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Advancing the Quantum Advantage: Hybrid Quantum Systems and the Future of American High-Tech Leadership

ARTHUR HERMAN
QUANTUM ALLIANCE INITIATIVE

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Arthur Herman is a senior fellow and director of the Quantum Alliance Initiative at Hudson Institute. His research programs analyze defense, energy, and technology issues.

Dr. Herman is the author of ten books, including the *New York Times* best seller *How the Scots Invented the Modern World,* the Pulitzer Prize finalist *Gandhi and Churchill: The Epic Rivalry that Destroyed an Empire and Forged Our Age, Freedom's Forge: How American Business Produced Victory in World War II* (which *The Economist* named one of its best books of 2012), *To Rule the Waves, Douglas MacArthur: American Warrior,* and *1917: Lenin, Wilson, and the Birth of the New World Disorder,* and most recently *The Viking Heart: How Scandinavians Conquered the World.*

Dr. Herman is a frequent contributor to *Commentary, Mosaic,* the *National Review,* the *New York Post,* and the *Wall Street Journal.* He was also the first non-British citizen to be named to the Scottish Arts Council from 2007 to 2009. He received his BA from the University of Minnesota and PhD from Johns Hopkins University in history and classics.

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EXECUTIVE SUMMARY

Quantum computers mark a transformational revolution in information technology. Whereas most computers process data using bits that consist of either a zero or one, quantum computers can use those digits simultaneously through superposition.[1]

The many resulting benefits will include the discovery of new drugs, new processes for carbon capture and advanced battery research, and a new exactitude in weather prediction, including in dealing with climate change.[2] All in all, experts expect the global quantum computing industry to grow to $450–850 billion in value in the next 15 to 30 years.[3]

Yet because of the challenges of engineering qubits—the physical basis of quantum computing—most authorities push the timeline for full-scale quantum computer commercialization beyond 2040 and as far as 2050. Even some quantum experts do not expect any big breakthroughs until the 2030s at the earliest.

The true path to the quantum future is the combination of quantum and classical digital technology, especially in computing, which will powerfully accelerate access to the potential benefits of quantum information science.

While key players in the industry, including IBM and Microsoft, have recognized the potential synergy of hybrid architectures and applications, the federal government needs to expand its attention and resources devoted to this aspect of securing America's quantum future and its leadership in the twenty-first century.

1. REIMAGINING QUANTUM ADVANTAGE

The term *quantum advantage* has usually referred to the demonstrated success in solving a complex problem faster on a quantum computer than on a conventional machine, even a supercomputer.[4] Today, however, it has come to mean solving real-world practical problems by leveraging the computational advantage that quantum computers bring to information science.[5]

In fact, expanding the uses of the quantum-conventional interface can bring about the practical effects of achieving quantum advantage long before engineers finally overcome the problems associated with large-scale quantum computing.

In fact, the single-minded focus on quantum engineering as a math problem (i.e., on adding together enough qubits to create a computer that can solve problems faster and quicker than today's fastest supercomputers, aka "quantum advantage") stems from a serious misperception of the nature of quantum technology. That misperception can be dangerous. Even today, it can retard US leadership not only in quantum information science but in related high-tech areas that can benefit from tapping into quantum's full potential.

That misplaced focus may also be a setback in terms of national security, where focusing on quantum computing as a future or "emerging" technology means missing key opportunities in the near term. In that sense, the quantum revolution is not some distant transformational event but is happening right now. The quantum-conventional computer interface is not a transitional or "bridge" phenomenon but will shape the reality of both arms of advance information science for many decades to come, not only for quantum computing but also for artificial intelligence, biotech, and the entire spectrum of high tech.

Photo: (Gremlin via Getty Images)

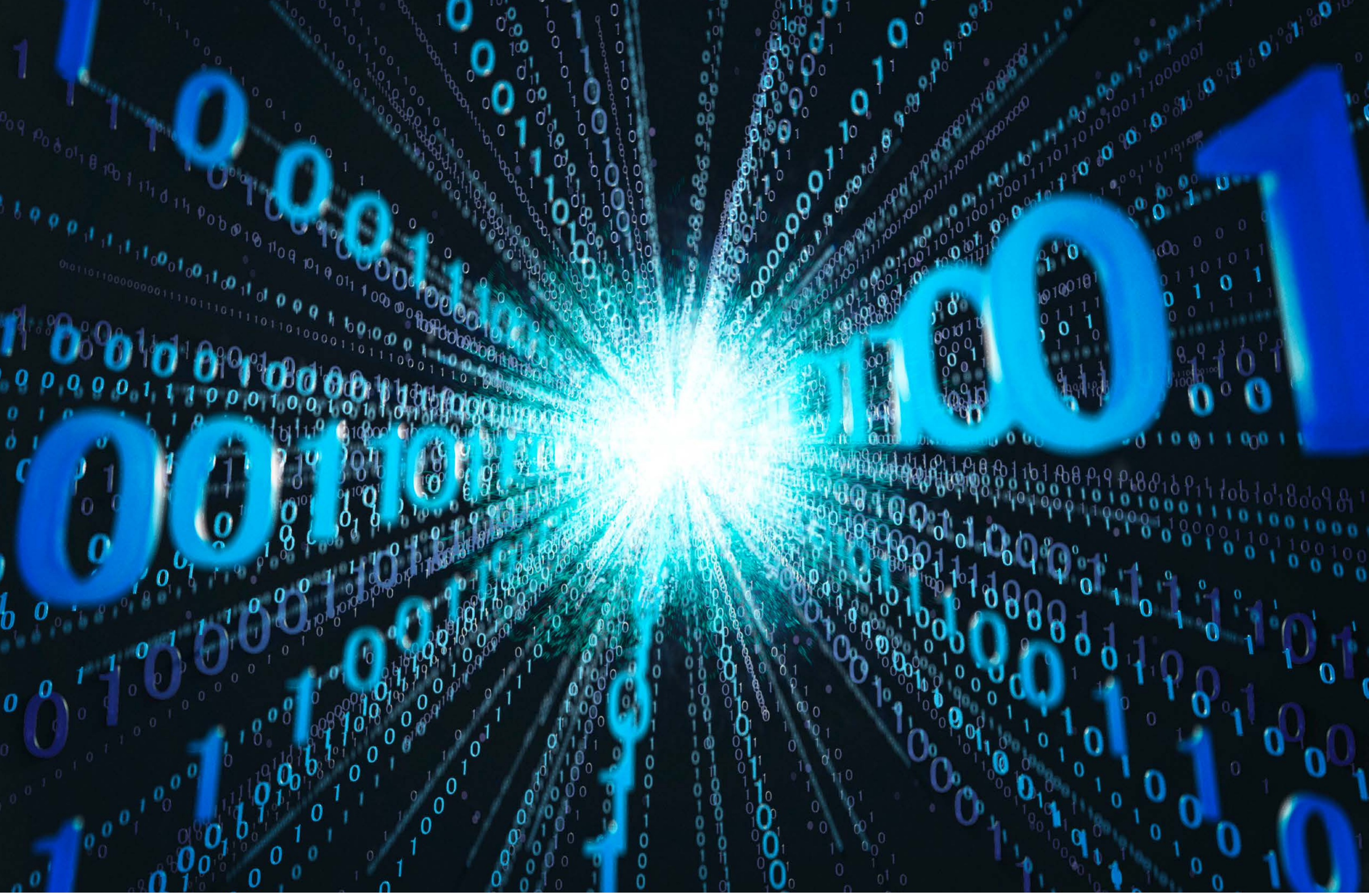


Photo: (Yuichiro Chino via Getty Images)

2. HOW ARE QUANTUM AND CONVENTIONAL COMPUTERS DIFFERENT?

Quantum computers harness the unique property of subatomic particles in their quantum state to make calculations and process data. In the strange world of quantum mechanics, electrons and photons can exist in two physical positions at the same time (physicists call it *superposition*). All current computing, even that of supercomputers, processes data in a linear sequence of ones and zeros. Every bit, the smallest unit of data, has to be one of these two numbers.

But a quantum bit, or "qubit," can be a combination of zero and one at the same time. When we add more qubits to the system through a process known as entanglement, the computing power for a certain class of problems grows exponentially. Ten entangled qubits can do one thousand calculations at once; 30 can do a billion. This will allow quantum computers of the future to solve specific problems thousands of times faster than the fastest supercomputer—the equivalent of being able to read every book in the Library of Congress at once instead of one at a time.[6]

Whether engineers build the qubits of a quantum computer using ions (by companies such as IonQ and Honeywell), photons or particles of light (for example, by PsiQuantum and Xanadu), electrons (the basis of IBM's and Microsoft's quantum computers), or atoms (like Berkeley-based Atom Computing), the final result will be computing power that far exceeds that of even the fastest and most sophisticated conventional computers. By one estimate, a quantum computer with 100 stable logical qubits will offer more computing possibilities than all the bits in all the hard drives in the world. In a computer with 300 qubits, that figure will be more than all the atoms in the universe.[7]

Experts see the benefits from this quantum computing power flowing into four related avenues:

- Simulations, including at the submolecular level, that can lead to new drug discoveries and the creation of new advanced materials.
- Optimization modeling that will enormously improve risk management and logistics.
- Machine learning (ML), with quantum computers serving as a powerful AI accelerator for technologies like autonomous vehicles.
- Cryptography, including breaking existing public encryption systems and post-quantum and quantum cryptography (a keen area of interest for national security and cybersecurity professionals, including the NSA and other intelligence agencies).

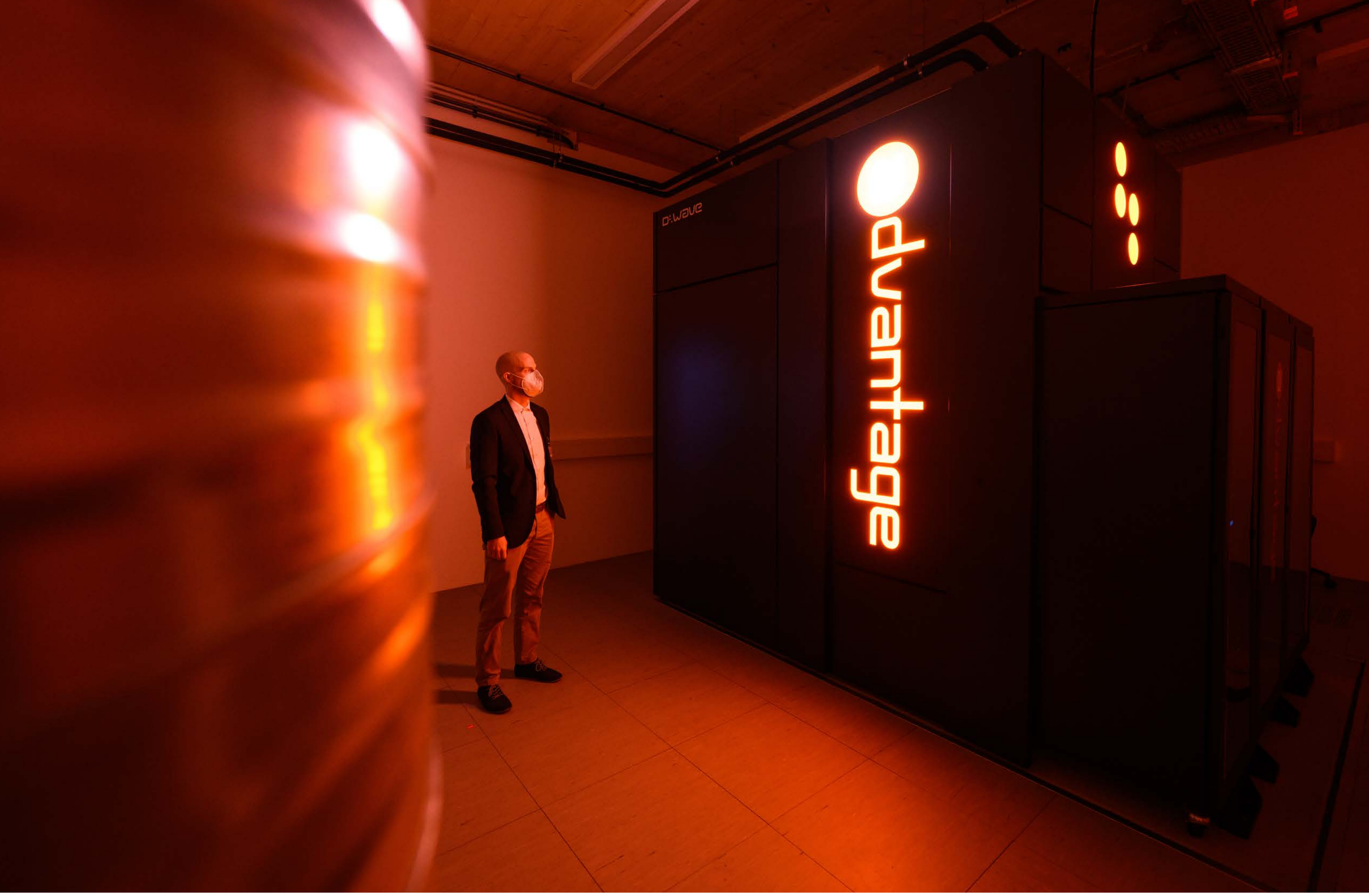
In addition, quantum computers will serve to boost the development of their own next-generation offspring, which means the "takeoff" of the quantum computing industry could come with astonishing speed.

However, many recognize that the quantum revolution may not come as fast as optimists believe. Today's quantum computers are expensive and complicated to construct, are very difficult to scale up, and, in the case of superconductivity logic-gate computers like those of IBM or Microsoft or Google, require temperatures colder than interstellar space to operate. Above all, the challenges of decoherence (meaning that qubits are inherently unstable) and the resulting "noise" that generates a high rate of error mean that building a computer with the hundreds or thousands of entangled qubits necessary for the biggest breakthroughs seems a far-off engineering challenge.

Some quantum skeptics even insist we may never achieve these goals.

Regarding the timeline for quantum computers, a RAND Corporation report published in 2021 concluded, "Most of these technologies are still in the laboratory. Applications of quantum sensing could become commercially or militarily ready within the next few years. Although limited commercial deployment of quantum communication technology already exists, the most-useful military applications still lie many years away."[8]

Fortunately, however, an alternative path exists: developing the full potential of hybrid quantum systems.



3. WHAT IS HYBRID QUANTUM COMPUTING?

Hybrid in the quantum industry refers to the combination of quantum and classical digital technology. In the case of computing, that means a quantum computer and a classical computer working together to solve a problem.

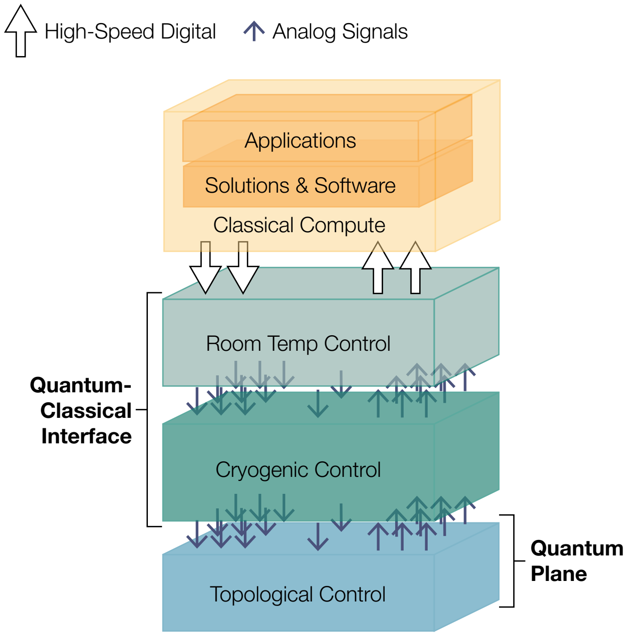
In one sense, experts will agree that the phrase *hybrid systems* describes virtually every aspect of quantum computing. Quantum computer scientists and engineers rely on classical computers at every stage of running a quantum computer program. This includes the system that choreographs the machine's physical components and executes the quantum gates that enable computing to take place. It includes the software and hardware that measure and interpret the computation's results; it also includes the computers operating in the cloud that collect and convert user-submitted programs from conventional computers to a set of commands that users can run on the quantum computer.[9]

In short, "hybrid" computation creates a collaboration in which users run different aspects of a problem through the quantum and classical components within the system. The division of labor depends on which system is best suited to solve a particular aspect of the problem.

Here is a rough model of how a hybrid system would work, in the case of a gate-based system that integrates quantum hardware with the classic components of the same system.

An employee of Forschungszentrum Jülich stands next to the D-Wave Systems Advantage quantum computer, the first such system with a processor architecture of over 5,000 qubits to go into operation outside North America, at the Forschungszentrum Jülich research center on January 17, 2022, in Julich, Germany. (Photo by Lukas Schulze via Getty Images)

Figure 1: Quantum Computing Stack



Source: Chetan Nayak, “Full Stack Ahead: Pioneering Quantum Hardware Allows for Controlling up to Thousands of Qubits at Cryogenic Temperatures,” Microsoft Research Blog, January 27, 2021, https://www.microsoft.com/en-us/research/blog/full-stack-ahead-pioneering-quantum-hardware-allows-for-controlling-up-to-thousands-of-qubits-at-cryogenic-temperatures/.

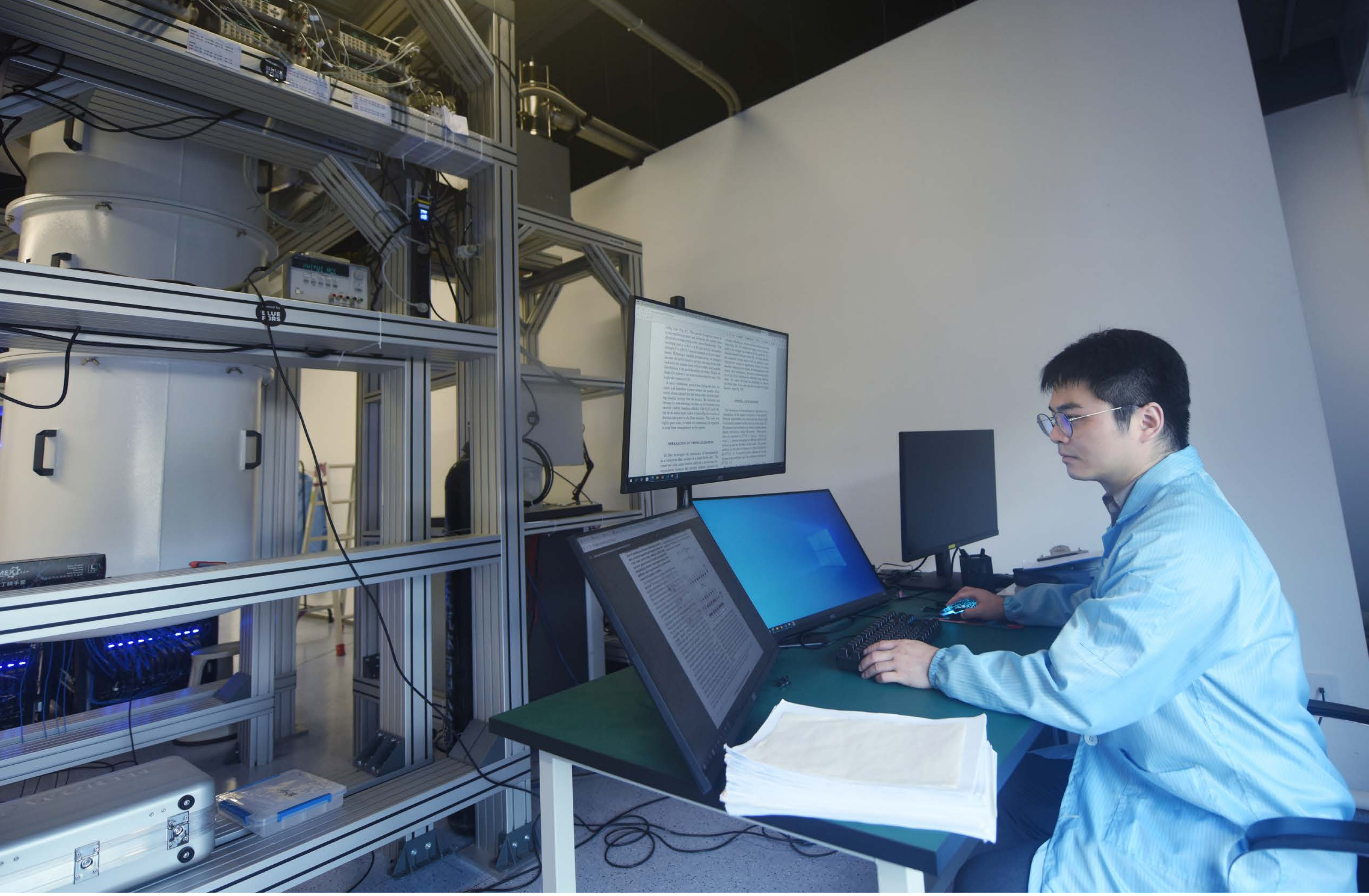
First is the *quantum layer*, where the qubits exist and where actual quantum computing takes place.

Then comes *a control and measurement layer* that (in the case of a logic gate superconducting system) operates at or near cryogenic temperatures to stabilize the qubits for computation purposes. It controls the operation and measurement of the qubits.

A classic-operated *control processor layer* is maintained at or near room temperature. It controls the sequence of operations and measurements needed by the quantum algorithm, including determining the need for and control of iterative operations (i.e., the required repetition of instructions or processing) to arrive at a result.

Finally, the *host processor layer* uses a classical computer to access large storage arrays and networks and user interfaces like the cloud. It handles user instructions and reads out the results of the quantum computations.

This kind of quantum-classical hybrid computing “stack” comes in a variety of shapes and sizes, depending on the company and the hybrid approach.[10]



4. USES OF QUANTUM HYBRID SYSTEMS

Unfortunately, some analysts persist in using the term *hybrid* to suggest that this interface will be only a temporary phase or "bridge" to full-scale quantum computing and related uses of quantum technology.[11] But increasingly companies are realizing that hybrid systems are an integral part of the quantum future as well as the quantum present.

It will, for example, be the primary means by which non-quantum users access quantum capability, primarily through the cloud. Hybrid systems are models for easy access to quantum technologies, including pathways to the cloud, high-performance computing (HPC), and AI. They represent a major step toward the commercialization of quantum technology.

Likewise, "hybrid computing, where a regular computer's processor and a quantum co-processor are paired into a feedback loop, gives researchers a more robust and flexible approach than trying to use a quantum computer alone," noted researchers at the University of Waterloo in 2021.

Waterloo's researchers designed an algorithm to run a sequence of measurements of an entangled quantum state on a conventional computer, making it possible to use relatively few small quantum states tailored to the specific problem. In addition, the algorithm offered high error tolerance—the bane of current quantum computing modalities—meaning it could operate in a wide spectrum of quantum systems.[12]

Photo Caption: Scientist performs calculations on the quantum computer-based "Taiyuan-1" superconducting quantum computing cloud platform at the Hangzhou International Science and Innovation Center of Zhejiang University in Xiaoshan, China, on July 22, 2022. (CFOTO/ Future Publishing via Getty Images)

This is only one example of how engineers can set up the hybrid interface. Others include hybrid architecture to facilitate access to quantum systems through cloud platforms; hybrid algorithms to facilitate interface between classical and quantum computers, supercomputers, and AI/ML applications; and hybrid hardware solutions. In the broader term, developing the quantum–AI/ML interface can lead to a complex synergy in which both can feed off each other and accelerate each other's development.

Building and designing the systems that facilitate the interface between quantum and conventional elements, then, are not simply temporary fixes. They are foundational to the future of quantum technology adoption. While even major players in the industry, like Microsoft, IBM, and Dell, recognize this reality, policymakers need to recognize it as well and guide our national quantum policy accordingly.[13]

In this sense, hybridization of quantum technology will be a constant factor going forward in the development of quantum information science. This process will be a key factor in speeding up the timeline for the advent of the Quantum Age, both for creators and users—including in the use of quantum computing for national security purposes.

Either way, governments will increasingly need to stop thinking of quantum computing as a separate and esoteric, not to say exotic, technology. To paraphrase Winston Churchill, policymakers need to stop treating quantum computing as a scientific mystery wrapped in an enigma, (i.e., as the enigma of quantum mechanics wrapped in the mystery of how to advance toward a large-scale quantum computer that minimizes "noise" while delivering the promised exponentially greater computing power).

Policymakers should base government policy on a more holistic approach, one that acknowledges that the government and private sector will likely integrate quantum computing technology with and alongside a variety of other technologies well into the future. This acknowledgment would offer huge opportunities for use cases as well as for further research and development.

A quantum engineering manager on October 18, 2019 at IBM's research facility in Yorktown Heights, New York. (Photo by Misha Friedman via Getty Images)

5. HYBRID QUANTUM SYSTEMS TODAY

In one sense, *hybridization* describes almost all current quantum computing approaches. From the very first experiments with quantum computing, scientists and engineers have had to rely on classical computers to support the operation of quantum computers, from the system that organizes the computer's subcomponents and executes quantum logic gates, to the software and hardware that analyze and interpret the results of a quantum computation, to the computers that provide the cloud platform for converting classically based programs into programs that quantum hardware can run.[14]

In practice, though, when most experts discuss "hybrid" computation, they are referring to an approach to quantum computing that builds on a more interactive collaboration between classical and quantum technology. In this approach, they run the different aspects of a particular problem through the quantum and classical tools best suited for each stage.

Experts are also realizing that there will be a need for classical computation as a part of the solution to many problems for a long time to come. A general schema would use classical computers for the "grunt work" of quickly processing large amounts of data and for initial calculations, but reserve quantum computing for the most complex parts of the problem (i.e., modeling or optimization). Overall, that means users of quantum computers will need access to data centers that can integrate high-performance supercomputing systems with quantum computers via the cloud or other shared platforms.

Numerous companies and organizations have been working on ways to connect their quantum computing projects with the outside world via classical methods. What follows are key examples of those efforts.

Quantum Simulators and Quantum Annealing

Quantum simulators mimic quantum computing processes using a purely classical system. They allow developers to study and experiment with algorithms and applications suitable for use in a quantum system before running the programs on an actual quantum computer.

Fujitsu offers one of the best-known examples of a simulator, which it describes as "quantum-inspired" although its operations are completely conventionally (i.e., digitally) based. Although built largely for experimental purposes, at a certain scale the Fujitsu's output is more "quantum-like" than that of quantum computers themselves, especially at 40 qubits or less.[15]

Since 2011, the Canadian company D-Wave Systems has been using a genuine hybrid quantum-classical computing architecture known as quantum annealing for specific commercial applications.

Founded in 1999, D-Wave introduced D-Wave One in 2011 as "the world's first commercially available quantum computer." The system used a 128-qubit chip set to do the calculations, then used a classical system to read the results generated by the qubits in their lowest energy states—unlike full-scale quantum computers like Google or Microsoft's, which need much higher energy states to do calculations.[16]

At first critics were skeptical of the D-Wave hybrid approach, but over the last decade D-Wave has been able to tackle a range of optimization and modeling problems for clients around the world while increasing the number of qubits in play. It has progressed from the D-Wave 2000Q released in January 2017 with 2,048 qubits to the Advantage in 2020 with 5,640 qubits.

GlaxoSmithKline (GSK) recently tested the value of the annealing approach. The pharmaceutical firm had been experimenting with using the most advanced quantum devices to solve problems. It compared IBM's quantum computing model with that of D-Wave's Advantage system to get a better picture of what to expect from those leading the quantum race. GSK concluded that the method that D-Wave's 5,000-qubit Advantage system uses could compete against classical computers and start addressing realistic problems. On the other hand, gate-based quantum computers, such as the one that IBM is building, still fell too short of enough qubits to run problems relevant to the real world.[17]

More recently, D-Wave has been expanding its hybrid approach by applying innovations in fabrication and scale to advance the gate-based quantum computing approach as a whole. Meanwhile, other companies have been exploring the hybrid landscape with a variety of approaches and end-projects.

Microsoft Quantum Lab: Gooseberry and Azure

The Microsoft Quantum Lab at the University of Sydney has developed hardware enabling quantum computers to connect to non-quantum systems while maintaining the stability of the qubits—a very challenging engineering feat. This specialized complementary metal–oxide–semiconductor (CMOS) is known as Gooseberry and includes the functions required to take in digital inputs and then create parallel qubit control signals. Gooseberry's design will enable it to scale to support thousands of qubits in future quantum computers.

Gooseberry also takes on one of the other key challenges in quantum computer design, namely the need to maintain an ultra-low Kelvin cryogenic ecosystem to stabilize qubits. Gooseberry can operate at temperatures found inside standard commercially available research refrigerators.

The Microsoft Quantum Lab has also developed a general-purpose cryo-to-compute core that uses liquid helium to operate at slightly higher temperatures. This core performs the classical computations needed to create the instructions that are sent to Gooseberry. Then Gooseberry translates those instructions into voltage pulses to control the qubits. The combination of the cryo-to-compute core plus Gooseberry is one solution to the problem of creating the thousands of inputs and outputs needed to control thousands of qubits.[18]

Additionally, Microsoft has expanded its cloud service Azure to include access to its quantum computing services. As tech writer Alexander Gillis noted, “Azure Quantum focuses on integrating quantum computing tools and its Azure cloud service. With Azure Quantum, users will be provided with software that enables customers to write code that can run on quantum hardware.”[19]

Intel and Horse Ridge

One of the challenges facing hybrid quantum systems is the so-called interconnect wiring bottleneck (i.e., the performance restraints that connections can impose on integrated circuit, or IC, performance). Longtime IC veteran Intel has taken on this challenge with its Horse Ridge chip, the first-of-its-kind cryogenic control chip for use by quantum computers. As the company has described it, “Horse Ridge will enable control of multiple quantum bits (qubits) and set a clear path toward scaling larger systems,” including hybrid systems.[20]

In December 2020, the company released a second-generation version of the chip, dubbed Horse Ridge II. Again, to quote the company, “Ridge II supports enhanced capabilities and higher levels of integration for elegant control of the quantum system. New features include the ability to manipulate and read qubit states and control the potential of several gates required to entangle multiple qubits.” This means important control functions for the computer’s operations can get closer to the qubits themselves, which streamlines the entire control process for quantum systems.

The new chip is an important development for hybridization of quantum computing because it simplifies the interface between the *control and measurement layer* of the system, which shares the cryogenic environment with the qubits, and the *control processor layer*, which relies on classical computing control electronics to manage the overall system—but which cannot operate in those same extremely low temperatures.[21]

IonQ and Hybrid Algorithms

The other essential ingredient in running hybrid quantum systems is the algorithms that can translate from one computing universe to the other (i.e., from the quantum universe to the digital universe).

Matthew Keesan—vice president of Product Development at Maryland-based IonQ Inc., a pioneer in the development of ion trap or ion-based quantum computing—has stated that these hybrid quantum-classical algorithms provide an important means for users to get the most benefit from a current quantum computer.

“Superconducting gate speeds are very fast, but you’re going to need potentially 10,000 or 100,000 or even a million physical qubits to represent one logical qubit to do the necessary error correction because of low quality,” Keesan told an audience at a February 2022 HPC event hosted by Dell Computers.[22]

One way around this problem is using the Variational Quantum Eigensolver (VQE) algorithm, a hybrid algorithm that’s also useful for a variety of chemistry applications.

“There are lots of things that classical computers are better, or faster at, especially with our current generations of hardware. By letting the quantum computer do what it’s good at, and the classical computer do what it’s good at, you can get more out of both,” Keesan said.

In a recent IonQ press release, Keesan explained how the company uses VQE to calculate the “ground state”—the most chemically stable configuration—of a molecule. It does this by constantly calculating the energy of a given configuration and comparing it to previously calculated energy configurations until the user arrives at an optimal answer.

The algorithm can perform the same function with a quantum computer. As Keesan describes:

> If I'm trying to optimize some parameter based on some function, find some maxima or minima, I can do this by comparing the value of the function in that state classically. That part doesn't need a quantum computer. I prepare the state on the quantum computer, bring the results back to the classical computer, then generate a slightly new state, walking the state space in this interplay between classical and quantum computers.[23]

The result is an ability to do the kind of breakthrough research experts anticipate with large-scale quantum computers, using the effective interaction of the quantum and classical parts of the VQE algorithm. This is only one example of how algorithms that can support both quantum and classical computing functions become accelerators for achieving "quantum advantage" in real time rather than at some defined point in the future.

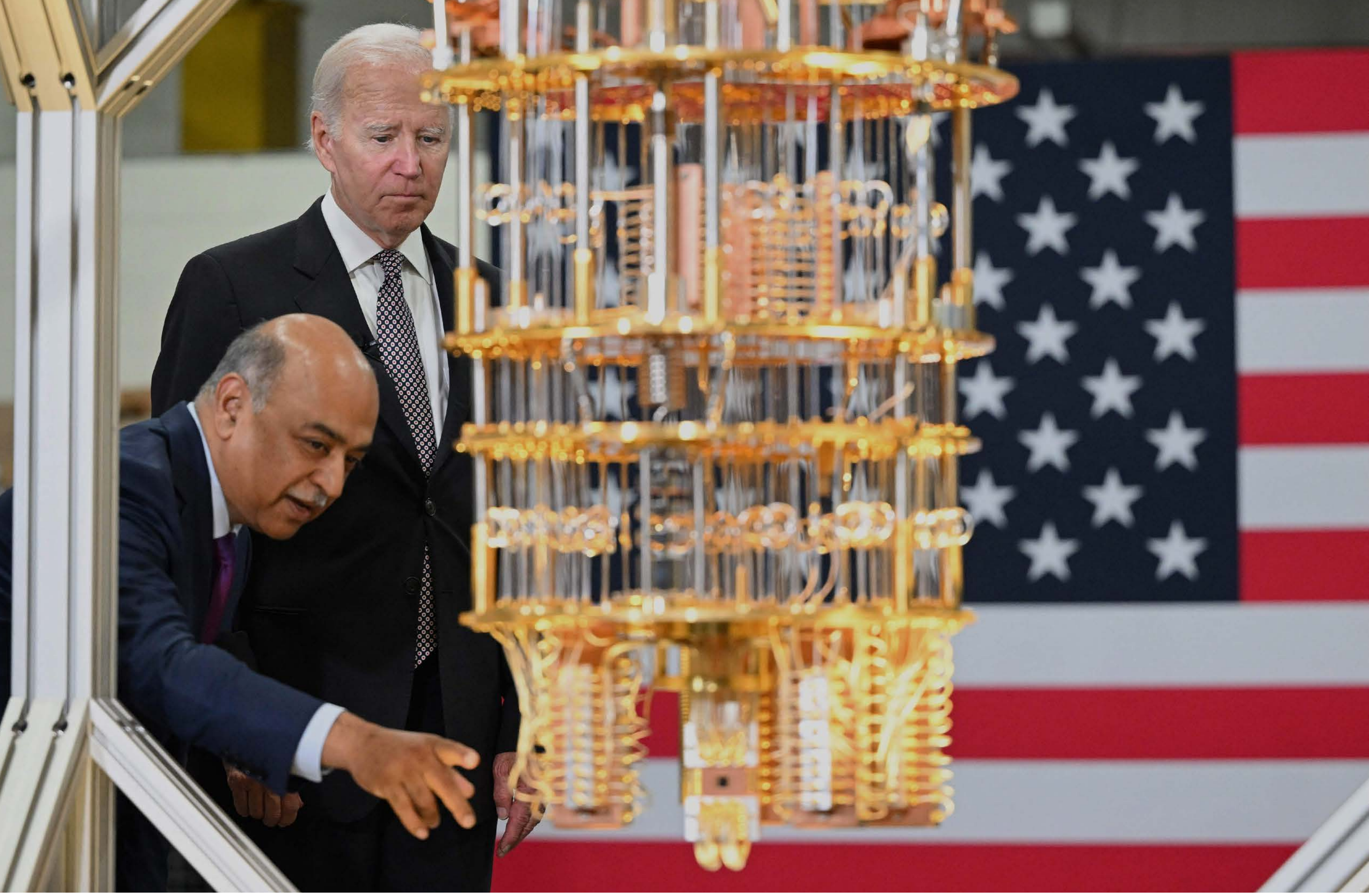
Rigetti: Hybrid Quantum and Machine Learning

Quantum-classical hybrid architectures can also progress developments in other advanced technologies, such as machine learning and AI.

Rigetti Computing, the California-based quantum computer firm, has been working on hybrid architectures that combine quantum computers and classical computers in the cloud since its founding. Very recently, Rigetti reached an agreement to integrate Rigetti Quantum Processing Units (QPUs) with semiconductor company Ampere Computing's Altra Max cloud-native processors. Together, these create a hybrid computing ecosystem for machine learning applications. Ampere's Altra Max powered cloud servers will be able to process the large amounts of data necessary for machine learning applications, together with quantum calculations performed on Rigetti QPUs.

As Rigetti's founder and CEO Chad Rigetti framed it, "Together, we're focused on building the most powerful cloud computers and enabling customers to solve many of the world's most important and pressing problems."[24]

With a simulator optimized for Altra Max, Rigetti customers will have the ability to build and test quantum computations of increased complexity, with higher performance, and at a significantly lower cost. As Ampere's founder and CEO Renée James explained, "Quantum machine learning is emerging as a significant opportunity for scientific computing users and their providers of public and private clouds." The two companies also anticipate working together to create quantum computer simulation software that they can run on Ampere Altra Max processors.



6. HYBRID SYSTEMS AND THE ROLE OF GOVERNMENT

Until recently, the US government's primary research and development effort in quantum technology and hybrid systems has centered in the Department of Energy (DOE).

Certain labs involved in quantum research have carried out important projects in the hybrid sector.

The Pacific Northwest National Lab, for example, has been engaged in a series of experiments that look for ways to devise hybrid solutions for dealing with "noisy" quantum computers. The company aims to mitigate errors in current quantum computers and arrive at clearer and more accurate readings.[25]

At Los Alamos National Lab, scientists have been working on algorithms for noisy quantum computers. "Known as variational quantum algorithms, they use the quantum boxes to manipulate quantum systems while shifting much of the workload to classical computers to let them do what they currently do best: solve optimization problems."[26]

At Oak Ridge, quantum scientists have been working with Nvidia and United Kingdom-based Quantinuum on a "quantum compiler" for developing a low-level machine language that quantum and classical computers can use to communicate with each other.[27]

Photo Caption: President Joe Biden looks at a quantum computer with IBM CEO Arvind Krishna as he tours the IBM facility in Poughkeepsie, New York, on October 6, 2022. (Photo by MANDEL NGAN/AFP via Getty Images)

Overall, given their impressive arsenal of supercomputers, the DOE national labs represent a significant opportunity to showcase how quantum and classical technology can work together not only in a lab setting but also in a production stream for technology that can be ready for commercialization.

Likewise, Congress's mandate for the "quantum user expansion for science and technology" (QUEST) program currently in legislation, which it developed to encourage more access to DOE quantum resources, inevitably means there will be many more opportunities for hybrid classical-quantum interface in the national labs setting.

The QUEST Act, introduced in March 2021, which is now part of the COMPETES Act in the US House of Representatives, which in turn is now held in conference with the Senate's US Innovation and Competition Act. The ultimate fate of both bills in the current Congress remains uncertain.

Finally, the US Defense Department's Advanced Research Projects Agency (DARPA) has been participating in a program known as Optimization with Noisy Intermediate-Scale Quantum Devices (ONISQ) since 2019. The program aims to take advantage of the power of quantum information processing before fully operable quantum computers become available. It focuses on pursuing a hybrid model combining intermediate-sized quantum devices with classical systems to tackle complicated optimization problems—the forte of quantum computers. As the website explains, "Perfectly stable and accurate quantum processors may be decades away, but successful hybrid systems would be a major breakthrough."[28]

The ONISQ Phase 1 launch began in 2020. In January 2022, Universities Space Research Association (USRA) announced the start of Phase 2, which includes collaboration with Rigetti Computing, one of the quantum pioneers in developing hybrid systems mentioned above, to process the variational quantum algorithms that the team develops.[29]

DARPA's interest in the possibilities of hybrid systems is significant because the cultivation of stronger quantum-conventional interfaces can have powerful national security implications.

7. HYBRID SYSTEMS AND THE QUANTUM RACE WITH CHINA

Consider this April 14, 2022, headline from *Defense One*: "China May Have Just Taken the Lead in the Quantum Computing Race." The article stated:

> In 2019, Google reported that its 53-qubit Sycamore processor had completed in 3.3 minutes a task that would have taken a traditional supercomputer at least 2.5 days. Last October, China's 66-qubit Zuchongzhi 2 quantum processor reportedly completed the same task 1 million times faster. That processor was developed by a team of researchers from the Chinese Academy of Sciences Center for Excellence in Quantum Information and Quantum Physics, in conjunction with the Shanghai Institute of Technical Physics and the Shanghai Institute of Microsystem and Information Technology.

The article went on to state that the government and private sector often use traditional supercomputers, like those of the US military and the People's Liberation Army's Fifty-Sixth Research Institute, to conduct complex simulations for equipment design and to analyze large amounts of data to identify otherwise hidden trends and connections.[30] Not only will access to

Photo Caption: Visitors look at Alibaba DAMO Academy's core components of quantum computer during the Apsara Conference 2021 on October 19, 2021, in Hangzhou, China. (Photo by Long Wei/VCG via Getty Images) quantum computing accelerate these applications, but it can also lead to an even more significant—and dangerous—goal: decrypting an opponent's most sensitive data and networks.

As I explain in a July 2021 *Forbes* column, "scientists have been quietly finding ways to turn factorization—the decryption process that leads to Q-Day [when large-scale quantum computers are able to factorize the large prime numbers that underlie our public encryption systems]—into an optimization problem instead of relying on Shor's algorithm, the paradigm for discussing quantum decryption since the 1990s."

My column points out that Chinese scientists have already realized this, as demonstrated by one study that showed how to factor a large number using only 89 noisy qubits. It explains:

> They then showed it's possible to factorize a RSA-768 encryption number—the current factorization record using classical computers—with 147,454 noisy qubits. That's a tiny fraction of the millions of qubits a large quantum computer would need to reach the 4,000 stable qubit threshold, and within reach of the architecture of an annealer like D-Wave Systems.

My column continues:

> Sure enough, in 2020 three Chinese researchers found a way to use the D-Wave quantum computer to factorize large integers, that completely bypasses Shor's algorithm. "Thus," they concluded, "post-quantum cryptography should consider further the potential of the D-Wave quantum computer for deciphering the RSA cryptosystem in future." In effect, these researchers found a way to turn decryption using quantum technology into a straightforward process on a timeline much shorter than ten years: perhaps four to five years is more likely.[31]

The only possible conclusion is that more extensive and systematic use of hybrid systems will inevitably speed up this development (i.e., the ability to use quantum computing processes to decrypt existing encryption systems). In short, the winner of the quantum race may gain a decisive advantage by focusing on the hybrid option rather than by simply looking for ways to add more qubits until they reach a 4,000-stable-qubit benchmark.

8. HYBRID QUANTUM SYSTEMS: POLICY RECOMMENDATIONS

The 2021 RAND Corporation report on the global race for quantum technology sums up one way to think about where hybrid quantum systems fit into the larger picture of the coming quantum revolution:

> The United States, China, the European Union, the United Kingdom, and Canada all have specific national initiatives to encourage quantum-related research. The United States and China dominate in overall spending and the most-important technology demonstrations, but Canada, the United Kingdom, and the European Union also lead in certain subfields. China is the world leader in quantum communication, and the United States is the world leader in quantum computing.[32]

That leadership depends on many factors. It is not just a matter of scaling the qubit mountain, advancing qubit design and architecture, or reducing noise to acceptable levels. It also depends on the degree to which government understands that quantum hybrid technologies will be crucial to moving toward quantum advantage. They are key to computing and are a necessary part of high-tech culture and society because they provide early-stage access to quantum technology and facilitate adoption and applied R&D by industry.

Photo Caption: (Doug Armand via Getty Images)

The truth is that the hybrid solution to quantum computing is here to stay. It will certainly bring the advent of a transformative Quantum Age faster than anyone predicted. Policymakers and key government agencies, including the Department of Defense and Department of Homeland Security, need to adjust their sights accordingly. They will need to rebalance the distribution of resources devoted to "quantum information science," to reflect this reality—and maintain US leadership in the rapidly changing quantum technology environment.

Government needs to take a holistic approach to understanding the quantum future—one that anticipates not only how quantum computers will replace or at least supplant conventional digital computer science, but also how quantum computing will be integrated with digital information science well into the future. This means the government should understand that the discipline of quantum information science (QIS) will include conventional computing technologies that can interface with quantum-based applications.

With this in mind, the US government needs to implement four policies regarding quantum hybrid systems:

First, include "hybrid systems" in descriptions of the types of quantum information science that qualify for funding as part of current and future quantum information science programs, including the National Quantum Initiative and the Department of Energy's QIS Centers.

Second, pass the QUEST Act, which will expand the mandate for allowing access to DOE supercomputers for quantum purposes as part of its QIS Centers–funded research.

Third, expand the parameters of the QUEST program to specifically include "quantum hybrid systems."

As noted above, the goal of the QUEST program is to have the DOE expand access to quantum computing hardware and quantum computing in the cloud in order to, in the words of the bill introduced in March 2021, (1) "enhance the quantum research enterprise of the United States, (2) educate the future quantum computing workforce, and (3) accelerate the advancement of US quantum computing capabilities."[33] The DOE should also adjust these goals to include quantum hybrid solutions.

Further, government should realize that hybrid systems can ensure access to quantum talent and quantum skills for a broad range of populations. Indeed, building up the resources devoted to hybrid systems can inspire and attract the next generation of quantum engineers and workers, whose backgrounds do not require a PhD or in-depth knowledge of quantum physics.

With that in mind, QUEST could also trigger investment in high-performance computing data centers that directly integrate with quantum computing resources. The result would be a pathway to providing broad access to quantum-based solutions seamlessly—a pathway that will be critical to building near-term quantum hybrid applications, creating opportunities to develop a quantum-trained information science workforce, and making sure that the "digital divide" does not become a "quantum divide" in future.

Fourth, create a government task force on hybrid systems and cybersecurity threats, including China.

The government too often treats the national security implications of quantum computing (i.e., decryption potential) as a distant threat. In fact, as the Chinese experiment with decrypting RSA using the D-Wave system proves, the hybrid model could create shortcuts to Q-Day that disrupt plans regarding quantum security. No one is suggesting that hybrid systems will suddenly transform the quantum threat into an imminent or urgent threat. But the goal of such a task force will be to determine a more realistic timeline so that surprises are few and options for dealing with the threat are many.

CONCLUSION: HYBRID SYSTEMS AND THE QUANTUM FUTURE

In future it will be useful to think about quantum technology in the same way we think about nuclear power and energy. Like nuclear fission and fusion, quantum computing can unleash the almost unimaginable power of nature, both for good and for ill.

But just as the advent of commercially available nuclear power did not mean replacing the gas-driven automobile with nuclear-powered cars, it also did not result in every home having a nuclear power plant in its backyard, as some enthusiasts in the early days of nuclear power liked to imagine—although 70 years later, small nuclear reactors are closer to reality than critics try to suggest.[34]

Instead, in the days when nuclear energy was still an emerging technology, we learned how to use nuclear power to take on the nation's big energy challenges, including supporting the power grid, even as the internal combustion engine remained the driver of economic growth and personal freedom.

The process by which new technologies take over from and replace earlier technologies is historically long and drawn-out—as the transition from combustion engines to electric vehicles is proving.

Likewise, the transition from digital to post-digital or quantum-driven information technology will be a long one, if such a transition takes place at all. There will likely always be a need for classical computation as a part of the solutions to many problems. But the most complex parts of those problems are often best suited for quantum computers, including through cloud platforms and integrated data centers with both high-performance and supercomputing systems combined with quantum computers. The reverse is also true. Quantum computing in its current and emerging states can accelerate other advanced technologies, such as machine learning, 5G and 6G wireless technology, and AI. In fact, the advent of AI will reach its full potential only when we link it to the extraordinary computing power of quantum.

At the same time, awareness of the full potential of quantum hybrid technology can also have beneficial national security implications. It can accelerate the potential of quantum computers as a national security tool; it can also make policymakers realize that Q-Day may be coming sooner than some expect, thanks to the hybridization of quantum's decryption potential.

China's experiments in this regard should give us all pause. If these are what China is willing to reveal in open-source outlets such as through scientists, we need to ask what they are engaged in behind the curtain. As I concluded in my Forbes column on this subject more than a year ago, if there is a shortcut to achieve what a large-scale quantum computer can do using hybrid technology, China's military and intelligence services will certainly want to find out.[35]

So should ours. Likewise, our policymakers need to take a full measure of the potential of quantum hybrid systems as we stand at the threshold of the Age of Quantum.

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