D-Wave Background
Company Background

- Founded in 1999; Vancouver, BC
- World’s first quantum computing company
- Public customers:
  - Lockheed Martin/USC
  - Google/NASA Ames
  - Los Alamos National Lab
  - Temporal Defense Systems
  - Oak Ridge National Laboratory
- Other customer projects done via cloud access to systems in D-Wave’s facilities
- 150 U.S. patents/200 Worldwide
- 160 employees; 45 with Ph. D
D-Wave Unveils US Gov’t Subsidiary, Names Independent Board Members

D-Wave Systems has established a new subsidiary that will work to provide quantum computer systems to U.S. government agencies and has appointed executives that will serve on the subsidiary’s independent board.

The company said Tuesday Jeffrey Harris, chairman of the U.S. Geospatial Intelligence Foundation and former president of special programs at Lockheed Martin, will serve as chairman of the board at D-Wave Government.

Rene Copeland, director of government sales for D-Wave Systems, will also serve as president of D-Wave’s U.S. government subsidiary.
Processor Environment

- Cooled to 0.012 Kelvin, 175 times colder than interstellar space
- Shielded to 50,000 times 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
Mission

To help solve the most challenging problems in the multiverse:

• Optimization
• Machine Learning
• Monte Carlo/Sampling
• Material Science
Quantum Computing
Computing circa- 1955
D-Wave; Adiabatic Quantum Annealing (AQC)

- Gate Mode (Google, IBM, Intel, startups)
- Topological (Microsoft)
- Annealing (D-Wave, Google, IARPA)
How it Works
Why Quantum Computing Matters
The End of Moore’s Law ??

- There’s a law about Moore’s law

- “The number of people predicting the death of Moore’s law doubles every two years.”
  
  Peter Lee, a vice-president at Microsoft Research
Getting To Commercial-Scale Real Problems

Computational Performance

More powerful systems
- More qubits
- Denser connectivity
- Features & controls
- Software & algorithms
- Universal processor

Easier to use
- Software & apps
- Cloud Services for machine learning
- Developer ecosystem
- Increase reliability and use through cloud

Benchmark problems
Commercial problems
Classical
Quantum Investment

Figure 4. Quantum technology investments worldwide (from Netherlands government presentation at the EU Flagship launch, May 2016)*.
June 2007 Top 500

<table>
<thead>
<tr>
<th></th>
<th>Country</th>
<th>Organization</th>
<th>Manufacturer</th>
<th>Supercomputer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>USA</td>
<td>DOE/NNSA/LLNL</td>
<td>IBM</td>
<td>BlueGene/L</td>
</tr>
<tr>
<td>2</td>
<td>USA</td>
<td>DOE/SC/ORNL</td>
<td>CRAY</td>
<td>Jaguar</td>
</tr>
<tr>
<td>3</td>
<td>USA</td>
<td>NNSA/Sandia</td>
<td>CRAY</td>
<td>Red Storm</td>
</tr>
<tr>
<td>4</td>
<td>USA</td>
<td>TJ Watson</td>
<td>IBM</td>
<td>BGW</td>
</tr>
<tr>
<td>5</td>
<td>USA</td>
<td>BNL</td>
<td>IBM</td>
<td>NY Blue</td>
</tr>
<tr>
<td>6</td>
<td>USA</td>
<td>DOE/NNSA/LLNL</td>
<td>IBM</td>
<td>ASC Purple</td>
</tr>
<tr>
<td>7</td>
<td>USA</td>
<td>RPI</td>
<td>IBM</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>USA</td>
<td>NCSA</td>
<td>Dell</td>
<td>Abe</td>
</tr>
<tr>
<td>9</td>
<td>SPAIN</td>
<td>Barcelona SC</td>
<td>IBM</td>
<td>MareNostrum</td>
</tr>
<tr>
<td>10</td>
<td>GERMANY</td>
<td>LRZ</td>
<td>HPE</td>
<td>HLRB-II</td>
</tr>
</tbody>
</table>

US held 8 of the Top 10 positions with Europe holding the remaining 2 positions
June 2017

<table>
<thead>
<tr>
<th></th>
<th>Country</th>
<th>System/Location</th>
<th>Manufacturer</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CHINA</td>
<td>NSC Center at Wuxi</td>
<td>Sunway</td>
<td>Taihu Light</td>
</tr>
<tr>
<td>2</td>
<td>CHINA</td>
<td>NSC GUANGZHOU</td>
<td>Exp + Xeon Phi</td>
<td>Tainhe -2</td>
</tr>
<tr>
<td>3</td>
<td>SWITZERLAND</td>
<td>CSCS</td>
<td>CRAY</td>
<td>Piz Daint</td>
</tr>
<tr>
<td>4</td>
<td>USA</td>
<td>DOE/SC/ORNL</td>
<td>CRAY</td>
<td>Titan</td>
</tr>
<tr>
<td>5</td>
<td>USA</td>
<td>DOE/NNSA/LLNL</td>
<td>IBM</td>
<td>Sequoia</td>
</tr>
<tr>
<td>6</td>
<td>USA</td>
<td>DOE/LBNL/NERSC</td>
<td>CRAY</td>
<td>Cori</td>
</tr>
<tr>
<td>7</td>
<td>JAPAN</td>
<td>Joibt Ctr for Adv HPC</td>
<td>Intel + Fujitsu</td>
<td>kforest-PACS</td>
</tr>
<tr>
<td>8</td>
<td>JAPAN</td>
<td>RIKEN</td>
<td>Fujitsu</td>
<td>K-computer</td>
</tr>
<tr>
<td>9</td>
<td>USA</td>
<td>DOE/SC/ANL</td>
<td>IBM</td>
<td>Mira</td>
</tr>
<tr>
<td>10</td>
<td>USA</td>
<td>DOE/NNSA/LANL</td>
<td>CRAY</td>
<td>Trinity</td>
</tr>
</tbody>
</table>

Of the Top 10 positions
- US holds 4 positions
- Europe holds 1 position
- Japan holds 2 positions
- China holds 2 positions
2017 Top 500 (Top 10 systems)

<table>
<thead>
<tr>
<th>Country</th>
<th>No Systems</th>
<th>% Total Perf</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>169</td>
<td>33.5%</td>
</tr>
<tr>
<td>China</td>
<td>159</td>
<td>31%</td>
</tr>
</tbody>
</table>

Top 2 Chinese systems > remaining 8 Top 10 systems combined
China building world’s biggest quantum research facility
Centre could boost military’s code-breaking ability and navigation of stealth submarines

• “Our plan is that by 2020, or maybe as soon as next year, to achieve ‘quantum supremacy’ with calculation power one million times to all existing computers around the world combined,” Pan Jianwei was quoted as saying by Anhui Business Daily, which is run by the provincial government.

• “Another key mission of the laboratory is to build the nation’s first quantum computer that could break an encrypted message in seconds.

• It was unclear whether the computer could be used for code-breaking.

• Construction work is expected to finish in 2 ½ years with a budget of 76 billion yuan (HK$91.6 billion; ~$11B USD)”
Quantum Computing Activities
Jülich rated D-Wave as the only scaled quantum computer

Jülich Supercomputing Center created a framework for Quantum Technology Readiness Levels

QTRL
Quantum Technology Readiness Levels describing the maturity of Quantum Computing Technology

- QTRL9: QCs (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

http://www.fz-juelich.de/ias/jsc/EN/Research/ModellingSimulation/QIP/QTRL/_node.html
LANL Rapid Response Projects

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

The LANL Rapid Response Project results for 2016 and 2017 are available as PDF's via the link:

LANL Project Summary

LANL Rapid Response Projects 2016

- Efficient Combinatorial Optimization using Quantum Annealing
- Constrained Shortest Path Estimation on the D-Wave 2X
- Graph Partitioning using the D-Wave for Electronic Structure Problems
- Generative Modeling for Machine Learning on the D-Wave
- Solving Sparse Representations for Object Classification using the Quantum D-Wave 2X Machine
- A Programmable Embedder: A Staged Approach for Mapping Problems to the Chimera Graph
- Ising Simulations on the D-Wave QPU
- D-Wave Quantum Computer as an Efficient Classical Sampler
- Challenges and Successes of Solving Binary Quadratic Programming Benchmarks on the DW2X QPU
- Topological Sphere Packing on the D-Wave
- Quantum Uncertainty Quantification for Physical Models using ToQ.jl

LANL Rapid Response Projects 2017

- Leveraging LANL’s D-WAVE 2X for Random Number Generation
- Beyond Pairwise Ising Models in D-Wave: Searching for Hidden Multi-Body Interactions
- Using the D-Wave 2X to Explore the Formation of Global Terrorist Networks
- Connecting D-Wave 2X to Bayesian Inference Image Analysis
- Quantum interaction of a few particle system mediated by photons
- Simulations of non-local spin interaction in atomic magnetometers using LANL’s D-Wave 2X
- Problem Reformulation and Matrix Sparsification
- Quantum Annealing Approaches to Graph Partitioning for Electronic Structure Problems
- Nonnegative/Binary Matrix Factorization with a D-Wave Quantum Annealer
- A Rigorous Comparison of the D-Wave 2X to Established B-QP Solution Methods
- Solving Sparse Representation for Object Classification Using the D-Wave 2X
FY 2017: Quantum Testbed Pathfinder

**Purpose:** To provide decision support for future investments in quantum computing (QC) hardware and increase both breadth and depth of expertise in QC hardware in the DOE community.

**Emphasis:** Research in the relationship between device architecture and application performance, including development of meaningful metrics for evaluating device performance.

**Timeline & Proposals:** A DOE National Laboratory Announcement was issued in June 2017. 6 proposals were received in July 2017.

**2 Awards:**
- Advanced Quantum-Enabled Simulation (LBNL, LLNL, UC Berkeley);
- Methods and Interfaces for Quantum Acceleration of Scientific Applications (ORNL, IBM, IonQ, Georgia Tech);
## Factorization by Quantum Computer

<table>
<thead>
<tr>
<th>Year</th>
<th>Number Factored</th>
<th>How, Who</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>21</td>
<td>Gate model, Shor’s</td>
</tr>
<tr>
<td>2012</td>
<td>143</td>
<td>QA, experimental NMR device</td>
</tr>
<tr>
<td>2014</td>
<td>56,153</td>
<td>QA, Dattani &amp; Bryans, mathematical trick works for factors which differ at only 2 bits</td>
</tr>
<tr>
<td>2017</td>
<td>200,099</td>
<td>QA, Dridi &amp; Alghassi (1QBit), D-Wave QPU</td>
</tr>
<tr>
<td>2017</td>
<td>291,311</td>
<td>QA, Li, Dattani et al. experimental NMR device</td>
</tr>
</tbody>
</table>

![Diagram of how to factor numbers](https://i.isanumber.blogspot.com)
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
Traffic Flow Optimization

Original (un-optimized) 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!
Portfolio Optimization

Financial Portfolio Management using Adiabatic Quantum Optimization:
The Case of Abu Dhabi Securities Exchange

Nada Elsokkary and Faisal Shah Khan
Quantum Computing Research Group
Department of Applied Mathematics and Sciences
Khalifa University, Abu Dhabi UAE

Davide La Torre
Department of Economics, Management, and Quantitative Methods, University of Milan, Milan Italy
Department of Mathematics
Nazarbayev University, Astana Kazakhstan

Travis S. Humble
Quantum Computing Institute
Oak Ridge National Laboratory
Oak Ridge, Tennessee USA

Joel Gottlieb
D-Wave Systems, Inc.
British Columbia Canada

1. Introduction

Financial portfolio selection is the problem of optimal allocation of a fixed budget to a collection of assets (commodities, bonds, securities etc.) which produces random returns over time. The word optimal, however, can have different meanings. For instance, one could define optimal so that a solution to the portfolio problem maximizes expected or average value of the return. While this definition is intuitively appealing, it is also naive because the values of a random process can deviate from the expected value. A definition of optimal should therefore incorporate deviations from the expected value. In his 1952 paper [4], Harry Markowitz proposed just such a definition of optimal for the financial portfolio selection problem. Markowitz proposed that the problem has an optimal solution when an investor maximizes expected return and minimizes variance in the values of the return. In other words, an investor should look to maximize gain and minimize risk for a given financial portfolio.

Markowitz’s portfolio selection theory also formalizes the wisdom of portfolio diversification, where instead of allocating the largest fractions of the budget to a select number of assets with largest expected return, an investor allocates his budget to many assets with the hope that the fortune of some of these assets will not be influenced by the misfortune of some others.

Formally, consider a portfolio with \( n \) assets. Let \( a_i \) be the percentage allocation of the total budget to asset \( i \) and let \( R_i \) denote the random variable representing the return from asset \( i \). Further, let \( R \) denote the random variable for the return from the entire portfolio. Then

\[
R = \sum_i a_i R_i
\]

whereby the expected return from the the portfolio is

\[
E(R) = \sum_i a_i E(R_i)
\]

due to the linearity of expectation. Next, consider the variance of \( R \) which is given by

\[
\text{Var}(R) = \sum_{i,j} a_i a_j \text{Cov}(R_i, R_j)
\]

where \( \text{Cov}(R_i, R_j) \) is the co-variance of the random variables \( R_i \) and \( R_j \) and which reduces to the variance of \( R_i \) for \( i = j \). An investor working with respect to Markowitz theory will maximize (1) while minimizing (2). The information that the investor needs to achieve these two tasks is the pairs of statistics \( [E(R_i), \text{Cov}(R_i, R_j)] \). In his paper, Markowitz refers to these pairs as \((E, V)\) combinations and assures that it is always possible to identify an optimal one.

More mathematically, this is a bicriteria quadratic optimization problem in which the set of all optimal solutions yield the so-called efficient frontier or efficient portfolios. Among all optimal portfolios, the decision...
Exploiting the structure of data in an information search space:
- Clusters/blobs
- Stranded trajectories (POL)
- Similar objects, activities, events from different datasets (mixing of colors)
- Intersections = Complex Interactions
Google Image Search vs Bing Image Search vs. DF Search Engine

Google Image Search

Google Image Search

Bing Image Search

Bing Image Search

DataFission Search

DataFission Search
D-Wave Technical Progress

Number of Qubits

<table>
<thead>
<tr>
<th>Year</th>
<th>Qubits</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>4 qubit</td>
</tr>
<tr>
<td>2006</td>
<td>16 qubit</td>
</tr>
<tr>
<td>2010</td>
<td>28 qubit</td>
</tr>
<tr>
<td>2014</td>
<td>512 qubit</td>
</tr>
<tr>
<td>2016</td>
<td>1,000 qubit</td>
</tr>
<tr>
<td>2019</td>
<td>2,000 qubit</td>
</tr>
</tbody>
</table>
D-Wave Software Environment

**Applications**

**Compilers**

**Translators**

**Intermediate Representation**

**Host Library and Command Line Interface**

**System Interface and Control**

**Quantum Machine Instruction**

**Target System**

- **Environment/Libraries**
  - 1Qbit SDK
  - JADE/Quelle...

- **LANL Assembler**

- **C, C++, MATLAB Python**

- **“QUORTRAN”**

- **“Q++”**

- **Optimization**
  - QSAGE

- **Constraint Satisfaction**
  - ToQ

- **Sampling SAT, ML**
  - ...

- **“Virtual” QUBO**

- **QUBO**

- **qbsolv**

- **SAPI**

- **QMI**

- **DW**

**Applications**

- **“QUORTRAN”**

- **“Q++”**

- **Sampling SAT, ML**

- **“Virtual” QUBO**

- **QUBO**

- **qbsolv**

- **SAPI**

- **QMI**

- **DW**

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http://d-waveprogramming-12-2017.eventzilla.net
To register for the conference, go to: http://qubits2017.eventzilla.net. There is a registration fee of $150 to defray some of the costs of the conference.
For More Information See

• D-Wave Users Group Presentations 2016:

• D-Wave Users Group Presentations 2017:
  – dwavefederal.com/qubits-2017/

• LANL Rapid Response Projects:
Thank You