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

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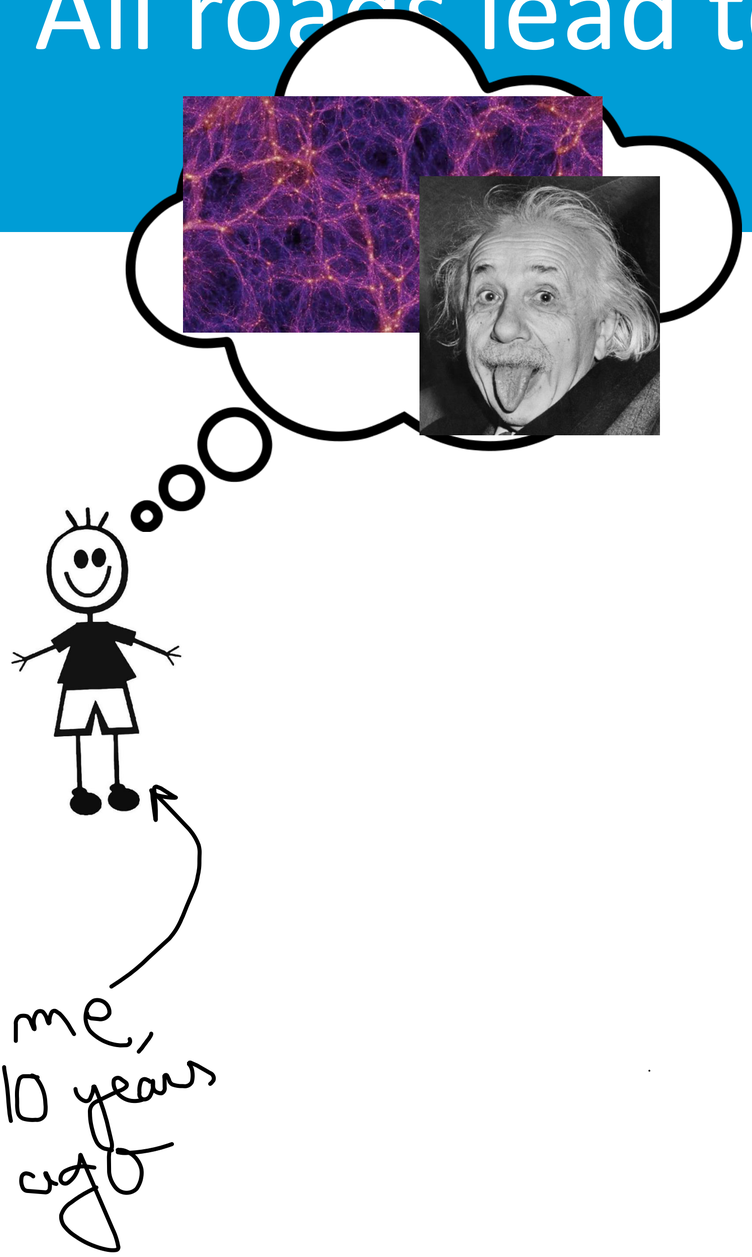
All roads lead to quantum



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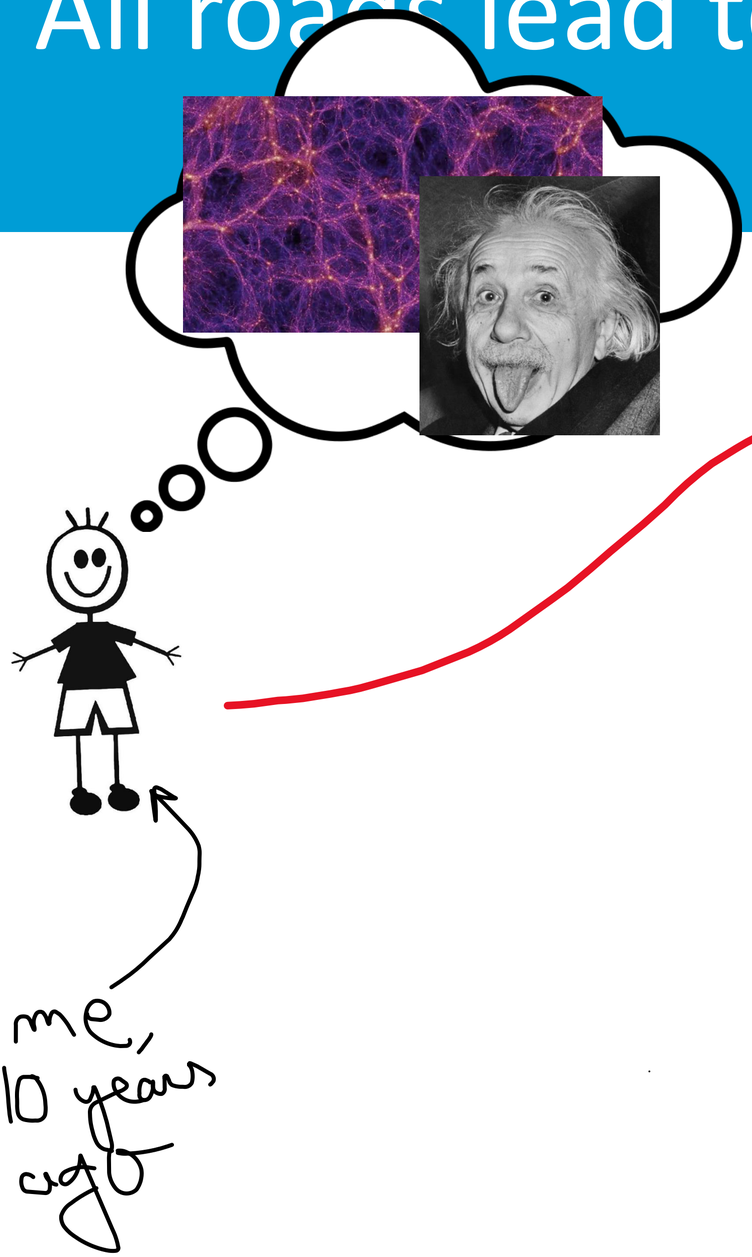

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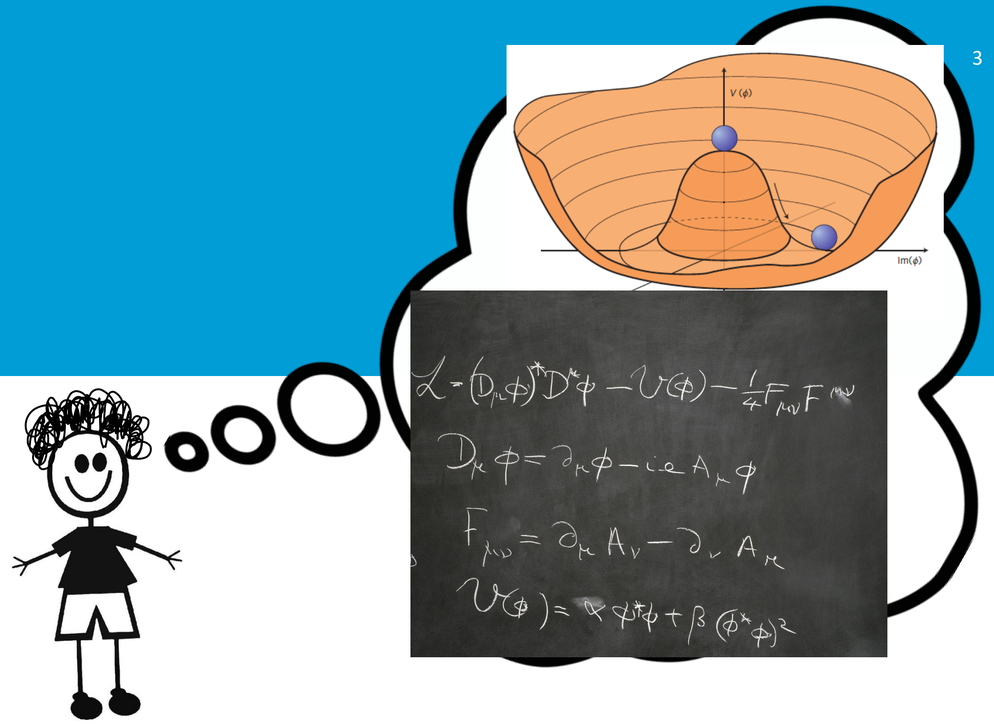

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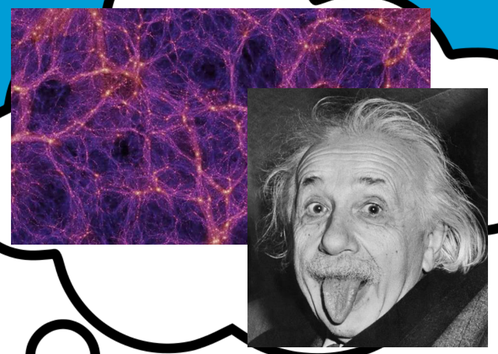
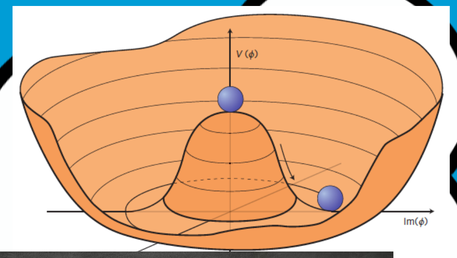
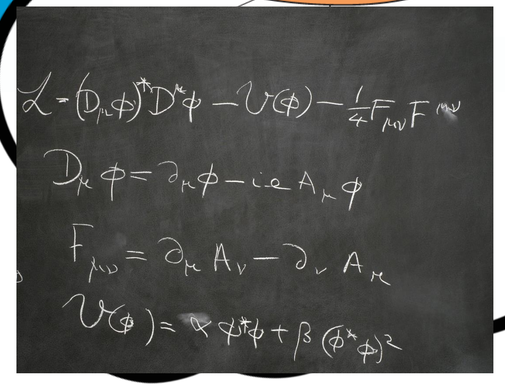


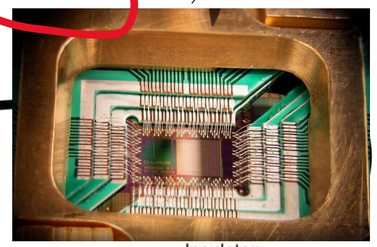




3 years later

3 years later

me, 10 years ago



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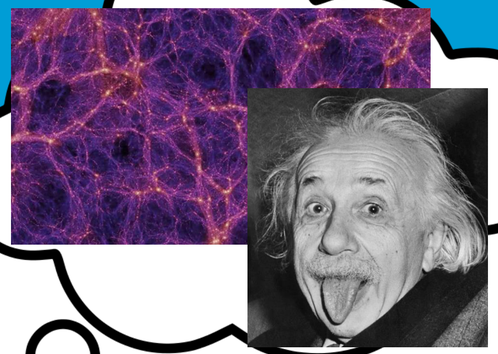

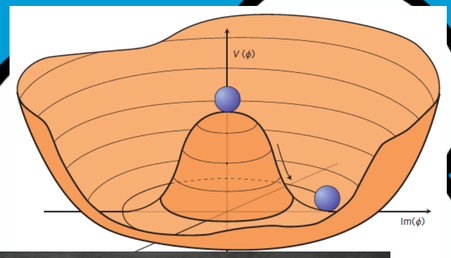

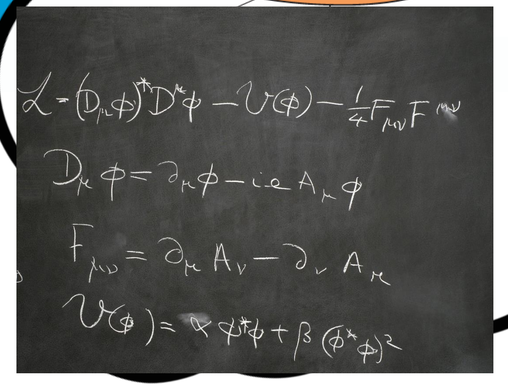

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4 years... later!!!

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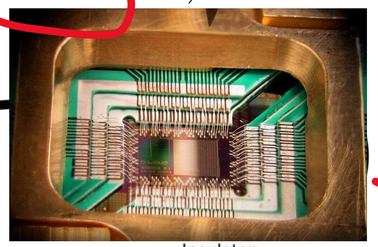

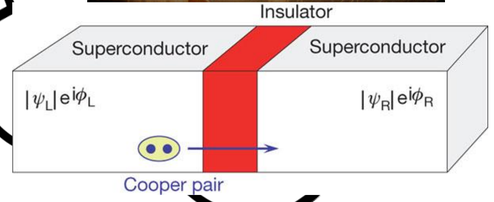

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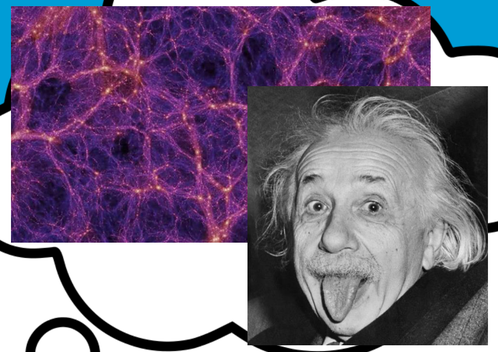

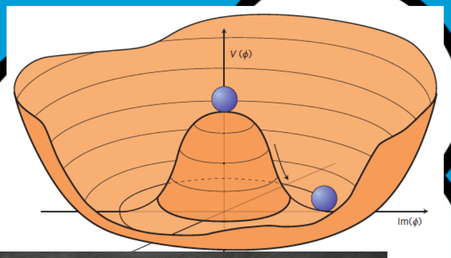

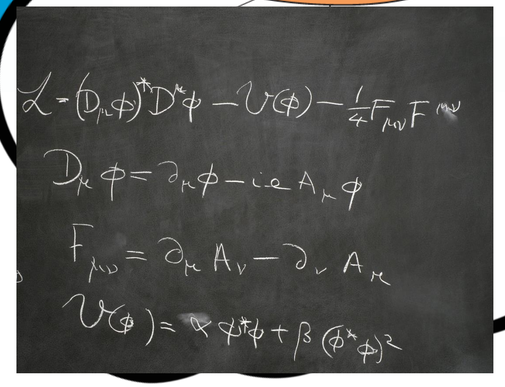

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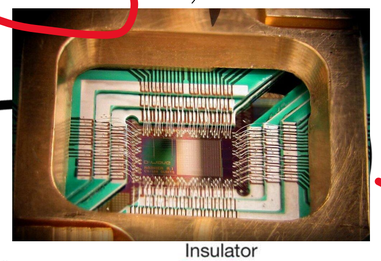

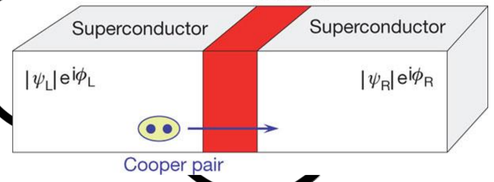

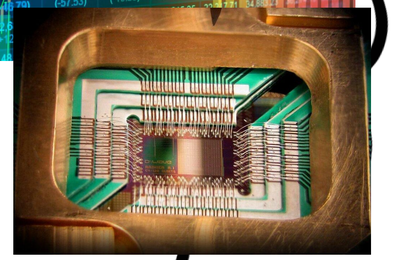

Quantum Computing

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

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Quantum Computing

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

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The pillars of quantum computing

Entanglement and superposition

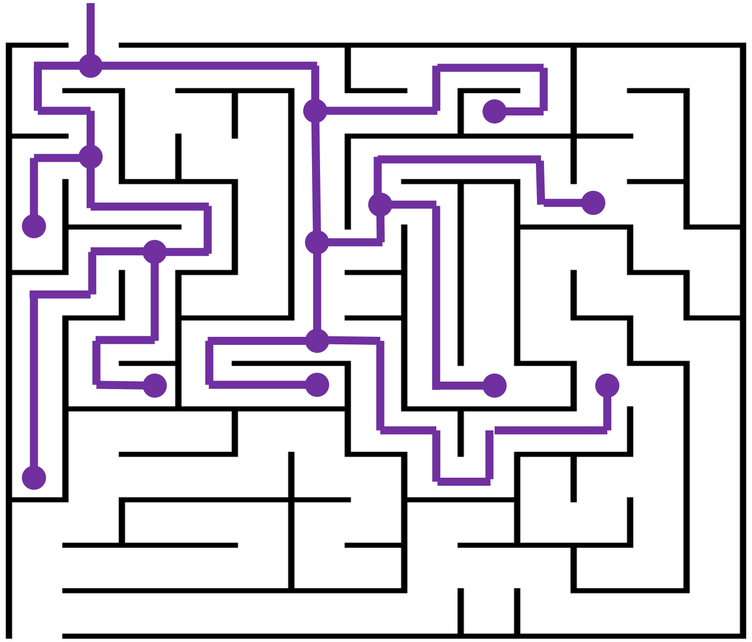
Entanglement

“Asking the question”

+

Superposition

“Getting the answer”



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Quantum Computer

“Exponentially efficient optimization and search machine”

Annealer versus Universal

Two approaches for different problems

Annealer Quantum Computer	Universal Quantum Computer
Special purpose solver figuring out the best configuration of qubits	General purpose solver with algorithms that control individual qubits

Annealer versus Universal

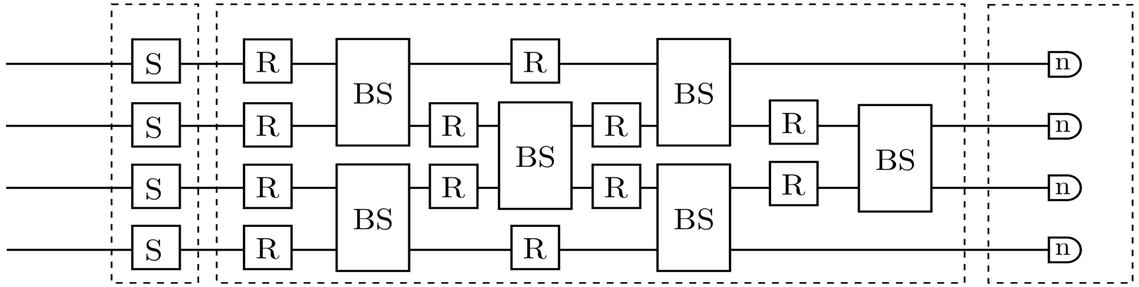
Two approaches for different problems

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

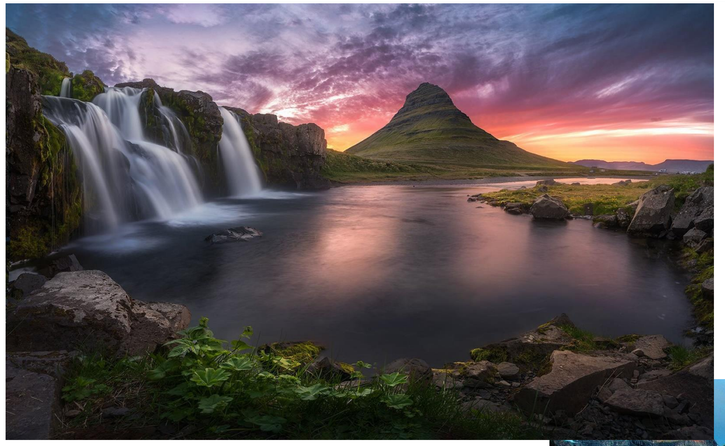


Annealer versus Universal

Two approaches for different problems

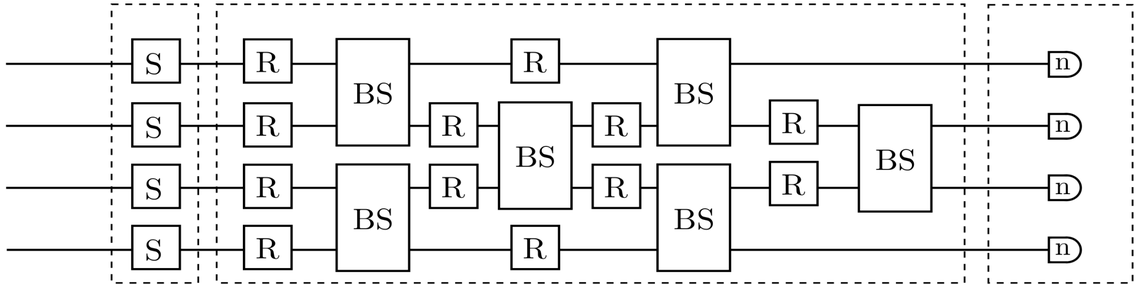
Annealer Quantum Computer

Special purpose solver figuring out the best configuration of qubits



Universal Quantum Computer

General purpose solver with algorithms that control individual qubits



Quantum Computing

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

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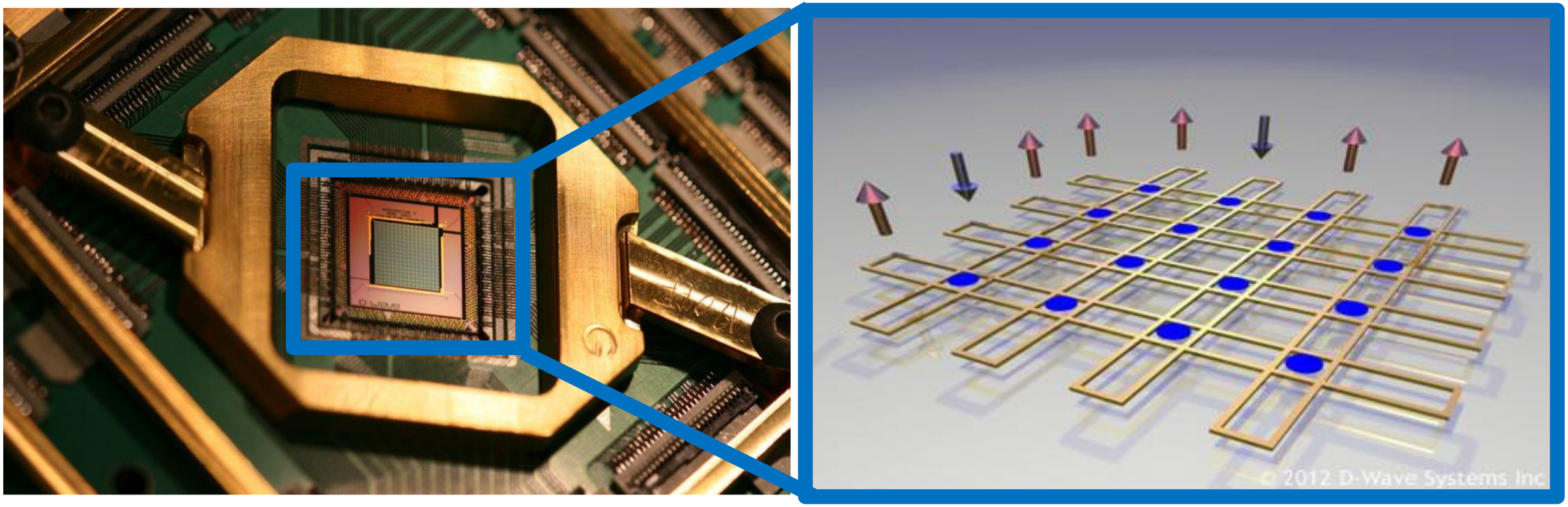
The Annealer

An Analog Solver for Ising Models



The Annealer

An Analog Solver for Ising Models

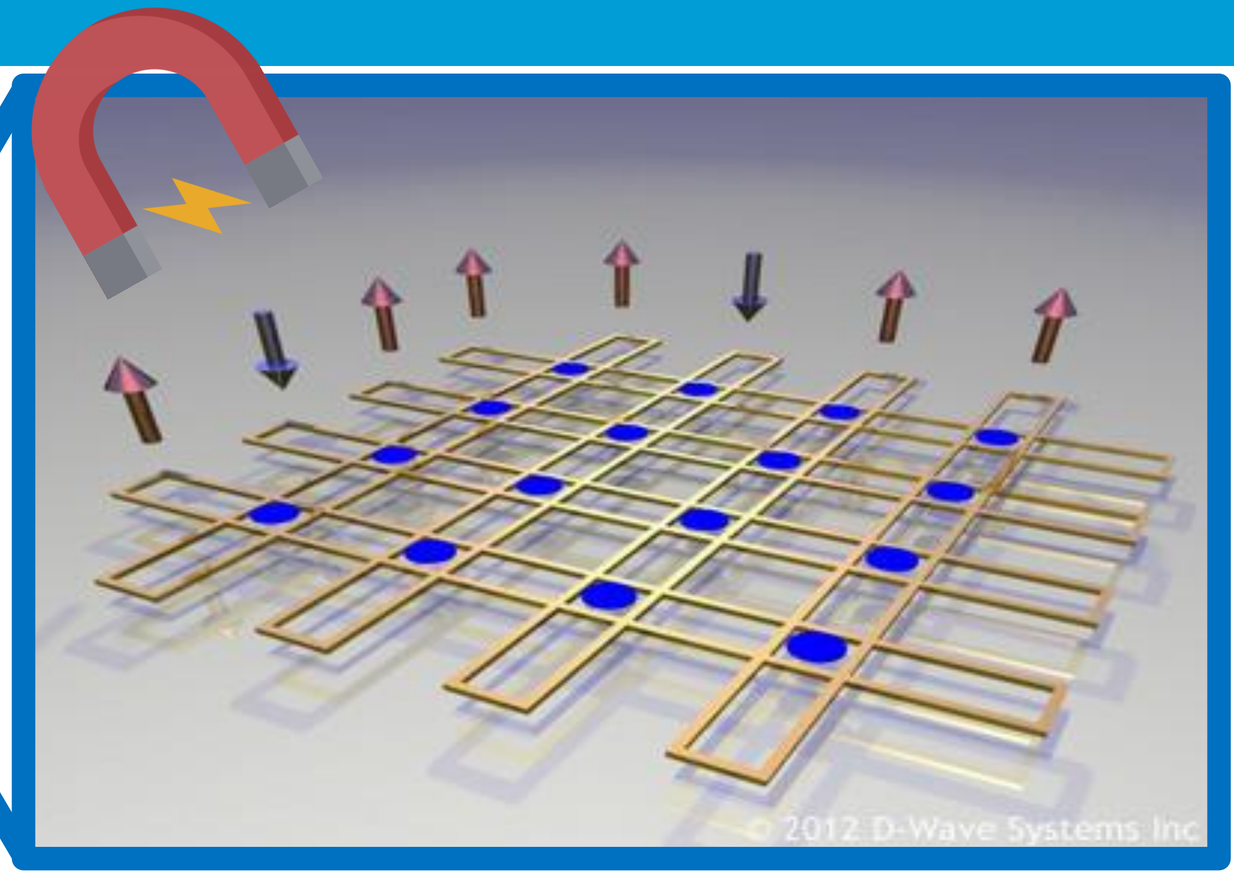
Bias

Qubit

$$H_P = -\sum_i h_i S_i - \sum_{i<j} J_{ij} S_i S_j$$

Couplers

Qubit Interaction



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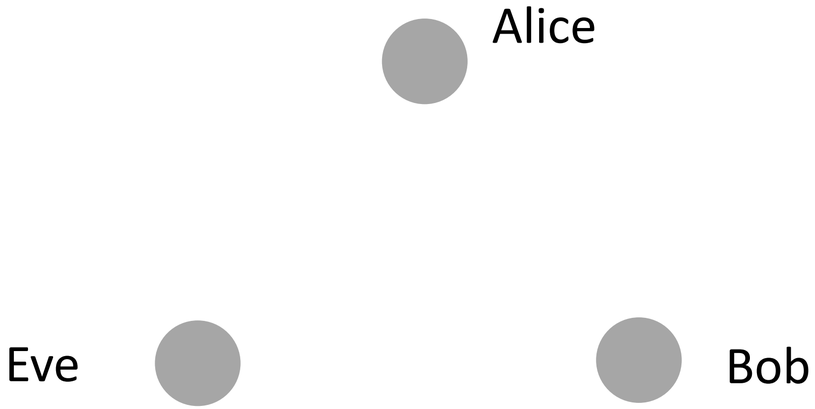
$$-\sum_{ij} J_{ij} S_i S_j$$



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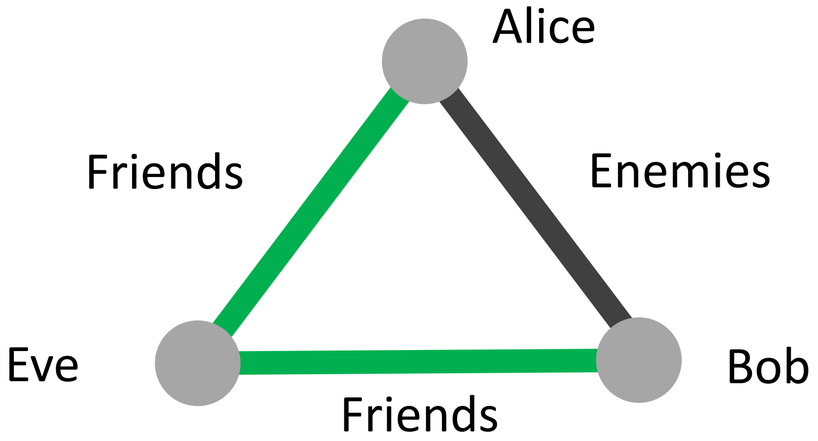

- **Put people in groups to minimize social frustration**:
  - blue people, red people
  - What color to assign to Alice, Bob and Eve?

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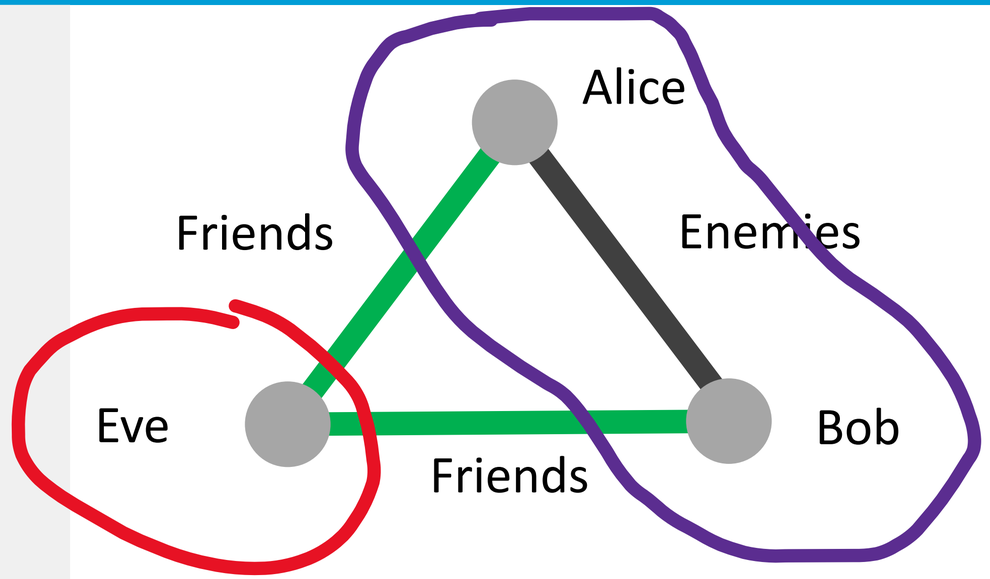

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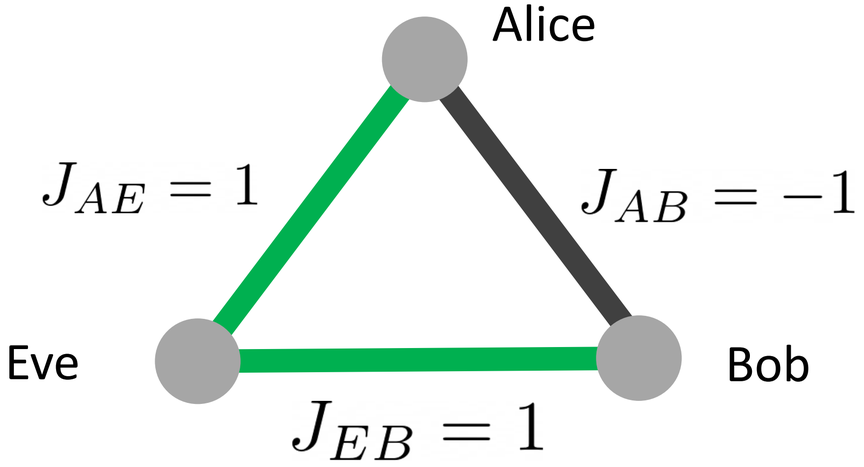
$$-\sum_{ij} J_{ij} S_i S_j$$

- **Color to bit:**
  - Blue: $S_i = -1$
  - Red: $S_i = 1$
- **Connection to bit:**
  - Friend: $J_{ij} = 1$
  - Ennemy: $J_{ij} = -1$



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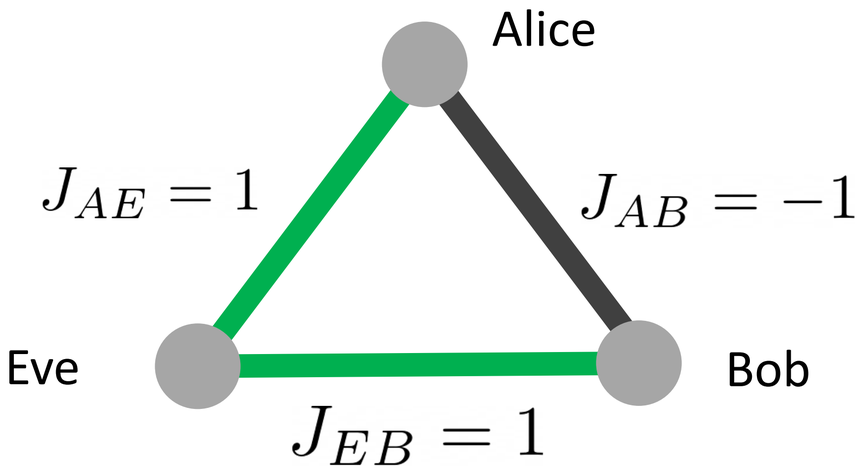

Alice	Bob	Eve	Energy
-1	-1	-1	
1	-1	-1	
-1	1	-1	
-1	1	1	
1	1	1	
1	-1	1	
1	1	-1	
-1	-1	1	

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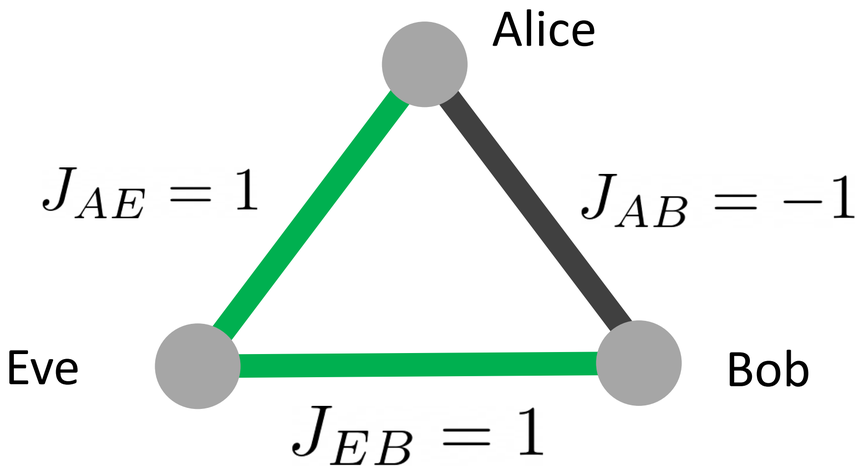

Alice	Bob	Eve	Energy
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1	-1	-1	-1
-1	1	-1	-1
-1	1	1	-1
1	1	1	-1
1	-1	1	-1
1	1	-1	3
-1	-1	1	3

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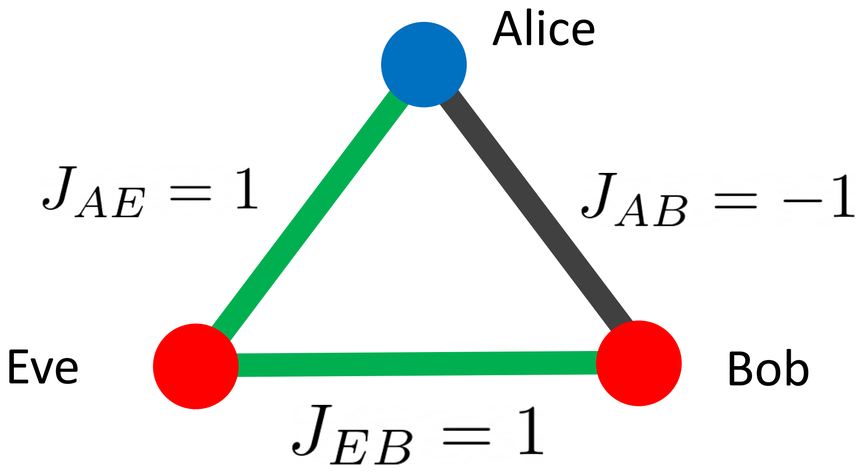

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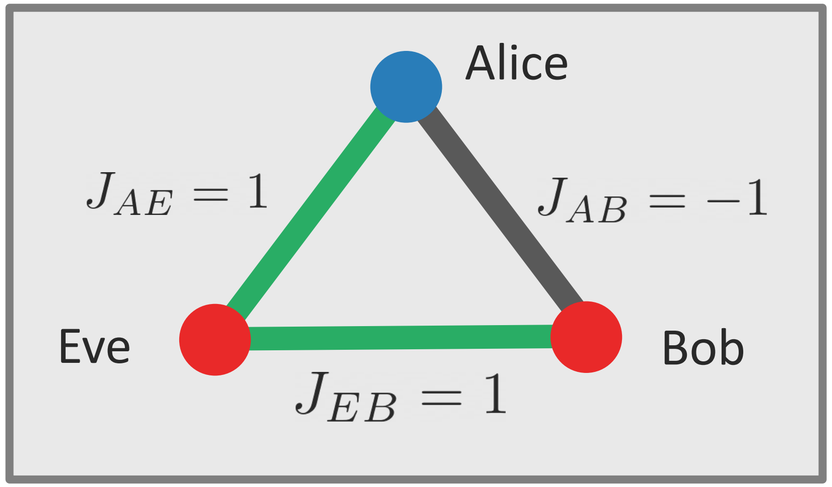

$$
\begin{aligned}
|\text{Output}\rangle = & A|-1,-1,-1\rangle + B|1,-1,-1\rangle \\
& + C|-1,1,-1\rangle + D|-1,1,1\rangle \\
& + E|1,1,1\rangle + F|1,-1,-1\rangle \\
& + G|1,1,-1\rangle + H|-1,-1,1\rangle
\end{aligned}
$$

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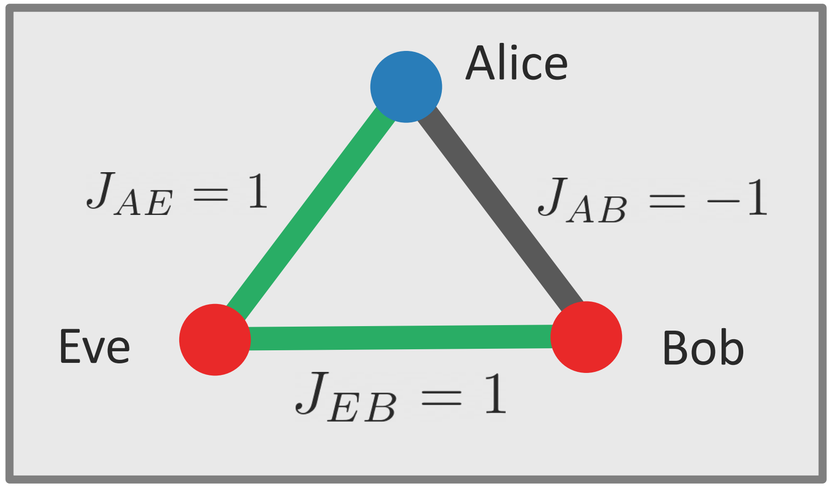

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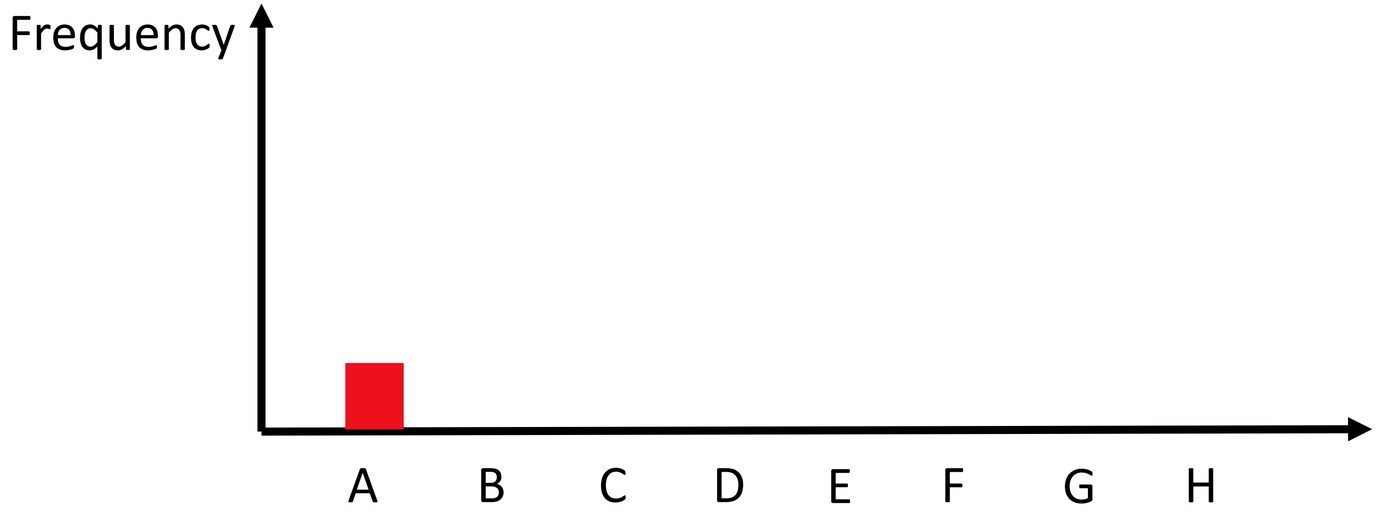

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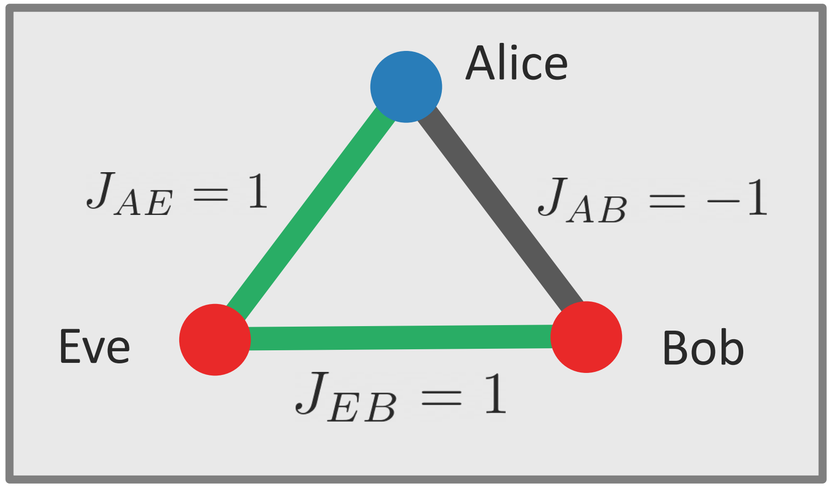

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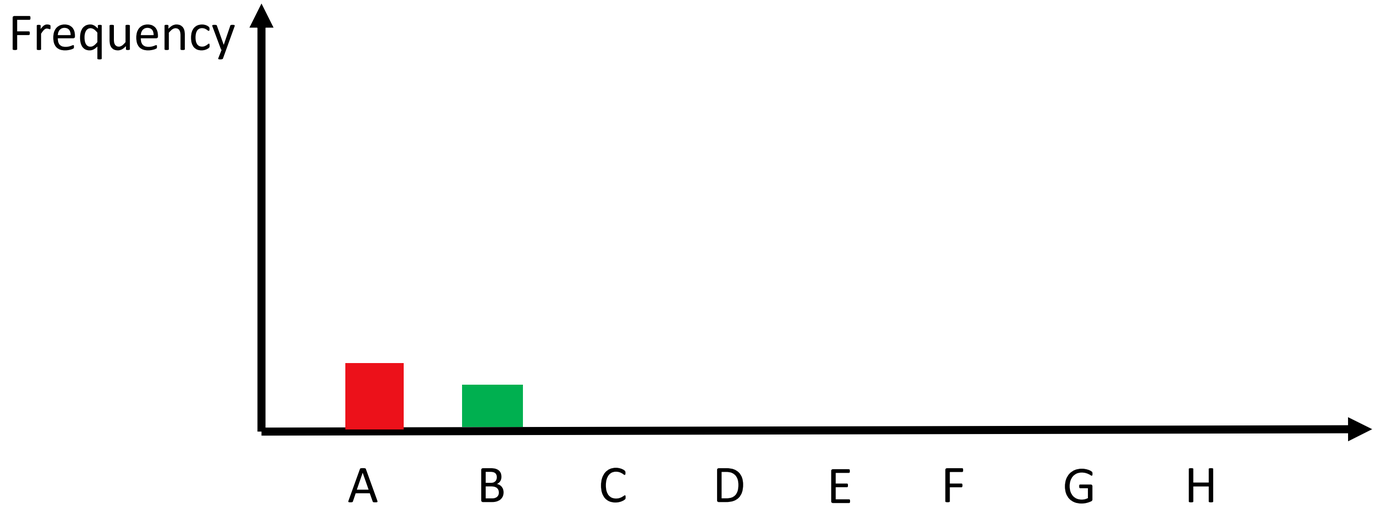

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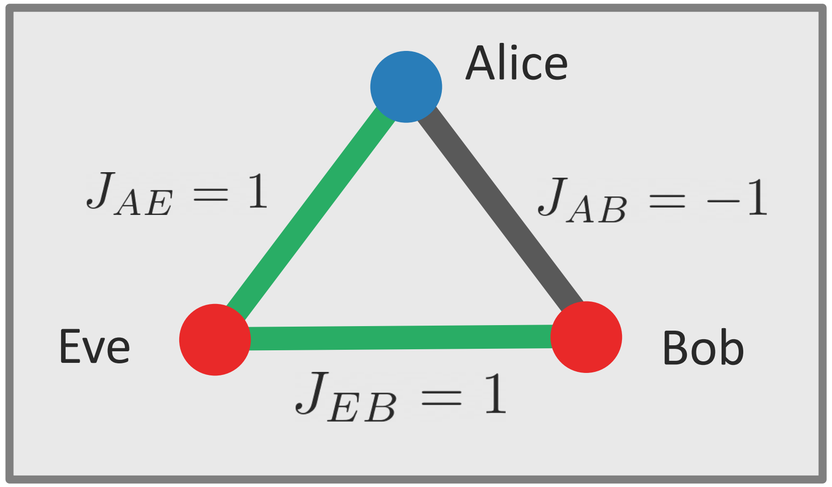

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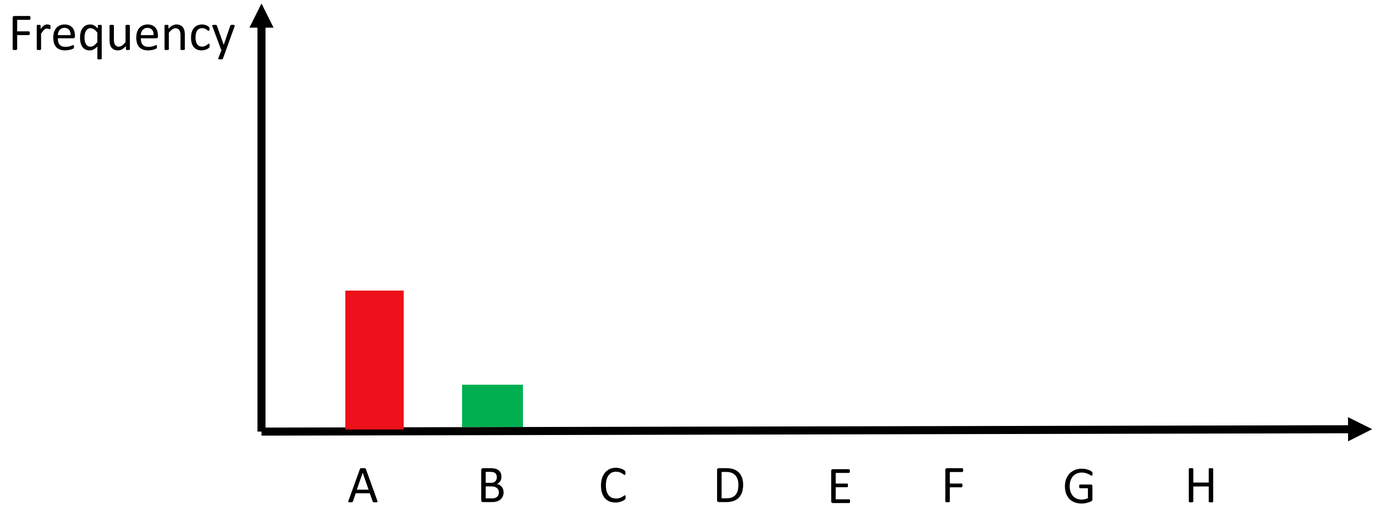

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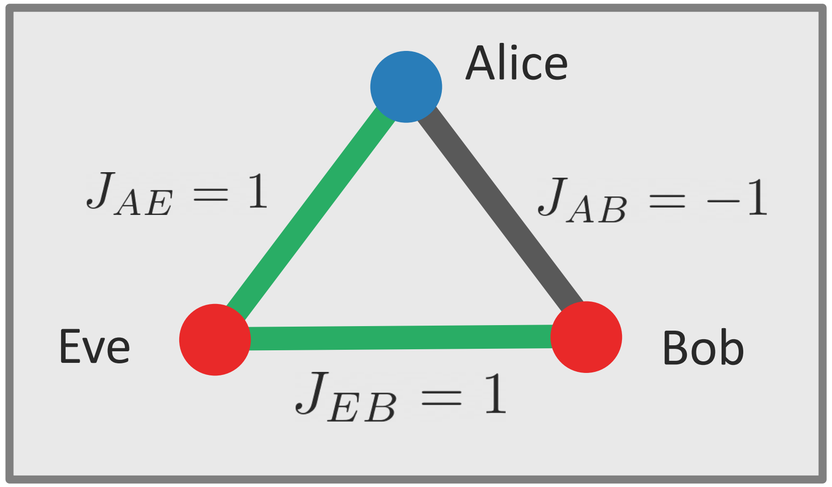

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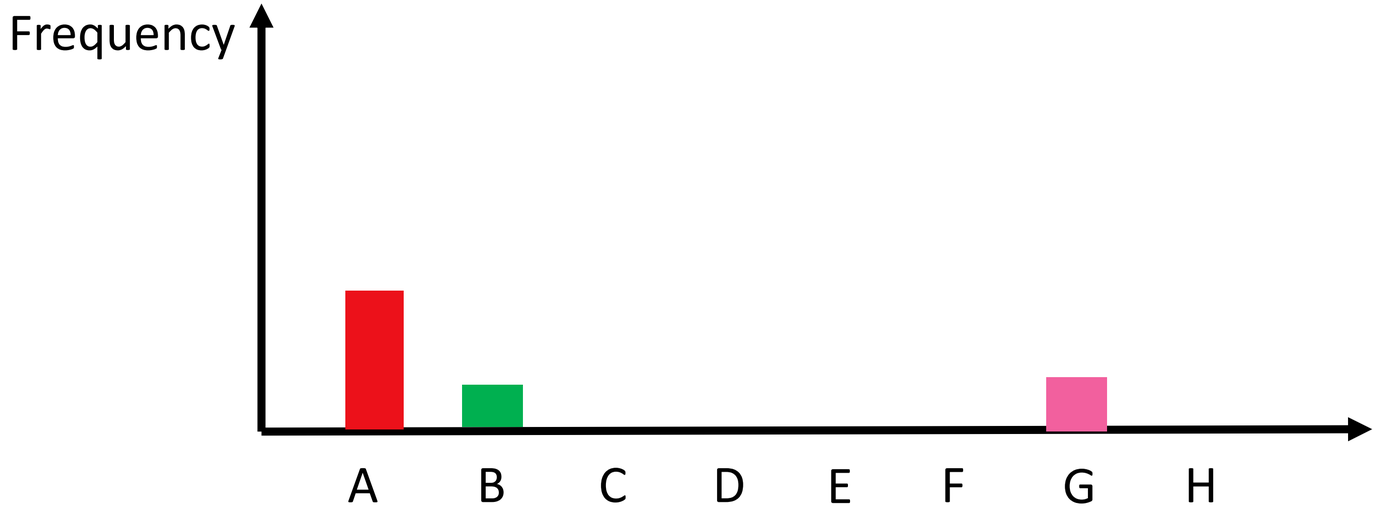

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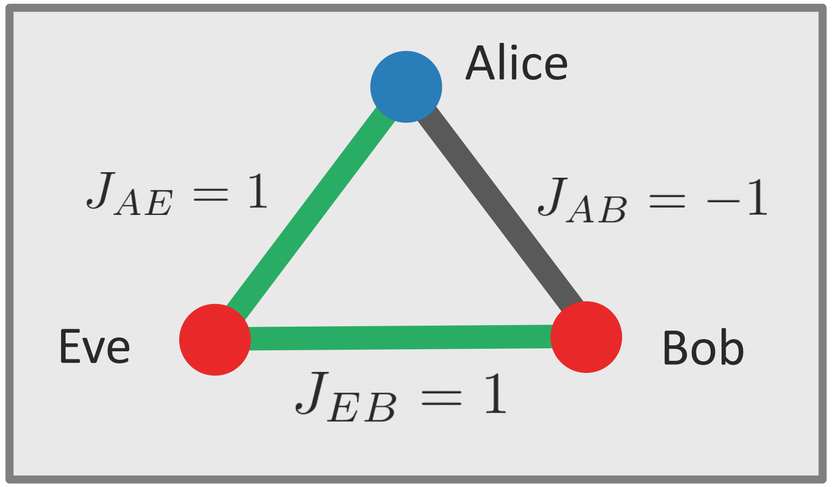

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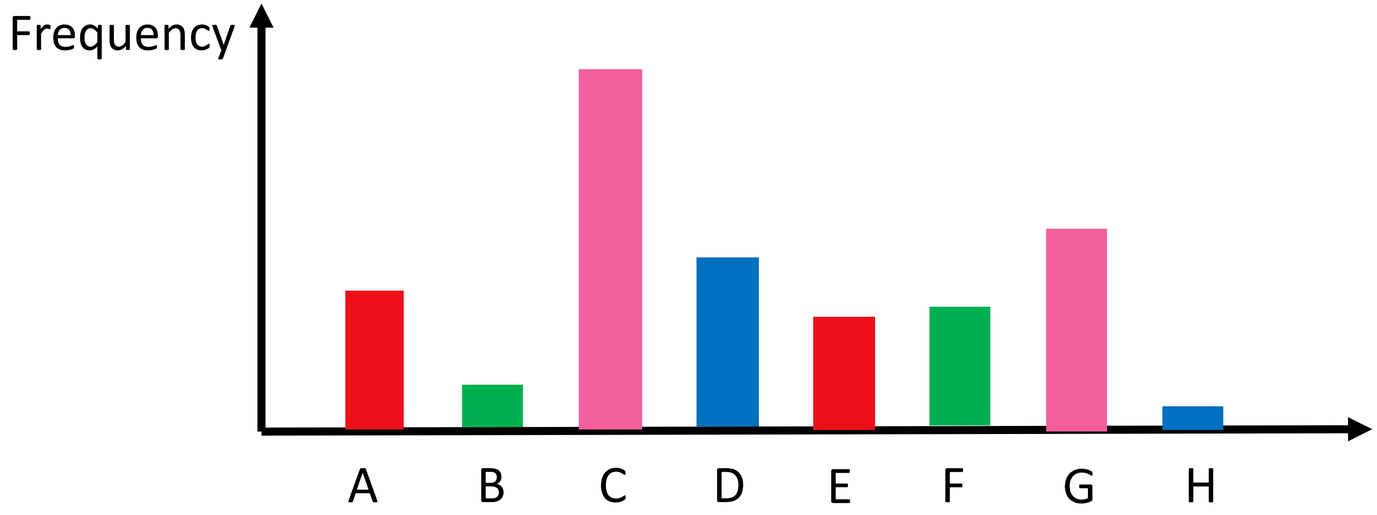

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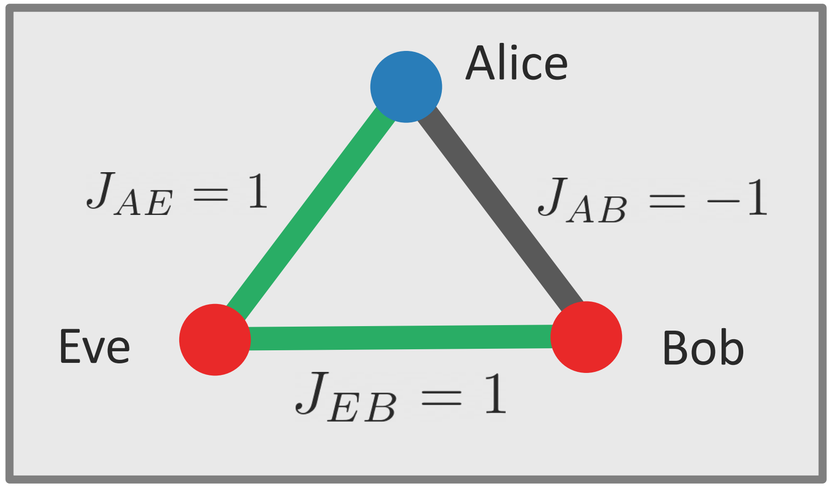
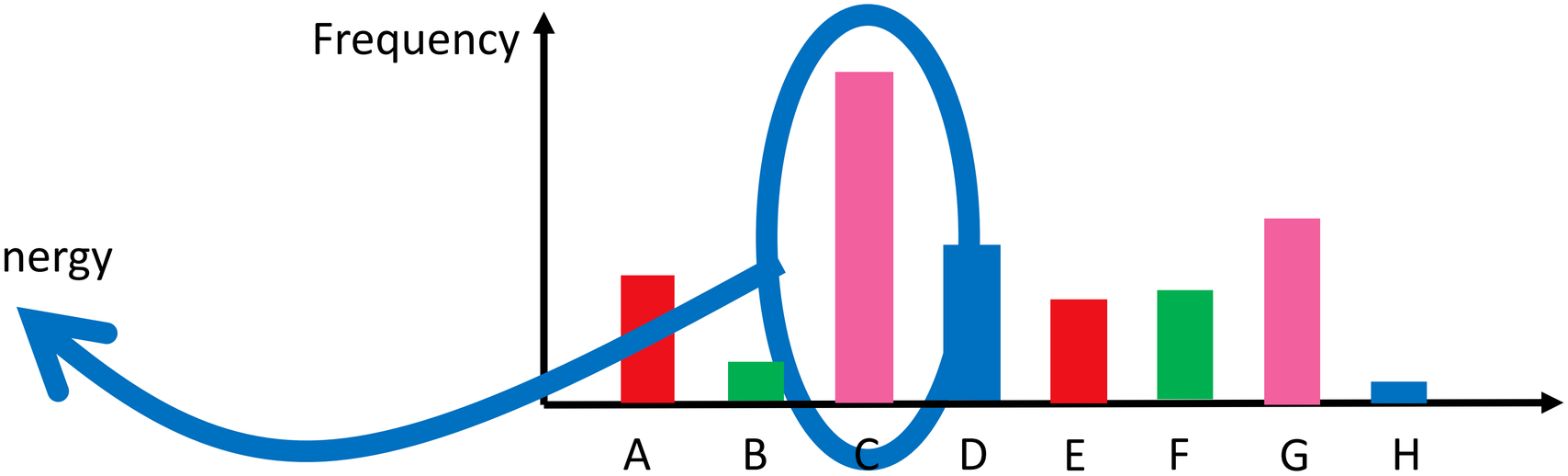


$$|\text{Output}\rangle = A|-1,-1,-1\rangle + B|1,-1,-1\rangle + C|-1,1,-1\rangle + D|-1,1,1\rangle + E|1,1,1\rangle + F|1,-1,-1\rangle + G|1,1,-1\rangle + H|-1,-1,1\rangle$$

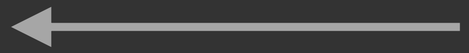
Best outcome

- Most likely outcome
- Outcome with lowest energy



Quantum Computing

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



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Renaissance in material physics

A Simulation Worth A Trillion Dollars

nature

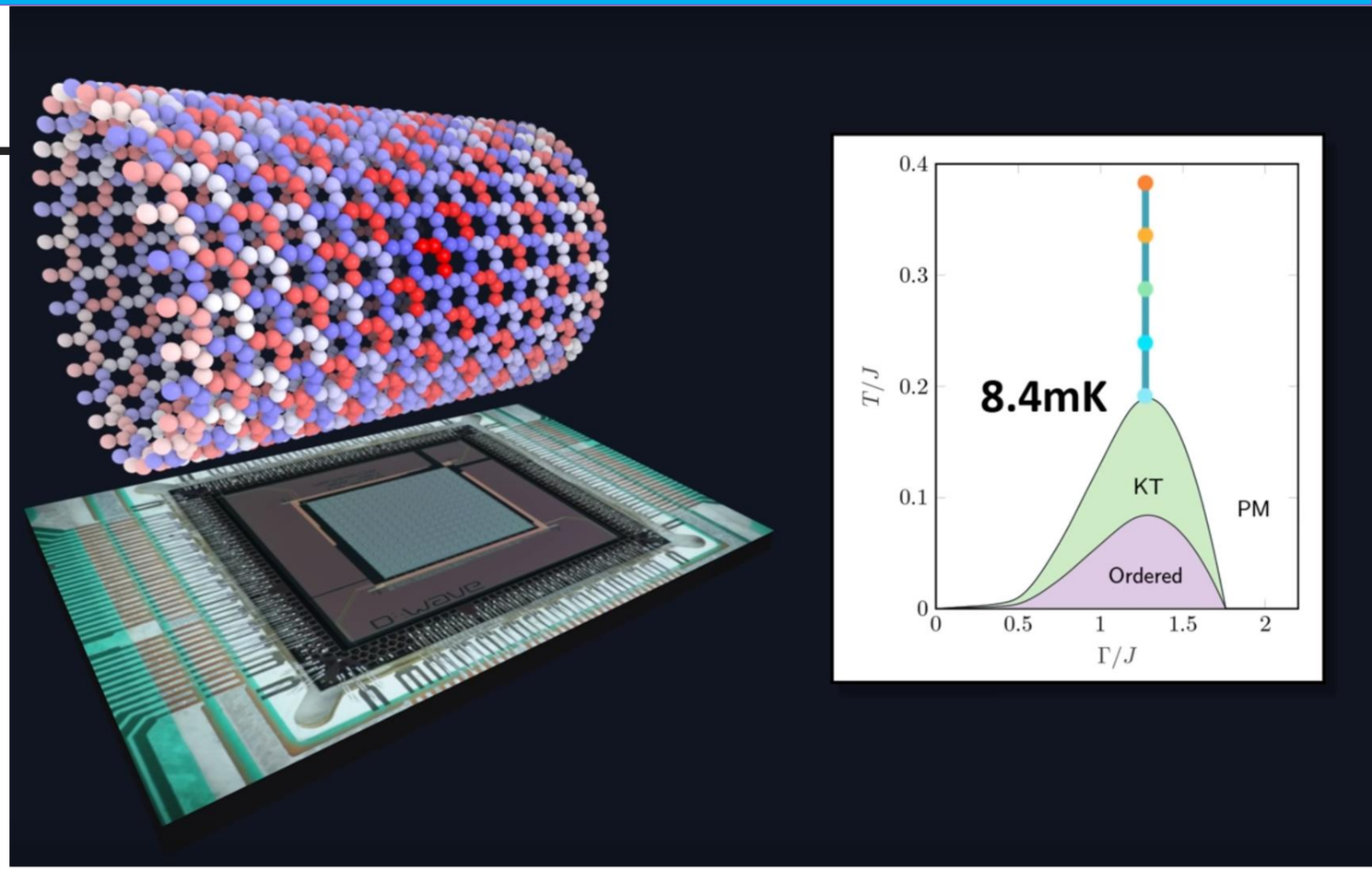
Letter | Published: 22 August 2018

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

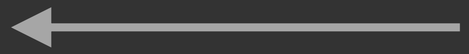
5147 Accesses | **41** Citations | **219** Altmetric | Metrics



- 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



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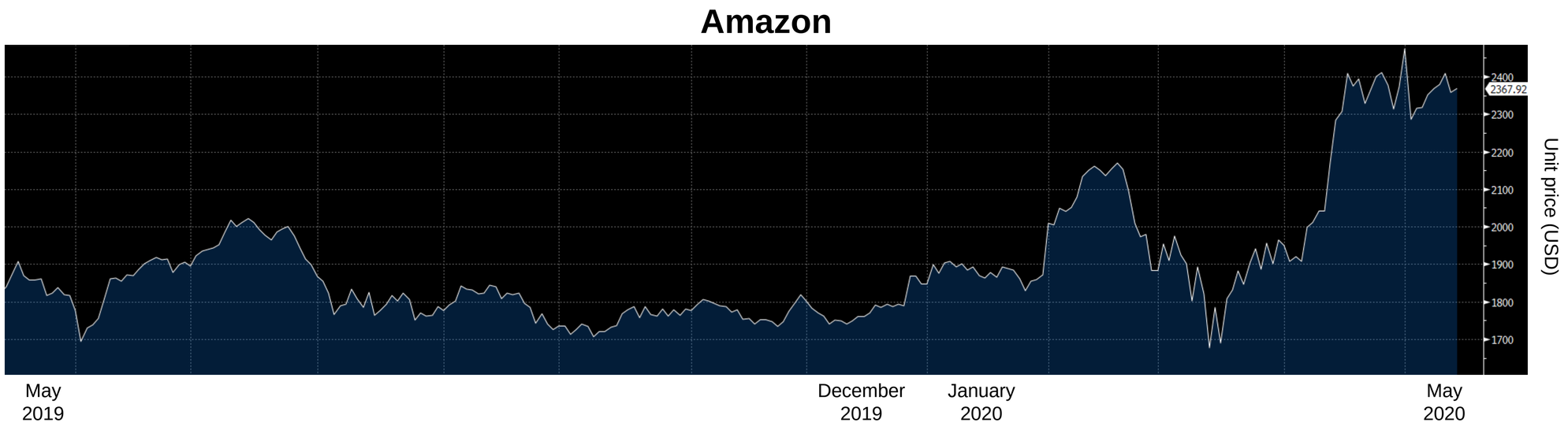
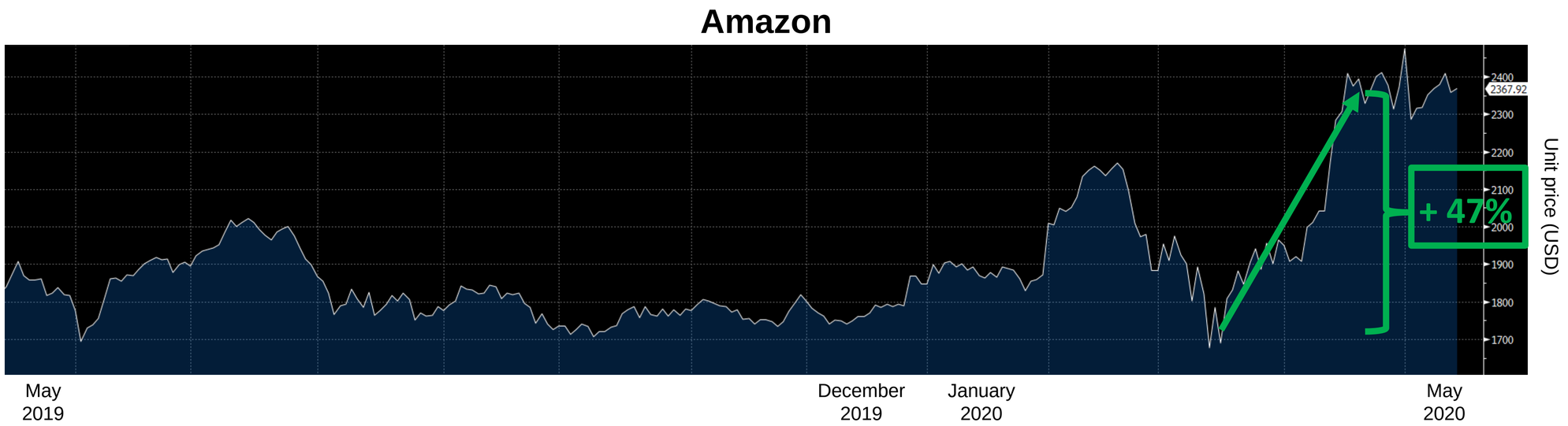
Quantum Computing in Finance

Modern Portfolio Theory in a Nutshell



Quantum Computing in Finance

Modern Portfolio Theory in a Nutshell



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

Buy Low – Sell High: **buy** unit at $1,700 and **sell** at $2,367,

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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

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,

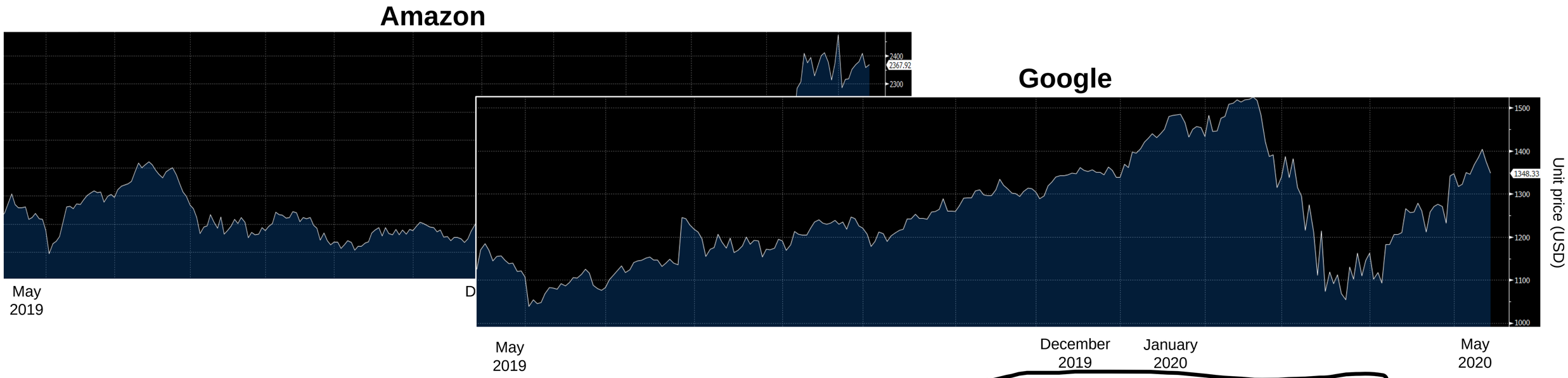
gain +22% on investment

Return on Investment (ROI):

$$R(t) = r(t)$$

Quantum Computing in Finance

Modern Portfolio Theory in a Nutshell



"20% of all your stocks are Amazon stocks"
"80% of all your stocks are Google stocks"

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

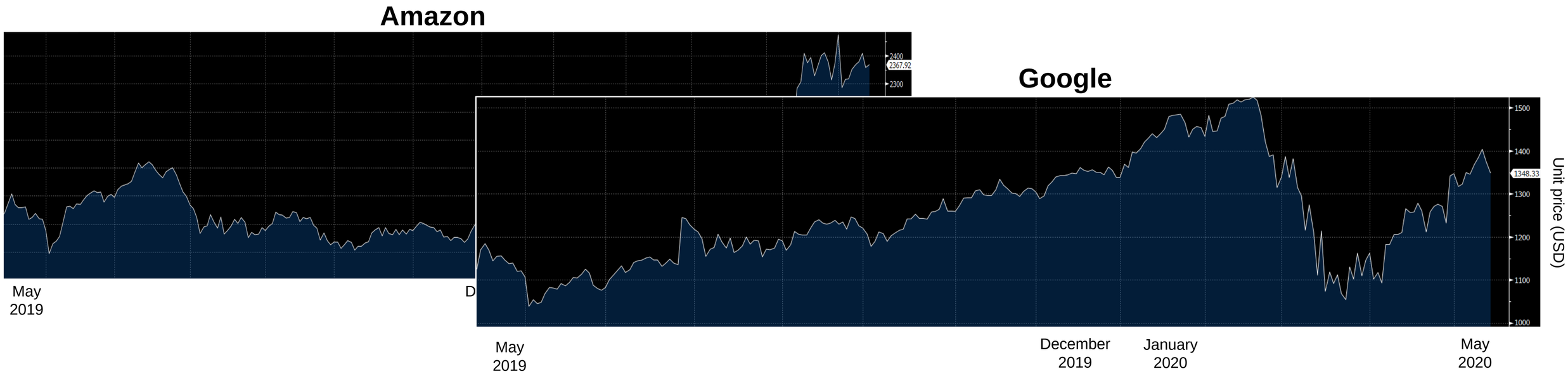
$$R(t) = w_1 r_1(t) + w_2 r_2(t)$$

- **Return on Investment on Portfolio of N stocks:**

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

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):**

Variance of single stock

$$V = \langle R^2 \rangle - \langle R \rangle^2$$

$$= \sum_{i,j} w_i w_j \sigma_i \sigma_j \left(\langle r_i r_j \rangle - \langle r_i \rangle \langle r_j \rangle \right)$$

$$= \sum_{i,j} w_i w_j \rho_{ij}$$

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**

$$
\begin{aligned}
H &= R - qV \\
&= \sum_i r_i w_i - \sum_i \sum_j q \rho_{ij} w_i w_j
\end{aligned}
$$

Quantum Computing in Finance

Modern Portfolio Theory in a Nutshell

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lagrange multiplier = risk tolerance

Quantum Computing in Finance

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Ising Model

$$H_P = \sum_i h_i S_i - \sum_{i,j} J_{ij} S_i S_j$$

Quantum Computing in Finance

Modern Portfolio Theory in a Nutshell

- **Goal of trading**
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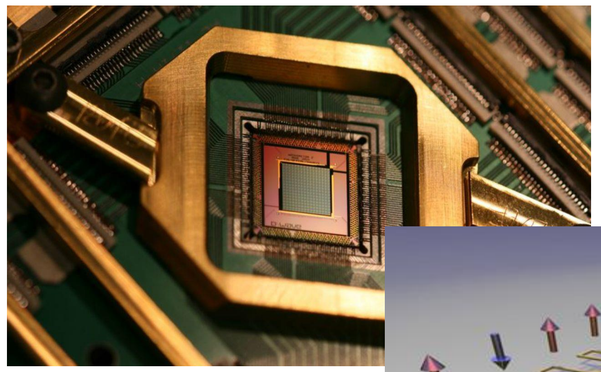

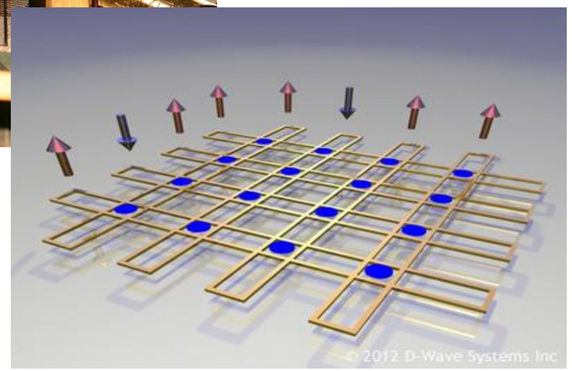

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Quantum Computing in Finance

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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

$$H = R - qV$$

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

with T time steps

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

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

with constraint $\sum_i w_{it} = K$

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$$w_{it} = \begin{cases} i = 1, \cdots, N \text{ equities in portfolio} \\ t = 1, \cdots, T \text{ time step forecasting} \end{cases}$$

N x T binary variables

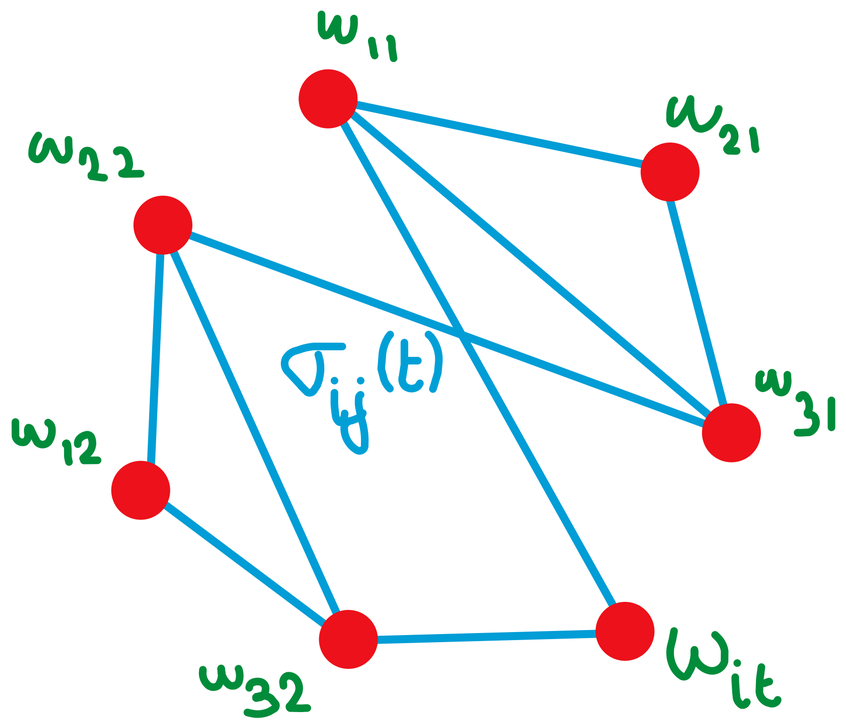
Quantum Computing for Finance: Overview and Prospects, R. Orus, S. Mugel and E. Lizaso
Reviews in Physics 4 (2019)

Quantum Computing in Finance

Modern Portfolio Theory in a Nutshell

NxT binary variables

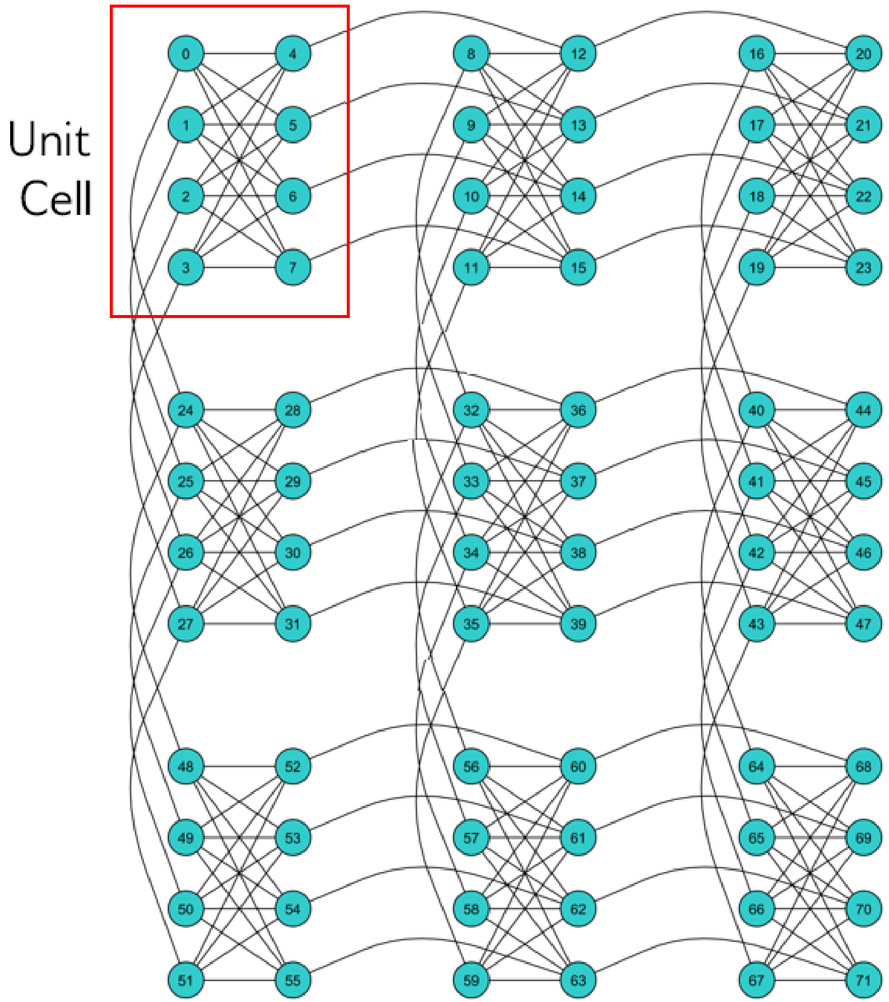
$$H = \sum_{t=1}^{T} \left(\sum_{i} r_i(t) w_{it} - q \sum_{i,j} \sigma_{ij}(t) w_{it} w_{jt} \right) - M \sum_{t=1}^{T} \left(K - \sum_{i} w_{it} \right)^2$$



- 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

$$
\begin{aligned}
V &= 1 + L\min(\mathrm{M}, \mathrm{N}) \\
&= 1 + 4 \times 16 \\
&= 65 \\
&\geq N \times T
\end{aligned}
$$

- 65 assets, 1 time step
- 32 assets, 2 time steps
- 16 assets, 4 time steps

Classical Portfolio Optimization can capture hundreds of assets

Quantum Computing

5. **Outlook**
   - Democratization
   - Quantum Advantage

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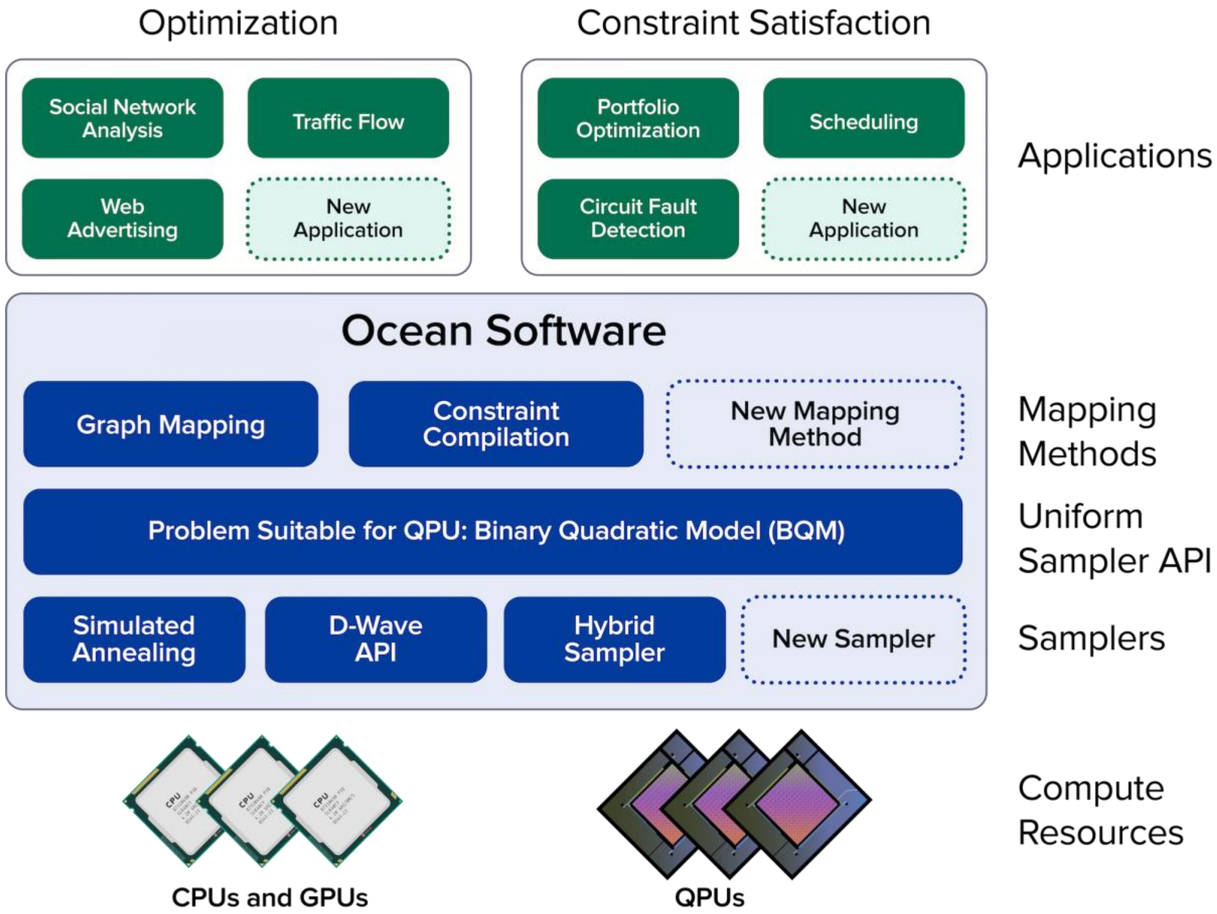
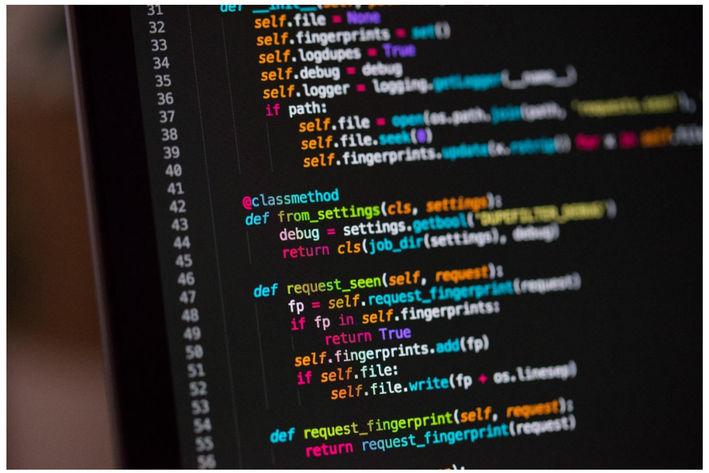
Democratization of Quantum

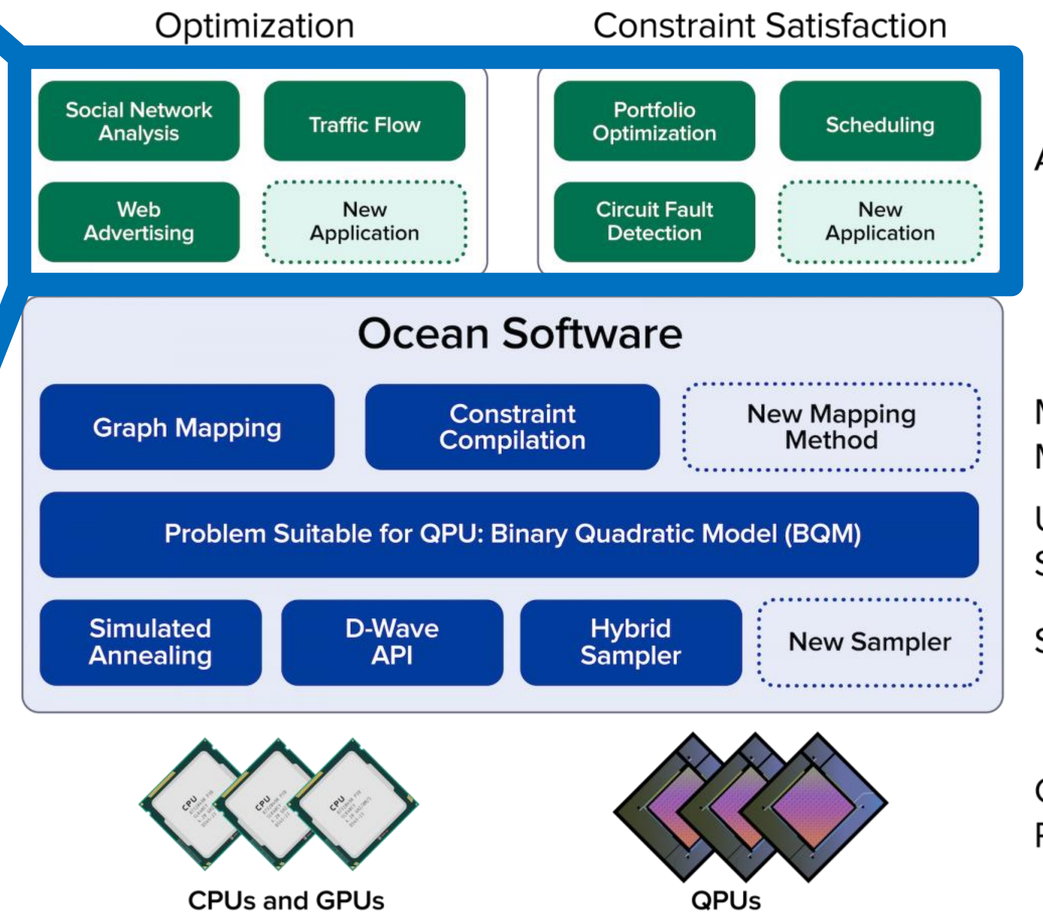
D-Wave open source software stack



Democratization of Quantum

D-Wave open source software stack





Democratization of Quantum

D-Wave open source software stack

Mapping method:

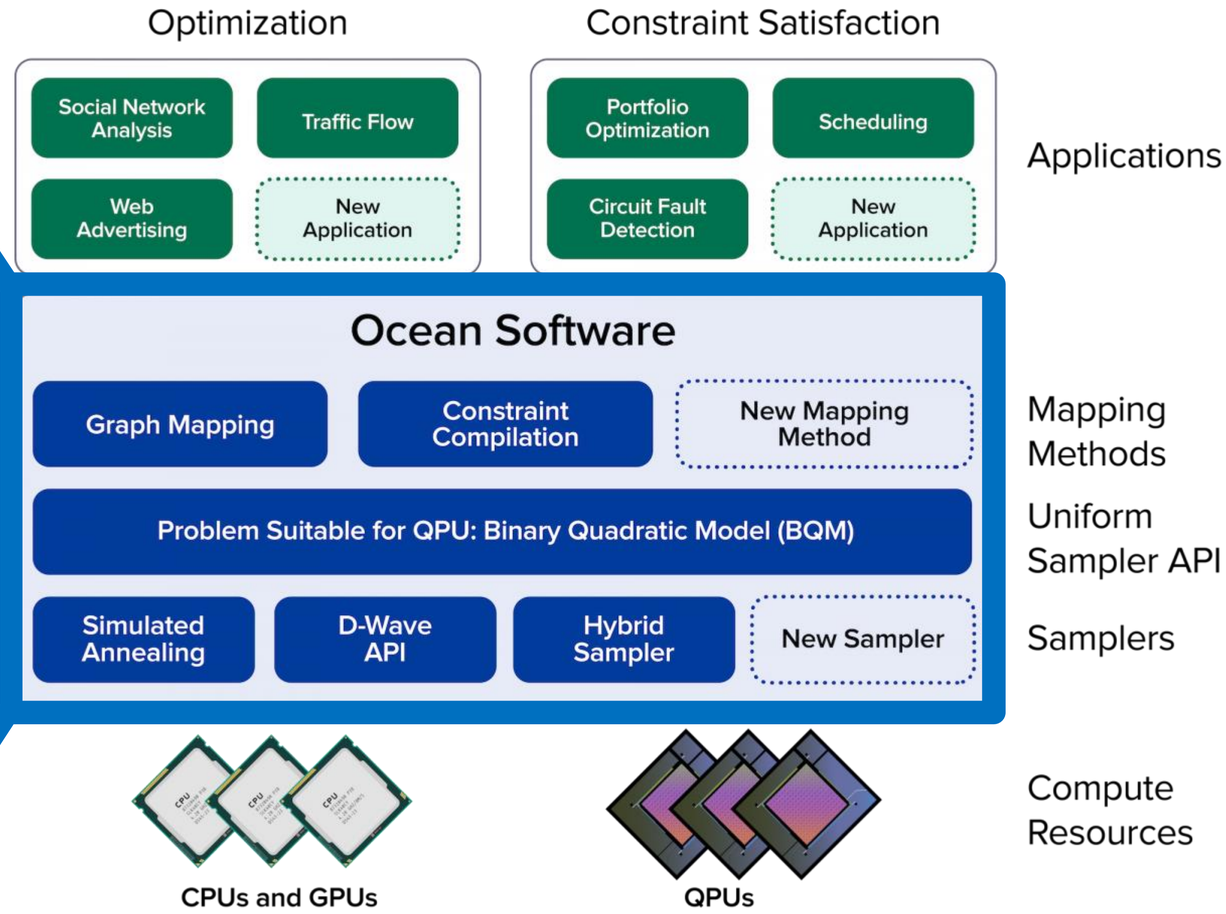
Python tools implementing known problems,graph cliques, graph similarities, etc.

Sampler API:

Defines device to use, connects to the device, and requires user authentification.

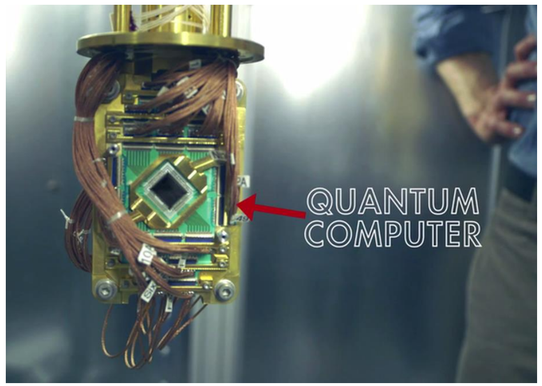
Sampler Embedding Strategy:

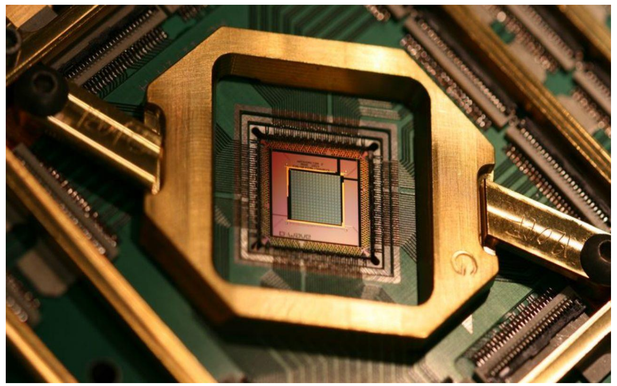
Converts the problem into QPU compatible code, e.g. Ising model or QUBO.

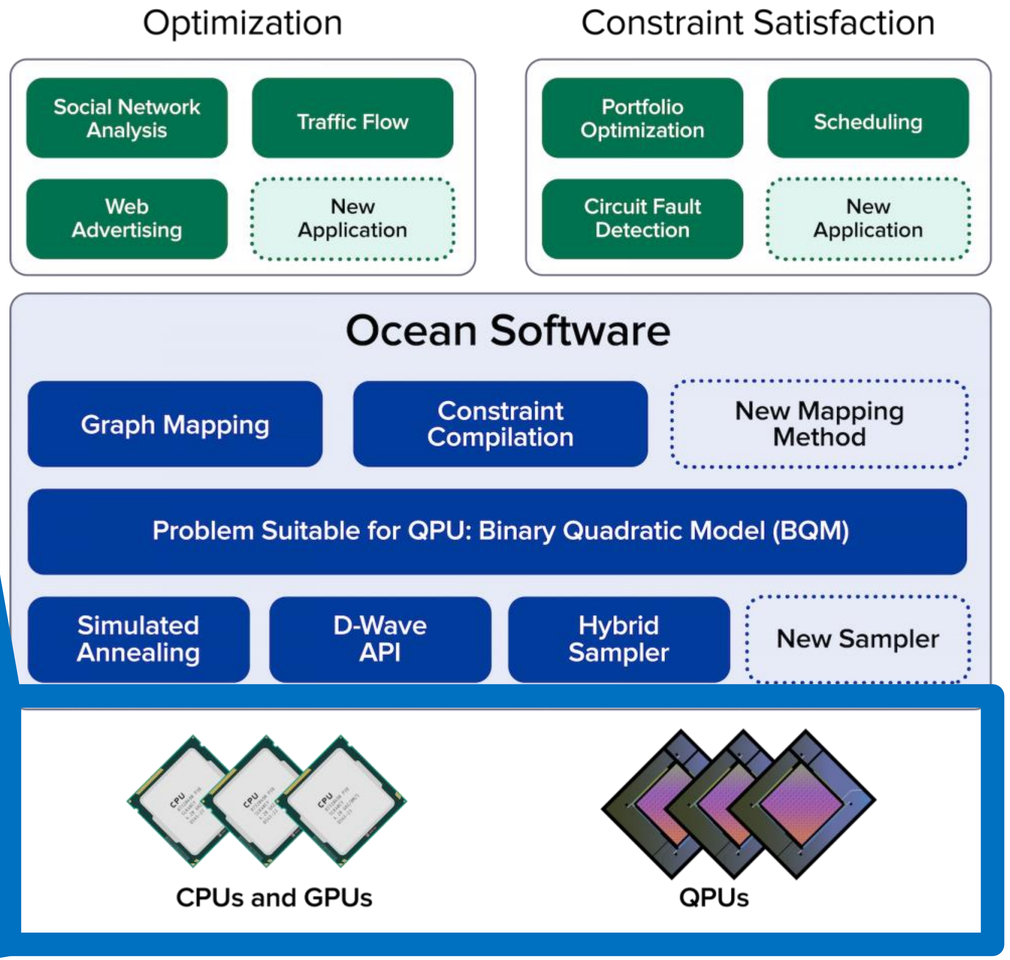


Democratization of Quantum

D-Wave open source software stack



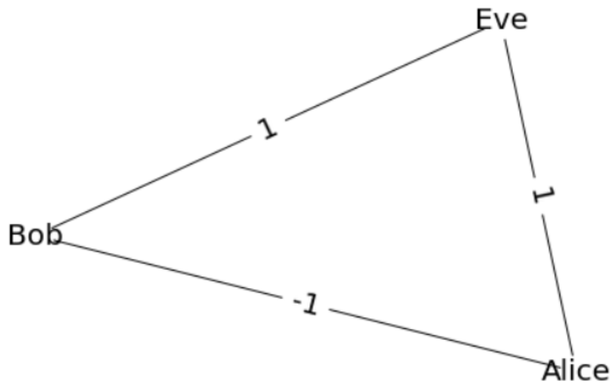


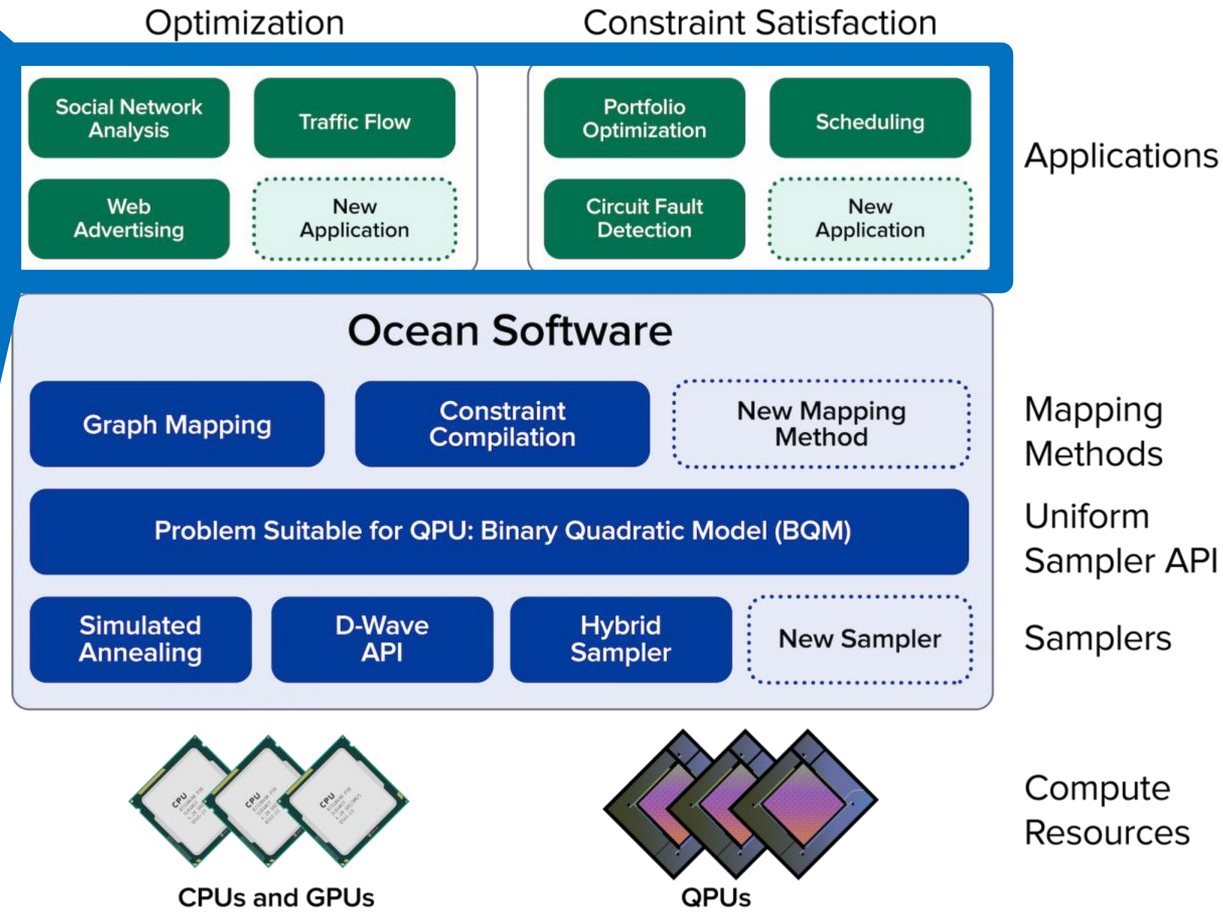


Democratization of Quantum

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)
```

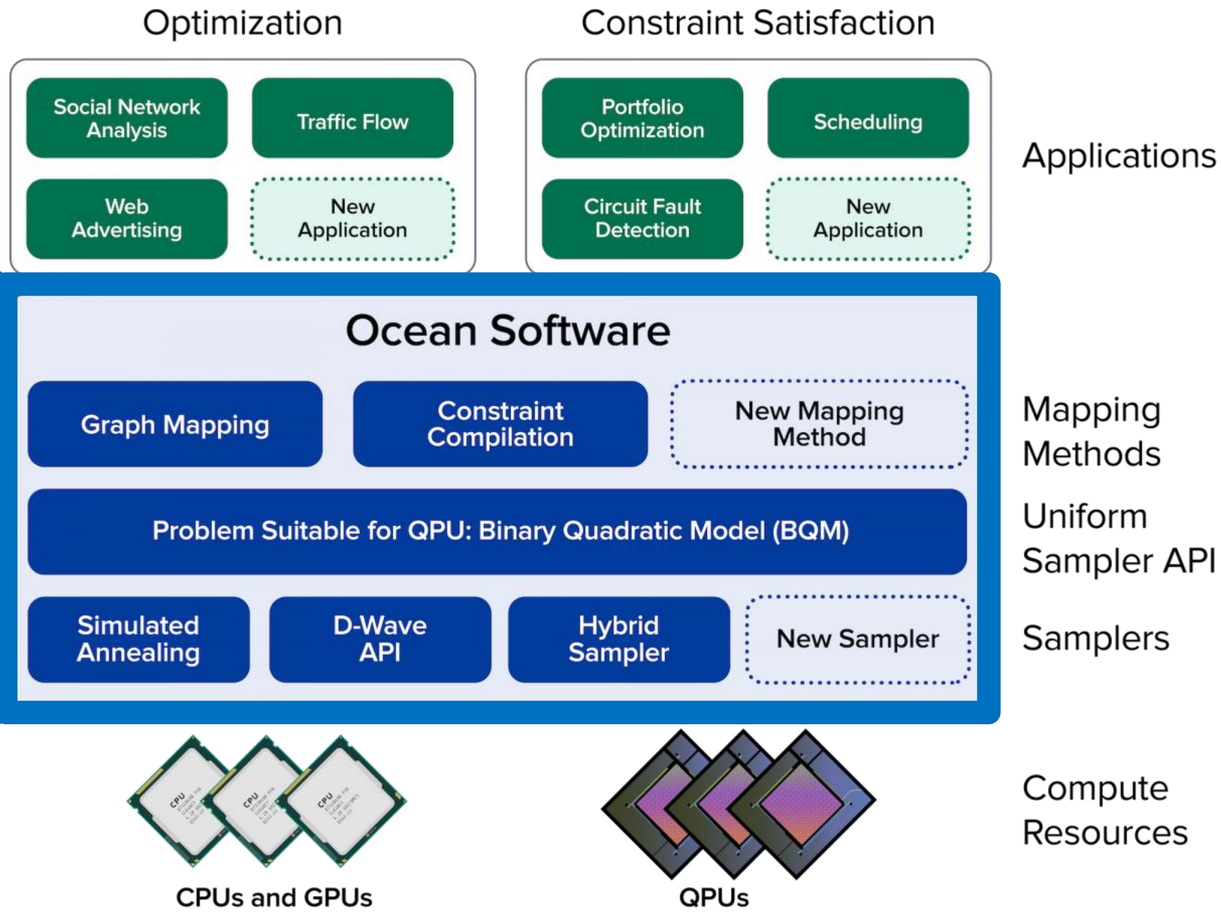




Democratization of Quantum

D-Wave open source software stack

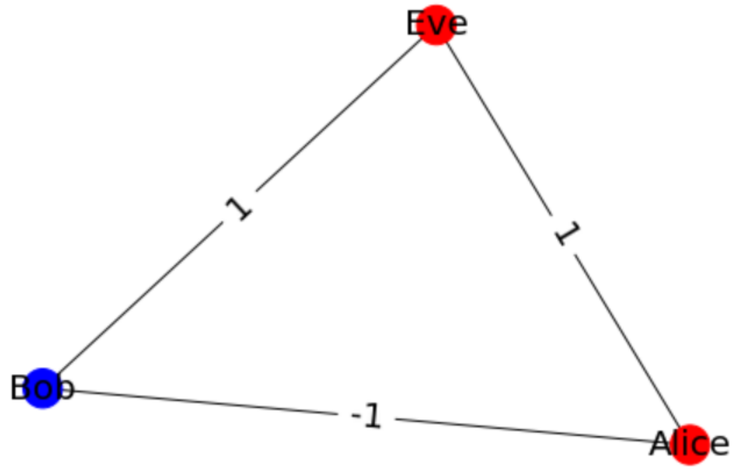
```
from dwave.system.samplers import DWaveSampler
from dwave.system.composites import EmbeddingComposite
import dwave_networkx as dnx
import dimod


my_token = 'my_token'
sampler = DWaveSampler(solver='DW_2000Q_5', token=my_token)
sampler_embed = EmbeddingComposite(sampler)
```

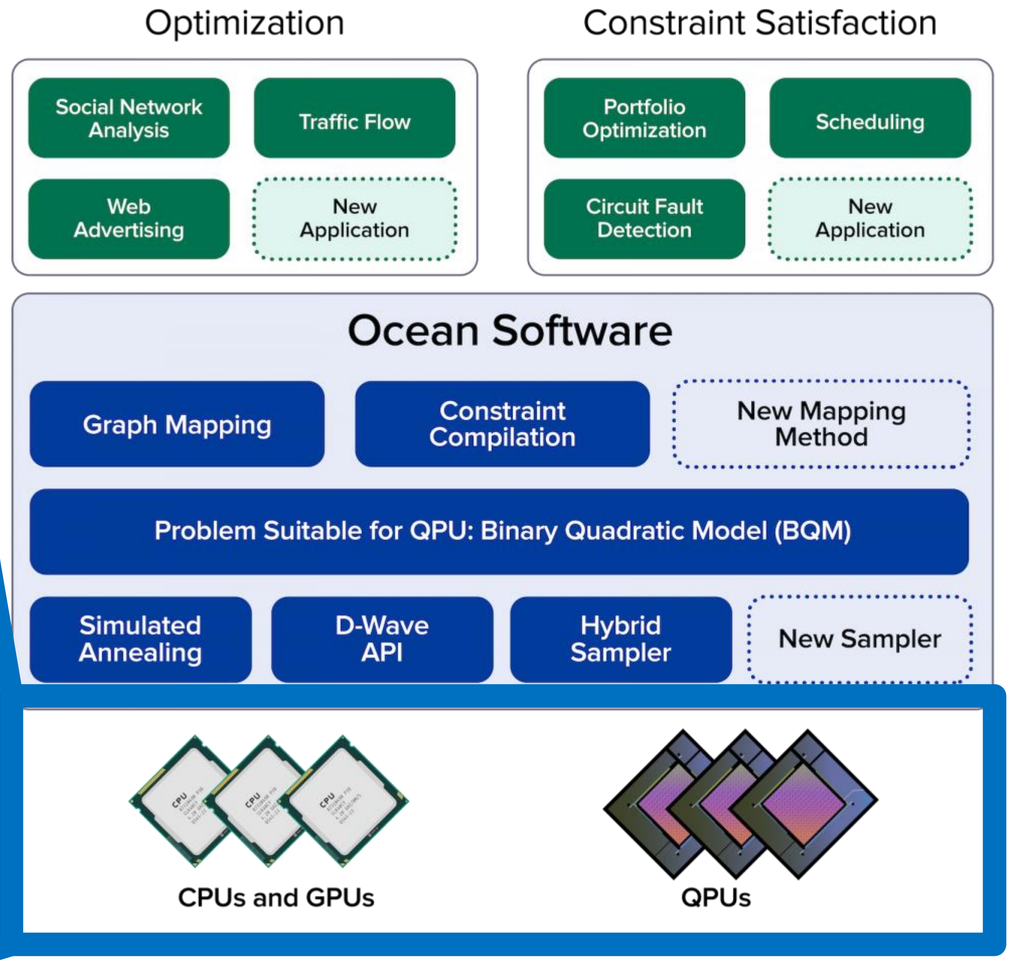


Democratization of Quantum

D-Wave open source software stack

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





Democratization of Quantum

D-Wave open source software stack

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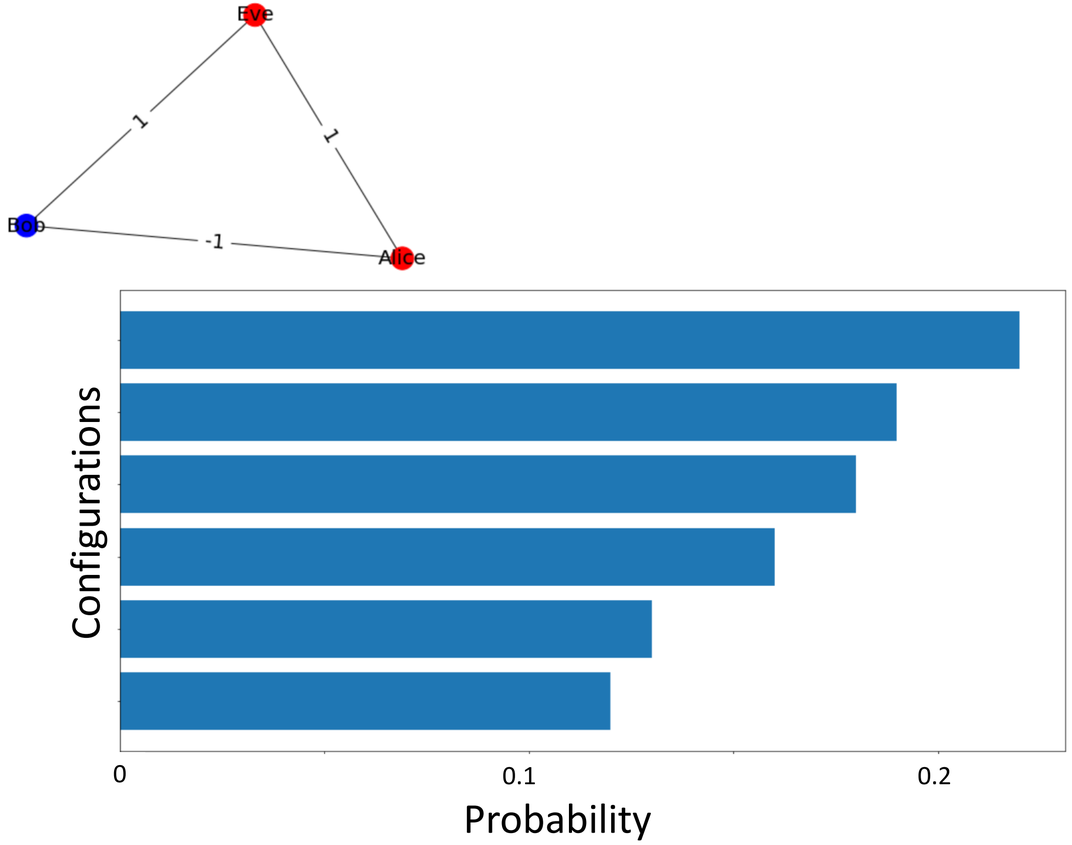


Optimization

Constraint Satisfaction

Social Network Analysis

Traffic Flow

Web Advertising

New Application

Portfolio Optimization

Scheduling

Circuit Fault Detection

New Application

Applications

Ocean Software

Graph Mapping

Constraint Compilation

New Mapping Method

Mapping Methods

Problem Suitable for QPU: Binary Quadratic Model (BQM)

Uniform Sampler API

Simulated Annealing

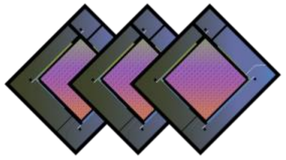
D-Wave API

Hybrid Sampler

New Sampler

Samplers

CPUs and GPUs



QPUs

Compute Resources

Democratization of Quantum

D-Wave open source software stack

```
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```
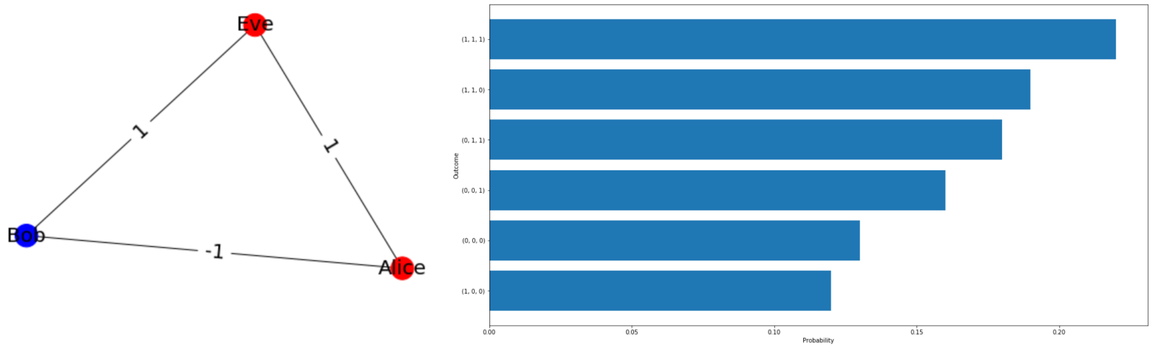
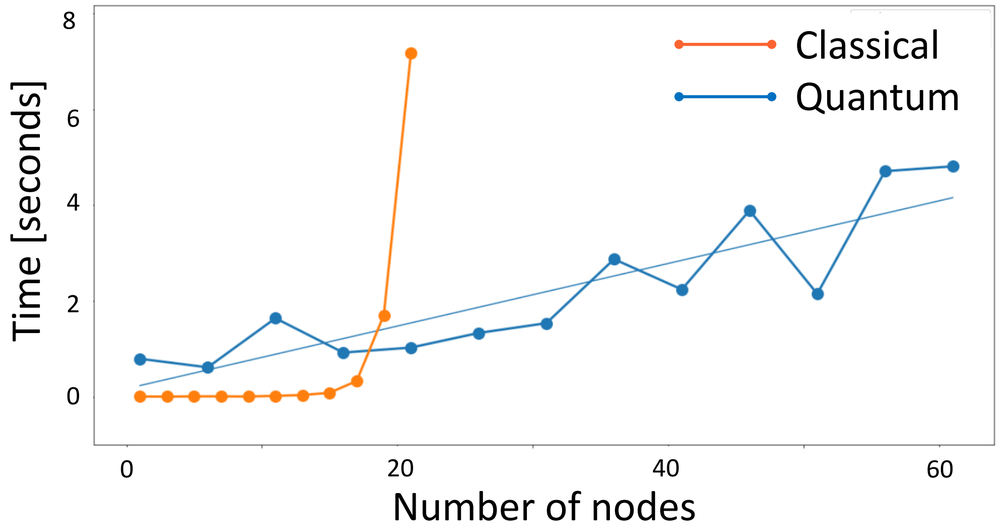
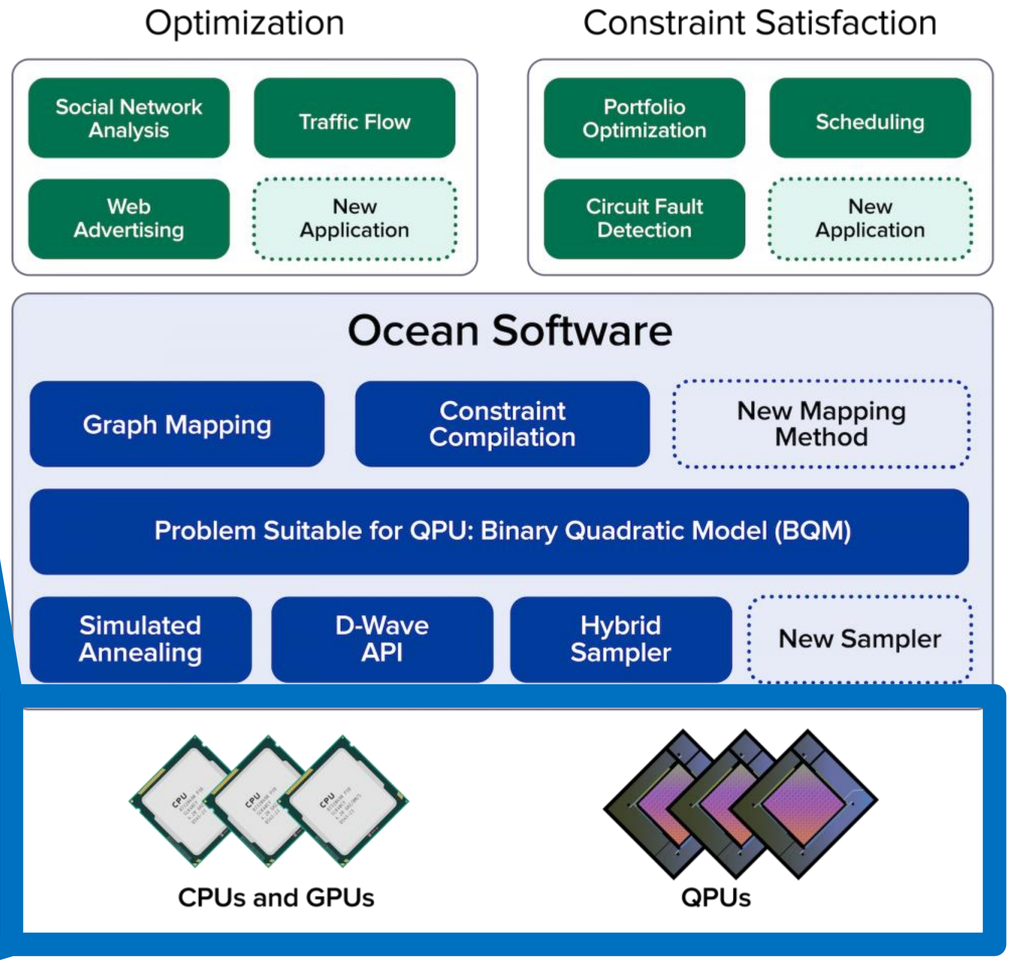



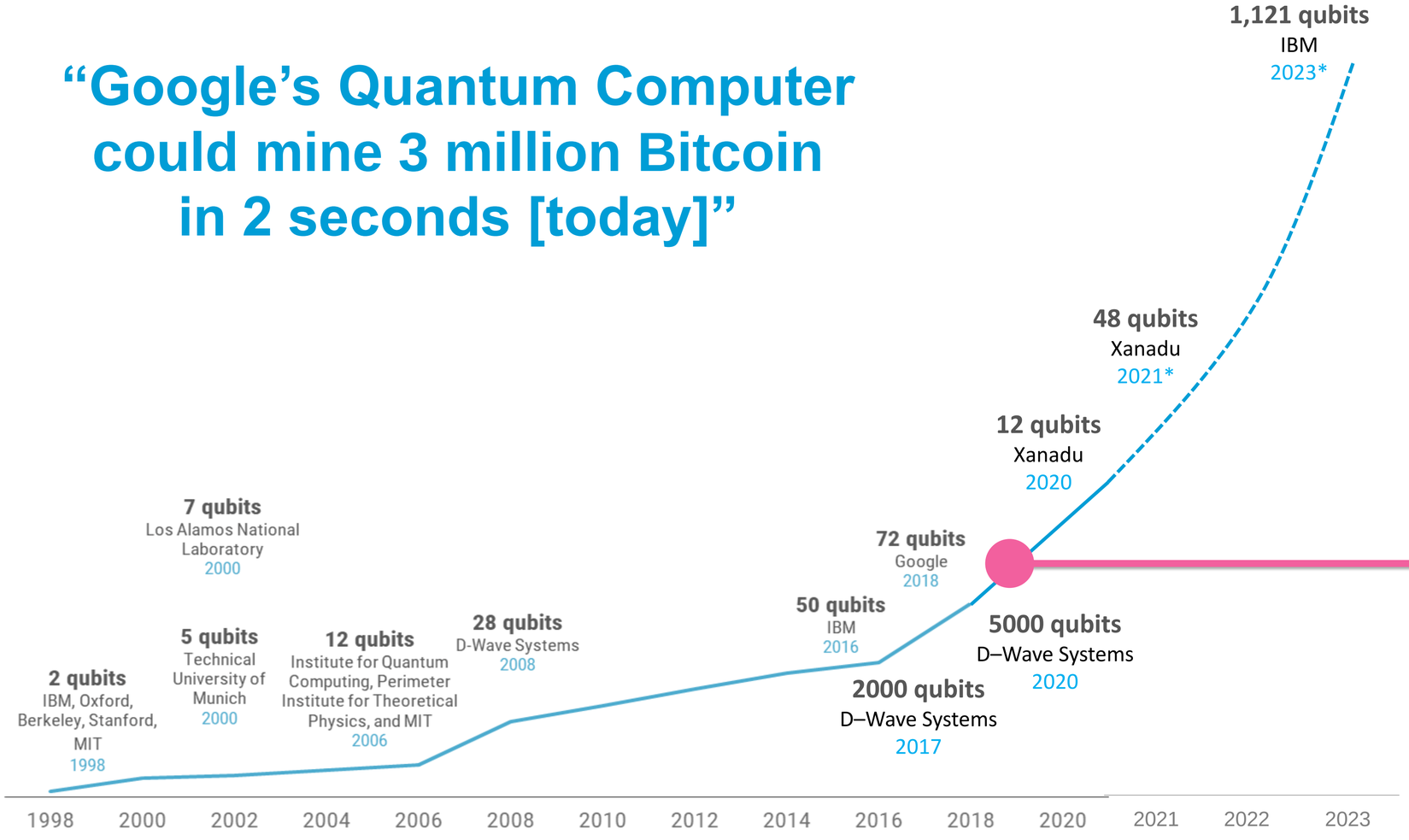




Why Quantum Computing Now?

Did We Just Pass the Tipping Point?

"Google's Quantum Computer could mine 3 million Bitcoin in 2 seconds [today]"



Article | Published: 23 October 2019

Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, [...] John M. Martinis

Nature **574**, 505–510(2019) | Cite this article

758k Accesses | **291** Citations | **6007** Altmetric | Metrics

DSA Lab - Scotiabank
Full stack data science

Understanding the business

Data environment

Data Science

Delivering results

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?

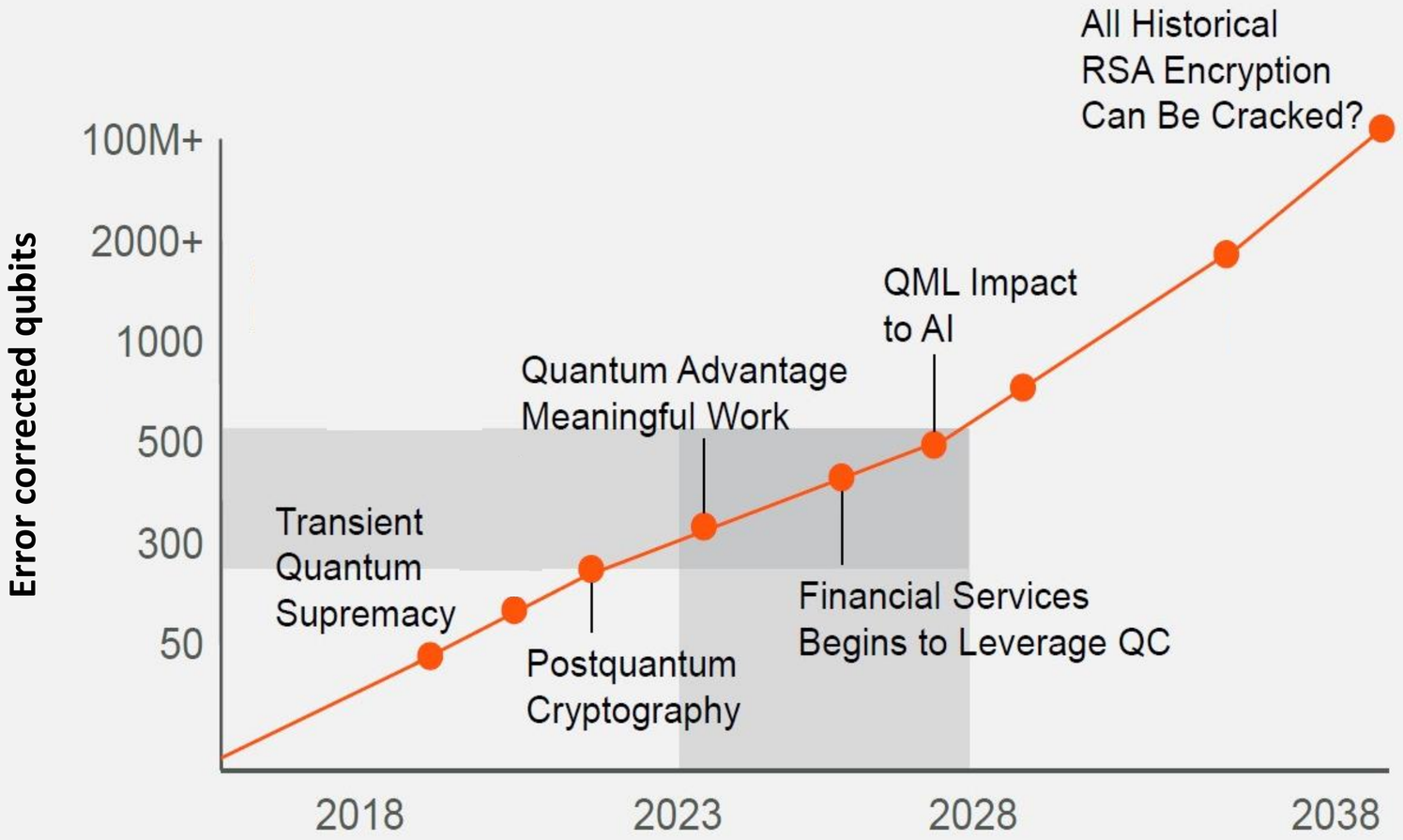
For annealers, rephrase your optimization or search problem into a Ising model.

Thank you

Back up

Why Quantum Computing Now?

Did We Just Pass the Tipping Point?



Note: Dates are speculative

Gartner

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**

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