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Quantum Computing in the Real World

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By Steve Conway; Earl C. Joseph, Ph.D.; and Robert Sorensen

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As Moore's law–related advances in the clock speeds of CPUs have slowed, interest in alternative processor technologies has escalated. Combining CPUs with processing elements specialized for data-parallel, throughput-intensive tasks — NVIDIA general-purpose graphics processing units (GPGPUs), Intel Xeon Phi many-core arrays, or field-programmable gate arrays (FPGAs) — can keep evolutionary performance moving forward on most high-performance computing (HPC) problems. But some scientifically and economically important classes of problems are so daunting that trying to solve them with these "classic" computer technologies would take prodigious amounts of time — months, years, decades, or longer in extreme cases. These problem classes exist in optimization, machine learning/deep learning, cognitive computing/artificial intelligence (AI), pattern recognition and anomaly detection, financial analysis, software/hardware verification and validation, scheduling and logistics, precision medicine, and bioinformatics. Experts generally agree that practical quantum computers could solve these problems quickly, often in mere seconds. Impressive academic research is being conducted on quantum computing, but the path from academic research to a commercial product is long and arduous. Today, only one company, D-Wave Systems Inc., offers a commercial product based on quantum computing principles. The D-Wave 2X system is a quantum annealer, meaning it is designed to solve only a subset — albeit an important subset — of quantum computing problems. Although academic experts debate whether the D-Wave system is a "true" quantum computer, with strong opinions on both sides, it's clear that where quantum computing in the real world is concerned, D-Wave is the global leader. In December 2015, Google and NASA announced that their shared D-Wave 2X computer solved a complex optimization problem up to 100 million times faster than a single-core classic computer did. Google called these results "intriguing and very encouraging." IDC believes that D-Wave Systems has a major head start in real-world quantum computing and is well positioned to maintain market leadership by advancing quantum annealing capabilities and moving over time beyond annealing to other areas of quantum computing.

The Promise of Quantum Computing

Strengths and Limitations of Classic Supercomputers

Especially during the past 15 years, the peak performance numbers of classic HPC systems — their hypothetical speed limits — have skyrocketed. On the November 1999 list of the world's most powerful supercomputers (**www.top500.org**), the number 1 system boasted 9,632 cores and peak performance of 3.2 teraflops (TF). Fast-forward 16 years to the November 2015 list and the number 1 supercomputer featured 3.1 million processor cores and peak performance of 54.9 petaflops (PF). That's a 324-fold increase in the core count and a 17,156-fold leap in peak performance.

Sound impressive? Yes and no. A 17,156-fold improvement in peak performance is no small feat, but these figures mean that the speedup for a single core was only 52.9 times in 15 years (17,156/324). Fully exploiting the 2015 supercomputer for a single problem would require harnessing 321.8 times as many cores (3.1 million cores/9,632 cores) as were needed to fully utilize its 1999 predecessor. That is also no small feat for many codes. But that's not all. The 1999 winner included only CPUs, but its 2015 counterpart featured a heterogeneous mix of CPUs and accelerators, adding another layer of complexity.

In summary, lagging advances in CPU core clock speeds in relation to system peak performance have challenged the HPC community to "go parallel" to an unprecedented extent. One helpful strategy has been to combine CPUs' proven prowess in instruction-level parallelism (ILP) with newer processing elements that are more adept at handling data-level parallelism (DLP), such as NVIDIA GPGPUs, Intel Xeon Phi many-core arrays, or FPGAs. This strategy should keep the sustained performance of most problems moving forward in an evolutionary way on classic "von Neumann architecture" computers. However, the overall efficiency as measured by the actual CPU usage versus the peak capability of the leading supercomputers continues to decline — many of the biggest systems in the world are delivering only a small percentage of their peak performance to applications.

Where Quantum Computers Fit

But there are narrow classes of problems that can't be solved by classic computers in reasonable time frames. As noted previously, intractable problems exist within the larger domains of optimization, machine learning/deep learning, cognitive computing/AI, pattern recognition and anomaly detection, financial analysis, software/hardware verification and validation, scheduling and logistics, precision medicine, and bioinformatics.

For these problems, which are often scientifically and economically important, classic computers — even with an optimal mix of ILP and DLP abilities — are simply the wrong tools for the job. That's because even the most powerful classic supercomputer might take months, years, decades, or longer to run one of these problems to completion. In the most extreme cases, some experts say, a classic computer could not finish the job in the remaining lifetime of the Earth. Some examples of these high-value problems are as follows:

- Creating security passwords that would take the most accomplished hacker using a classic computer centuries to crack
- Instantly zeroing in on sophisticated global fraud schemes (or terrorism plots) that might go undetected for years by conventional computers
- Identifying the cause of a potential new pandemic before it has time to spread beyond its origin site

Experts generally agree that quantum computers, assuming they become practical, could tackle these problems and similar daunting problems in a matter of seconds.

Burgeoning Research on Quantum Computing

It's beyond the scope of this paper to attempt a detailed definition of quantum computing. In a nutshell, though, a quantum computer performs calculations on the basis of quantum theory. Although quantum computing might make sense for only a narrow range of all computing problems, these problems are important enough to justify the increasing attention being paid to quantum computing in government, academia, and industry.

- Already, about 7,000 researchers around the world are working in the field of quantum computing. Annual research spending is on the order of $1.7 billion. (Source: European Commission Workshop on Quantum Technologies and Industry. May 6, 2015. Brussels.)
- In 2012, Serge Haroche (France) and David J. Wineland (America) shared the Nobel Prize in Physics "for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems."
- IBM and Microsoft are among the companies making strong R&D investments in quantum computing research. Neither company has announced plans for a quantum computing product, however.

The D-Wave 2X: The World's First Quantum Computer Product

The major challenge with quantum computing, as with any promising new approach, is turning theory into practice in order to tackle real-world problems. Because quantum computing principles are so different from classic computing principles, the task of designing and building a quantum computer is extremely daunting. In the real world, this will happen in stages.

The first stage in this evolutionary process is represented by D-Wave's analog computer, which is designed to address problems that are amenable to quantum annealing. To IDC's knowledge, this is the first and only computer product that is being used today to tackle quantum computing problems. Publicly known users include Google, NASA, Lockheed Martin, USC/ISI, and Los Alamos National Laboratory.

- An example of a complex optimization problem for the D-Wave system's quantum annealing capability is finding the lowest elevation point in a landscape. A classic computer would test every point in the landscape in serial fashion — a process that might take years or more to compute — while the D-Wave computer is designed to simultaneously test all elevations in the landscape, producing the most likely answer instantaneously.

It's beyond the scope of this paper to attempt a technical explication of the workings of the D-Wave 2X quantum computer. There are other good sources for that information. It's enough to provide a few key facts before moving on to the important work being done on D-Wave 2X systems today.

- D-Wave Systems, founded in 1999, is a privately held company with offices in Vancouver, British Columbia, Canada; Palo Alto, California; and Washington, D.C.
- D-Wave's blue-chip investors include venture firm Draper Fisher Jurvetson (funder of Skype and Tesla Motors); Bezos Expeditions (private investment firm of Amazon founder Jeff Bezos); In-Q-Tel, the investment arm of the U.S. intelligence community; Goldman Sachs; BDC Capital; DFJ; GrowthWorks; International Investment & Underwriting; and Kensington Partners.
- The D-Wave 2X quantum computer outwardly resembles a classic computer cabinet, except that its innovative niobium processor is hidden inside a custom-designed cooling unit that keeps the processor at a constant temperature of -459^{o} Fahrenheit — 180 times colder than interstellar space. The computer is also heavily shielded against vibrations and noise. The entire system including cooling generates only 25kW of heat compared with multiple MW for high-end classic supercomputers.
- The computer is able to exploit over 1,000 quantum bits, or qubits. (D-Wave aims to double the qubit count every one to two years.) This means, in theory, the D-Wave 2X computer could search concurrently through a solution space with 2^{1000} potential solutions. That's a far larger number than all the atoms in the universe. A D-Wave 2x system with 1,000 qubits has been delivered to Google, and Lockheed Martin's system was recently upgraded to the same capability. Los Alamos National Laboratory has started using the same D-Wave 2X system.

There is debate in academic circles about whether the D-Wave system is a fully qualified quantum computer on the grounds that it does quantum annealing and hence is designed to tackle only a subset of all quantum computing problems. Some academic scientists vehemently agree that the D-Wave system is fully qualified, while others vehemently disagree.

What remains undeniable is that the D-Wave 2X is the first and only computer available today that was designed to solve quantum problems. New approaches to real-world computing take time to mature. It is unreasonable to expect early implementations to fully realize the potential embodied in the related theory. The development of quantum computers will follow an evolutionary path that may take another decade or two, or even longer, to satisfy nearly all academic theoreticians.

Early Work Being Done on the D-Wave 2X Quantum Computer

In the meantime, the important exploratory work begin done on the D-Wave quantum computer by NASA, Google, Los Alamos National Laboratory, Lockheed Martin, and others will advance the body of knowledge about quantum computing in the real world. For example:

- In December 2015, Google and NASA announced that their shared D-Wave 2X quantum annealing computer solved a complex optimization problem up to 100 million times faster than a single-core classic computer did. Google said these results were "intriguing and very encouraging," although there is "more work ahead to turn quantum enhanced optimization into a practical technology."
- The Quantum Artificial Intelligence Laboratory, operated by NASA and Google at NASA Ames Research Center, is exploring multiple problems. NASA is interested in problems such as scheduling astronauts' International Space Station activities and optimizing the routing of the Curiosity rover on the surface of Mars.
- Google has been using the D-Wave quantum computer to investigate applying quantum technology to machine learning problems.
- Lockheed Martin uses the D-Wave computer to explore its application to more exhaustive software validation and verification.

The Future of D-Wave and Quantum Computing

It's too soon to say whether D-Wave will remain at the forefront of the evolution of quantum computers by also being the first to deploy a quantum computer whose use extends beyond annealing. Given the extreme difficulty of that task, it may take another decade or longer for the first real-world general-purpose quantum computer product to enter the marketplace. What's certain is that D-Wave has an important head start over potential competitors in this evolutionary process and should benefit greatly from the experiences of its users today and in the interim. For the more foreseeable future, the yardstick for measuring real-world progress in quantum computing is likely to be D-Wave's plan to double the number of qubits in its system every year or so. The company has met that goal so far.

Opportunities

- **Leverage the high interest level in quantum computing and D-Wave's track record to sell more of the current systems.** Given the escalating research activity in quantum computing and the fact that D-Wave offers the only quantum computer product on the market today, IDC believes D-Wave is well positioned to ramp up the sales of its systems in the next few years. We see a growing subset of researchers wanting to gain hands-on experience with an early quantum computer, following the examples of Google, NASA, Lockheed Martin, and Los Alamos National Laboratory.
- **Maintain the lead in real-world quantum computing.** D-Wave has built a substantial lead in real-world quantum computing by developing the world's first computer product based on quantum computing principles — and by placing this product in the hands of researchers at a small but growing number of high-profile organizations. D-Wave has a strong opportunity to maintain and perhaps extend this lead, first by fulfilling its plan to double the qubits (capability) in its quantum annealing computers and then, in the future, by being the first to develop products that broaden the applicability of quantum computers beyond annealing.

- **Continue to develop software to make D-Wave quantum computers easier to use.** Exploiting a revolutionary computer such as the D-Wave 2X requires highly innovative software. D-Wave and its partners deserve congratulations for progress on early software tools to make the systems easier to use. Clearly, further software advances will boost the market opportunity for D-Wave quantum computers by making it easier for users in various domains to exploit the computers productively.

Challenges

- **Work with customers/users to identify additional problems that showcase the value of the D-Wave computer.** As noted, Google and NASA were encouraged by the 100 million-fold speedup they obtained on a complex optimization problem run on their D-Wave system. The next step — an important one for D-Wave — is to identify one or more "killer applications" with strong potential to accelerate demand for the company's quantum computing platform.
- **Address academic critics and competitive fear, uncertainty, and doubt (FUD).** D-Wave has strong adherents and strong detractors in the academic community — those who believe the D-Wave system is a quantum computer and critics who claim that only a computer that does more than just annealing qualifies as a quantum computer. Some potential competitors have joined the ranks of the critics (perhaps because these vendors are also conducting research without having tried to build a real-world computer based on quantum principles). Although the academic debate probably isn't too important to current and potential customers, IDC believes that D-Wave needs to address this situation by describing the realities of moving beyond research to build a quantum computer today, as well as the time and effort it might take to extend quantum computing capabilities past annealing.

Conclusion

IDC believes the growing research momentum behind quantum computing R&D is a strong indication that this revolutionary approach to problem-solving is not just a passing phenomenon and will have an important impact on the future of the computing industry. Moore's law–related progress in classic computing technology has already slowed, but sustained performance for most scientific-technical computing problems will continue to advance, thanks especially to greater exploitation of parallelism and complementing CPUs with processing elements adept at data-level parallelism. Even so, classic computers are not the right tools for tackling certain classes of problems that are important scientifically and economically. IDC believes that quantum computing is likely to mature to the point where it joins classic computing as a differentiated approach that provides substantially faster, more cost-effective performance for these problem classes.

D-Wave Systems is the only company that offers a real-world quantum computing product today. D-Wave has sold copies of this computer to a small, growing number of high-profile organizations, giving the company a substantial lead in this early market. D-Wave is well positioned to maintain and perhaps extend this lead by following its plan to increase the capabilities of the D-Wave quantum annealing computers and, in the future, by being the first to develop products that broaden the applicability of quantum computers beyond annealing. In the meantime, the company should continue working to identify one or more "killer applications" for its quantum annealer while addressing critics by describing the realities of building a quantum computer today and the long, arduous path to extend quantum computing capabilities past annealing.

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Global Headquarters: 5 Speen Street Framingham, MA 01701 USA P.508.872.8200 F.508.935.4015 www.idc.com