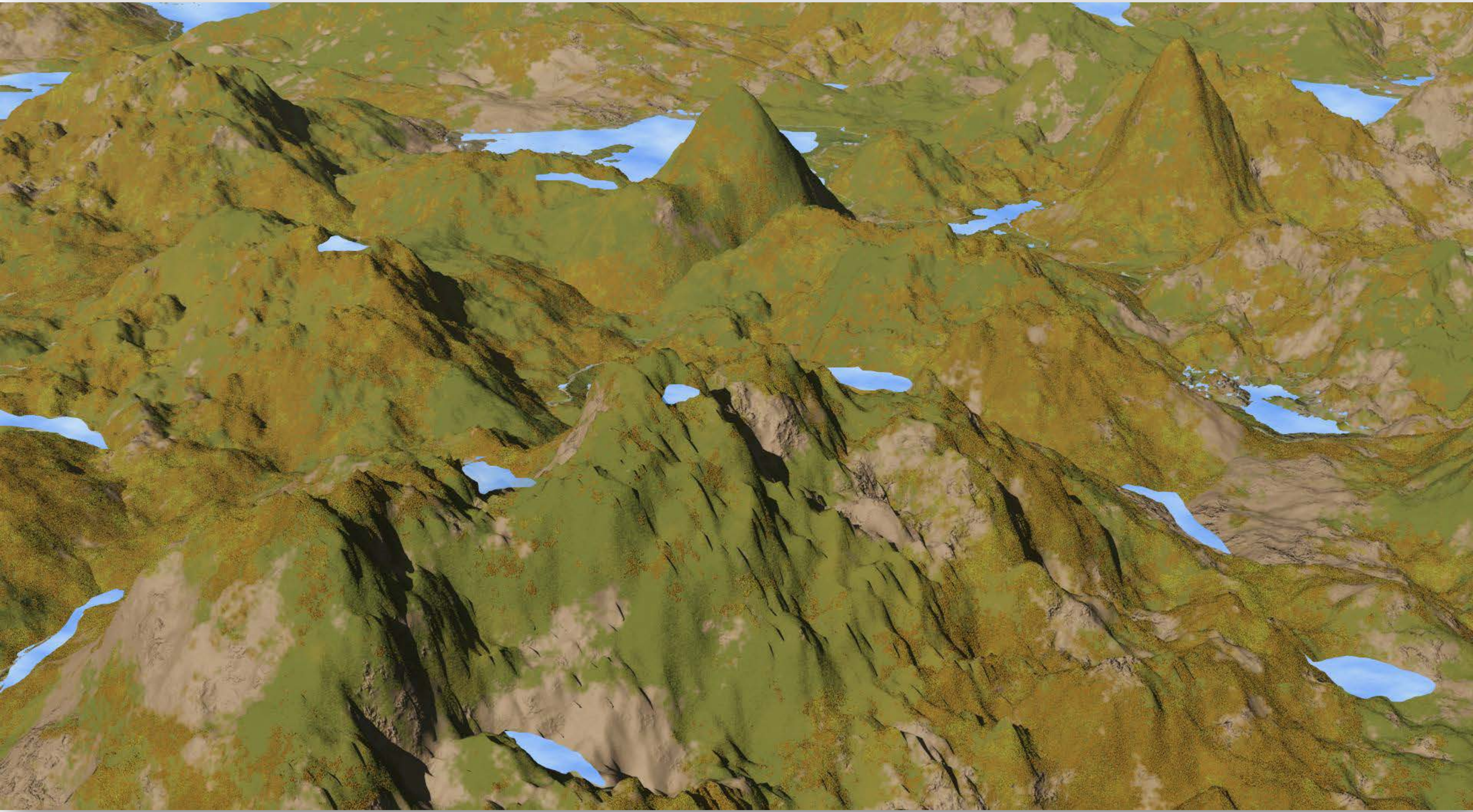
# How it Works





# Company Background

- Founded in 1999
- World's first quantum computing company
- Public customers:
  - Lockheed Martin/USC
  - Google/NASA Ames
  - Los Alamos National Lab
- Other customer projects done via cloud access to systems in D-Wave's facilities
- 120+ U.S. patents



# Mission

## To help solve the most challenging problems in the multiverse:

- Optimization
- Machine Learning
- Monte Carlo/Sampling



# But, It Is Fundamentally Different Than Anything You've Ever Done Before!

| | Intel 64 | D-Wave |
|---|---|---|
| Performance (GFLOPS) | ~20 (12 cores) | 0 |
| Precision (bits) | 64 | 4-5 |
| MIPS | ~12,000 (12 cores) | 0.01 |
| Instructions | 245+ (A-M)<br>251+ (N-Z) | 1 |
| Operating Temp. | 67.9° C | -273° C |
| Power Cons. | 100 w +/- | ~0 |
| Devices | 4B+ transistors | 1000 qubits |
| Maturity | 1945-2016 | ~1950's |

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# The D-Wave 2X

1000+ qubits

Performance: up to 600X
Synthetic cases –
100,000,000X

Power: <25 kW

Three orders:
- Google/NASA
- LANL
- Lockheed Martin/USC

# D-Wave Container -"SCIF-like" - No RF Interference


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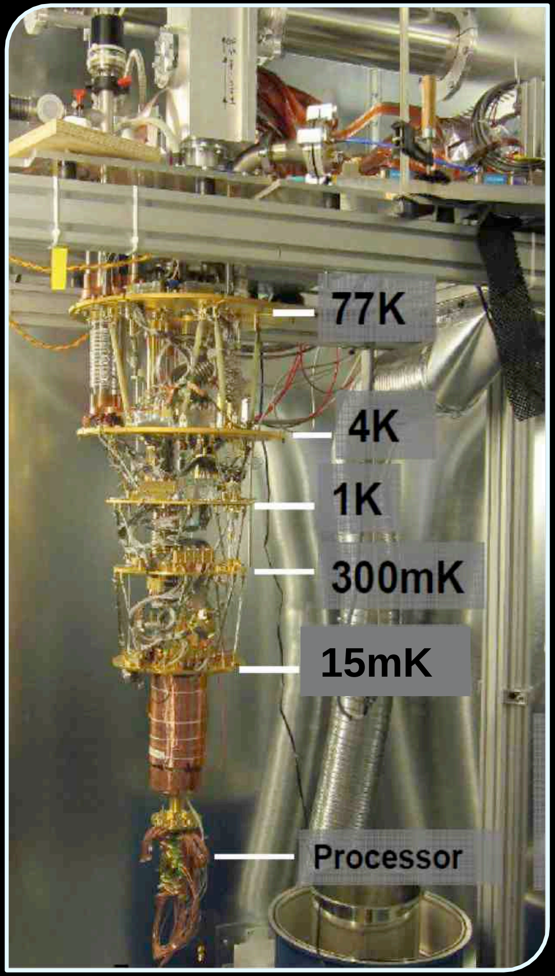
# System Shielding

- 16 Layers between the quantum chip and the outside world
- Shielding preserves the quantum calculation

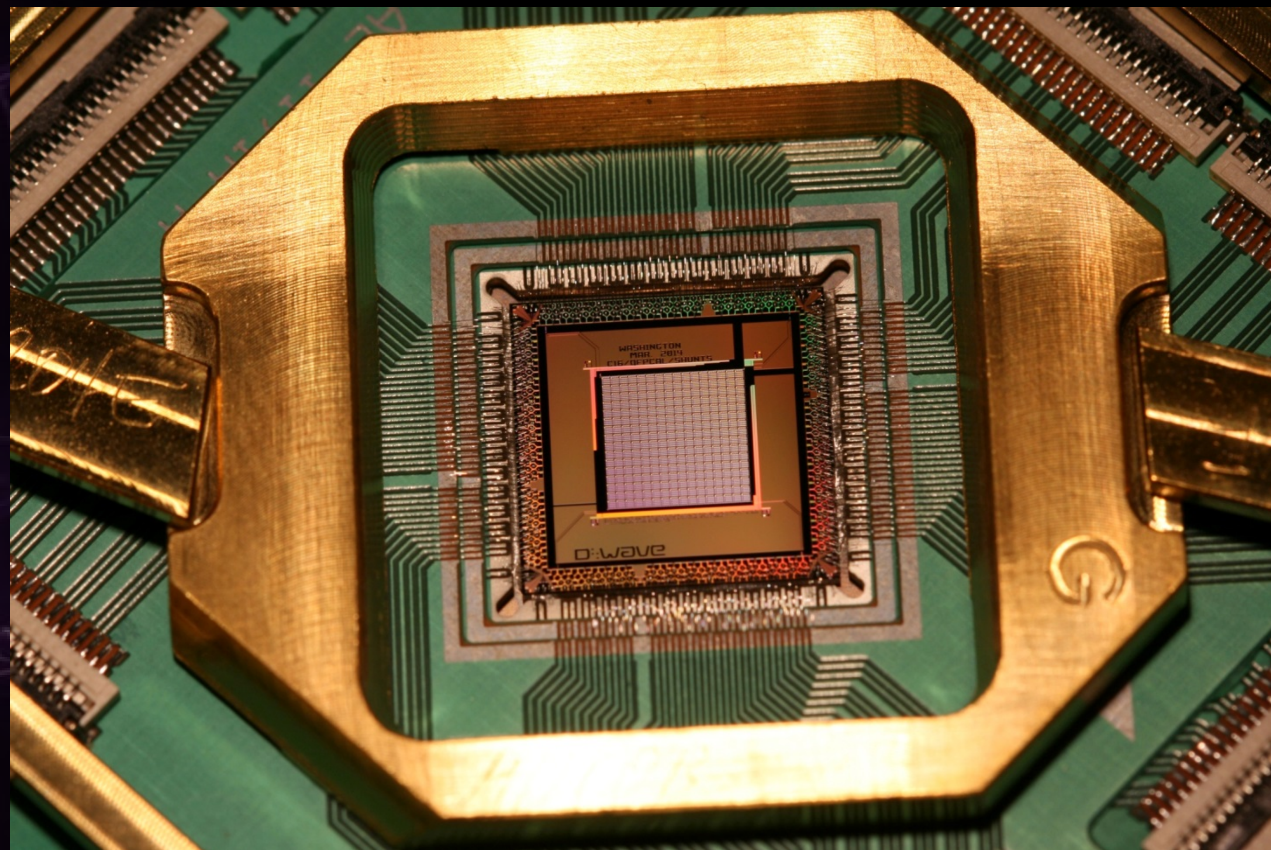

 

# Processor Environment

- Cooled to 0.015 Kelvin, 175x colder than interstellar space
- Shielded to 50,000 × less than Earth's magnetic field
- In a high vacuum: pressure is 10 billion times lower than atmospheric pressure
- On low vibration floor
- <25 kW total power consumption – for the next few generations



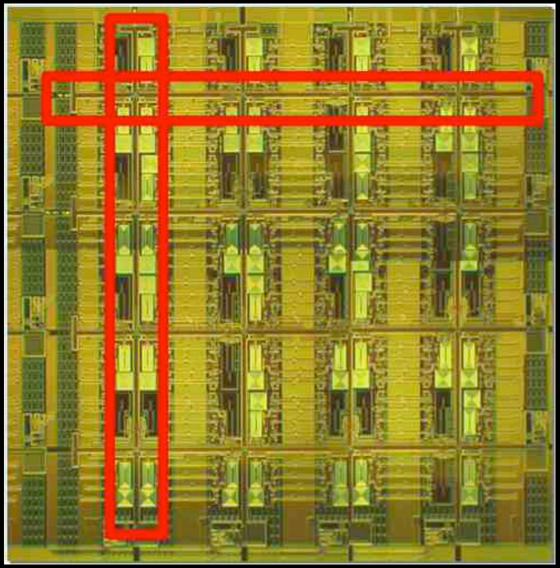
# D-Wave 2X Quantum Processor



# Processing Using D-Wave

- A lattice of superconducting loops (qubits)
- Chilled near absolute zero to quiet noise
- User maps a problem into search for "lowest point in a vast landscape" which corresponds to the best possible outcome
- Processor considers all possibilities simultaneously to satisfy the network of relationships with the lowest energy
- The final state of the qubits yields the answer



# Programming Model

| | | |
|---|---|---|
| QUBIT | $q_i$ | Quantum bit which participates in annealing cycle and settles into one of two possible final states: $\{0,1\}$ |
| COUPLER | $q_i q_j$ | Physical device that allows one **qubit** to influence another **qubit** |
| WEIGHT | $a_i$ | Real-valued constant associated with each **qubit**, which influences the **qubit's** tendency to collapse into its two possible final states; controlled by the programmer |
| STRENGTH | $b_{ij}$ | Real-valued constant associated with each **coupler**, which controls the influence exerted by one **qubit** on another; controlled by the programmer |
| OBJECTIVE | $Obj$ | Real-valued function which is minimized during the annealing cycle |

$$\boldsymbol{Obj(a_i, b_{ij}; q_i) = \sum_i a_i\, q_i + \sum_{ij} b_{ij} q_i\, q_j}$$

The system **samples** from the $q_i$ that minimize the objective

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 | 

# Programming Environment

- Operates in a hybrid mode with a HPC System or Data Analytic Engine acting as a co-processor or accelerator
- D-Wave system is "front-ended" on a network by a standard server (Host)
- User formulates problem as a series of Quantum Machine Instructions (QMIs)
- Host sends QMI to quantum processor (QP)
- QP samples from the distribution of bit-strings defined by the QMI
- Results are returned to the Host and back to the user

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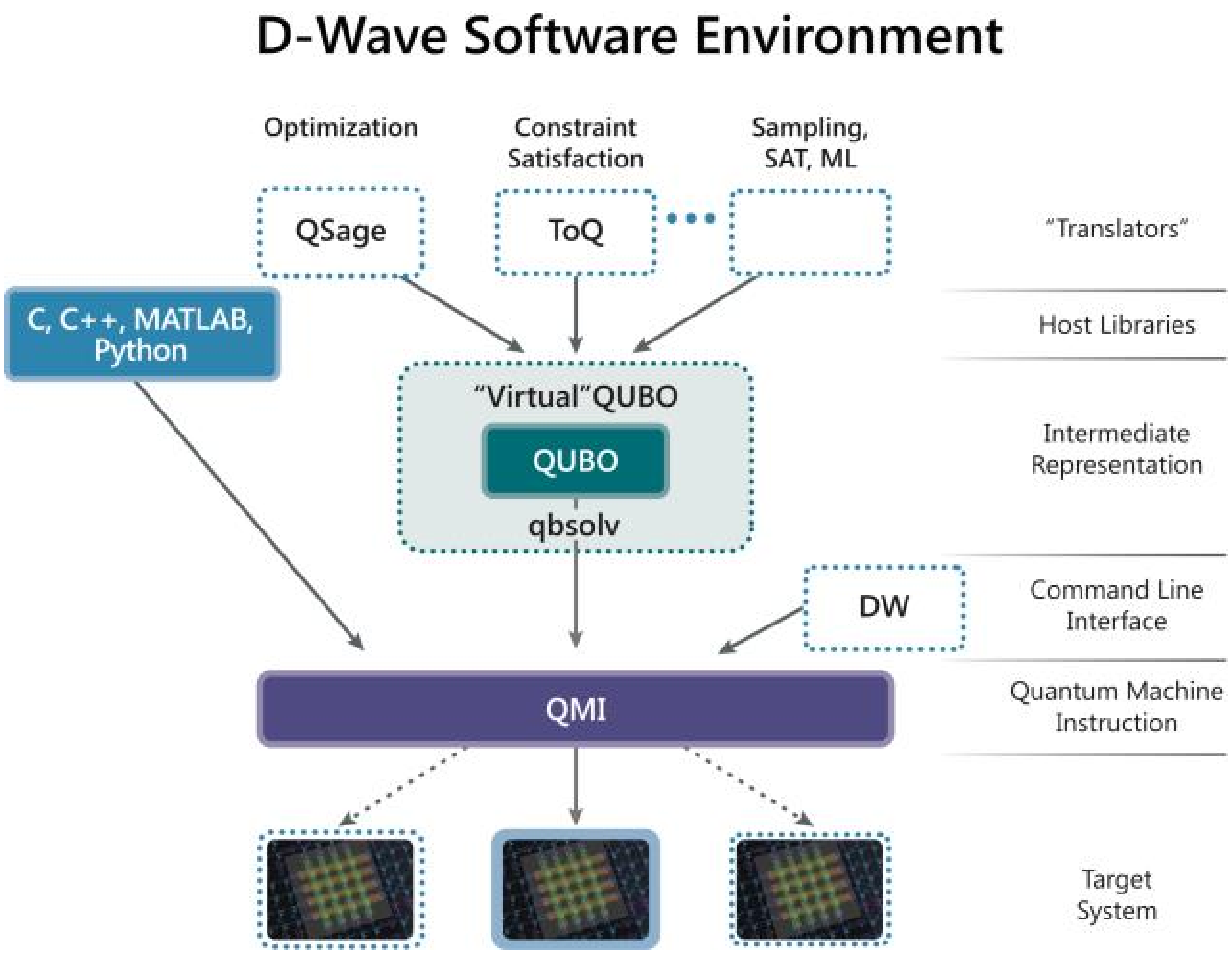
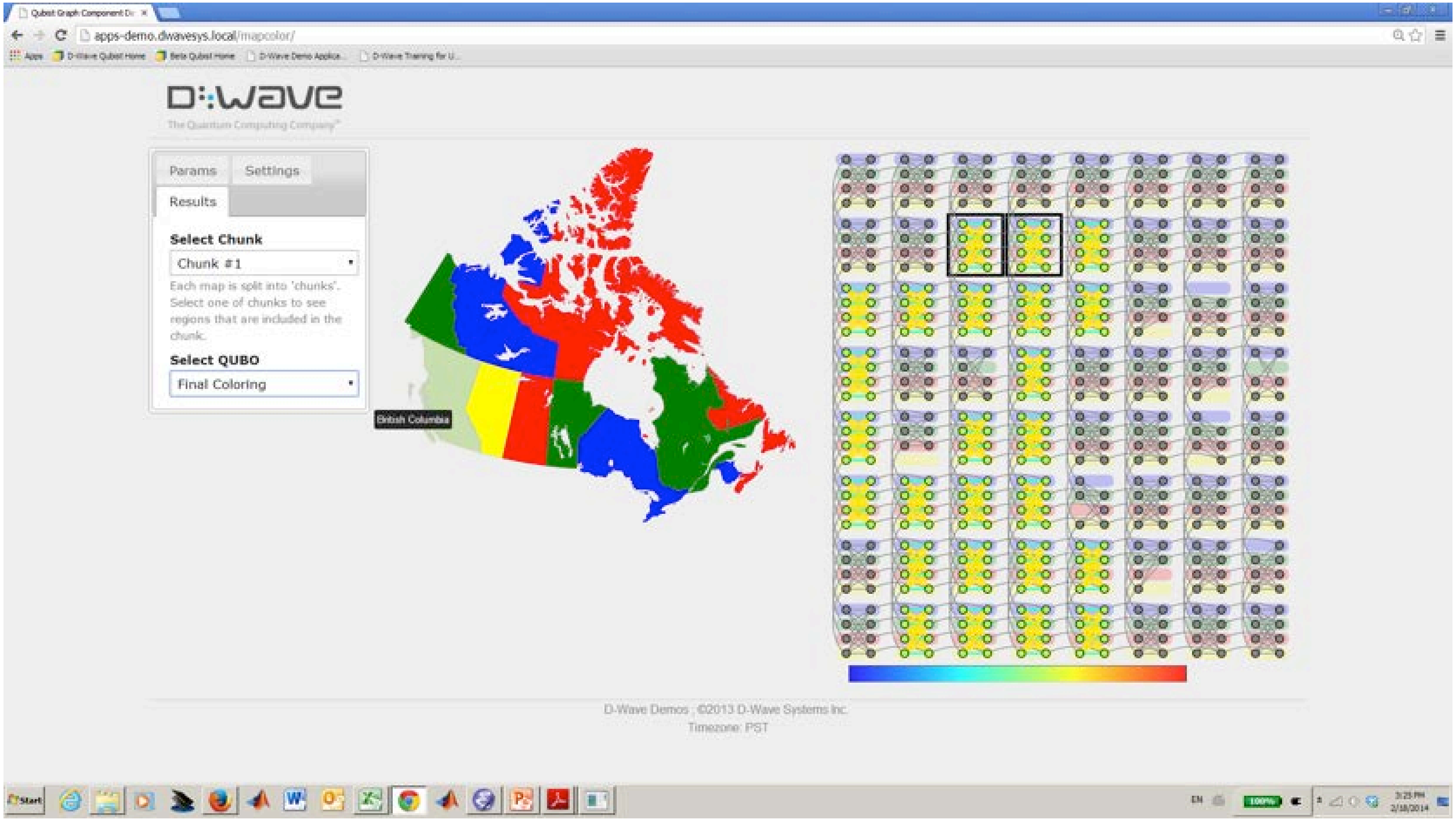
# D-Wave Software Environment





# Colors encoded in unit cells





# Example: 4-coloring Canada's provinces



# Scaling up...

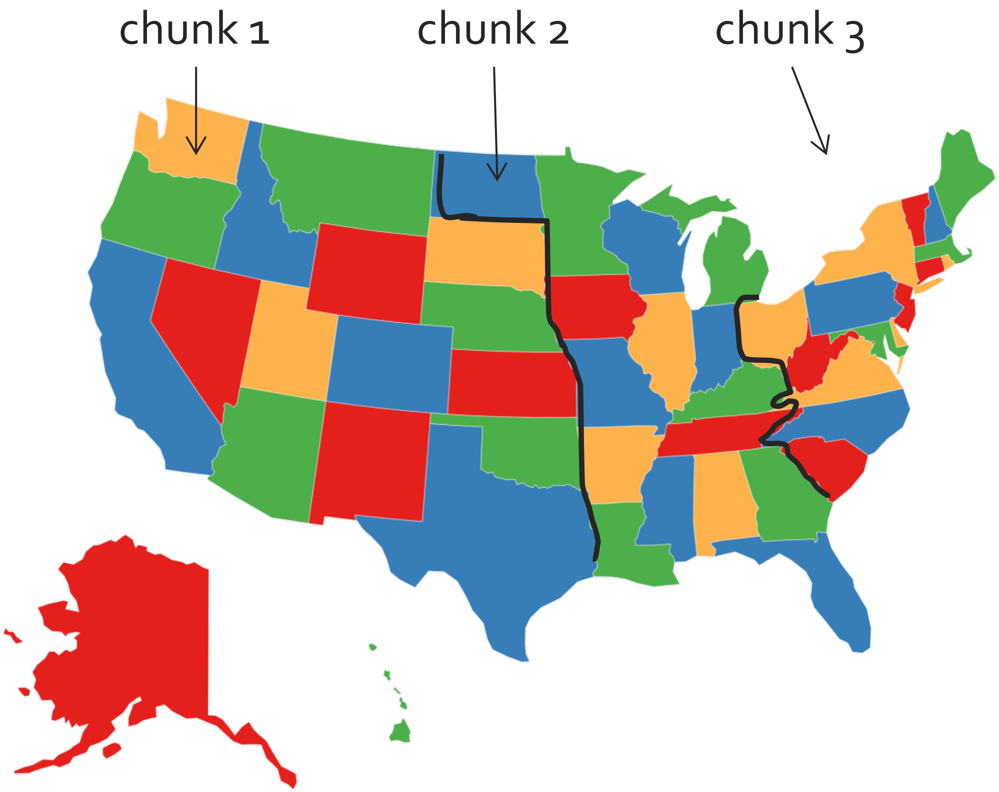
- We cannot fit all the states into unit cells of the chip...
- ...so we adopt a divide-and-conquer strategy

Divide the US map into chunks.

Process the first chunk and get valid colorings for the first chunk of states.

Use these colorings to *bias* the second chunk.

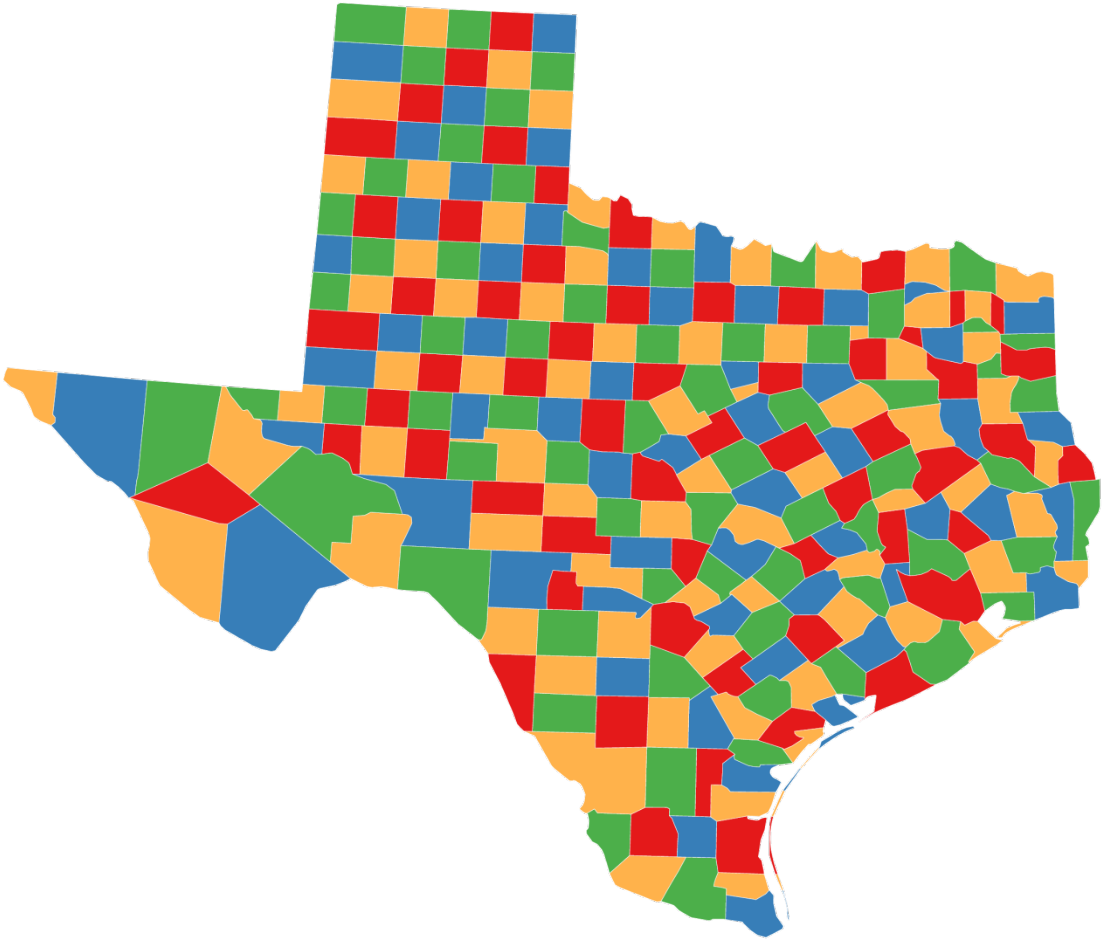
Repeat.





# ...and up...



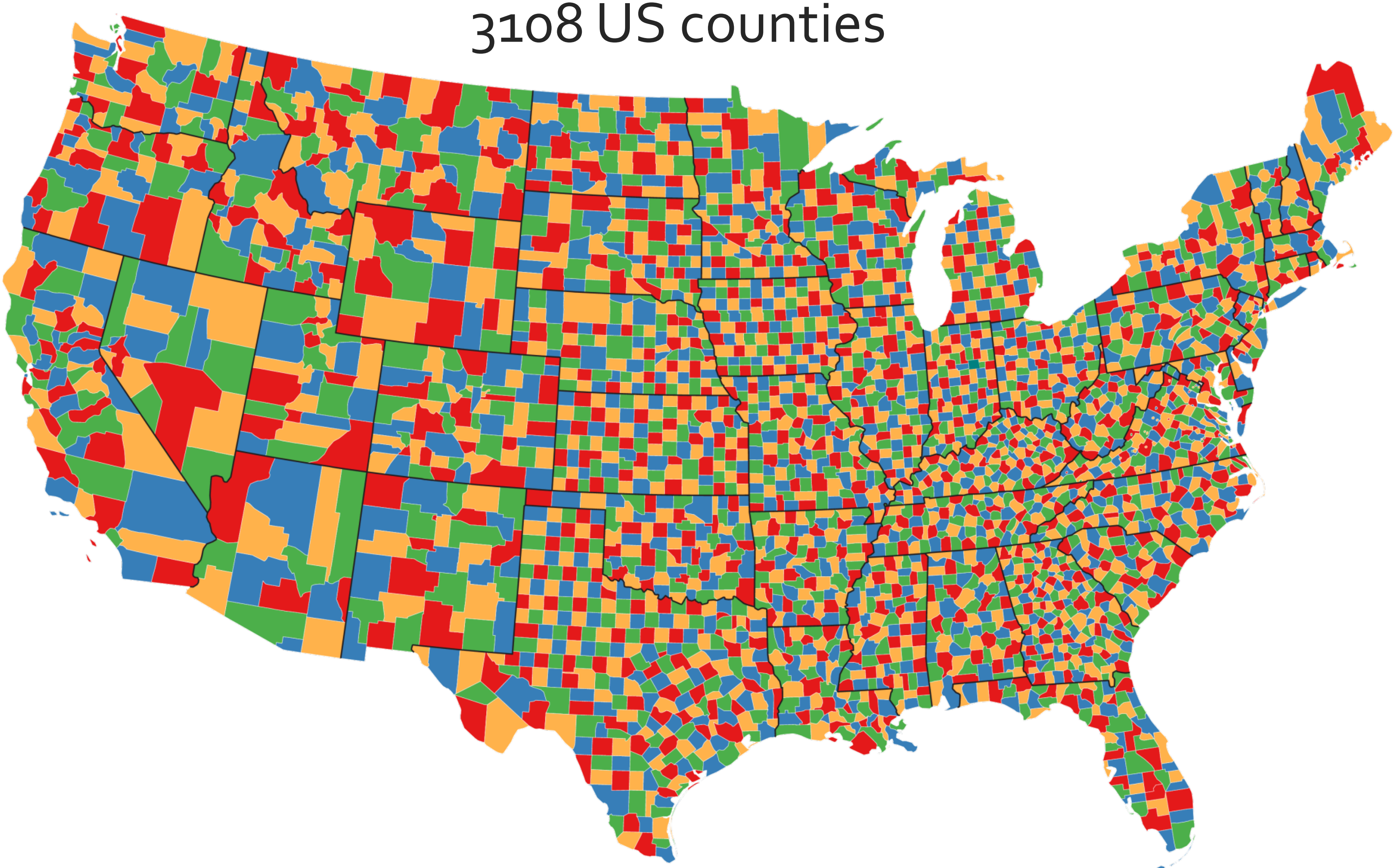
254 counties in Texas



# ...and up

## 3108 US counties



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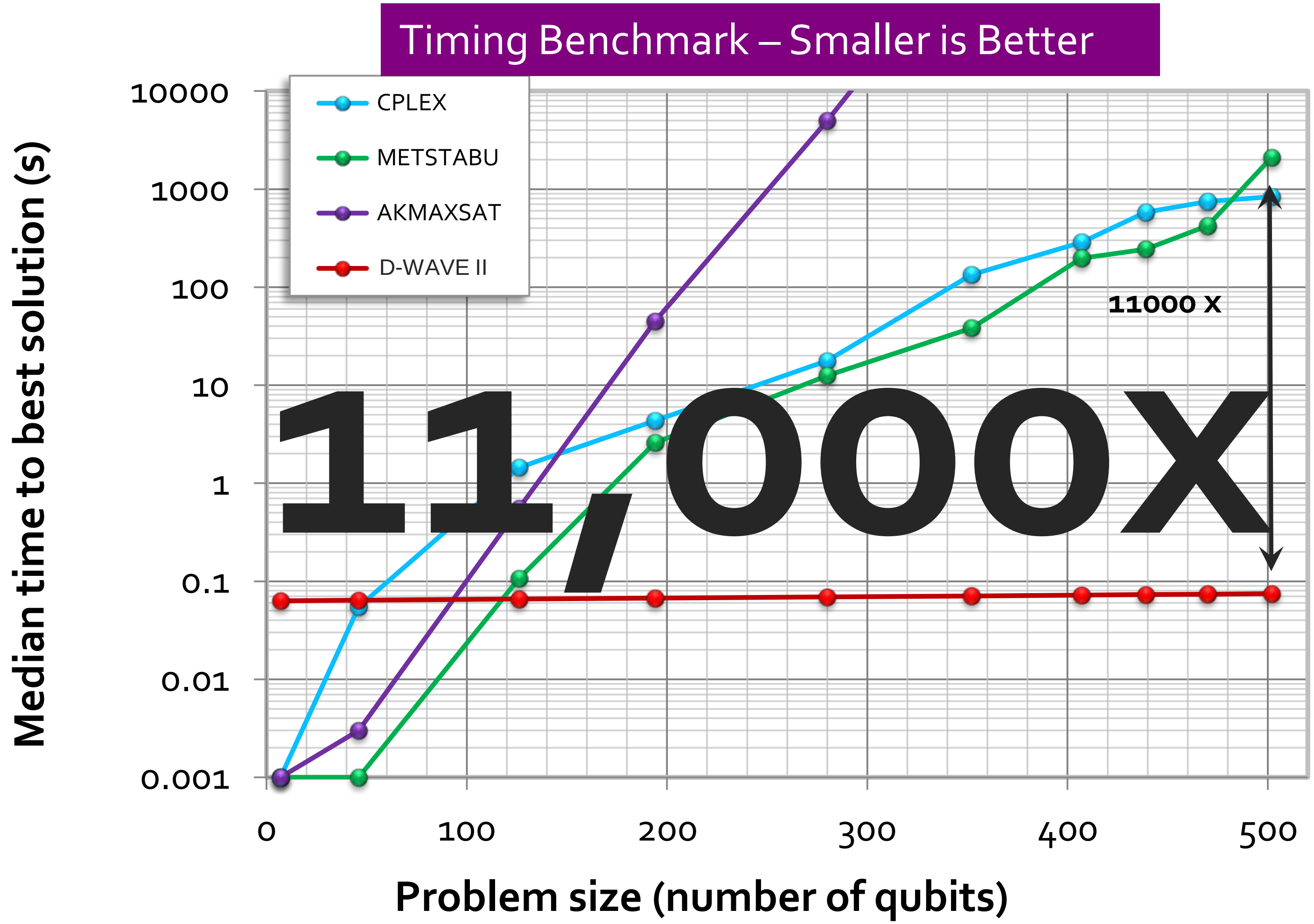
# Google Optimization Benchmarks (2013)

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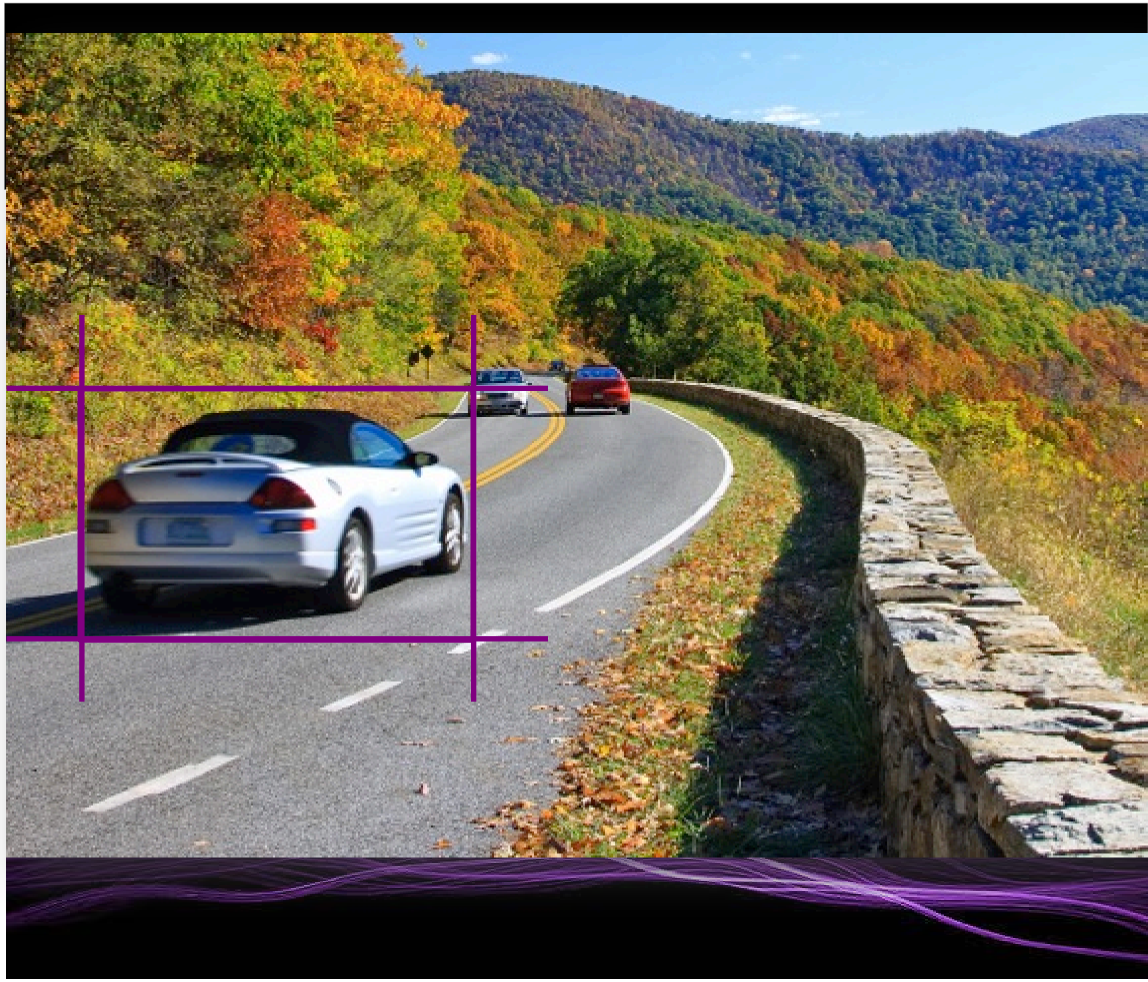
# Machine Learning: Binary Classification

- Traditional algorithm recognized car about 84% of the time
- Google/D-Wave Qboost algorithm implemented to recognize a car (cars have big shadows!)
- "Quantum Classifier" was more accurate (94%) and more efficient
- Ported quantum classifier back to traditional computer, more accurate and fewer CPU cycles (less power)!



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# Google Blog December 8, 2015

## When can Quantum Annealing win?

Tuesday, December 08, 2015

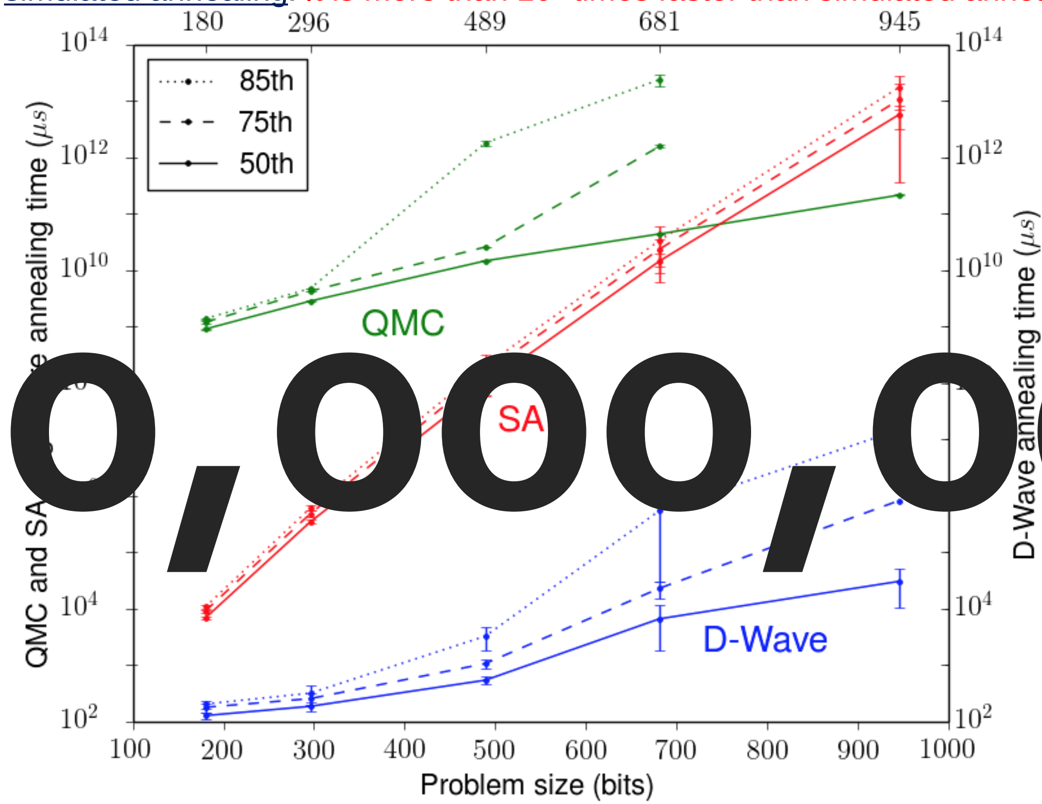
http://googleresearch.blogspot.ca/2015/12/when-can-quantum-annealing-win.html

Posted by Hartmut Neven, Director of Engineering

-

During the last two years, the Google Quantum AI team has made progress in understanding the physics governing quantum annealers. We recently applied these new insights to construct proof-of-principle optimization problems and programmed these into the D-Wave 2X quantum annealer that Google operates jointly with NASA. The problems were designed to demonstrate that quantum annealing can offer runtime advantages for hard optimization problems characterized by rugged energy landscapes

We found that for problem instances involving nearly 1000 binary variables, quantum annealing significantly outperforms its classical counterpart, simulated annealing. It is more than $10^8$ times faster than simulated annealing running on a single core.




**100,000,000X**

# The Beginning of an Industry

| Hardware | Software Tools | Algorithms/Apps | Gov. Funded R&D |
|---|---|---|---|
| **Production** | | | |
| D-Wave 2X | D-Wave qOp | D-Wave Users | |
| | - dw, qbsolv, ToQ | 1Qbit | |
| | | QC Ware | |
| | 1QBit SDK | QxBranch | |
| | LANL Assembler | . . . | |
| | . . . | | |
| Research | | | |
| IBM Research (5Q) | IBM, MS, . . . | | EC €1B |
| | | | UK Hubs |
| | ORNL JADE | | IARPA QEO |
| U Bristol (2Q) | Poland QuTiP | | . . . |
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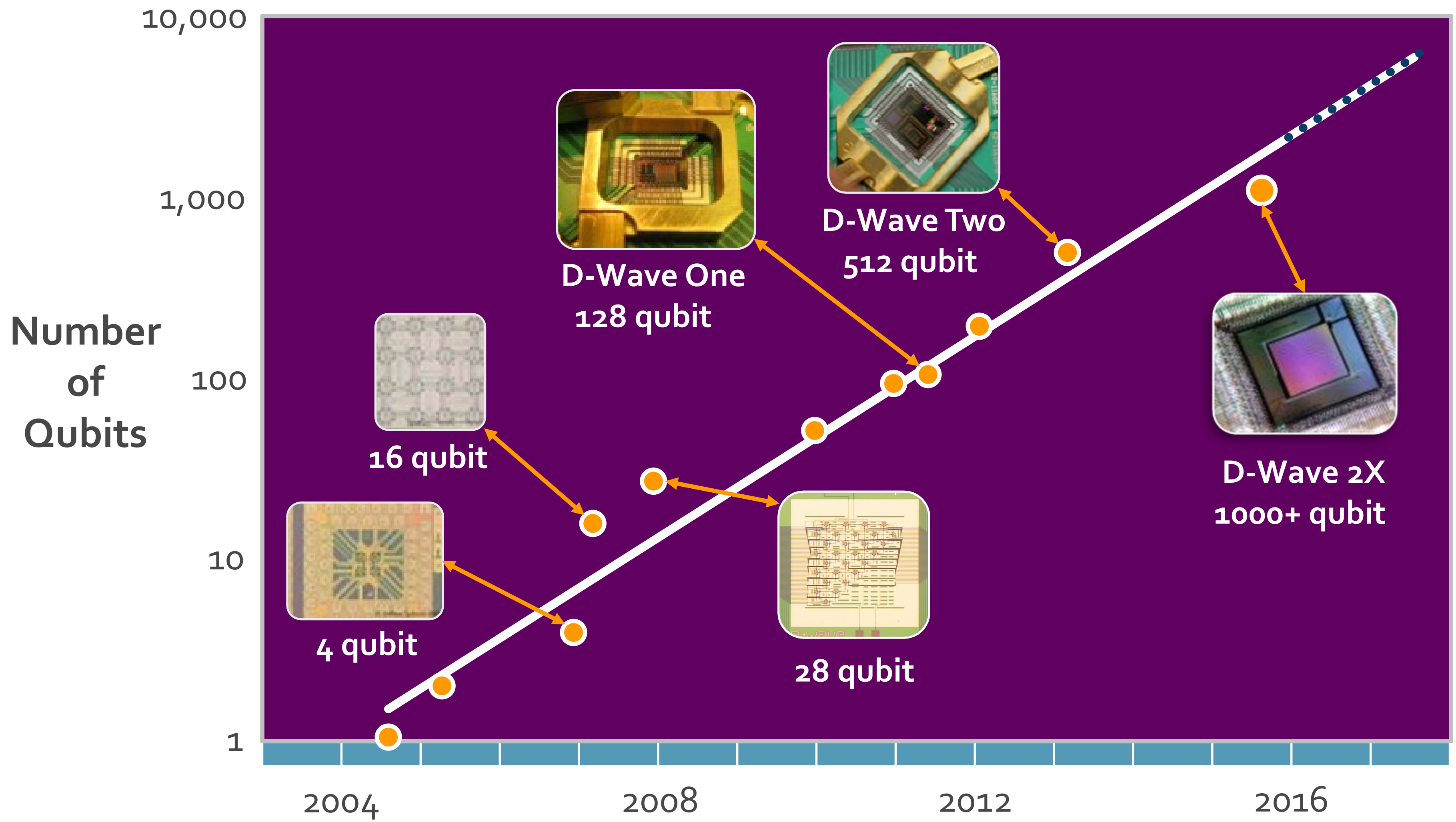
# The Most Advanced Quantum Computer in the World

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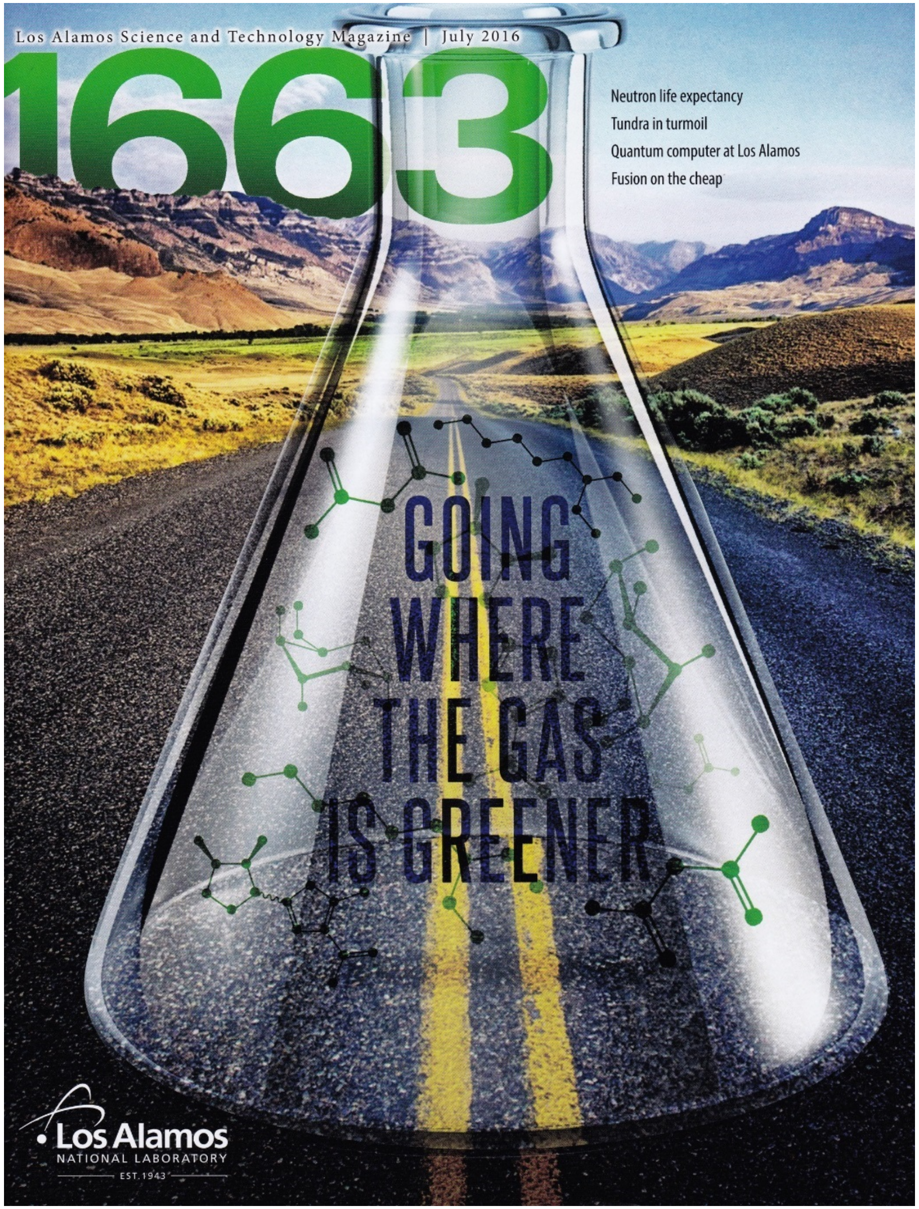
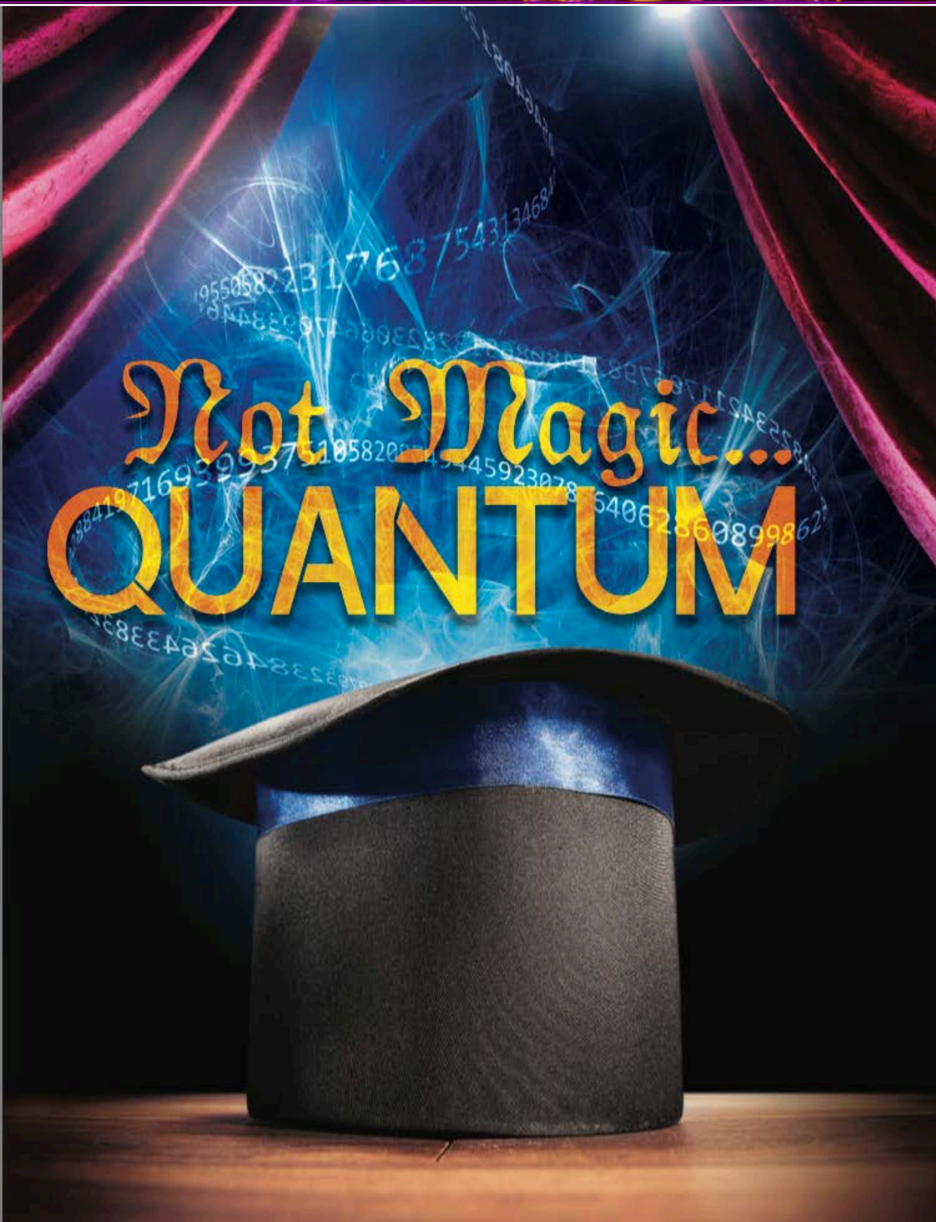

Los Alamos Science and Technology Magazine | July 2016
1663
Neutron life expectancy
Tundra in turmoil
Quantum computer at Los Alamos
Fusion on the cheap
GOING WHERE THE GAS IS GREENER
Los Alamos
NATIONAL LABORATORY
EST. 1943




## A nascent commercial quantum computer has arrived at Los Alamos. It could solve certain problems with such astonishing speed that it would be like pulling answers out of a hat.

A famous physicist once said, "If you think you understand quantum mechanics, you don't understand quantum mechanics." That physicist was Richard Feynman—Los Alamos alumnus, wisecracker, and Nobel laureate—describing a mind-bending subfield of physics wherein the rules of classical mechanics seem to vanish in a puff of smoke.

During Feynman's years at Los Alamos, the fledgling laboratory's "computers" were mostly women, many the wives of scientists, who sat at desks for eight hours a day, computing by hand the complex calculations required by the Manhattan Project. Shortly thereafter, the top-secret ENIAC (Electronic Numerical Integrator And Computer)—located in Pennsylvania and regarded as the first general-purpose electronic computer—helped post-war Los Alamos scientists to refine nuclear weapons and to explore other weapons technologies. Soon Los Alamos officials recognized the need for on-site leading-edge computing technologies. The first and second MANIAC computers (Mathematical Analyzer, Numerical Integrator, And Computer) were built in-house during the 1950s and 60s. In the 1970s supercomputers came on the scene and the Laboratory was first to purchase Cray, Connection Machine, and IBM supercomputers. At present, the Laboratory is installing its latest Cray supercomputer, a classical-computing beast dubbed Trinity, which once installed will be one of the most advanced computers in the world. But last month the newest addition to the Lab's family of futuristic computers arrived, and it's a horse of a different color: a quantum computer with potentially extraordinary capabilities that are just beginning to be explored.

Quantum computers have long been on the horizon as conventional computing technologies have raced toward their physical limits. (Moore's Law, an observation that the number of transistors that can fit onto a computer chip doubles every two years, is nearing its expiration date as certain features approach the size of atoms.) And to be certain, general-purpose quantum computers remain on the horizon. However, with the acquisition of this highly specialized quantum computer, Los Alamos, in partnership with Lawrence Livermore and Sandia National Laboratories, is helping to blaze the trail into beyond-Moore's Law computing technology. This new machine could be a game changer for simulation and computing tools that support the Laboratory's mission of stockpile stewardship without nuclear testing. It may also enable a slew of broader national security and computer science applications. But it will undoubtedly draw a community of top creative thinkers in computational physics, computer science, and numerical methods to Los Alamos—reaffirming the Lab's reputation as a computing technology pioneer.

### Weird science

Albert Einstein famously rejected parts of the theory of quantum mechanics. His skepticism is understandable. The theory, after all, said that a single subatomic particle could occupy multiple places at the same time. A particle could move from one location to another without traversing the space between. And multiple particles that had previously interacted and then separated by vast distances, could somehow "know" what each other was up to. It didn't seem to align with what scientists thought they knew.

Einstein's friend and contemporary, Niels Bohr, argued in favor of the theory and embraced its peculiarities, declaring, "Everything we call real is made of things we cannot call real." Einstein and Bohr publically hashed it out over the years in a series of collegial debates that delved deep into the philosophy of nature itself. Bohr's view prevailed and science has since borne it out. Even though Einstein was never fully satisfied by it, quantum mechanics is now generally accepted as the fundamental way of the world.

One of the hard-to-get-your-head-around concepts at the heart of quantum mechanics is called superposition. Simplistically, superposition is the idea that something can be in multiple states at the same time. A single electron can have both up and down spin, a single photon can travel both this path and that one, and, conceptually, a luckless cat in a box can be both dead and alive. Until you check, that is. Once the electron's spin is measured, or the photon is tracked, or the box lid is lifted, the system goes classical and assumes either one state or the other.

The lifting of the lid causes decoherence—another oddity of the quantum world. For a system to exist in a state of superposition it must not interact with its environment at all, including observers or scientific instruments. The loss of any