D-Wave
The Quantum Computing Company™

Quantum Computing and High Performance Computing Workshop

Quantum Computing for the Real World Today

Andy Mason

18th December 2018

Early Applications of Quantum Computing

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

Company Background

Founded in 1999

World's first quantum computing company

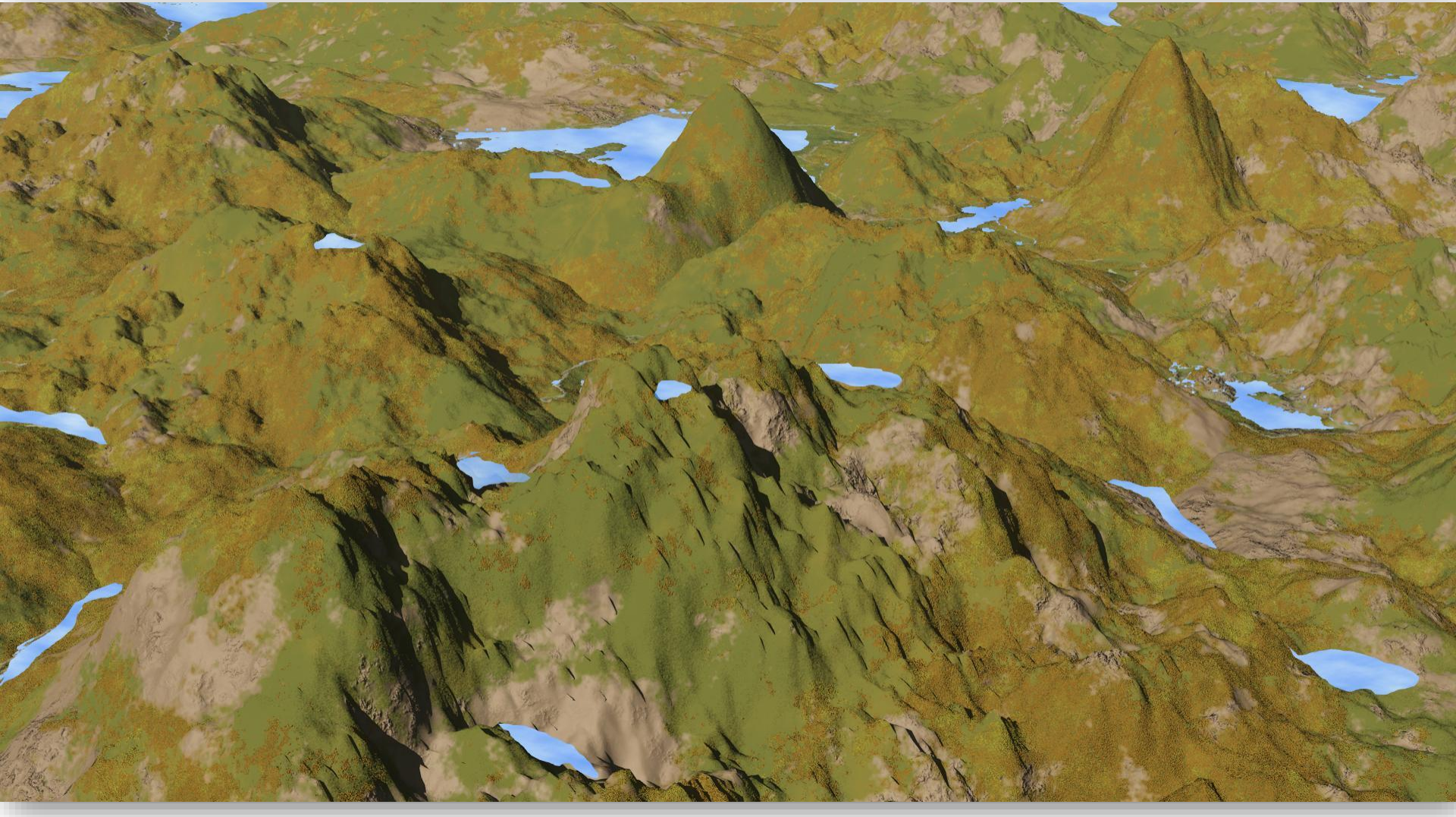
Public customers:

- Lockheed Martin/USC
  Google/NASA Ames/USRA
- Los Alamos National Laboratory
- Cybersecurity - 1
- Oak Ridge National Laboratory

>30 other cloud customer projects

~ 100 early applications ~160 U.S. patents

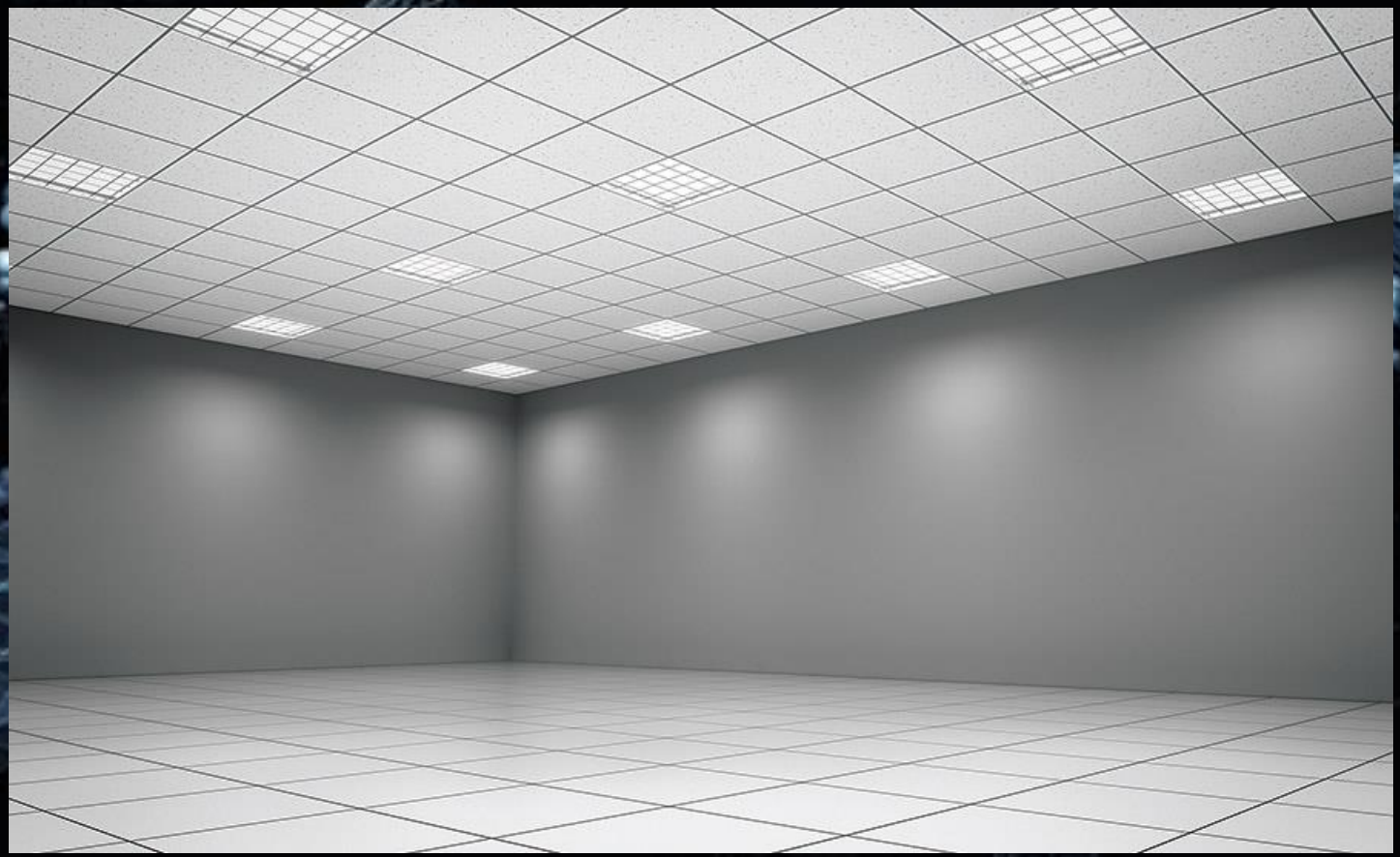
How it Works



European D-Wave Quantum Computing

- Customers & Partnerships

What do you think a quantum computer centre of the future would look like?



At D-Wave, we don't have to dream …….

2 of the 18 quantum computers in the D-Wave quantum computer centre in Burnaby

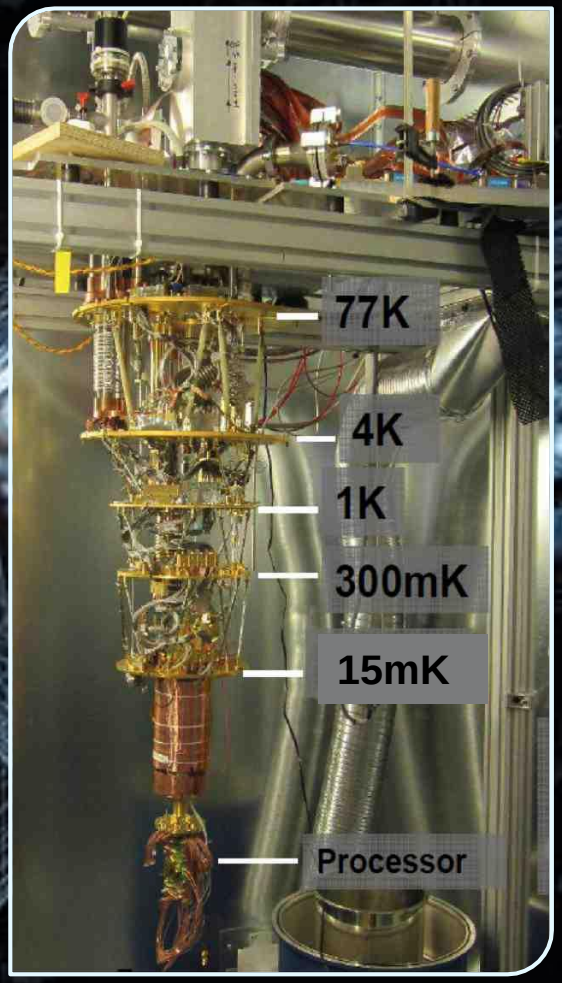
System Shielding

- 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



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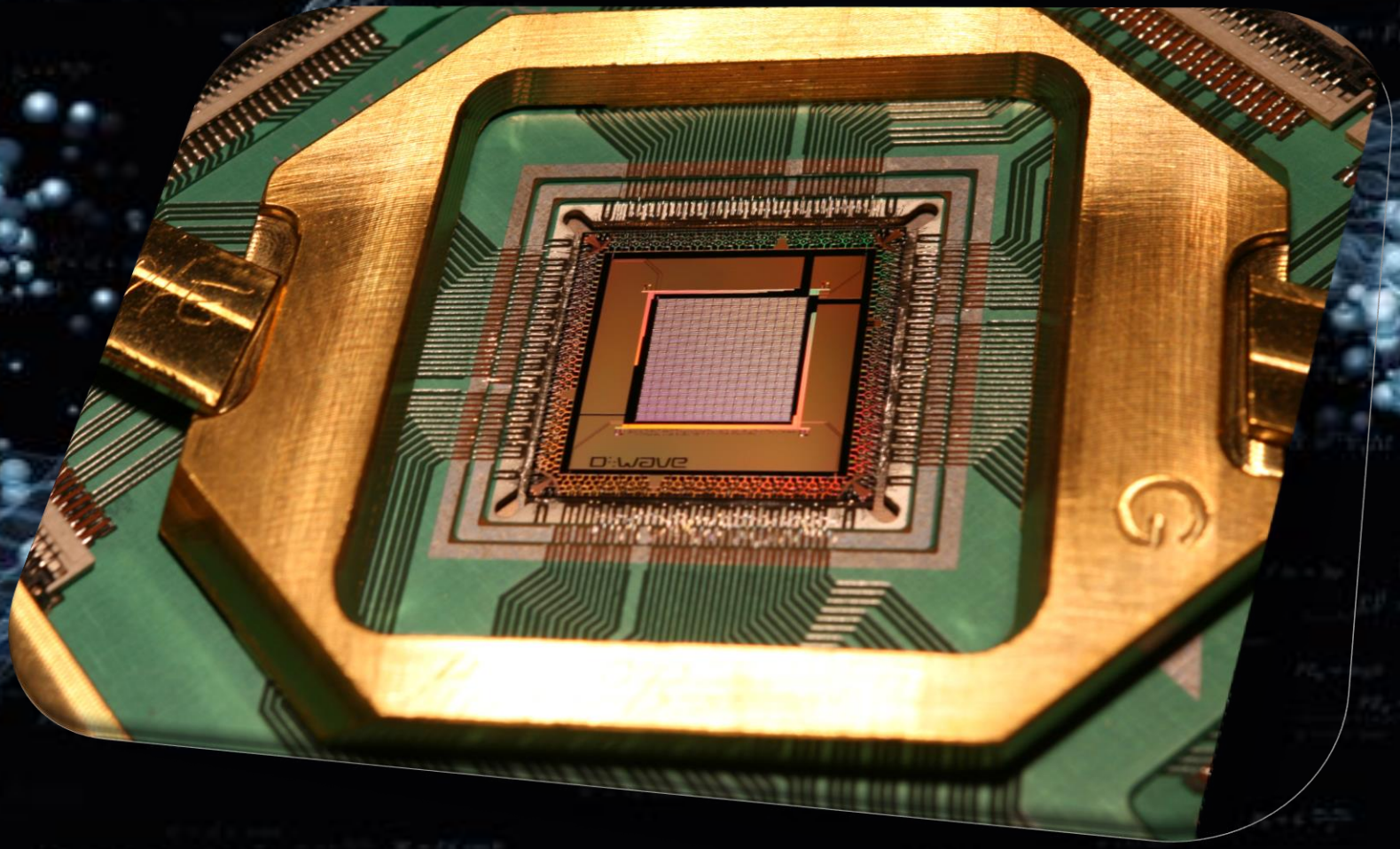
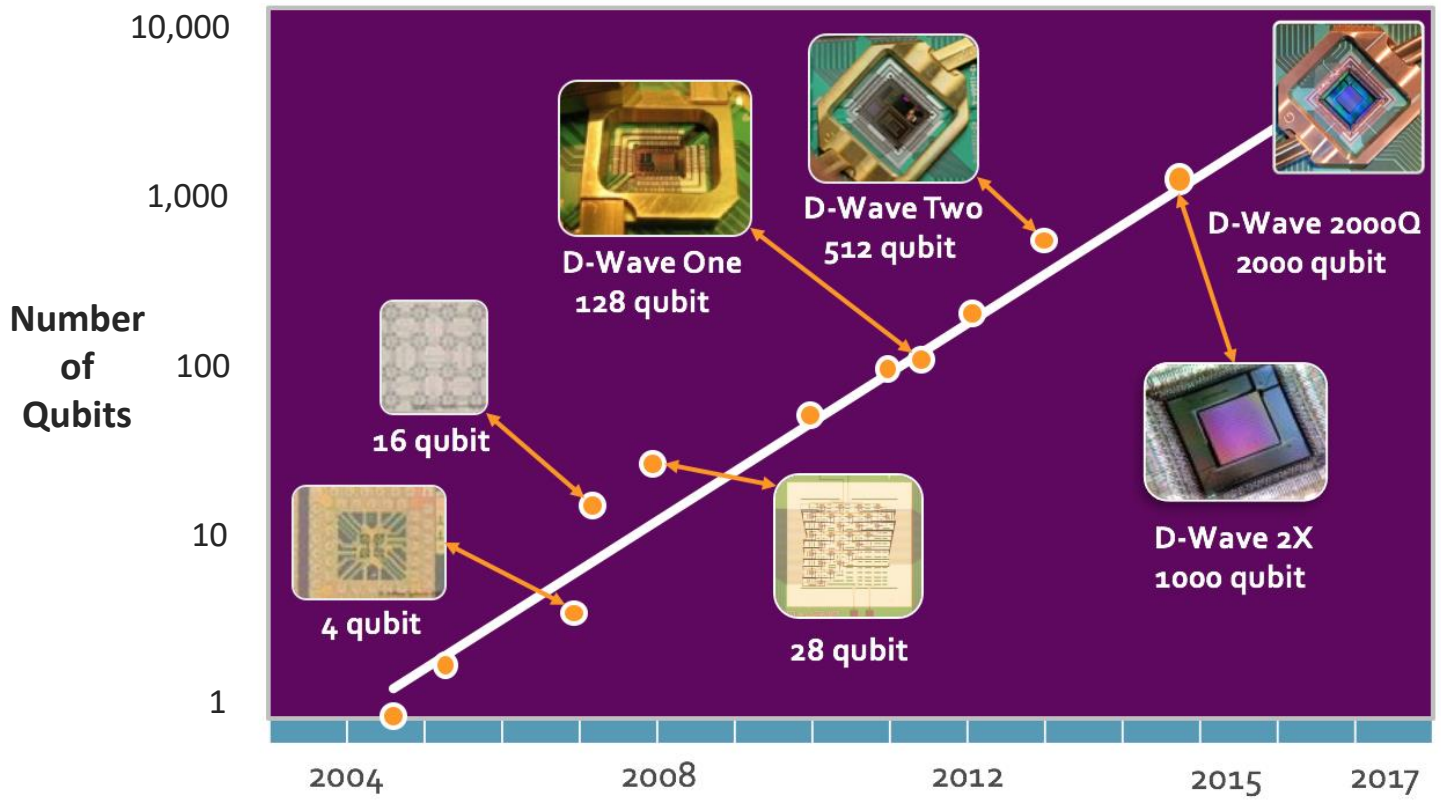
D-Wave 2000Q Quantum Processor



D-Wave Product Generations



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Application Status

- Over 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, performance or quality of answers is approaching and occasionally better than classical computing
- But, small problems, not production ready yet
- Many papers/presentations, problem formulations, and open source software available

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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

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The Question that drove us …

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

YES: Traffic flow optimisation

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

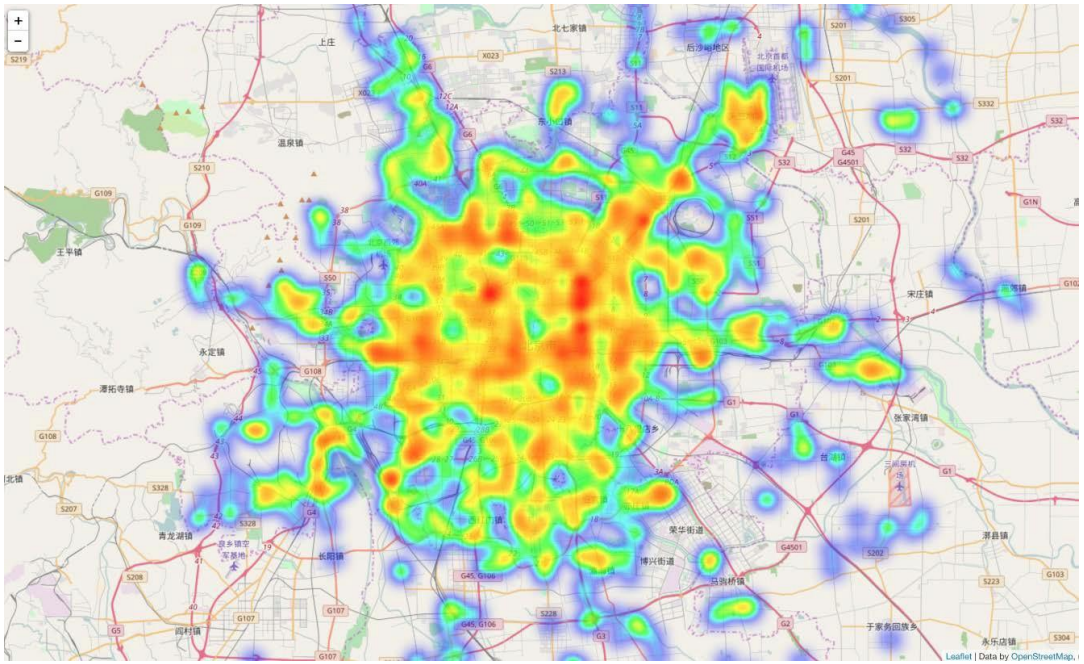
Image courtesy of think4photop at FreeDigitalPhotos.net

Public data set: T-Drive trajectory

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

Beijing

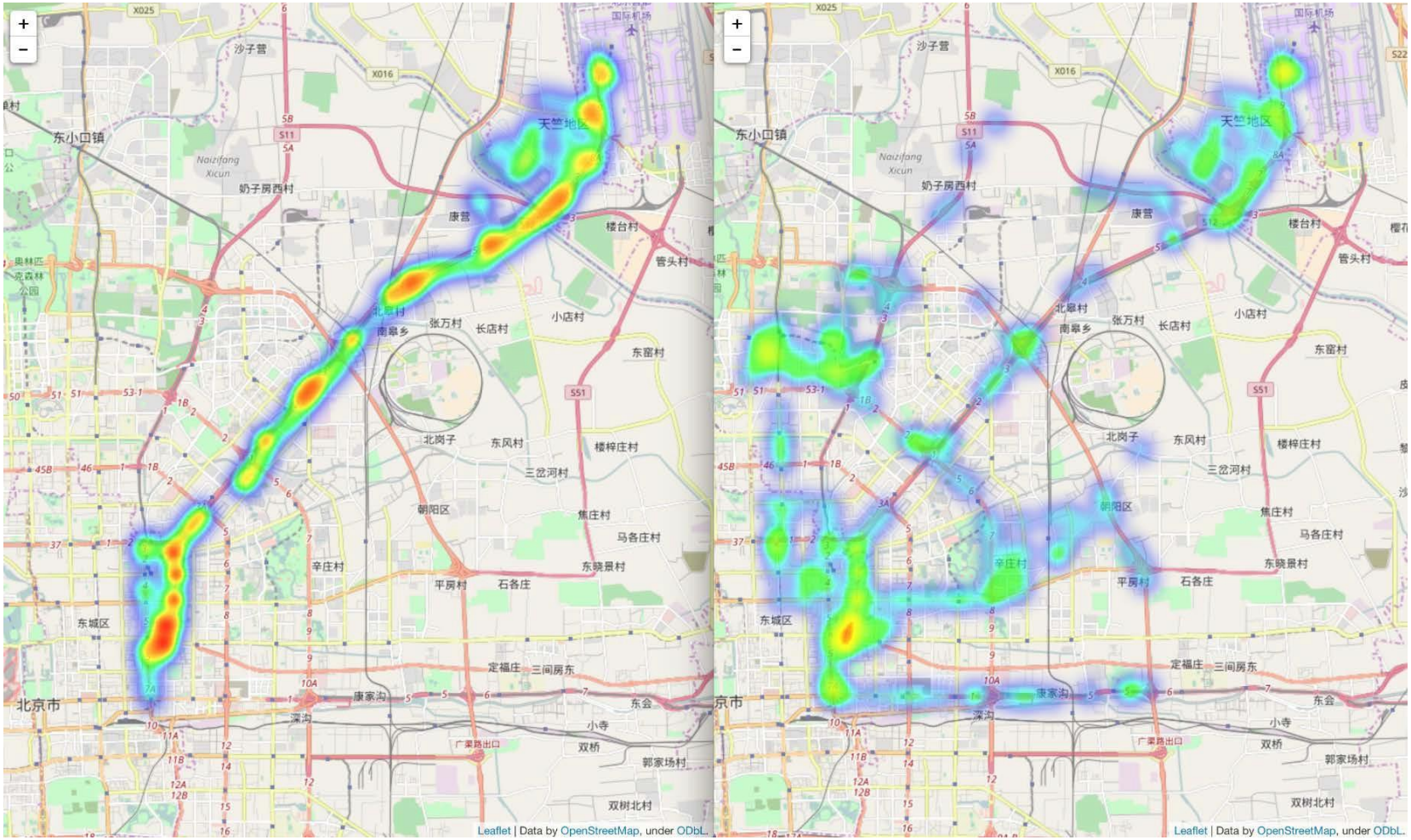
- ~ 10.000 Taxis
- 2.2. – 8.2.2008



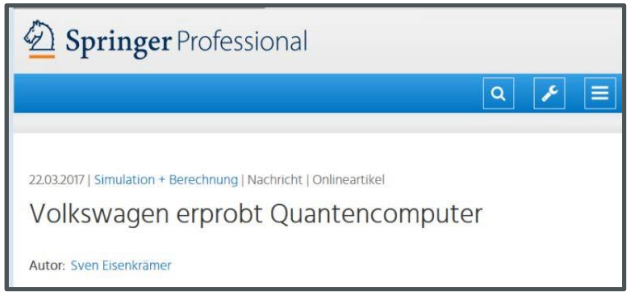
data example:

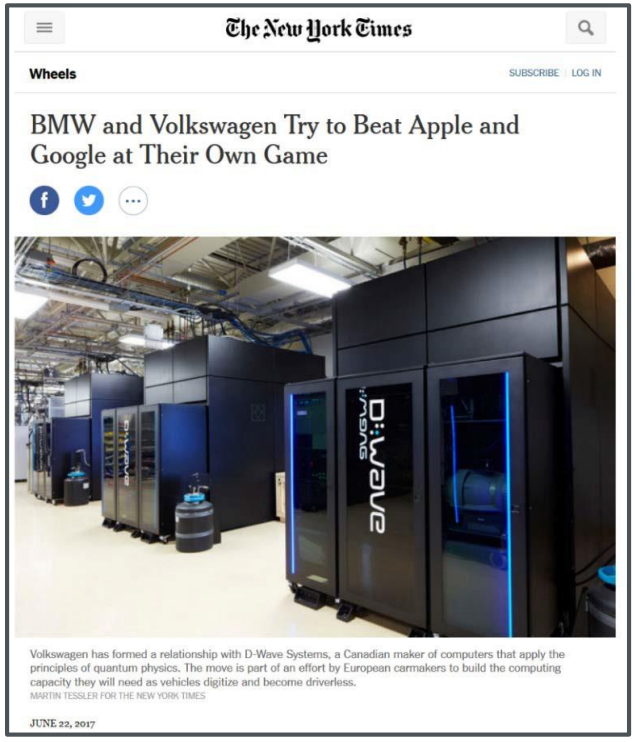
```
1,2008-02-02 15:36:08,116.51172,39.92123
1,2008-02-02 15:46:08,116.51135,39.93883
1,2008-02-02 15:46:08,116.51135,39.93883
1,2008-02-02 15:56:08,116.51627,39.91034
1,2008-02-02 16:06:08,116.47186,39.91248
1,2008-02-02 16:16:08,116.47217,39.92498
1,2008-02-02 16:26:08,116.47179,39.90718
1,2008-02-02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

Result: unoptimised vs optimised traffic



Volkswagen Quantum Computing in the news





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HETEROGENEOUS QUANTUM COMPUTING FOR SATELLITE OPTIMIZATION

GIDEON BASS

BOOZ ALLEN HAMILTON

September 2017

Booz | Allen | Hamilton

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QUANTUM ANNEALING HAS MANY REAL-WORLD APPLICATIONS

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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

Quantum Computing for Aerospace Research

Tobias Stollenwerk and Elisabeth Lobe

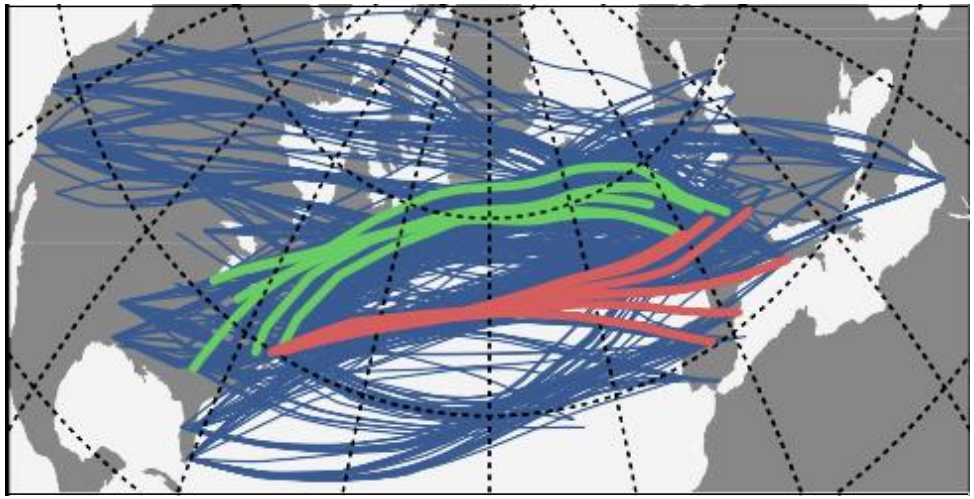
German Aerospace Center (DLR)

DLR

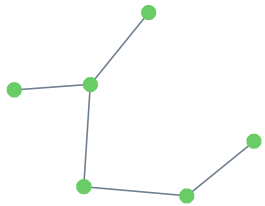
Subdivision of the Problem

arXiv:1711.04889

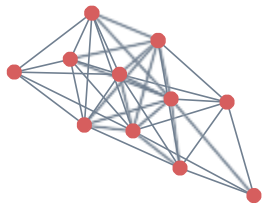
- Assume maximal delay. E.g. d_{max} = 18 min.
- Conflict graph: Flights as vertices, conflicts as edges



$N_f = 6, N_c = 5$



$N_f = 11, N_c = 40$



- 51 connected components of the conflict graph

DENSO
Crafting the Core

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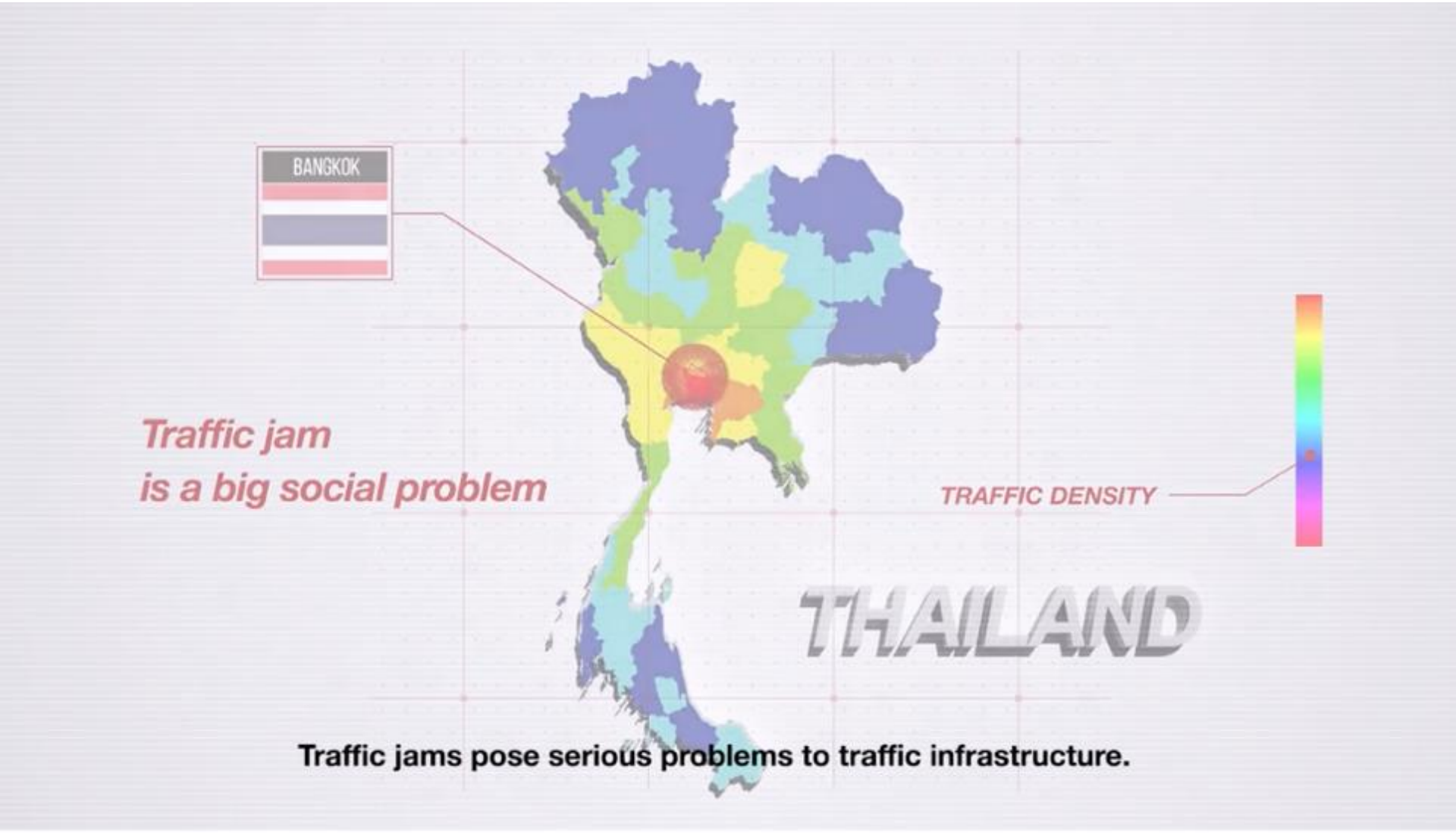

DENSO
Crafting the Core

Value obtained by optimization

1. Traffic jam alleviation

2. Better access for emergency vehicles

3. Streamlining of logistics

Quantum Technology for Mobility IoT / 量子コンピュータが拓く新たなモビリティIoT

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Display Advertising Optimization by Quantum Annealing Processor

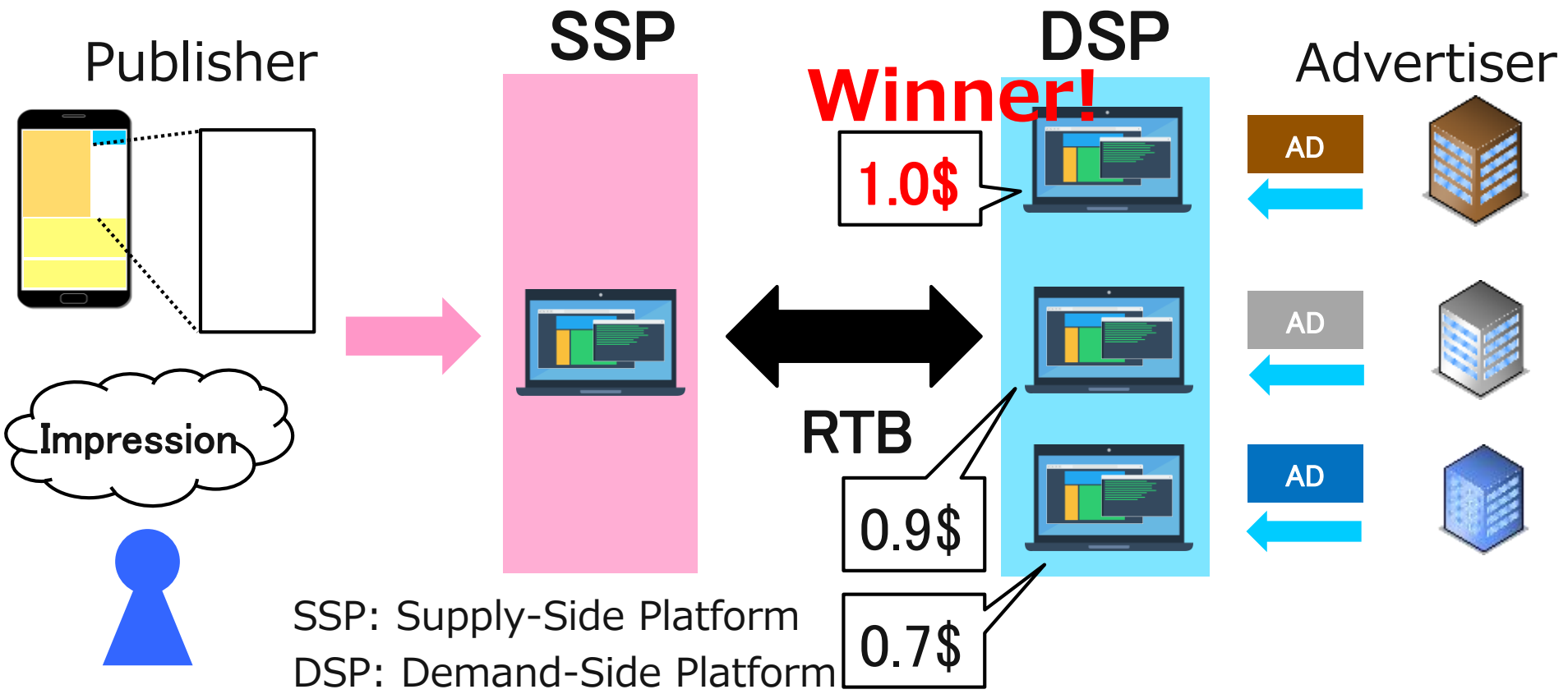
Shinichi Takayanagi*, Kotaro Tanahashi*, Shu Tanaka†

*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

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.

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 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

+

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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

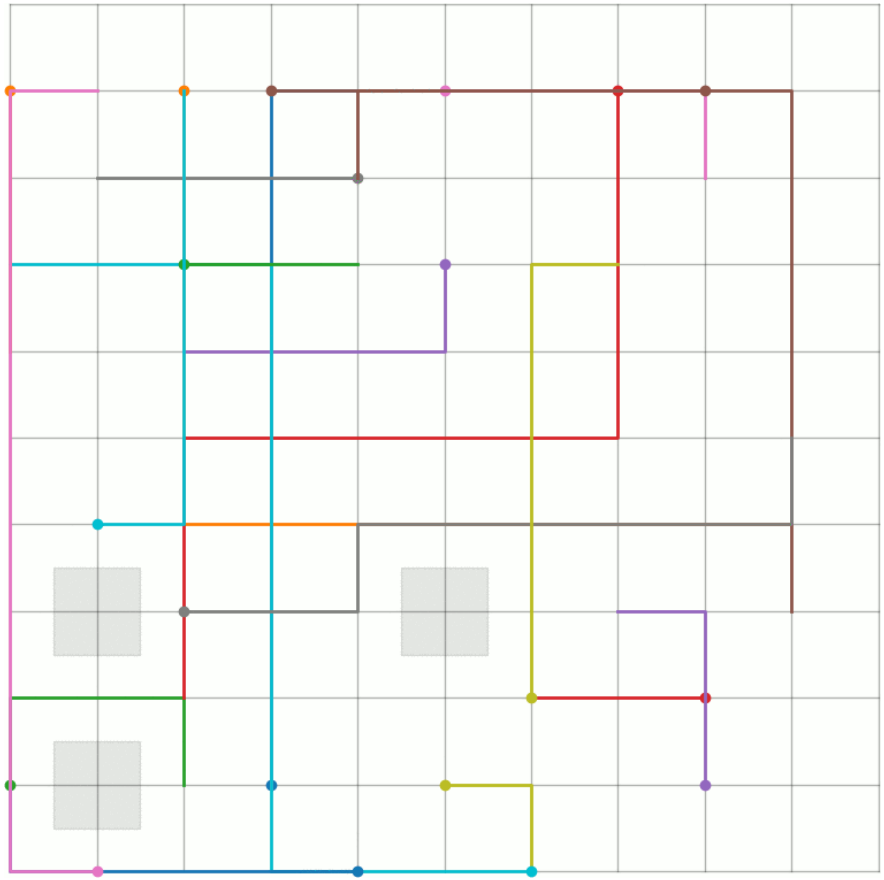
Recently signed with Kroger (USA) to build 20 CFCs


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

Problem Summary

- Large number/density of robots
- Each robot is assigned two destinations
  - Product to collect
  - Drop off location
- High traffic areas can occur
  - Popular products
  - Drop off locations
- Collisions must be avoided
- Need to balance two separate time constraints
  - Travel time of each robot. So no long pauses!
  - Time to drop off all current products

First Pass

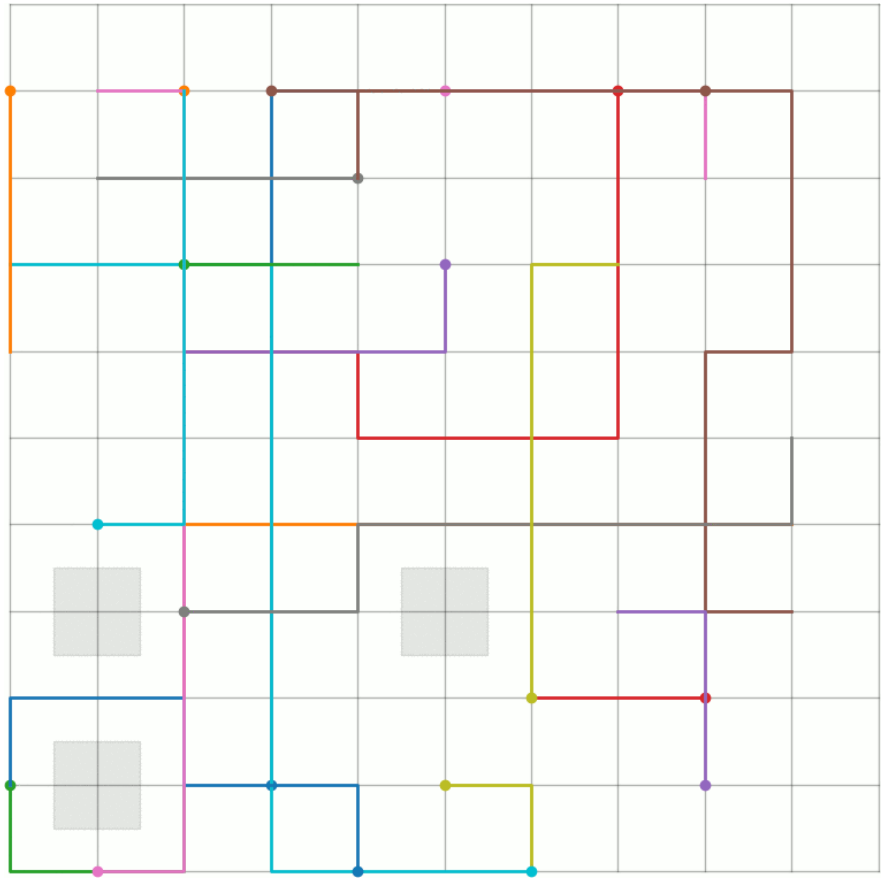


Works!

Still have collisions ✗

We can do better

Solving Collisions



Retry with more candidates for robots that collide

Reduce candidates for non colliding robots

No more collisions!

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

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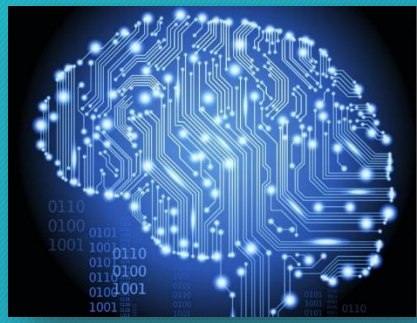


Predictive Health Analytics

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

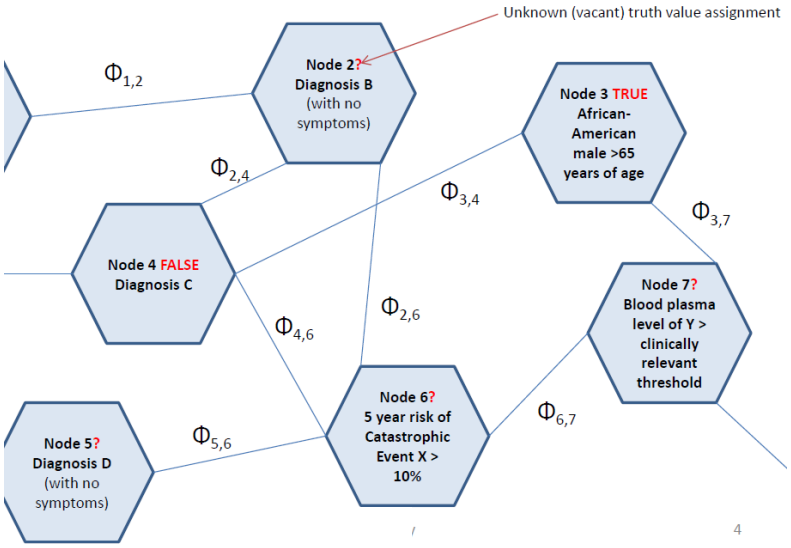
David Sahner, M.D.
sahnerdavid@gmail.com

APRIL 2018

Precision Quantum Medicine Concept: "Fill in the Blanks" in a Graphical Model

Background and Broad Vision:

- Predictive analytics are promising and topical, **but solutions typically enable focused prediction** (of, e.g., readmission, adherence, single disease outcome, etc.)
- What if we could **simultaneously detect a person's risk of hundreds of illnesses and outcomes by leveraging a huge graphical medical knowledge database that captures numerous logical interdependencies?**

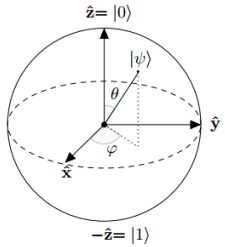


Markov Network: ***Lines (edges) exist between nodes that are linked mechanistically (and/or based on published data). Edge weights established by Big Data. For John Q. Patient, only some nodal truth values known.***
Q: What are most likely truth values for the other nodes?

Question: Given the available data for John Q. Patient (e.g., history, SNPs, labs, meds, etc.), what are the *likeliest* truth value assignments for scores/hundreds of "unknown nodes"?

Problem Reframed: How do we "optimize" truth value assignments for unknown nodes, gaining broad insight into the probabilities of many potential co-morbidities, risks, & outcomes for John Q. Patient?

- *Such knowledge would assist in diagnostic screening and preventive care, improving outcomes,* ***but this "optimization problem" rapidly becomes intractable based on (classical) computational demands***



Circulating current in a qubit loop enables two spin states along z axis to exist in superposition.

Possible Solution: A novel formulation as problem Hamiltonian (**H**) enables a quantum solution to the "nodal truth value" optimization problem, letting us populate the likeliest truth value assignments (T/F) for John's "unknown nodes"

- Quantum annealing nudges "initial" **H** to "problem **H**"
- Ground state of problem **H** encodes solution
- With accretion of new clinical data in a given case, the algorithm can be recursively applied to obtain even deeper knowledge.

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

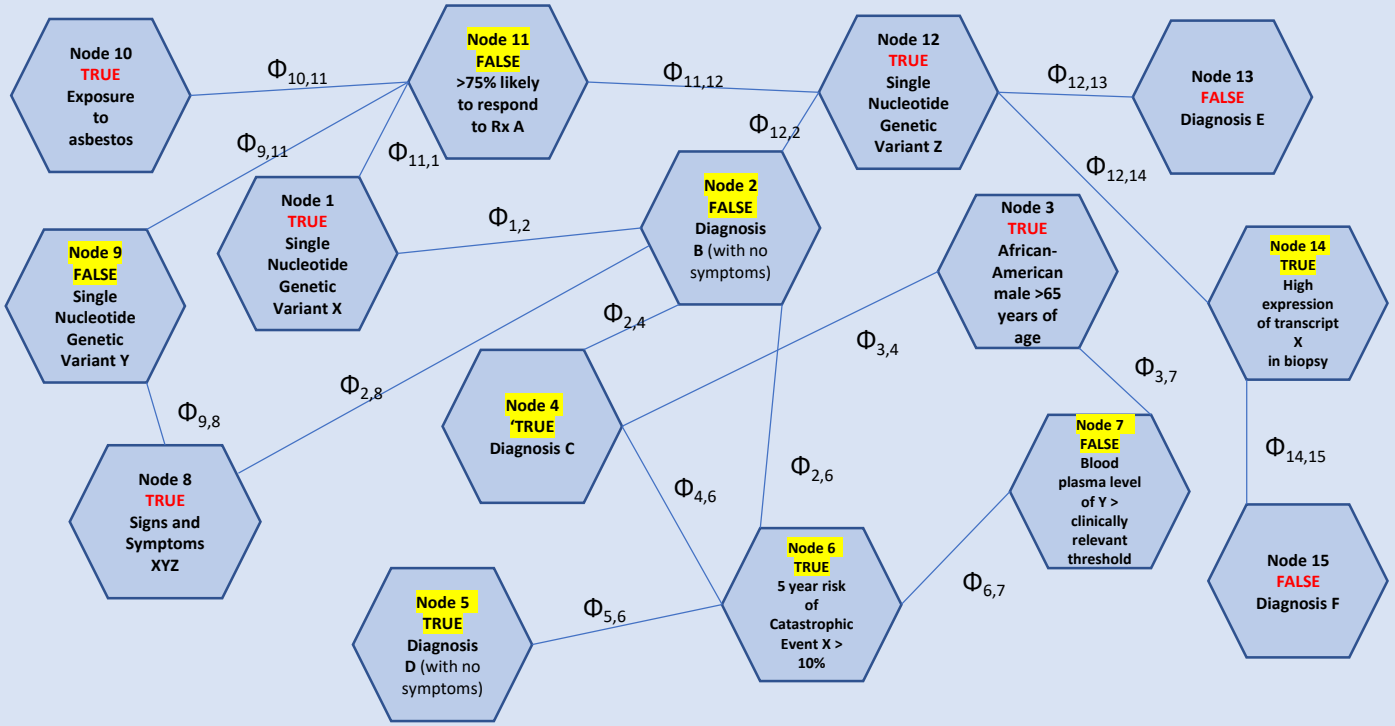
Can recursively apply after acquisition of more data to deepen insights

---

*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)

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VOLKSWAGEN
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Material simulation on D-Wave

Qubits Europe 2018, Munich

12.04.2018 - Michael Streif

DATA:LAB MUNICH

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Electronic structure calculations on quantum computers

- Mainly targeted by gate model approaches
- Quantum algorithms: variational quantum eigensolver (VQE), phase estimation algorithm (PEA)
- Current gate model devices suffer from different challenges:
  - Small number of qubits
  - Decoherence effects
  - Imperfect qubits and gates

Can we instead use a quantum annealer, e.g. a D-Wave machine, for such calculations?

Yes! [1]

[1] Xia, Teng, and Kais. "Electronic Structure Calculations and the Ising Hamiltonian." *The Journal of Physical Chemistry B* (2017)

Take home message

- It is possible to use a D-Wave machine for electronic structure calculations

Outlook

- Improve the results by increasing the accuracy parameter r
- Study the scaling behavior for larger systems
- Find new approaches for larger molecules and implement these on a D-Wave quantum computer

12

Scott N. Genin, PhD
Head of Materials Discovery

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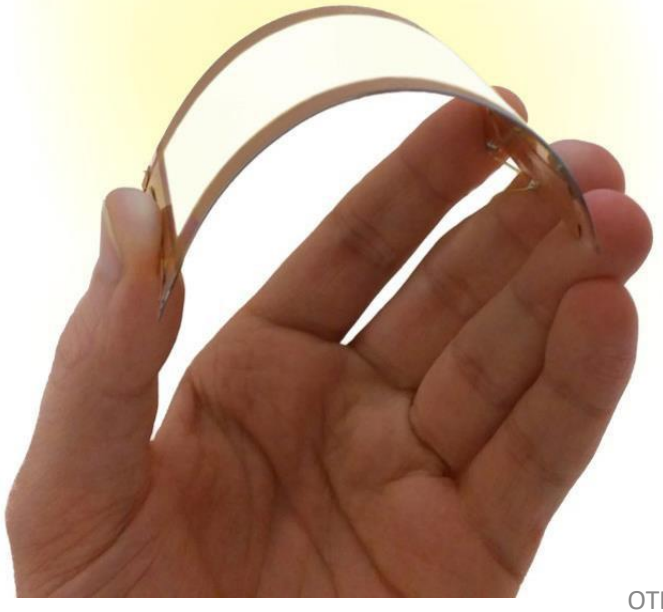
Applications of Quantum Computing in Computational Chemistry

May 2018



OTI Lumionics

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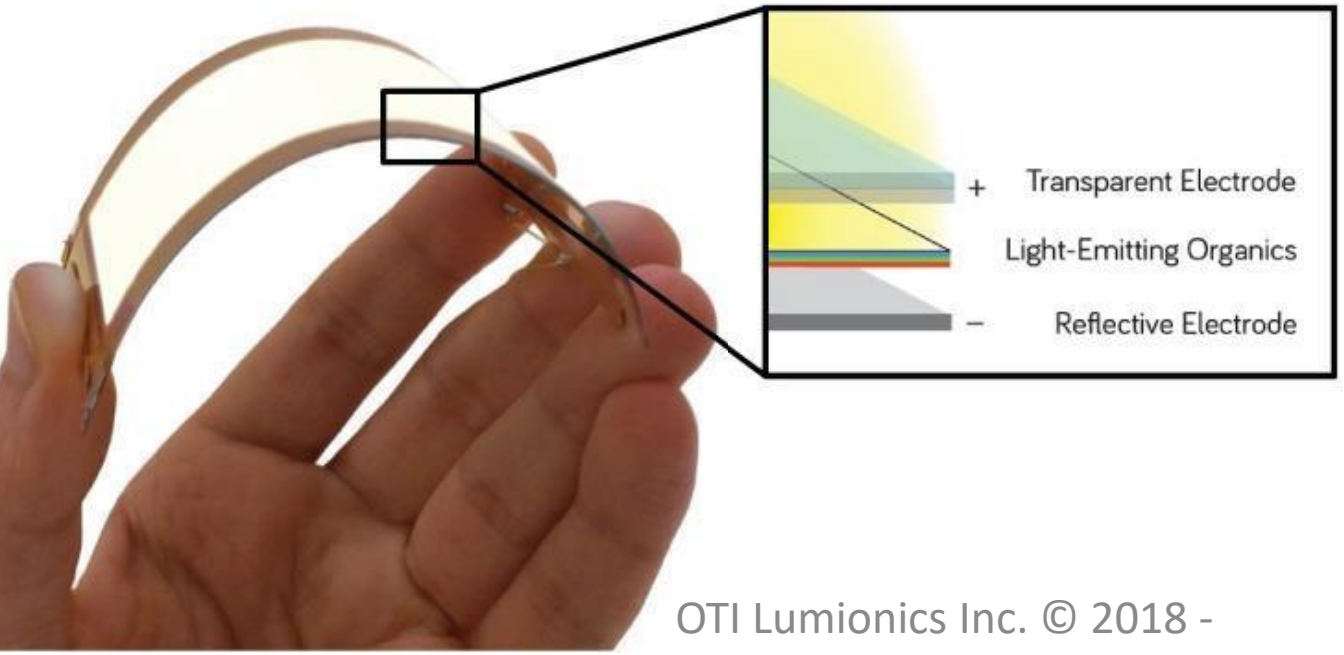
What We Do

Materials Discovery

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

Organic Light Emitting Diode (OLED)

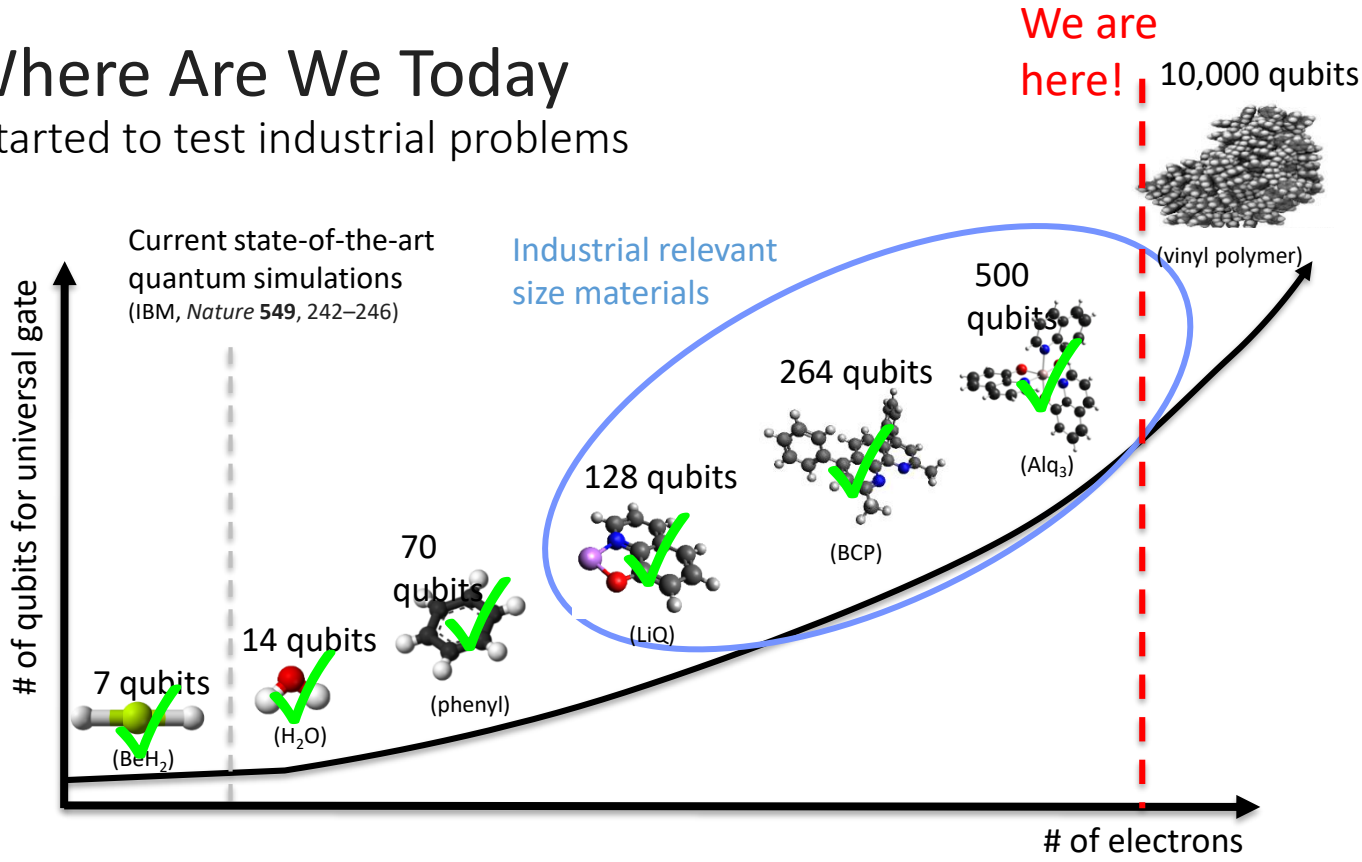
Light from organic pigments sandwiched between electrodes



Organic Pigments

Where Are We Today

Started to test industrial problems



We have demonstrated industrial relevant size simulations on quantum hardware

1/7/2019

“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

“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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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

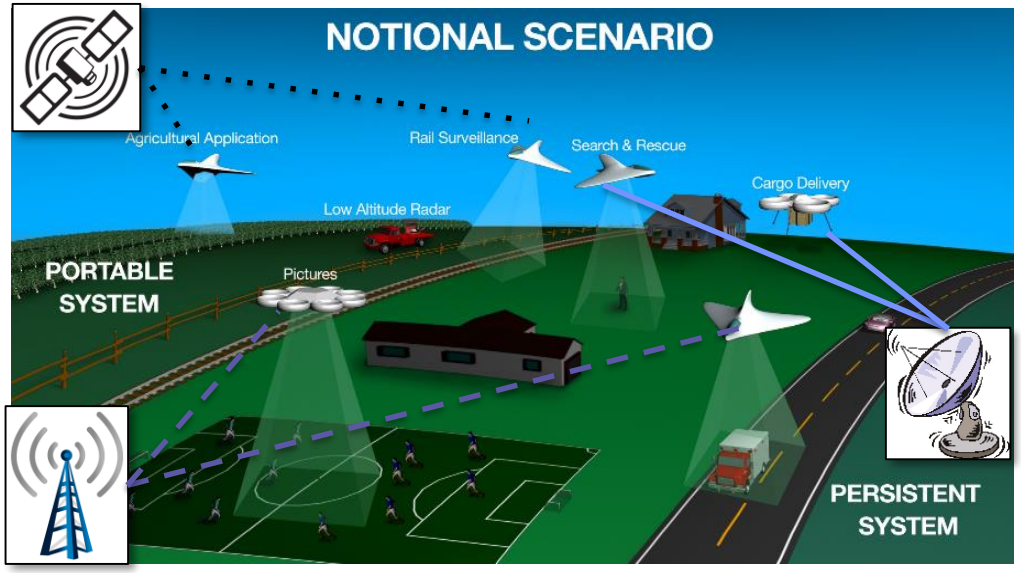
Future

- 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

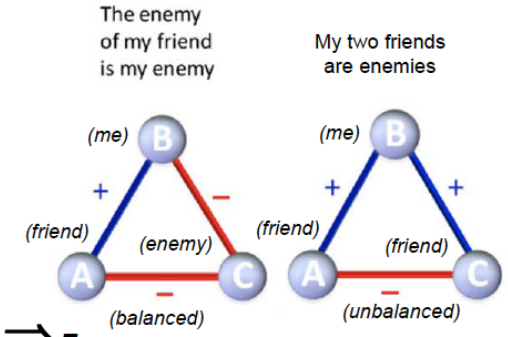
Using the D Wave 2X Quantum Computer to Explore the Formation of Global Terrorist Networks

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*

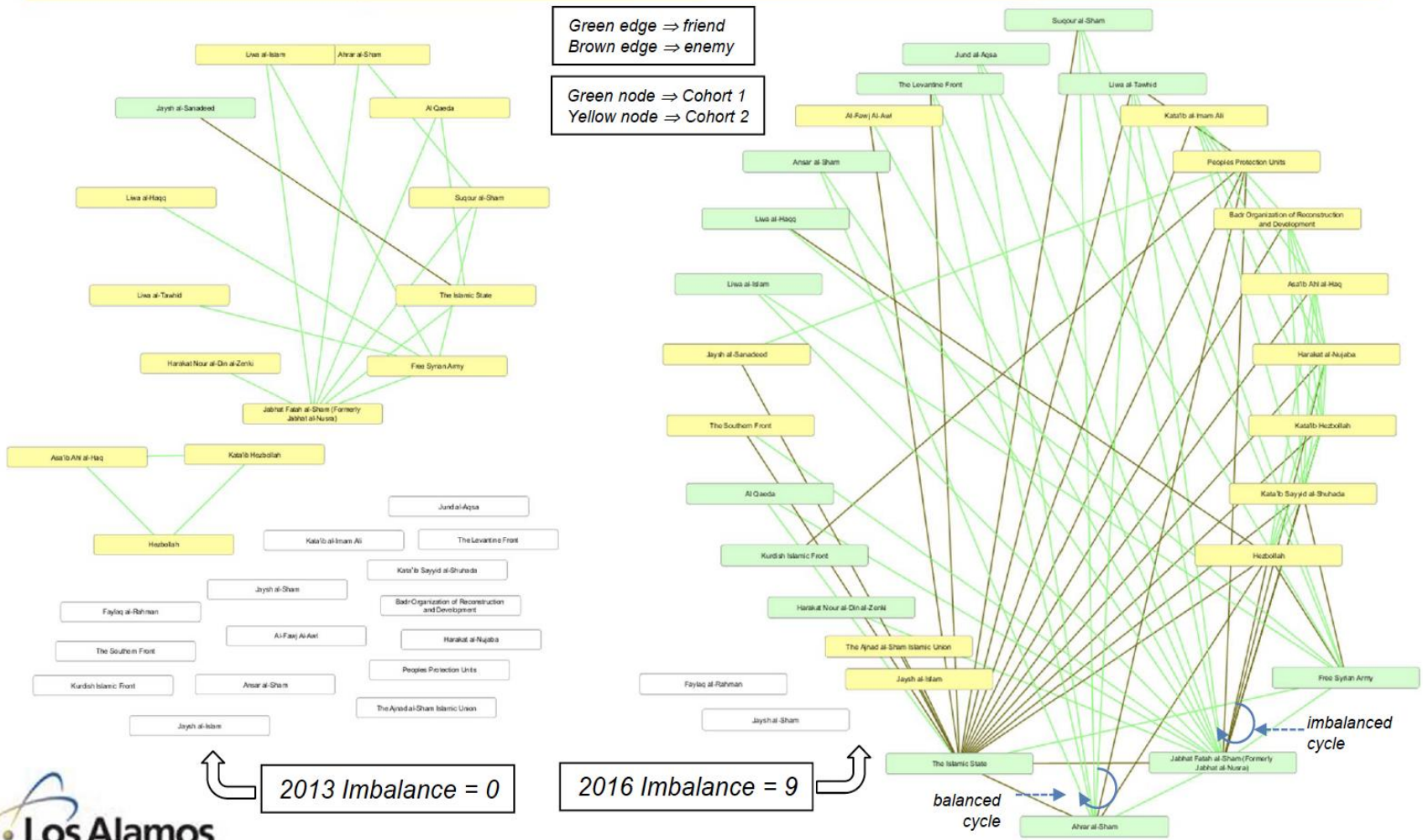


- There is an Ising model equivalent to this problem
  - $H = \sum_{i,j}\left(1 - J_{ij}s_i s_j\right) \ni J_{ij}, s_i \in \{-1,1\}$

Effectively measures the number of edge rule violations

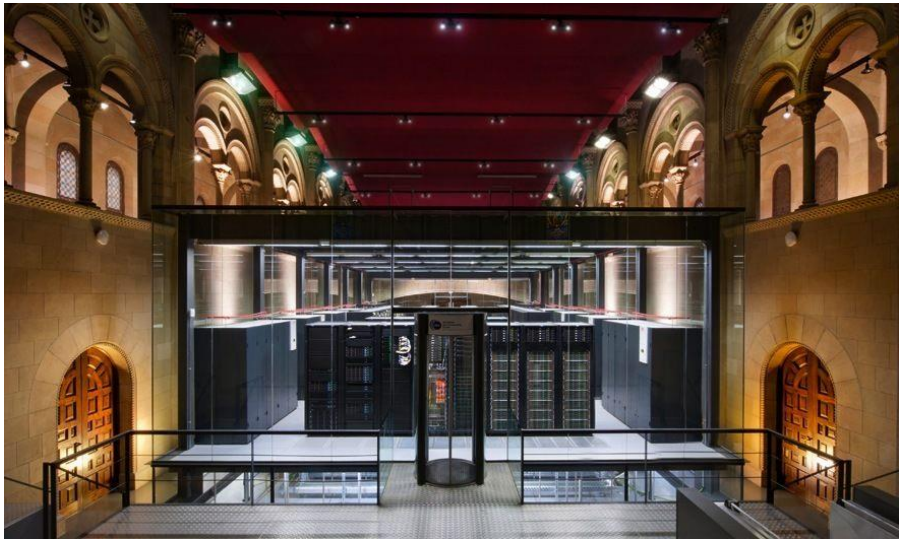
PNAS / December 27, 2011 / vol. 108 / no. 52 / 20953–20958

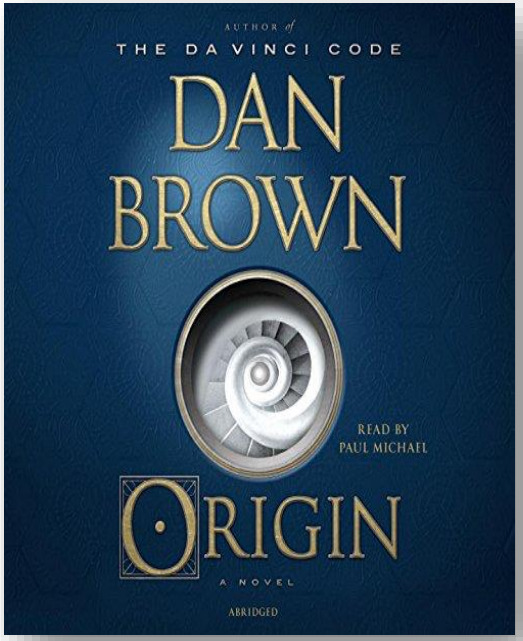
Syrian Theater Networks

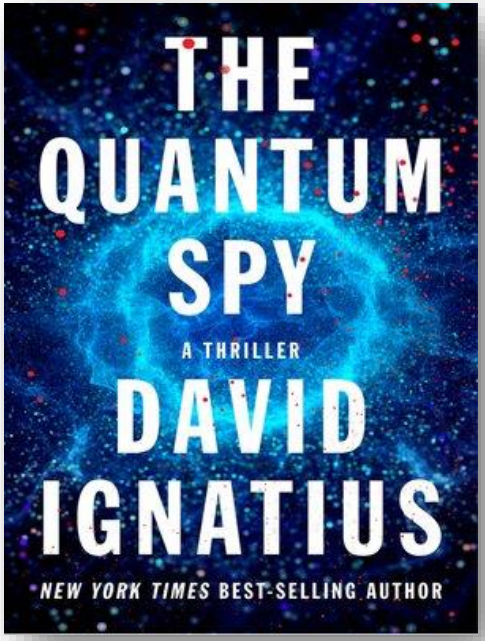


Early Applications of Quantum Computing

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







Early Applications of Quantum Computing

- Overview
- Proto-Apps
- **New Apps – closer to production**
  - DENSO
  - Recruit Communications
  - VW

DENSO
Crafting the Core

Autonomously Guided Vehicle (AGV) efficiency in factories

Japanese

https://www.youtube.com/watch?v=31vnkvCj3kM

English

https://www.youtube.com/watch?v=4zW3_lhRYDc

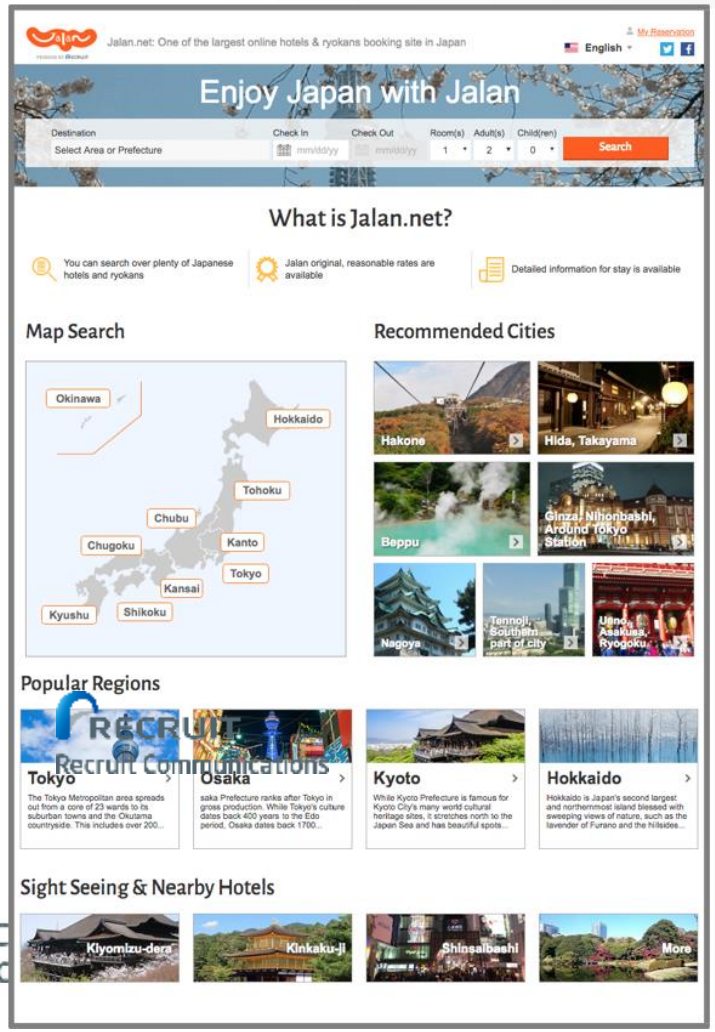
Qubits North America 2018

Item Listing Optimization Considering Di
in E-Commerce Websites

Naoki Nishimura
Recruit Communications Co., Ltd.
nishimura@r.recruit.co.jp

RECRUIT
Recruit Commu

Introduction of Recruit Group



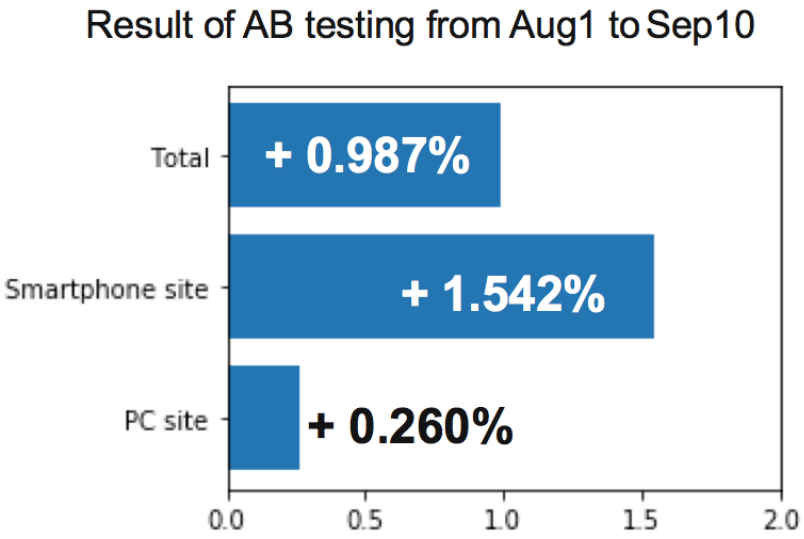
- Recruit Group provides various kinds of online services ; from job search to online shopping ; across the globe.
- Examples: Travel reservation, Restaurant reservation, Housing information sites, etc…

Housing	Life & Local O2O	Bridal & Baby
Beauty	Education	Human Resources
Travel	Automobile	IT & Trends Media
		Dining

- Today's topic is the use case of D;Wave on the hotel reservation site "Jalan"
  - https://www.jalan.net/en

The result of practical AB testing on our site

Sales uplift considering both sales and diversity

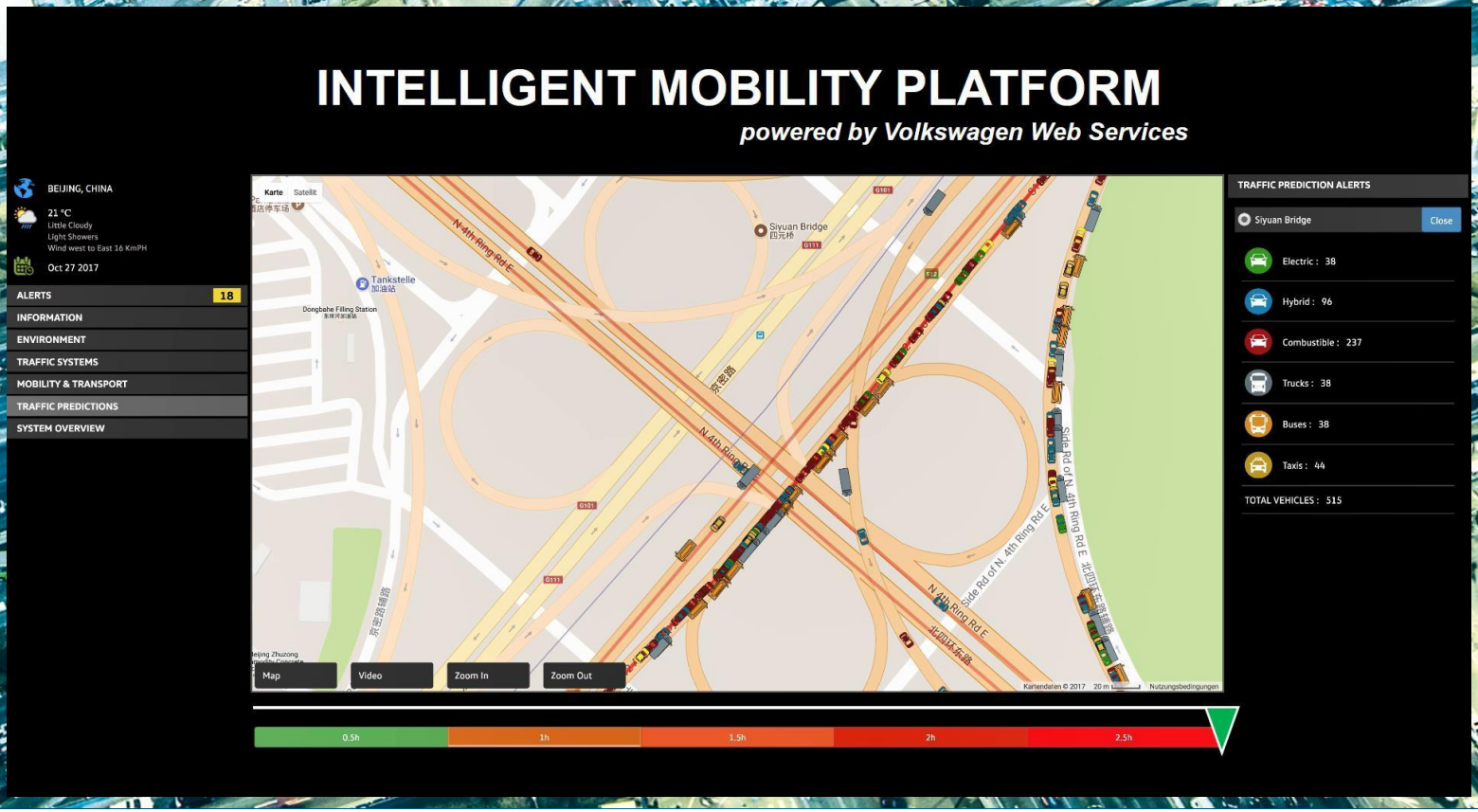


- In AB testing, we observed better performance considering **both sales and diversity** than considering sales alone
  - **Total sales uplift +0.987%**
- Considering diversity is especially important in smartphone sites
- Future work
  - Adjustment of the diversity parameter in real AB testing

Quantum Mobility

MARTIN HOFMANN, CIO Volkswagen Group

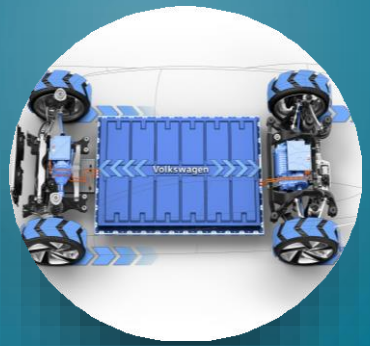
Web Summit 2017



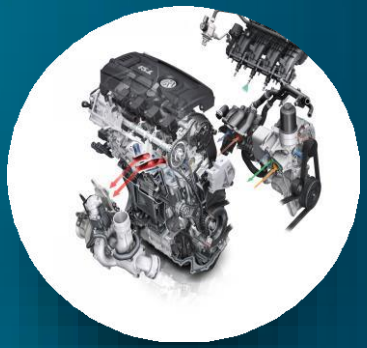
Quantum Projects at Volkswagen Group

Optimizing Traffic Flow
reducing traffic jams and emission

Material Simulation
designing new battery materials



Design Optimization
designing the optimal engine block



Volkswagen Group is the first automotive company having filed three quantum patents pending and proud voting member of IEEE Quantum Computing standards

Quantum Project 2:
Demand Prediction for Taxis WMC 2018

Objectives

- support taxi driver and dispatcher to increase and optimize business

Approach

- predict demand of taxis in Realtime: Where? When? How many?

Results

- transparency where and when to find customers
- optimal allocation of taxis
- less waiting time for customers

Circles of n kilometers around demand spots are used to locate taxis close to a demand spot

VOLKSWAGEN AKTIENGESELLSCHAFT · D-Wave The Quantum Computing Company™ · TERALYTICS · orange™

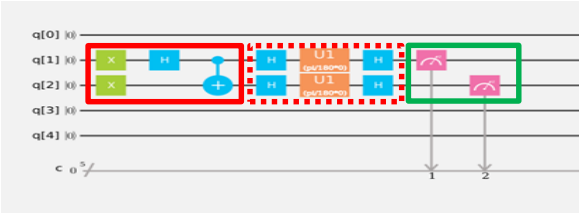
Web Summit 2019

Applications, Software Tools, Training and Remote Access

- ~100 “Proto-apps” today!
- New D-Wave software tools
  - OCEAN
- New customer software tools
  - Los Alamos, Oak Ridge, DLR, . . .
- More training programs, and on-line training
- New LEAP easy access to D-Wave systems
- Second D-Wave Europe’s “Qubits Users Group” meeting March 26-28, 2019 in Milan

Longer-term Quest for General Purpose QC

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



~1-75 Qubits

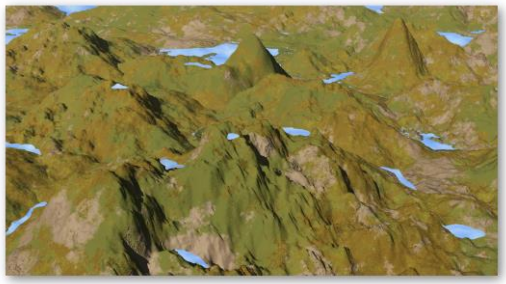
No Error Correction (EC)

- Quantum Chemistry
- Optimization?
- Machine Learning?

Qubit "Quality"

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

Quantum Annealing



2000+ Qubits

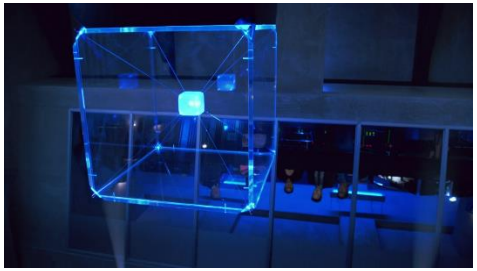
- Optimization
- Machine Learning
- Material Science

Qubit "Quality"

Control

Topology

General Purpose QC (Universal)



Accurate

Repeatable

Run Any Quantum Program

Quantum Speedup

D:wave
The Quantum Computing Company™

For More Information See

D-Wave Users Group Presentations:

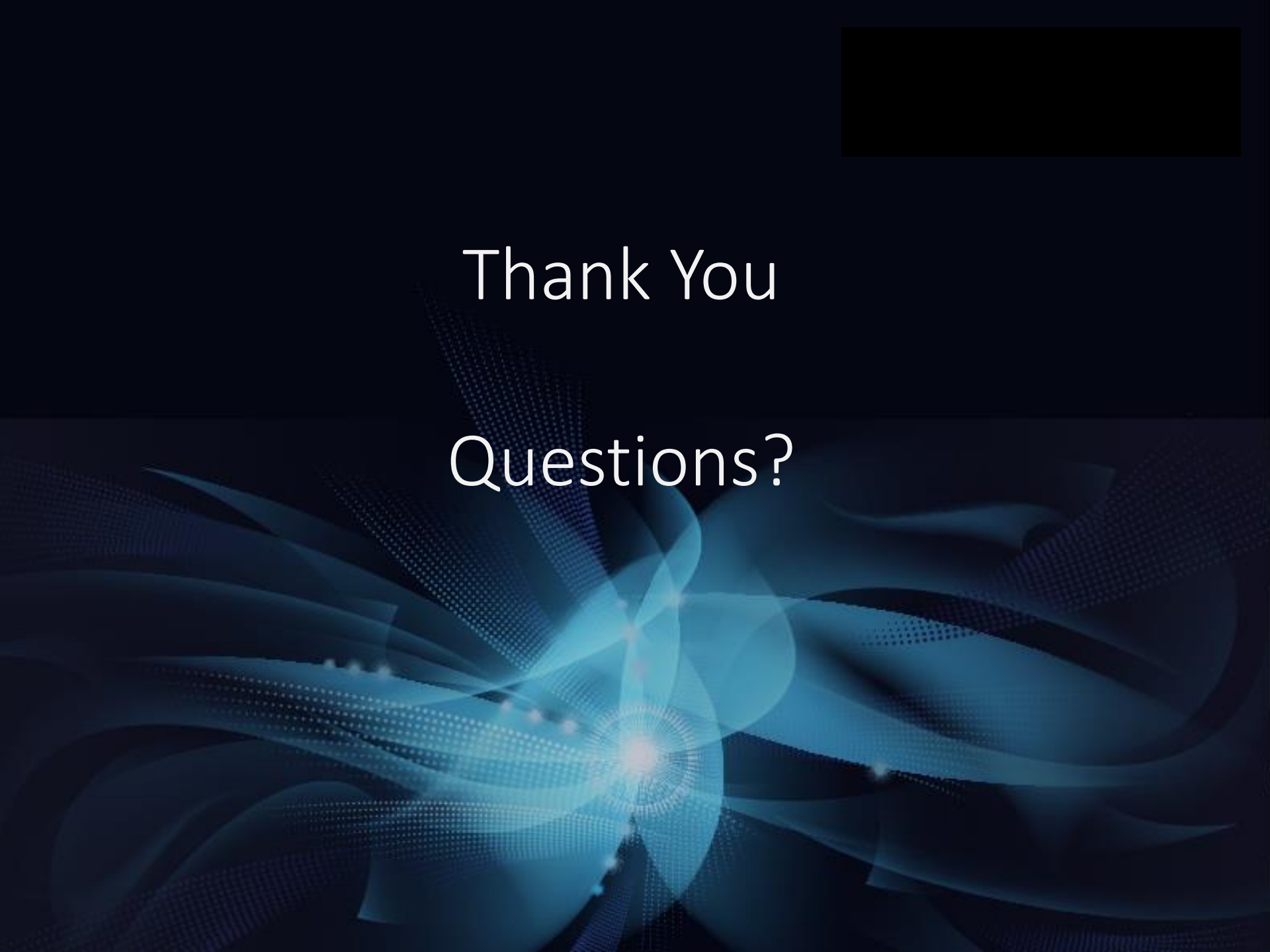
- https://dwavefederal.com/qubits-2016/
- https://dwavefederal.com/qubits-2017/
- https://www.dwavesys.com/qubits-europe-2018
- https://www.dwavesys.com/qubits-north-america-2018

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)


Thank You
Questions?