

The D-Wave 2000Q™ Quantum Computer Technology Overview



Quantum Computing for the Real World Today



Despite the incredible power of today's supercomputers, many complex computing problems cannot be addressed by conventional systems. The huge growth of data and our need to better understand everything from the universe to our own DNA leads us to seek new tools that can help provide answers. Quantum computing is the next frontier in computing, providing an entirely new approach to solving the world's most difficult challenges.

D-Wave Systems is the leader in the development and delivery of quantum computing systems and software, and the world's only commercial supplier of quantum computers. Our mission is to unlock the power of quantum computing for the world. We believe that quantum computing will enable solutions to the most challenging national defense, scientific, technical, and commercial problems.

D-Wave's systems are being used by some of the world's most advanced organizations, including Lockheed Martin, Google, NASA Ames, the University of Southern California, and Los Alamos National Laboratory. D-Wave currently has more than 140 granted US patents and has published over 90 scientific papers, many of which have appeared in leading science journals.

Quantum Computing

To speed computation, quantum computers tap directly into an unimaginably vast fabric of reality—the strange and counterintuitive world of quantum mechanics. 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.

The D-Wave 2000Q™ quantum computer leverages quantum dynamics to accelerate and enable new methods for solving discrete optimization, sampling, and machine learning problems. D-Wave systems use a process called **quantum annealing** to search for solutions to a problem. Quantum annealing is fundamentally different from classical computing. It harnesses the natural tendency of real-world quantum systems to find low-energy states. If an optimization problem is analogous to a landscape of peaks and valleys, for instance, each coordinate represents a possible solution and its elevation represents its energy. The best solution is that with the lowest energy corresponding to the lowest point in the deepest valley in the landscape.

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.

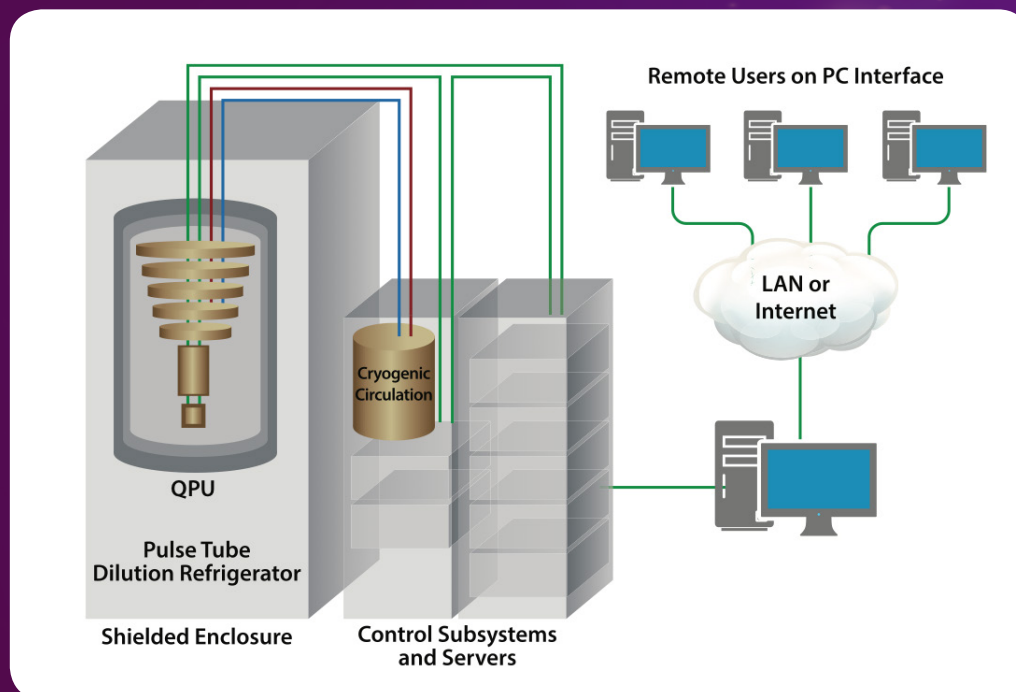
Simple on the Outside, Extraordinary on the Inside



The D-Wave 2000Q system has a footprint of approximately 10' x 7' x 10' (L x W x H). Its physical enclosure 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.

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.

The D-Wave 2000Q system can be integrated into standard data centers, high-performance computing environments, as well as private and public clouds. Systems are also accessible online through D-Wave's hosted cloud environment.



Colder than Interstellar Space

The D-Wave 2000Q system 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.

D-Wave's "dry" dilution refrigerator uses liquid helium refrigerant in a closed-loop system, avoiding the need for on-site replenishment.

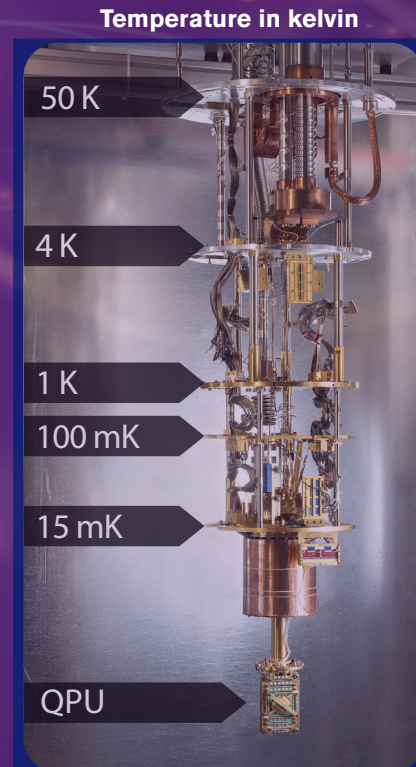
While dilution refrigerators are not uncommon in research environments, D-Wave has advanced the technology to ensure long run-life and reliability in a commercial product setting. Despite the extreme environment inside the system, a standard data center can normally accommodate the D-Wave 2000Q quantum computer.

I/O, Shielding, and Materials

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.

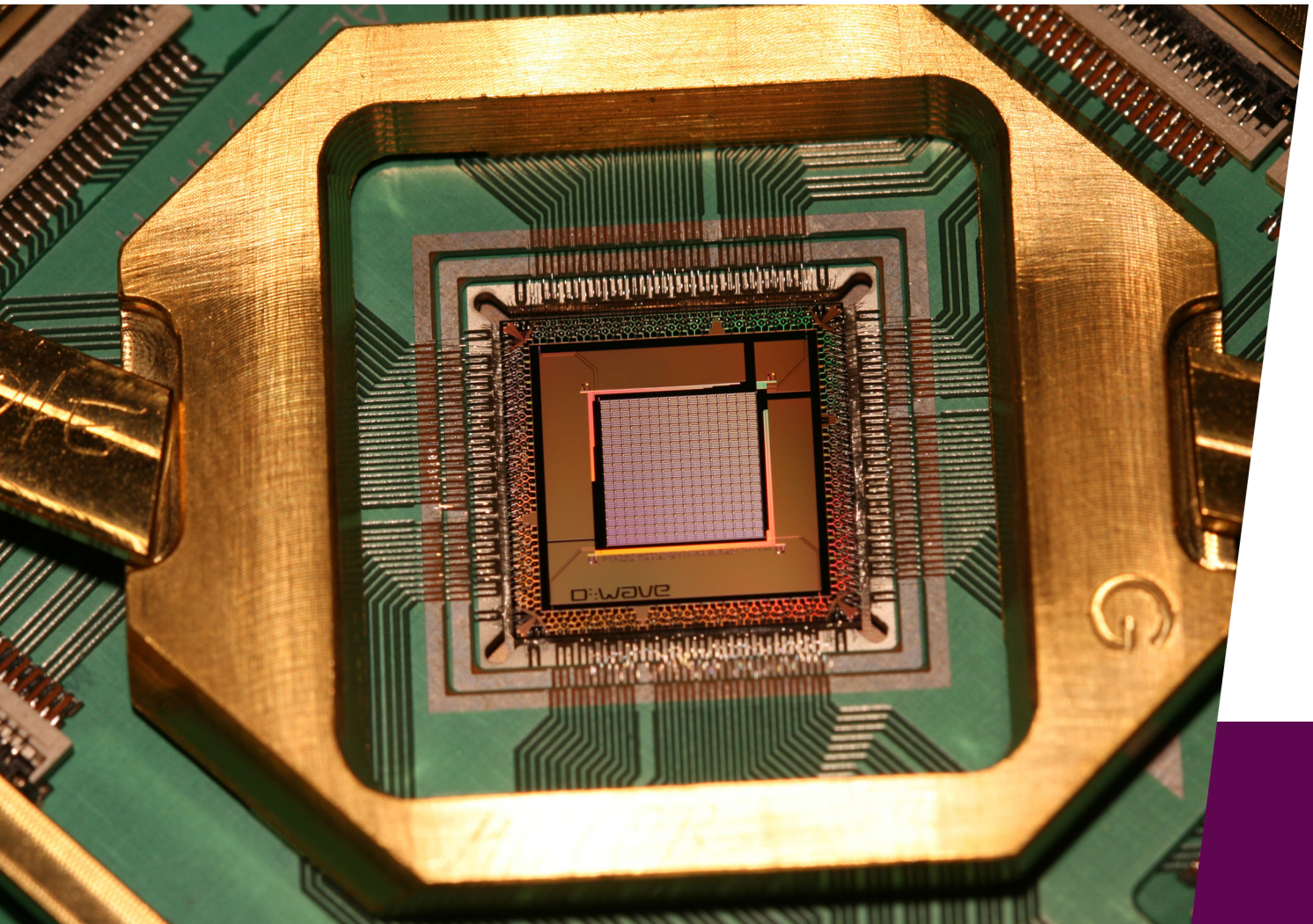
The magnetic shielding subsystem provides the low-field environment required for the QPU, using high-permeability and superconducting materials to achieve fields below 1 nanotesla. This is 50,000 times less than the Earth's magnetic field.



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.



The Quantum Processing Unit



The D-Wave QPU is built from a lattice of tiny loops of the metal niobium, each of which is one qubit (shown on the next page, in red). Below temperatures of 9.2 kelvin, niobium becomes a superconductor and exhibits quantum mechanical effects.

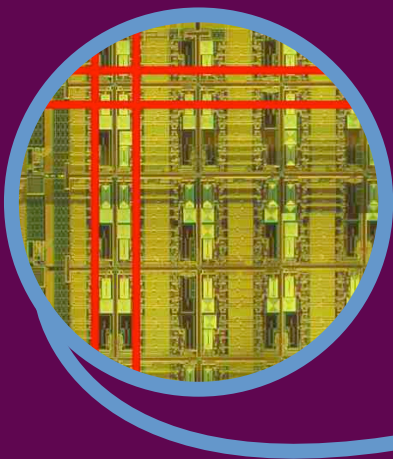
When in a quantum state, current flows in both directions simultaneously, which means that the qubit is in superposition—that is, in both a 0 and a 1 state at the same time. At the end of the problem-solving process, this superposition collapses into one of the two classical states, 0 or 1.

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.

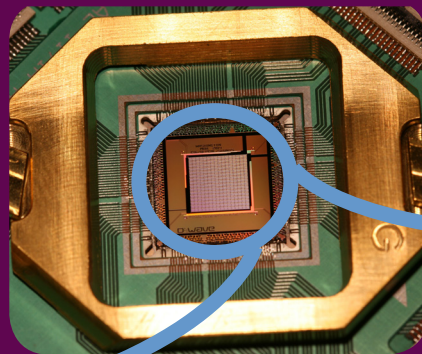
When the QPU arrives at a solution to a problem, all qubits settle into their final states and the values they hold are returned to the user as a bit string.

The D-Wave 2000Q system has up to 2048 qubits and 5600 couplers. To reach this scale, it uses 128,000 Josephson junctions, which makes the D-Wave 2000Q QPU by far the most complex superconducting integrated circuit ever built.

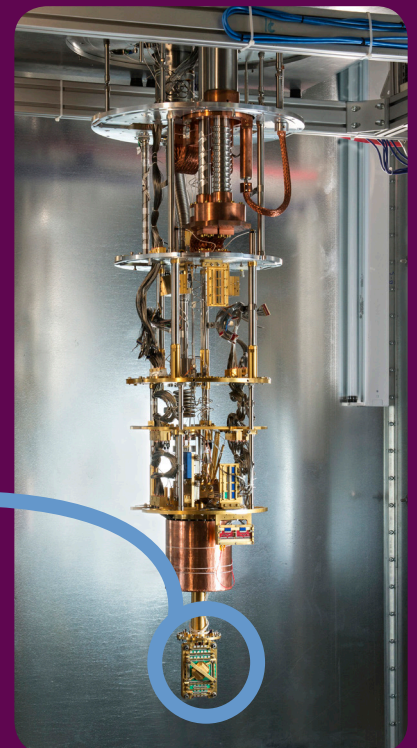
Qubits in red



Quantum processing unit



Inside the D-Wave enclosure



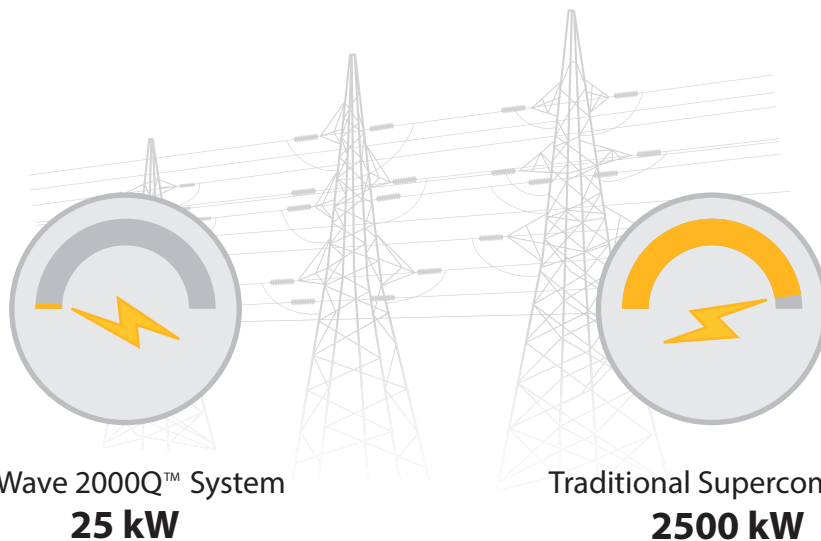
Energy Efficient

Unlike the CPUs of classical computers, D-Wave's superconducting QPU dissipates negligible amounts of heat during computation.

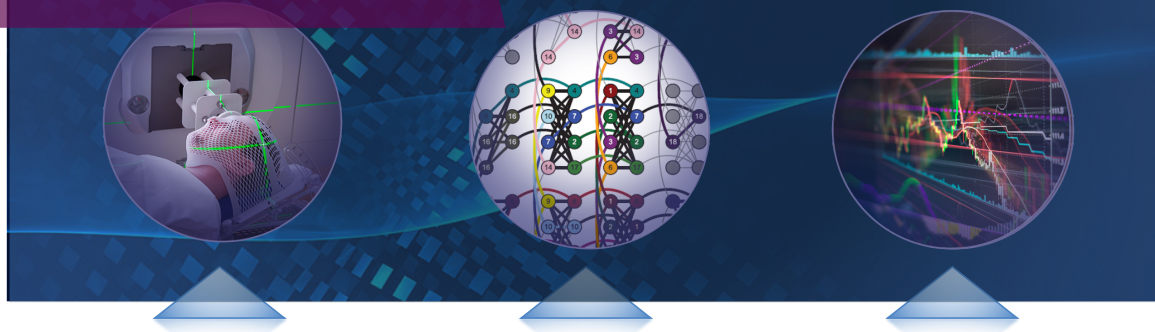
While traditional supercomputers generate massive amounts of heat and consume massive amounts of power, the D-Wave system consumes less than 25 kW of power, most of which goes towards operating the cooling and front-end servers. This low power consumption has remained constant since the introduction of the first D-Wave system despite the dramatic increase in system performance with each successive product generation.

The required water cooling is on par with what a kitchen tap can provide. The required air conditioning is one-tenth of what would be expected in a data center for a system with a similar footprint.

As more powerful D-Wave systems are released in the future, power consumption will remain constant, resulting in huge increases in performance per watt and per dollar. Tens of kilowatts means tens of thousands of dollars in operating costs per year in contrast to millions of dollars per year for even a modest high-performance computer system that consumes megawatts of power. If realized today, exascale supercomputers would consume power on the order of that produced by the Hoover dam.



Applications



Quantum computers will change the world, leading to better and faster solutions to the most challenging problems, and to unprecedented applications. D-Wave quantum computers are ideally suited to solving many hard problems in optimization, machine learning, sampling and cyber security.

With 2000 qubits and new control features, the D-Wave 2000Q quantum computer can solve larger problems than was previously possible, and with better performance. A growing community of developers are using the unique capabilities of D-Wave systems to solve challenging problems in a diverse set of application areas including:

Machine Learning & Computer Science

- Detecting statistical anomalies
- Finding compressed models
- Recognizing images and patterns
- Training neural networks
- Verifying and validating software
- Classifying unstructured data
- Diagnosing circuit faults

Security & Mission Planning

- Detecting computer viruses & network intrusion
- Scheduling resources and optimal paths
- Determining set membership
- Analyzing graph properties
- Factoring integers

Financial Modeling

- Detecting market instabilities
- Developing trading strategies
- Optimizing trading trajectories
- Optimizing asset pricing and hedging
- Optimizing portfolios

Healthcare & Medicine

- Detecting fraud
- Generating targeted cancer drug therapies
- Optimizing radiotherapy treatments
- Creating protein models

Improved Annealing Path Control

Certain problems benefit when some qubits anneal slightly before or after others. The *anneal offsets* feature, introduced with the D-Wave 2000Q system, lets users advance or delay anneal paths to enhance application performance. Algorithms using this feature have shown performance improvements of up to 1000 times for some problem types.

Software and Programming

Just as the classical computing world needed a software ecosystem to build a broad community of application developers and users, the quantum computing world does as well. D-Wave, new quantum software companies, D-Wave customers, and users are starting to develop system software, higher level tools, and applications that leverage the power of the D-Wave system.

The D-Wave 2000Q system provides a standard Internet API (based on RESTful services), with client libraries available for C/C++, Python, and MATLAB. This interface allows users to access the system either as a cloud resource over a network, or integrated into their high-performance computing environments and data centers. Access is also available through D-Wave's hosted cloud service. Using D-Wave's development tools and client libraries, developers can create algorithms and applications within their existing environments using industry-standard tools.

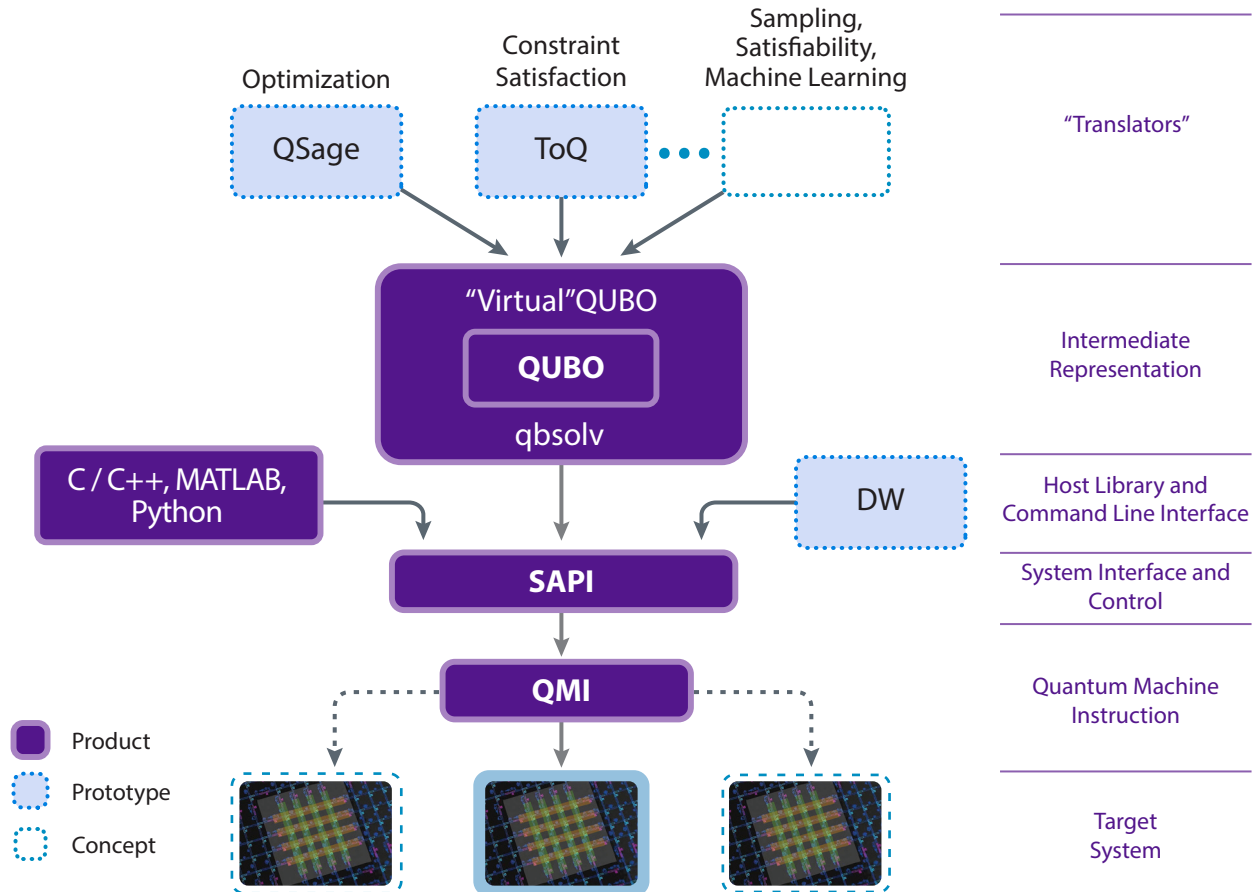
While users can submit problems to the system in a number of different ways, ultimately a problem represents a set of values that correspond to the weights of the qubits and the strength of the couplers. The system takes these values along with other user-specified parameters and sends a single quantum machine instruction (QMI) to the QPU. Problem solutions correspond to the optimal configuration of qubits found; that is, the lowest points in the energy landscape. These values are returned to the user program over the network.

Because quantum computers are probabilistic rather than deterministic, multiple values can be returned, providing not only the best solution found, but also other very good alternatives from which to choose. Users can specify the number of solutions they want the system to return.

Users can submit problems to the D-Wave quantum computer in several ways:

- Using a program in C, C++, Python, or MATLAB to create and execute quantum machine instructions
- Using a D-Wave tool such as:
 - QSage, a translator designed for optimization problems
 - ToQ, a high level language translator used for constraint satisfaction problems and designed to let users “speak” in the language of their problem domain
 - qbsolv, an open-source, hybrid partitioning optimization solver for problems that are larger than will fit natively on the QPU
 - dw, which executes QMIs created via a text editor
- By directly programming the system via QMIs

D-Wave Software Environment



What's Next

While the D-Wave quantum computer is the most advanced in the world, the quantum computing revolution has only begun. Our vision is of a future where quantum computers will be accessible and of value to all, solving the world's most complex computing problems. This will require advances in many dimensions and contributions from experts in diverse domains. It is exciting to see increasing investment worldwide, advances in research and technology, and a growing ecosystem of developers, users, and applications needed to deliver on that vision.

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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