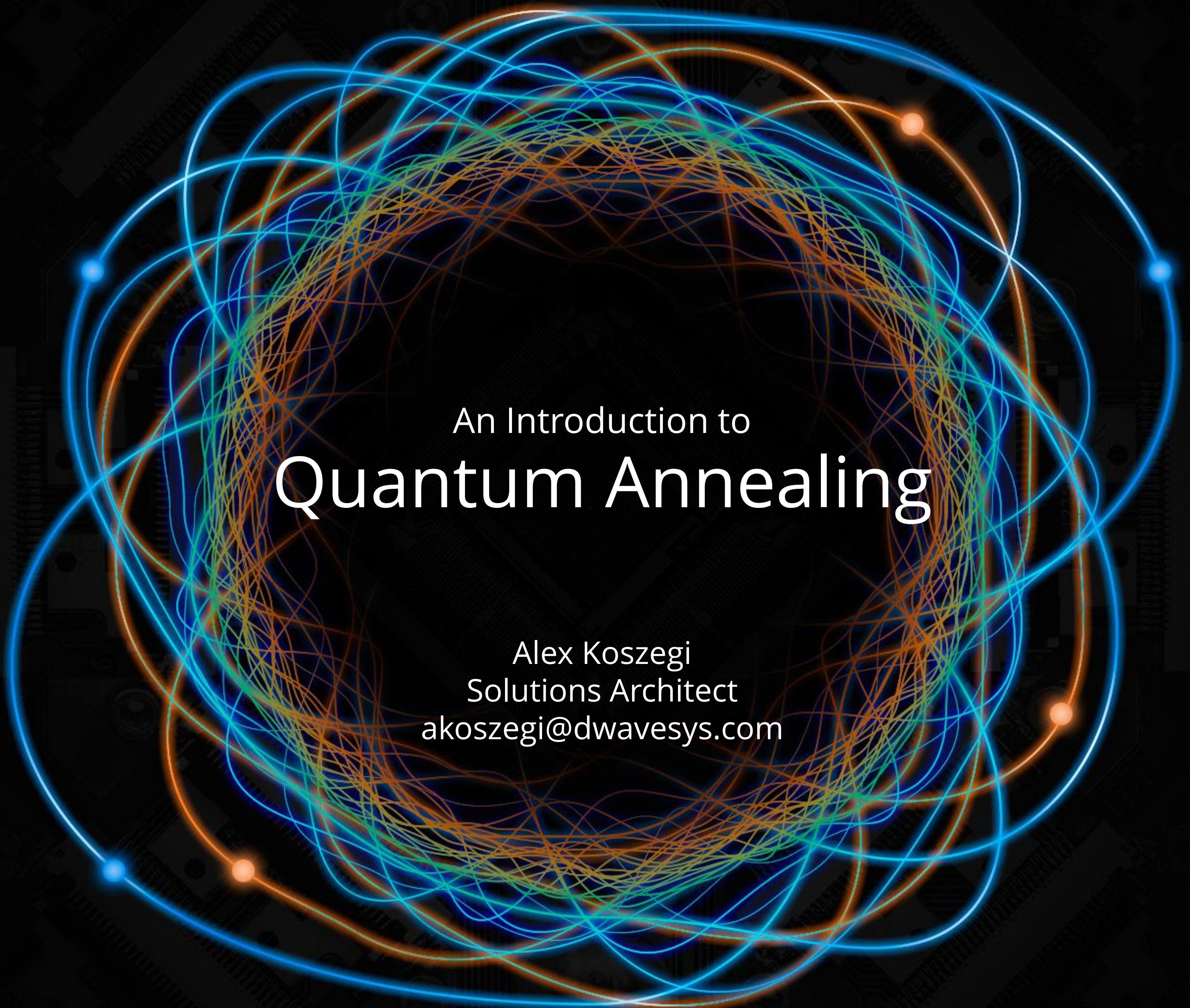


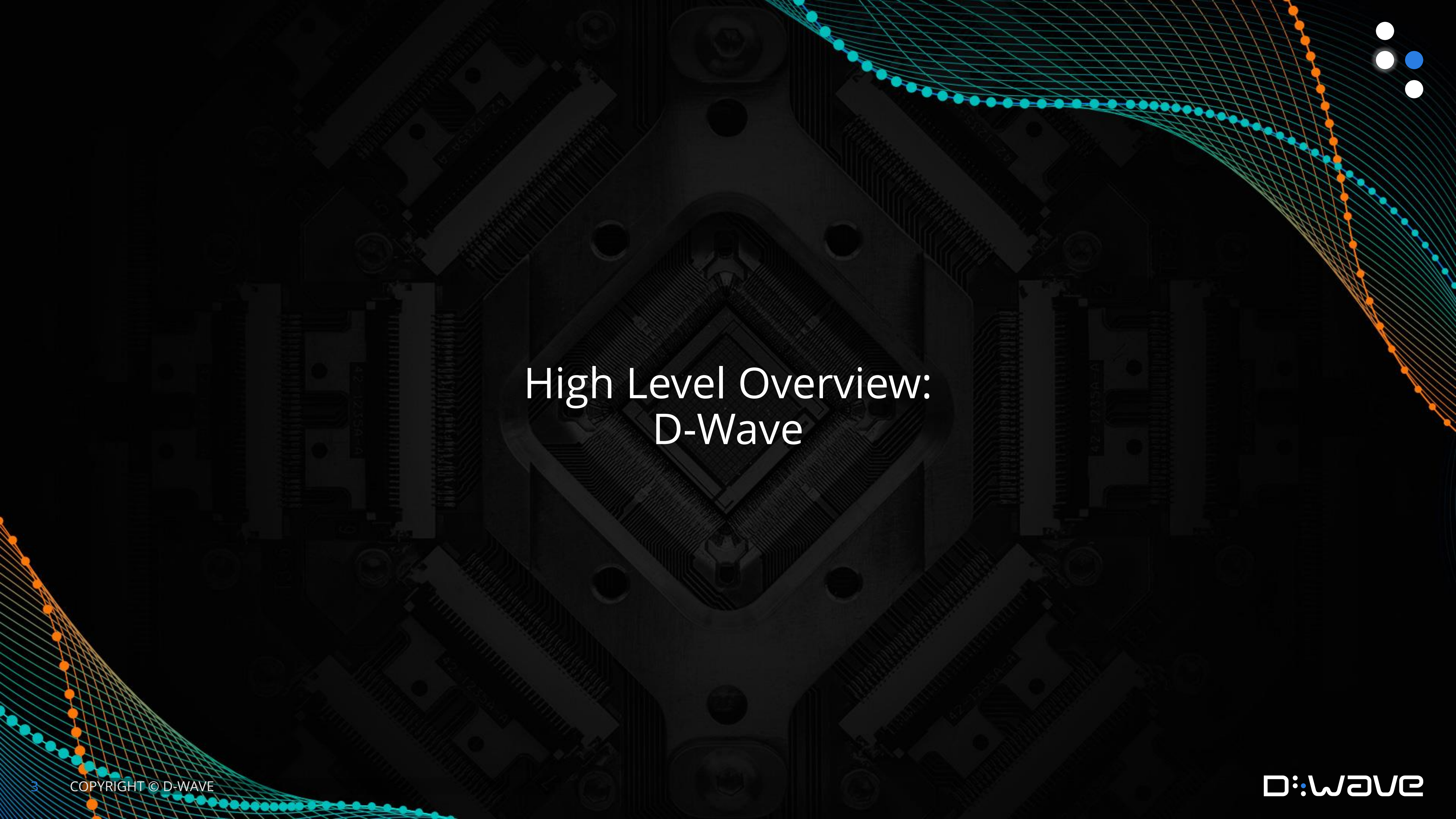
An Introduction to

Quantum Annealing

Alex Koszegi
Solutions Architect
akoszegi@dwavesys.com

Outline

1. D-Wave
2. Applications
3. Quantum Annealing
4. D-Wave’s Implementation
5. Lab Tour
6. Q&A



High Level Overview: D-Wave

THE FUTURE IS NOW

You Are Here

The first 20 years

Quantum computing is highly theoretical, impractical and only available to a small group within the scientific community

PHASE 1 Speed Up On Benchmark Problem

100x speedup over best classical heuristics

PHASE 2 Speed Up On Physics Problems

3Mx speedup over best classical heuristics

Early Applications

PHASE 3 Customer Advantage

Theoretical Foundation Strengthened

Professional services go-to-market yielding business applications running in production with demonstrated ROI

- Menten **100x** speedup
- Save-on-Foods **500X** speedup
- VW **80%** waste reduction

PHASE 4 Quantum Advantage

Quantum computers demonstrate absolute advantage on real world problems

QUANTUM TECHNOLOGY MILESTONES

Demonstrations of Quantum Dynamics

2011

Tunneling
(8 qubit system)

Quantum annealing with manufactured spins
Johnson *et al, Nature* ***473*****,** 194

2015

Entanglement
(2 and 8 qubit systems)

Entanglement in a quantum annealing processor
Lanting *et al*, Phys Review X **no. 4(2)**, p.021 041

Quantum Simulations

2018

Magnetic phase transitions
(8x8x8 lattice, 512 qubits)

Phase transitions in a programmable quantum spin glass simulator
Harris *et al, Science* **361,** 162

KT phase transition
(1800 qubit systems)

Observation of topological phenomena in a programmable lattice of 1,800 qubits
King *et al, Nature* **560**, 456

2021

Scaling advantage over quantum Monte Carlo
(1440 qubits)

Scaling advantage over path-integral Monte Carlo in quantum simulation of geometrically frustrated magnets
King *et al*, Nat. Comm. **12**, 1113

Demonstrations of Coherence

2022

Coherence
(2000 qubits)

Coherent quantum annealing in a programmable 2,000 qubit Ising chain. Nature Physics, 18(11), 1324-1328

2023

Coherence
(**5000** qubits)

Quantum critical dynamics in a 5,000-qubit programmable spin glass. Nature, 1-6.

Built for Business

D-WAVE advantage

The most connected and powerful quantum computer

Supports hybrid applications of real-world size

- Up to 1 million variables

Annealing quantum processor design

- 5,000+ qubits

Ongoing increases in coherence & connectivity

POWERFUL HYBRID SOLVERS

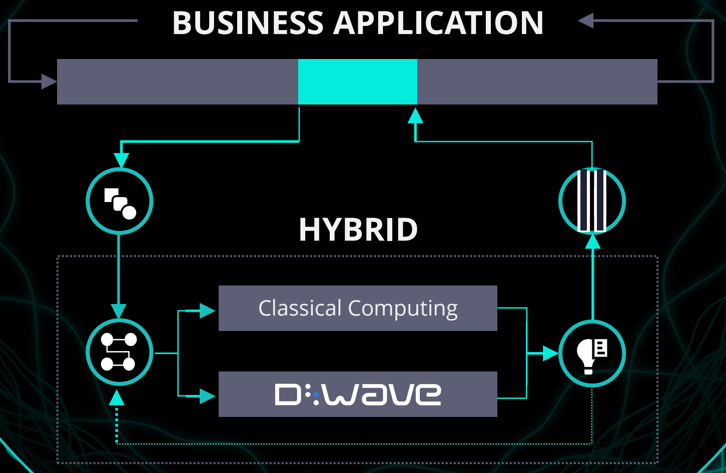
CONSTRAINED QUADRATIC MODEL SOLVER

- More native representation of problem
- Unlocks larger application problems
- Inequality & equality constraints; Up to 100,000
- Binary, integer, and real/continuous variables

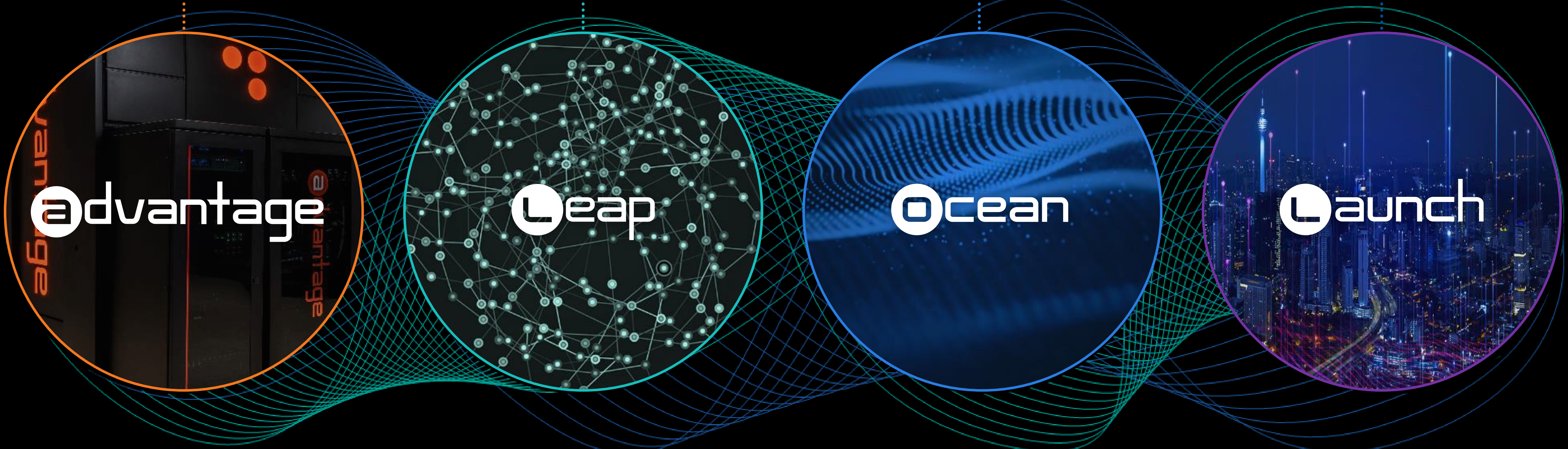
BINARY QUADRATIC MODEL SOLVER

- Up to 1,000,000 variables
- Enables enterprise-scale problem solving
- Accepts problems with binary variable

SOLVERS THAT RUN PROBLEMS ON A COMBINATION OF QUANTUM AND CLASSICAL RESOURCES



A Comprehensive, Full-Stack, Commercial Quantum Platform



QUANTUM COMPUTERS

5 generations of
annealing quantum computers

Advantage$^{\text{TM}}$ currently has
5000+ Qubits

CLOUD SERVICE

Cloud access to the D-Wave$^{\text{TM}}$ quantum
computer & quantum hybrid solvers

99% up-time
with real time access

DEVELOPER TOOLS

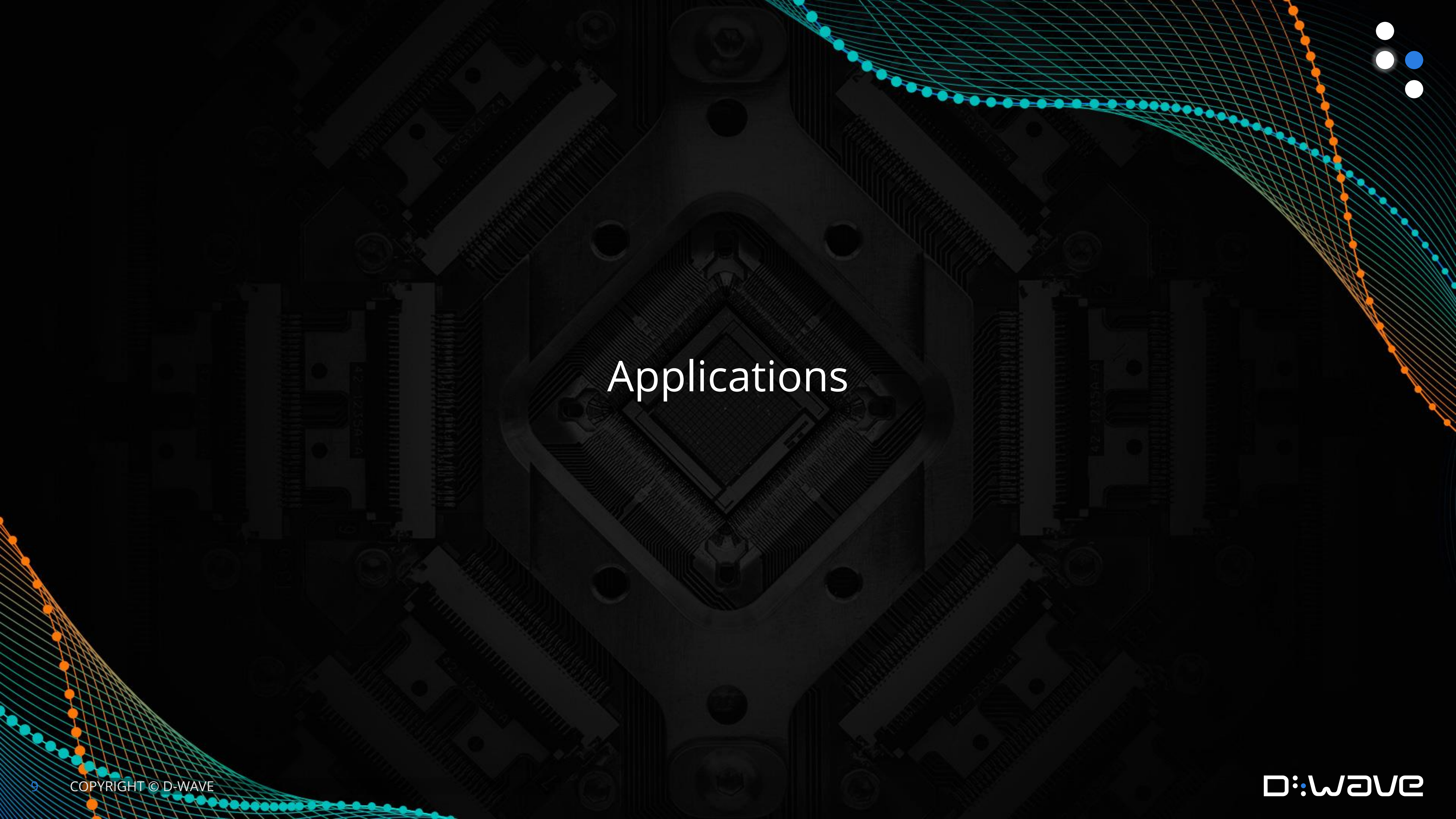
Open-source developer tools
built in Python

Available through Leap$^{\text{TM}}$ IDE
or local download

PROFESSIONAL SERVICES

Customer onboard to
quantum computing applications

4 Phase
engagement model



Applications

REAL-WORLD, COMMERCIAL APPLICATIONS TODAY ACROSS KEY VERTICALS

LOGISTICS

Shipping container logistics
Employee scheduling
Farm to market food delivery
Last mile vehicle routing

PHARMA

Protein folding
Clinical trials
Drug discovery

FINANCE

Portfolio risk reduction and return optimization
Marketing campaign optimization
Fraud detection

AUTOMATE E-COMM DRIVER SCHEDULING

BUSINESS IMPACT:

Pattison Food Group provides next day delivery of food and health products across western Canada and the US. Schedules were manually created for over 100 stores and 500 drivers until October 2022, when its quantum-hybrid e-commerce driver auto-scheduler (QEDA) was deployed to production.

QUANTUM-HYBRID SOLUTION:

QEDA pairs drivers with location-specific shifts so that the business needs are met (even when understaffed), driver shift and location preferences are accommodated, and schedules are consistent week to week.

BUSINESS VALUE:

This solution meets all business requirements, reduces manual scheduling time by 80% and allows schedulers to easily adapt to last minute changes due to sickness and absence.

> **"We will be the first grocery chain to actually use quantum computing to serve our business needs."**
>
> —Benny Wai, Manager of Analytics Development at Pattison Food Group

Pattison Food Group

LOGISTICS OPTIMIZATION AT PORT OF LA

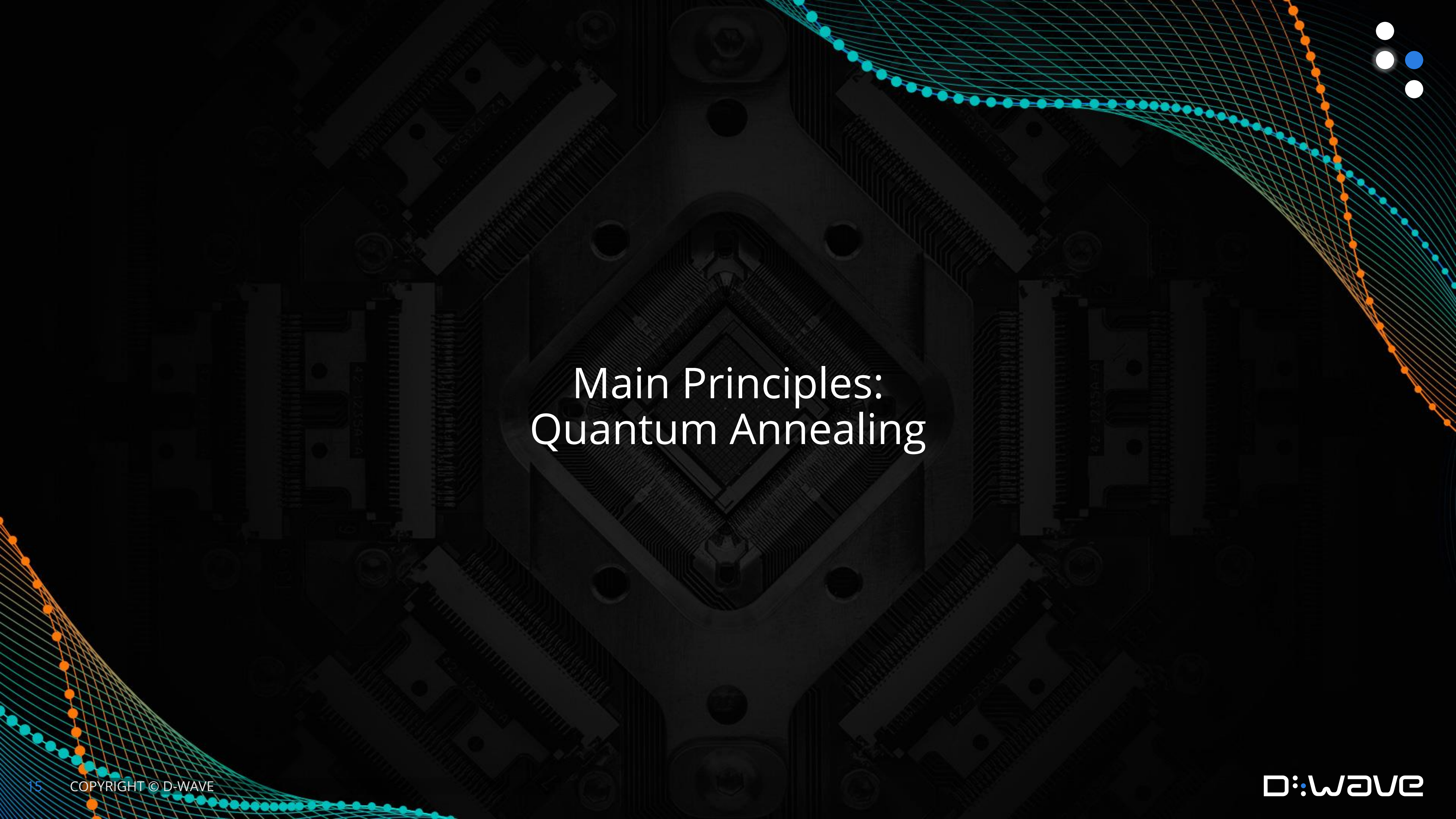
60%

MORE CARGO
HANDLED EACH DAY
PER CRANE

SAVANTX

D-Wave's quantum system is used as part of the SavantX HONE optimization engine at the Port of Los Angeles. The goal is to expedite delivery of containers out of the terminal while increasing the amount of cargo that can be handled.

> "With HONE and D-Wave, each huge crane handled 60% more cargo per day, while the turnaround time for trucks was reduced by 12%."
>
> — SAVANTX TEAM



Main Principles: Quantum Annealing

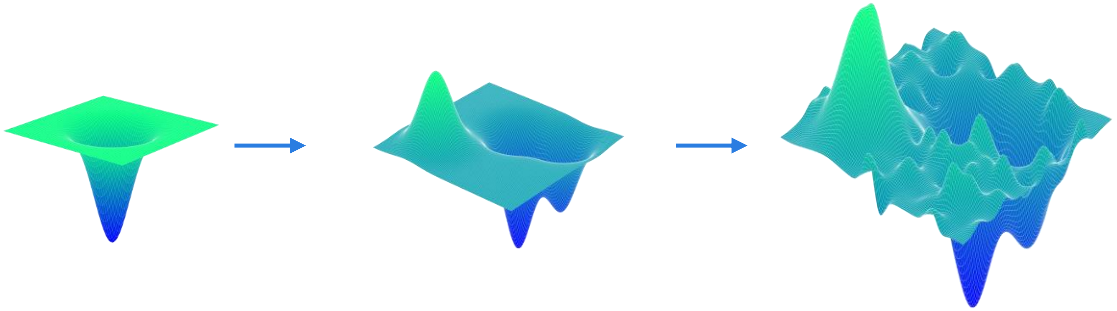
Quantum Annealing

What is quantum annealing?

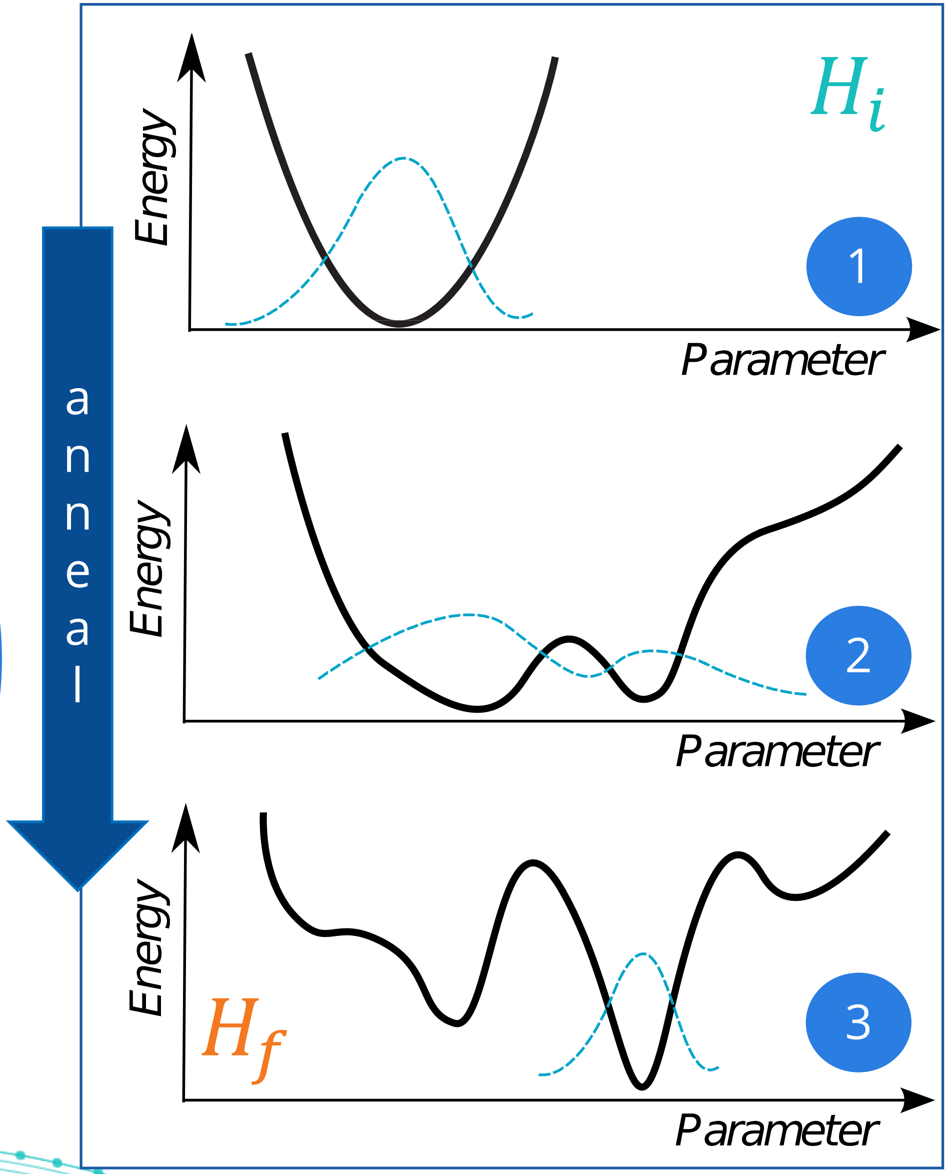
- A process that uses quantum mechanical effects to find a global minimum of an objective function
- Naturally solves optimization problems

Adiabatic Theorem

- Start a quantum system in the ground-state of a Hamiltonian (energy landscape)
- If that Hamiltonian changes slowly enough in time, the system will end up in the ground state of the final Hamiltonian



Quantum Annealing



1

- Single global minimum
- Ground state

2

- Multiple shallow minima with narrow barriers that allow tunneling
- Wavefunction delocalized across them

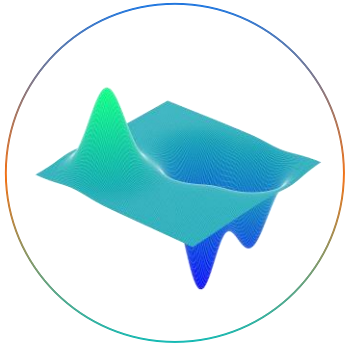
3

- Many deep minima
- Wavefunction localized around global minimum
- The ground state is a classical spin state

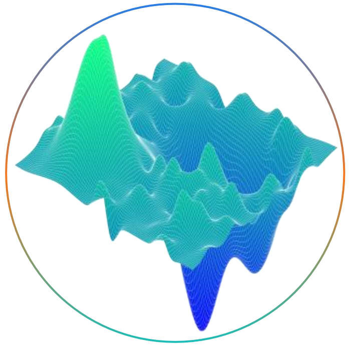
Quantum Annealing - Transverse Field Ising Hamiltonian

$$H_{ising} = \underbrace{\frac{-A(s)}{2}\left(\sum_{i}\sigma_x^{(i)}\right)}_{\text{Transverse Field Hamiltonian}} + \underbrace{\frac{B(s)}{2}\left(\sum_{i} h_i\sigma_z^{(i)} + \sum_{i>j} J_{i,j}\sigma_z^{(i)}\sigma_z^{(j)}\right)}_{\text{Problem Hamiltonian}}$$

Transverse Field Hamiltonian



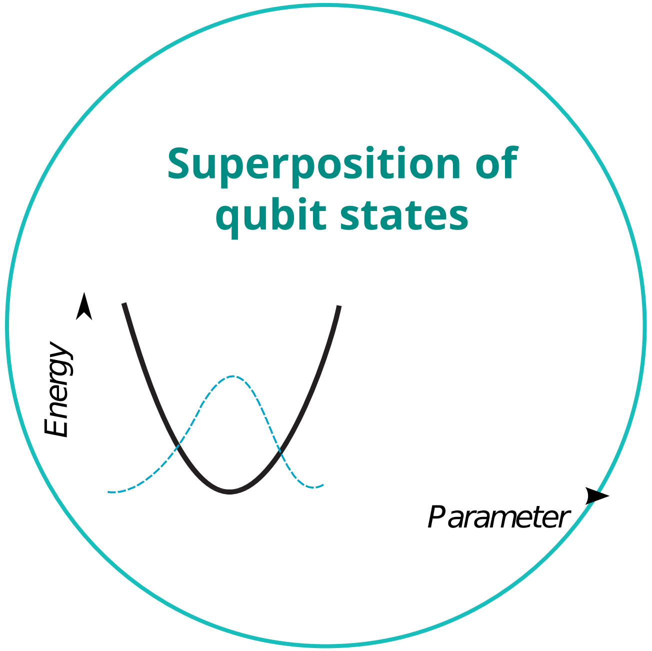
Transverse Field + Problem Hamiltonian



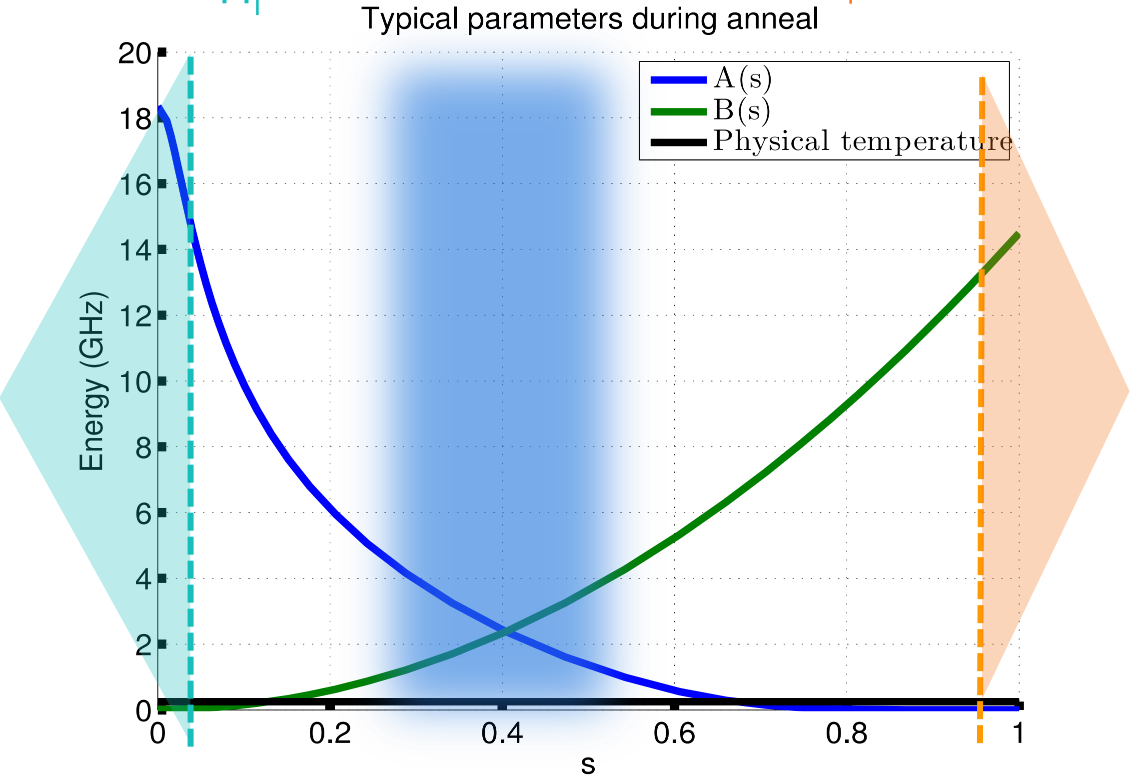
Problem Hamiltonian

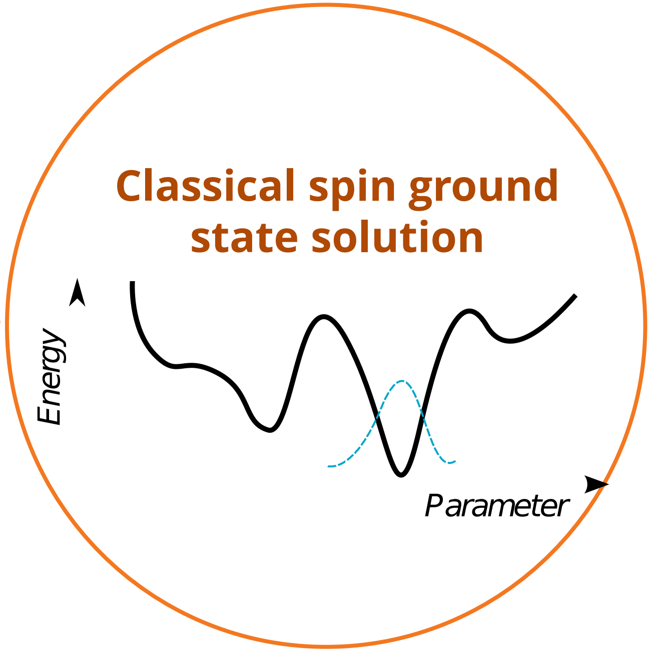
Quantum Annealing - Transverse Field Ising Hamiltonian

$$H(s) = -A(s)\underbrace{\left[\sum_{\boldsymbol{i}} \boldsymbol{\sigma}_{\boldsymbol{x}}^{(\boldsymbol{i})}\right]}_{H_i} + B(s)\underbrace{\left[-\sum_{i} h_i \sigma_z^{(i)} + \sum_{i,j>i} J_{ij}\sigma_z^{(i)}\sigma_z^{(j)}\right]}_{H_f}$$



Superposition of qubit states



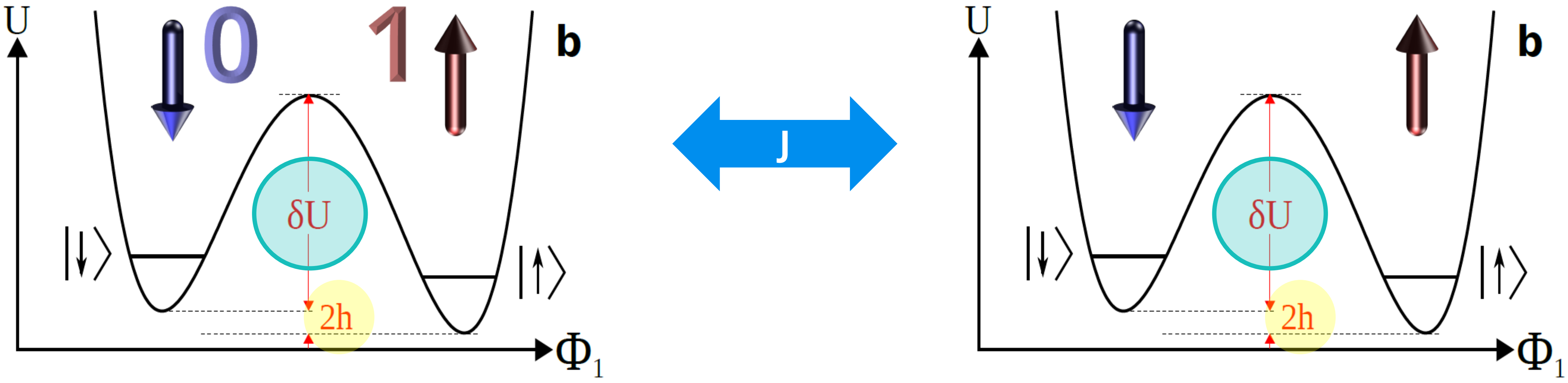


Classical spin ground state solution

anneal

Quantum Annealing - Transverse Field Ising Hamiltonian

$$H(s) = -A(s)\left[\sum_i \boldsymbol{\sigma}_x^{(i)}\right] + B(s)\left[-\sum_i h_i \sigma_z^{(i)} + \sum_{i,j>i} J_{ij}\sigma_z^{(i)}\sigma_z^{(j)}\right]$$



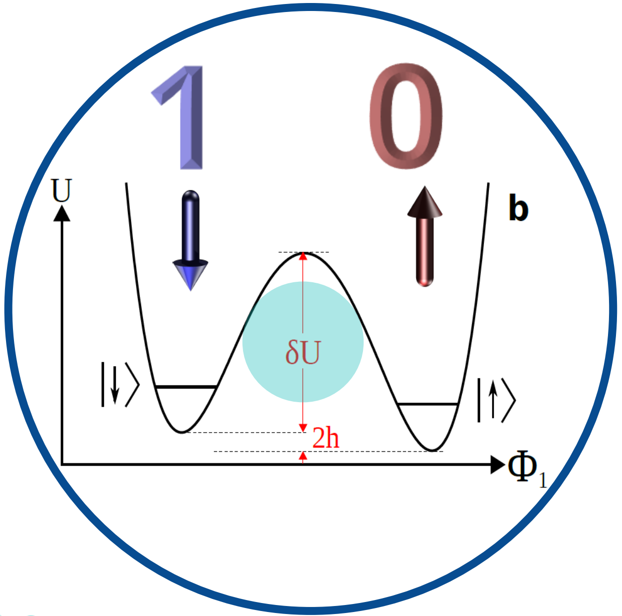
h_i and J_{ij} are specified with **programmable on-chip** control circuitry

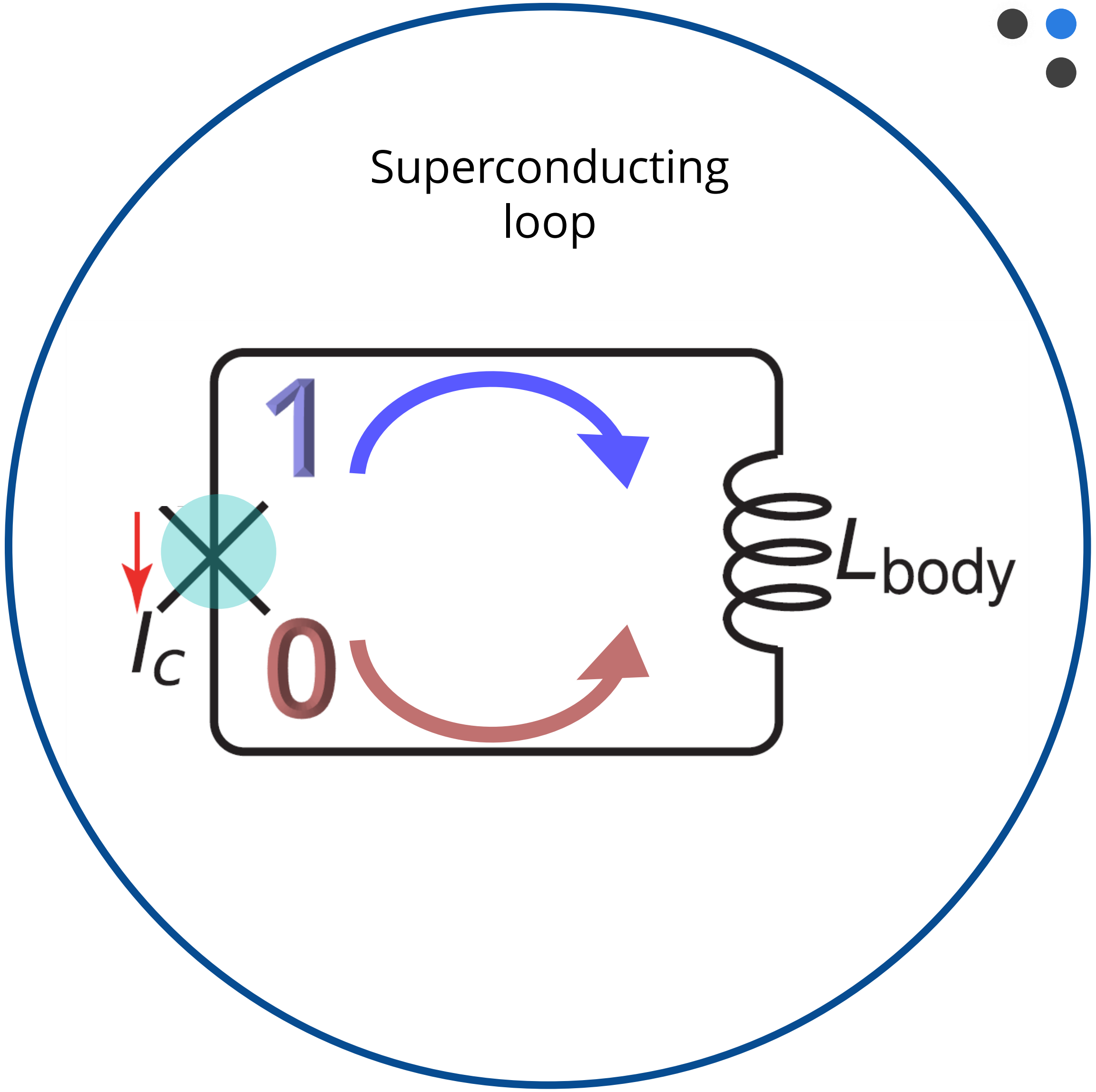
Main Principles:
D-Wave’s Implementation

The Qubit – RF SQUID

Josephson Junction
creates barrier in potential

Critical current I_c
determines the barrier height

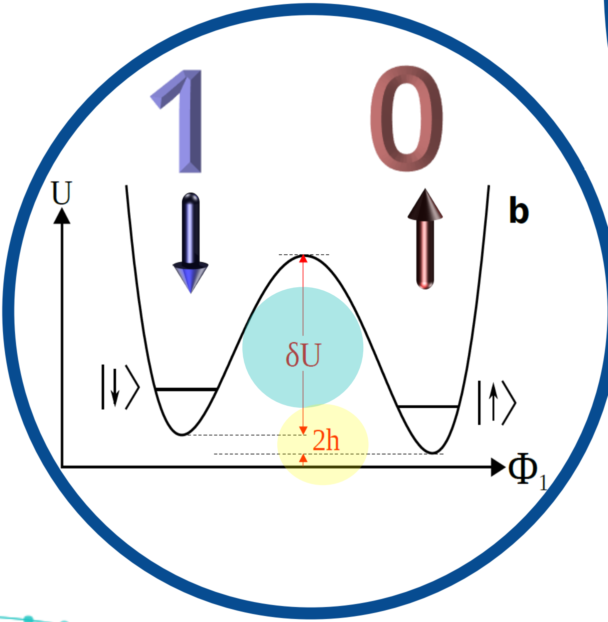


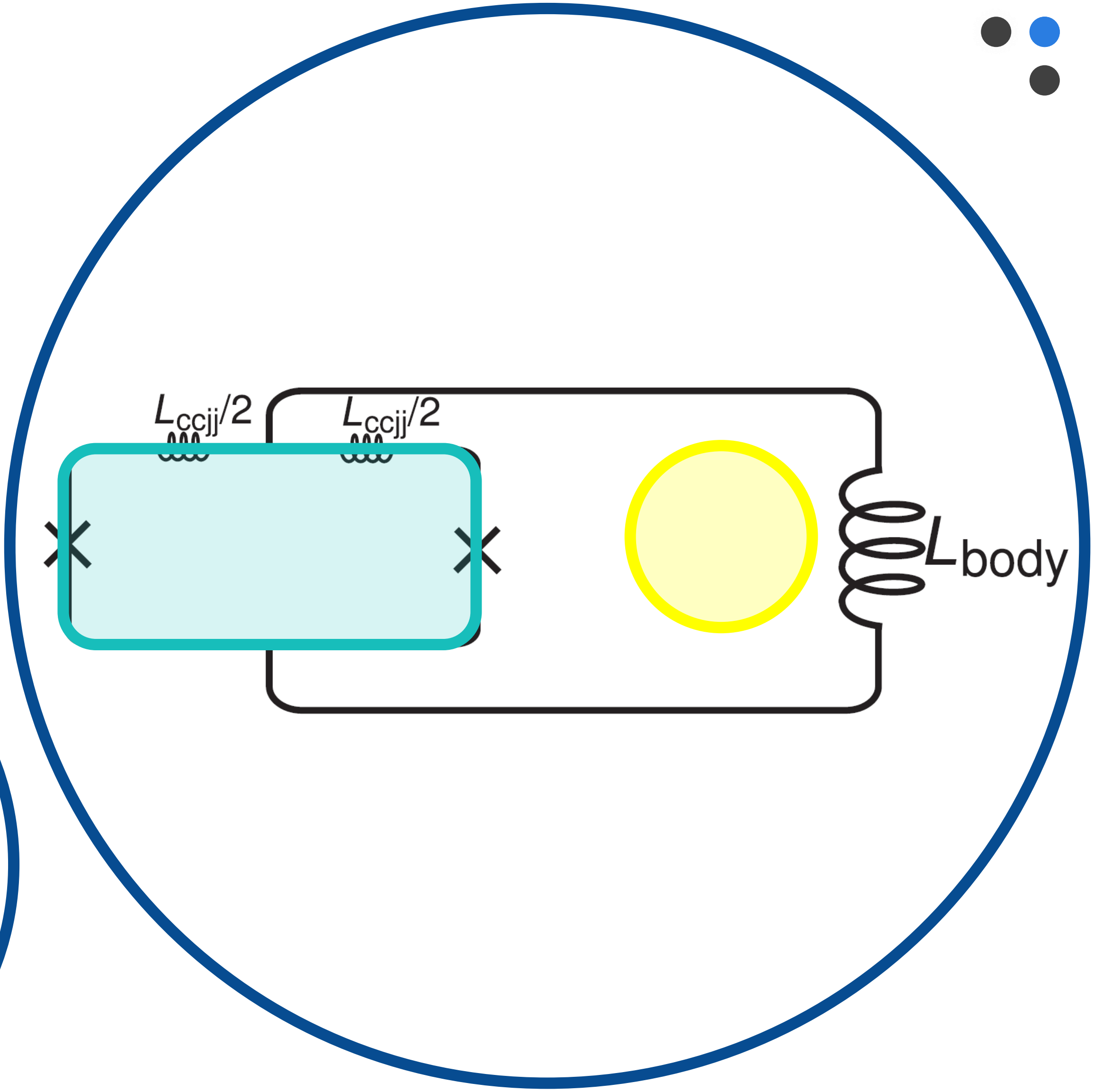


The Qubit – RF SQUID

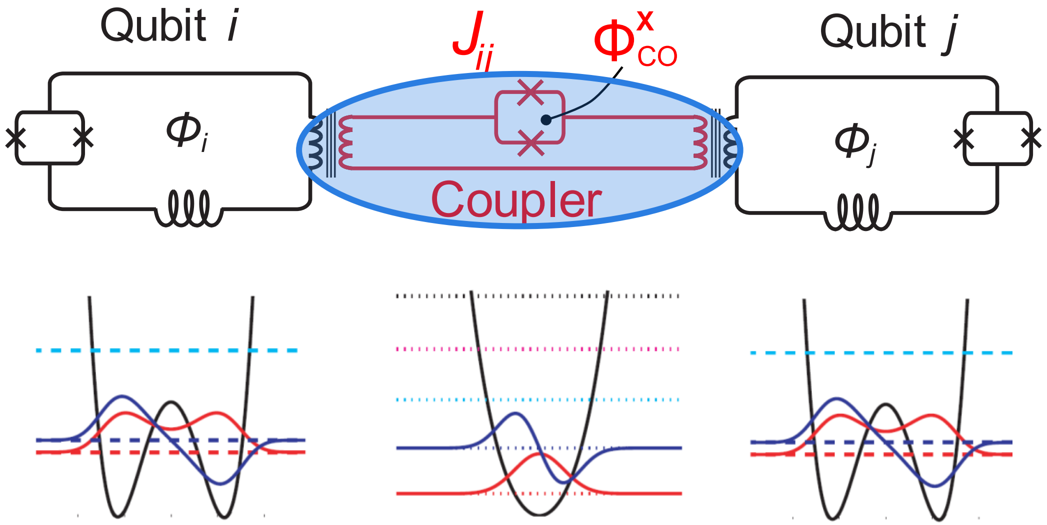
$$H(s) = -A(s)\left[\sum_i \boldsymbol{\sigma}_{\boldsymbol{x}}^{(\boldsymbol{i})}\right] + B(s)\left[-\sum_i h_i \sigma_z^{(i)} + \sum_{i,j>i} J_{ij}\sigma_z^{(i)}\sigma_z^{(j)}\right]$$

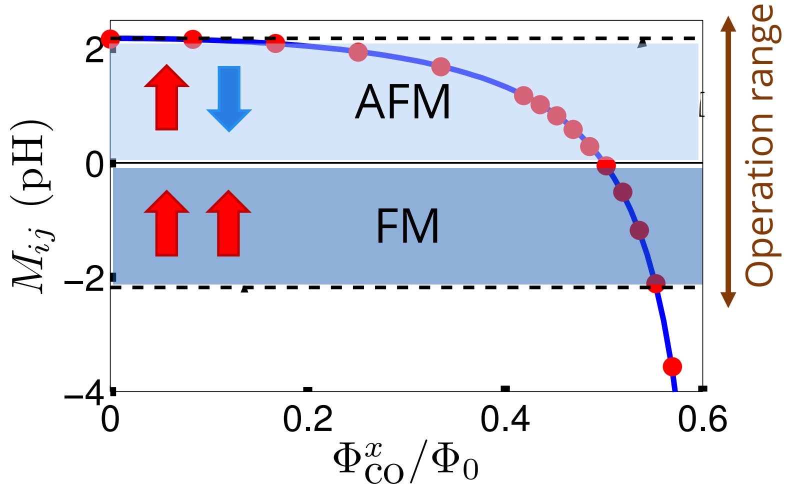
Compound Josephson Junction (CJJ) creates a **tunable** barrier





The Qubit – Coupling Qubits



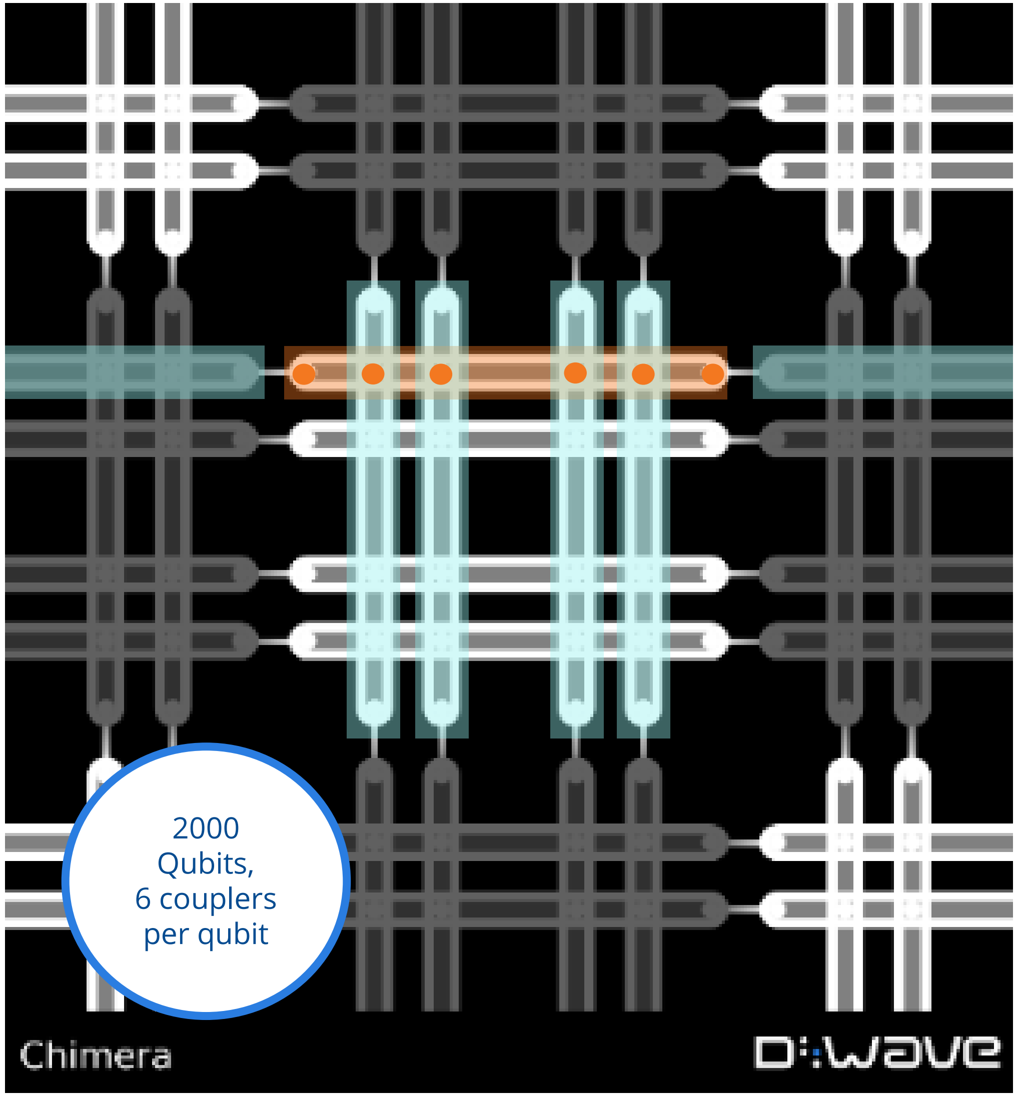


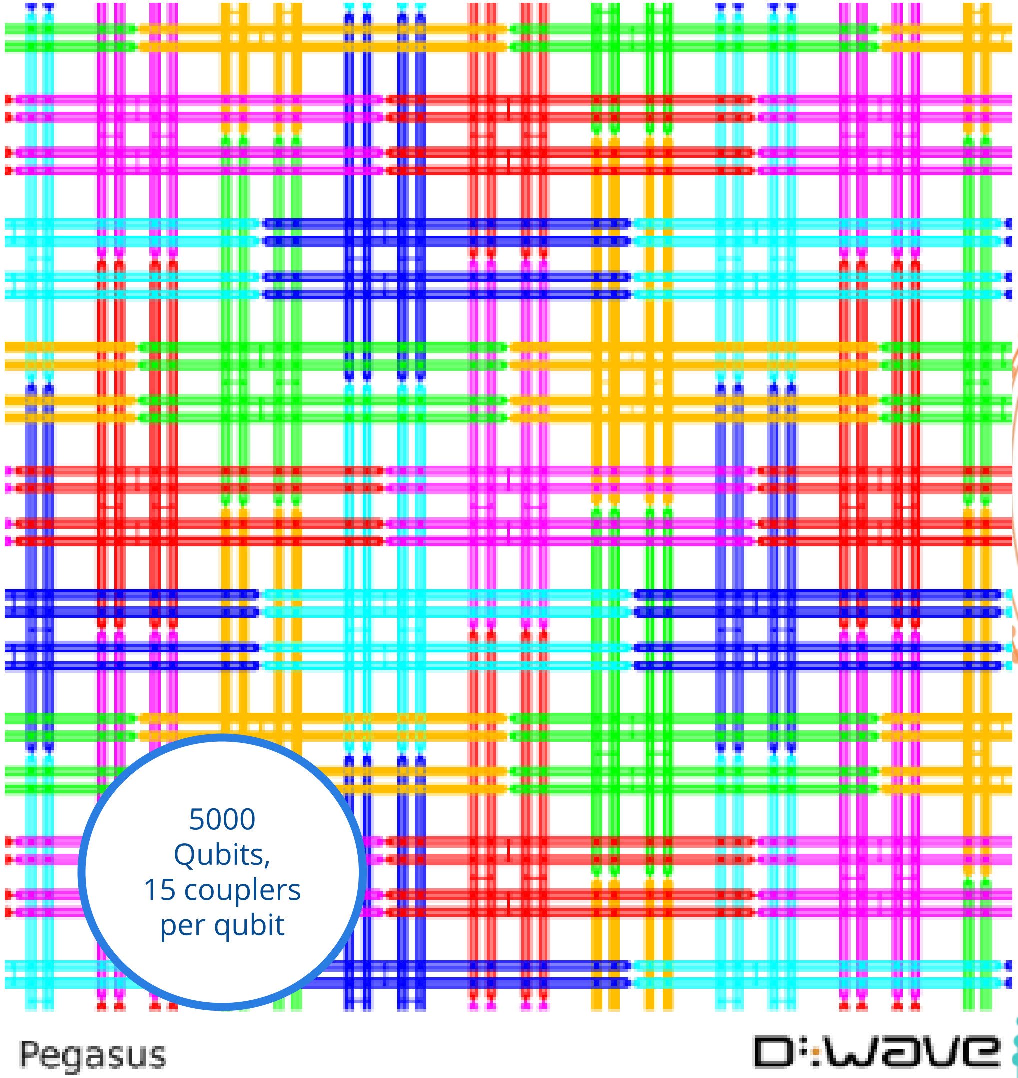
A mono-stable two-junction RF SQUID provides a tunable mutual inductance

$$M_{ij} = \frac{J_{ij}}{|I_p(t)|^2}$$

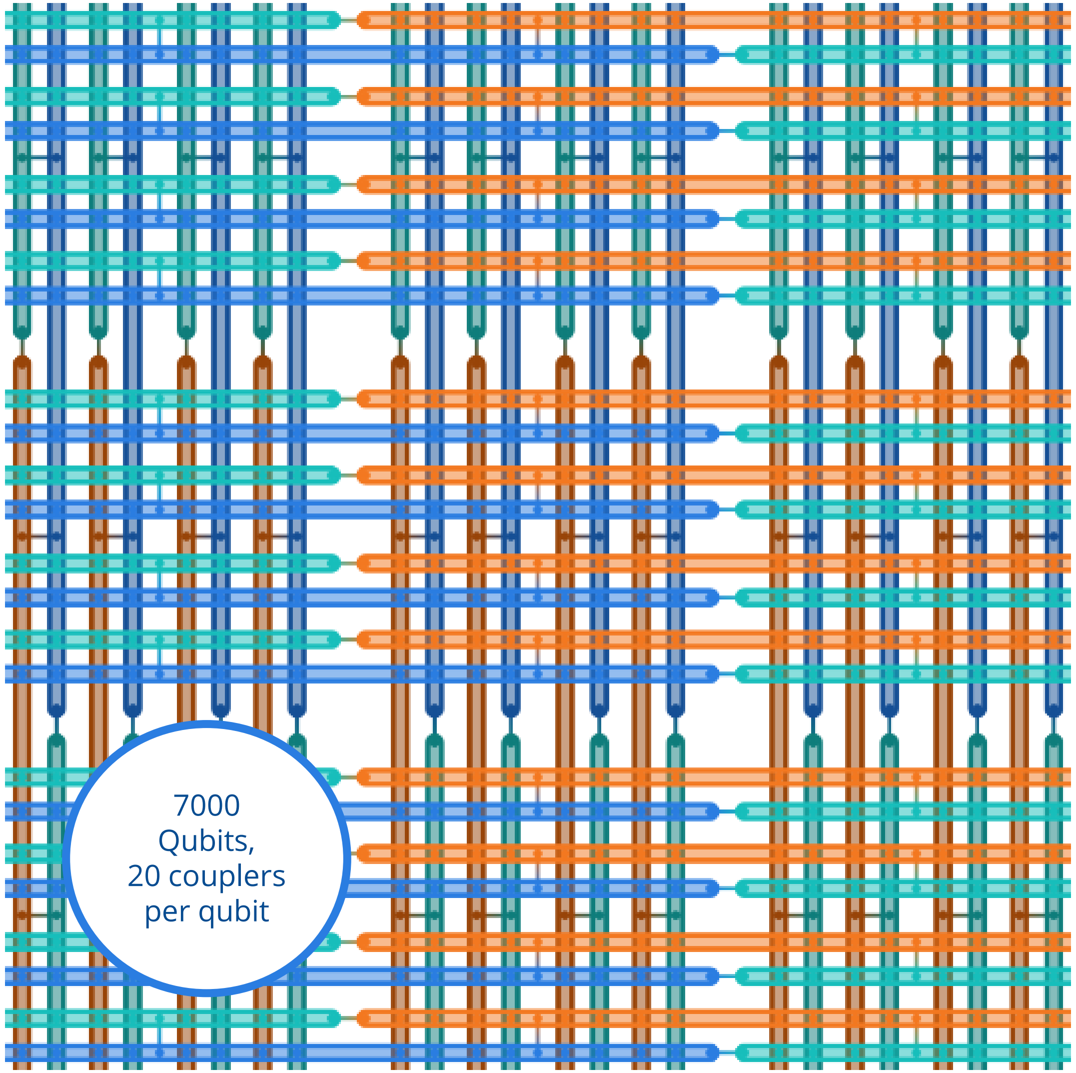
$$H(s) = -A(s)\left[\sum_{\boldsymbol{i}} \boldsymbol{\sigma}_{\boldsymbol{x}}^{(\boldsymbol{i})}\right] + B(s)\left[-\sum_{i} h_i\sigma_z^{(i)} + \sum_{i,j>i} J_{ij}\sigma_z^{(i)}\sigma_z^{(j)}\right]$$

The Chip - Processor Layout


2000
Qubits,
6 couplers
per qubit


5000
Qubits,
15 couplers
per qubit

The Chip - Processor Layout



7000 Qubits, 20 couplers per qubit

Fig. 25 Zephyr unit cells: for the center unit cell, one group of eight half qubits are shown in orange, another in blue.

Lab Tour!

Lab Tour:
Video 1: https://youtu.be/zDotDiK2UuY?t=1
Video 2: https://youtu.be/AGByZoYUlU0

Differences Between Annealing and Gate

	Quantum Annealing	Gate
The Foundation	• Physical implementation of a class of quantum algorithms • Continuously interpolates between uniform σ^x and user-defined σ^z	• Can perform different algorithms, some of which have shown a theoretical quadratic or exponential speed up over classical algorithms for certain problems • Full access to operations on the Bloch sphere
Hardware Scalability	• Easier to fabricate and calibrate larger scale processors • Difficult to achieve full connectivity and reduce intrinsic noise sources (flux and charge noise) • Naturally fault tolerant	• Difficult to fabricate larger scale processors due to need for increased coherence times • Difficult to achieve fully error corrected systems

Use Cases	• Optimization problems
	  • Scheduling, portfolio optimization, logistics
	• Can simulate certain quantum systems (Quantum spin ice, Shastry-Sutherland Ising Model, KT phase transition simulation)
		• General applications
		  • Material science, quantum chemistry, drug discovery
		• Can simulate quantum systems

Quantum Annealing vs QAOA

	Quantum Annealing	Quantum Approximate Optimization Algorithm (QAOA)
General	Continuously changes from a driver to the problem Hamiltonian.	Attempts to approximate quantum annealing by mixing a driver and problem Hamiltonian over discrete iterations.
Computation Time	Typical operation times below ~100 ms for N <= 5000.	Experiments show operation times of minutes for N <= 50 due to NP-hard algorithmic parameter tuning.
Solution Quality	Consistently shows higher probability of sampling the ground state (>90%) in studies comparing against QAOA.	Empirical tests suggest low probability (0.01% – 80%) of finding the ground state. Highly dependent on the input and hardware.

Summary

Summary

D-Wave is currently the only quantum annealing provider.

Our current generation, Advantage, has over 5000 qubits. Advantage2 will have over 7000 qubits.

Since 2011 we have published demonstrations of quantum effects in our processors and simulations that show up to a 3 million times speed up compared to classical techniques.

Quantum annealing will likely always be the best quantum technology for optimization problems.

D-Wave supports quantum-hybrid production applications today.

Additional Resources

Sign up for a free Leap account to access code examples and run problems today:
https://cloud.dwavesys.com/leap/signup/

Learn more about our applications:
https://dwavequantum.com/learn/featured-applications/

Learn more about our technology:
https://dwavequantum.com/learn/resource-library/

QA vs QAOA

- Why D-Wave is Bullish on Quantum Annealing – Catherine McGeoch
  https://youtu.be/lAeZ_hs9OBw
- Lubinski et al., Optimization Applications as Quantum Performance Benchmarks (2023)
  https://arxiv.org/abs/2302.02278
- Lotshaw et al. Scaling Quantum Approximate Optimization on Near-term Hardware (2022)
  https://arxiv.org/abs/2201.022477