Report of the Working Group on Educational Curriculum Needs for Quantum Information Sciences

Executive Summary

As part of the Consolidated Appropriations Act, 2021, the Department of Energy (DOE) Office of Science (SC) was directed to provide to the Committees on Appropriations of both Houses of Congress a plan to meet universities' educational curriculum needs to support a future scientific workforce utilizing artificial intelligence, quantum information science and machine learning. Because these topics require different skill sets, as a first step SC formed a working group (WG) composed of representatives from universities, industry, and the DOE national laboratories to develop a plan to define and meet these needs for quantum information science (QIS). The rapidly emerging field of QIS has the potential to produce innovations in quantum computing, simulation, communication, and sensing, which are critical to our nation's future economic and national security. As a new and strongly technology-oriented field, QIS requires a well-trained workforce.

The WG first assessed current activities in formal training of QIS scientists and engineers at universities and within DOE SC research programs to understand the current state of QIS curricula and efforts by university faculty members to improve them, which was defined as the "supply side" of a future workforce. Next, the WG assessed activities to understand the needed knowledge, skills, and experience for the future workforce in QIS, the "demand side," including assessments being conducted by industry, as well as a high-level assessment of the current range of activities across DOE national laboratories and research programs, including its five National QIS Research Centers. The WG determined that DOE and its national laboratories have both significant needs for developing a future QIS workforce and significant opportunities to support universities in developing this workforce. In this latter case, it was particularly noted that through SC's Workforce Development for Teachers and Students (WDTS) and other science, technology, engineering, and mathematics (STEM) workforce training programs at the national laboratories, students can obtain critically needed on-hands research experiences that are difficult for many universities and colleges, including minority-serving institutions, to provide. To gain more insight into these educational needs and opportunities, a plan was put forth that would assess the types of skills, experience, and knowledge that would be required for the future QIS workforce at national laboratories and other SC QIS research programs, including undergraduate interns, graduate students, post-doctoral associates, and permanent staff. This information would then be used to identify specific actions that can be taken to support universities more fully prepare students for careers in QIS.

I. Foreword

As part of the Consolidated Appropriations Act, 2021, the Department of Energy (DOE) Office of Science (SC) was directed to provide to the Committees on Appropriations of both Houses of Congress a plan to meet universities' educational curriculum needs to support a future scientific workforce utilizing artificial intelligence, quantum information science and machine learning. Because these three areas are quite broad and require different skills, as a first step SC formed a working group (WG) to develop a plan to define and meet these needs in quantum information science (QIS). Once formulated, the process employed for QIS will be used to develop similar plans for machine learning and artificial intelligence. This report focuses on a plan for DOE SC to support universities in developing a future scientific workforce in QIS.

II. Introduction

Recognizing the great potential of QIS, and also aware of the growing international competition in this promising new area of science and technology, Congress passed the National Quantum Initiative Act, which became law in December 2018. The DOE SC is an integral partner in the National Quantum Initiative (NQI) and has launched a range of research programs in QIS. Research projects range from single investigators within specific disciplines to large, highly integrated, multi-institutional centers that span multiple offices within SC.

The SC WG was formed with the attached charter (Appendix A), to develop "a plan that will be used to establish the knowledge base and skill set/competencies requirements needed for developing a curriculum in QIS for educating future scientists in the area." The WG met weekly (virtually) for four weeks and included representatives of industry, universities, and DOE national laboratories. A list of WG members and their affiliations is attached (Appendix B).

Early in the discussions, the WG concluded that there are two communities that must contribute to curriculum development for QIS. We refer to these as the "supply side" and the "demand side." The supply side is composed of educational, degree granting institutions, as well as the National Science Foundation (NSF), which directly supports educational research. Colleges and research universities play an important role here. The demand side is composed of industries supporting development and manufacturing of technologies based on QIS, as well as both government laboratories and universities conducting research and development in QIS. It is in this demand side that the DOE has its most important role, because its complex of seventeen national laboratories is a large and growing employer of QIS scientists and engineers. As pointed out below, the DOE also has a role on the supply side in the training of QIS scientists and engineers, but that is secondary to its role in defining the knowledge base, skills, and experience needed to participate in DOE-funded QIS activities.

Below we summarize what the WG learned about activities on the supply side. We then review activities that are collecting data on the industry needs on the demand side. Following this we identify opportunities in which the DOE can contribute to curriculum development by providing information about QIS activities supported by SC on the demand side, as well as expanding its existing activities on the supply side.

III. Supply Side

This section summarizes current activities in training of QIS scientists and engineers at universities, other federal agencies, and DOE SC.

Higher Education Activities in QIS Curriculum Development

The rapidly emerging field of QIS has its origins primarily in the field of physics, where early studies centered on the study of quantum phenomena. However recent advances have demonstrated that quantum phenomena can be controlled to yield wholly new capabilities that will give rise to innovations in quantum computing, simulation, communication, and sensing. These advances are critical to our nation's future economic and national security. To realize these new technologies and maintain U.S. leadership in QIS, educational programs must be established to prepare a well-trained workforce—from technicians who will produce the new technologies in industry to researchers in our national laboratories and universities who will discover new capabilities to underpin next-generation technologies. As QIS is an intrinsically interdisciplinary field, the challenge for the future is to develop education programs that break down barriers between departments and colleges and bridge the gaps between various traditional programs in science and engineering. In addition, there is a growing need to expand QIS education at the undergraduate and community-college levels to lay the foundation for the new quantum ecosystem.

To meet these needs, universities are ramping up their efforts, developing new courses in quantum information science and technology across both undergraduate and graduate levels. QIS-related courses at the undergraduate level mostly cover fundamental concepts, offer a broad introduction to quantum information topics, and are usually taken as electives at the upper division. Courses on QIS at the graduate level cover a wider variety of topics with more rigor and depth and are becoming relatively common in physics, engineering, and computer science programs, although far yet from being widespread. At least one school (University of Chicago) offers a minor in quantum information science in their molecular engineering bachelor's program, but such a minor at the undergraduate level is not common. More common are quantum information-related tracks at the master's level within disciplines such as physics, engineering, and computer science. For instance, Duke University offers a quantum computing concentration in their engineering master's program, including hardware and software tracks to prepare students for either academic research or industry positions. A few universities offer an entire master's program in quantum science or technology, such as the University of California Los Angeles, the University of South Carolina, and the Colorado School of Mines, to name a few. Several schools offer graduate professional certificates in quantum science or technology. For example, the University of New Mexico has developed an interdisciplinary Ph.D. concentration in QIS (to begin Fall 2021), which will be added to the existing Ph.D. in physics or computer engineering. And recently, a Ph.D. in quantum science and engineering was announced at Harvard University.[1] Nearly all schools with minor or major programs in quantum information science and technology provide some hands-on experience in the form of research projects; however, providing this type of experience is expensive and availability will be limited at many institutions, including many minority serving institutions. While there are some opportunities for students to gain experience during industrial internships, these opportunities are still rare. As discussed below, the WG noted that this is an area where DOE can play a critical role.

The National Science Foundation Activities in QIS Curriculum Development

The NSF, together with the DOE and the National Institute for Standards and Technology (NIST), plays an important role in the NQI. The NSF is also addressing the need to build interdisciplinary training and grow QIS programs in new directions beyond the traditional physics focus. For example, NSF created the Quantum Computing and Information Science Faculty Fellowship (QCIS-FF) program with seed funding to incentivize the hiring of new tenure-track faculty in QIS within engineering departments and break down barriers between colleges of arts & sciences and engineering.

Recognizing that "quantum engineering" is an emerging discipline, NSF created a Quantum Engineering Education (QEE) committee to address the need for a new quantum engineering educational program. This committee is considering what an undergraduate quantum engineering program will look like in the context of existing engineering disciplines and how it is distinguished from quantum science education. As part of the committee's deliberations, they are considering various options for training students, as well as retraining professionals, in quantum engineering. One major theme that has arisen in the QEE committee's deliberations is the need for hands-on training and an increased emphasis on design. As stated above, the committee recognized that the infrastructure to support this training may be available at some universities, but generally it could be cost prohibitive to have such infrastructure at every university. Using online quantum computers offers one solution to this disparity, as well as leveraging internships in industry, or as outlined below, at DOE's national laboratories.

[1] https://news.harvard.edu/gazette/story/2021/04/harvard-launches-new-ph-d-program-in-quantum-science/

DOE National QIS Research Centers

The DOE National QIS Research Centers (NQISRCs) constitute the first large-scale QIS effort that crosses the technical breadth of DOE SC.[2] The NQISRCs aim to create and steward the ecosystem needed to foster and facilitate advancement of QIS, with major anticipated impact on national security, economic competitiveness, and America's continued leadership in science. Workforce development is a rapidly emerging need to support the application of QIS research, and the NQISRCs provide a differentiated and complementary opportunity to federal and other efforts in this area. The centers can support new models of training driven by their research, offering exciting opportunities for students and trainees through access to unique DOE facilities and close collaboration with industry and other partners. The workforce needed to sustain research efforts at the NQISRCs will continue to grow, with current needs projected at hundreds of positions across the centers, ranging from Ph.D. research staff members to undergraduate intern positions. Like these centers, the NSF-funded Quantum Leap Challenge Institutes (QLCIs) also expand basic research and help to develop the QIS workforce pipeline. The NSF QLCIs all have programs in education and workforce development and the DOE NQISRCs should coordinate its efforts where appropriate.

DOE QIS Workforce Development Activities

DOE's national laboratories have a long history of offering faculty and students opportunities for research experiences. The laboratories offer resources that can be extremely valuable in training the QIS workforce, including unique facilities and instrumentation accessible to faculty and students and a cadre of leading researchers who can provide one-on-one training and mentoring. Further, these experts often give lectures to augment a university course or teach short courses at professional meetings or at the national laboratories during the summer.

Student internships at DOE laboratories provide undergraduates with the opportunity for significant "face time" with cutting-edge researchers. These internships are typically offered during the summer and complements training found in a typical university environment; academic-year programs and co-op programs are also available at many laboratories. These one-on-one interactions can often be transformational in encouraging students to pursue STEM careers. Further, these experiences offer the ability to train on advanced QIS equipment that would not be available in many university laboratories. Put in a broader context, the educational experience in many advanced fields, such as QIS, greatly benefit by collaborations between universities and national laboratories, with the universities serving as the core of the educational process and the national laboratories providing an essential and vibrant research experience to complement classroom instruction.

In addition to undergraduate internships, the national laboratories offer longer term programs for training graduate students, providing more in-depth research experiences while working

[2] https://science.osti.gov/Initiatives/QIS/QIS-Centers/

closely with leading experts. Some of these programs are informal, with collaboration between principal investigators at a laboratory and a specific university, while some are more formal with direct ties to formal graduate programs at one or more universities. Post-doctoral programs are also widely available at national laboratories to provide in depth training in specific fields.

The NQISRCs are involved in several of these workforce training activities. In particular, to meet the growing demand for a QIS-ready workforce, the NQISRCs have established a joint Workforce Working Group to coordinate center workforce development activities. Near-term activities include the development of an open-data tool for stakeholders to enable discussions between students and employers; partnerships with universities, community colleges, workforce boards, and industry; and the creation of opportunities for a diverse set of students and postdocs to conduct research across the DOE centers. In addition, the NQISRCs recognize the potential to benefit from interactions with the QED-C (see below) and will be coordinating a training program with input from QED-C and industrial partners to address critical industry workforce needs.

IV. Demand Side

This section summarizes activities focused on activities being conducted for the assessment of workforce needs in industry and provides an overview of current QIS activities across DOE SC.

Quantum Economic Development Consortium Activities

The WG heard a presentation on the Quantum Economic Development Consortium (QED-C). This is a consortium of over 150 stakeholders from industry, academia, national laboratories, and other organizations, which aims to enable and grow the U.S. quantum industry.[3] A major activity of the consortium has been the assessment of the current industry workforce and future needs based on survey of QED-C members. In 2020 QED-C surveyed its corporate members about the jobs they expect to fill in the next five years, along with the desired skills, knowledge, and degrees (level and discipline) for future employees. Based on responses from 57 businesses, the survey identified a need for skills related to computer science, such as algorithm development and modeling/simulation. However, many of the skills sought are not quantum-specific and for many jobs, bachelor's or master's degree are desired. In addition to relevant skills and knowledge, employers seek graduates with hands-on experience.

[3] https://quantumconsortium.org/

Overview of current DOE QIS activities

To understand the role SC will play in employing scientists and engineers in QIS research, it is valuable to summarize its current QIS activities. SC's efforts in QIS leverage its unique strengths to support quantum computing, simulation, communication, and sensing. In addition, DOE supports creation of tools, equipment, and instrumentation that go beyond what was previously imaginable to study and understand quantum systems. These research activities are providing DOE community resources that enable the entire QIS ecosystem to innovate. Specifically, SC targets applications in four major areas: quantum computing, analogue quantum simulation, quantum communication, and quantum sensing and microscopy. QIS activities are conducted under a variety of SC programs, including, but not restricted to, the NQISRCs.

DOE user facilities have a suite of advanced resources critical for accelerating progress in QIS, including world-leading capabilities in x-ray light sources and neutron scattering facilities, high performance computing, and nanoscale science research centers. For example, single photon generation is required for all-optical quantum computing and communications. Researchers at the Center for Integrated Nanotechnologies (CINT) Nanoscale Science Research Center developed a way to controllably place localized defect sites into 2D materials over large areas.[4] Such wafer-scale integration paths are critical for scale-up to future QIS architectures and systems. In another example, a topological superconductor employs 2D quasiparticles called Majorana zero modes as the qubit for quantum computation. These modes are more stable than alternatives such as photon polarization or electron spins. Neutron scattering at the Spallation Neutron Source (SNS) enabled the search for these modes in a quantum material.[5] A new Quantum Computing User Program (QC UP) has been established as part of the Oak Ridge Leadership Computing Facility to provide access to industry quantum computing resources.[6] All of these user facilities are available to the broad user community based on merit-based review. In addition, DOE has adopted a multi-pronged approach for research on quantum computing testbeds for science at Sandia National Laboratories and Lawrence Berkeley National Laboratory to provide access to novel quantum computing hardware, enabling foundational research to explore high-risk, high-reward approaches.[7] Similarly, quantum network demonstration infrastructure is being developed at Brookhaven National Laboratory, Argonne National Laboratory and Fermi National Accelerator Laboratory in partnership with universities

[4] W. Wu, C. K. Dass, J. R. Hendrickson, R. D. Montaño, R. E. Fischer, X. Zhang, T. H. Choudhury, J. M. Redwing, Y. Wang, and M. T. Pettes, "Locally defined quantum emission from epitaxial few-layer tungsten diselenide," *Applied Physics Letters* **114**, 213102 (2019). [DOI: 10.1063/1.5091779].

[5] Chunruo Duan, Kalyan Sasmal, M. Brian Maple, Andrey Podlesnyak, Jian-Xin Zhu, Qimiao Si, and Pengcheng Dai, "Incommensurate Spin Fluctuations in the Spin-Triplet Superconductor Candidate UTe_2," *Phys. Rev. Lett*. **125**, 237003 (2020).

[6] https://www.olcf.ornl.gov/olcf-resources/compute-systems/quantum-computing-user-program/

[7] https://qscout.sandia.gov and https://aqt.lbl.gov

and industry.[8] Some are, and others may become, accessible as testbeds for the broader scientific community.

V. Conclusion: Opportunities Identified by the QIS Working Group

Our WG concluded that DOE SC and its national laboratories have both significant needs for developing a QIS workforce to meet its future mission needs and significant opportunities to support universities in training a future QIS workforce. One opportunity identified by the WG was that the SC should continue, and, if feasible, expand its workforce development activities at the undergraduate, graduate, and post-doctoral levels, as discussed above. In particular, collaboration with universities and colleges to provide research opportunities is an important contribution to the undergraduate and graduate curricula for QIS education and employment.

A unique and important opportunity for SC to help colleges and universities prepare students for employment in QIS is to define the skills, experience, and knowledge needed at various levels to participate in SC-sponsored QIS research; this could be determined by surveying anticipated workforce needs in QIS. The following sequence of steps would allow SC to assess these requirements for the future QIS workforce needed across its laboratories and other research programs:

- First, the national laboratories could provide information on the skills, experience, and knowledge requirements anticipated for future QIS positions, including undergraduate interns, graduate students, postdocs, and permanent staff. In the latter case, information should be included for engineering and technical staff positions, as well as scientific staff. The labs should include all research activities that involve QIS, not only those in the QIS centers.
- Second, following completion of the lab survey, this compiled information should be circulated to all researchers outside the laboratories involved in SC-sponsored QIS research to augment the lists requirements provided by the laboratories. This should include investigators participating in Energy Frontier Research Centers as well as individual SC grants. Subsequently, the list of positions and requirements should be posted on a survey website and the broad SC-funded community should be encouraged to provide comments.
- Third, once the list has been vetted by the SC research community, an invitation should be sent to educators at a wide variety of educational institutions to visit the survey

[8] http://qit.physics.sunysb.edu/wordpress/?page_id=485 and https://www.anl.gov/article/us-department-of-energy-unveils-blueprint-for-the-quantum-internet-at-launch-to-the-future-quantum

website to provide comments and suggestions of how SC could help colleges and universities prepare students appropriately.

Once these suggestions are received, SC can use the results to evaluate steps that can be taken to help universities more fully prepare students for careers in QIS. For example, the DOE could analyze the existing internship programs and other educational activities it supports to evaluate what is needed to fulfill the QIS workforce needs and look for opportunities to expand these programs. Another example is summer schools hosted by the laboratories.

The WG stressed that it is important to make a special effort to include Historically Black Colleges and Universities (HBCUs) and Minority Serving Institutions (MSIs) in these invitations. These educational institutions are, by design, committed to providing training and research opportunities to all students including historically underrepresented students. For example, there may be additional opportunities for faculty from HBCUs and MSIs to participate in QIS research at DOE labs alone or with their students. As discussed above, focusing DOE attention on HBCUs and MSIs can help to address their research infrastructural needs and capabilities in QIS.

The WG observed that DOE has opportunities to enhance education activities provided at universities. Specifically, the QIS expertise may not be available from existing faculty at many universities, such as HBCUs and MSIs, and the expertise of researchers and unique resources available at DOE national laboratory personnel can help fill those gaps by providing enriching research experiences and training.

Finally, coordination with other Federal Agencies is important. The WG encourages SC to do this as much as possible.

VI. Appendix A: Working Group Charter

Working Group Charter

Educational Curriculum Needs to Support Future Scientists Utilizing Artificial Intelligence (AI), Quantum Information Science (QIS), and Machine Learning (ML)

Chartered by: The Office of the Deputy Director for Science Programs with support from the Office of Workforce Development for Teachers and Scientists (WDTS).

Purpose: As part of the Consolidated Appropriations Act, 2021, "...the Committee directs the Department to establish a working group comprised of the Office of Science and national laboratories and a consortium of universities to assist universities in the development of a curriculum to promote the next generation of scientists utilizing artificial intelligence, quantum information science, and machine learning. The Committee directs the Department to provide a report and briefing to the Committee within 180 days of enactment of this act on a plan to meet universities educational curriculum needs to support this future scientific workforce."

The Working Group (WG) will focus on developing a plan that will be used to establish the knowledge base and skill set/competencies requirements needed for developing a curriculum in QIS for educating future scientists in the area. Subsequently, the lessons learned from developing the QIS plan will be extended to AI and ML.

Mode: A series of four virtual (Zoom) WG meetings in March, including a kickoff meeting, followed by two focused virtual discussion meetings, and finishing with a summary session to present findings.

When:	Kickoff Meeting:	**March 17, 2021**
	Meeting 1**:**	**March 24, 2021**
	Meeting 2**:**	**March 31, 2021**
	Summary Session**:**	**April 7, 2021**

Deliverable: A letter report that defines the scope of work and next steps needed to address the Congressional language by **April 15, 2021.**

Planning Team: Comprised a chair and two co-chairs, with Ping Ge and Michelle Buchanan representing DOE/SC. Planning team will develop a work plan for the WG (topics, speakers, background materials), finalize list of attendees, and invite WG members in late February.

Attendees: Will be by invitation only and will include representatives from the SC programs, DOE national laboratories, industry, and universities. Invitees will include experts in QIS and its application to SC mission areas, along with experts in education and workforce development.

The Working Group may be augmented with experts from specific topic areas to provided additional expertise as needed (e.g., speakers).

Motivation: Emerging capabilities in AI, QIS, and ML are rapidly becoming foundational tools for scientific discovery and advancement. Preparing the next generation of scientists in these areas will be critically important for maintaining U.S. science leadership in a competitive global environment. These rapidly evolving areas call for colleges and universities to establish new curricula to equip next generation scientists and engineers with the knowledge to both use and advance these capabilities in their careers. The expertise in the Office of Science and its national laboratories can assist universities in establishing the requirements for the knowledge base and skill set/competencies needed to develop new educational curriculum for preparing future scientists to utilize and advance artificial intelligence, quantum information science, and machine learning.

Major Topics:

- Understanding what knowledge/skill sets/competencies future researchers need in QIS to both use and advance these capabilities in their careers.
- Defining the current state of QIS educational programs.
- Defining gaps and barriers in various educational environments.

VII. Appendix B: Working Group Members and Member Affiliations

Name	Affiliation	Role
Marc Kastner	Massachusetts Institute of Technology, Stanford University	Chair
JoAnne Hewett	SLAC National Accelerator Laboratory	Co-chair
Valerie Taylor	Argonne National Laboratory	Co-chair
Timothy Akers	Morgan State University	
Abraham Asfaw	IBM	
Alexandra (Sasha) Boltasseva	Purdue University	
Ivan Deutsch	University of New Mexico	
Murray Gibson	Florida A&M University, Florida State University	
Ania Bleszynski Jayich	University of California - Santa Barbara	
Eduardo Mucciolo	University of Central Florida	
Ricardo Olenewa	Google	
William Oliver	Massachusetts Institute of Technology	
Irfan Siddiqi	Lawrence Berkeley National Laboratory	
Harriet Kung	U.S. Department of Energy, Office of Science	
Michelle Buchanan	U.S. Department of Energy, Office of Science	
Ping Ge	U.S. Department of Energy, Office of Science	
Natalia Melcer	U.S. Department of Energy, Office of Science	