Quantum Computing

How a century-old theory
is about to revolutionize the world (again)

Matthias Le Dall – Data Science and Analytics Lab
York University – Physics and Astronomy Colloquium
September 22nd, 2020
All roads lead to quantum
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Quantum Computing

2. The Basic Principles
   - Superposition vs Entanglement and Annealer vs Universal

3. How to think like a Quantum Computer
   - Annealer as an Ising Model Solver

4. Uses Cases
   - Topological States of Matter
   - Portfolio Optimization

5. Outlook
   - Democratization
   - Quantum Advantage
2. The Basic Principles
   - Superposition vs Entanglement and Annealer vs Universal
The pillars of quantum computing
Entanglement and superposition

Entanglement
“Asking the question”

Superposition
“Getting the answer”

Quantum Computer
“Exponentially efficient optimization and search machine”
Annealer versus Universal
Two approaches for different problems

Annealer Quantum Computer
Special purpose solver figuring out the best configuration of qubits

Universal Quantum Computer
General purpose solver with algorithms that control individual qubits
Annealer versus Universal
Two approaches for different problems

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3. How to think like a Quantum Computer
   - Annealer as an Ising Model Solver
The Annealer
An Analog Solver for Ising Models
The Annealer
An Analog Solver for Ising Models

\[ H_P = - \sum_i h_i S_i - \sum_{i<j} J_{ij} S_i S_j \]
The Annealer
An Analog Solver for Ising Models

$$- \sum_{i,j} J_{ij} S_i S_j$$

Alice
Bob
Eve
The Annealer
An Analog Solver for Ising Models

\[ - \sum_{i,j} J_{ij} S_i S_j \]

- Put people in groups to minimize social frustration:
  - blue people, red people
  - What color to assign to Alice, Bob and Eve?
The Annealer
An Analog Solver for Ising Models

\[- \sum_{i,j} J_{ij} S_i S_j\]

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An Analog Solver for Ising Models

\[-\sum_{i,j} J_{ij} S_i S_j\]

• Color to bit:
  • Blue: \( S_i = -1 \)
  • Red: \( S_i = 1 \)

• Connection to bit:
  • Friend: \( J_{ij} = 1 \)
  • Ennemy: \( J_{ij} = -1 \)

![Diagram showing connections between Alice, Bob, and Eve with interaction parameters: \( J_{AE} = 1 \), \( J_{AB} = -1 \), \( J_{EB} = 1 \).]
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An Analog Solver for Ising Models

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<th>Eve</th>
<th>Energy</th>
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<td>$J_{AE}$ = 1</td>
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\[
\begin{align*}
J_{AE} &= 1 \\
J_{EB} &= 1 \\
J_{AB} &= -1
\end{align*}
\]

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\[ |\text{Output}\rangle = A| -1, -1, -1\rangle + B|1, -1, -1\rangle + C| -1, 1, -1\rangle + D| -1, 1, 1\rangle + E|1, 1, 1\rangle + F|1, -1, -1\rangle + G|1, 1, -1\rangle + H| -1, -1, 1\rangle \]
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An Analog Solver for Ising Models

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Frequency

- A
- B
- C
- D
- E
- F
- G
- H
The Annealer
An Analog Solver for Ising Models

\[ |\text{Output}\rangle = A|\text{-1, -1, -1}\rangle + B|\text{1, -1, -1}\rangle + C|\text{-1, 1, -1}\rangle + D|\text{-1, 1, 1}\rangle + E|\text{1, 1, 1}\rangle + F|\text{1, -1, -1}\rangle + G|\text{1, 1, -1}\rangle + H|\text{-1, -1, 1}\rangle \]
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The Annealer
An Analog Solver for Ising Models

Best outcome
Most likely outcome
Outcome with lowest energy

\[ |\text{Output}\rangle = A|1, -1, -1\rangle + B|1, -1, -1\rangle + C|1, 1, -1\rangle + D|1, 1, 1\rangle + E|1, 1, 1\rangle + F|1, -1, -1\rangle + G|1, 1, -1\rangle + H|1, -1, 1\rangle \]
Quantum Computing

4. Uses Cases
   - Topological States of Matter
   - Portfolio Optimization
Renaissance in material physics
A Simulation Worth A Trillion Dollars

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

Andrew D. King, Juan Carrasquilla, [...], Mohammad H. Amin

Nature 560, 456–460 (2018) | Cite this article
5147 Accesses | 41 Citations | 219 Altmetric | Metrics

- D-Wave simulated topological states of matter
- Can be used to design exotic materials
- What’s next?
Quantum Computing

4. Uses Cases
   - Topological States of Matter
   - Portfolio Optimization
Quantum Computing in Finance
Modern Portfolio Theory in a Nutshell

Amazon

<table>
<thead>
<tr>
<th>Month</th>
<th>Unit price (USD)</th>
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<td>May 2019</td>
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<tr>
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Quantum Computing in Finance
Modern Portfolio Theory in a Nutshell

Amazon

May 2019
December 2019
January 2020
May 2020

Buy Low – Sell High: buy unit at $1,700 and sell at $2,367, gain +47% on investment
Quantum Computing in Finance
Modern Portfolio Theory in a Nutshell

Amazon

Buy Low – Sell High:
buy unit at $1,700 and sell at $2,367,
gain +47% on investment

Sell High – Buy Low:
sell unit at $2,200 and buy at $1,700,
gain +22% on investment
Quantum Computing in Finance
Modern Portfolio Theory in a Nutshell

**Amazon**

**Buy Low – Sell High:**
- buy unit at $1,700 and sell at $2,367,
- gain +47% on investment

**Sell High – Buy Low:**
- sell unit at $2,200 and buy at $1,700,
- gain +22% on investment

Return on Investment (ROI):

\[ R(t) = r(t) \]
Quantum Computing in Finance
Modern Portfolio Theory in a Nutshell

- Return on Investment (ROI) on Portfolio of 2 stocks:

\[ R(t) = w_1 r_1(t) + w_2 r_2(t) \]

- Return on Investment on Portfolio of N stocks:

\[ R(t) = \sum_{i=1}^{N} w_i r_i(t) \]

“20% of all your stocks are Amazon stocks”
“80% of all your stocks are Google stocks”
Quantum Computing in Finance
Modern Portfolio Theory in a Nutshell

- **Risk**
  - How much could we lose if we made a mistake and didn’t sell/buy at the right time?
  - How fast does the price fluctuate, and how big are the fluctuations?
  - Measured by variance (volatility):

\[
V = \langle R^2 \rangle - \langle R \rangle^2 \\
= \sum_{i,j} w_i w_j \sigma_i \sigma_j \left( \langle r_i r_j \rangle - \langle r_i \rangle \langle r_j \rangle \right) \\
= \sum_{i,j} w_i w_j \rho_{ij}
\]

Variance of single stock

Covariance Matrix
Quantum Computing in Finance
Modern Portfolio Theory in a Nutshell

- Goal of trading
  - Maximize the return while minimizing the risk
  - What’s the best combination of weights for optimal trading strategy?

- Goal is to maximize the following function

\[
H = R - qV = \sum_i r_i w_i - \sum_i \sum_j q \rho_{ij} w_i w_j
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Quantum Computing in Finance
Modern Portfolio Theory in a Nutshell

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Quantum Computing in Finance
Modern Portfolio Theory in a Nutshell

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Modern Portfolio Theory in a Nutshell

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Quantum Computing in Finance
Modern Portfolio Theory in a Nutshell

\[ H = R - qV \]

\[ = \sum_i r_i w_i - \sum_i \sum_j q \sigma_{ij} w_i w_j \]

with \( T \) time steps

\[ H = \sum_{t=1}^{T} \left( \sum_i r_i(t) w_{it} - q \sum_{i,j} \sigma_{ij}(t) w_{it} w_{jt} \right) \]
Quantum Computing in Finance
Modern Portfolio Theory in a Nutshell

\[ H = R - qV \]
\[ = \sum_i r_i w_i - \sum_i \sum_j q \sigma_{ij} w_i w_j \]

\[ H = \sum_{t=1}^T \left( \sum_i r_i(t) w_{it} - q \sum_{i,j} \sigma_{ij}(t) w_{it} w_{jt} \right) - M \sum_{t=1}^T \left( K - \sum_i w_{it} \right)^2 \]

with \( T \) time steps

Quantum Computing for Finance: Overview and Prospects, R. Orus, S. Mugel and E. Lizaso
Reviews in Physics 4 (2019)
Quantum Computing in Finance

Modern Portfolio Theory in a Nutshell

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with constraint

\[ \sum_i w_{it} = K \]

\( w_{it} = \begin{cases} 
1, & i = 1, \cdots, N \text{ equities in portfolio} \\
0, & t = 1, \cdots, T \text{ time step forecasting} 
\end{cases} \)
Quantum Computing in Finance
Modern Portfolio Theory in a Nutshell

\[ H = \sum_{t=1}^{T} \left( \sum_{i} r_i(t)w_{it} - q \sum_{i,j} \sigma_{ij}(t)w_{it}w_{jt} \right) - M \sum_{t=1}^{T} \left( K - \sum_{i} w_{it} \right)^2 \]

- How many assets can our algorithm capture?
- How many time steps can our algorithm forecast?
- What is the biggest graph that we can embed onto a quantum computer?
Quantum Computing in Finance
Modern Portfolio Theory in a Nutshell

Chimera Minor Embedding

- D-Wave 2000Q chip = 2048 physical qubits
- Unit cell = 2x4 physical qubits = 8 physics qubits
- Chimera graph = 16x16 unit cells = 16x16x2x4 = 2048 physical qubits
- Largest fully connected graph that can be embedded on a chimera graph

\[ V = 1 + L_{\text{min}} (M, N) = 1 + 4 \times 16 = 65 \geq N \times T \]

Classical Portfolio Optimization can capture hundreds of assets
Quantum Computing

5. Outlook
   • Democratization
   • Quantum Advantage
Democratization of Quantum
D-Wave open source software stack
Democratization of Quantum

D-Wave open source software stack
Democratization of Quantum
D-Wave open source software stack

Mapping method:
Python tools implementing known problems, graph cliques, graph similarities, etc.

Sampler API:
Defines device to use, connects to the device, and requires user authentication.

Sampler Embedding Strategy:
Converts the problem into QPU compatible code, e.g., Ising model or QUBO.
Democratization of Quantum
D-Wave open source software stack

Ocean Software

- Graph Mapping
- Constraint Compilation
- New Mapping Method
- Problem Suitable for QPU: Binary Quadratic Model (BQM)
- Simulated Annealing
- D-Wave API
- Hybrid Sampler
- New Sampler

Applications
- Social Network Analysis
- Traffic Flow
- Web Advertising
- New Application
- Portfolio Optimization
- Scheduling
- Circuit Fault Detection
- New Application

Mapping Methods
- Uniform Sampler API

Compute Resources
- CPUs and GPUs
- QPUs
Democratization of Quantum D-Wave open source software stack

# Create a K3 complete graph (default node labels are indexical from 0)
G = nx.complete_graph(3)
# Randomly assign +1 or -1 relationship signs to all edges. Rename node 0 to Alice, 1 to Bob, etc.
G.add_edges_from([(u, v, {'sign': 2*random.randint(0, 1)-1}) for u, v in G.edges])
nx.relabel_nodes(G, {0: 'Alice', 1: 'Bob', 2: 'Eve'}, copy=False)
Democratization of Quantum

D-Wave open source software stack

```python
from dwave.system.samplers import DWaveSampler
from dwave.system.composites import EmbeddingComposite
import dwave_networkx as dnx
import dimod

def measure(circuit, sampler):
    # Measure the state of the quantum circuit
    result = sampler.sample_circuit(circuit)
    # Process the results
    return result

def process_results(results):
    # Process the results of the quantum circuit
    # Example: Extract and return the measurement data
    return results
```

Ocean Software

- Social Network Analysis
- Web Advertising
- Traffic Flow
- New Application
- Portfolio Optimization
- Circuit Fault Detection
- New Application
- Scheduling

Applications

- Mapping Methods
- Uniform Sampler API
- Samplers

Compute Resources

- CPUs and GPUs
- QPUs
Democratization of Quantum

D-Wave open source software stack

```python
imbalance, bicoloring = dnx.structural_imbalance(G, sampler_embed)
```
Democratization of Quantum
D-Wave open source software stack

imbalance, bicoloring = dnx.structural_imbalance(G, sampler_embed)
Democratization of Quantum

D-Wave open source software stack

```
imbalance, bicoloring = dnx.structural_imbalance(G, sampler_embed)
```

![Graph showing comparison between classical and quantum time vs number of nodes]

- **Optimization**
  - Social Network Analysis
  - Traffic Flow
  - Web Advertising
  - New Application

- **Constraint Satisfaction**
  - Portfolio Optimization
  - Scheduling
  - Circuit Fault Detection
  - New Application

![Ocean Software diagram]

- **Applications**
- **Mapping Methods**
- **Uniform Sampler API**
- **Samplers**
- **Compute Resources**

- **Problem Suitable for QPU: Binary Quadratic Model (BQM)**
- **Graph Mapping**
- **Constraint Compilation**
- **New Mapping Method**
- **Simulated Annealing**
- **D-Wave API**
- **Hybrid Sampler**
- **New Sampler**

- **CPUs and GPUs**
- **QPU**s
Why Quantum Computing Now?
Did We Just Pass the Tipping Point?

“Google’s Quantum Computer could mine 3 million Bitcoin in 2 seconds [today]”
Understanding the business
Team of leaders who have business and technical expertise
- Ongoing conversation with partners within the bank
- Ensure product solves their problem
- Support Treasury, Capital Markets, ...

Data environment
Team of Machine Learning, AI, database and software engineers
- Data acquisition
- Maintenance of databases
- Automated data ingestion

Data Science
Team of data scientists leading projects
- Data Cleaning, Exploration and Visualization
- Descriptive and predictive analysis
- Interacting with business and data engineers

Delivering results
Software and dashboards development
- Collaboration between data scientists and data engineers
- Feedback from business clients
Concluding Remarks

Are Quantum Computers black boxes?
No. They are entanglement and superposition that work in tandem.

Can we leverage the technology today?
Yes. Most companies have cloud-enabled QPUs that can be accessed via Python in the cloud.

How do we leverage the technology?
For annealers, rephrase your optimization or search problem into a Ising model.

Thank you
Back up
Why Quantum Computing Now?
Did We Just Pass the Tipping Point?

Error corrected qubits

- Transient Quantum Supremacy
- Quantum Advantage: Meaningful Work
- Postquantum Cryptography
- Financial Services Begins to Leverage QC
- QML Impact to AI
- All Historical RSA Encryption Can Be Cracked?

Note: Dates are speculative

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The pillars of quantum computing
Entanglement and superposition

- **Classical bits:**
  - 0 xor 1
  - exclusive

- **2-bit register:**
  - All 2-bit combinations
  - 11, 00, 10, 01

- **N-bit register:**
  - \(2^N\) possibilities

- **Quantum bit:**
  - 0 or 1
  - inclusive

- **Quantum bit state**

\[
|\psi\rangle = \alpha|0\rangle + \beta|1\rangle
\]

- **Measurement probabilities**

\[
P(1) = |\beta|^2
\]
\[
P(0) = |\alpha|^2
\]