PRACTICAL QUANTUM COMPUTING

D-Wave Technology Overview

D-Wave

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D-Wave is the leader in the development and delivery of quantum computing systems, software, and services. Our mission is to unlock the power of quantum computing by delivering customer value through practical applications.

Quantum computers have the potential to solve complex computational problems that can't be solved by even the most powerful classical supercomputers. D-Wave's quantum computer leverages quantum dynamics to accelerate and enable new methods for solving problems in discrete optimization, constraint satisfaction, artificial intelligence, machine learning, materials science, and simulation.

While the quantum computing market is emerging, D-Wave users have already developed over 200 early applications for problems spanning airline scheduling, election modeling, quantum chemistry simulation, automotive design, preventative healthcare, logistics, and more. Many have also developed software tools that make it easier to develop new applications.

D-Wave's systems are being used by some of the world's most advanced organizations, from global enterprises such as Lockheed Martin, DENSO, and Volkswagen, to national research centers such as NASA Ames, Los Alamos National Laboratory, and Forschungszentrum Jülich. D-Wave currently has more than 185 granted US patents and has published over 100 scientific papers, many of which have appeared in leading science journals.

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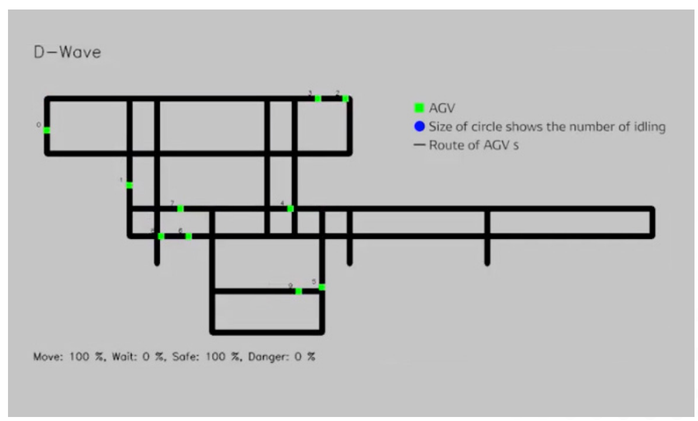
200+ Early Applications

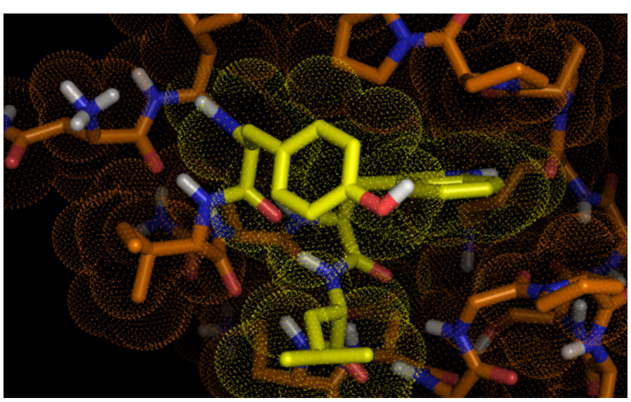
From finding new OLED materials to protein folding, from ensuring the safest and most efficient paths for autonomous vehicles in factories to optimizing supply chains, and from financial modeling to aircraft fault detection—quantum computing is already delivering early business results.

A few examples:

Volkswagen was the first car manufacturer to use a quantum computer to calculate traffic flows. Using movement data collected from 418 taxi cabs in one of the busiest cities in the world—Beijing—the team sought to optimize traffic flow between the city center and the airport. Following a successful proof-of-concept, Volkswagen developed the first-of-its-kind, in-production quantum application, a mobile app which predicts the best route to any given destination. The app was used to route buses at the 2019 WebSummit in Lisbon.

DENSO recently completed proof-of-concept work aimed at optimizing control of Automated Guided Vehicles (AGVs) on their factory floors. Using the power of hybrid quantum-classical computing, DENSO narrowed down and ranked the optimal number of paths AGVs could take around the factory. Then they focused on reducing traffic congestion. The results were significant: researchers were able to produce solutions that reduced the amount of time each AGV spent waiting for a clear route to open up by an average of 15%, even when focusing on safety over speed.





Menten AI is harnessing the unique capabilities of quantum computers for applications in life science and biotechnology. Their initial experiment—aimed at determining whether or not a quantum computer could handle the protein design problem without needing it to be simplified or reduced in size—was a success, and led to the development of the first quantum-designed molecule. Using a quantum-classical algorithm resulted in better solutions, up to 100x faster, compared to classical systems.

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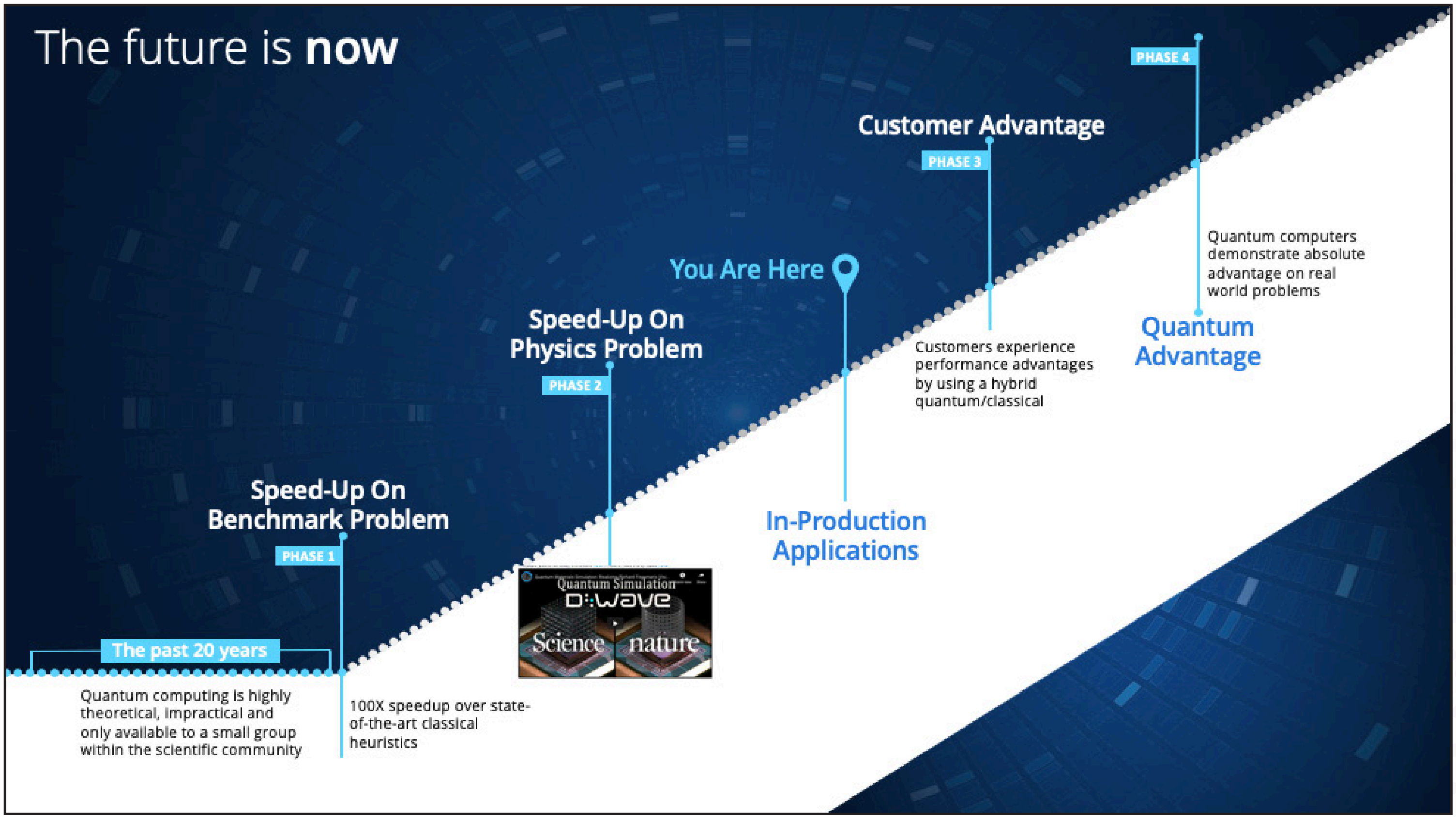
Quantum Value

Of the more than 200 early applications, an increasing number have demonstrated that D-Wave systems are approaching, and sometimes surpassing, conventional computing in terms of performance or solution quality, heralding the first examples of real customer application advantage on quantum computers.

How long will it be until quantum computers deliver significant advantage for real-world applications? Here are a few recent D-Wave milestones:

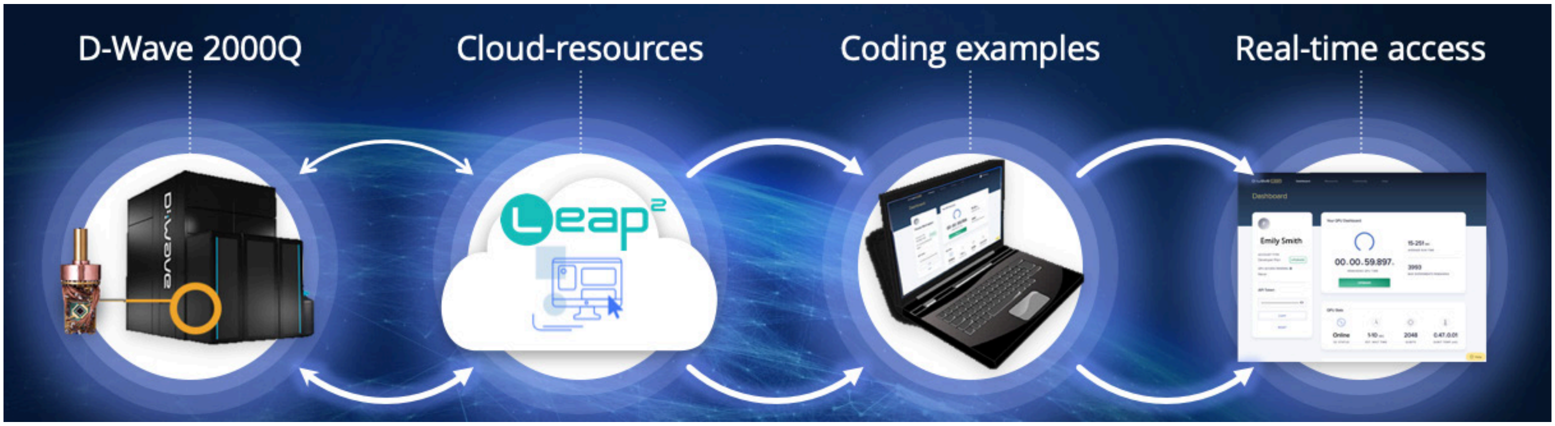
- In January, 2017, researchers at NASA and Texas A&M demonstrated 100X speedup for D-Wave quantum computers over state-of-the-art classical heuristics on a benchmark problem. While the results were compelling, this was not yet a real-world problem.
- In the summer of 2018, D-Wave published groundbreaking papers in *Science* and *Nature* that detailed breakthroughs in the simulation of physical systems.
- In late 2019, the first production quantum application was introduced by Volkswagen. As new D-Wave technology rolls out in 2020, more real-world applications will show performance advantages using a hybrid quantum-classical approach. This "customer advantage" is our near-term goal, and we believe it will lead to quantum advantage on real-world problems.

To enable practical quantum computing and deliver customer advantage, D-Wave has developed a family of quantum products. These include advanced quantum processors and systems, and Leap™, the real-time quantum cloud and quantum application environment (QAE). We'll explore those topics next.



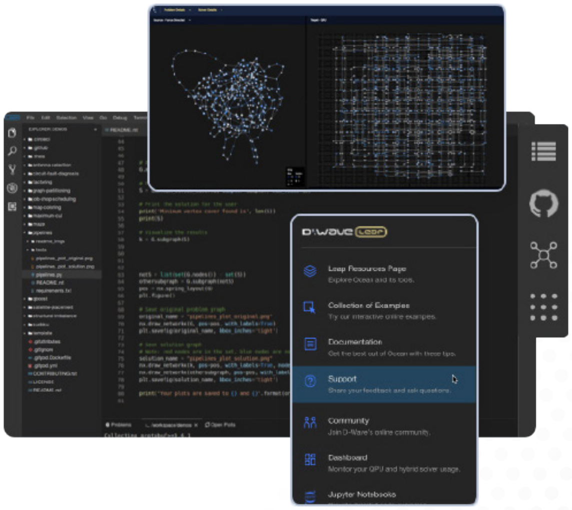
Leap: The Quantum Cloud Service Built for Business

D-Wave Leap is the only real-time quantum cloud service and quantum application environment (QAE). Leap speeds the development of real-world quantum applications through online access to a live quantum computer, and with comprehensive development tools, resources, and a vibrant online community.



In addition to providing immediate cloud access to D-Wave quantum computers, Leap includes:

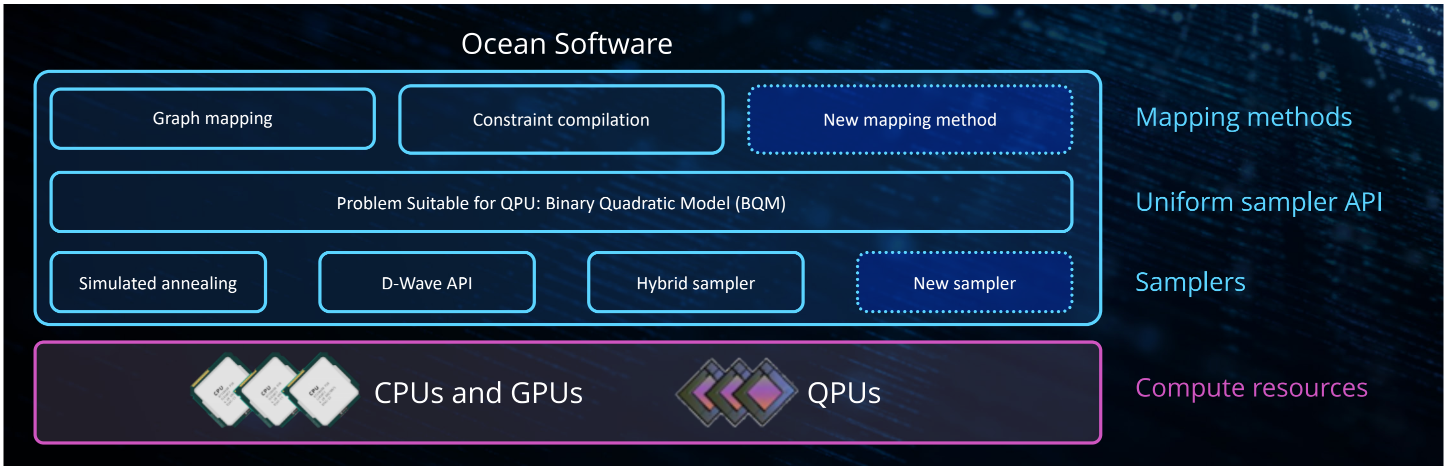
- The **hybrid solver,** a managed cloud-based service allowing users to easily solve large and complex problems of up to 10,000 variables. The solver automatically runs problems on a collection of quantum and classical cloud resources, using D-Wave's advanced algorithms to decide the best way to solve a problem.
- The **Integrated Developer Environment (IDE),** a prebuilt, ready-to-code environment in the cloud for quantum hybrid Python development. The Leap IDE has the latest Ocean SDK set up and configured, and includes the new D-Wave problem inspector and Python debugging tools. Seamless GitHub integration means that developers can easily access the latest examples and contribute to the Ocean tools from within the IDE.
- The **problem inspector,** that allows more advanced quantum developers to visually see how their problems map onto the quantum processing unit (QPU). By showing the logical and embedded structure of a problem, the inspector displays the solutions returned from the QPU and provides alerts that allow developers to improve their results.
- Leap also enables **instant collaboration** through its online community of quantum developers.



The Ocean Software Development Suite

For quantum computing, as for classical, solving a problem requires that it be formulated in a way the computer and its software understand. D-Wave's Ocean SDK includes a suite of open-source Python tools designed to solve hard problems with quantum computers. Ocean helps reformulate an application's problem for the quantum computer or a quantum-classical hybrid workflow. The SDK also handles communications between application code and the quantum computer.

Ocean software can abstract away much of the mathematics and programming for some types of problems. At its heart is a binary quadratic model (BQM) class that together with other Ocean tools helps formulate various optimization problems. It also provides an API to binary quadratic samplers (the component used to minimize a BQM and therefore solve the original problem), such as the D-Wave system and classical algorithms you can run on your computer.



Ocean contains:

Mapping Methods: Tools that translate the application goal and data into a problem form suitable for quantum computing. They also receive solution samples and translate them back into solutions for the application layer. For example, dwave_networkx helps map structural imbalance analysis into a BQM.

Uniform Sampler API: An abstraction layer that represents the problem in a form that can access the selected sampler.

Samplers: Tools that receive a problem in the form of a BQM and return solution samples. Ocean implements several samplers that use the D-Wave QPU, the cloud-based hybrid solver, as well as classical compute resources. You can use Ocean tools to customize a D-Wave sampler, create your own, or use existing hybrid or classical ones.

The open source dwave-hybrid framework provides a Python framework for building a variety of flexible hybrid workflows. These use quantum and classical resources together to find good solutions to a problem.

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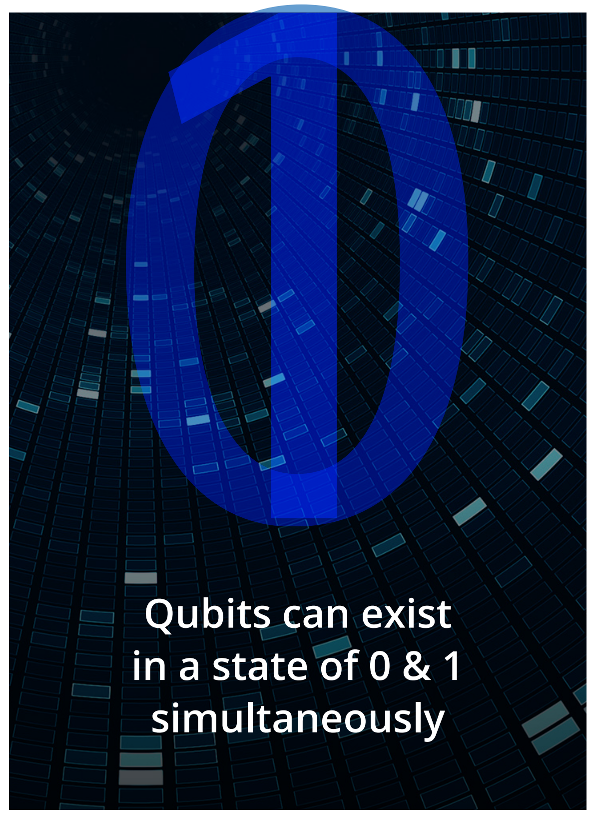
How D-Wave Systems Work

Rather than store information using bits represented by 0s or 1s as conventional computers do, quantum computers use quantum bits, or qubits, to encode information as 0s, 1s, or both simultaneously. This superposition of states, along with the quantum effects of entanglement and quantum tunneling, enable quantum computers to consider and manipulate many combinations of bits simultaneously.



D-Wave's computers use quantum annealing to solve problems represented as mathematical functions (resembling a landscape of peaks and valleys) by harnessing the quantum mechanical effects, to find their global minima, corresponding to optimal or near optimal solutions.

Computation is performed by initializing the quantum processing unit (QPU) into a ground state of a known problem and annealing the system toward the problem to be solved such that it remains in a low energy state throughout the process. At the end of the computation, each qubit ends up as either a 0 or 1. This final state is the optimal or near-optimal solution to the problem to be solved.

In nature, physical systems tend to evolve toward their lowest energy state: objects slide down hills, hot things cool down, and so on. This behavior also applies to quantum systems. To imagine this, think of a traveler looking for the best solution by finding the lowest valley in the energy landscape that represents the problem. Classical algorithms seek the lowest valley by placing the traveler at some point in the landscape and allowing that traveler to move based on local variations. While it is generally most efficient to move downhill and avoid climbing hills that are too high, such classical algorithms are prone to leading the traveler into nearby valleys that may not be the global minimum. Numerous trials are typically required, with many travelers beginning their journeys from different points.

In contrast, quantum annealing begins with the traveler simultaneously occupying many coordinates thanks to the quantum phenomenon of superposition. The probability of being at any given coordinate smoothly evolves as annealing progresses, with the probability increasing around the coordinates of deep valleys. Quantum tunneling allows the traveler to pass through hills—rather than be forced to climb them—reducing the chance of becoming trapped in valleys that are not the global minimum. Quantum entanglement further improves the outcome by allowing the traveler to discover correlations between the coordinates that lead to deep valleys.

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Simple on the Outside, Extraordinary on the Inside

The physical enclosure of the D-Wave system houses sophisticated cryogenic refrigeration, shielding, and I/O systems to support a single thumbnail-sized QPU. Most of the physical volume of the system is required to accommodate the refrigeration system and to provide easy service access. While traditional supercomputers generate massive amounts of heat and consume massive amounts of power, the D-Wave system consumes less than 25 kW of power, most of which goes towards operating the cooling and front-end servers.

For quantum effects to play a role in computation, the QPU requires an extreme, isolated environment. The refrigerator and layers of shielding create an internal high vacuum environment with a temperature close to absolute zero that is isolated from external magnetic fields, vibration, and RF signals of any form. Adjoining cabinets contain the control subsystems and the front-end servers that provide connectivity to the system.

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Inside the D-Wave Enclosure

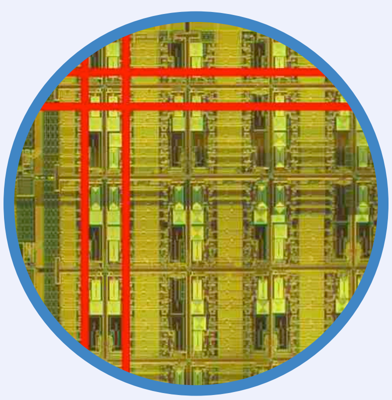
The D-Wave QPU operates near absolute zero. This extremely low temperature, along with the shielded environment that isolates the QPU from its surroundings, enables the QPU to behave quantum-mechanically. D-Wave systems operate at less than 15 millikelvin, approximately 180 times colder than interstellar space.

The extreme isolated environment required for the QPU places unusual demands on the design, materials, and manufacturing processes required for the various subsystems.

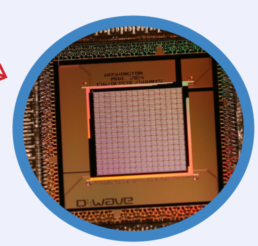
The I/O subsystem that passes information to the QPU and back while filtering out all unwanted noise requires a variety of normal and superconducting materials to provide the required performance.

The magnetic shielding subsystem provides the low-field environment required for the QPU, using high-permeability and superconducting materials to achieve fields below 1 nanotesla. This is 50,000 times less than the Earth's magnetic field.

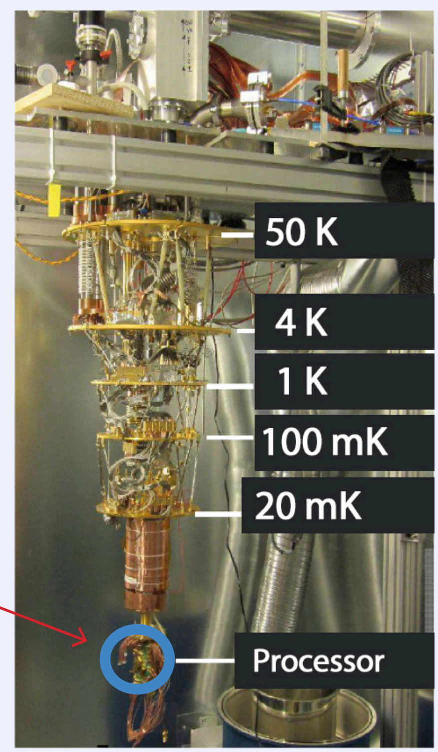
Starting at room temperature at the top, the temperature decreases at each level until it is close to absolute zero where the QPU itself is located.



Qubits in red



Quantum processing unit



Temperature in kelvin

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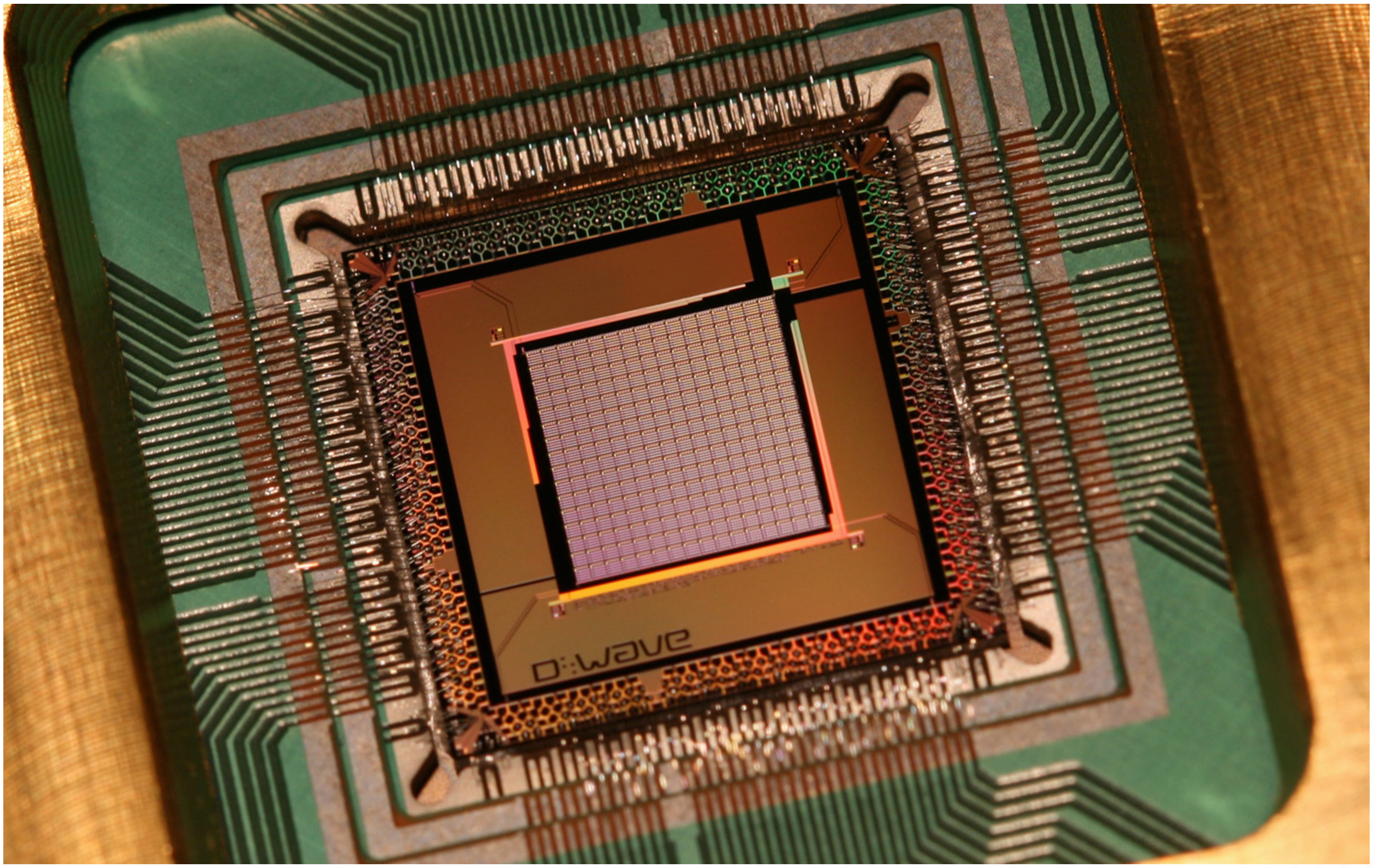
The Quantum Processing Unit

The D-Wave QPU is built from tiny loops of metal, each of which is one qubit (shown on the previous page, in red). At very low temperatures, close to absolute zero, these loops become superconductors and exhibit quantum-mechanical effects.



When in a quantum state, current flows in both directions simultaneously, which means that the qubit is in superposition—that is, in both a 0 and a 1 state at the same time. At the end of the problem-solving process, this superposition collapses into one of the two classical states, 0 or 1.

Going from a single qubit to a multi-qubit QPU requires that the qubits be interconnected to exchange information. Qubits are connected via couplers, which are also superconducting loops. The interconnection of qubits and couplers, together with control circuitry to manage the magnetic fields, creates an integrated fabric of programmable quantum devices.

When the QPU arrives at a solution to a problem, all qubits settle into their final states and the values they hold are returned to the user as a bit string.

The D-Wave Advantage

Since the initial introduction of the 2000Q™ system, D-Wave has introduced a series of advancements in both hardware and software. Designed to speed the development of commercial quantum applications, the Advantage™ quantum system will power a new hardware and software platform that will accelerate and ease the delivery of quantum computing applications that deliver customer benefits for real-world applications.

Components of the Advantage platform will come to market throughout 2020 via ongoing QPU and software updates to be made available through Leap.

The Advantage system will include:

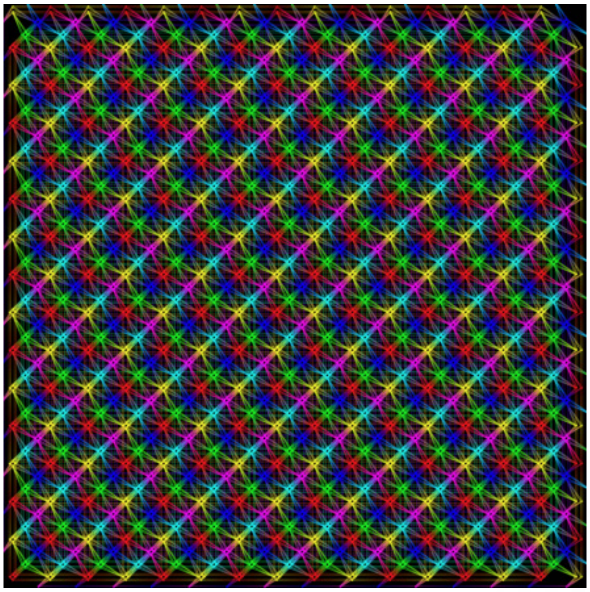
New Topology:
The Pegasus™ topology is the most connected of any commercial quantum system in the world. Currently, each qubit in the Chimera™ topology is connected to six other qubits. With the Pegasus topology, each qubit is connected to 15 other qubits. With two and a half times more connectivity, Pegasus enables the embedding of larger problems with fewer physical qubits than the Chimera topology.

Lower Noise:
The next-generation system will include the lowest-noise commercially-available quantum processing units (QPUs) ever produced by D-Wave. This new QPU technology further improves qubit coherence, and paves the way to even greater speedups for existing and new quantum computing applications.

Increased Qubit Count:
With more than 5000 qubits, the next-generation platform will more than double the qubit count of the existing D-Wave 2000Q system. Combining more qubits with the new topology will give quantum programmers access to a larger, denser, and more powerful graph to solve larger problems.

Expansion of Hybrid Software & Tools:
Further investments in ease-of-use, automation, and new tools will provide an even more powerful hybrid rapid development environment. The hybrid software and tools will build on the existing D-Wave hybrid solvers, allowing easy access to both classical and the next-generation quantum platforms in the familiar coding environment, Python.

The Pegasus topology



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The probabilities are endless™

Ready to get started? Sign up for Leap at cloud.dwavesys.com/leap/signup/

To learn more, contact us or check out our videos, white papers, scientific papers, and other content at **www.dwavesys.com/resources.**

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