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Before the

United States House of Representatives Committee on Oversight and Government Reform
Subcommittee on Cybersecurity, Information Technology, and Government Innovation

Hearing Titled “Preparing for the Quantum Age: When Cryptography Breaks”

Tuesday, June 24, 2025

First and foremost, I would like to thank Chairwoman Mace, Ranking Member Shontel Brown, and the Honorable Members of the House Oversight Committee on Cybersecurity, Information Technology, and Government Innovation for your continued interest in and support for quantum technologies, including quantum computation, quantum sensing, and quantum cryptography, and classical post-quantum cryptography. I particularly applaud your conception of and support for the Department of Defense Quantum Computing Center of Excellence, which would advance potentially transformative technologies for our armed services. Quantum technologies are critical to our nation's scientific and computing infrastructure, health, prosperity, and defense. I thank the committee for providing me with the opportunity to testify regarding these important matters.

My Background

My name is Brenda Rubenstein and I am currently an Associate Professor of Chemistry and Physics, set to become the Vernon Krieble Professor of Chemistry and Director of the Data Science Institute at Brown University in Providence, Rhode Island. To provide context for this discussion, **I am an expert in quantum and statistical mechanics with 20 years of experience who has led several large research teams focused on better understanding quantum architectures and leveraging quantum computing for health**. I am currently helping to lead a multi-institution team funded by Wellcome Leap, the philanthropic arm of GlaxoSmithKline (GSK), **to develop some of the first techniques for modeling biology on quantum computers that will help us unlock new therapeutics.**

My experience transcends academia; before arriving at Brown, I worked on quantum simulations as a Lawrence Postdoctoral Fellow at Lawrence Livermore National Laboratory and as a Department of Energy Computational Science Graduate Fellow (CSGF) at Los Alamos National Laboratory. I moreover represent quantum science on the US Defense Science Study Group and have been involved in the founding of multiple alternative computing startups, including AtomICs, focused on molecular storage, and Azulene, focused on combining machine learning and quantum mechanics to improve therapeutics and catalysis. At Brown, I teach over 400 undergraduates quantum mechanics per year and have had the privilege of research mentoring nearly 25 graduate students, over 70 undergraduates, and many dozens of high schoolers from all parts of the United States in the quantum sciences in the nine years I have been there. Many of my students have become leading quantum researchers in industry, academia, and the government. I believe this experience positions me to provide insights into opportunities for and challenges affecting the US quantum workforce.

Quantum Technologies Are Essential to American Leadership

Over the past several decades, computing has emerged as one of the cornerstones of technology, if not all of society, enabling transformative advances in communication, human health, business, and defense. In 1952, my grandfather was among the first mathematicians to use UNIVAC, one of the first classical computers, to predict the 1952 election (and, as the story goes, the computer got it right, while the media and pollsters initially got it wrong); seventy years later, it is hard to imagine life without computers billions of times more powerful per dollar.

Nonetheless, despite their exceptional computing power, **classical computers cannot accurately *and* efficiently solve every known problem.** There are wide classes of problems including optimization problems, as commonly seen in finance, economics, and even biology, and materials discovery problems involving the design of new more efficient catalysts for energy harvesting and therapeutics for disease that are taxing, if not insurmountable, for classical computers. Quantum computers hold the promise to substantially, in some cases exponentially, reduce the computational cost of these classes of problems and others, enabling us to more rapidly and directly design cutting-edge materials and medicines, and even make statistical predictions about everything from elections to the evolution of the cosmos. These capabilities will have profound impacts not only on science and medicine, but on the well-being of all of society. Moreover, quantum computing and quantum technologies such as quantum sensors and quantum cryptography will enable faster, more discreet, and more autonomous predictions and actions on the battlefield, promoting our national defense.

These advances may sound like a luxury, but given the central importance of computing in our society, those who are the first to make these advances will rapidly reap their benefits to the potential disadvantage of others. And, given the multipolar world in which we live, if America does not realize these advances, others most certainly will, leaving us technologically vulnerable and behind.

As Vannevar Bush wrote to President Roosevelt in 1944, but rings equally true today about quantum technologies: “Progress in the war against disease depends upon a flow of new scientific knowledge. New products, new industries, and more jobs require continuous additions to knowledge of the laws of nature, and the application of that knowledge to practical purposes. Similarly, our defense against aggression demands new knowledge so that we can develop new and improved weapons. This essential, new knowledge can be obtained only through basic scientific research…without scientific progress no amount of achievement in other directions can insure our health, prosperity, and security as a nation in the modern world.”

There Is No Quantum Science Without a Quantum Workforce

Critical to realizing advances in the quantum sciences is establishing and securing a well-educated quantum workforce. As with all great endeavors, American ambitions of leading in the quantum sciences rest on ensuring that we have a large and renewable pool of talented, motivated, and dedicated people educated not only in quantum mechanics and computing, but also in important adjacent fields such as electrical engineering, chemistry, biology, and mathematics. As Vannevar Bush so eloquently phrased it decades ago, “We shall have rapid or slow advance on any scientific frontier depending on the number of highly qualified and trained scientists exploring it.” After all, we may be able to find a way to make a widget, but if no one knows how to use, test, or improve it, it may as well not have been made at all.

While this can be said of any field, what stands out about quantum science is **that it is fundamentally interdisciplinary - and daring -** meaning that it requires an especially skilled and supported workforce. While we are making significant progress - **since I was a graduate student alone, the world has gone from having quantum theories to real quantum hardware that is being used by many thousands everyday** - we still have to surmount key technical challenges to realizing quantum hardware that can demonstrate valuable quantum advantage and utility, and even if we resolve these challenges, we will need multidisciplinary scientists who can pollinate other fields with these gains. In other words, there is a limited quantum recipe or textbook to follow. As a result, the quantum sciences demand a particularly agile workforce that is broadly educated, can translate across fields, can innovate around challenges, and can imagine realities that have not yet come to pass. Fortunately, America’s long tradition of educating Americans to be intellectually agile means that America is well-posed to lead in the quantum sciences.

However, the US is currently struggling to foster such a workforce. In part because of the intellectual and technological challenges that surround this field and the risks associated with those challenges, comparatively few Americans opt into studying the quantum sciences, and even fewer Americans are familiar with what quantum science may offer their fields. These workforce development challenges are particularly acute for the experimental quantum sciences. While many trainees can - and voluntarily do - practice quantum simulation skills from their home using such as valuable tools as IBM’s Qiskit and its related tutorials, it is not nearly as easy to train students in the design, construction, and testing of physical quantum hardware, which requires intricate knowledge of and experience using advanced electrical engineering, circuitry, and cryogenic technologies.

Because of our aging demographics and the fact that many of our peer nations have substantially larger populations that have the potential to field a larger quantum workforce, **it is also critical that we cultivate our quantum science workforce from all swaths of American life**, from all backgrounds and areas of the country. We cannot afford to lose this race because we overlooked some of our most talented racers. In the words of former Presidential Science Advisor Dr. Eric Lander, we must grow the high tech workforce by “not just cloning the people who are in it, but expanding to include everybody in this country who wants to be a part of it.”

Funding for Basic Research is Critical for Maintaining a Quantum Workforce

One of the indispensable ways that we train the next-generation of scientists in all fields, but especially in quantum science, is through basic research conducted at the undergraduate, graduate, and even increasingly, high school levels. Basic research is scientific research conducted with the aim of improving scientific theories for better understanding and predicting natural or other phenomena, but basic research is not *basic* in level at all. Basic research often begins by posing a question or hypothesis and asking researchers, often trainees, to leverage their pure and applied knowledge to answer that question. Since these questions are typically cutting-edge, there is no clear path to the answer and researchers usually have to blaze their own trails, first acquiring the knowledge and skills they need to even construct a path and then persevering down many incorrect trails until they find the (or one of the) right paths. Many students at first find this process daunting given its uncertainty (which indeed it is), but such training in how to solve basic research problems is irreplaceable as it teaches future researchers independence, dedication, the value of hard work, collaboration and communication skills, and most importantly, how to break down the seemingly impossible into smaller possible steps. These skills are not only indispensable in science and technology, but in so many high-demand careers, including business and politics.

Moreover, **the field of quantum science descended from basic thoughts and ideas**. Feynman's original conception of quantum computation stemmed from completely basic interests: Feynman, a Nobel prize winning theoretical physicist, found such a device worthy of his thought and potentially transformative. Many of the algorithms we use to quantum compute today, including the Variational Quantum Eigensolver and Quantum Phase Estimation algorithms, also owe their roots to basic electronic structure theory, including quantum Monte Carlo methods (my expertise). Charles Bennett, my academic sibling at Lawrence Livermore National Laboratory, conceived of one of the primary quantum communications protocols, BB84, from largely basic motivations. Today, many quantum architectures make widespread use of Josephson junctions, which also had basic origins. **It is hard to imagine modern quantum science without these basic insights.**

The majority of basic research training in the US today is conducted at US colleges and universities. Although industry and the government unquestionably contribute invaluable training through internships and other tools, they cannot practically scale to accommodate the hundreds of thousands of students that pass through our institutions of higher education, and because of the value they rightfully attach to their own time, often only want to train the best of our student population. Thus, most trainees interested in the quantum sciences receive their first practical introduction to the field in basic science laboratories throughout this country. Our institutions of higher learning can therefore be thought of as incubators that grow the future quantum workforce that supplies industry and the government.

Indeed, **our basic science training pipeline, while still imperfect and leaky, has long been the envy of the world.** As someone who has trained and taught in multiple countries, I can attest to the fact that most other countries, even countries wealthier than the United States on a per capita basis, do not expose their students to basic research conducted in a real laboratory environment until deep into their graduate studies. This leaves their populations book-smart, but not necessarily research-smart, which leaves a sometimes impenetrable gap trainees must broach to become scientifically productive, especially in crucial industry or government settings. Many cite this as the key reason why other countries struggle to produce as many successful scientific startups as the United States. For this reason, scores of students from abroad have historically and continue to seek our world-class training.

For many American scientists like me, this scientific basic research pipeline begins as early as middle or high school often with NSF- and DOD-funded programs such as science fairs (Regeneron, Broadcom, etc.), hackathons, and other competitions (USAMO, USABO, etc.) designed to spark students' creativity and innovation. It then continues through college where a combination of university, private, and government funding is used to support undergraduate research and into graduate school where this same important combination of institutions supports graduate research fellowships that turn into dissertations. These graduate students, who have now often been exposed to 5-10 years of basic research, then become invaluable assets to our quantum science and other workforces.

To use myself as an example, I first became involved in science when a middle school teacher encouraged me to lead a team into the NSF/Christopher Columbus Award for Community Innovation, for which we designed a project (new for its time!) that developed laser systems to help trains detect people on the tracks, thereby reducing railroad fatalities. This partially NSF-funded award was the first to expose me to active and practical problem-solving in science. After being fortunate enough to attend an elite publicly-funded STEM high school, I was then funded by the NSF and the Barry Goldwater Scholarship to pursue a variety of undergraduate research experiences that further refined my research skills. As a graduate student, I received both the NSF Graduate Research Fellowship (GRFP) and the DOE Computational Science Graduate Fellowship (CSGF), which granted me the autonomy to pursue high-risk, high-reward research and develop my skills as an independent researcher. Since receiving my PhD, my work has been supported by the National Science Foundation, Department of Energy, Department of Defense, and a variety of private foundations. I have since leveraged those awards to found multiple companies, provide advice to government agencies, and train students who have since founded their own companies and contributed their talents to some of America's prized technology firms. I recount my story because it is illustrative of so many researchers: federal-funding was critical to constructing the pipeline that has been so pivotal to our careers and to ultimately positioning us to make meaningful contributions to larger American society in the form of discoveries, jobs, and defense. And, much of the funding for early portions of the pipeline comes with a relatively small price tag.

The Quantum Workforce Pipeline Is Being Shut Off

Nonetheless, proposed federal budget cuts and other actions put much of this pipeline at risk. Plans to reduce the National Science Foundation budget for the Mathematical and Physical Sciences by 50% or more will reduce much of the basic quantum research that led to our current quantum technologies and now synergistically enhances our quantum science research and vice-versa. These reductions will make quantum funding more scarce and more concentrated, likely most adversely affecting EPSCoR and other states with less historical scientific infrastructure and preventing the US from leveraging all of its human capital. **Even wealthier institutions are starting to shutter labs, close graduate admissions and graduate degree programs, and redirect resources.** A dark cloud hangs over most American researchers today, blunting their usual zeal for research. While Universities and private foundations can provide some funding, these cuts substantially curtail the graduate students who can be trained and the instruments that can be built that advance the field; **as was the case before World War II and our subsequent government investments in science, private funding alone cannot plug this massive gap.**

However, beyond faculty-level research grants, which may be viewed as funding at the end of the pipeline, the budget for science graduate fellowships, including the NSF GRFP that I and over 70 Nobel prizewinners have received, has been substantially reduced. Offices charged with performing outreach to prospective, young talent have taken significant hits. Research for Undergraduate

Experiences (REU) opportunities that often grant undergraduates their first formal research experiences may be eliminated. Looking back at my and many other researchers' trajectories, these cuts leave scientists like me to ask whether the pipeline that grew us will exist at all - and how future American quantum leaders will be trained.

Indeed, as someone who teaches many hundreds of ambitious young students and researchers per year, **these cuts have already had marked impacts on the psyches of our trainees**. I am fortunate to work with many outstanding minds and virtually all are now scared for their futures - *because they are not sure whether there will be any such future for them.* As should be the case, our students, particularly in this very competitive job market, are always hyper focused on their next jobs and achieving their next goals. Given the uncertainty reductions to research investments have created, many of my best students have started to think about jobs beyond science, and potentially "Batchelor's degreeing it out," i.e., closing their scientific chapters with a BS. Indeed, **one of my star undergraduates who was recently named a Lindau Nobel Laureate, one of the highest honors for undergraduate researchers across the world, has begun considering "just" receiving a Physics degree "for fun" and then moving onto greener pastures. The fact that emerging leaders are beginning to leave with their feet as early as during their college careers is deeply disturbing.** *Who will be our next-generation of scientific leaders?*

Funding for Basic Research Can Ensure American Quantum Competitiveness

I therefore view our desire to support quantum research for defense, medicine, and other societal purposes as the mountain vista with the priceless view that we seek. But, to reach that mountain vista, we must traverse the underlying mountain, however arduous, by providing the investments and support needed. Federal funding has long supported the pipeline that has trained students in the basic research needed to make contributions to quantum science, to reach that mountain vista. Recent reductions will substantially reduce our quantum preparedness and competitiveness. It is crucial to think fruitfully about how we will sustain our long-envied training pipeline through the combined resources and braintrust of industry, government, academic, and other partners, including through cross-institutional fellowships and internships as well as consortia that bring industry, government, and academia to bear on the greatest quantum and regional challenges of the day.