Report on NSF EPSCoR Workshop on Quantum Computing, Information, Science, & Engineering

NSF, Alexandria, VA, March 23rd–24th, 2023

Erik K. Hobbie
North Dakota State University

Mark A. Novotny
Mississippi State University

Margaret Kim
University of Alabama

Eirini E. Tsiropoulou
University of New Mexico

Elizabeth Behrman
Wichita State University

Samee U. Khan
Mississippi State University

Quantum computing, quantum information science, and engineering have emerged as vital and rapidly advancing fields with global significance. Recognizing the importance of quantum research and the need to develop a quantum-ready workforce, the National Quantum Initiative Act (NQIA) of 2019 emphasized the importance of these endeavors. In line with this objective, this workshop aimed to bring together researchers and administrators from various states and territories participating in the Established Program to Stimulate Competitive Research (EPSCoR) program. The aim was to explore how their institutions can enhance their contributions to quantum computing, quantum information science, and engineering.

During the workshop, attendees were able to familiarize themselves with the latest advancements and the current state of selected topics in quantum computing and quantum information science and engineering. The workshop was designed to achieve two main goals of intellectual merit:

a) Foster a collaborative research environment: The workshop encouraged researchers to exchange ideas by providing a platform for interaction and collaboration. This collaboration will help drive progress in quantum computing, quantum information science, and engineering within the EPSCoR jurisdictions.

b) Determine the state of affairs: The workshop acted as a litmus test to evaluate the progress and readiness of institutions involved in the EPSCoR program concerning quantum computing and quantum information science and engineering. This assessment will provide valuable insights into the program's strengths, weaknesses, and potential areas of improvement.

In addition to these intellectual merit goals, the workshop aimed to have broader impacts by facilitating academic institutions to understand why and how they can contribute to educating their undergraduate and graduate students for a quantum-ready workforce. By sharing examples and insights, the workshop empowered institutions to better prepare their students for the demands of the emerging field.

Moreover, the workshop catalyzed new collaborations. As attendees learned about other quantum researchers and institutions, organic and robust partnerships are expected to form, aligning with the vision of the NQIA and EPSCoR.

The findings from the workshop are tabulated in this report. We hope that the tangible outcomes of the workshop, combined with the knowledge shared, will shape the future of quantum research and education, leaving a lasting impression on the scientific community and beyond.

Acknowledgments: This report would not have been possible without the dedication of the session scribes, namely (listed alphabetically): Matthew Beach, Bhavika Bhalgamiya, Lashaunda Bobbett, Kenzie Ellenberger, Rebecca Garcia, and Hunter Harris. The workshop organizers are incredibly grateful to all participants for their time and thoughtful discussions.

This material is based upon work supported by the National Science Foundation under Grant No. OIA-2202377. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Executive Summary

The workshop was organized to allow participants to have a robust discussion among themselves (breakout session) and interact with industry representatives and government officials through a panel discussion. An academic panel also was organized. The EPSCoR Section Head and Assistant Directors of the Directorates for Mathematical and Physical Sciences, Engineering, and Computer and Information Science and Engineering welcomed the workshop participants. The schedule of the workshop can be observed in Appendix I. A list of participants is provided in Appendix II, and the list of workshop organizers and advisory board members is provided in Appendix III.

The main findings of the workshop unfolded in the **five** parallel breakout sessions, each with an accumulated duration of five hours. The results of the breakout sessions are summarized below; however, we strongly encourage the readers to read the detailed findings in the subsequent sections.

EPSCoR Capabilities, Challenges, and Opportunities: The participants discussed the capabilities, challenges, and opportunities of the EPSCoR states in quantum computation, information science, and engineering (qCISE). The challenges include limited access to tools and equipment, grant competitiveness, underemphasized specific regions and industries, competition for access to national laboratories, and the need for collaboration between EPSCoR and non-EPSCoR jurisdictions. To bridge these gaps, it was suggested to focus on regional support, build an EPSCoR network for collaboration and resource sharing, establish centers of shared infrastructure, and develop a universal set of quantum information curricula. By addressing these challenges, EPSCoR states can enhance their research competitiveness in qCISE.

Noisy Intermediate-Scale Quantum (NISQ) hardware enablement: The NISQ Hardware Enablement breakout sessions highlight the challenges and potential solutions regarding the accessibility of NISQ hardware for research and education purposes. The main issue is the limited availability and high cost of physical (on-premise) and cloud-accessed quantum computers. Physical access is challenging due to geographic constraints, intellectual property restrictions, and rapid hardware evolution. Cloud access comes with limitations on data control. Education and research have different hardware requirements, with education needing smaller, affordable quantum computers and research requiring more computational power. Simulators can be substitutes for real hardware access, but they have limitations. Recommendations include creating a national facility for quantum computers and providing affordable educational quantum computers.

Application Enablement: Application Enablement in qCISE involves leveraging quantum technologies to develop real-world applications across various industries. The field encompasses quantum computing, quantum communication, quantum sensing, quantum simulation, and quantum metrology. The primary challenges identified in qCISE application development breakout sessions include the high cost of enabling technology and hardware, the need for fault-tolerant quantum computers, industry collaboration, data retention limitations, and funding opportunities for smaller research groups. The discussions highlighted applications, such as quantum AI and biomedical sensing, quantum materials science and spectroscopy, quantum optimization and cybersecurity, and quantum telecommunication and networks, showcasing their potential impact in machine learning, healthcare, materials science, optimization, and secure communication.

System Software: Quantum system software has the potential to revolutionize classical computer science and engineering by offering computationally efficient solutions to complex problems. The challenges in this field include understanding the similarities and differences between classical and quantum software, identifying real-life applications where quantum software can be beneficial, addressing open research challenges, designing interdisciplinary programs, and ensuring access to infrastructure. Quantum system software involves software stacks, hybrid quantum-classical systems, quantum machine learning algorithms, and quantum cryptography. While classical and quantum software shares similarities in mapping circuits and using sequence and circuit models, they differ in information representation, randomness, and compatibility. Real-life quantum software applications include optimizing delivery routes, material simulation, finance, transportation, and drug discovery.

Curricula: The session highlighted the importance of training a quantum-ready workforce and emphasized collaboration among researchers and administrators. Five key challenges were identified: creating a sustainable curriculum, sharing resources across EPSCoR states, defining appropriate prerequisites, funding shared hardware, and implementing targeted outreach. Recommendations included collaboration between universities, sharing software and hardware resources, developing outreach programs, and establishing repositories for shared resources. Building a sustainable curriculum requires transdisciplinary collaboration, accessible courses, shared resources such as textbooks and simulations, and funding for expensive hardware. Collaboration with industry is crucial for funding and research opportunities. Outreach efforts should include summer/winter programs, internships, and research experiences for students.

EPSCoR Capabilities, Challenges, and Opportunities

Summary: The Established Program to Stimulate Competitive Research (EPSCoR) program was created to provide funding opportunities to areas of the country that have historically received less financial support through the various avenues of federal and state-funded research, particularly in areas of STEM. The goal of EPSCoR is to nurture strategic partnerships between federal and state agencies, universities, and industry to continually improve research capability, infrastructure, and competitiveness to boost national workforce growth and success in strategic areas of STEM. Quantum computation, information science, and engineering (qCISE) is a burgeoning, broad, interdisciplinary research area of critical national interest, and there is untapped potential for commercial and technical growth in the regions of the United States that have traditionally held EPSCoR status. Here, we identify existing gaps in the capabilities of such states concerning non-EPSCoR states, and we outline ways that we might strive to eliminate these gaps. In doing so, we acknowledge that there are two tracks to consider in the realm of qCISE as it currently exists, which we delineate as *software* and *hardware* for brevity.

Challenge 1: A reemerging theme of concern throughout the 2-day workshop was access to tools, facilities, machines, and equipment. For example, a common problem for EPSCoR researchers working in the software realm is access to actual quantum computers and processors. Quantum processing time is expensive and highly competitive, and it can be challenging to compete with non-EPSCoR schools in this arena, given the relative paucity of access to resources. Similarly, researchers working in the realm of quantum hardware (or, more generally, quantum materials) need access to equipment (such as dilution refrigerators and advanced nanofabrication facilities) that is commonly available at larger, non-EPSCoR universities but that often does not exist at the smaller universities that are characteristic of EPSCoR states.

Challenge 2: The second most common concern in the two-day workshop was grant competitiveness for PIs in EPSCoR states. There are many challenges faced by the faculty at such institutions, from a lack of state support to a lack of access to high-end resources. At the same time, there is considerable inhomogeneity across all EPSCoR jurisdictions regarding financial resources, baseline competitiveness, and degree of geographical isolation. When paired with the fact that EPSCoR is relatively underfunded and is intended to be an enabler and not a supplier, this creates a significant disconnect between perception and reality that can act as a barrier to progress and growth in these states.

Challenge 3: There is also the accurate perception of an under-emphasis on some new-growth regions of the commercial research & development (R&D) sector in EPSCoR states as it relates to qCISE. Using North Dakota as an example, there is great emphasis on agriculture, given the huge role this plays in the state economy. STEM areas that naturally complement “ag” (or agricultural science and engineering, in general), such as drones and plant sciences, are well-positioned and benefit significantly from this narrowed emphasis. In contrast, areas that appear divergent from this focus tend to be overlooked and poorly supported. This is unfortunate, given the opportunities many EPSCoR states offer potential businesses, including cheap real estate, ample space for growth, central geographic locations, and in some cases, a burgeoning population of qualified STEM workers. EPSCoR Jurisdictions should be encouraged to engage with the National Quantum Initiative and develop plans for creating local university/industry hubs. Otherwise, there will continue to be a disconnect between education/research efforts and state priorities.

Challenge 4: Competition for access to national labs and centers can be a way to account for limitations in access and capabilities for EPSCoR states, but these facilities typically make no distinctions based on EPSCoR. Non-EPSCoR schools are generally equipped with more substantial and deeper support staff in research and creative activity, which offers advantages in competing for access to these resources. This resides in the same vein as Challenges 1 and 2 above but focuses explicitly on national labs. The consensus was that while we can and should partner as teams to address these issues collectively (see Challenge 5), having internal contacts at National labs is the most effective route to access.

Challenge 5: While there was a common question of how to partner with non-EPSCoR schools to address some of the above challenges, it became evident during the workshop that there might be better approaches than this. Instead, a coalition of EPSCoR efforts could better serve the competitive needs of the jurisdiction, with the MonArk Quantum Foundry frequently cited as an example of specific success. By building the infrastructure ourselves, we control what it prioritizes and how it is accessed.

Introduction: The interdisciplinary nature of quantum information science was emphasized frequently throughout the workshop, and this aspect of quantum science and engineering presents an opportunity. To have the most significant impact at the EPSCoR level, some degree of differentiation, like software and hardware, is advisable. Regarding hardware, trapped ions and superconducting qubits are two leading platforms for scalable quantum computing. Trapped ions rely on surface-electrode trap technology to build chip-scale ion traps and integrated photonics for laser cooling and control. Monolithic integration and modularity are two complementary architectures for scalability, and the potential for monolithic integration has been demonstrated by fabricating an ion trap in a commercial CMOS foundry. On the other hand, superconducting qubits are manufactured using conventional semiconductor lithography with thin films of superconductors, such as aluminum or niobium, in the form of Josephson junctions. The fabrication process leverages techniques and materials compatible with silicon CMOS manufacturing, and the final devices are shielded and cooled to milli-Kelvin temperatures for operation. Other promising platforms for quantum information science, such as those based on ultracold atomic and molecular qubits, have also been discussed. However, beyond these specific examples, there is a significant cluster of EPSCoR researchers working in the much broader realm of what can loosely be defined as *quantum materials*, where this work can be considered foundational or even ancillary to the future of qubit hardware but has enormous potential for impact in areas of quantum sensing, photonics, and energy. At the same time, researchers working in the quantum software realm need access to specialized machines to carry out meaningful work. Although these two tracks have somewhat divergent foci, they are united to an extent under the interdisciplinary umbrella of qCISE, and a level of regular interaction between the tracks is highly encouraged. However, the training plan for each is very different. Software engineers may not need to be encumbered with learning advanced quantum mechanics and microfabrication techniques; in contrast, hardware engineers can do meaningful and even groundbreaking work without ever interacting with a virtual quantum machine. This inherent dichotomy needs to be acknowledged and leveraged accordingly.

In terms of bridging the gaps cited above, the response is best made thematically instead of following the list of challenges above to avoid redundancy. The discussion below offers ideas for addressing and overcoming these gaps or challenges as gleaned from the three breakout sessions over the two-day workshop. Each concept addresses multiple challenges, and we have tried to present them in the order of highest potential impact, paying critical attention to the two specific tracks cited above.

The Importance of Regional Support: During the workshop, it became apparent that state support is critical for EPSCoR research and development success. This question arose frequently and might offer a way to delineate those states that should strive to be leaders in establishing EPSCoR qCISE expertise and those who are best suited to participate or contribute. For the central EPSCoR states, it was repeatedly pointed out that agriculture or agriculture-related topics are routinely given preference because of the prominent role agriculture plays in regional economies. This is viewed as an obstacle to growing widespread EPSCoR expertise in quantum science. To illustrate this, we consider two remarkably similar institutions in neighboring EPSCoR states, Montana State University and North Dakota State University (NDSU).

The MonArk Quantum Foundry is an NSF-supported program jointly led by Montana State University (MSU) and the University of Arkansas (UA), with the overarching mission of accelerating two-dimensional materials research for quantum technologies in the US. Although both institutions are in EPSCoR states, they have markedly different profiles. UA has an enrollment of around 28,000 and an endowment of $2.6B.

They compete in the Southeastern Athletic Conference, with a D1 athletics budget of $150M. In contrast, MSU has an enrollment of around 17,000, an endowment of $180M, and competes in the Big Sky Conference with a D1 athletics budget of just over $23M. This disparity under the broader classification of EPSCoR states is notable and receives discussion below.

Regardless of this academic disparity – or perhaps because of it – the pairing of these two schools would appear to be a fruitful one, and it creates a fertile ground for significant growth and sustainability in R&D. In part because of its location, Bozeman hosts an impressive list of large and small tech companies, with notable examples being Oracle and MKS Instruments. Similarly, Fayetteville is home to several tech companies, spanning software, IT, and nanomanufacturing. Northwest Arkansas is rapidly becoming one of the best locations in the country for technology startup ventures, boasting nearly ten times the number of early-stage startups compared to the average American city. The concentration of Fortune 500 companies in Arkansas (*e.g.*, Walmart, Tyson Foods, and J.B. Hunt) portends significant state support. This commercial infrastructure implies a preexisting level of state support and commitment to relevant STEM disciplines critical to growing the collaborative research effort in qCISE across the EPSCoR states. It is likely part of the reason this part of the country is home to such a strong tech entrepreneurial spirit.

With an endowment of $460M and an enrollment of just over 12,000, NDSU is similar in stature to MSU in many ways. Both are classified as Carnegie R1 research institutions, and both are in rapidly growing metropolitan areas adjacent to the upper great planes (Bozeman and Fargo). The difference reflects a disparity in state support and a mismatch with the surrounding industry. Like MSU recently experienced, NDSU received significant NSF EPSCoR support in the first decade of the 21st century and critical federal earmarks to establish research expertise in nanotechnology and materials science. However, after the relevant funding dried up, some enterprises disappeared or became inactive, although NDSU still hosts a highly active core of interdisciplinary research focused on quantum materials. What has flourished instead in Fargo is dynamic growth in areas of materials science that are directly about agricultural interests, most notably biobased polymers, renewable plastics from agricultural waste, and the affiliated additive manufacturing platforms. Much of this growth, in turn, was directly enabled by NDSU's longstanding reputation and success in research focused on coatings and polymeric materials.

This difference highlights the vital role of the local and state environment for building, nurturing, and sustaining expertise in not just qCISE but any STEM focus. As we discuss next, there is a pressing need to build qCISE research networks across the EPSCoR landscape, which can take different forms. Along the two tracks already delineated, EPSCoR states should seek out fertile locales for building the centers of shared infrastructure that will benefit the quantum revolution. These could be in separate locations based on the two parallel tracks of software and hardware. In the interest of the growth and longevity of the resulting enterprise(s), the geographic locations designated to lead these efforts should be chosen wisely based on suitable commerce, infrastructure, and state commitment.

Building an EPSCoR Network: Another point that frequently arose during the workshop was the need for meaningful widespread interaction between EPSCoR institutions working in the topical area of qCISE. This can take many forms, and the goal of the collective effort will likely dictate the precise shape. However, the need for organized EPSCoR collaborations focused explicitly on machine access, quantum materials research, and quantum education was apparent. Again, a model for this might be found in MonArk. Pairing small EPSCoR states with larger ones with a similar focus and overlapping areas of expertise (*e.g.*, software, hardware, curriculum) might be a powerful way to appease disparity and foster collaboration and growth across EPSCoR states. MonArk also demonstrates that geography can be a manageable factor in the assembly and success of such associations. These network interactions could be as informal as a GitHub for sharing software, curriculum, and teaching tools or as formal as a large research center, ideally supported by an equal mix of state, industry, and NSF/Federal funds.

During the workshop, NSF upper administration noted that the foundation receives relatively few applications for large center grants from EPSCoR states. The reasons for this could be many, but it likely comes down to a perceived lack of competitive standing. Beyond the EPSCoR Track RFPs, it needs to be clarified how the entity strives to do what it claims to do, and in arenas where EPSCoR schools compete head-to-head against non-EPSCoR schools, there is a looming sense of limited advantage that may be justified. The significance or relevance of EPSCoR status often must be clarified within a typical NSF single-PI panel pool. At the same time, constraints on researchers in EPSCoR states related to workforce readiness and limited infrastructure can hinder their ability to generate enough competitive proposals to break through and win awards. Utilizing each other's strengths through a collective might be a way to overcome the competitive limitations of individual institutions and win a significant center award in a pool of non-EPSCoR states. The NSF also indicated that workshop proposals are currently undersubscribed, which might be a helpful resource in planning and building such collective efforts.

The natural question is, "What might these networks look like?" One could envision a cluster of several state pairings similar in scope and alignment to MonArk, acting under a collective qCISE umbrella, but focused on specific areas like software, machine access, hardware, and curriculum. Interaction within each area of expertise would be distinctive. Still, interactions among the broader participants could be much more general and informal, focusing on various aspects of funding, training, access, and national workforce development across the EPSCoR landscape. The specific site for each hub would be chosen using the characteristics outlined in Section 2 as guidance. For example, the University of Rhode Island recently signed a 3-year contract with IBM for access to large quantum computers, including the new 433-qubit Osprey, and workshop attendees expressed a willingness to network with others on sharing, access, and collaboration. Brown University, therefore, might be well-suited to a large-school role in forming a center focused on quantum software, possibly paired with other EPSCoR schools of lesser financial stature.

Such networks or hubs might also prove helpful in laying the foundation of a universal set of quantum information curricula. It was noted throughout the workshop that the training requirements along the respective tracks of software and hardware are, in fact, quite different, and this differentiation by topical area was not necessarily anticipated. However, in hindsight, it makes practical sense. There is no need to teach advanced or even perhaps intermediate quantum mechanics to quantum software engineers. However, a subset of participants was explicitly interested in the *ab initio* modeling of quantum materials, presenting some degree of an exception. It was also noted that quantum hardware engineers become scarce in academia by the time they reach the postdoctoral level due in part to great industrial demand for this explicit subset of skills. A formal network of well-funded centers in EPSCoR states might help alleviate this vacuum by exposing qualified graduate students working on quantum materials to concepts and opportunities specific to quantum machine hardware engineering and maintenance. In materials science in general, it is not uncommon to do postdoctoral work in a field slightly different from the topical area of the thesis, and graduates with quantum-materials expertise could conceivably master the skills required for quantum hardware engineering in a short amount of time. The collective and varied experiences of different teaching and training efforts across the EPSCoR landscape could help streamline the convergence of qCISE. This would benefit the qCISE by providing improved workforce training and efficiency.

NSF Industry-University Collaborative Research Centers (IUCRC) are another way that this Quantum ecosystem might be achieved, in this case, in a manner that leverages industrial involvement and creates the foundation for an EPSCoR network, from which we can mine some relevant examples that involve EPSCoR states.

The Center for Atomically Thin Multifunctional Coatings (ATOMIC) is a partnership between Rice University, Boise State University, and Pennsylvania State University (PSU) focused on the design and engineering of advanced coatings from two-dimensional layered materials, such as graphene, hexagonal boron nitride (h-BN), and the layered (2D) transition metal dichalcogenide materials. Specific application areas are corrosion, oxidation/abrasion, friction/wear, energy storage/harvesting, and general large-scale synthesis and deposition of novel multifunctional coatings. Created in 2015, the center still exists under the broader umbrella of PSU's Materials Research Institute. This example speaks to the potential longevity and ultimate fate of IUCRCs.

As another example, the Center for Solid-State Electric Power Storage (CEPS), created in 2021, is led by the South Dakota School of Mines and Technology (SDSMT) and teams Syracuse University, Northeastern University, and SDSMT with industry partners to target solid-state energy storage technology for a range of applications, including portable/medical applications, the automotive industry, centralized/decentralized electric grids, military applications, and national energy security. CEPS benefits industrial partners by leveraging research dollars, networking opportunities, and student training efforts. This center has several prominent industrial partners of note.

Finally, the Center for Bioplastics and Biocomposites (CB2) at Iowa State University, the University of Georgia, Washington State University, and NDSU are IUCRC-focused bioplastics and biocomposites. The emphasis is on job creation related to sustainable manufacturing and converting crop waste to materials. The center also strives to support education and diversity by engaging undergraduate and graduate students in research on sustainable materials.

Several of the points discussed so far would have to be considered, along with a period of careful planning and vetting. What a qCISE IUCRC would look like, where it would be located, and which industrial partners would be involved in an open and interesting question. The two tracks of software and hardware loom large here, and it is unclear how these would mesh under a single IUCRC. This open question would take a grassroots effort to clarify and realize.

Grading the EPSCoR Collective: As has been noted more than once, there is considerable disparity or mismatch across the EPSCoR label in institutional stature related to size, depth of capabilities, the strength of resources, geographic setting, appropriated, and endowed funding. Brown University has an endowment of \$6.5B, while the University of Iowa has an endowment of \$3.1B. Both are classified as EPSCoR institutions. In contrast, the University of Wyoming has an endowment of \$751M million, and the University of Nevada, Reno, has an endowment of \$458M. Because the EPSCoR status of these states is likely to remain the same for a while, it is crucial to consider this variation when formulating a vision of what an EPSCoR qCISE center or hub would look like. The EPSCoR states must determine this, but MonArk offers a possible model again. On a purely hypothetical level, one might visualize a set of four EPSCoR Track pairings like the Arkansas/Montana model: two focused on hardware and two focused on software, with one or two Industry-University Collaborative Research Centers. This would form a formal collaborative network, which could sprout off more informal interactions related to teaching and curriculum. On some level, the effort to build this must rise from the EPSCoR collective in a logical and heuristic manner, and smaller-scale NSF-funded workshops focused on this question might be a beneficial and fruitful path forward.

The Role of NSF: In the context of the NSF, the most meaningful impact of NSF EPSCoR is through the various Research Infrastructure Improvement Tracks, and these should be leveraged to the greatest extent possible in bridging the challenges listed at the start of this report. NSF can also play a significant role in co-funding other large awards, with a relevant example again being the MonArk collaboration. In this sense, the program is working as it should and is fulfilling its designated role of providing research funding to areas of the country that have historically received less financial support through the various avenues of federal and state-funded research, particularly in areas of STEM. In the realm of small single-PI awards and – to an extent – large center grants, NSF could play a more significant role. Still, presumably, this would be contingent on increases in federal support.

NISQ Hardware Enablement

Summary: Noisy Intermediate-Scale Quantum (NISQ) hardware enablement issues center around accessibility to hardware. Without quantum hardware enabling active experimentation by researchers, educators, and students, the quantum revolution may be consigned to a distant future. The rapid explosion in available NISQ hardware presents unique opportunities and challenges to researchers and funding agencies seeking to advance quantum computing, information, science, and engineering (qCISE). The two overarching hardware needs are access to research endeavors and training and education. The challenges for NISQ hardware access, particularly for researchers and educators at EPSCoR states, identified during the two-day workshop are described below.

Challenge 1: The main problem with NISQ hardware enablement is general accessibility. There are quantum computers available to a select few with the proper connections or free access for quantum computers with minimal time or resources. However, adequate general access is needed for research and educational purposes. The mechanisms for accessing these quantum computers are expensive, limited, and challenging to navigate. Furthermore, companies want to avoid costly and lengthy legal requirements and licensing agreements with many qCISE-interested universities. Quantum computing hardware can be accessed physically but generally through the cloud. Both forms of access come with different problems, as described below.

Challenge 1(a): One of the ways to access quantum hardware is in person. However, physical access to NISQ hardware is rarely possible due to geographic distance, intellectual property restrictions, and the rapid evolution of NISQ technology, causing devices to become outdated. It is challenging to keep up with the latest hardware needed for education and research, especially given the prohibitive cost of state-of-the-art NISQ computers.

Challenge 1(b): The cloud is the second way to access quantum hardware. Cloud access is generally more convenient and flexible for the user, allowing the latest hardware to be available. This access does come with limitations. Some limitations with cloud access are that it may not provide all the data or quantum control the user needs and may not allow users full access to quantum computers. A further limitation of the research is that high-end resources can have limited availability due to limited uptime, and companies usually need to readily share the projected timelines for their current generation of hardware to become unavailable.

Challenge 2: With the growth of quantum computing as a distinct field of study with close ties to traditional high-performance computing, education and research needs must be addressed. However, NISQ hardware requirements of teaching and research represent distinct use cases. What are the differences between these needs, and how can they be met?

Challenge 3: Simulators of NISQ hardware are environments that mimic the behavior of quantum computers. These are more accessible to users and cost-effective only if the quantum volume is small. The simulators can be used to help develop quantum algorithms but are not a replacement for actual NISQ hardware. The issues with these environments are the computational limits, the lack of noise within the simulators as seen on real quantum hardware, and the inability to experiment on a *bona fide*, imperfect quantum system, potentially revealing unexpected but essential behavior. Real hardware access is needed in research and education, and simulators are not a suitable replacement.

Several potential solutions were identified to address these challenges. These solutions include building a national facility for state-of-the-art quantum computers that allows on-site user access, modeled along the lines of previous successful NSF ventures. This would help mitigate the accessibility issue for both research and education. Two main types of quantum computers were identified that need to be accessible. The first type is for education, and this could be a relatively affordable small quantum computer that has yet to develop fully. The second type would support research and consist of more extensive, fully developed quantum computers (potentially newer, experimental systems) that can offer users cloud and physical access. Ideally, more than one system architecture would be made available. These quantum computers and access can only be obtained directly from companies actively manufacturing NISQ hardware or prominent cloud vendors. They are relatively expensive to acquire for individual research groups or universities.

Introduction: Noisy intermediate-scale quantum (NISQ) refers to the current era of quantum computing. The available quantum computers now are not fault-tolerant, contain noise that results in errors, and are susceptible to quantum decoherence. Their computational power and usefulness are limited due to error and decoherence rates. The term intermediate-scale describes, for example, the quantum volume of the quantum computer. The current quantum computers are large enough that they cannot be simulated using classical computers but are too small to enable full quantum error correction.

There are two ways to access NISQ hardware: physical and cloud. Quantum computers must be set up within a laboratory and will not work outside of specific environments, often involving expensive cryogenic cooling and high vacuum requirements. Due to these environmental conditions, most device access is through the cloud. Several companies offer cloud access for users to run programs on their vendor-specific NISQ computers.

Access to hardware is essential to develop a robust quantum-ready workforce. Both education and research require NISQ hardware. These requirements vary based on how the hardware will be used. Learning more about the current hardware available for both research and the classroom will benefit the advancement and future of quantum hardware.

Access to Physical and Cloud-Based NISQ Hardware: Access to hardware is one of the main problems within the quantum computing field for research and education. This hardware is costly, difficult to obtain, and hard to sustain. With more advancements being constantly made to quantum hardware, physical quantum computers will continue to be outdated quickly. Since quantum computers are costly, buying an obsolete device within a short timeframe is not sustainable. The essence of the problem is that the timescale between generations of different NISQ computers from even a single company is currently less than or comparable to the typical timetable for a student to complete a Ph.D. degree. However, many users have projects that could be improved by accessing quantum computers through the cloud, one being the information made available to the user. Users are concerned with not having full access to the quantum computer and all the data and quantum controls. Only a fraction of the data from various levels within the quantum computer is available to users, as determined by the providers; this can limit the value of the access level and the data itself. Another area for improvement with accessing quantum computers via the cloud is that many users would prefer to partner directly with industry vendors rather than third-party providers. Third-party industry providers have been a point of failure that, with adequate contractual obligations to the research and education community, can positively impact research and education efforts on NISQ computers.

A barrier to purchasing physical quantum computers is that one cannot buy one. These quantum computers are not mass-produced and are rarely sold to be used outside of cloud access. A proper way to purchase or lease and access quantum computers from the companies building them must be established. This is exasperated by the prohibitive cost for a single university, in the tens of millions of dollars, for any current state-of-the-art NISQ computer. For research accessibility, quantum computers need to be purchased. These quantum computers would be within the \$20 to \$50 million range, plus annual maintenance costs in the 5% to 10% range. Nevertheless, companies need to begin selling quantum computers to survive. Hosting everything where users only ever access the hardware through the cloud and do not directly purchase devices will not allow the companies making NISQ computers to survive. If no one buys quantum computers, companies will stop building them.

There are many ways to access quantum computers at this point; primary access is via the cloud to develop applications for the hardware. Using third-party providers such as Google, Amazon Web Services, and Microsoft, users can access several types of quantum computers to create and run their programs on real quantum computers. For some of these services, there is free usage. Generally, free usage is minimal and cannot be used as a sustainable solution for the accessibility issue for either research or education. With free access, there is no guarantee that the key will remain for the timeframe of either a semester for educational use or a graduate student research project. The paid options for access can be quite costly, sometimes prohibitively so. One possible solution to help mitigate the accessibility to physical hardware issues would be to create a large national or regional quantum computing facility. This facility would contain shared quantum computing resources for multiple institutions, including EPSCoR participants. A model example of this type of facility is the National High Magnetic Field Laboratory. A national facility could include physical and remote access to quantum computers, which could be housed on-site. A set of on-site quantum computers would be part of a research and development program to continually push the technology forward, as may be included in the lab's mission. Some user research may consist of access to these systems. Alternatively, users could request time as cloud access to "workhorse" systems also housed either in the facility or by system providers, in a somewhat similar model to the NSF 23-518 solicitation, which funded ACCESS (Advanced Cyberinfrastructure Coordination Ecosystem: Services & Support). The funding mechanism design must address the unique challenges of state-of-the-art NISQ computers that may necessitate a hybrid approach for researchers and educators to access quantum computers.

Another solution to cost, accessibility, and capacity issues would be for institutions to partner with each other and for NSF to purchase and use a cloud-hosted quantum computer at either one of the partner institutions or the quantum computer company. Either of these solutions would enable a single point-of-contact for the NISQ vendor, thereby centralizing administrative overhead, including the necessary legal resources required – this is particularly important for mid-sized NISQ companies.

Research versus Education Needs: Education and research require different things, from quantum computing hardware. Education needs small programmable quantum computers; a fully complete system with a small number of qubits (even as few as four) could give students a nontrivial quantum programming experience and hold their interest. Such quantum computers should allow students to access quantum controls, gaining invaluable experience to graduate into the quantum-ready workforce. Research requires more computational power; therefore, larger qubit quantum computers. These quantum computers are expensive to purchase and need to be updated. Cost represents the most significant barrier to buying these physical quantum computers for education and research. Many of today's cloud-accessible quantum computing resources are not readily accessible for education. For educational institutions, there are no available hardware resources that can be used for teaching students about quantum hardware and software. Options are either prohibitively expensive or are limited to short trial access periods that may not be sufficient for student learning. The available free resources are minimal and therefore not sustainable for education. There is a need for access to both hardware and software for education.

Many students will not be interested in learning quantum computing if there is no physical quantum computer to see, work on, and tinker with. Students will not learn quantum computer intricacies if everything is accessed only through the cloud. They would need hardware to learn about the hardware correctly.

On the education side, hardware other than quantum computers can be used for students to learn how physical NISQ hardware works. For example, a quantum computer such as Infleqtion's miniMOT is more accessible (smaller, simpler, and commercially available) and appropriate for classroom use. This product can be used for students to learn how to optimize physical parameters to make their first magneto-optical trap (MOT). Once the parameters for this quantum computer are optimized, it can create a trap of cold atoms – this is one of the first steps for cold atom quantum applications. Smaller quantum computers like this can be used as a springboard experience toward more complex applications like cold atom gate-model quantum computing or Bose-Einstein Condensate (BEC). Pairing hands-on time like this with lessons in quantum applications through cloud-based platforms could be a solution in education for students to learn both hardware and software for quantum computers and beyond. This presents a short-term goal for other quantum hardware manufacturers and universities to develop proof-of-concept learning platforms to build, engage, and sustain a quantum-ready workforce.

A solution for the educational side of accessibility is for universities to have affordable quantum hardware systems, not necessarily quantum computers. These lower-capacity quantum computers allow students to learn by taking them apart, modifying them, and putting them back together, ideally with the possibility of improving the devices. The device should be within the $50,000 to $150,000 range to fit within budgets for universities and equipment funding agency mechanisms.

Need for Real Hardware Access: While simulators could be a starting point for learning how to program on a quantum computer, they cannot replace learning on a real quantum computer. There is no substitute for a real quantum computer when teaching quantum computing. Simulators are not viable because they have different capabilities, such as quantum volume, compared with current NISQ computers—a foundational appreciation for the hardware and software is needed for training students. A further difficulty of simulators is the substantial increase in classical computer resources required if the simulator considers the actual error rates and types of any particular NISQ computer.

Simulators may be a starting point for teaching how to program on a quantum computer, but they cannot replace learning on a real quantum computer. There is a significant learning curve when moving from classical computing to quantum computing in the way to think about the architecture and algorithms, and it even requires unlearning about the system architecture and problem and output setup due to the fundamental differences in the physics of quantum and classical computing. A simulator could help inexperienced users understand quantum computer architecture and design. For initial testing, a simulator could also be used as an intermediate point between the concept and the problem. Simulators can bridge the gap between classical and quantum computing but cannot replace real quantum hardware.

Recommendations to the NSF: The primary request to the NSF for the NISQ hardware breakout sessions is to provide access to NISQ computers critical to quantum research and education, including cloud-accessible hardware and physical access to hardware. Hardware access is essential for education to build and maintain a quantum-ready workforce. For research and applications, hardware access is crucial for expanding and accelerating work in qCISE. The recommendation is for funding mechanisms, physical hardware, and cloud access to be available to fit the unique constraints of NISQ hardware.

NISQ hardware educational needs could be met with hardware in the $50,000-$150,000 range. The NISQ computer could, for now, be a three-to-eight-qubit quantum computer or a compact cold atom quantum computer, for example. These quantum computers would have to be enough to make the future quantum workforce diverse, including geographically dispersed in most EPSCoR jurisdictions. Depending on the hardware, it may be possible for universities to share such hardware resources, for instance, on a semester-by-semester basis.

One or more flagship facilities with a robust in-house research and development program that will be a nexus for interdisciplinary expertise required to make significant strides in developing subsequent technologies and materials platforms for qCISE should be considered.

The NISQ computer research hardware needs can only be met with sufficient access to one or more state-of-the-art quantum computers. One major obstacle is the initial cost for each quantum computer in the range of $20M to $50M. Different hardware implementations (e.g., superconducting, neutral cold atom, trapped ion, photonic) of NISQ computers have unique strengths and weaknesses when a specific science or engineering application is considered. Hence purchasing or leasing a small number of state-of-the-art NISQ computers is essential for the US to be a leader in this quantum technology revolution. There was considerable support in the EPSCoR community for a national user facility that university researchers and students from all institutions could visit and access via the cloud, like a hybrid model between the National Magnet Laboratory and NSF ACCESS facilities. A service provider university would be the single point of contact for the vendors while supplying cloud access and help facilities to a broad spectrum of geographically dispersed researchers and students. Another recommendation would be for funding mechanisms for longer-term programs at service providers, a month to a semester in length, for qCISE students and researchers to be able to be near the hardware and simultaneously physically interact with other people active in qCISE. Funding mechanisms for universities to participate in the unique challenges of NISQ computers must be found for NSF to advance its overall mission, including under the National Quantum Initiative.

Application Enablement

Summary: Application Enablement of Quantum Computing and Quantum Information Science and Engineering (qCISE) refers to leveraging quantum technologies to develop and optimize real-world applications, industries, and businesses. qCISE involves interdisciplinary fields focused on the principles and applications of quantum mechanics to create modern technologies for computing, communication, simulation, sensing, and metrology. The range of qCISE applications is vast and can potentially transform various industries and domains. Researchers from the EPSCoR states in the United States participated in a two-day workshop to discuss the main challenges identified in the field of qCISE Application Enablement. These primary challenges and promises are summarized below, and much more extensive details are provided in the full report.

Challenge 1: Prohibitive cost of enabling technology and hardware was the leading challenge discussed in this session regarding qCISE application development. This high cost makes adequate access to quantum computing platforms prohibitive to researchers in academia, especially for graduate and undergraduate students who will be the future workforce to access sufficient time on quantum computers. Moreover, the cost of the necessary equipment to fabricate and control quantum devices is high financially and in human resource training. The complexity of quantum technology requires extensive training in a subset of several challenging technical areas, including cryogenic, microwave, and nanofabrication techniques, *etc*. In the pedagogical arena, there is the additional challenge of training faculty and providing equipment access so that they can develop a relevant hands-on qCISE curriculum. Moreover, outside major industrial firms, only some research labs nationwide can build their full-size quantum computers.

Challenge 2: Today's Noisy Intermediate-Scale Quantum (NISQ)-era computers are not yet fault-tolerant and are sensitive to their environment, which makes them prone to decoherence. NISQ-era algorithms compensate for some of this with error mitigation to produce more accurate results. To build fault-tolerant quantum computers, it is essential to make the quantum devices as precise as possible, but the fundamental laws of quantum mechanics limit their ultimate accuracy. Therefore, more importantly, investments must be made in identifying topological matter and developing quantum control protocols to mitigate errors and optimize fidelity.

Challenge 3: Another challenge discussed was the industry perspective on making quantum computers and related devices, motivated by the logic of the marketplace and the requirements of making a profit. These requirements run counter to allowing academic groups free access to research on industry-developed quantum platforms. There should be collaborations between educational groups and industries to promote quantum applications.

Challenge 4: The fundamental no-cloning theorem of quantum mechanics challenges data retention. This happens because keeping track of the original information after a quantum measurement is impossible, making duplicating the data/information on quantum computers impossible. This leads to concerns about the loss of data and the full range of initial reports submitted to a quantum computer.

Challenge 5: This challenge is the primary concern for smaller research groups that may have extraordinary expertise but need more funding opportunities to pursue specific aspects of quantum technology. It is primarily applied to researchers from the EPSCoR states. On top of this, there are a few restrictions for the initial proposal submission. There should be more funding opportunities and fewer constraints on the applications to promote quantum awareness and diversity.

Introduction: Quantum Computing and Quantum Information Science and Engineering (QISE) have a wide range of potential applications that can revolutionize various industries and domains. Enabling qCISE is about harnessing the power of quantum technologies to develop practical applications and solutions for real-world problems. This requires a holistic approach, encompassing algorithm development, hardware research, software tools, and stakeholder collaboration.

qCISE is an interdisciplinary field that combines principles from quantum physics, computer science, and engineering to study, design, and develop modern technologies based on the unique properties of quantum mechanics, such as superposition and entanglement. This field emerged from the realization that quantum mechanics will fundamentally transform how we process, transmit, and store information, leading to many potential applications and technologies. qCISE is still a rapidly evolving field, with many theoretical and experimental challenges to overcome. However, the potential for groundbreaking discoveries and technological advancements makes it an exciting and promising area of research. Some critical qCISE regions include:

Quantum Computing: Quantum computers use qubits instead of classical bits and can perform much more effectively and powerfully than their classical equivalents. They can solve problems intractable for classical computers, such as factoring large numbers, simulating quantum systems, and optimizing complex systems.

Quantum Communication: Quantum communication leverages the principles of quantum mechanics to transmit information securely. Techniques such as quantum key distribution (QKD) rely on the principles of quantum mechanics to create cryptographic keys immune to eavesdropping.

Quantum Sensing: Quantum sensors exploit quantum phenomena to achieve the ultimate sensitivity and precision of classical sensors or perform where classical sensors cannot (*e.g.*, GPS-denied environments). Applications include gravitational wave detection, gravity gradiometry, physics beyond the standard model, and sensing of magnetic, inertial, and rotational forces with unmatched precision.

Quantum Simulator: Quantum simulator is a device or computer program that mimics a quantum system's behavior to study its properties and dynamics, which are difficult or impossible to simulate with classical computers due to the exponential number of parameters needed to describe a quantum system. This can aid in understanding fundamental physics, chemistry, and materials science processes.

Quantum Metrology: This field uses quantum techniques to enhance the accuracy and precision of measurement devices, such as atomic clocks and interferometers.

The main agenda of this qCISE Application Enablement breakout session was focused on discovering new quantum applications and their implementation in the real world. Experts from academia and industry, such as Infleqtion, PQ Secure, and IonQ, discussed the perspectives of various current and potential applications in the area categorized and listed above. In the following sections, a series of conclusions and recommendations based on the discussions during the workshop are summarized to represent the background knowledge and research efforts performed by researchers in EPSCoR states.

Application Enablement in Quantum AI and Biomedical Sensing: The first application addressed in this session was the application of quantum computers in *artificial intelligence (AI) and Biomedical Sensing*. Quantum AI and Biomedical Sensing are two fields under intense development and can profoundly shape our future. Quantum AI applies principles of quantum mechanics to improve machine learning algorithms. At the same time, Biomedical Sensing refers to technologies capable of detecting and monitoring biological processes at various scales, from individual molecules to entire organisms. Both fields are actively being explored for their potential to enable new applications, boost productivity, and improve outcomes in various areas, including autonomous vehicles and voice recognition.

Speed and Efficiency: Quantum computers can theoretically process large amounts of data exponentially faster than classical computers. Quantum machine learning algorithms could thus solve complex problems more efficiently. Quantum AI holds promise for several significant advances in computing and machine learning: *Quantum Optimization*: This is an area where quantum AI could potentially excel, especially in complex tasks like supply chain management, logistics, financial modeling, drug discovery, and more.

Enhanced Machine Learning Models: Quantum AI could also enhance existing machine learning models by efficiently processing and understanding high-dimensional data, which could be particularly useful in areas like image and voice recognition, natural language processing, and more.

Biomedical Sensing can help in early disease detection, disease progression monitoring, and evaluating treatments' effectiveness. It is also crucial in personalized medicine and real-time health monitoring.

Disease Diagnosis and Monitoring: The development of sensors that can detect disease biomarkers at the molecular level can allow for the early detection of diseases like cancer and Alzheimer’s.

Personalized Medicine: Biomedical sensors can help implement customized medicine by monitoring a patient's response to a particular treatment and adjusting doses accordingly.

Wearable Health Monitors: There are ongoing efforts to integrate biomedical sensors into wearable devices to monitor health vitals like heart rate, blood pressure, glucose level, etc., in real-time, offering immediate feedback to users and healthcare professionals.

Integrating Quantum AI with Biomedical Sensing could bring a revolutionary shift in healthcare and life sciences. Quantum machine learning algorithms could be applied to analyze vast amounts of data from biomedical sensors quickly and accurately, facilitating early diagnosis, personalized treatment, real-time health monitoring, and more. This synergy could usher in a new predictive, preventive, and customized healthcare era.

Quantum biomedical sensors are under development at several start-up companies. It is possible to use quantum computers to develop a machine-learning model to detect cancer from images and videos shortly. CausalAI, the next generation of enterprise AI developed by causaLens, which promotes a platform that can reason and make choices as humans do, has proved the advantage of the new quantum computing in histopathological cancer detection.

Application Enablement in Quantum Materials Science, Spectroscopy, and GPS: The first application discussed in this session was 2D semiconductors for quantum devices and *quantum photonics*. Photonics plays a crucial and significant role in quantum communication. The development of quantum photonics faces three main three challenges: **(a)** the possibility of multiple photon interactions instead of the two photons; **(b)** the unidimensional generation of quantum/photon pairs; and **(c)** a high degree of nonlinearity. There is also the practical challenge of producing quantum photonic chips. There is potential for quantum spectroscopy using entangled photons, such as the Boson sampler, to study photonic interactions. However, there is a significant measurement challenge in quantum photonics or quantum spectroscopy: entangled states are difficult to interrogate, and no algorithms or methods can measure entanglement without disturbing it. In addition, there are no traditional means of measuring quantum scattering in various conditions, which is one of the critical conditions of the measurements. Panel members proposed that noise spectrum measurements can be one of the ways to overcome this limitation.

Many currently available quantum technologies exist, such as ion traps, cold atoms, superconducting qubits, and diamond NV centers. The panel members focused on NV centers as a platform to test quantum control protocols in both engineering and quantum sensing modalities. It was suggested that one of the future technological applications of NV centers would be developing the quantum gyroscope for navigation applications. Another device is atomic clocks which are used in *GPS satellites*. There was also a discussion of NV centers improving coherence for dense systems and controlling magnetic dipole interactions.

Quantum spin liquids were another topic of discussion, and questions whether there is the possibility to synthesize bulk material that hosts quantum spin liquid. However, at present, we lack an indisputable experimental metric for unambiguously identifying the quantum spin liquid states – for this reason, such a state of matter was not detected yet. There is no clear theoretical paradigm for the identification of quantum spin liquid. There may be exciting possibilities in Bose-Einstein condensates (BECs) made of excitons, analogous to the BECs made from Rydberg atoms in table-top systems produced by ColdQuanta/Infleqtion Company. However, there are many unknowns in exciton-based BECs, which is very early.

While classical spectroscopy has a wide range of applications, it is non-coherent. The additional coherence in quantum systems would add novel capabilities in *quantum spectroscopy.* The participants discussed quantum simulators designed with microwave techniques reaching the THz frequency range and how to make optical measurements for such a quantum device. Another possibility could be of using a photon entanglement device.

Application Enablement in Quantum Optimization and Cyber Security: One of the exciting applications of quantum computers relies on their *optimization* capabilities. Classical optimization has proved to help solve many optimization problems but addressing NP-complete issues is quite challenging, which could be overcome by quantum optimizers. Quantum optimization can be leveraged in almost all areas, such as finance, public health, and traffic control, and finding the place with the best mobile network coverage. A recent study by Volkswagen Company reported that current generations of D-Wave quantum annealers had been proven helpful in optimizing traffic. Quantum annealing techniques have also been brought to bear in such disparate problems as diet planning, bin packing problems, and financial forecasting.

Accordingly, it is an important topic to explore in the session about the comparison and analysis between the classical co-processor and quantum co-processor, which leads to the comparison between *classical optimization versus quantum optimization,* in which the capability of quantum optimization compared to the classical optimization was challenged by the industry applications. However, there was some controversy over the claimed advantages of quantum optimization.

Another exciting application is quantum computing in *Cyber Security*. Quantum computing has the potential to impact cybersecurity significantly. On the one hand, it could break current encryption methods, such as RSA and elliptic curve cryptography, by solving large-number factorization problems and discrete logarithm problems more efficiently. This would pose a threat to existing secure communication systems and sensitive data. On the other hand, quantum computing can also enhance cybersecurity. For example, quantum key distribution (QKD) is a secure communication method that uses quantum mechanics to generate and distribute encryption keys. QKD is considered more secure than traditional encryption methods because it relies on the fundamental properties of quantum mechanics, making it almost immune to eavesdropping or hacking. Quantum computing can improve cybersecurity in several ways, such as enhancing encryption methods, strengthening authentication protocols, and developing new security algorithms. Here are some specific examples of how quantum computing can be used for cybersecurity:

- Quantum Key Distribution (QKD): QKD is a secure communication method that uses quantum mechanics to generate and distribute encryption keys. It relies on the fundamental properties of quantum mechanics, like the Heisenberg Uncertainty Principle and the no-cloning theorem, which make it almost immune to eavesdropping or hacking. Organizations can establish secure communication channels resistant to attacks by employing QKD, even from quantum computers.
- Quantum Cryptography: As quantum computers have the potential to break widely used cryptographic methods like RSA and elliptic curve cryptography, researchers are working on developing post-quantum cryptographic algorithms. These new algorithms are designed to be secure against classical

and quantum computers, ensuring protecting sensitive information in a future where quantum computers are prevalent.

- Secure Multi-Party Computation (SMPC): Quantum computing can enhance SMPC. This cryptographic technique allows multiple parties to perform joint computations on their confidential data without revealing the data to others. Quantum-enhanced SMPC could enable more efficient and secure collaborations between organizations or individuals, protecting sensitive information from unauthorized access or leaks.
- Quantum Random Number Generation: High-quality random numbers are crucial for cryptographic operations like key generation and encryption. Quantum random number generators harness the inherent unpredictability of quantum mechanics to produce accurate random numbers, which can be used to improve the security of cryptographic systems.

Application Enablement in Quantum Telecommunication and Networks: Quantum networking is an emerging field that aims to build communication networks using the principles of quantum mechanics. It involves creating, transmitting, and manipulating quantum states of information, known as qubits, over long distances. Quantum networking offers more security, speed, and efficiency advantages than classical communication networks. Quantum telecommunication uses quantum mechanics principles to transmit and manipulate information securely and efficiently. It offers several advantages over classical communication methods, including increased security, faster data processing, and potential new applications. Here are some of the critical applications of Quantum Telecommunication and Networks:

- Quantum Key Distribution (QKD): One of the most prominent applications of quantum networking is QKD, which enables secure key exchange between two parties. QKD relies on the properties of quantum mechanics, such as superposition and entanglement, to ensure the security of key distribution. Any attempt to intercept the communication would be detected, making it virtually immune to eavesdropping. This can be used to establish highly secure communication channels for sensitive data transmission.
- Quantum Internet: Quantum networking can pave the way for a quantum internet, enabling the exchange of quantum information between quantum computers, sensors, and other devices over long distances. A quantum internet could provide a highly secure, fast, and efficient communication infrastructure that leverages the unique capabilities of quantum computers and other quantum technologies.
- Quantum-Secure Communication: Quantum telecommunication can be used to develop communication systems resistant to attacks from quantum computers. By combining QKD with post-quantum cryptographic algorithms, quantum-secure communication can protect data from classical and quantum eavesdropping, ensuring long-term confidentiality and integrity of information.
- Distributed Quantum Computing: Quantum networking can distribute quantum computing resources across multiple locations, allowing users to access and share quantum processing power. This can lead to the development of quantum cloud computing services, where users can run complex quantum algorithms on remote quantum computers, potentially revolutionizing various industries, such as finance, drug discovery, and optimization.
- Quantum Sensor Networks: Quantum networking can create networks of sensitive quantum sensors that can share and process information in impossible ways with classical sensors. These networks could have precision measurements, navigation, and environmental monitoring applications.
- Teleportation and Quantum Repeaters: Quantum networking can enable quantum teleportation, which transfers quantum information from one location to another using entangled qubits. Quantum repeaters can extend the range of quantum communication by correcting errors and maintaining entanglement over long distances, which is crucial for building large-scale quantum networks.

Application Enablement in Education and Research: Quantum computing and information science are rapidly developing fields with significant potential to revolutionize various industries and applications. Investing in education and research is crucial to prepare the next generation of scientists, engineers, and professionals in these areas. Here are some ways to promote quantum computing and information science education and research:

Academic Programs: Establish and expand undergraduate, graduate, and postgraduate programs dedicated to quantum computing and information science. These programs should cover the fundamentals of quantum mechanics, quantum information theory, quantum algorithms, and quantum hardware, as well as interdisciplinary applications in cryptography, optimization, and machine learning.

Research Institutes and Collaborations: Create and support research institutes, centers, or consortia focused on quantum computing and information science to facilitate innovative research and development. Encourage collaborations between academia, industry, and government organizations to share knowledge, resources, and expertise and accelerate innovation in the field.

Funding Opportunities: Provide funding opportunities for research projects, infrastructure development, and quantum computing and information science academic positions. This can include grants, fellowships, and scholarships to support students, researchers, and faculty members working in these areas.
Curriculum Development: Develop and update curricula to incorporate quantum computing and information science topics into existing science, technology, engineering, and mathematics (STEM) courses. Encourage the development of interdisciplinary studies that combine quantum principles with other fields like computer science, physics, and materials science.

Workshops, Conferences, and Seminars: Organize and participate in workshops, conferences, and seminars to promote knowledge exchange, networking, and collaboration among researchers, educators, and practitioners in quantum computing and information science.

Online Learning Platforms and Resources: Develop and provide access to online learning platforms and resources, such as MOOCs (Massive Open Online Courses), video lectures, and tutorials to reach a broader audience interested in learning about quantum computing and information science.

Outreach Programs: Create outreach programs to raise awareness and spark interest in quantum computing and information science among school students, teachers, and the general public. These programs can include interactive demonstrations, lectures, and hands-on activities to introduce quantum technologies' basic concepts and potential applications.

Industry Partnerships: Foster partnerships between academia and industry to facilitate the exchange of knowledge, resources, and expertise. These partnerships can help identify industry-relevant research problems, provide internship and job opportunities for students, and ensure that academic programs are aligned with the skills and knowledge required by the job market.

Introducing quantum computing and information science concepts at the K-12 level can help spark interest in these fields and prepare students for future academic and career paths. Here are some strategies and ideas for incorporating quantum computing and information science into K-12 education:

Integrating Concepts into Existing Curriculum: Introduce basic concepts of quantum mechanics, quantum computing, and information science into existing science, technology, engineering, and mathematics (STEM) courses. For instance, when teaching about computing or binary systems, educators can briefly discuss qubits and their unique properties compared to classical bits.

Age-Appropriate Resources: Develop age-appropriate learning materials, such as textbooks, videos, and interactive simulations, to explain quantum concepts in an engaging and accessible manner. Use analogies, visualizations, and real-world examples to illustrate the principles of quantum mechanics, superposition, entanglement, and quantum computing.

Hands-on Activities: Design hands-on activities and experiments that help students explore quantum principles and their applications. For example, create simple games or simulations demonstrating superposition, entanglement, or basic quantum algorithms.

Collaborations with Local Institutions: Partner with local universities, research institutions, or industry partners to organize guest lectures, workshops, or field trips related to quantum computing and information science. This can help students gain exposure to real-world applications, research, and career opportunities in these fields.

Teacher Training and Support: Provide professional development opportunities for teachers to learn about quantum computing and information science, including workshops, seminars, and online courses. This can help educators feel more confident in teaching and incorporating these topics into their curriculum.

Competitions and Challenges: Organize or participate in regional, national, or international quantum computing and information science competitions or challenges, which can inspire students to learn more about the subject and showcase their skills and knowledge.
Awareness and Outreach: Promote awareness of quantum computing and information science among students, parents, and the broader community through events, presentations, or demonstrations. This can help generate interest and support for incorporating these topics into K-12 education.

Incorporating quantum computing and information science concepts into K-12 education can foster an early interest in these fields and better prepare students for future academic and professional opportunities in emerging technologies.

Recommendations for NSF: We recommended a few steps on what we can do together to facilitate quantum sensing or quantum applications in the context of the NSF EPSCoR program:

1. EPSCoR programs focused on quantum information science and engineering.
2. More funding opportunities and proposals for smaller interdisciplinary teams on quantum science, engineering, and related areas are discussed above.
3. The NSF needs to remove constraints on grant applications and call for proposals in the topics of quantum Information Science and Engineering.
4. NSF-wide program to support student exchanges to facilitate collaborations between different disciplines if appropriate funding is provided to facilitate such discussions.
5. There should be funding opportunities focused on broad access to advanced quantum equipment (such as dilution refrigerators, high precision measurements, and microwave control devices) available at the National Labs or funding opportunities for collaborative research of building the infrastructure or national sites.

System Software

Summary: Quantum system software promises to revolutionize how classical computer science and engineering-related problems are solved by introducing computationally efficient and fast solutions to complex problems. The main challenges are summarized below, and much more extensive details are provided in the subsequent text.

Challenge 1: Classical software has successfully addressed several challenging research problems, from optimization to machine learning algorithms and computer compilers. While quantum software shares several similarities with classical software, fundamental differences that exploit the quantum physical principles have made the research and industrial community rethink how to address traditional software-based problems. What are classical and quantum software's main similarities and differences, and the new potential avenues these differences enable?

Challenge 2: For any new software initiative to be viable and attract investors to support its development, the plan for real-life applications that it can help needs to be in place. What novel or existing real-life applications can quantum software improve upon or generally find applicability?

Challenge 3: Quantum System Software has made tremendous progress over the last decade, primarily focusing on Quantum Machine Learning, error correction, and data parallelism. What open research challenges should the research and industrial communities jointly concentrate on?

Challenge 4: The field of quantum computing is highly interdisciplinary among various fields of study, including Electrical and Computer Engineering, Physics, and Computer Science. How can we design interdisciplinary programs, workforce development, education, and research opportunities for students, industry, and researchers (faculty, postdoc, *etc.*) to thrive in developing qCISE system software?

Challenge 5: Access to infrastructure is particularly crucial for advancing research and development in quantum computing, information, science, and engineering. Infrastructure, including physical and technological resources such as laboratory facilities, equipment, and other computing resources in quantum computing, is expensive and poses a steep threshold for entry. What are the core infrastructure and research-based needs of the research community in the EPSCoR states to ensure success in developing qCISE system software?

Introduction: Quantum computing is based on the principles of quantum mechanics, which involve using quantum bits, or qubits, that can exist simultaneously in multiple states. It is necessary to design algorithms tailored explicitly to quantum computers' capabilities to develop quantum software. These algorithms fundamentally differ from classical algorithms in many aspects while also having some similarities. The development of such quantum algorithms will require new mathematical and computational techniques. While it is impossible to convert between these two-computing software, *i.e.*, classical and quantum computing, it is possible to design hybrid classical-quantum algorithms that combine the strengths of classical and quantum computing to solve specific problems more efficiently. These algorithms typically involve using classical computers to preprocess data and perform classical computations and then using quantum computers to perform detailed analyses that are more efficiently performed on quantum hardware. The downside to a hybrid algorithm is that it only sometimes converts between the two-computing software. Research efforts are necessary to solidify a solution to this conversion problem, but quantum hardware is still in the preliminary stages.

In years to come, qCISE System Software will continue to evolve, help evolve, helping advance the field of quantum computing as we know it. Developing system software that can efficiently run quantum algorithms on quantum computers is challenging. Currently, the qCISE software is still in the primitive, almost pre-assembly-language stage of development. Creating various libraries for software that can run on quantum computers is expected to contribute dramatically to developing quantum system software. Human capabilities are insufficient to deal with all the possibilities and functionalities of a quantum computer. Therefore, Machine Learning and Artificial Intelligence or AI-enabled software must be executed on quantum computers. Quantum compilers are essential for quantum computing as they translate classical algorithms into quantum circuits that can be performed on quantum computers. Existing quantum compilers cannot handle a higher-level Python-type code and run it in a quantum computer, so specialized quantum programming languages such as Q# and Quil are needed to create quantum circuits. Researchers are actively working to develop better compilers that can translate classical algorithms into quantum circuits with greater efficiency and accuracy.

In the following sections, a series of conclusions and recommendations based on the discussions from the NSF EPSCoR Workshop on Quantum Computing, Information, Science, and Engineering – System Software are summarized that include the ongoing research efforts of researchers in EPSCoR states, the open research problems that they are interested in pursuing, as well as their research-based needs to be successful in developing quantum system software.

Components of qCISE System Software: The qCISE system software should comprise several main components, each of which plays a vital role in quantum computing. The first component is the software stack for qCISE, which includes an application, intermediate representation, compilers, and a quantum computer. The application is responsible for defining the problem to be solved, while the intermediate representation serves as an abstraction layer between the application and the quantum computer. The compilers translate the code from the intermediate representation to the quantum computer's native language, allowing it to execute the problem efficiently. Another critical component of the qCISE system software is the hybrid-quantum-classical system. This system combines classical and quantum computing resources to solve optimization problems such as graph coloring, partition, and traveling salesman problems. The quantum approximate optimization algorithm (QAOA) is an example of a hybrid algorithm that can be used in this system. It uses quantum circuits to solve optimization problems by creating a superposition of workable solutions and measuring them to obtain the best solution. Moreover, the qCISE system software should also include quantum machine learning (QML) algorithms designed to solve clustering problems. Clustering is a typical unsupervised learning task in which data points are grouped into similar clusters. QML algorithms use quantum circuits to perform the clustering process, leveraging the power of quantum parallelism and superposition to speed up the computation. These algorithms have the potential to significantly enhance data analysis capabilities and improve pattern recognition in various fields, including finance, healthcare, and logistics.

Quantum Fourier Transforms, Throughput, Latency, Security, and Quantum Cryptography-related quantum system software have also attracted the research community’s interest. Qiskit defines Quantum Fourier Transforms as implementing the discrete Fourier transforms over the amplitudes of a wave function. Some examples of Quantum Fourier Transforms (QFT) include Shor’s algorithm (factoring more significant numbers) and Grover’s algorithm (searching an unstructured database). QFT can be essential for entanglement or state transfer in quantum system software. Qiskit can be used to implement the QFT on a quantum computer to prepare states for transmission over a quantum channel, including entangled states and superpositions. The QFT is a powerful tool in the realm of quantum communication. It can be used to prepare entangled states for use in quantum teleportation and superposition states for quantum key distribution. Qiskit provides tools for optimizing quantum circuits for specific hardware backends, which can help improve QFT-based communication protocols' performance. As quantum system software advances, the QFT and other quantum algorithms will play an increasingly vital role in developing new communication protocols and applications.

Quantum system software is critical in managing latency and optimizing performance in quantum communication networks. It manages the data flow between nodes, minimizes the time required for error correction and fault tolerance, and ensures that quantum channels operate at peak efficiency. To address these challenges, quantum system software must be carefully designed and optimized to minimize latency and maximize performance. Throughput is also essential while developing quantum system software, referring to the rate at which quantum information can be transmitted between nodes in a quantum-based network. Researchers and scientists are constantly developing new protocols and technologies that aim to optimize the transmission and processing of quantum information to improve throughput further. Quantum system software is critical in enhancing throughput by optimizing the routing of quantum information and providing efficient error correction and fault tolerance protocols. This requires high-level algorithms and protocols that can operate in real-time and with minimal latency while still providing elevated levels of reliability and security.

Quantum cryptography is a tool used in quantum system software, using the principles of quantum mechanics to transmit information over a network securely. To implement quantum cryptography, the system software must manage the transmission and reception of quantum information and perform the necessary error correction and post-processing to extract the secret key to encrypt and decrypt the communication. To address these challenges, researchers and developers are working to develop secure and robust system software for quantum cryptography, which involves a combination of hardware design, algorithm development, and software engineering, as well as careful testing and validation.

On the other hand, post-quantum cryptography is about using classical cryptographic and mathematical challenging problems to provide security against the attack of quantum computers. There are some algorithms that NIST has recommended for standardization and are supposed to be secure from quantum attacks. As per the migration roadmap given by the government, many efforts must be made to develop, implement, deploy, and integrate post-quantum cryptography in real-world applications. It also requires interdisciplinary effort to address secure and assured implementations. Although quantum computers with relevant power are not built to break the current security protocols, it is well-known that attackers can download encrypted data now and decrypt them in the future when they have access to such a cryptographically relevant quantum computer.

Much of quantum computers' promise is in quantum calculations on quantum data, which cannot be done on a classical computer. Another significant assurance partially realized is solving classical problems (e.g., optimization, factoring, search) much more efficiently than classical computers. This brings up the need for software that preprocesses classical data into a quantum state representation that can be used as inputs or initial states for quantum computing. One of the workshop discussions centered on the need for preprocessing software to efficiently (meaning using the fewest quantum states) represent medical images or medical DNA data for processing and classification on a quantum computer.

Classical Software versus Quantum Software: This section highlights the similarities and differences between classical and quantum software.

Similarities: Mapping circuits on architecture is essential for designing and implementing classical and quantum software. In classical computing, the mapping process involves selecting an optimal arrangement of logical gates to execute a program most efficiently. In quantum computing, this process involves mapping qubits onto physical qubits in a quantum device while preserving the desired gate operation. Quantum circuits are affected by several factors, such as connectivity constraints, limited qubit coherence time, and error rates, which require additional steps in the mapping process to ensure that the quantum circuit runs optimally on the quantum device. A critical aspect of quantum mapping is identifying the most efficient route between logical gates, considering the constraints of the physical architecture. In contrast, the classical mapping process has a more straightforward approach to routing, as the physical architecture of a classical computer is relatively simple. In quantum mapping processes, the latency constraints must be respected within the quantum circuits operations to guarantee their connectivity and smooth gate operations.

Sequence and circuit models are essential concepts in both classical and quantum software. In classical software, the sequence model refers to the execution of a series of instructions in a predefined order. In contrast, the sequence model in quantum computing refers to the ordered sequence of quantum gates applied to a set of qubits to perform a specific computation. The circuit model in quantum computing is similar to the classical circuit model, with each gate acting on one or more qubits. The hybrid quantum-classical model is also an essential concept in classical and quantum software, combining classical and quantum algorithms to solve complex problems that cannot be efficiently solved using classical methods alone. This model is commonly used in quantum machine learning, where classical algorithms are used to train quantum models, and quantum algorithms are used to perform predictions or classifications.

Digital annealing is a technique for solving optimization problems using a digital processor designed to simulate an annealing process as it occurs in nature. It is similar to classical and quantum computing in that it searches through many possible solutions to an optimization problem and finds the lowest-energy solution. Digital annealing is well-suited for issues that are too large for classical computing algorithms to solve but have yet to be practical for quantum computers, such as the traveling salesman problem, where the goal is to find the shortest possible route that visits several cities. It has also been applied to other optimization problems, such as clustering and graph partitioning, with promising results.

Differences: Classical computing and quantum computing differ in various aspects, such as the size and infrastructure required for quantum computing, the range of possibilities for information representation, the inherent randomness in quantum computing, and the compatibility among classical and quantum computing executed algorithms based on quantum sensor data. Classical computing is based on classical bits that can either be 0 or 1. In contrast, quantum computing uses quantum bits (qubits) that can represent many states simultaneously, giving rise to a much more comprehensive range of possibilities for information representation. Moreover, quantum sensors can provide data that can be fed into quantum computing executed algorithms, making it much more expensive to have a quantum computer in place than a classical one. These differences emphasize the importance of understanding the unique properties of quantum computing and its potential applications in various fields.

Challenges: One of the significant challenges when deciding between quantum and classical computation is to know which approach would be best suited. While, in general, every problem can be solved using a quantum computer, it would be very unwise due to the enormous costs of quantum computing. Many issues can efficiently or at least be translated to a desired degree of accuracy using classical computers. For others, it is known that the probability of obtaining suitable solutions using classical computation is exceptionally low, and at last, most problems lie somewhat between these two extremes. Hence, finding qualitative and quantitative measures to distinguish between these problems is essential and can save costs and computation time. Progress in this direction is expected to come from studying energy landscapes. Energy landscapes depict the features of optimization problems and can point to funnels (multiple or singular) that either complicate or ease a classical optimization process. They also give a quantitative measure of entropic barriers and insights into traps and have been linked to kinetic and thermodynamic features. As such, they are a valuable tool for statements about the complexity and difficulty of optimization tasks and can help save costs and effort.

Real-life Applications: In quantum and classical software, real-life applications can help solve complex problems more efficiently. The first significant application identified is the distribution of goods to homes. So classical software could be used to help optimize specific routes for delivery vehicles, which can minimize the distance traveled and help reduce fuel consumption, for example. For quantum algorithms, it can help optimize the same problem but on a larger scale with databases by solving complex optimization problems in polynomial time. Next, another real-life application is that of material simulation. Material simulation is used by quantum software to use quantum mechanics to model the behavior of atoms and molecules in which it can predict the properties of materials that are greater in strength, elasticity, and conductivity. This information can help develop new materials with specific properties, which can be used in various industries, such as aerospace, automotive, and electronics. Among the various real-life applications that attracted the participants' interest, great attention was given to applying quantum computing in finance. Specifically, quantum algorithms could help speed up financial-related simulations and operations, such as transactions, verification, authentication, *etc*. Moreover, quantum computing and quantum-based software can contribute to the optimization of portfolios and support complex financial derivatives. In parallel, quantum computing can improve the accuracy in predicting market trends and price changes of products, thus, helping investors make better-informed decisions.

Another real-life application is identified in the field of transportation. Both classical and quantum software could be used in the everyday activities of flight schedules and the problem of employee scheduling and vehicle routing related to the transportation field. The quantum software can help reduce travel time and cost, minimize the use of resources such as fuel and workforce, and can help improve overall efficiency across the board. Lastly, another real-life application identified is the use of quantum computing for drug and material discovery. Classical software can help predict these specific properties for drug and material properties, but using quantum computing can provide more accurate and detailed predictions by modeling certain behaviors of atoms and molecules at a certain quantum level. By exploiting the achievements in quantum and classical software, discovering certain new drugs and materials can be more effective and efficient than we currently have.

Open Research Problems: The field of classical and quantum software is rapidly developing, but many open research problems still need to be addressed. One of the challenges is error correction, as quantum computers are highly susceptible to errors due to environmental noise and other factors. Another critical research problem is the development of optimization solvers. Quantum machine learning (QML) is another crucial area of research in quantum software, and the challenge is to develop algorithms that can leverage the unique properties of quantum computing to solve machine learning problems more efficiently than classical computers. Data parallelism is also a key challenge in the field of quantum software. The development of quantum software requires the development of algorithms that can efficiently process enormous amounts of data in a distributed manner across multiple qubits. Cost efficiency and robustness are also essential considerations in developing quantum software. Quantum computers are still in their infancy, and the cost of building and maintaining them can be prohibitively high. It is essential to create algorithms that can efficiently use quantum resources while also being robust to environmental noise and other sources of error. Other open research problems in quantum software include the development of quantum intermediate representations, compatible and portable software between different quantum systems, and decomposing complex problems into multiple parts that can be fed into quantum computers for more efficient processing. Addressing these open research problems will be essential to unlocking the full potential of quantum computing for a wide range of applications.

qCISE System Software & Education: The quantum field is interdisciplinary amongst various fields of study. Not every Institution teaches the same basic computer programming classes at different schools of academia. Specifically, there is some commonality in which students take courses on Python, C, *etc*. Moreover, there needs to be a unified standard programming language between the various disciplines, especially when dealing with quantum computers. The students can substantially benefit by hosting coding training sessions among different departments at the same Institution or other Institutions, e.g., in the same state. Sessions like that would help teach students and professors to write scientific code and even handle various memory options. This can benefit other engineering departments across multiple institutions, especially if the students and professors must be exposed to coding. The training sessions could be implemented in a few ways, such as summer or online courses, to even having a specific GitHub to obtain more knowledge about code. Another topic of interest, focusing on computer programming, is converting from one programming platform to another.

A significant concern is that only a few institutions offer courses on quantum or a degree program in general. Most institutions provide a "flagship" degree; examples include Physics and Computer Science, and then a possible concentration in quantum. For instance, only a few universities offer these concentrations. While providing these courses and degree programs, professors must ensure those students have strong physics (quantum mechanics), linear algebra, probability, and computer science backgrounds. Quantum mechanics is the foundation of quantum science and provides the fundamental principles that govern quantum systems. Understanding quantum systems' behavior and the principles underlying quantum algorithms and protocols is challenging without a firm understanding. Linear algebra is essential for quantum computing, as it is used to formulate algorithms and implement quantum gates. A strong sense of linear algebra and probability is necessary to develop and understand quantum algorithms and protocols. Computer science is essential for understanding the principles of quantum computation, such as algorithms, error correction, and quantum information theory, as well as the practical tools for quantum computing, such as programming languages, simulators, and quantum hardware. A common trend observed in some universities to decrease the number of mathematics courses (e.g., eliminating linear algebra from the default "flagship" undergraduate programs or replacing the theory of probability or statistics with the data science courses) and computer science theory will negatively affect the foundational knowledge of students, their ability to join quantum computing workforce and advance the economic growth of the United States.

The quantum field can be studied in many disciplines, from physics to engineering. Most university students major in one sentence (maybe physics or even mathematics), then possibly have a concentration or minor in a field dealing with quantum. A good recommendation presented by the professors in this session is to have possible interdisciplinary courses or programs. This can include joint degree programs at an institution. For example, a potential joint degree combines physics and computer science, emphasizing quantum science. Besides having a joint degree program, specific courses can also be developed to help educate students or professors with an interdisciplinary background.

Internships in quantum can provide students with hands-on experience working on real-world quantum projects, exposure to industry and academia, mentorship opportunities, research opportunities, and a competitive advantage when seeking employment. These experiences can help students solidify concepts, apply them in a real-world context, build their professional network, develop critical thinking, problem-solving, and research skills, and stand out in a competitive job market. Industrial partners can provide students access to innovative hardware and software, joint projects, professional networks, and interdisciplinary collaboration opportunities to gain practical experience in quantum computing and quantum technologies. They can also serve as a communication channel between academia and industry, helping to bridge the gap between theoretical and practical applications of quantum. Structured collaboration, such as internships and joint projects, can help to accelerate the development and implementation of quantum technologies and foster a culture of innovation and collaboration. These opportunities can help students develop their skills and prepare for careers in quantum.

Infrastructure and Research-based Needs: For advancing research and development in quantum computing, information, science, and engineering, access to infrastructure is crucial. Infrastructure encompasses physical and technological resources, including laboratory facilities, equipment, and other computing resources. Quantum computing infrastructure is essential because the cost to operate is prohibitively high. The prohibitive cost of quantum computing is due to a few factors: **(a)** Quantum computing requires high-performance computing resources to run simulation tasks. In conducting some research, some companies have free access to specific modes, but most of the time, it is costly to run simulations for a long time; and **(b)** R&D is still early in the works to advance the quantum field. Due to it being in the initial stages, it requires a good amount of money to make crucial investments in quantum infrastructure.

The participants were left with a question of what some of the needs are, such as equipment, software, or other resources to help further their research on future NSF-funded projects. The following main findings and outcomes from this discussion are summarized below.

The need to have more five qubit systems to help further education and research purposes was identified. Through further research, IBM released a five qubit in 2016 which helped start manufacturing more qubit quantum computers. Researchers and students can free-test their quantum circuits through IBM's Quantum Platform. IBM states that this free platform best suits educators, new learners, and developers. This system can efficiently teach students about quantum computing principles, algorithms, and mechanics. It would benefit the EPSCOR researchers and students to access some larger (27-qubit or more) Quantum Platforms. Colleges and universities should advocate for their peers about implementing this free service into courses, lecture series, etc.

Next, the need and desire to develop courses and curricula between EPSCoR states were identified to bridge the gap between disciplines. Quantum brings in researchers from various fields, such as physics, computer science, and engineering. Every researcher is different, especially in what they know about quantum. Courses and curricula could be made available for students and researchers to understand the interdisciplinary nature of quantum computing, which can help develop the student’s skills and knowledge for the future. Institutions should come together and plan different curriculums instead of investing time and effort in isolated initiatives. This curriculum can be included in summer school or everyday online courses to which free access is granted to the public. Along with developing courses and curricula, an excellent recommendation would be to invite professional societies to their respective campuses. Professional organizations such as IEEE (Institute of Electrical and Electronics Engineers) to APS (American Physical Society) can bring various workshops and lecture series to help educate students on the distinct types of research areas of current or longstanding interest.

Lastly, collaboration with industrial partners is crucial for advancing quantum computing. However, legal challenges need to be overcome to collaborate with these partners. The NSF can facilitate this process by providing guidance and support to universities seeking to collaborate with industrial partners. This can help universities avoid legal challenges and streamline the collaboration process.

Curricula

Summary: The primary purpose of the qCISE Curricula breakout session was to discuss developing effective, sustainable, and efficient ways to structure and deliver a curriculum on quantum computing and quantum information science and engineering at the university level. The National Quantum Initiative Act 2019 stressed the importance of quantum research endeavors and training a quantum-ready workforce. In this workshop, researchers and administrators that contribute to the field of quantum computing and quantum information and engineering were brought together to discuss how they could collaborate and further scientific advancement. Three breakout sessions were held on the topic of qCISE curricula. Five challenges were identified, and solutions were debated among professors and administrators during each breakout session. A summary of the suggested recommendations is: **(a)** universities should collaborate, share software and hardware resources, and communicate regularly to leverage expertise; and **(b)** outreach programs should be developed to recruit new students and prepare current students for a quantum workforce.

Challenge 1: A sustainable curriculum is needed. Courses should be structured to be broadly accessible and train students for a quantum workforce. The curriculum should also be modular and updated as the field is further developed.

Challenge 2: Resources should be shared across the EPSCoR states to build a sustainable curriculum. A repository should be developed to hold shared resources and open courseware.

Challenge 3: Using the shared resources from the EPSCoR states, appropriate mandatory prerequisites should be defined for enrolling in a qCISE class. The classes should encompass electrical engineering, computer science, physics, and linear algebra topics that can enable students to complete the course assignments.

Challenge 4: Shared hardware, such as quantum computers, is expensive but requires the necessary investment. A collaborative effort is needed to fund shared hardware that universities in the EPSCoR states can share.

Challenge 5: Targeted Outreach Universities in the EPSCoR states should collaborate for outreach for potential students and learning opportunities for current students. Summer and winter programs should be developed alongside internship and research experiences for undergraduates.

Introduction: It is vital to develop a sustainable curriculum for qCISE. The curriculum should be accessible for newer students unfamiliar with qCISE concepts without becoming too elementary in its approach. The curriculum must serve as a gateway into the industry or academia should the student want to pursue a career in qCISE. Universities within the EPSCoR states should share resources and leverage their expertise to build a sustainable curriculum. Further collaboration should be done to set up outreach for potential students and individuals in the industry to contribute towards building a comprehensive and viable qCISE program. The discussion below explores these challenges further in depth to provide insight into why the challenges exist and what possible steps can be taken to address these challenges.

The Importance of Building a Sustainable Curriculum: Building a sustainable curriculum in the qCISE academic field is vital to further scientific advancement. The qCISE field pulls much knowledge from disparate fields such as electrical engineering, computer science, physics, mathematics, etc. Building a sustainable curriculum means a transdisciplinary collaboration between universities and departments within their respective universities. A sustainable curriculum also means a constant flow of new and graduating students hired into the industry. There must be an outreach to attract new students and collaboration with the industry to fill jobs with graduating students. Funding a qCISE program also needs to be considered in building sustainability.

It was repeatedly mentioned that many students needed to be adequately prepared for courses in quantum computing. Depending on their academic background, students take classes from various departments that only sometimes possess the traditionally expected understanding of quantum mechanics or computer science for qCISE. Much thought is needed to determine the appropriate prerequisites for a qCISE course. It was noted that many professors in attendance only required linear algebra as a prerequisite for their course. A consensus was reached that linear algebra was the most crucial class before course enrollment, no matter what degree plan a student pursues. Students can benefit from a basic grasp of coding and critical concepts in quantum mechanics, such as superposition, so computer science and high-level physics were also recommended to be taken before enrollment in quantum computing or quantum information course. However, these requirements seemed limited to some who felt a qCISE course should be interdisciplinary and broadly accessible. At all levels, courses should be structured so students can learn the material without being drowned in dense quantum mechanics theory.

Students from many diverse backgrounds have an interest in taking a qCISE class. They also have different motivations for taking such a course. It was suggested that a course could have a two-part structure to address this variation. The first half of the course can be focused on core theoretical topics. The second half of the course could be focused on research and presentation. This method allows students from a variety of backgrounds to both learn the necessary material and get what they need from the course through individual study. It was agreed that this course delivery method allowed students to understand what they wanted while reinforcing a unified understanding of quantum-related material. Different populations can be served with a flexible course design. It was generally thought that, rather than one model, we should aim for the blooming of a hundred flowers while sharing experiences among ourselves.

Building a Library of Shared Resources: Building a sustainable curriculum and qCISE program would greatly benefit from universities' collaboration and sharing of their resources. The shared resources should include ideas about how to structure the courses, the best textbooks to teach out of, links to simulations, python notebooks, and more. The method of putting this together was proposed to be done through GitHub. The GitHub would be accessed by professors that wish to contribute.

Many textbooks on quantum mechanics and its various applications within the STEM field exist. Not all texts are suitable for all course designs, and finding a text that fits the proposed course can be difficult. Some textbooks needed more detail, while others needed to be less dense. A shared resource for courseware would allow professors to upload their thoughts on textbooks they have read and provide insight on which textbook would be the best to teach.

Simulations are an excellent way for students to visualize the behavior of atoms and wave functions. Many simulations are available online and can be implemented into the course to show students examples of various concepts. In the shared GitHub, professors could upload links to different simulations. Python notebooks could also be uploaded, allowing a collaborative effort to update code and build new simulations. This would contribute to helping students build up necessary coding skills as they could mess with the code and simulations as a course assignment.

Another contribution that could be made in the shared repository is open courseware. Links to YouTube videos, lectures, slide presentations, and syllabi could be uploaded. This would give professors teaching CISE-related course material to help build their course. This would help foster a collective and efficient method of developing a sustainable qCISE program. This would also encourage communication across multiple universities within the EPSCoR states. Shared courseware would be beneficial to developing better courses and quickly correcting deficiencies in how qCISE courses are taught in the present.

Funding Shared Hardware: Quantum computers are costly. Commercial quantum computers like D-Wave 2000Q with 2000 qubits costs $15M. Universities in the EPSCoR states need funding to purchase one of these computers. Many of these computers support free or inexpensive cloud access for education, but the service is highly subscribed, and many educators felt the strain made classroom use impractical. It was proposed that universities participating in the workshop pool their funding and purchase shared hardware. This would allow the universities to conduct necessary qCISE research and provide dedicated educational opportunities. This would also allow opportunities for students to engage in research as well. Alternatively, universities could use other quantum hardware, like Nuclear Magnetic Resonance (NMR) machines or two-qubit computers, which are much more affordable options, or fund dedicated computing time for education in EPSCoR states. These alternative avenues to accessing equipment would only allow for little research but could be used for students to acquire hands-on abilities.

Outreach: To build a sustainable curriculum, we must maintain a relatively stable stream of students entering the program. There must be classes for the students to enroll in and teachers for the courses. It would be beneficial if individuals from industry could collaborate with the universities to provide research opportunities and funding for the program. There should be opportunities for undergraduate students to partake in research and internships to gain valuable work experiences. Research opportunities for graduate students should also be available if the student wishes to pursue a career in academia. Industrial representatives emphasized that traditional strengths, such as good communication and basic engineering/science abilities, remain the most important; however, some acquaintance with a QISE curriculum would make a candidate stand out. Much discussion was devoted to accomplishing proper outreach for the qCISE field within the EPSCoR states. It was discussed that summer or winter schools could be set up for K-12 and college students interested in furthering their education on qCISE topics. These programs between semesters could provide students with critical skills desired in both industry and their academic careers. Skills, such as coding and basic quantum theory, could be taught to program attendees at multiple levels of understanding. More elementary explanations could be provided for students in K-12 with an emphasis on hands-on experience. Research experience for undergraduates would also be a possibility. This would give the necessary experience to students wishing to further their academic careers and provide much-needed help in cutting-edge research to the National Science Foundation. Another critical aspect of building a sustainable qCISE program requires collaboration and outreach to the industry. The industry could fund research projects and summer or winter programs for future and current students. This is necessary for the universities to build up their programs. Internships and co-ops could be provided to give students essential work experience. This would also work for the industry in filling jobs that need to be filled with employees that have experience with qCISE topics.

Appendix I

Workshop Schedule

Day 1 (Full-Day)

Time	Event	Room
08:00–08:20	Meet and Greet	2030
8:20–8:30	Workshop Genesis, Logistics & Expectations	2030
8:30–8:40	Welcome by Section Head EPSCoR • Sandra Richardson	2030
8:40–9:10	Remarks by NSF Assistant Directors • Sean L. Jones – MPS (slides) • Susan S. Margulies – ENG (slides) • Margaret Martonosi – CISE (slides)	2030
9:10–10:00	Academic Panel (Samee U. Khan (moderator) | Lashaunda Bobbett (scribe)) • Susan Atlas – University of New Mexico • Christian Binek – University of Nebraska at Lincoln • Nicholas Borys – Montana State University • Madalina Furis – University of Oklahoma	2030
10:00–10:30	Break and Social	
10:30–12:30	Parallel Breakout Sessions • EPSCoR Capabilities, Challenges, and Opportunities (Erik K. Hobbie (moderator) | Rebecca Garcia (scribe)) • NISQ Hardware Enablement (Mark A. Novotny (moderator) | Kenzie Ellenberger (scribe)) • qCISE Application Enablement (Margaret Kim (moderator) | Bhavika Bhalgamiya (scribe)) • qCISE System Software (Eirini E. Tsiropoulou (moderator) | Hunter Harris (scribe)) • qCISE Curricula (Elizabeth Behrman (moderator) | Matthew Beach (scribe))	2240 2190 2180 2170 2160
12:30–13:40	Lunch Break (On your own)	
13:40–14:00	Session Readouts by Moderators (3 minutes; initial observations)	2030
14:00–16:00	Parallel Breakout Sessions • EPSCoR Capabilities, Challenges, and Opportunities (Erik K. Hobbie (moderator) | Rebecca Garcia (scribe)) • NISQ Hardware Enablement (Mark A. Novotny (moderator) | Kenzie Ellenberger (scribe)) • qCISE Application Enablement (Margaret Kim (moderator) | Bhavika Bhalgamiya (scribe)) • qCISE System Software (Eirini E. Tsiropoulou (moderator) | Hunter Harris (scribe)) • qCISE Curricula (Elizabeth Behrman (moderator) | Matthew Beach (scribe))	2240 2190 2180 2170 2160
16:10–17:00	Industry Panel (Samee U. Khan (moderator) | Lashaunda Bobbett (scribe)) • Reza Azarderakhsh – PQSecure and Florida Atlantic U. • Alex Condello – D-Wave • David Steuerman – IonQ • Alex Tingle – ColdQuanta | Infleqtion	2030

Day 2 (Half-Day)

Time	Event	Room
08:00–08:20	Session Readouts by Moderators (3 minutes; refined observations)	2030
08:30–09:30	Parallel Breakout Sessions • EPSCoR Capabilities, Challenges, and Opportunities (Erik K. Hobbie (moderator) | Rebecca Garcia (scribe)) • NISQ Hardware Enablement (Mark A. Novotny (moderator) | Kenzie Ellenberger (scribe)) • qCISE Application Enablement (Margaret Kim (moderator) | Bhavika Bhalgamiya (scribe)) • qCISE System Software (Eirini E. Tsiropoulou (moderator) | Hunter Harris (scribe)) • qCISE Curricula (Elizabeth Behrman (moderator) | Matthew Beach (scribe))	2240 2190 2180 2170 2160
09:30–10:00	Break and Social	
10:00–10:50	Government Panel (Samee U. Khan (moderator) | Lashaunda Bobbett (scribe)) • Lucas Brady – NASA • Alexander Cronin – NSF • Andrew Schwartz – DOE • Phil Smith – Argonne National Lab; Q-NEXT • Mukund Vengalattore – DARPA	2030
11:00–11:30	Session Readouts by Moderators (5 minutes; take-home message)	2030
11:30–12:00	Open Microphone	2030
12:00-12:05	Closing Remarks by Organizers	2030

Appendix II

List of NSF Workshop Participants March 23–24, 2023

Name	Affiliation
Alexander Zaslavsky	Brown University
Bakhtiyor Rasulev	North Dakota State University
Chandrasekhar Ramanathan	Dartmouth College
Daniel Sheehy	Louisiana State University
Daniel Takaki	University of Kansas
Denis Candido	University of Iowa
Elizabeth Behrman	Wichita State University
Erik Hobbie	North Dakota State University
Evangelos Miliordos	Auburn University
Fei Xue	University of Alabama at Birmingham
James Steck	Wichita State University
Jifa Tian	University of Wyoming
Jinjun Liu	University of Louisville
Khoa Luu	University of Arkansas
Lu Peng	Tulane University
Mark Ku	University of Delaware
Matthew Panthani	Iowa State University
Qing Shao	University of Kentucky
Qiang Huang	University of Alabama
Ravitej Uppu	University of Iowa
Seongsin Kim	University of Alabama
Timur Tscherbul	University of Nevada – Reno
Tudor Stanescu	West Virginia University
Vesna Mitrovic	Brown University
Wenchao Ge	University of Rhode Island
William Gannon	University of Kentucky
Yan Zhou	University of Nevada – Las Vegas
Yanwen Wu	University of South Carolina
Yaroslaw Bazaliy	University of South Carolina
Yen Loh	University of North Dakota
Yuriy Pershin	University of South Carolina
Wenli Bi	University of Alabama at Birmingham
Anton Vorontsov	Montana State University
Yongki Choi	North Dakota State University
Katja Biswas	University of Southern Mississippi
Eirini Tsiropoulou	University of New Mexico
Shawna Hollen	University of New Hampshire
Christian Binek	University of Nebraska at Lincoln
Susan Atlas	University of New Mexico
Nicholas Borys	Montana State University
Madalina Furis	The University of Oklahoma
Bernard Zygelman	University of Nevada – Las Vegas
Ilya Safro	University of Delaware

Government Attendees	
Name	**Affiliation**
Lucas Brady	NASA
Mukund Vengalattore	DARPA
Andrew Schwartz	DOE
Raju Namburu	USACE Army
Corey Trahan	USACE-ERDC
Ruth Cheng	US Army ERDC/ITL
Phil Smith	Argonne National Lab; Q-NEXT
Geetha Senthil	NIH

Industrial Attendees	
Name	**Affiliation**
Alex Tingle	ColdQuanta | Infleqtion
Reza Azarderakhsh	PQSecure and Florida Atlantic U
Alexander Condello	D-Wave
David Steuerman	IonQ

Observers	
Name	**Affiliation**
Vipin Chaudhary	Case Western Reserve University
Qiang Guan	Kent State University
Shuai Xu	Case Western Reserve University
Giselle Munn	Mississippi State University
Ali Gurbuz	Mississippi State University
Amin Amirlatifi	Mississippi State University
Gautam Moong	Mississippi State University

NSF Attendees	
Name	**Affiliation**
Pinhas Ben-Tzvi	EPSCoR
Alexander Cronin	PHY
Matthew McCune	ECCS

Organizing Committee	
Name	**Affiliation**
Samee Khan	Mississippi State University
Mark Novotny	Mississippi State University
Rebecca Garcia	Mississippi State University
Kenzie Ellenberger	Mississippi State University
Bhavika Bhalgamiya	Mississippi State University
Hunter Harris	Mississippi State University
Matthew Beach	Mississippi State University
Lashaunda Bobbett	Mississippi State University

Appendix III

List of NSF Workshop Organizers & Advisory Board March 23rd – March 24th, 2023

Organizers	
Samee U. Khan	Department of Electrical & Computer Engineering, Mississippi State University
Mark A. Novotny	Department of Physics and Astronomy, Mississippi State University

Advisory Board	
Name	**Institution/Organization**
Laura Thomas	ColdQuanta | Infleqtion
Bernard Zygelman	U. of Nevada – Las Vegas
Ilya Safro	U. of Delaware
Alberto Marino	U. of Oklahoma and Oak Ridge National Laboratory
Heeralal Janwa	U. of Puerto Rico
Irene Qualters	Los Alamos National Lab
Lan (Samantha) Li	Boise State University
Christian Binek	U. of Nebraska, Lincoln
Layla Hormozi	Brookhaven National Lab