Timing Is Everything

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Computationally differentiated organizations should now be finding appropriate high-value apps and mapping them to D-Wave systems for possible compelling performance advantage in 2 years.
Agenda

Identifying near-term technology

• Delivering differentiated performance
• Adopting quantum annealing technology rationally
• Navigating by early applications successes
Two Main Paths to Quantum Computing

Gate-model architecture

- Described by Deutsch (1985) with significant theoretical work to today
- Key algorithms defined in 1990s
- Major issue of error correction identified by Preskill in 1998
  - Believed to require 100-1000 physical qubits for every logical qubit
- First quantum algorithm demoed on physical qubits in 1998
- Google recently announced system with 72 physical qubits
- Digital nature in question
  - Preskill: “noisy intermediate-scale quantum” (NISQ) computers

Quantum-annealing architecture

- Nishimori (1998) and Farhi (1999) described ability to find low energy states
- Rose (2004) identified path for building such systems
- D-Wave (2010+) has delivered 4 generations of systems, the latest with 2000 qubits
- Problems friendly to D-Wave topology show ~1000X advantage
- Real-world problems ~parity
- New system generations every ~2yr
QTRL
Quantum Technology Readiness Levels describing the maturity of Quantum Computing Technology

QTRL9
QC (QAs) exceed power of classical computers

QTRL8
Scalable version of QC (QA) completed and qualified in test

QTRL7
Prototype QC (QA) built solving small but user-relevant problems

QTRL6
Components integrated in small quantum processor w/ error correction

QTRL5
Components integrated in small quantum processor w/o error correction

QTRL4
Multi-qubit system fabricated; classical devices for qubit manipulation developed

QTRL3
Imperfect physical qubits fabricated

QTRL2
Applications / technologically relevant algorithms formulated

QTRL1
Theoretical framework for quantum computation (annealing) formulated

D-Wave quantum annealer
IBM
Google
Experimental qubit devices

© Kristel Michielsen, Thomas Lippert – Forschungszentrum Jülich
(http://www.fz-juelich.de/ias/jsc/EN/Research/ModellingSimulation/QIP/QTRL_node.html)
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# Programming Model / Quantum Machine Instruction

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

**Known as**
- Quadratic unconstrained binary optimization (QUBO) problem
- Ising model
- Unconstrained binary quadratic problem (UBQP)

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

The system samples from the \( q_i \) that minimize the objective.
Delivering Differentiated Performance

• Today (D-Wave 2000Q™):
  – For some problems structured to D-Wave topology, ~1000X performance advantage
  – For real-world problems, rough parity

• Quantum performance advantage will be delivered only from (sub)problems that fit on the quantum processing unit (QPU) ...

• But decomposing solvers split big problems into QPU-size problems

• So, let’s focus on how QPU-size problems grow
Delivering Differentiated Performance

- Today (D-Wave 2000Q™): In practice, problems of ~64 variables fit on the QPU
- Next-gen D-Wave system targeted at 4-5K qubits with denser topology

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Change</th>
<th>Effect on #variables in QMI</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>More qubits</td>
<td>2-2.5X more</td>
<td>* 1.4-1.6</td>
<td></td>
</tr>
<tr>
<td>Denser topology</td>
<td>2.5X more</td>
<td>* 2.8</td>
<td>Higher perf due to shorter chains</td>
</tr>
<tr>
<td>QA changes</td>
<td>TBD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Better algs/tools</td>
<td></td>
<td>* 1.3</td>
<td>RBC embedding (e.g.)</td>
</tr>
<tr>
<td>Aggregate change</td>
<td></td>
<td>* 5.46 == 326 vars</td>
<td></td>
</tr>
</tbody>
</table>

- Some problems shift from classically tractable to intractable between 64 and 326 variables: e.g., Markov networks (~50 today; 100s intractable)

◊ Roy et al.’s “Boosting integer factoring ...” showed that per-qubit advance/delay of annealing in some cases led to a 1000X performance increase (i.e., fraction of valid results)
Significant Technical Challenges

• Increasing #connections/qubit by 2.5X
• Higher fraction of results valid (e.g., improved 1/f noise, shorter chains due to higher average degree)
• Maximizing multi-qubit tunneling (e.g., improved T1 times)
• Understand best uses of reverse anneal, pause, quench, and advance/delay
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Probabilities from Technology-Adoption Point of View

- 99%: Disseminate to other likely use cases
- 97%: Monitor closely
- 90%: Be prepared to deploy with multiple use cases
- 67%: Ensure fluent; first use case readily deployable
- 33%: Ensure prepared; understand technology in depth and have hands-on experience with likely first uses
- 10%: Monitor closely
- 3%: Don’t have to consider seriously, but monitor
- 1%:
Steps to Integrate D-Wave Execution

• Become coarsely familiar with QUBO formulation and underlying quantum machine instruction

• Find problems that plausibly benefit from D-Wave execution
  – Discrete optimization, well representable as QUBO
  – 1K – 100K problem variables
  – Better/faster answers are valuable to your org

• Formulate the problem for D-Wave
  – Typically using QUBO or higher-level abstraction
  – Low-level APIs are available for those who want more control (and effort)

• Assess performance
  – Tune directly
  – Give feedback to tool developers
Subject-matter-expert-relevant APIs

**Applications**
- Social Network Analysis
- Circuit Fault Diagnosis
- Document Classification
- Generative Machine Learning

**Methods**
- QUBO/Ising/BQP Decomposition (QBSolv)
- Pre- and Post-Processing
  - Embedding (Minorminer), ...

**Uniform Sampler API**
- Simulated Annealing
- D-Wave SAPI
- DW Open Microclient

**Samplers**

**Compute Resources**
- CPUs and GPUs
- QPUs

**Available**
- Conceptual Prototype

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Navigating by early applications successes
Digital pioneering work: Volkswagen uses quantum computers

- Cooperation with leading quantum computing company D-Wave Systems
- World premiere at CeBIT research project for traffic flow optimization

The Volkswagen Group is the world’s first automaker to use quantum computers, further expanding its digital competence for the future. In this context, Volkswagen Group IT is cooperating successfully with leading quantum computing company D-Wave Systems on a research project for traffic flow optimization. In the course of this project, IT experts from the Volkswagen labs in San Francisco and Munich have been the first to develop a small mobility program on the D-Wave quantum computer. Quantum computers can solve highly complex problems many times faster than conventional supercomputers. In the future, quantum computing technology will be used primarily by scientific institutes, government agencies, and the aerospace sector.

At CeBIT 2017 in Hannover, Volkswagen and D-Wave will be announcing their strategic cooperation and, as a world premiere, demonstrating a software program that optimizes traffic flow on a quantum computer. In the course of this project, experts from the Volkswagen Code Lab in San Francisco and the Volkswagen Data Lab in Munich and used data from approximately 10,000 taxis in Beijing.

Dr. Martin Hoffmann, CIO of the Volkswagen Group, says: “We are doing digital pioneering work. Quantum computing offers huge potential!”

Research project successful: Volkswagen IT experts use quantum computing for traffic flow optimization

Volkswagen collabora avec le canadien D-Wave pour tester l’informatique quantique

Volkswagen profite du CeBIT 2017 à Hanovre pour dévoiler un partenariat avec la société canadienne D-Wave. Objectif : explorer la puissance de calcul de l’informatique quantique pour résoudre les problèmes de la vie quotidienne de demain.”

Volkswagen uses quantum computer for traffic flow research

The company claims to be the first automaker to use quantum computers. Volkswagen claims to be the first automaker to use quantum computers, joining with D-Wave Systems on a research project for traffic flow optimization.

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Proof-of-concept demonstration:

*Can a D-Wave system be used to optimize real-world data?*

**Traffic Flow Optimization:**

- Dataset used was an open-source collection of GPS coordinates from over 10,000 taxis in Beijing (from 2008)
- 418 cars travelling from the city center to the airport were chosen (high congestion)
- Each car was proposed 3 possible routes; each route is a sequence of roads to take
- **Objective:** Assign each taxi to a route, such that each's route minimally overlaps with all other cars' routes (to resolve the congestion)
Traffic Flow Optimization

Constraints:

- Each car must be assigned to exactly one route
- Time from origin (city center) to destination (airport) must be minimized for all cars
- Solution must resolve congestion along the main route, and must not cause congestion on other routes
- Answer from D-Wave machine must be a sensible and interpretable solution to the problem
Original (unoptimized) vs. Final (optimized):

Results:

• Cars now dispersed among many possible routes to destination
• Congestion along main route was resolved and no additional congestion created
• Results from the D-Wave system were meaningful relative to the application
• Successful proof-of-concept demonstration!
Quantum Machine Learning for Election Modelling

Max Henderson, Ph.D.
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?
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

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 states' 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
Display Advertising Optimization by Quantum Annealing Processor

Shinichi Takayanagi*, Kotaro Tanahashi*, Shu Tanaka†

*Recruit Communications Co., Ltd.
† Waseda University, JST PRESTO
Performance measure - real world data with Greedy and D-Wave

- Hourly performance of each strategy
- Greedy method: Choose maximum CTR edge for each user

- Quantum annealing (QA) finds a better solution than the greedy method
  - Almost same CTR level
  - Low variation of CTR

- QA / D-Wave
- Greedy
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.
Computationally differentiated organizations should now be finding appropriate high-value apps and mapping them to D-Wave systems for possible compelling performance advantage in 2 years.
For More Information, See

D-Wave Users Group Presentations:

• 2018 (European): https://www.dwavesys.com/qubits-europe-2018


• 2016:

LANL Rapid Response Projects:
