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

- Jagiellonian University in Kraków
- Universiteit Leiden, The Netherlands
- University of BRISTOL
- LMU Ludwig-Maximilians-Universität München
- JÜLICH Forschungszentrum
- Volkswagen
- UNIVERSITY OF OXFORD
- Durham University
- CINECA
- CSC
- ocado, The online supermarket
- REPLY DATA
- Hartree Centre, Science & Technology Facilities Council
- Imperial College London
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
D-Wave 2000Q Quantum Processor
D-Wave Product Generations

- D-Wave One: 128 qubits
- D-Wave Two: 512 qubits
- D-Wave 2000Q: 2000 qubits
- D-Wave 2X: 1000 qubits

Number of Qubits:
- 1
- 10
- 100
- 1000
- 10,000

Timeline:
- 2004
- 2008
- 2012
- 2015
- 2017
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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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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
The Question that drove us …

Is there a \textit{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


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

Using Quantum Computers to Fight Traffic Jams
With help from quantum computers, VW wants to inform drivers 45 minutes in advance of impending gridlock.

Volkswagen erprobt Quantencomputer
Autor: Sven Eisenkraemer

Volkswagen Pilots Quantum Computing Experiments
Quantum computing has vast potential, but high technology hurdles remain

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
QUANTUM Annealing Has Many Real-World Applications
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)
Subdivision of the Problem

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

- 51 connected components of the conflict graph
Optimize the moment
Quantum technology for Mobility IoT
Traffic jam is a big social problem

Traffic jams pose serious problems to traffic infrastructure.
But DENSO's quantum computing solution enables calculations of an enormous number of combinations due to the effect of quantum superposition.
Value obtained by optimization

1. Traffic jam alleviation
2. Better access for emergency vehicles
3. Streamlining of logistics
Display Advertising Optimization by Quantum Annealing Processor

Shinichi Takayanagi*, Kotaro Tanahashi*, Shu Tanaka†

*Recruit Communications Co., Ltd.
† Waseda University, JST PRESTO
Behind the Scenes

Publisher

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

Impression

Winner!

0.9$
0.7$
1.0$

31
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
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
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.
Routing Warehouse Robots

James Clark
High Performance Software Engineer
STFC Hartree Centre
james.clark@stfc.ac.uk

Luke Mason
High Performance Software Lead
STFC Hartree Centre
luke.mason@stfc.ac.uk
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
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?

**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*

**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.

**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?
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**

**Personalized Input**
- Electronic Health Record data: medical history, medications, imaging and lab results, immunization dates, allergies, demographic information, etc.
- Panomic biomarker data
- Python API interface (SAPI) with D Wave

**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

*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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Material simulation on D-Wave

Qubits Europe 2018, Munich
12.04.2018 - Michael Streif
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]

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
Applications of Quantum Computing in Computational Chemistry

May 2018
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
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 $8 \times 8 \times 8$ 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 1970s 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 simulation. 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.

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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


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 \( \Rightarrow + \); different \( \Rightarrow - \)**
    - Given the edge signs, what is the best cohort assignment to nodes that tries to follow the edge rule? \( \Rightarrow NP\text{-}Hard \) problem
- There is an Ising model equivalent to this problem
  - \( H = \sum_{i,j} (1 - J_{ij}s_is_j) \equiv J_{ij}, s_i \in \{-1,1\} \)

*Effectively measures the number of edge rule violations*
Syrian Theater Networks

Green edge ⇒ friend
Brown edge ⇒ enemy

Green node ⇒ Cohort 1
Yellow node ⇒ Cohort 2

2013 Imbalance = 0
2016 Imbalance = 9
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Early Applications of Quantum Computing

- Overview
- Proto-Apps
- New Apps – closer to production
  - DENSO
  - Recruit Communications
  - VW
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 Diversity in E-Commerce Websites

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

<table>
<thead>
<tr>
<th>Housing</th>
<th>Life &amp; Local O2O</th>
<th>Bridal &amp; Baby</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beauty</td>
<td>Education</td>
<td>Human Resources</td>
</tr>
<tr>
<td>Travel</td>
<td>Automobile</td>
<td>IT &amp; Trends Media</td>
</tr>
<tr>
<td>Sight Seeing &amp; Nearby Hotels</td>
<td></td>
<td>Dining</td>
</tr>
</tbody>
</table>

- 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**

Result of AB testing from Aug 1 to Sep 10

- Total: +0.987%
- Smartphone site: +1.542%
- PC site: +0.260%

- In AB testing, we observed better performance considering **both sales and diversity** than considering sales alone
  - Total sales uplift $\geq 0.987$
- 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
INTELLIGENT MOBILITY PLATFORM
powered by Volkswagen Web Services
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.
Web Summit 2019

Quantum Traffic Optimization

Predictive mobility platform
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

**General Purpose QC (Universal)**

Accurate
Repeatable
Run Any Quantum Program
Quantum Speedup
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:

DENSO Videos:
• https://www.youtube.com/watch?v=Bx9GLH_GkIA (CES – Bangkok)
• https://www.youtube.com/watch?v=BkowVxTn6EU (CES – Factory)
• https://www.youtube.com/watch?v=4zW3_lhRYDc (AGV’s)
Thank You

Questions?