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Summary

Quantum computing holds great promise in solving compelling problems facing society today including drug design to food production. While the United States is on the forefront of many technologies, gaps in funding have left the U.S. scrambling to stay ahead in quantum computing. Major well-funded initiatives have been announced in Europe and China. Gaps in funding in the U.S. have significantly reduced the number of qualified quantum computing experts available for companies to hire to design and build quantum applications and hardware.

Much of historical funding has focused on two efforts: algorithm development and quantum device development. As a result, several (but not many) algorithms have been developed, all of which assume a perfect machine with abundant qubits that hold their values for a significant amount of time. This has left two major gaps that quantum computer science needs to fill.

First, there is a gap between usable quantum applications and theoretical quantum algorithms. The federal government needs to fund researchers to better understand how to bridge that gap, educators and researchers to create instructional materials to teach people how to create applications even without full understanding of quantum hardware, and educators use those to train computer scientists.

Second, there is a gap between the assumptions current applications make about the size of the computer and length of time it can operate that make near-term computers fall short of the promise to compute faster than traditional computers. The federal government needs to fund quantum computer science research groups to develop the knowledge and tools to both automatically optimize programs for real hardware constraints and expose particular details to programmers that might affect how they write their programs.

Finally, we must look beyond the current challenges and fund the K-12 STEM Pipeline to sustain our nation's long-term global competitiveness.

Full Testimony

Thank you for the opportunity to testify, Mr. Chairman and the ranking member. I am honored to be here before you and the Committee to offer testimony on the potential for commercially-available quantum computers and America's global competitiveness in Quantum Technology. For your background, my research is in computer science and computer science education. I am also the Director of Computer Science Education at UChicago STEM Education and a Research Associate Professor in the Department of Computer Science at the University of Chicago. I began working in quantum computer science in 2000, but, as I will discuss later, my participation has reflected the inconsistent academic funding in that area.

I am testifying today on behalf of the University of Chicago, UChicago STEM Education, and the EPICQ quantum computing project, a multi-institution collaboration between the University of Chicago, MIT, Princeton, Duke, and UC Santa Barbara. The goal of the project is to bridge the gap between the perfect machines that applications need and the error-prone machines that are on the horizon. As the lead investigator for quantum education for the EPiQC quantum computing project in the NSF Expeditions in Computing Program (NSF's largest single-project investments), it is my mission to provide education and awareness at all levels of the educational pipeline so that we can train a robust workforce to develop and utilize these machines.

Promise of quantum

Quantum computing holds great promise for several commercial applications.

One promising area is in drug design. As the baby boomer generation ages, the incidence of Alzheimer's is predicted to increase from 1.5% to 50% in 2050. Medicaid spending on Alzheimer's is projected to rise from less than 5% of the 2020 budget to nearly 25% in 2040 (Bredfeldt, 2015). In the past two years, J&J, Merck, Pfizer, and Eli Lilly have cancelled their Alzheimer's drug trials, a disappointing end of a long, expensive road that consumed significant federal research funds. Quantum computing may someday provide simulation accuracy to predict whether these drugs would reduce the accumulation of amyloid plaque, allowing emphasis on the deeper question of whether removing this plaque buildup slows or reverses cognitive impairment. Thus, quantum computing would have allowed either a success in one of these drugs or a quicker pivot to alternative approaches.

A second promising area is in fertilizer production, through better understanding the biological nitrogen fixation by the enzyme nitrogenase. The current industrial HaberBosch catalyst requires high temperatures and pressures and is therefore energy intensive (Reiher, et al). Unlocking the secrets of this process through quantum simulation could vastly reduce the energy costs of food production throughout the world.

Global Competitiveness

While the United States has historically been on the forefront of computer science, computer systems, and emerging technologies, lapses in public funding for quantum computing have allowed global competitors to make great strides. International initiatives include the European Union (EU) Flagship Quantum Program ($1.3 billion / 10 years), the UK Quantum Hub Network ($400 million / five years), and the Netherlands QuTech Initiative ($150 million / 10 years). China is building a new $11.9 billion quantum computing research facility in Hefei. On the commercial front, Chinese companies Baidu, Alibaba, and Tencent Holdings have announced major initiatives in Quantum Computing. In February, Alibaba became the second company worldwide, behind IBM, to announce a more than 10-qubit cloud quantum computer.

Why isn't the United States farther ahead? To answer that, we need to look at historical funding trends. Academic institutions play a central role in the development of commercial quantum computers, a role previously played in many key technologies, as conceived by Vannevar Bush after World War II. They make research strides that develop ideas to the point where they become commercially viable, a point now reached for quantum computing. Research groups provide tools that all companies, not just one, can benefit from. Finally, universities create a workforce of bachelor's, master's, and PhD-level experts to contribute to those commercial efforts. Quantum computer science, our research area, explores optimizations necessary to make quantum hardware usable to software. Our most recent PhD graduate had job offers from four companies.

Had funding been consistent over the past 17 years since the inception of quantum computer science, approximately 200 PhD students, and many more MS and BS students, could have been produced. However, only 8 of those 17 years have been funded, wreaking havoc on both the research progress and the graduate student training pipeline, and resulting in only 10 PhD students, and undergraduate programs are only now being created. The DARPA QUIST program first recognized that device-level progress was not sufficient - progress needed to be made in how to create a system of many qubits working together. In 2001, the first quantum computing science project, QARC, was funded. However, when the first round of funding expired in 2006, the next five years of funding was only open to classified projects. In 2011, IARPA awarded 5-year grants. Just over a year into it, the grant was cancelled, just as collaborating groups had hired post-docs and accepted graduate students. Most let go their postdocs and transitioned their graduate students to traditional computer science subjects. Through this journey, research groups came and went as group leaders chose not to expose themselves or their students to this level of uncertainty. Now, few senior students are in the pipeline to feed companies developing quantum computers. Developing this pipeline of students, or retraining existing professionals, is critical the success of commercial quantum computers.

Challenges

Quantum computing harnesses the quantum physics properties of fundamental particles, operating on them to perform useful work. However, the scale of the challenge in bringing these computers to the point of usefulness cannot be underestimated. These challenges can largely be split into two areas - building stable machines that protect quantum bits long enough for the calculations to complete and writing software to take advantage of the quantum state in ways that provide exponential advantage over current machines.

My esteemed colleague and co-panelist Prof. Christopher Monroe can talk to you about the physical challenges present in creating stable machines. I am here to talk about the increasingly important role that computer scientists need to take to make these computers perform useful work.

Much of historical funding has focused on two efforts: algorithm development and quantum device development. As a result, several (but not many) algorithms have been developed, all of which assume a perfect machine with abundant qubits that hold their values for a significant amount of time. At the same time, great strides have been made in devices. 50-qubit machines have been built that perform computation. However, they do not yet perform useful computation. That is, a quantum computer is currently no more powerful than an 80’s desktop.

We ask ourselves - What is necessary to implement a known algorithm to model nitrogen fixation for improving fertilizer production? Next, what is necessary to modify an algorithm to write an application that will simulate potential drugs for Alzheimer’s on a quantum computer in order to shorten development time? First, we need resources and workforce training to develop more algorithms and understand how to apply those algorithms to new situations. Second, we need knowledge and tools to better tailor algorithms to the limitations imposed by emerging quantum hardware.

Applications-Algorithms Gap

The relationship between an algorithm and an application is a bit like the relationship between a screw and a house. The architects and builders need to understand when to use a screw or nail and how to use them, but that knowledge alone does not build a house. They also need to place the wood and drywall in the right places so the screws and nails can do their jobs and result in a useful structure. You can not build software with algorithms alone - you need to understand how to apply them to real problems.

In traditional computing, years have been spent designing algorithms, learning how to express and reason about their properties, teaching aspiring computer scientists how to choose between algorithms and how to use them in real-world problems. Quantum algorithms are a long way from being ready for this level of teaching. Theorists know how to express and reason about their properties. However, making the leap to use is a large gap that must be filled. Quantum algorithms are expressed at a hardware level, requiring intimate knowledge of qubits. In traditional computing, application developers no longer need to understand what happens at the binary / bit level - programming languages and software libraries have been developed that allow programmers to think at a much higher level, and that has led to substantial reduction in the amount of time it takes programmers to write code. It is akin to the difference between Home Depot and IKEA - do you want to provide only basic building materials or make some partially-fabricated kits?

Algorithms-Hardware Gap

There is a huge gap between the stability hardware provides (and will in the near future) and the stability algorithms assume. In conventional computing, hardware has been stable for decades, and instability has only occurred recently with the seemingly relentless shrinking of transistors through Moore's Law. Still, low-cost error-correction techniques can protect most operations and memory. Not so for Quantum Computing.

What would happen if you had planned to prepare a gourmet meal for 10, but when you arrived, there were only supplies for 6, and you could only use the kitchen for two hours prior to the meal? You would need to adjust your plans. Current quantum computers can only sustain computations for a limited time, and they are very small. Some modifications can be automated - each person will get smaller portions. Changes like this can be automated. However, for more advanced modifications like shortages of specific ingredients, the plan needs to be rethought. This requires the algorithm designer to create a modified algorithm.

Recommendations

In order to realize quantum computing, the federal government needs a funding initiative aimed at filling these gaps. Tools and educational materials must be developed for the computing side of quantum computing. Without these, we will have machines with little useful software to run on them. It is only through an interdisciplinary effort between hardware designers, experts in target application areas, and computer scientists, that we can tackle these challenges. If this work is done in the public domain, then all businesses will benefit from the resulting tools and expertise.

Tools:

Software Infrastructure: Automated tools that optimize code for limited, unstable hardware.

Error-Aware Algorithms: Expose and education algorithms developers about specific details of errors in the hardware for which there are no automatic optimizations. Collaboratively create strategies for modifying algorithms given specific error patterns in different device technologies.

Languages or Software Libraries: Tools that allow quantum software developers to program quantum algorithms with incomplete understanding of qubits and the operations that directly affect them.

Workforce Development:

Quantum Algorithms in CS: Graduate-level applied quantum algorithms instructional materials that goes beyond the characteristics of quantum algorithms to focus on how to use them in real-world applications. Highly trained individuals could go on to work in interdisciplinary teams with non-computer scientists to write applications or write languages or software libraries to abstract quantum-level details of algorithms away from application implementers.

Quantum Applications beyond CS: Graduate-level instructional materials co-designed by application area experts and quantum computing experts that would teach students what types of problems can be solved using quantum computing and to modify one application for a different problem, given an existing application and languages developed above. Individuals would work closely with computer scientists trained in quantum algorithms to create new quantum applications.

Quantum Computer Science Course: Graduate-level instructional materials that relate quantum computing systems to conventional systems, providing training or retraining to students who already know how to build conventional systems. They would develop the software infrastructure tools above and work at quantum computing companies.

STEM Pipeline: We need to mobilize now to train the innovators of tomorrow. Pushing forward quantum computing requires deep expertise in computer science and physics, and in order to widen our pool of talent, we must support the CSforAll movement to make computer science an integral part of K-12 education. Robust programming skills are increasingly important in not only all STEM fields, but economics, finance, and increasingly liberal arts fields. Early, positive exposure to computer science enlarges the talent pool by attracting individuals who would not otherwise consider such careers.

Conclusion

With a significant investment in hardware, software, and workforce development, I am confident the United States can maintain its dominance in computing and quantum computing. This concludes my remarks. I appreciate this opportunity to speak with Subcommittee members, and I am happy to answer any questions you might have.

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