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The Quantum Computing Company™

An Introduction to Quantum Computing

CERN

Bo Ewald
October 17, 2017

Bo Ewald

November 5, 2018

TOPICS

- Introduction to Quantum Computing
  - Introduction and Background
  - Quantum Annealing
- Early Applications
  - Optimization
  - Machine Learning
  - Material Science
  - Cybersecurity
  - Fiction
- Final Thoughts

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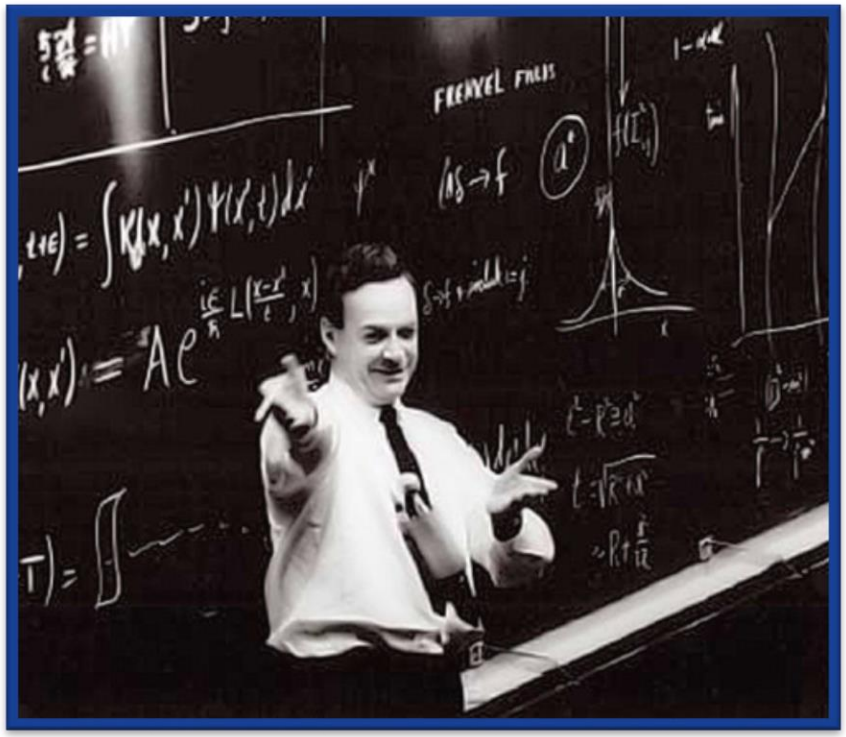
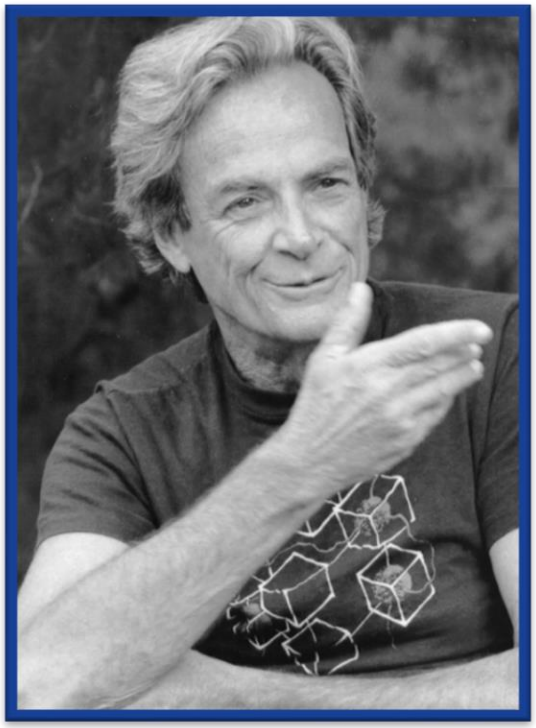
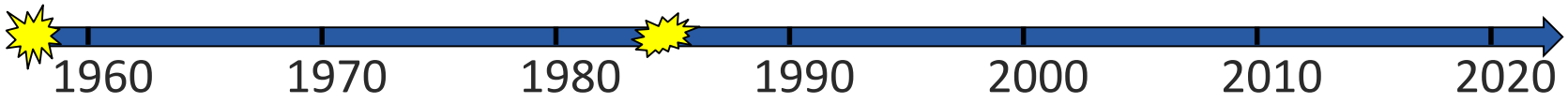
Richard Feynman – Proposed Quantum Computer in 1981







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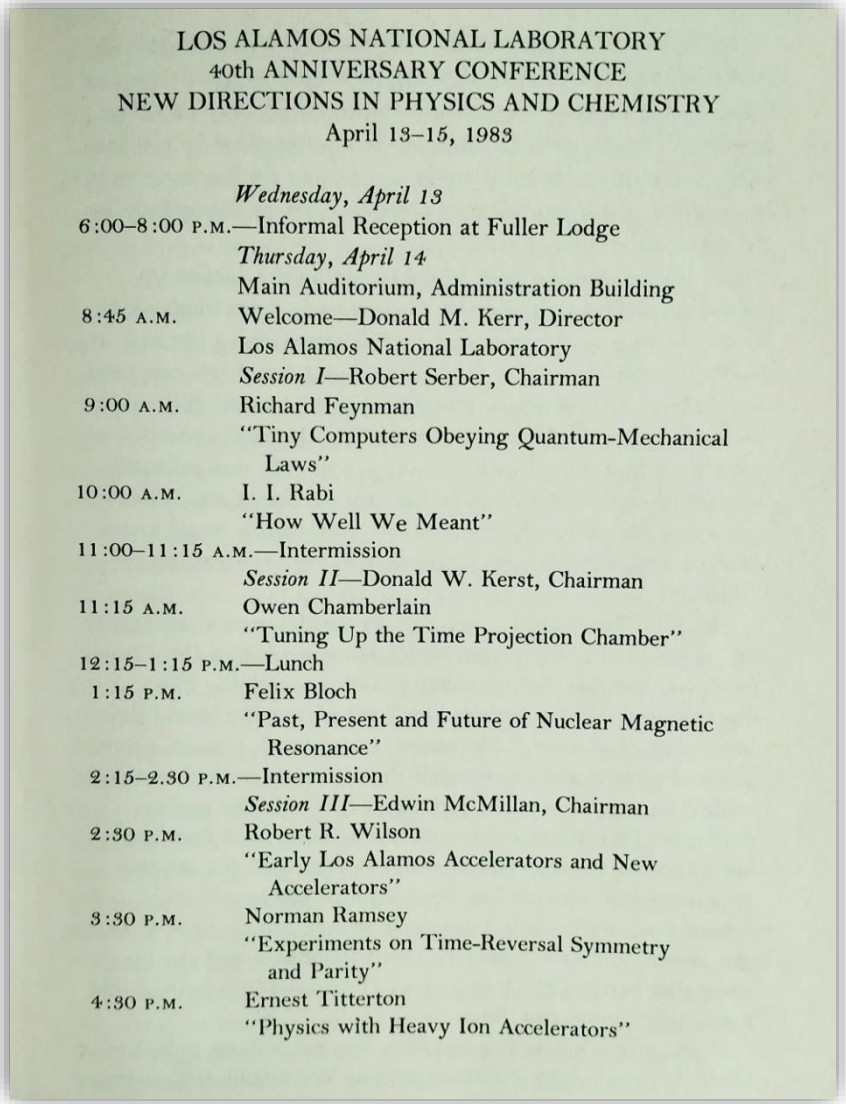
April 1983 – Richard Feynman's Talk at Los Alamos



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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The “Marriage” Between Technology and Architecture

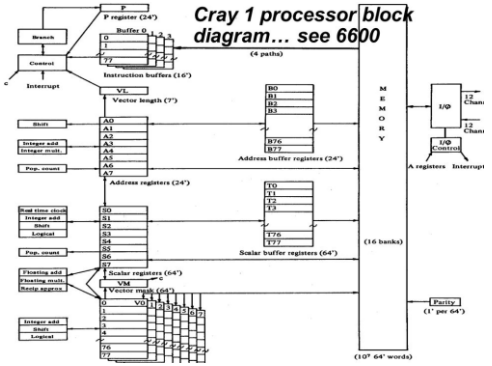
- To design and build any computer, one must select a compatible technology and a system architecture

- Technology – the physical devices (IC’s, PCB’s, interconnects, etc) used to implement the hardware

- Architecture – the organization and rules that govern how the computer will operate
  - Digital – CISC (Intel x86), RISC (MIPS, SPARC),

    Vector (Cray), SIMD (CM-1), Volta (NVIDIA)
  - Quantum – Gate or Circuit (IBM, Rigetti)

    Annealing (D-Wave, ARPA QEO)



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Quantum Technology – "qubit" Building Blocks

Quest for qubits

Gabriel Popkin*

Science 02 Dec 2016:
Vol. 354, Issue 6316, pp. 1090-1093
DOI: 10.1126/science.354.6316.1090

A bit of the action

In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.

	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies
Pros	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
Cons	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

CREDITS: (GRAPHIC) C. BICKEL/*SCIENCE*; (DATA) GABRIEL POPKIN

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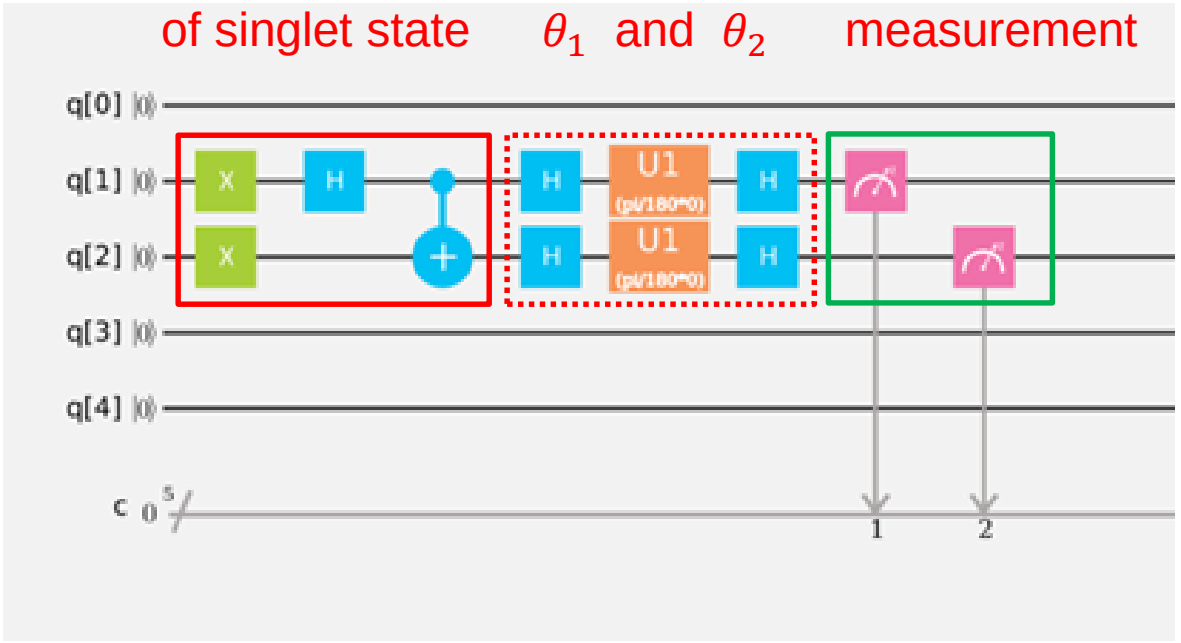
Simulation on IBM Quantum Experience (IBM QX)

IBM QX, Yorktown Heights, USA

Preparation of singlet state

Rotation by θ_1 and θ_2

Readout measurement



X X-gate:

$X|0\rangle = |1\rangle$

$X|1\rangle = |0\rangle$

H Hadamard gate:

$H|0\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$

$H|1\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$

U1 phase-gate:

$U1|0\rangle = |0\rangle$, $U1|1\rangle = e^{i\theta}|1\rangle$

CNOT gate: $C_{01}|0_1 0_0\rangle = |0_1 0_0\rangle$

$C_{01}|0_1 1_0\rangle = |1_1 1_0\rangle$

$C_{01}|1_1 0_0\rangle = |1_1 0_0\rangle$

$C_{01}|1_1 1_0\rangle = |0_1 1_0\rangle$

Simulated Annealing on Digital Computers

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

Equation of State Calculations by Fast Computing Machines

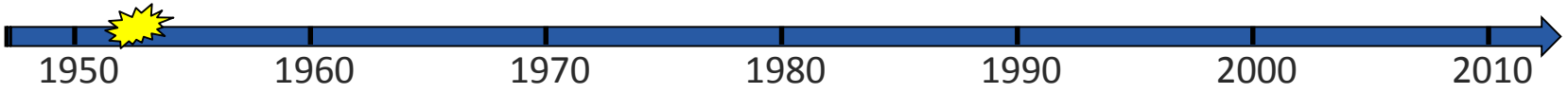
NICHOLAS METROPOLIS, ARIANNA W. ROSENBLUTH, MARSHALL N. ROSENBLUTH, AND AUGUSTA H. TELLER,
Los Alamos Scientific Laboratory, Los Alamos, New Mexico

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.



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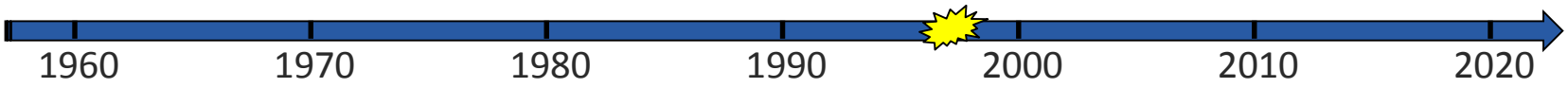
Quantum Annealing Outlined by Tokyo Tech

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]



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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

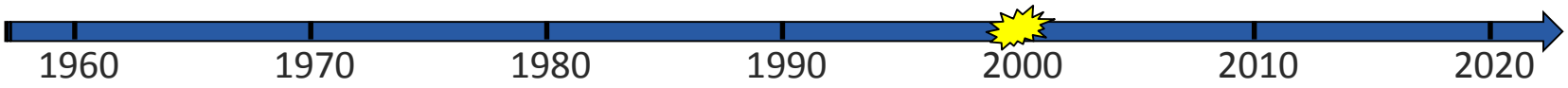
MIT CTP # 2936

quant-ph/0001106

quant-ph/0001106v1 28 Jan 2000

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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Company Background

- Founded in 1999
- World's first quantum computing company
- Public system customers:
  - Lockheed Martin/USC
  - Google/NASA Ames/USRA
  - Los Alamos National Laboratory
  - Cybersecurity - 1
  - Oak Ridge National Laboratory
- ~30 other remote access customers
- ~160 U.S. patents

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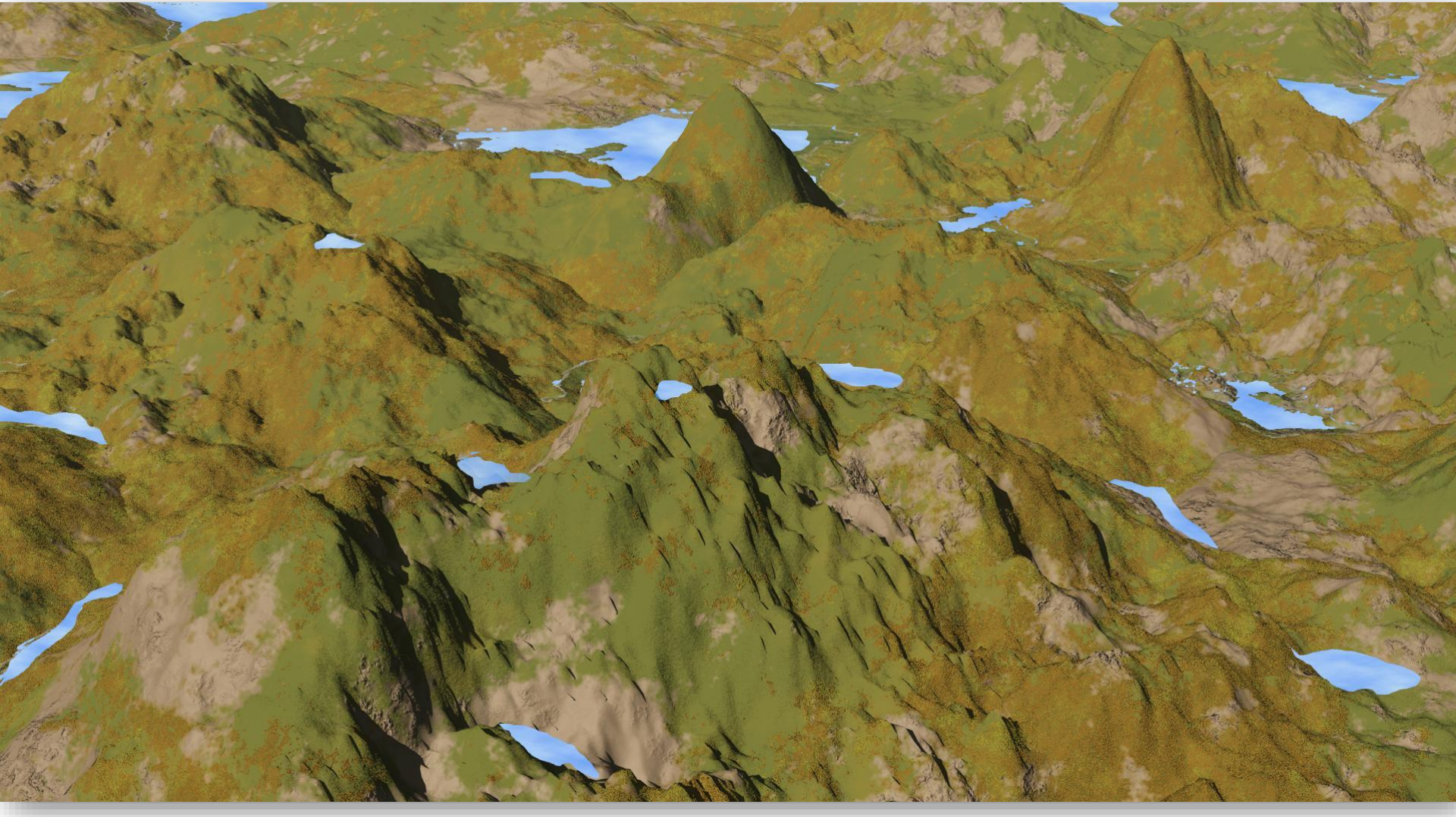
How it Works



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D-Wave Container –Faraday Cage - No RF Interference

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System Shielding

- 16 Layers between the quantum chip and the outside world
- Shielding helps preserve the quantum state

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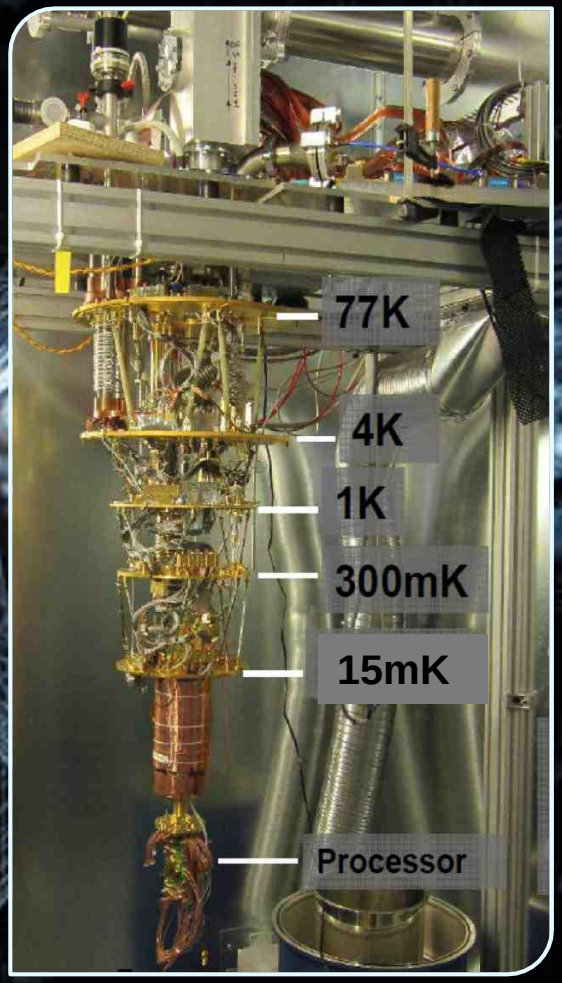
Processor Environment

- 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



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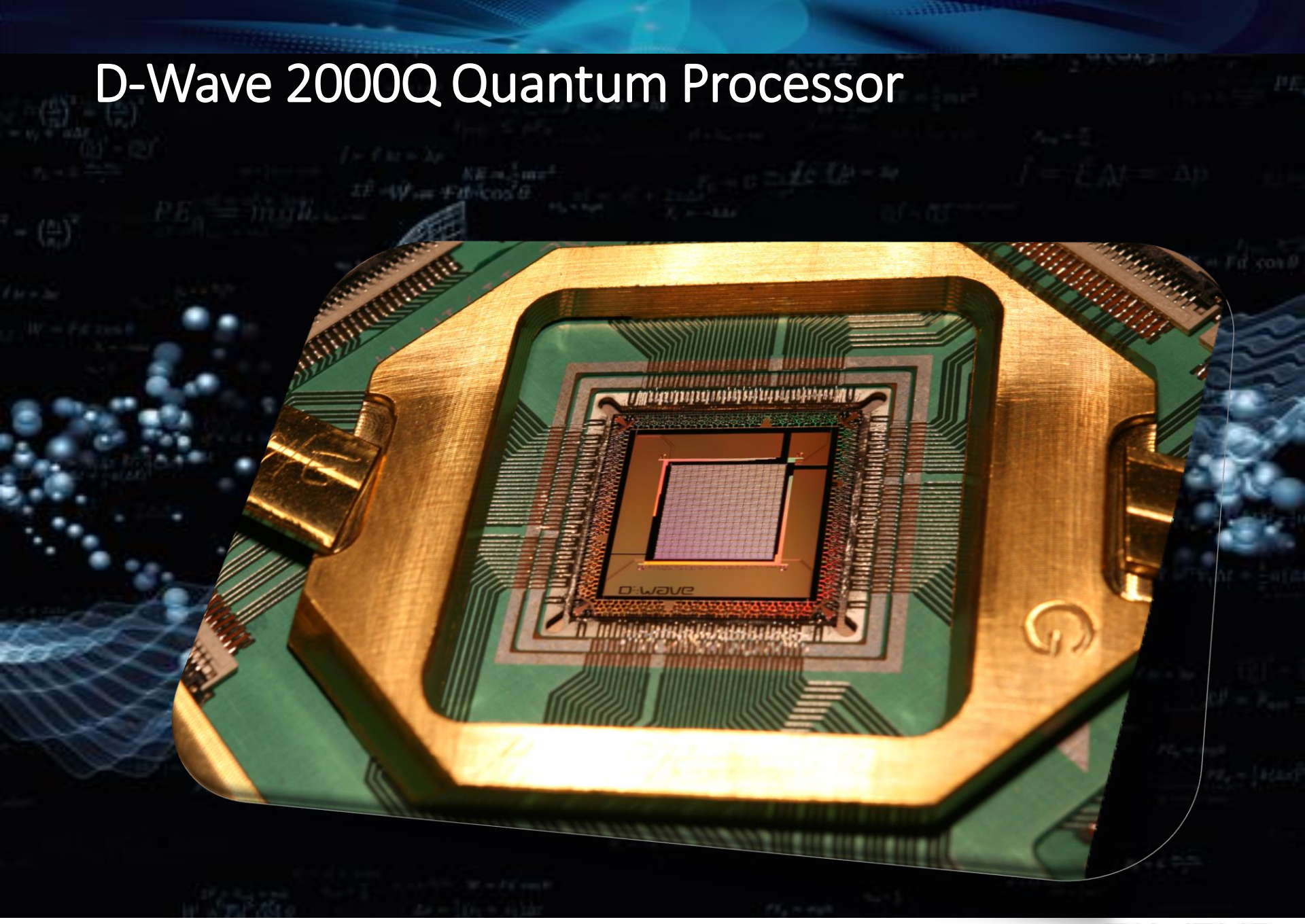
D-Wave 2000Q Quantum Processor



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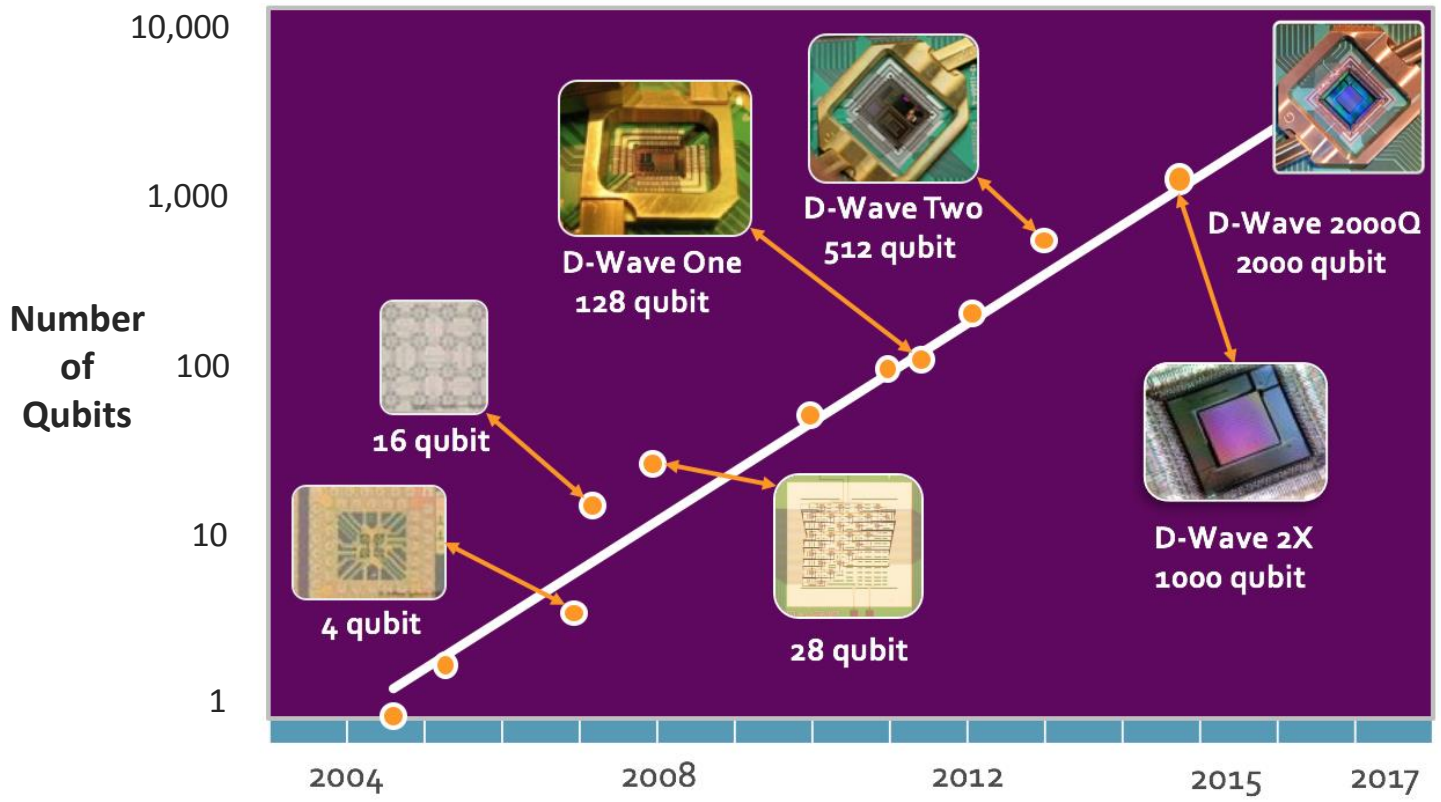
D-Wave Product Generations



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Early Applications of Quantum Computing

- Overview
- Proto-Apps
  - Optimization
  - Machine Learning
  - Material Science
  - Cybersecurity
  - Fiction

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Application Status

- About 100 “Proto-Apps” have been demonstrated by customers on D-Wave systems
- Roughly:
  - Optimization 50%
  - AI/ML 20%
  - Material Science 10%
  - Other 20%
- In about half of the proto-apps, performance or quality of answers is approaching and occasionally better than classical computing
- But, all are small problems, not production ready yet
- Many papers/presentations, problem formulations, and open source software available

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Customers with Installed Systems - Application Areas

- **Lockheed/USC ISI**
  - Software Verification and Validation
  - Optimization – Aeronautics
  - Performance Characterization & Physics
- **Google/NASA Ames/USRA**
  - Machine Learning
  - Optimization
  - Performance Characterization & Physics
  - Research
- **Los Alamos National Laboratory**
  - Optimization
  - Machine Learning, Sampling
  - Software Stack
  - Simulating Quantum Systems
  - Other (good) Ideas
- **CS - 1**
  - Cybersecurity
- **Oak Ridge National Laboratory**
  - Similar to Los Alamos
  - Material Science & Chemistry

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Cloud Customer - Application Areas

- **Volkswagen (Germany/US)**
  - Traffic flow optimization
  - Battery simulation
  - Acoustic shape optimization
- **DENSO (Japan)**
  - Traffic flow optimization
  - Manufacturing process optimization
- **Recruit Communications (Japan)**
  - Internet advertising optimization
  - Machine Learning
- **DLR (Germany)**
  - Air traffic route optimization
  - Airport gate scheduling
- **QxBranch (US/Australia)**
  - ML for election modeling
- **Tohoku University (Japan)**
  - Tsunami evacuation modeling
- **STFC/Ocado (UK)**
  - Optimization of warehouse robots
- **OTI (Canada)**
  - Material science
- **Nomura Securities (Japan)**
  - Financial portfolio optimization
- **British Telecom (UK)**
  - Cell phone network optimization

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Public Customers and Industry Segments

Natl Centers	Def/ Intel	Universities	Web	Auto/Aero/Mfg	Finance	Telecom	Oil & Gas	S/W Partners
Systems								
NASA LANL	Lockheed CS-1	USC USRA	Google					
Cloud								
ORNL JSC (DE) CINECA (IT) CSC (FI) STFC (UK) XXXX (JP)	MITRE	UMBC Miss State Tohoku (JP) Waseda (JP) Oxford (UK) Purdue Michigan State LMU (DE) Plantagenet (UK) UCL, Bristol Tokyo (JP)	Recruit (JP) Ocado (UK) XXXX (JP) XXXX (JP) XXXX (JP) Reply (IT)	VW (DE) Toyota Tsusho (JP) DENSO (JP) Fixstars (JP) Toyota CRL (JP) JFE Steel (JP) XXXX (JP) XXXX (JP)	Nomura (JP) XXXX (JP) XXXX (CA)	BT (UK) XXXX (JP)		1QBit (CA) QxBranch QCWare Strangeworks CDL OTI . . .
Training and Projects								
	ARL AFRL USN XXXX XXXX	VA Tech/Hume					XXXX	

USRA QuAIL Research Opportunity

tinyurl.com/USRA-RFP2019

- **Competitive Selections**
  - Cycle 1 (512 qubit processor): 8 of 14 selected – 57%
  - Cycle 2 (1152 qubit processor): 10 of 15 selected – 67%
  - Cycle 3 (2048 qubit processor): 12 of 15 selected – 80%

- **Diversity of Selected Organizations**
  - 23 Universities + 7 Industrial Research Organizations
  - 19 U.S. Organizations + 11 International Organizations
  - Computer Science, Physics, Mathematics, Electrical Engineering, Operations Research, Chemistry, Aerospace Engineering, Finance

- **Diversity of Research**
  - Quantum Physics -> Algorithms -> Applications
  - Machine Learning for Image Analysis, Communications, Materials Science, Biology, Finance

RFP CYCLE 1 & 2 SELECTIONS (18 of 29 selected)

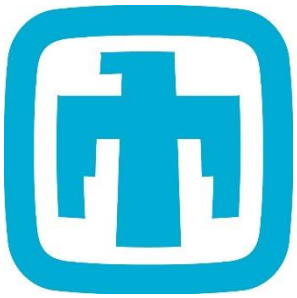
Purdue University · UC San Diego · ETH zürich · Mississippi State · Carnegie Mellon University · Università di Verona · Tecnológico de Monterrey · Scuola Normale Superiore · UBC · USC University of Southern California · BITS Pilani (Pilani | Dubai | Goa | Hyderabad) · Booz | Allen | Hamilton · UCL · parc Palo Alto Research Center · QCWare

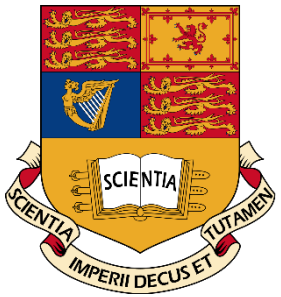
RFP CYCLE 3 (12 of 15 selected)

Princeton University · UC San Diego · Standard Chartered · USC University of Southern California · Carnegie Mellon University · Johns Hopkins University · Universidade Federal de Pernambuco · REPLY DATA · Mississippi State · University of Michigan

Broadening the Community of LANL D-Wave Users

- **LANL has opened up its D-Wave system to external collaborators**
  - Mostly from other DOE national laboratories but a few from industry and academia—including international
  - Wide variety of topical areas
- **Recent projects include**
  - Hydrolic inverse analysis (LANL)
  - Radiographic inference (LANL)
  - Sparse surrogate models in uncertainty quantification (SNL)
  - Topology-aware compute-task assignment (LBNL)
  - More scalable quantum annealing (Imperial College London)
  - Simulating many-body quantum systems (Jagiellonian U.)





ORNL begins a second-year with the D-Wave

- A growing community of users with access to the DW 2000Q processor
- Multiple active projects across optimization, machine learning, physics, and chemistry
- New starts in high-energy physic, basic energy sciences and applied mathematics

D-Wave "Rapid Response" Projects (Stephan Eidenbenz, ISTI)

Round 1 (June 2016)

1. Accelerating Deep Learning with Quantum Annealing
2. Constrained Shortest Path Estimation
3. D-Wave Quantum Computer as an Efficient Classical Sampler
4. Efficient Combinatorial Optimization using Quantum Computing
5. Functional Topological Particle Padding
6. gms2q—Translation of B-QCQP to D-Wave
7. Graph Partitioning using the D-Wave for Electronic Structure Problems
8. Ising Simulations on the D-Wave QPU
9. Inferring Sparse Representations for Object Classification using the Quantum D-Wave 2X machine
10. Quantum Uncertainty Quantification for Physical Models using ToQ.jl
11. Phylogenetics calculations

Round 2 (December 2016)

1. Preprocessing Methods for Scalable Quantum Annealing
2. QA Approaches to Graph Partitioning for Electronic Structure Problems
3. Combinatorial Blind Source Separation Using "Ising"
4. Rigorous Comparison of "Ising" to Established B-QP Solution Methods

Round 3 (January 2017)

1. The Cost of Embedding
2. Beyond Pairwise Ising Models in D-Wave: Searching for Hidden Multi-Body Interactions
3. Leveraging "Ising" for Random Number Generation
4. Quantum Interaction of Few Particle Systems Mediated by Photons
5. Simulations of Non-local-Spin Interaction in Atomic Magnetometers on "Ising"
6. Connecting "Ising" to Bayesian Inference Image Analysis
7. Characterizing Structural Uncertainty in Models of Complex Systems
8. Using "Ising" to Explore the Formation of Global Terrorist Networks

Use Case	2016	2017	Total	%
Combinatorial Optimization	5	5	10	45%
Machine Learning, Sampling	2	2	4	18%
Understanding Device Physics	2	1	3	14%
Software Stack/Embeddings	1	1	2	9%
Simulating Quantum Systems		2	2	9%
Other (good) Ideas	1		1	5%
Total	11	11	22	100%

The LANL Rapid Response Project results for 2016 and 2017 are available as PDF's at:
http://www.lanl.gov/projects/national-security-education-center/information-science-technology/dwave/index.php

Early Applications of Quantum Computing

- Overview
- Proto-Apps
  - Optimization
  - Machine Learning
  - Material Science
  - Cybersecurity
  - Fiction

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VOLKSWAGEN

AKTIENGESELLSCHAFT

Quantum Computing at Volkswagen:

Traffic Flow Optimization using the D-Wave Quantum Annealer

D-Wave Users Group Meeting - National Harbour, MD

27.09.2017 – Dr. Gabriele Compostella

DATA:LAB MUNICH

The Question that drove us …

Is there a ***real-world*** problem that could be addressed with a Quantum Computer?

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YES: Traffic flow optimisation

Everybody knows traffic (jam) and normally nobody likes it.

Image courtesy of think4photop at FreeDigitalPhotos.net

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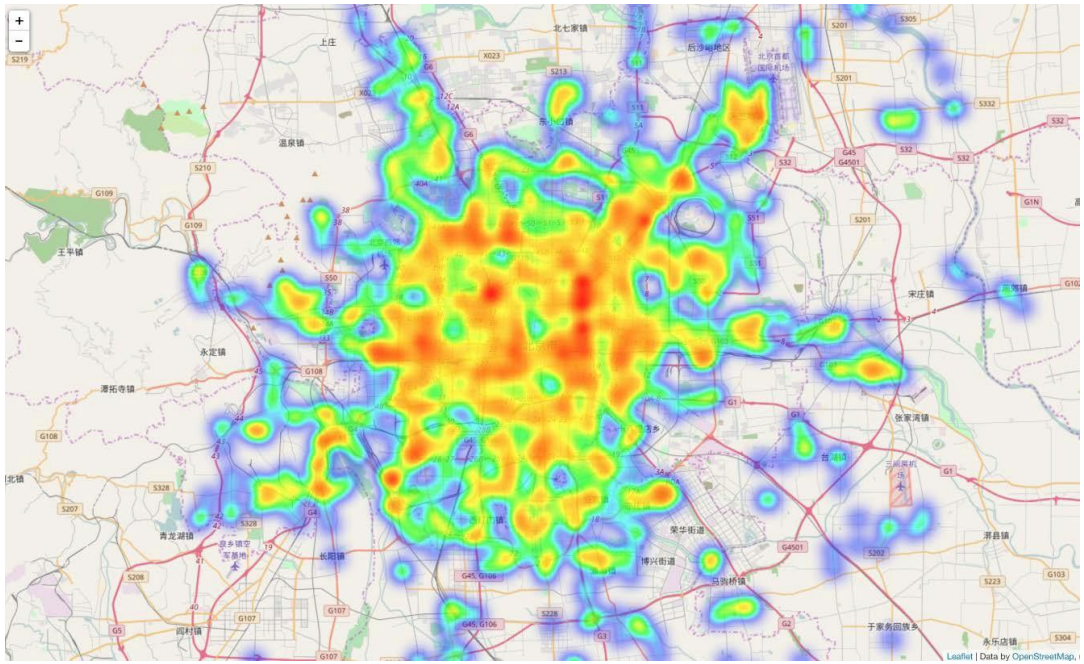
Public data set: T-Drive trajectory

https://www.microsoft.com/en-us/research/publication/t-drive-trajectory-data-sample/

Beijing

- ~ 10.000 Taxis
- 2.2. – 8.2.2008

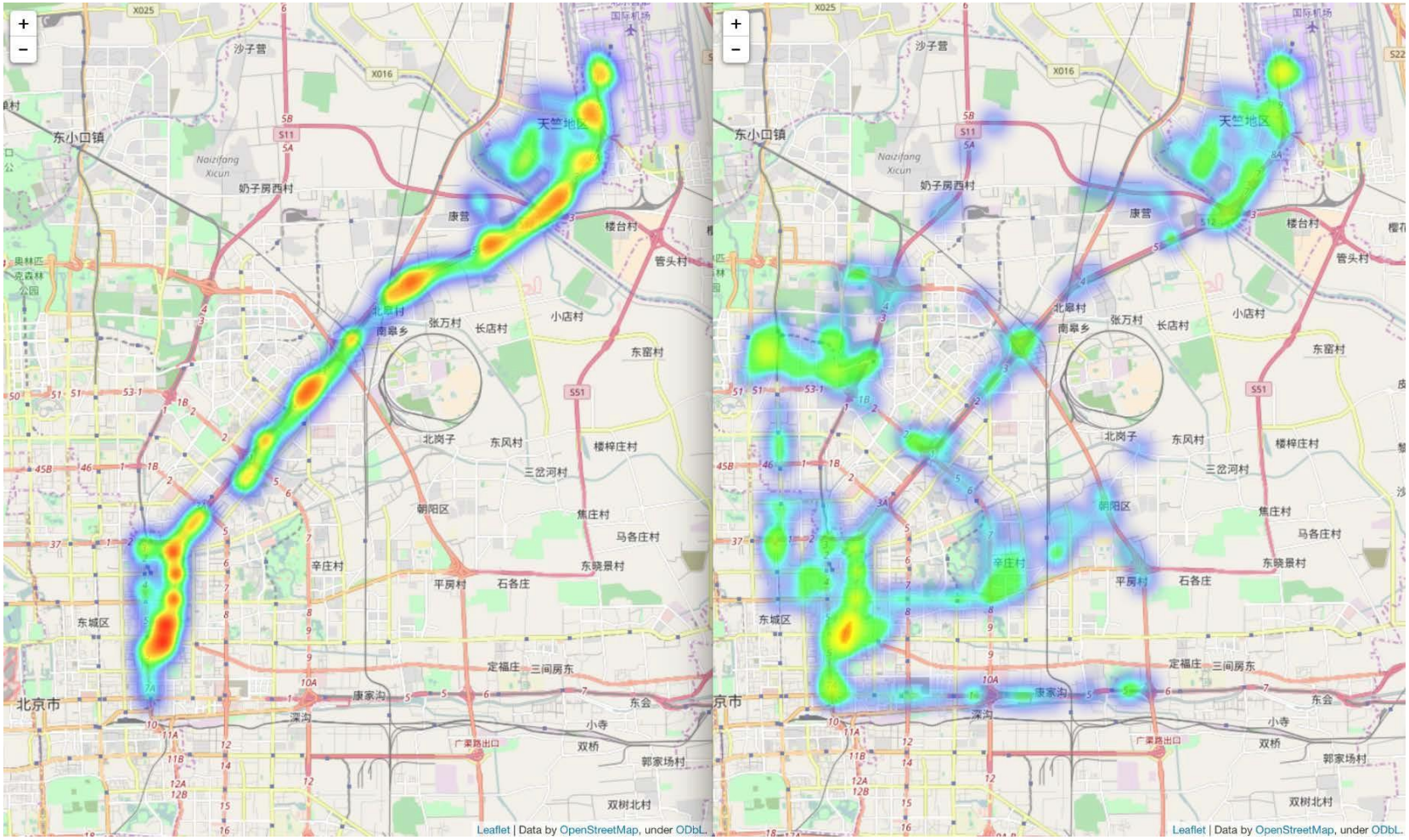


data example:

```
1,2008-02-02 15:36:08,116.51172,39.92123
1,2008-02-02 15:46:08,116.51135,39.93883
1,2008-02-02 15:46:08,116.51135,39.93883
1,2008-02-02 15:56:08,116.51627,39.91034
1,2008-02-02 16:06:08,116.47186,39.91248
1,2008-02-02 16:16:08,116.47217,39.92498
1,2008-02-02 16:26:08,116.47179,39.90718
1,2008-02-02 16:36:08,116.45617,39.90531
```

DATA:LAB MUNICH

Result: unoptimised vs optimised traffic



DATA:LAB MUNICH

Volkswagen Quantum Computing in the news

Friday June 30, 2017

TEST US! 12 WEEKS FOR 12€

Handelsblatt GLOBAL
GERMANY. EXPLAINED.

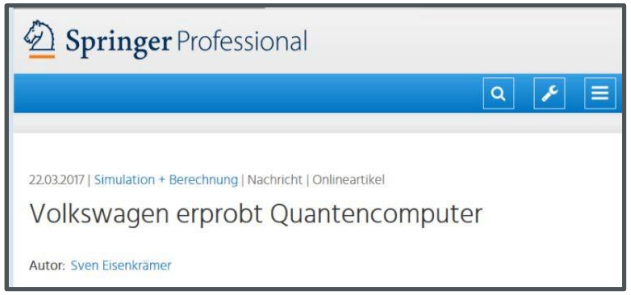
Companies & Markets Finance Politics Opinion S

VOLKSWAGEN RESEARCH

Using Quantum Computers to Fight Traffic Jams

With help from quantum computers, VW wants to inform drivers 45 minutes in advance of impending gridlock.

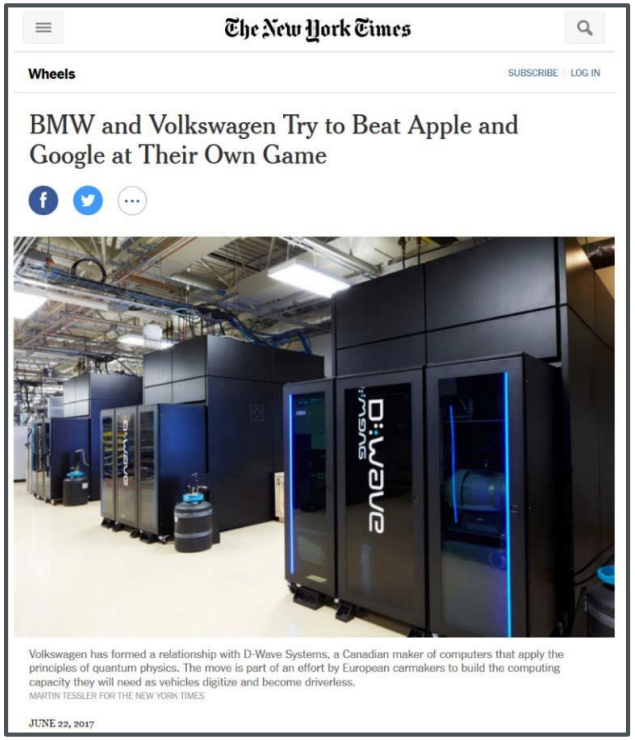
Christof Kerkmann Stefan Menzel 13. March 2017, 17:55


Springer Professional

22.03.2017 | Simulation + Berechnung | Nachricht | Onlineartikel

Volkswagen erprobt Quantencomputer

Autor: Sven Eisenkrämer


The New York Times

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BMW and Volkswagen Try to Beat Apple and Google at Their Own Game

Volkswagen has formed a relationship with D-Wave Systems, a Canadian maker of computers that apply the principles of quantum physics. The move is part of an effort by European carmakers to build the computing capacity they will need as vehicles digitize and become driverless.

MARTIN TESSLER FOR THE NEW YORK TIMES

JUNE 22, 2017

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Walgreens Ends Rite Aid Merger, Will Buy Half Its Stores

Sycamore Plans to Split Staples Into Three

CIO JOURNAL.

Volkswagen Pilots Quantum Computing Experiments

Quantum computing has vast potential, but high technology hurdles remain

By Sara Castellanos
May 8, 2017 10:10 am ET

VOLKSWAGEN
AKTIENGESELLSCHAFT

EN

The Beginnings of a Quantum Leap

The Volkswagen Group is the first car manufacturer using a quantum computer to calculate traffic flows.

HETEROGENEOUS QUANTUM COMPUTING FOR SATELLITE OPTIMIZATION

GIDEON BASS

BOOZ ALLEN HAMILTON

September 2017

Booz | Allen | Hamilton

CONCLUSIONS

+ As problems and datasets grow, modern computing systems have had to scale with them. Quantum computing offers a totally new and potentially disruptive computing paradigm.
+ For problems like this satellite optimization problem, heterogeneous quantum techniques will be required to solve the problem at larger scales.
+ Preliminary results on this problem using heterogeneous classical/quantum solutions are very promising.
+ Exploratory studies in this area have the potential to break new ground as one of the first applications of quantum computing to a real-world problem

Booz Allen Hamilton Restricted, Client Proprietary, and Business Confidential.

Quantum Computing for Aerospace Research

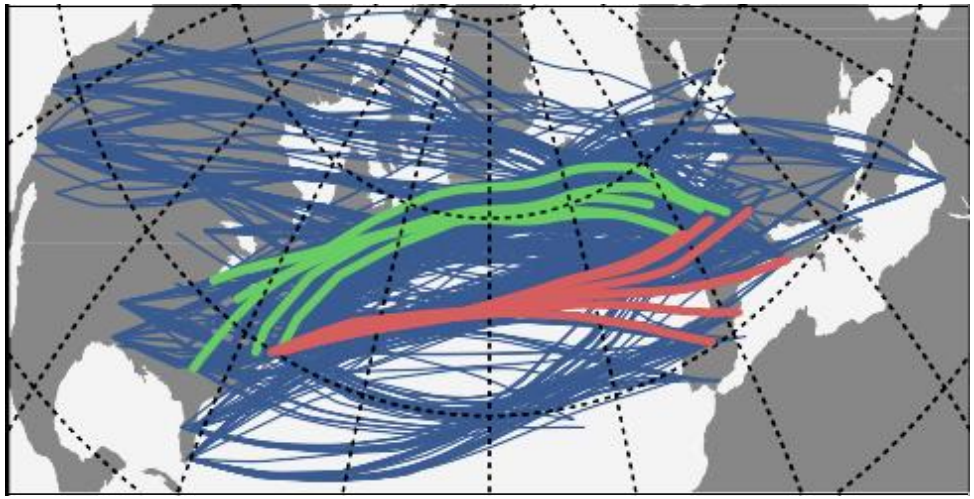
Tobias Stollenwerk and Elisabeth Lobe

German Aerospace Center (DLR)

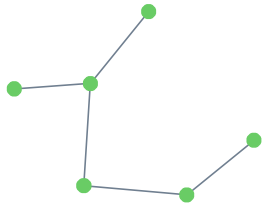
Subdivision of the Problem

arXiv:1711.04889

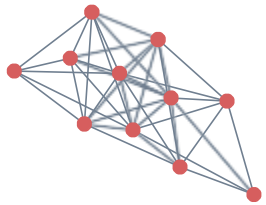
- Assume maximal delay. E.g. d_{max} = 18 min.
- Conflict graph: Flights as vertices, conflicts as edges



$N_f = 6, N_c = 5$



$N_f = 11, N_c = 40$



- 51 connected components of the conflict graph

Display Advertising Optimization by Quantum Annealing Processor

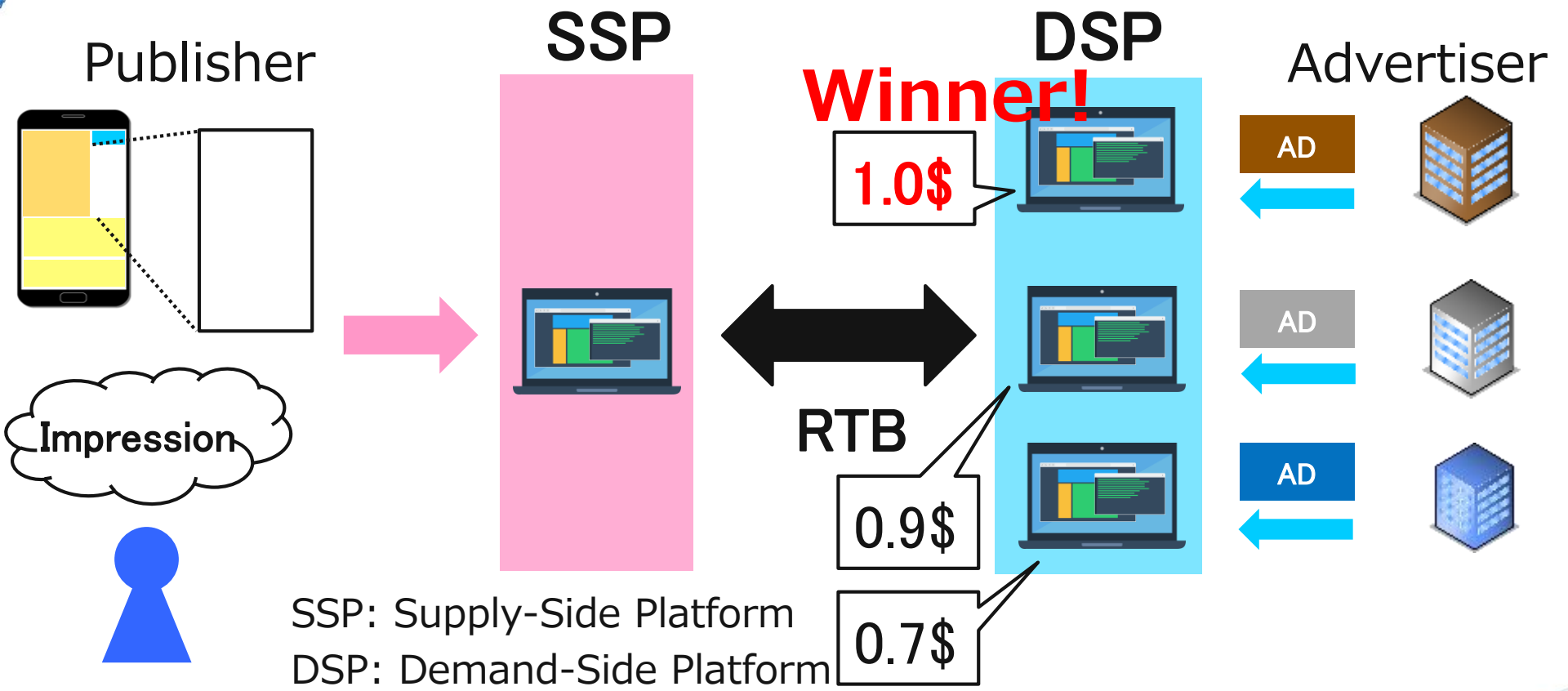
Shinichi Takayanagi*, Kotaro Tanahashi*, Shu Tanaka†

*Recruit Communications Co., Ltd.

† Waseda University, JST PRESTO

RECRUIT
Recruit Communications

Behind the Scenes



SSP: Supply-Side Platform
DSP: Demand-Side Platform
RTB: Real Time Bidding

RECRUIT
Recruit Communications

(C) Recruit Communications Co., Ltd.

4. Summary

- Budget pacing is important for display advertising
- Formulate the problem as QUBO
- Use D-Wave 2X to solve budget pacing control optimization problem
- Quantum annealing finds a better solution than the greedy method.

(C) Recruit Communications Co., Ltd.

About T-QARD

Tohoku University Quantum Annealing Research and Development

- ✓ D-Wave 2000Q is available
- ✓ Collaborations with various companies
- ✓ Active Researchers and Students

Tohoku University -Break limit of your potential- Quantum Annealing Research & Development QARD
Supported by JST project for creating START

DENSO Crafting the Core
NOMURA
mercari

Main Team Members (will participate in AQC2018)

- ✓Masayuki Ohzeki Leader
- ✓Masamichi J. Miyama Assistant Professor
- ✓Ryoji Miyazaki Assistant Professor
- ✓Shuntaro Okada (DENSO), Chako Takahashi,Shunta Arai, Takanori Suzuki and many graduate students and undergraduates

START CREST Sparse Modeling ImPACT QUANTUM ANNEALING MACHINE LEARNING

Optimisation for the Telecommunication Industry using Quantum Annealing

- Catherine White, Tudor Popa
- BT Applied Research

Plantagenet SYSTEMS BT UCL University of BRISTOL D:Wave The Quantum Computing Company™

HARD PROBLEMS IN TELECOMMUNICATIONS

Resource allocation and planning problems in telecommunications are often algorithmically hard… (e.g. NP hard or #P complete)

- Network layout problem (Steiner Tree)
- Job Scheduling
- Configuration of overlapping cells (placement, power, frequency assignment)
- Configurations of paths and wavelengths over core networks at layer 1 (RWA problem)

Hard problems we are trialling with DWave

- Half duplex mesh network
- Cell channel allocation
- Routing and Wavelength Assignment
- Network resilience – disjoint path routing
- Job shop scheduling
- Malicious traffic flow propagation and defensive strategies

Plantagenet SYSTEMS BT UCL University of BRISTOL D-Wave The Quantum Computing Company™

Conclusions

- D-Wave **reliably generates near optimums using a small number of anneal cycles**.
- Many discrete optimisation problems from the telecommunication industry **map very well** to the D-Wave
- If this performance can be maintained for larger processors, D-Wave will be a **significant technology** for this industry.
- **Chain-length minimisation** is a big issue. Hierarchical **connectivity** or bespoke architectures could be an interesting approach.
- Suggestion: D-Wave could make their built-in functions very flexible, i.e. provide variations on Graph Colouring to allow n-color allocation, and to provide preference on allocated color.

Plantagenet SYSTEMS BT UCL University of BRISTOL D-Wave The Quantum Computing Company™

Routing Warehouse Robots

+

James Clark
High Performance Software Engineer
STFC Hartree Centre
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Luke Mason
High Performance Software Lead
STFC Hartree Centre
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Ocado Technology

Ocado is the world's largest online-only supermarket

Ocado Technology builds the software for Ocado, Morrisons, and other customers

Recently signed with Kroger (USA) to build 20 CFCs

AA-C24
SP4
AA-C28
WP3A
AA-D64
WP3A
ocado
CREATED IN BRITAIN

Summary

- It is possible to route warehouse robots using D-Wave
- Hybrid quantum & classical computation method used
- Surprisingly easy to use the QPU so you can focus on the problem
- Benchmarking against current best practice to come

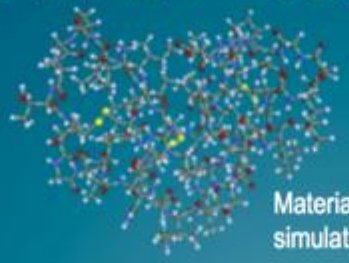
Near-term QC applications in industry

Florian Neukart

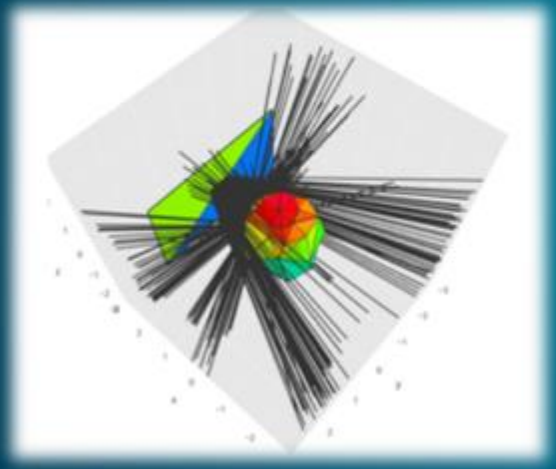
Volkswagen Group, Region Americas

WHAT'S HAPPENING AT VW (1)

With classical computers, many of the most complex problems can't be solved.



Materials simulation



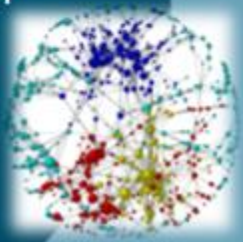
Finite elements design

Traffic flow optimization

Quantum annealing – some things we've done so far

- Traffic flow optimization
- Reinforcement learning (i.e. financial market prediction, self-driving vehicle)
- Finite elements
- Machine learning (i.e. neural networks, NNMF)
- Clustering (i.e. IT threat detection)
- Vehicle price prediction
- Vehicle weight minimization

Reinforcement learning



Clustering

VISION – FURTHER RESEARCH DIRECTIONS

Quantum machine learning

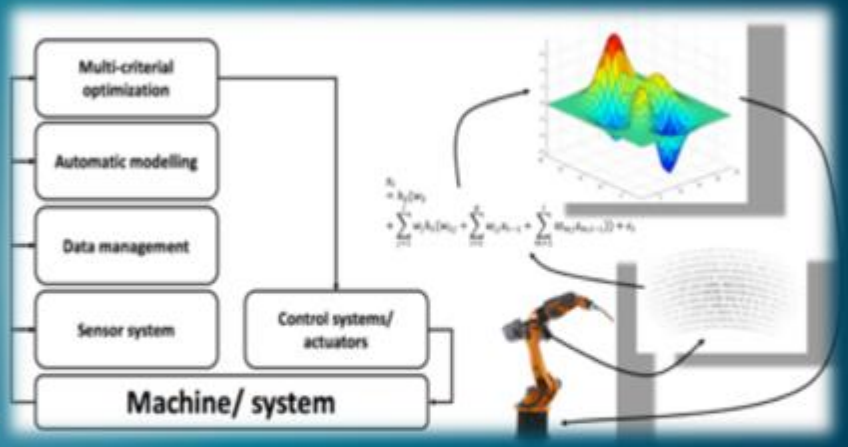
- Grover for ANN function evaluation
- Mapping ANNs directly on the chip
- Graph-splitting in terms of ANNs
- Stacking quantum RMBs to a deep belief net?
- Sampling weight space of ANNs
- Sampling for policy/ value evaluation in reinforcement learning
- Most efficient methods splitting classical and quantum ML
- Linear algebra simulation, i.e. least-squares linear regression

Quantum simulation

- Materials simulation, i.e. optimized anode or cathode-structure in terms of morphology, composition and doping
- High-temperature superconductivity

Quantum optimization

- Time-critical optimization problems, i.e. traffic flow
- Optimization of materials, robot behavior



Early Applications of Quantum Computing

- Overview
- Proto-Apps
  - Optimization
  - Machine Learning
  - Material Science
  - Cybersecurity
  - Fiction

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ISTI Rapid Response DWave Project (Dan O'Malley): Nonnegative/Binary Matrix Factorization

- **Low-rank matrix factorization**
  - $A \approx BC$ where $B_{i,j} \geq 0$ and $C_{i,j} \in \{0,1\}$
  - $\begin{bmatrix} & A & \end{bmatrix} \approx \begin{bmatrix} B \end{bmatrix} \begin{bmatrix} & C & \end{bmatrix}$

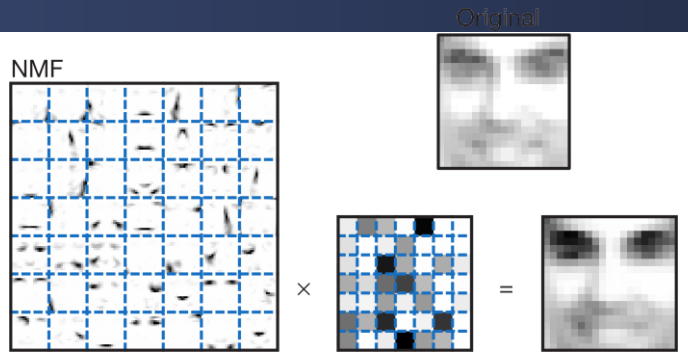
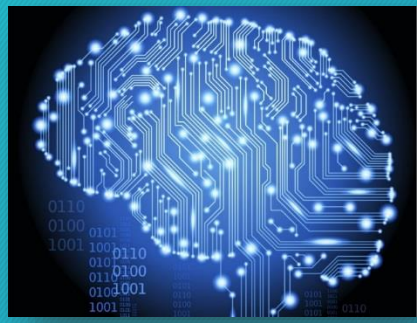


Image credit: Lee & Seung, *Nature* (1999)

- **Unsupervised machine-learning application**
  - Learn to represent a face as a linear combination of basis images
  - Goal is for basis images to correspond to intuitive notions of parts of faces

- **"Alternating least squares"**
  1. Randomly generate a binary C
  2. Solve $B = \arg\min_X \| A - XC \|_F$ classically
  3. Solve $C = \arg\min_X \| A - BX \|_F$ on the D-Wave
  4. Repeat from step 2
- **Results**
  - The D-Wave NMF approach results in a sparser C (85% vs. 13%) and denser but more lossy compression than the classical NMF approach
  - The D-Wave outperforms two state-of-the-art classical codes in a cumulative time-to-target benchmark when a low-to-moderate number of samples are used



Predictive Health Analytics

General Overview and a Potential Role for Quantum Annealing in the Enhancement of Patient Outcomes?

David Sahner, M.D.
sahnerdavid@gmail.com

APRIL 2018

Precision Quantum Medicine (PQM)

Personalized Input

Electronic Health Record data: medical history, medications, imaging and lab results, immunization dates, allergies, demographic information, etc.

Python API interface (SAPI) with D Wave

Panomic biomarker data

Personalized Output

Likely to enjoy 5-year cancer-free survival on regimen A, but not regimens B or C*

Likely to experience 75% improvement in psoriasis score (e.g., PASI) on drug D*

Likely to develop disease X within 1 year

Current undiagnosed conditions Y and Z likely, consider screening

Execute PQM Algorithm on
D Wave Machine (at Health Care System or Central Hub)
to which a Markov Network (MN) has been Mapped
MN Informed by Abundant Longitudinal Population-Based Data

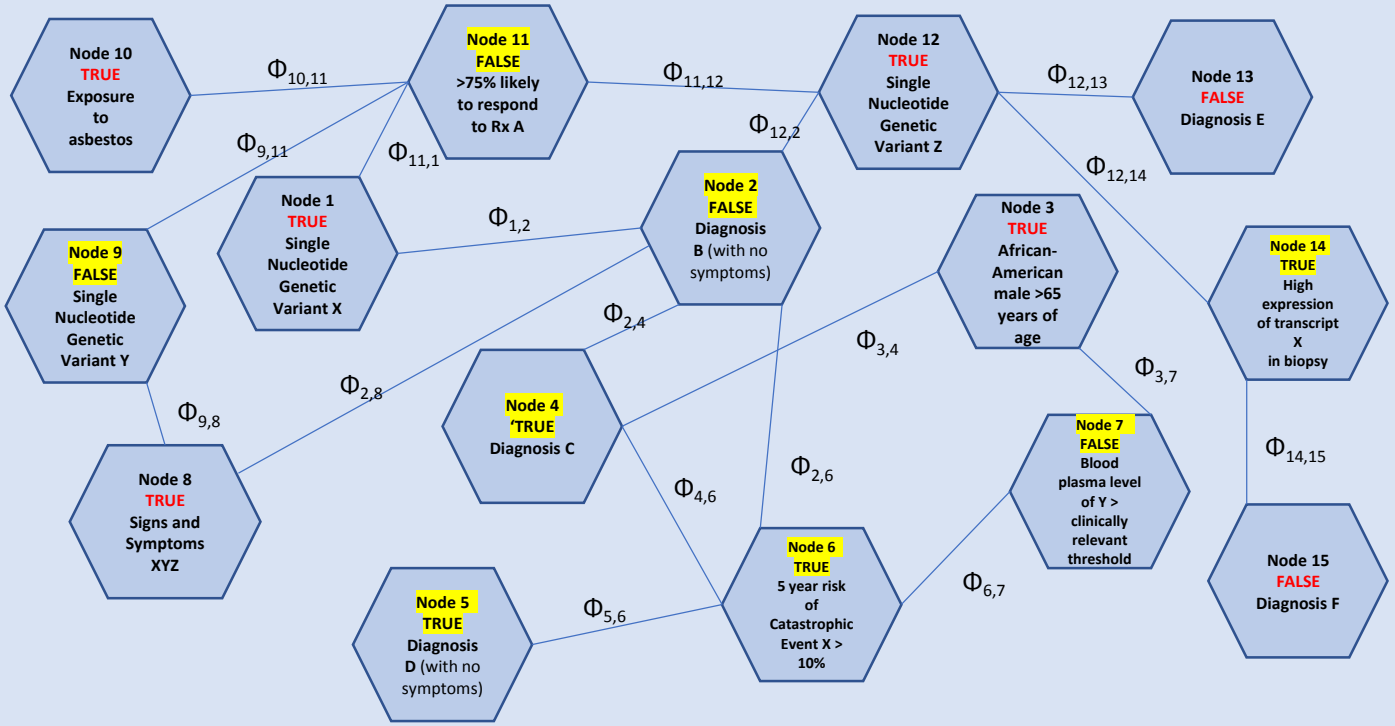
Can recursively apply after acquisition of more data to deepen insights

---

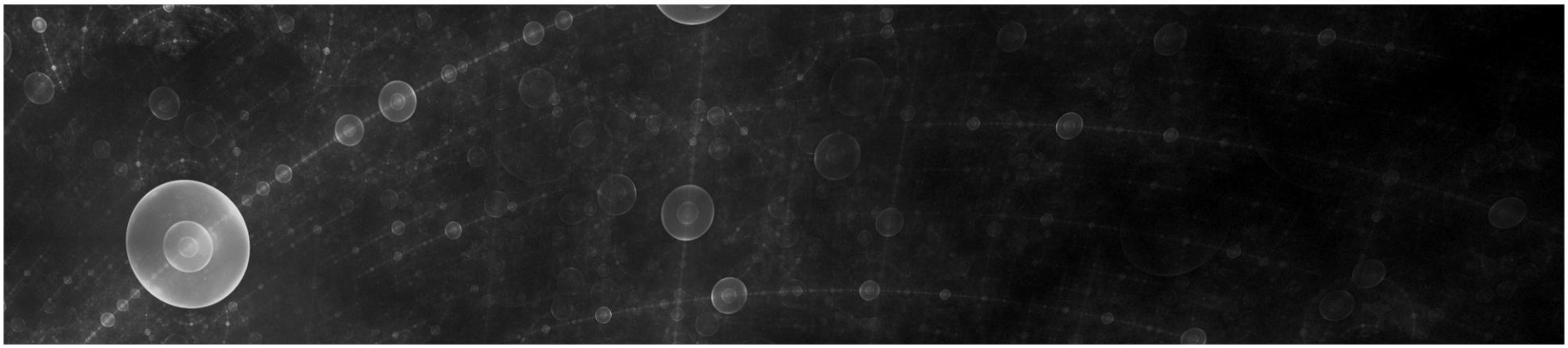
*Starred outputs are merely examples within two therapeutic areas.

Large health care systems may be equipped with their own D Wave machines mapped to Markov Networks informed by longitudinal population-based data from that health system. Centralized data entry and data importation would lead to brief actionable outputs for health care providers in the system (see examples above) ***based on an algorithm-enabled integrated analysis of that specific patient's data.***

Challenge: *What are the most likely truth values for nodes 2, 4, 5, 6, 7, 9, 11, and 14?*
Answers in yellow obtained using D Wave quantum simulator and appropriate biases

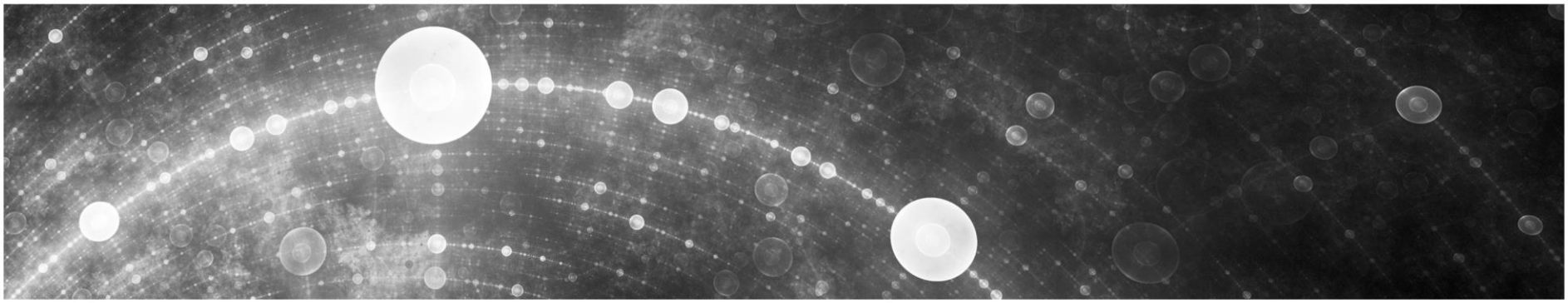


Predicted truth value assignments for nodes were consistent with results of a classical solver.
Plan to optimize implementation to harmonize objective function outputs. Note that the embedding for this problem required only 21 qubits (current D Wave machine has ~2000 qubits)



QxBranch

Quantum Machine Learning for Election Modelling



Election 2016: Case study in the difficultly of sampling

Survey finds Hillary Clinton has 'more than 99% chance' of winning election over Donald Trump

The Princeton Election Consortium found Ms Clinton has a projected 312 electoral votes across the country and only 270 are needed to win

Rachael Revesz New York | @RachaelRevesz | Saturday 5 November 2016 16:44 GMT | 106 comments

Where did the models go wrong?

ELECTION2016

FORECAST

PRESIDENT SENATE

By Natalie Jackson and Adam Hooper
Additional design by Alissa Scheller

PUBLISHED MONDAY, OCT. 3, 2016 12:56 P.M. EDT
UPDATED TUESDAY, NOV. 8, 2016, 12:43 A.M. EST

Photos: Getty

In the event of a tie, the newly elected House of Representatives will elect the president, and the newly elected Senate will elect the vice president.

CNN Money U.S. + Business Markets Tech Media Personal Finance Sma

A model that has correctly predicted the winner of every U.S. presidential race since Ronald Reagan in 1980 is forecasting a big victory for Hillary Clinton.

Clinton is expected to get 332 electoral votes, while Trump is predicted to get just 206, according to the Moody's Analytics model, which is based on three economic and three political factors.

Forecasting elections on a quantum computer

- Quantum computing research has shown potential benefits (speedups) in training various deep neural networks[1-3]

- Core idea: Use QC-trained models to simulate election results. Potential benefits:
  - More efficient sampling / training
  - Intrinsic, tuneable state correlations
  - Inclusion of additional error models

1. Adachi, Steven H., and Maxwell P. Henderson. "Application of quantum annealing to training of deep neural networks." *arXiv preprint arXiv:1510.06356* (2015).
2. Benedetti, Marcello, et al. "Estimation of effective temperatures in quantum annealers for sampling applications: A case study with possible applications in deep learning." *Physical Review A* 94.2 (2016): 022308.
3. Benedetti, Marcello, et al. "Quantum-assisted learning of graphical models with arbitrary pairwise connectivity." *arXiv preprint arXiv:1609.02542* (2016).

Summary

- The QC-trained networks were able to learn structure in polling data to make election forecasts in line with the models of 538
- Additionally, the QC-trained networks gave Trump a much higher likelihood of victory overall, even though the state's first order moments remained unchanged
    - Ideally in the future, we could rerun this method using correlations known with more detail in-house for 538
- Finally, the QC-trained networks trained quickly, and since each measurement is a simulation, each iteration of the training model produced 25,000 simulations (one for each national error model), which already eclipses the 20,000 simulations 538 performs each time they rerun their models

nature

Quantum annealing versus classical machine learning applied to a simplified computational biology problem

Richard Y. Li, Rosa Di Felice, Remo Rohs ✉ & Daniel A. Lidar ✉

"We have shown that DW performs comparably or slightly better than classical counterparts for classification when the training size is small, and competitively for ranking tasks.

Moreover, these results are consistent with a similar approach for the Higgs particle classification problem.. This robustness across completely different application domains suggests that these findings represent real present-day advantages of annealing approaches over traditional machine learning in the setting of small-size training data.

In areas of research where data sets with a small number of relevant samples may be more common, a QUBO approach such as QA realized via DW may be the algorithm of choice."

npj Quantum Information* **volume 4, Article number: 14(2018)

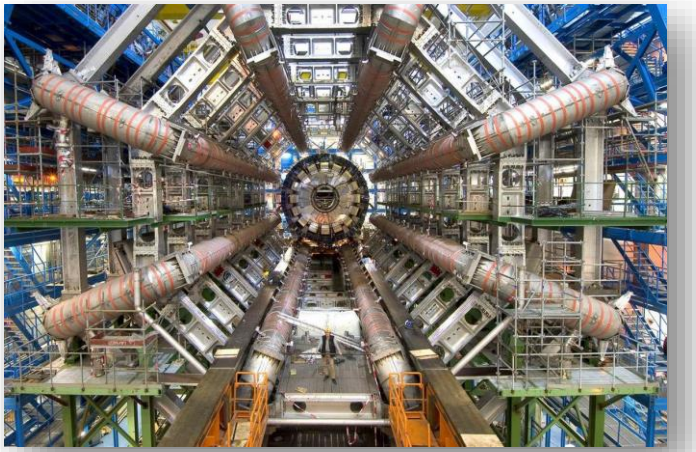
nature
International journal of science

Solving a Higgs optimization problem with quantum annealing for machine learning

Alex Mott, Joshua Job, Jean-Roch Vlimant, Daniel Lidar & Maria Spiropulu

"We show that the resulting quantum and classical annealing-based classifier systems perform comparably to the state-of-the-art machine learning methods that are currently used in particle physics[9,10]. However, in contrast to these methods, the annealing-based classifiers are simple functions of directly interpretable experimental parameters with clear physical meaning…"

*_Nature_ **volume 550**, pages 375-379 (19 October 2017)
doi:10.1038/nature24047



Early Applications of Quantum Computing

- Overview
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  - Machine Learning
  - **Material Science**
  - Cybersecurity
  - Fiction

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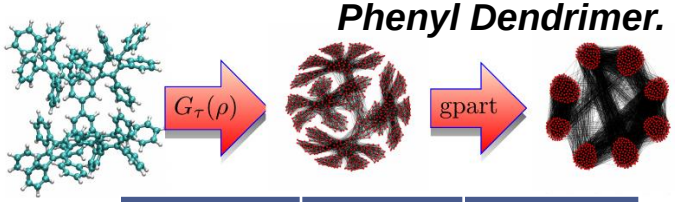
ISTI Rapid Response DWave Project (Sue Mniszewski): Quantum Annealing Approaches to Graph Partitioning for Electronic Structure Problems

- **Motivated by graph-based methods for quantum molecular dynamics (QMD) simulations**
- **Explored graph partitioning/clustering methods formulated as QUBOs on D-Wave 2X**
- **Used *sapi* and hybrid classical-quantum *qbsolv* software tools**
- **Comparison with *state-of-the-art* tools**
- **High-quality results on benchmark (Walshaw), random, and electronic structure graphs**

Graph	N	Best	METIS	KaHIP	qbsolv
Add20	2395	596	723	613	602
3elt	4720	90	91	90	90
Bcsstk33	8738	10171	10244	10171	10171

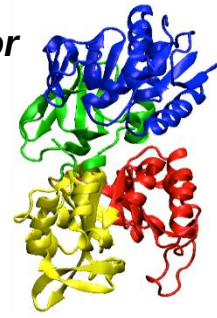
Minimize edge counts between 2 parts on Walshaw graphs.

k-Concurrent Partitioning for Phenyl Dendrimer.



k-parts	METIS	qbsolv
2	705	706
4	20876	2648
8	22371	15922
16	28666	26003

k-Concurrent clustering for IGPS Protein Structure: resulting 4 communities share common sub-structure. Comparable to classical methods.



What We Do

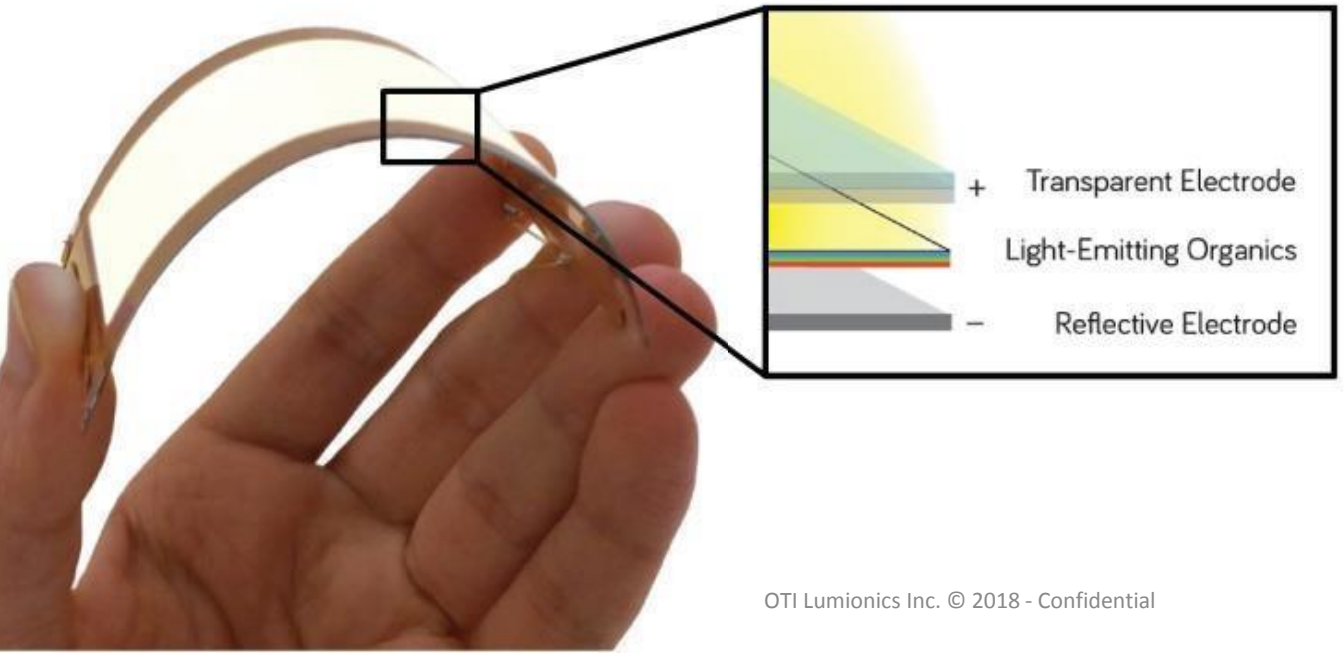
Materials Discovery

Developing advanced materials to solve large scale industrial problems for displays + lighting

OTI Lumionics Inc. © 2018 - Confidential

Organic Light Emitting Diode (OLED)

Light from organic pigments sandwiched between electrodes



Organic Pigments

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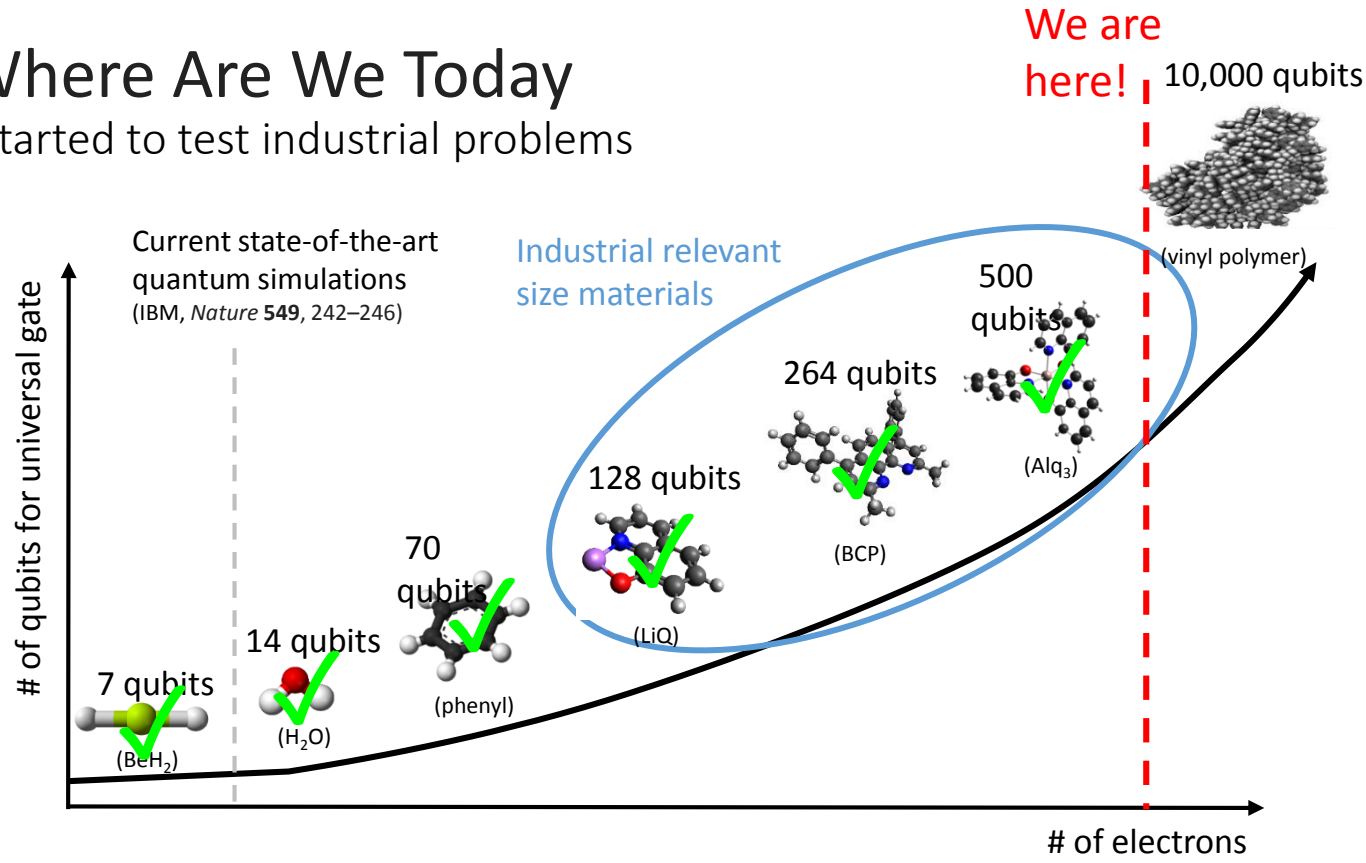
Where Are We Today

Started to test industrial problems



We have demonstrated industrial relevant size simulations on quantum hardware

11/5/2018

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“Phase transitions in a programmable quantum spin glass simulator”*

Abstract

Understanding magnetic phases in quantum mechanical systems is one of the essential goals in condensed matter physics, and the advent of prototype quantum simulation hardware has provided new tools for experimentally probing such systems. We report on the experimental realization of a quantum simulation of interacting Ising spins on three-dimensional cubic lattices up to dimensions 8 × 8 × 8 on a D-Wave processor (D-Wave Systems, Burnaby, Canada). The ability to control and read out the state of individual spins provides direct access to several order parameters, which we used to determine the lattice’s magnetic phases as well as critical disorder and one of its universal exponents. By tuning the degree of disorder and effective transverse magnetic field, we observed phase transitions between a paramagnetic, an antiferromagnetic, and a spin-glass phase.

*Science, Vol 361, Issue 6398, 13 July 2018

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“Observation of topological phenomena in a programmable lattice of 1,800 qubits”*

Abstract

The work of Berezinskii, Kosterlitz and Thouless in the 1970s1,2 revealed exotic phases of matter governed by the topological properties of low-dimensional materials such as thin films of superfluids and superconductors. A hallmark of this phenomenon is the appearance and interaction of vortices and antivortices in an angular degree of freedom—typified by the classical XY model—owing to thermal fluctuations. In the two-dimensional Ising model this angular degree of freedom is absent in the classical case, but with the addition of a transverse field it can emerge from the interplay between frustration and quantum fluctuations. Consequently, a Kosterlitz–Thouless phase transition has been predicted in the quantum system—the two-dimensional transverse-field Ising model—by theory and simulation3,4,5. Here we demonstrate a large-scale quantum simulation of this phenomenon in a network of 1,800 in situ programmable superconducting niobium flux qubits whose pairwise couplings are arranged in a fully frustrated square-octagonal lattice. Essential to the critical behaviour, we observe the emergence of a complex order parameter with continuous rotational symmetry, and the onset of quasi-long-range order as the system approaches a critical temperature. We describe and use a simple approach to statistical estimation with an annealing-based quantum processor that performs Monte Carlo sampling in a chain of reverse quantum annealing protocols. Observations are consistent with classical simulations across a range of Hamiltonian parameters. We anticipate that our approach of using a quantum processor as a programmable magnetic lattice will find widespread use in the simulation and development of exotic materials.

*Nature, volume 560, pages456–460 (2018)

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  - Machine Learning
  - Material Science
  - Cybersecurity
  - Fiction

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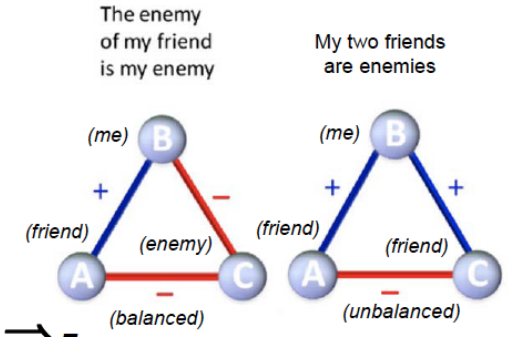
Using the D Wave 2X Quantum Computer to Explore the Formation of Global Terrorist Networks

John Ambrosiano (A 1), Benjamin Sims (CCS 6), Randy Roberts (A 1)

April 27, 2017

Using the D-Wave 2X to Explore Structural Balance Sensitivity in Radical Social Networks

- The D-Wave is a quantum annealing machine
- There is an area in the study of social networks called *structural balance*
  - Social network with signed edges
    - Bipartite nodes, labeled by cohort (+, -)
    - Signed edges: + for friendly, - for hostile
    - ***Edge rule: same cohort ⇒ +; different ⇒ -***
    - Given the edge signs, what is the best cohort assignment to nodes that tries to follow the edge rule? → *NP-Hard problem*

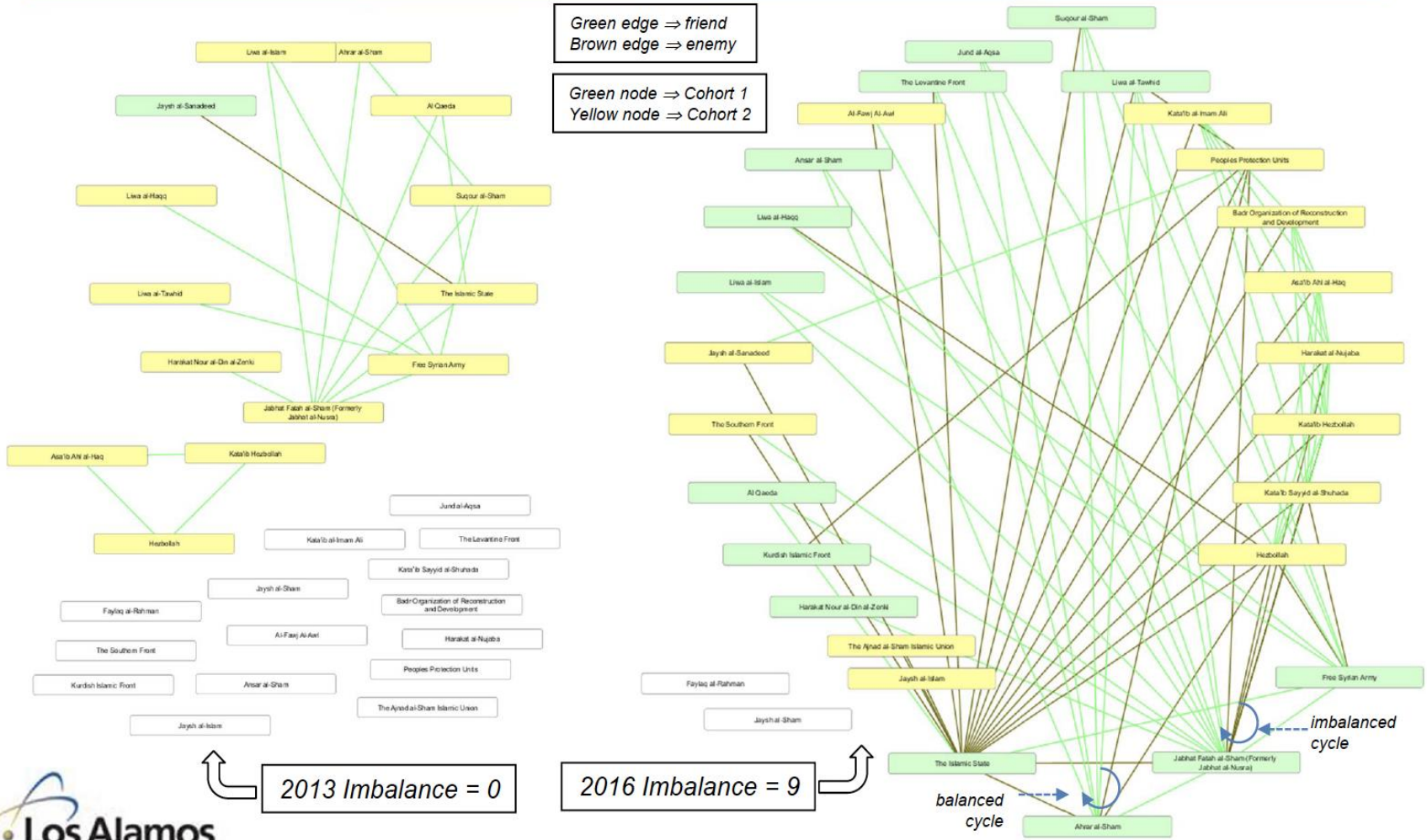


- There is an Ising model equivalent to this problem
  - $H = \sum_{i,j}\left(1 - J_{ij}s_i s_j\right) \ni J_{ij}, s_i \in \{-1,1\}$

Effectively measures the number of edge rule violations

PNAS / December 27, 2011 / vol. 108 / no. 52 / 20953–20958

Syrian Theater Networks



Newly funded effort in aeronautics

Feasibility study: Using quantum-classical hybrids to assure the **availability** of the UAS Traffic Management (UTM) network against communication disruptions

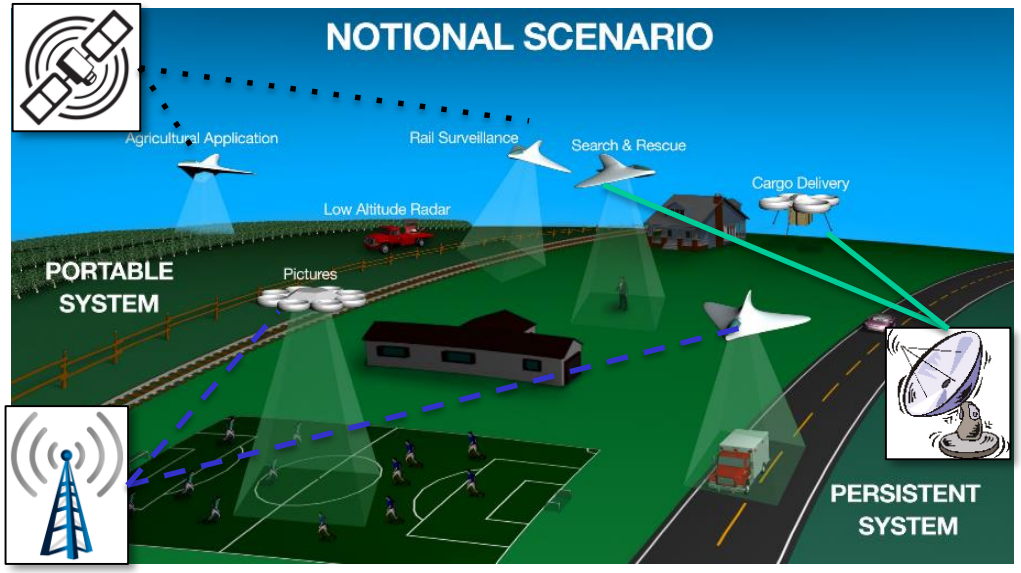
Future

- Higher vehicle density
- Heterogeneous air vehicles
- Mixed equipage
- Greater autonomy
- More vulnerability to communications disruptions

Explore quantum approaches to

- Robust network design
- Track and locate of a moving jammer
- Secure communication of codes supporting anti-jamming protocols

Joint with NASA Glenn, who are working on QKD for spread spectrum codes



Kopardekar, P., Rios, J., et. al., *Unmanned Aircraft System Traffic Management (UTM) Concept of Operations, DASC 2016*

30 month effort: harness the power of quantum computing and communication to address the cybersecurity challenge of availability

Prior work (NASA-DLR collaboration): T. Stollenwerk et al., Quantum Annealing Applied to De-Conflicting Optimal Trajectories for Air Traffic Management

Early Applications of Quantum Computing

- Overview
- Proto-Apps
  - Optimization
  - Machine Learning
  - Material Science
  - Cybersecurity
  - Fiction

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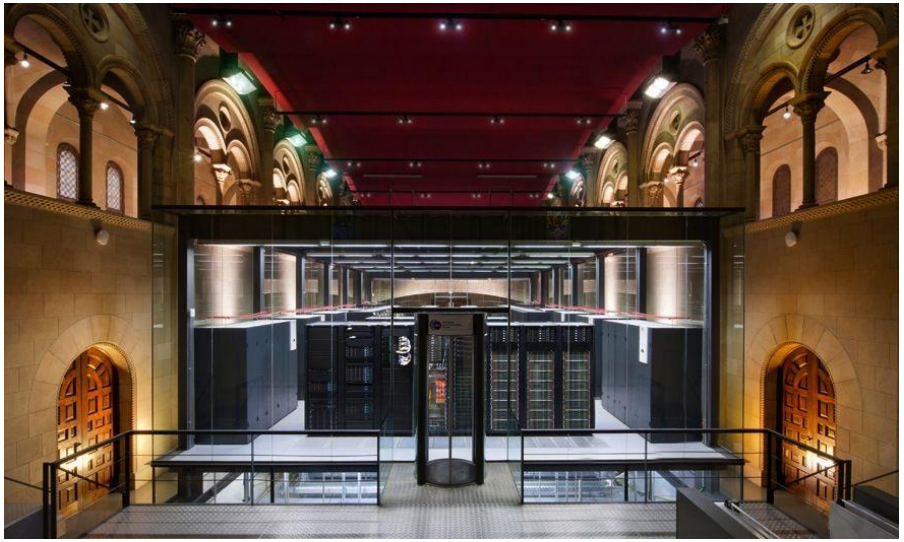

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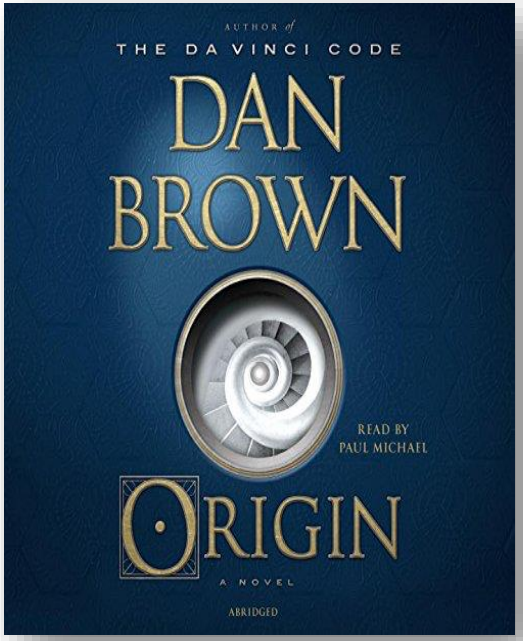

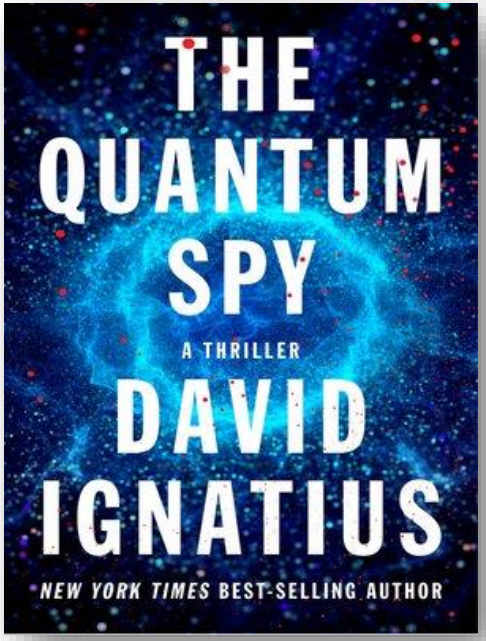

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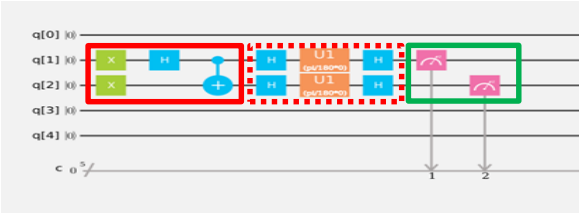
Longer-term Quest for General Purpose QC

Gate Model - Approximate QC or Noisy Intermediate Scale QC (NISQ)



~1-75 Qubits

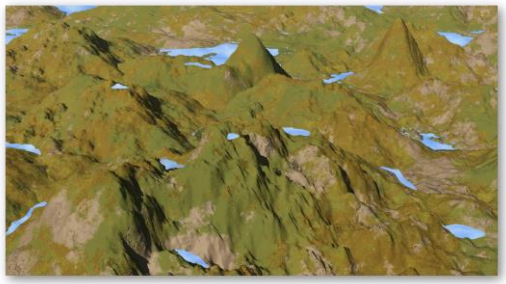
No Error Correction (EC)

- Quantum Chemistry
- Optimization?
- Machine Learning?

Qubit "Quality"

- Superconducting - ~1M EC Qubits?
- Ion - ~1K EC Qubits?
- Topo - ~100 EC Qubits?

Quantum Annealing

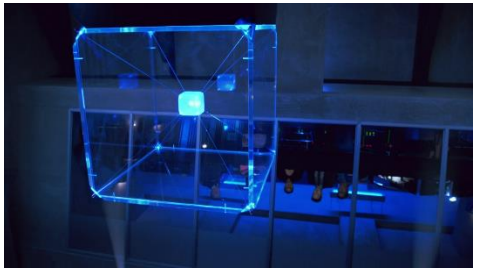


2000+ Qubits

- Optimization
- Machine Learning
- Material Science

Qubit "Quality"
Control
Topology

General Purpose QC (Universal)



Accurate
Repeatable
Run Any Quantum Program
Quantum Speedup

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For More Information See

D-Wave Users Group Presentations:

- https://dwavefederal.com/qubits-2016/
- https://dwavefederal.com/qubits-2017/
- https://www.dwavesys.com/qubits-europe-2018
- https://www.dwavesys.com/qubits-north-america-2018

LANL Rapid Response Projects:

- http://www.lanl.gov/projects//national-security-education-center/information-science-technology/dwave/index.php

DENSO Videos:

- https://www.youtube.com/watch?v=Bx9GLH_GklA (CES – Bangkok)
- https://www.youtube.com/watch?v=BkowVxTn6EU (CES – Factory)
- https://www.youtube.com/watch?v=4zW3_lhRYDc (AGV's)

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