The Quantum Computing Company™

The D-Wave 2X™ Quantum Computer

Technology Overview

D-Wave Systems

Founded in 1999, D-Wave Systems is the world's first quantum computing company. Our mission is to integrate new discoveries in physics, engineering, manufacturing, and computer science into breakthrough approaches to computation to help solve some of the world's most challenging computing problems.

Today D-Wave is the recognized leader in the development, fabrication, and integration of superconducting quantum computers. Our systems are being used by world-class organizations and institutions including Lockheed Martin, Google, NASA, and the University of Southern California. D-Wave has been granted over 125 US patents and has published over 80 scientific papers, many of which have appeared in leading science journals.

While we are only at the beginning of this journey, quantum computing has the potential to help solve some of the most complex technical, national defense, scientific, and commercial problems that organizations face.

Quantum Computing

To speed computation, quantum computers tap directly into an unimaginably vast fabric of reality – the strange and counter-intuitive 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 2X processor, with 1000 qubits, can evaluate all 2^{1000} possible solutions at the same time.

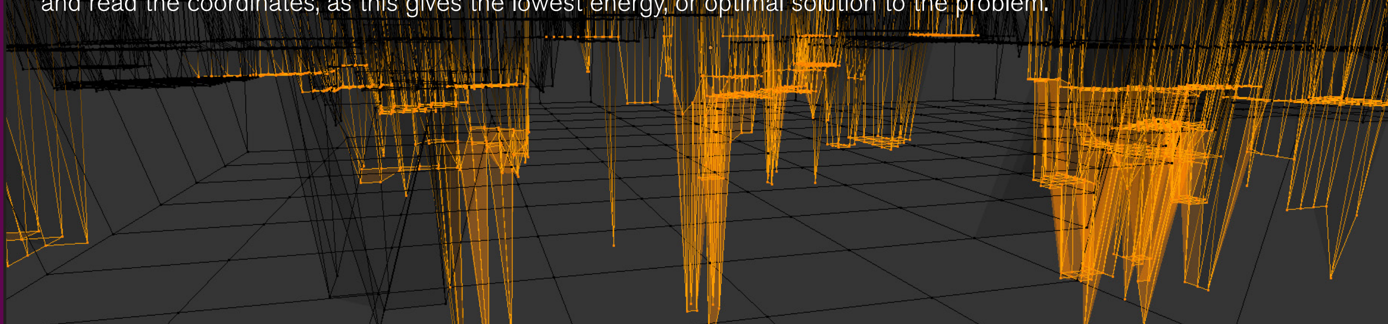
Qubits can exist in a state of 1 and 0 simultaneously

With 1000 qubits, the D-Wave 2X system can search through 2^{1000} possible solutions simultaneously.

The D-Wave 2X system implements a ***quantum annealing*** algorithm, which solves problems by searching for the global minimum of a function. This is fundamentally different from the familiar framework of classical computing built on logical operations, but it is relevant in many high value problems such as minimizing error in a voice recognition system, controlling risk in a financial portfolio, or reducing energy loss in an electrical grid.

While there are different ways in which users can submit problems to the system, at the level of the machine instruction of the quantum processor the system solves a Quadratic Unconstrained Binary Optimization Problem (QUBO), where binary variables are mapped to qubits and correlations between variables are mapped to couplings between qubits. The system of interacting qubits is evolved quantum mechanically via the annealing algorithm to find optimal or near-optimal solutions.

Solving problems with the D-Wave 2X system can be thought of as trying to find the lowest point on a landscape of peaks and valleys. Every possible solution is mapped to coordinates on the landscape, and the altitude of the landscape is the "energy'" or "cost" of the solution at that point. The aim is to find the lowest point or points on the map and read the coordinates, as this gives the lowest energy, or optimal solution to the problem.



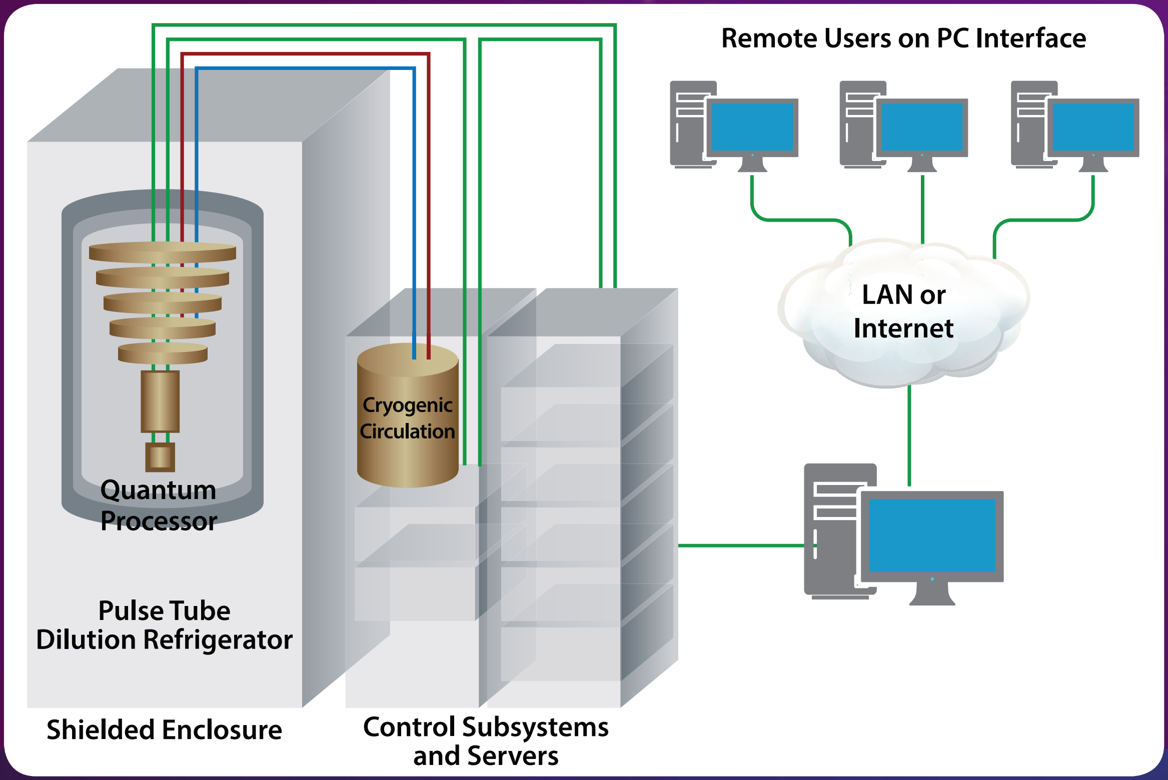
The special properties of quantum physics, such as quantum tunneling, allow the quantum computer to explore this landscape in ways that have never before been possible with classical systems. Quantum tunneling is like a layer of water that covers the entire landscape. As well as running over the surface, water can tunnel through the mountains as it looks for the lowest valley. The water is an analogy for the probability that a given solution will be returned. When the quantum computations occur, the 'water' (or probability) is pooled around the lowest valleys. The more water in a valley, the higher the probability of that solution being returned. A classical computer, on the other hand, is like a single traveler exploring the surface of a landscape one point at a time.

The D-Wave Quantum Computer

The physical footprint of the system is approximately 10' x 7' x 10' (L x W x H). It houses a sophisticated cryogenic refrigeration system, shielding and I/O systems that support a single thumbnail-sized quantum processor. Most of the physical volume of the current system is due to the size of the refrigeration system and to provide easy service access.

In order for the quantum effects to play a role in computation, the quantum processor must operate in an extreme isolated environment. The refrigerator and many layers of shielding create an internal environment with a temperature close to absolute zero that is isolated from external magnetic fields, vibration, and external RF signals of any form.

The adjoining cabinets contain the control subsystems and the front-end servers that provide connectivity to the system. The D-Wave 2X system can be deployed as part of a High Performance Computing (HPC) data center using standard interfaces and protocols.



Colder than Interstellar Space

Reducing the temperature of the quantum processor to near absolute zero is required to isolate it from its surroundings so that it can behave quantum mechanically. In general, the performance increases as temperature is lowered - the lower the temperature, the better. The D-Wave 2X processor operates at a temperature of 15 millikelvin, which is approximately 180 times colder than interstellar space.

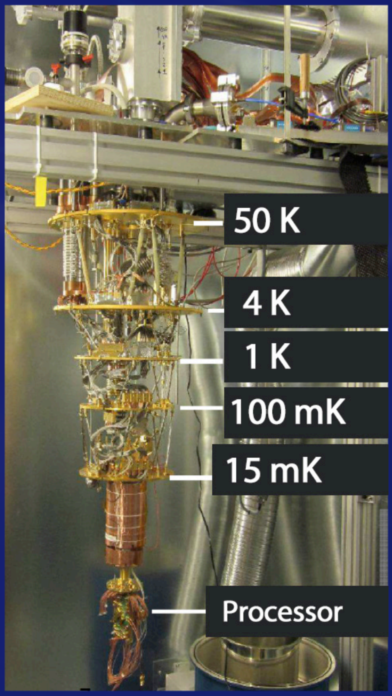
The refrigeration system used to cool the processor is known as a “dry” dilution refrigerator. It uses liquid helium in a closed-loop cycle in which it is recycled and re-condensed using a pulse tube cryocooler. The closed-loop refrigeration removes the need for on-site replenishment of liquid helium and makes the system suitable for remote deployment.

While dilution refrigerators are not uncommon in research environments, D-Wave has advanced the technology to ensure long life and high reliability.

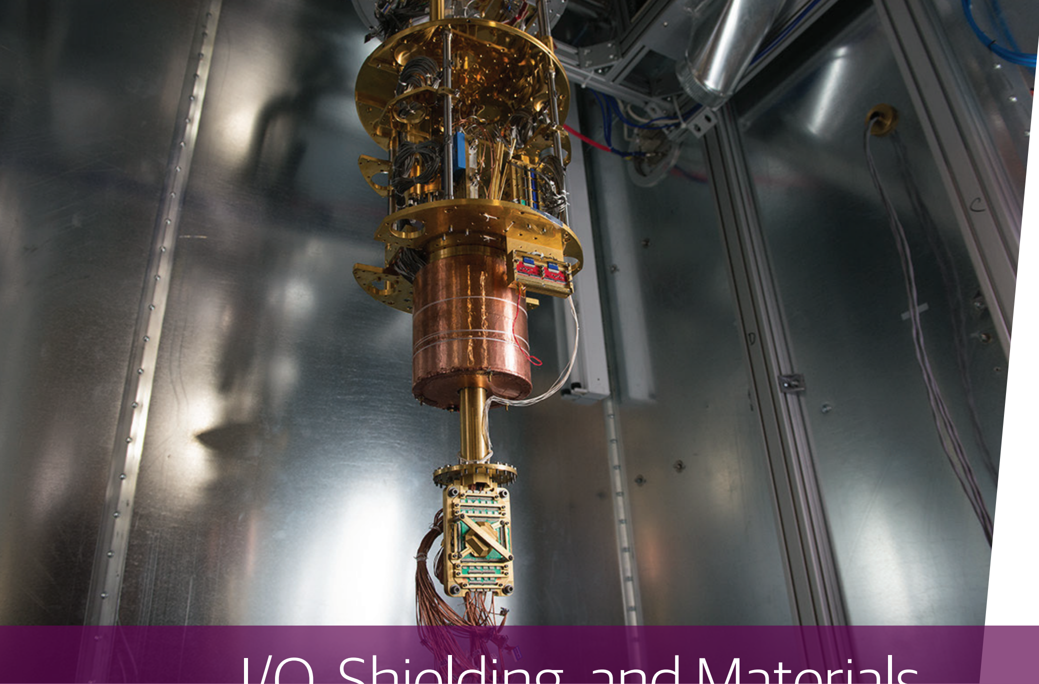
As the cooling power available at such low temperatures is extremely low, D-Wave has taken great care to minimize the heat loads and effectively manage the heat transfer within the system.

Despite the extreme environment inside the system, the D-Wave quantum computer can be located in a standard data center environment.

Temperature in Kelvin



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



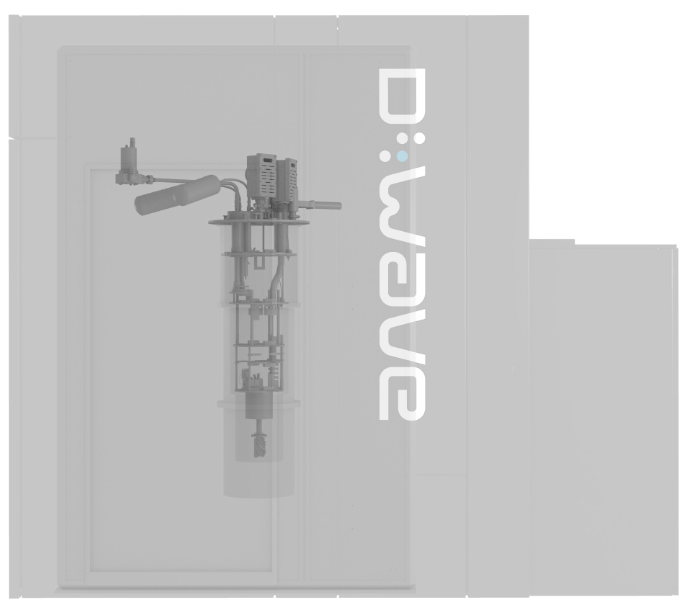
I/O, Shielding, and Materials

The I/O subsystem is responsible for passing information from the user to the processor and back. After receiving a problem from the user via standard web protocols, data is converted to analog signals and carried on normal conducting wires that transition to superconducting wires at low temperatures.

The requirements for the I/O and shielding subsystems placed many unusual demands on the design, materials and manufacturing processes required. The I/O subsystem was designed to filter out essentially all unwanted noise, function at millikelvin temperatures and withstand multiple warming and cooling cycles between room temperature and base temperature. The current I/O system uses 200 heavily filtered lines from the control electronics to the processor that were specifically designed for optimal system performance. The system also includes a variety of superconducting metals which often require unusual and non-standard manufacturing techniques. In addition, none of the materials close to the processor can be magnetic.

As the quantum processor is adversely affected by stray magnetic fields, extreme care had to be taken to exclude them. The magnetic shielding subsystem achieves fields less than 1 nanotesla across the processor in each axis. This is approximately 50,000x less than the Earth's magnetic field. This low magnetic field environment is achieved with a system comprised of multiple shields, some of them high permeability metals and some of them superconducting.

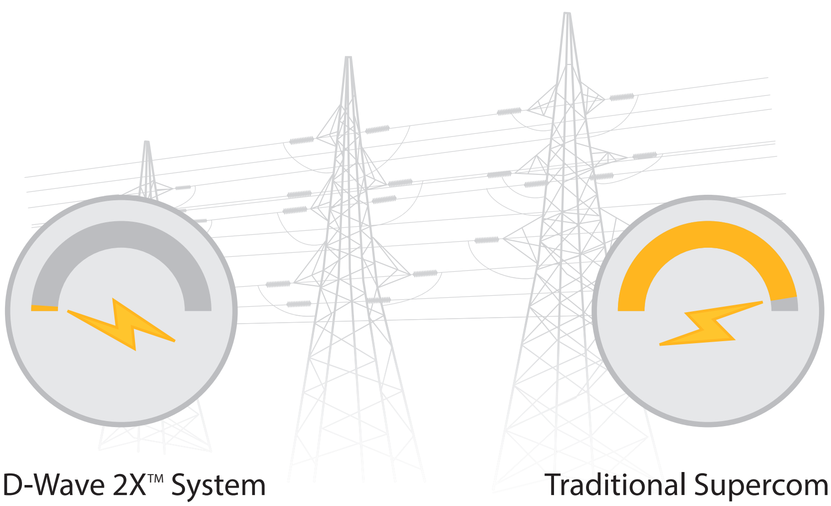
The system sits inside a shielded enclosure that screens out RF electromagnetic noise. The only path for signals between the inside and outside of the shielded enclosure is a digital optical channel carrying programming information in, and results of computations out. The processor resides in a high vacuum environment in which the pressure is 10 billion times lower than atmospheric pressure.



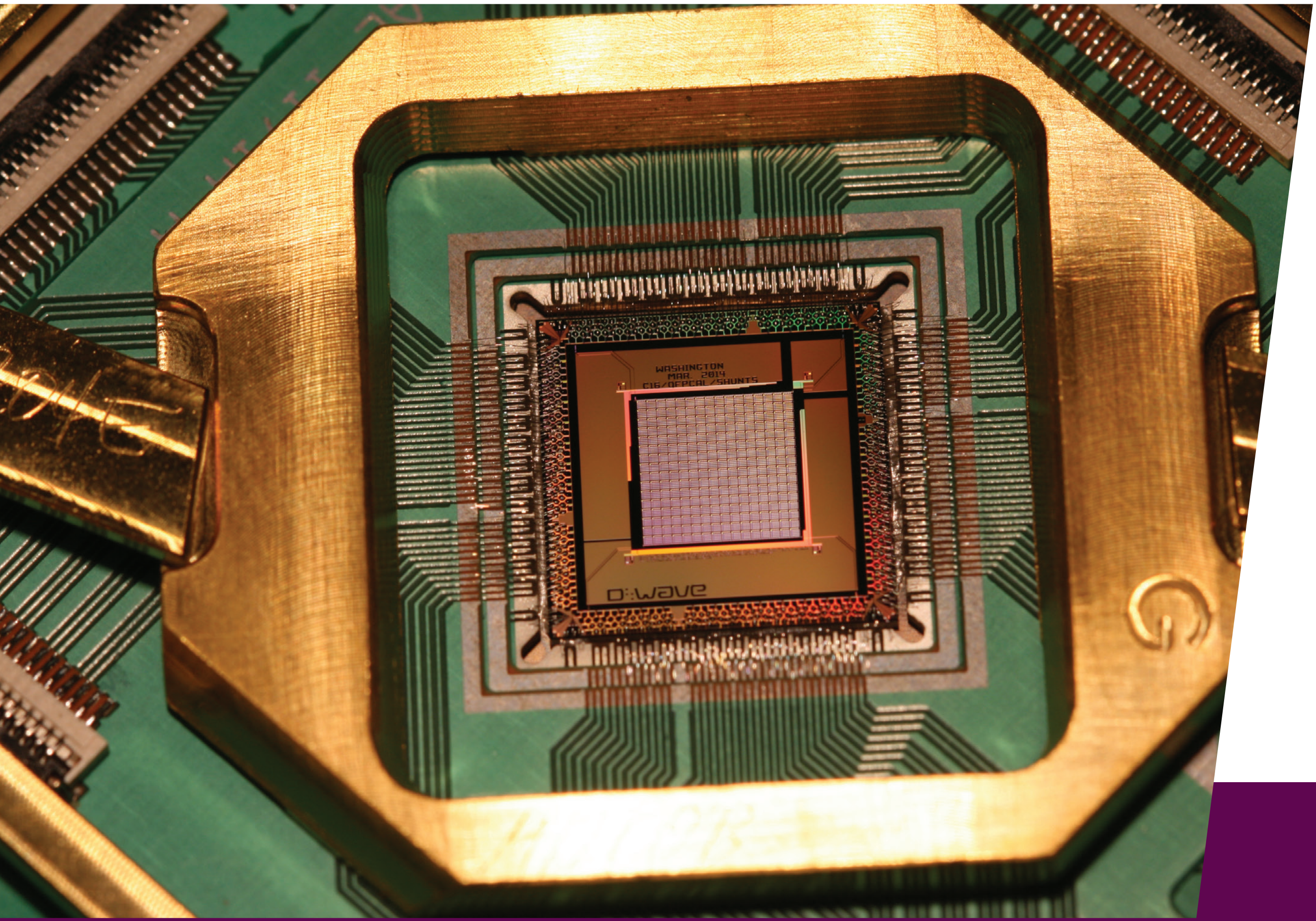
Power and Cooling

Unlike traditional supercomputers that generate massive amounts of heat and require huge amounts of power, the D-Wave system is based on superconducting electronics that do not dissipate heat and require little supply power. The D-Wave 2X consumes less than 25 kW of power, most of which is required for cooling and operating front-end servers. As more powerful quantum processors are released, this power requirement will remain low.

The system requires water cooling, but the amount of water needed is on par with what a kitchen tap can provide. The amount of air conditioning needed is a tiny fraction (1/10) of what would be expected in a data center given the footprint of the system.



The Quantum Processor



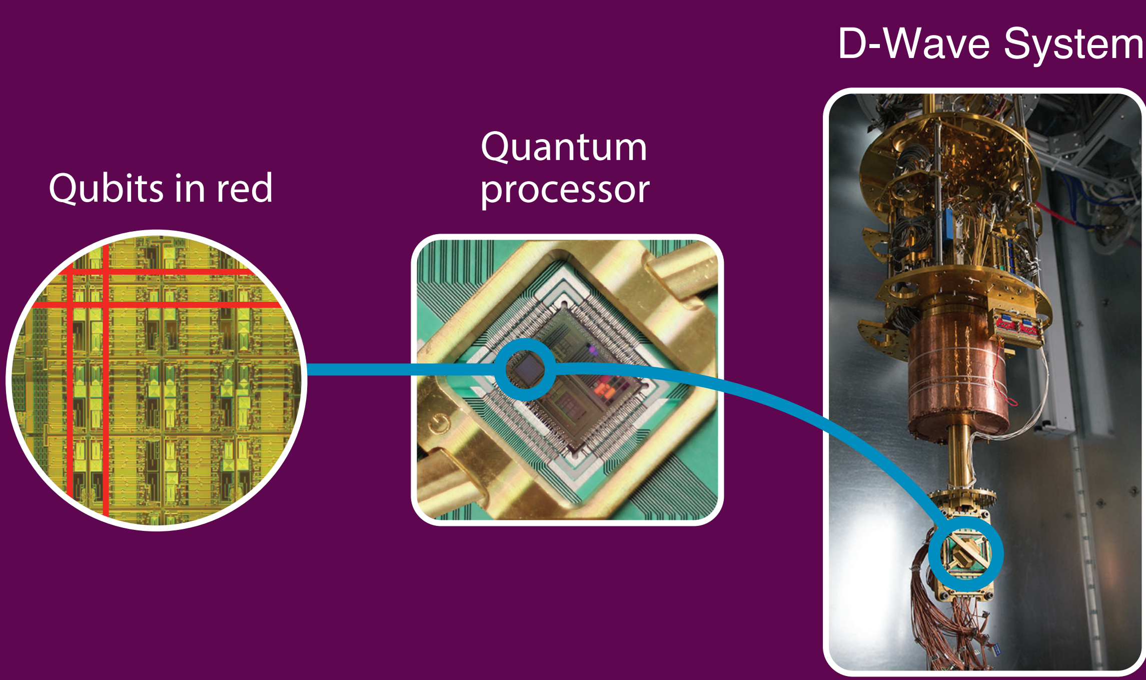
The D-Wave quantum processor is built from a lattice of tiny loops of the metal niobium, each of which is one quantum bit, or qubit (shown on the next page, outlined in red). When niobium is cooled down below 9.2 Kelvin it becomes a superconductor and starts to exhibit quantum mechanical effects.

By circulating current either clockwise or counter-clockwise, the superconducting qubit emits a magnetic field pointing downward or upward, encoding a logical 1 or 0. During quantum annealing, current flows clockwise and counter-clockwise simultaneously. This enables the qubits to be in a "superposition" state – that is, both a 0 and a 1 at the same time. At the end of the quantum annealing cycle the qubit "collapses" into one of the two states, either a 0 or 1.

In order to go from a single qubit to a multi-qubit processor, the qubits must be connected together to exchange information. This is achieved through the use of elements known as couplers, which are also made from superconducting loops. Putting many qubits and couplers together with control circuitry to manage the magnetic fields creates a fabric of programmable quantum devices.

After the computation has finished and the qubits have settled into their final (classical) 0 or 1 states, the values held by the qubits are returned to the user as a bit string of 0s and 1s.

The D-Wave 2X system is based on a fabric of 1000+ qubits and over 3000 couplers. In order to attain this scale the processors contain over 128,000 Josephson Junctions - believed to be the most complex superconductor integrated circuits ever built.



Software and Programming

The D-Wave 2X System has a web API with client libraries available for C, C++, Python and MATLAB. This interface allows the machine to be easily accessed as a cloud resource over a network. Using development tools and client libraries, users can write code in the language of their choice.

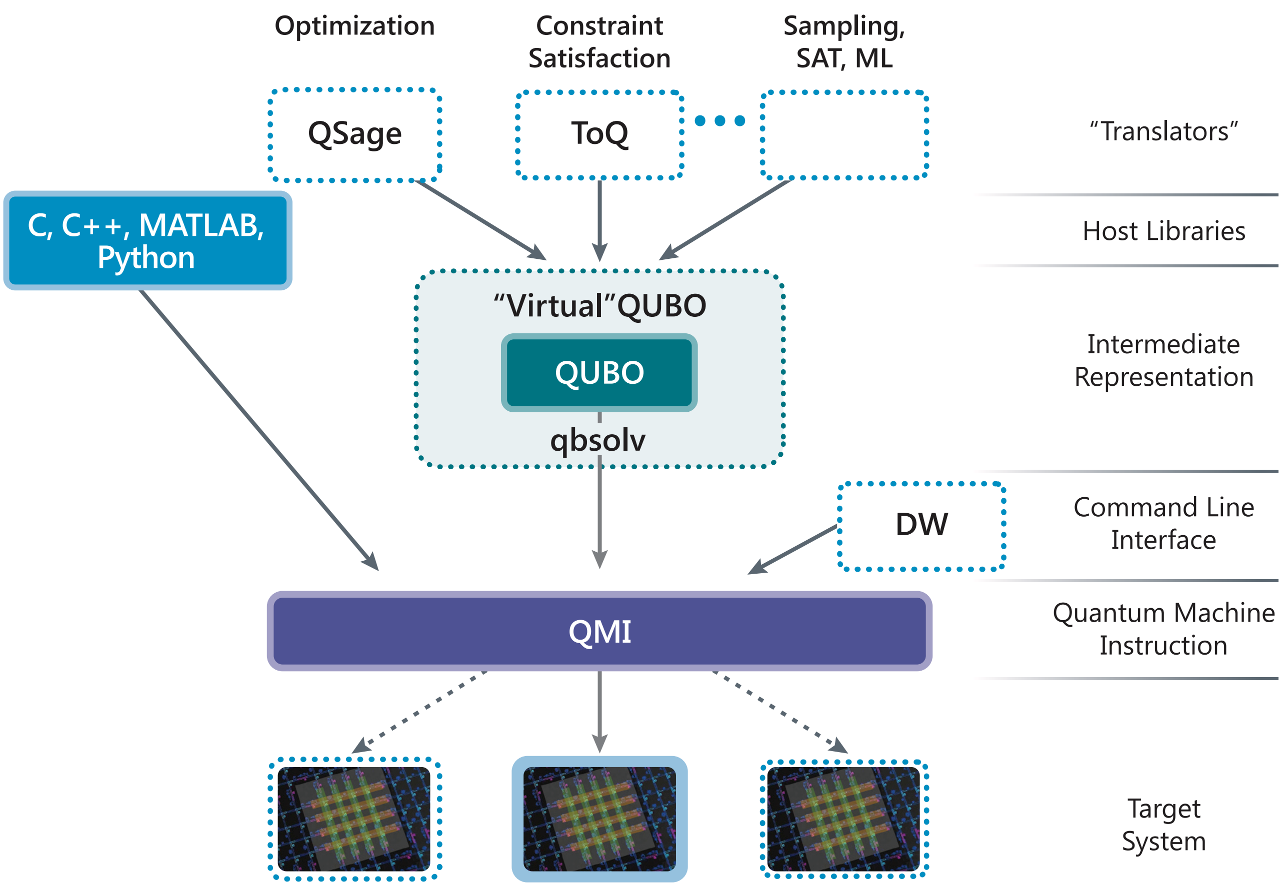
As described below, users can submit problems to the system in a number of different ways. Values corresponding to the "weights" of the qubits and coupling "strengths" of the interaction between them are submitted to the system, which then executes a single Quantum Machine Instruction (QMI) for processing. The solutions are values that correspond to the optimal configuration of qubits found, or the lowest points in the energy landscape. These values are returned to the user program over the network.

Because a quantum computer is 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.

There are multiple ways to submit a problem to the D-Wave quantum computer:

- Use a higher level program in C, C++, Python or MATLAB to create and execute a Quantum Machine Instruction
- Use one of the D-Wave tools under development including:
  - 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
- Directly program the system by using Quantum Machine Language to issue the Quantum Machine Instruction

D-Wave Software Environment



Dotted boxes indicate items are under development or are future capabilities.

What's Next

While the D-Wave quantum computer is the most advanced in the world, we are still at the very beginning of the evolution of quantum computing. In the coming years we expect to see great advances in all aspects of the technology, from computing hardware and environmental elements to system software and tools to a growing ecosystem of applications designed to take advantage of the unique characteristics of the quantum system.

It is truly an exciting time to be involved in the next great computing revolution. 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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