Catalyzing Industry-University Collaboration in Quantum Technologies

WORKSHOP REPORT

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Catalyzing Industry-University Collaboration in Quantum Technologies
March 14-15, 2018 Workshop Report

Institute for Creative Technologies
University of Southern California
Los Angeles, California

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Purpose of this Workshop

The NSF has identified *Quantum Leap* as a national priority through its *Big Ideas Initiative* and provided financial support to the UIDP to convene a strategic set of corporate leaders (complemented by academic, government, and other representatives) to determine the need and interest in supporting industry-inspired, academically-engaged research centers through substantive investments from both the corporate and government sectors. The goal of creating one or more industry-university collaborative research centers would be to bolster the country's standing in this broad area of quantum leap (communications - computing - materials - sensing) by identifying the strength of funding commitments from interested industrial organizations to invest in the use-inspired research roadmap we seek to create through this workshop.

The workshop's goal was to determine what type of industry-inspired, industry-initiated academic research consortia will help U.S. industry maintain and enhance its global leadership and competitive position in application areas involving quantum science and technologies and serve the commercial needs of companies that would participate and invest in such consortia.

This report summarizes the key insights and is not intended to be a detailed record of the entire proceedings. We encourage you to share this document with interested parties.

Executive Summary

University and industry representatives expressed high interest in the current state of the art and potential for quantum technologies under two broad groups. The first includes *industry developers* of quantum technologies, dominated by information technology companies such as Google, IBM, Intel, and Microsoft, as well as a set of smaller startup companies. These companies have large and active groups researching and developing core quantum technologies for quantum bits (qubits) that span qubit representations based on a range of physics models through programming models to applications. These companies are also forming strategic partnerships with academic institutions (both inside and outside the U.S.) to achieve their business goals. Within this group, there are opportunities to partner with government agencies to support larger scale efforts (and subsequent financial commitments) using existing vehicles such as jointly issued solicitations where both government and industry co-fund programs that academic (as well as others, such as national labs) researchers can earn.

The second large group consisted of potential quantum technology *users* spanning aerospace and defense, vehicles and transportation, pharmaceuticals and health care, logistics and supply chain management, and a diverse set of science and engineering domains. Many of these can be best characterized as "watching intently and waiting expectantly." Members of this group are not investing substantially in research or development but recognize that quantum technologies could either provide competitive advantage if they were early adopters or disruptions for business models currently predicated on traditional computing and communication technologies. Most members of this category expressed limited willingness to invest significant resources until quantum technologies were more mature; however, some company representatives were willing to consider an investment of modest resources for collaborative efforts provided through mechanisms such as the NSF Industry-University Cooperative Research Centers program.

University researchers are pursuing many of these same goals in collaboration with industry partners. An analysis[i] of global publications shows that there is a higher level of academic-corporate collaboration between U.S. universities and major U.S. companies than that found globally. For example, the data showed that over ninety percent (90%) of all papers Google co-authors and over eighty percent (80%) of papers that IBM and Microsoft author have at least one academic co-author. Generally, quantum technology research is both international and highly competitive, with high quality research being conducted worldwide supported primarily by government investments, notably in China and the European Union.

Quantum computers open possibilities that have little equivalent in classical simulation.[ii] Since 2012, venture capital funds have invested over $334 million into companies specializing in quantum computing.[iii] Globally, the market for quantum computing and technologies is expected to grow at a compound annual growth rate (CAGR) of 24.6% through 2024, when the products and services market would reach $8.45 billion.[iv] More than twenty countries are currently competing in the quantum space[v], with Chinese and European countries receiving significant government assistance. The European Commission is pursuing a $1.13 billion quantum technologies strategic plan, while China has invested $10 billion into its National Laboratory for Quantum Information Sciences.[vi]

State of the Art

The workshop participants quickly acknowledged that although quantum technologies are often viewed as synonymous with quantum computing, they encompass a much wider range including quantum sensing and measurement, communication, and cryptography. In addition, several technology areas are nearer to commercialization and deployment. The state of the art varies substantially across use areas, with quantum sensing and communication having already been demonstrated and entering commercial deployment.

Several alternative hardware approaches to quantum computing are currently being explored, with regular press reports trumpeting impending quantum supremacy[vii] (i.e., the crossover point where quantum computing solves a problem beyond the practical reach of traditional computing). However, much work remains before reliable quantum computing systems can be built and demonstrated. Current systems are both unreliable and subject to decoherence via environmental interactions. Error correction and scaling are active areas of research and development. In quantum error correction, many physical qubits are required to represent a single logical qubit suitable for application programming, which increases the number of qubits required for a viable quantum computer. These challenges are further

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[i] Calto, Daniel. *Quantum Computing Report.* Elsevier. March 20, 2018.
[ii] Ho, A., McClean J., and Ong, S.P. *The Promise and Challenges of Quantum Computing for Energy Storage.* Joule, Volume 2. Page 810.
[iii] Deans, D. *How quantum computing technology apps are gaining momentum.* Cloud Computing News, November 3, 2017. https://www.cloudcomputing-news.net/news/2017/nov/03/quantum-computing-technology-apps-gain-momentum/.
[iv] Bajpai, P. *Quantum Computing: What It Is, And Who The Major Players Are.* Nasdaq, March 26, 2018. https://www.nasdaq.com/article/quantum-computing-what-it-is-and-who-the-major-players-are-cm939998.
[v] Herman, Arthur. *Winning the Race in Quantum Computing.* American Affairs Journal, Volume II, Number 2. https://americanaffairsjournal.org/2018/05/winning-the-race-in-quantum-computing/.
[vi] Segal, Adam. *The Quantum Race the United States Can't Afford to Lose.* Council on Foreign Relations, April 18, 2018. https://www.cfr.org/blog/quantum-race-united-states-cant-afford-lose.
[vii] Mohseni, M., Read, P., and Neven, H. *Commercialize early quantum technologies.* Nature, Volume 543. Pages 171-174.

exacerbated by the cooling and power management designs required to interface a quantum computer to a traditional computing system.

Challenges and Opportunities

All workshop participants expressed excitement regarding the future of quantum technologies, though all were equally cognizant of the technical, organizational, social, and financial challenges inherent in developing and accelerating quantum technology development. University and industry representatives identified several distinct, though complementary, challenges. Most agreed that the highly interdisciplinary nature of quantum technology research would benefit from inclusion of quantum technology concepts in standard science and engineering curricula. This absence limits the available workforce, both in academia and industry.

Challenges

- *Startup and operating costs for quantum technology laboratories.* The high costs of experimental infrastructure are a high barrier to entry for new participants. This favors well-funded, extant laboratories when seeking new funds and limits educational opportunities.
- *Recruiting and sustaining multidisciplinary teams.* By its nature, quantum technologies research requires multidisciplinary research and development teams, which may be difficult to recruit and sustain.
- *Facilitating foreign national access and employment.* International students dominate many science, technology, engineering, and math (STEM) graduate programs, but technology access restrictions limit their opportunities for participation in quantum research and development programs.
- *Enabling technology availability.* Quantum experimentation depends on the availability of supporting technologies (e.g., cryogenic coolers), several of which have limited commercial demand. Like all nascent technologies, quantum depends on the development and nurturing of the entire technology ecosystem.
- *Supporting industry-academic partnerships.* All participants agree that building and enhancing partnerships that exploit what academic and industry partners do best was crucial to quantum technology development. Many noted the common barriers to such collaborations (e.g., intellectual property, personnel movement, and proprietary data protection).
- *Ensuring U.S. preeminence.* Given the potentially transformative potential of quantum technologies – communications, cryptography, sensing, and computing – the national security and economic competitiveness risks from loss of U.S. preeminence in computing and communication technologies are deep and profound. The U.S. government needs to begin defining appropriate rules (e.g., International Traffic in Arms Regulations) for those technologies deemed crucial and allow companies freedom to operate in other quantum areas.
- *Aligning market incentives.* Most companies are currently unwilling to invest at substantial levels until competitive advantage on business problems is clearer because of the relatively long time horizon and uncertainties surrounding quantum technologies. In a post-event survey, few attendees expressed a time horizon beyond five (5) years. Companies were overwhelmingly interested in supporting use-inspired research projects as expressed in Pasteur's quadrant (Figure 1) and which have immediate use for society. Information technology companies are an exception to this hesitancy.

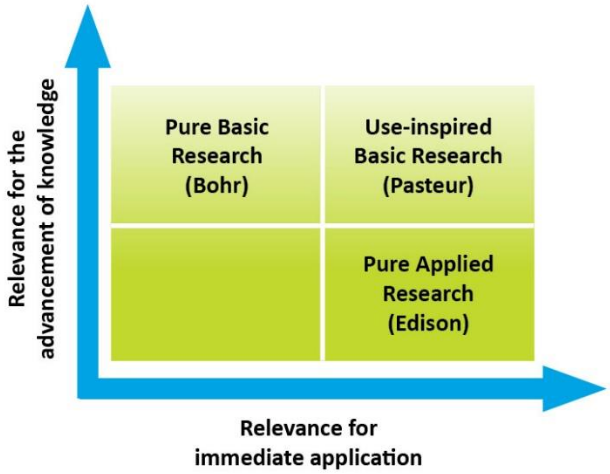


Figure 1. Pasteur's Quadrant[viii]

Opportunities

- *Deepening the talent pipeline.* Although publication data suggests strong university-industry partnerships, it is important to deepen the talent pipeline and broaden understanding of quantum approaches to classical technologies within industry. This would lead to more quality proposals/partnerships among industry, academia, and government.
- *Coevolution of technology and applications.* There is a need to broaden the understanding of the opportunities and benefits quantum technologies offer compared to classical approaches into the user and application community. Greater insight into application mapping to quantum devices would inform technology development. Similarly, broader understanding and education on quantum capabilities would inform application exploration.
- *Accelerating quantum communication and sensing.* Quantum sensing and communication technologies are more mature than quantum computing, with near term opportunities to accelerate their deployment and commercialization and leverage academic-corporate partnerships.
- *Expanding materials science research.* Given its dependence on materials properties, greater exploration of materials properties (purity, defects, and properties) for quantum device fabrication would advance quantum device testing and prototyping.
- *Enhancing government incentives and support.* Drawing on lessons learned from domestic and international collaboration projects and mechanisms, there was unanimous agreement that government can, and must, play a critical role in supporting basic research in quantum technologies and in facilitating academic-industry collaborations.

Recommendations and Next Steps

There was no clear consensus among academic and industry participants on a single next step; this could be partly due to the broad and diverse interests of the companies represented at the event. Advances are required in many domains, including materials science, reliability and resilience, classical support

[viii] Stokes DE. Pasteur's Quadrant. Basic science and technological innovation. Brookings Institute 1997.

technologies, programming models, and application mapping and development. This suggests the need for greater coordination and a need to point towards government facilitation towards the efficient use of resources in a wide range of enabling physical science and information technology research via a combination of individual investigator and center-based support.

The breadth of quantum technologies research challenges and the nascent state of many quantum technologies led several industry participants to question the near-term business value of the government-sponsored partnership models that have been applied in other domains. The five- to 10-year return on investment (ROI) horizon for quantum technologies is too far for most companies to invest heavily, or even for non-IT companies to invest in modestly. Others suggested that the level of some programs (such as the NSF I/UCRC program) is too low to advance the field substantially, particularly when potential applications are still so poorly understood.

There was broad agreement on the need for easy and inexpensive ways for industry to participate and monitor research progress (e.g. industry days or webinars) before pursuing NSF Grant Opportunities for Academic Liaison with Industry (GOALI), Partnerships for Innovation (PFI), or I/UCRC mechanisms. Likewise, there must be other mechanisms via which industry can suggest application challenges for NSF academic investment, such as responding to the NSF Emerging Frontiers in Research and Innovation. Another example is joint solicitation; the NSF Computer and Informational Science and Engineering Directorate has jointly issued solicitations with companies (or groups of companies) where academic researchers can apply for these joint funds using the NSF grant mechanism.

Others suggested the need for a Semiconductor Manufacturing Technology (SEMATECH) model as a non-profit industry-government consortium because of the national security implications of quantum technologies, where members could participate at differing levels. Others raised the important role of the Department of Energy's national laboratories as integrative research and development hubs for developing technologies, citing laboratory work on renewable energy as an example.

Despite widely varying perspectives, the belief that the U.S. government must play a greater role than at present, as a facilitator, convener, and funder, was unanimous. As is the case in the defense industry, the government is also a purchaser or consumer of products using technology funded through applied research. Recommendations included:

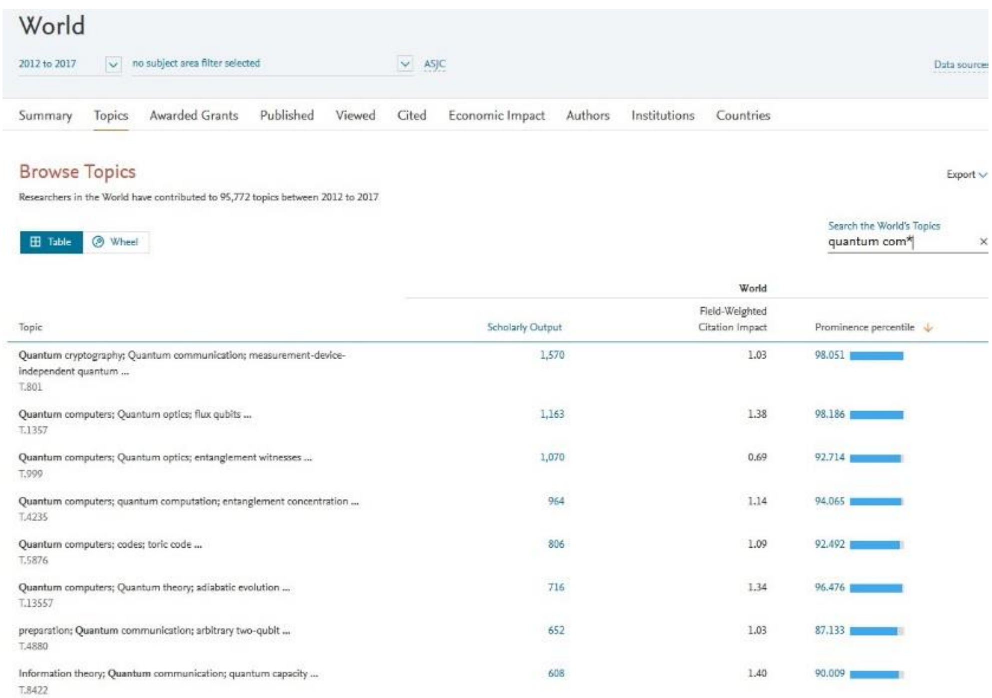
- Government funding for integrative academic research centers whether through existing or newly created grant mechanisms
- Broader informal and formal education and curriculum development on quantum technologies
- Ensuring testbed availability for experimentation
- Exploration of flexible university-industry collaboration models, including:
    - Education on quantum capabilities to industry, especially non-IT companies that will be future users
    - Problem matching to investment levels
    - Development of quantum-inspired algorithms for classical problems
    - Flexible investment models for multiple participation levels (technical and strategic)
    - Encouraging both technical and strategic university-industry collaborations

Broadly, there was substantive discussion surrounding the need for a technology and applications readiness roadmap to help shape and identify promising areas and mechanisms for public and private investment, on multiple time scales:

- *Near-term.* Targeting technologies (e.g., quantum sensors) at or near commercial readiness, where targeted corporate investments and university startups could transition ideas to practice.
- *Medium-term*. Identifying ideas and approaches where university-industry partnerships on a three- to five-year timeline could bring ideas to the near-term, enabled by strategic roadmaps.
- *Long-term*. Investing government resources to build basic research knowledge, coupled with strategic investments by information technology companies.

Varying Perspectives - Global Quantum Landscape

Elsevier provided an overview[ix] of the current quantum technologies landscape using publicly available information and their data analytics tools. Using the Topics of Prominence modeling technique as described in the presentation[x] [xi] [xii], Elsevier looked at quantum computing as a component of the larger field of quantum technologies. The quantum computing field was aggregated via keywords linked to a larger computer science ontology; it did not come directly from the topical model itself and was a "constructed" topic. Thus, the broader quantum computing topic lacks the precision of topics coming from the model itself. Actual topics coming directly from the model can be seen below:


World

2012 to 2017 | no subject area filter selected | ASJC | Data source

Summary | Topics | Awarded Grants | Published | Viewed | Cited | Economic Impact | Authors | Institutions | Countries

Browse Topics

Researchers in the World have contributed to 95,772 topics between 2012 to 2017

Table | Wheel

Search the World's Topics: quantum com*

Export

Topic	World: Scholarly Output	Field-Weighted Citation Impact	Prominence percentile
Quantum cryptography; Quantum communication; measurement-device-independent quantum ... T.801	1,570	1.03	98.051
Quantum computers; Quantum optics; flux qubits ... T.1357	1,163	1.38	98.186
Quantum computers; Quantum optics; entanglement witnesses ... T.999	1,070	0.69	92.714
Quantum computers; quantum computation; entanglement concentration ... T.4235	964	1.14	94.065
Quantum computers; codes; toric code ... T.5876	806	1.09	92.492
Quantum computers; Quantum theory; adiabatic evolution ... T.13557	716	1.34	96.476
preparation; Quantum communication; arbitrary two-qubit ... T.4880	652	1.03	87.133
Information theory; Quantum communication; quantum capacity ... T.8422	608	1.40	90.009

A number of key conclusions about the state of quantum computing in the U.S. vs. globally can be drawn from the analysis. For example, there is a higher level of academic-corporate between U.S. universities

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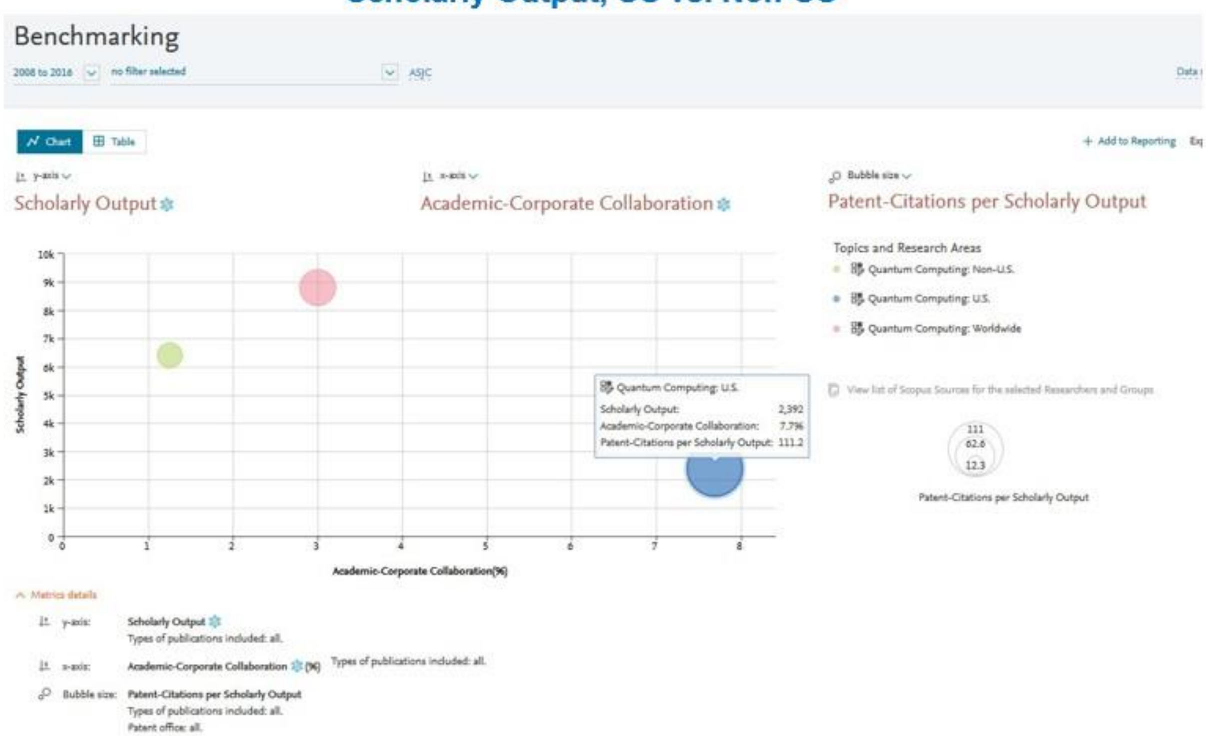
[ix] Calto, Daniel. *Quantum Computing Report.* Elsevier. March 20, 2018.
[x] Klavans, R. and Boyack, K.W. *Which Type of Citation Analysis Generates the Most Accurate Taxonomy of Scientific and Technical Knowledge?* Journal of the Association for Information Science and Technology, 68(4):984–998, 2017.
[xi] Klavans, R., & Boyack, K. W. (2017). *Research portfolio analysis and topic prominence.* Journal of Informetrics, Volume 11, Issue 4, November 2017, Pages 1158-1174.
[xii] Boyack, K.W. and R. Klavans, R. *Creation and analysis of large-scale bibliometric networks*. Springer Handbook of Science and Technology Indicators, 2018 (to appear).

and major U.S. corporations than the level of academic-corporate collaboration found globally. Quantum computing is a competitive field, with high-impact research being done globally with significant financial resources being dedicated to researching the field.

The graph below shows total scholarly output from 2012-2017 in quantum computing, totaling about 10,000 papers (including conference proceedings) globally with around 2,700 papers from the U.S. The x-axis represents the percentage of university-industry collaboration: 7.7% for the U.S., only 1.2% for the rest of the world. The size of the bubble indicates how often these papers were cited in worldwide patenting activity—111 papers per thousand in the U.S., or over 11% of all papers and conference proceedings written, vs. 21 papers per thousand for the rest of the world—a ratio of over 5:1. When measured by overall field-weighted citation impacts, the U.S. also stands out from the rest of the world in quality terms, with around 30% of U.S. papers among the top 10% cited worldwide, versus 15% for non-U.S. papers (top 10% among all fields and all papers published).

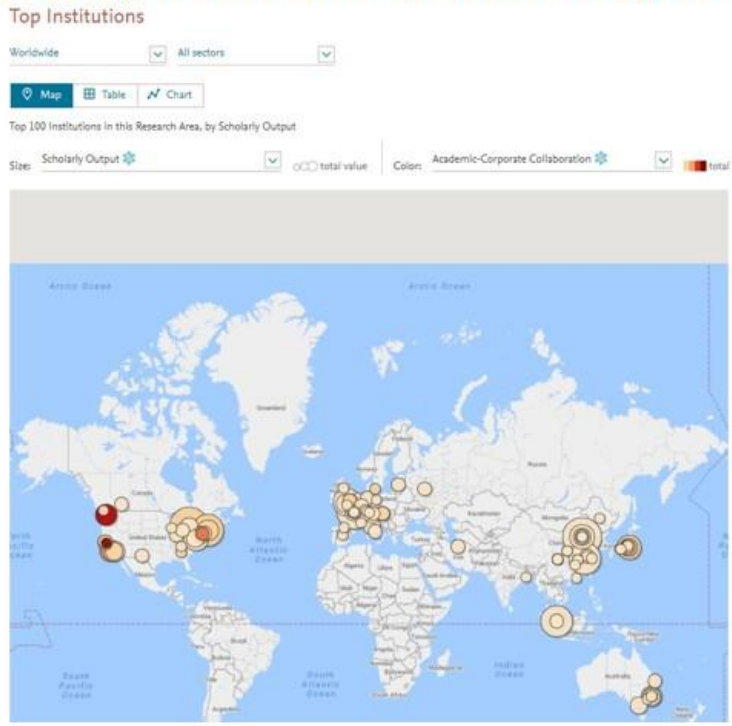
Major U.S. corporations, including Google, Microsoft, IBM, and Intel, are deeply embedded in the research network for quantum computing technologies in a way that other global firms are not. Over ninety percent (90%) of all papers Google co-authors and over eighty percent (80%) of papers that IBM and Microsoft author have at least one academic co-author. These papers are often very highly cited. In addition, national laboratories and U.S. funding agencies are an important contributor to overall output.

Quantum Computing: Academic-Corporate Collaboration and Patent Citations per Scholarly Output, US vs. Non-US



Papers are credited to the headquarters location for each corporation in the model, regardless of the sponsoring R&D location. Actual academic co-authors for major U.S. firms are overwhelmingly U.S. institutions. The top fifteen collaborators for Google, for example, are all U.S. institutions. Only one non-U.S. university, ETH Zurich, is among the top twenty. Competing firms, including Google, IBM, and Microsoft, are frequent co-authors (among the top 20 collaborators for each company). In the geomap below, the color intensity represents the level of academic-corporate collaboration, with the size of the bubble being the number of QC publications. The dark red dots represent U.S. tech companies. U.S. universities also have far higher levels of academic-corporate collaboration than the others. Europe and Asia are pale in comparison, but one or two Japanese firms also have a fairly high level of collaboration.

Quantum Computing Research Worldwide--Academic-Corporate Collaboration



The analysis demonstrates that the U.S. quantum computing landscape differs in fundamental ways from the remainder of the world leading to strong and potentially positive implications for U.S. primacy in quantum computing and quantum technologies. The integrated combination of corporations, universities, national labs, and funding agencies in the U.S. may allow for the simultaneous pursuit of productive fundamental research of the highest quality, while working on solving practical problems in Pasteur's quadrant and bringing promising technologies to market.

Given the implications for cryptography and national security in quantum computing, and its potential importance to innovations of a wide variety, the U.S. government should evaluate being more deeply involved in support for quantum computing than is usual for new technologies, along the lines of the SEMATECH collaboration. The NSF, Department of Energy (DOE), and others may be able to function effectively as a broker between the fundamental and applied research being done in the academic community with the commercial needs and uses of the corporate community, perhaps using existing programs and vehicles to help different kinds of entities to connect.

As a significant contributor to federal R&D, the Department of Defense (DOD) is vitally important to funding support for certain aspects of these technologies. Any increased level of involvement by the DOD and other US funding agencies will need to be balanced with the need to preserve an open research environment internationally, share findings, accelerate quantum computing research, and transform research findings into new technologies, products, and services of benefit to all.

China is currently pursuing quantum technologies with substantial financial resources and broad research efforts, while the United Kingdom and Australian governments have well-organized initiatives at the national level bringing together government, industry, and academia. The European Union recently launched the € 1 billion Quantum Technologies Flagship Program[xiii] focusing on quantum communications, sensing, simulation, and computing. U.S. primacy in these technologies is by no means guaranteed.

Session Highlights Provided by Attendees

Current Industry-University Collaborations – Quantum Technologies

This panel session discussed experiences from academia and industry on different collaboration methods to explore quantum technologies. One of the key themes was that quantum technology is a relatively nascent field, but there's opportunity to learn from what has been done domestically and internationally to further understanding and development of quantum technologies. It is also important to find ways to deepen the pipeline for talent in quantum (e.g. USRA's Quantum Academy[xiv]) as well as broaden understanding of industry experts so they can begin to see how classical approaches could be changed by quantum technologies.

Key Takeaways:

- Academic and corporate researchers and technologists should examine how development can be accelerated by implementing effective collaboration/partnership methods.
- Bridging the gap in understanding between classical approaches and quantum-inspired approaches will help to accelerate industry's identification of the areas where quantum technologies can be most valuable and will lead to more quality partnerships between industry, academia, and government.
- There is an opportunity to accelerate development of quantum technologies by understanding what areas within the ecosystem need help (e.g. supply chain, talent pipeline, "real-world" use cases to explore).

Industry Round Table – Evaluating the Current Technology Research and Commercialization Landscape

Industry is looking to address the most immediate commercialization opportunities. Panelists recommended that universities focus on basic research in hardware, basic research on algorithms, and quantum applications.

Key Takeaways:

- Equipment manufacturers are beginning to invest in quantum computing. There is a need to secure the supply chain.
- Panelists recommended increasing government investment in quantum fields, recognizing quantum technologies as a national security issue, and establishing proof points to facilitate university-industry partnerships.
- Universities should seek to determine what problems can be solved with quantum technologies.

[xiii] Bajpai, P. *Quantum Computing: What It Is, And Who The Major Players Are.* Nasdaq, March 26, 2018. https://www.nasdaq.com/article/quantum-computing-what-it-is-and-who-the-major-players-are-cm939998.
[xiv] *Feynman Academy.* USRA. https://www.usra.edu/quantum-computing#feynman.

Facilitated Breakout Session: Communications

Participants discussed quantum applications in communication - capacity, spatial nodes, and orbital angular momentum (OAM). Long-distance quantum-secured communication, i.e. quantum key distribution (QKD), in fibers need repeaters.

Key Takeaways:

- Early quantum applications may be in capacity and robustness.
- It is valuable to define the quantum classical divide and determine if is it useful.
- There is a longer-term need for quantum repeaters and engineering infrastructure.

Facilitated Breakout Session: Materials

Session participants were unable to define materials for quantum computing precisely but agreed that researchers are in a very early stage of hardware building and material development. There is a need for new materials that are resistant to defects. Participants recommended that the government find ways to incentivize materials scientists and chemists to study the role of materials and materials processing within quantum technology performance.

Key Takeaways:

- Agencies such as NSF can establish a materials research program aimed at achieving Josephson Junction behavior at room temperature.
- Government is an attractive intermediary to convene materials scientists, chemists, quantum physicists, and industry together to identify key challenges to address.
- Educational materials for the general scientific community are needed to explain the differences between quantum and classical computing.

Facilitated Breakout Session: Sensing

Quantum sensing will have a huge near-term impact and large market, if the problems relevant to industry can be identified and addressed. Academia and industry need to be integrated in quantum sensing areas.

Key Takeaways:

- Quantum sensing will have a large near-term impact.
- A different metric than one based on the number of publications to assess faculty productivity will foster academic-industry collaboration.
- Participants identified a need to train classical engineers into quantum engineers.

Facilitated Breakout Session: Simulation

Attendees agreed that “simulation” here refers to the use of quantum computing to simulate complex systems (e.g., chemistry), and not the use of classical computing to simulate quantum computers. Two key themes throughout the discussion included the core role of high-quality qubit technologies and error correction in enabling successful simulations, and the highly interdisciplinary nature of quantum simulation research and development teams.

Key Takeaways:

- Success and limitations in quantum simulation will depend upon the quality of the underlying qubit technology. Error rates and methodologies for addressing errors are also key.

- Government funders should recognize and support not just researchers trained directly in quantum simulation, but researchers with classical simulation backgrounds who want to take the leap into quantum simulation.
- Simulation teams are highly interdisciplinary, as demonstrated by industry quantum labs and paper authorship lists. Expertise is needed in quantum information, simulation, programming, machine learning, computer architecture, and the target domain.

Current Approaches to Federal Support for Industry-University Engagement

The session focused on understanding federal funding and support mechanism for university and industry collaboration and engagement. Presenters discussed how industry and academia can engage with them and leverage available funding. The NSF has specific programs that can be utilized (e.g. I/UCRC) to fund additional quantum technology initiatives, NASA Quail has funding for algorithms development and research use of their D-Wave machine, USAF Research Lab is an early adopter of technologies, and DoD is funding quantum technology R&D programs.

Key Takeaways:

- There are multiple ways to obtain federal support for U-I engagements.
- Workshop participants were encouraged to engage with a diverse number of government agencies for support.
- Panelists explained that they are open to new mechanisms for partnership.

Academic Leadership Panel

Quantum technology is more than quantum computing; quantum communication and sensing have nearer term potential for commercial deployment. Panelists asserted that industry-university partnerships are best when the values of each group are respected by the other. Perhaps most importantly, industry and government support are needed to make advances in this space.

Key Takeaways:

- Education should be broad-based because it is fundamental to quantum systems. Interdisciplinary education is needed.
- Panelists were not able to determine a clear roadmap for quantum technologies.
- Faculty startup costs are a significant hurdle to hiring more faculty. Shared facilities may be a way to address this.

Role of Small Businesses in Advancing Quantum Technology Commercialization – QC Ware Case Study

Founded in 2014 by a world-class team of aerospace and finance professionals, physicists, computer scientists, and quantum algorithm experts, QC Ware develops hardware-agnostic enterprise software solutions running on quantum computers. QC Ware has been successful in focusing their business development, getting some initial large business partners and seed funding from an investor fund. The role of startups is being a bridge to applications and customers. The core physics of realizing a quantum computer may be deep research, but there is much work to be done in developing the rest of the software stack and solving "problems of interest" to commercial business.

Key Takeaways:

- As with much of IT, startups are best suited for software, services and everything above bare-metal/materials.
- Start-ups need to work with partners to identify a clear value-added result and drive towards it for initial traction.

- University researchers, technology incubator corporations, and government agencies can be strategically aligned to identify addressable problems that can be solved.

Promising Areas for Collaboration and Setting Priorities Among the Technology Thrusts

In this session, research areas for industry-university collaboration were identified and prioritized among quantum technology thrusts (e.g. quantum computing, simulation, materials, sensing). Industry-university engagement mechanisms (existing and new) that may be well-suited for use-inspired quantum research were also explored. With regard to research thrusts, the wide gap between the problems that industry wants to solve (e.g. weather forecasting, genomics, pharmaceuticals, cryptography, lossless materials) and the current capability of quantum technology (often in the early concept stages) poses challenges in creating compelling value propositions, attracting industry interest, securing industry dollars, and developing research roadmaps and timelines. Research frameworks and engagement mechanisms that de-risk investment are critical because of the high-degree of uncertainty in quantum technology and the associated limited resources.

Key Takeaways:

- To add focus to research domains, knowledge gaps common to multiple quantum thrusts (e.g. noise mitigation, quantum heuristics, two level system theory, supply chain focused quantum enablers) should be prioritized as high impact topics to derive maximum value from the limited resources available for early stage quantum investments.
- A range of nationally coordinated industry-engagement models (e.g. I/UCRC, GOALI, Platforms for Advanced Wireless Research, Quantum Leap triplets, Expeditions in Computing) are available at NSF for partnership.
- Quantum research activities should emphasize workforce development not only for university students, but also for academic and industry practitioners.

Appendix A

Agenda

Wednesday, March 14, 2018	
11:00 AM – 4:00 PM	**Workshop Check-In and Registration**
12:00 – 12:30 PM	**GENERAL MEETING BEGINS**
12:30 – 12:45 PM	**Survey Results** Prior to the event, a survey was distributed to industry representatives and relevant insights will be shared with the workshop attendees.
12:45 – 1:30 PM	**Quantum Technologies – Review of the Current R&D Landscape** Elsevier will provide findings from their review of the nation's current quantum technology capabilities and benchmark against global activities.
1:30 – 1:45 PM	**BREAK**
1:45 – 2:30 PM	**Current Industry-University Collaborations - Quantum Technologies** There are a number of contemporary academic-corporate partnerships seeking to leverage each other's strengths and assets in order to advance their quantum technologies missions and goals. This session will highlight several of these current partnerships.
Wednesday, March 14, 2018	
2:30 – 3:30 PM	**Industry Round Table - Evaluating the Current Quantum Technology Research and Commercialization Landscape** Many companies are exploring strategies for developing a business case for making investments in quantum technologies. This session will feature company representatives who are actively evaluating how they can exploit the current quantum technology landscape to create viable business lines.
3:30 – 3:45 PM	**BREAK**
3:45 – 4:45 PM	**Facilitated Breakout Sessions by Application Areas** These breakout sessions will allow attendees to consider how academic-corporate collaborations can advance technology development within "quantum leap" thrust areas. **Communications** **Computing**

	Materials **Sensing** **Simulation**
4:45 – 5:15 PM	**Report Outs**
5:15 – 5:50 PM	**Current Approaches to Federal Support for Industry-University Engagement** This session will consider some of the current quantum technology efforts at the federal level and funding mechanisms available for future investments.
5:50 – 6:00 PM	**Day 1 Recap** During this session, workshop participants will be asked to identify key issues and findings that can be used to drive Day 2 discussions and advance the workshop goals.

Thursday, March 15, 2018	
8:00 – 8:15 AM	**Charge for Day 2**
8:15 – 9:30 AM	**Academic Leadership Panel** This panel will explore academia's interest in quantum technologies and how academic leaders are pursuing collaborations in this area.
9:30 – 10:00 AM	**Role of Small Businesses in Advancing Quantum Technology Commercialization** University start-ups and small businesses are a critical component to the quantum technology innovation ecosystem. This session will explore how these small firms can play a role in future efforts between large universities and companies.
10:00 – 10:15 AM	**BREAK**
10:15 – 11:15 AM	**Facilitated Discussion - Promising Areas for Collaboration and Setting Priorities Among the Technology Thrusts** Attendees will share their interests in making investments in specific research and commercialization areas.
11:15 AM – 12:15 PM	**Recommendations for Next Steps** The workshop's primary goal is to identify prime areas for co-creation among companies, government and universities. This session will utilize the learnings gathered from this event to accomplish this goal.
12:15 - 12:30 PM	**Conclusion**

Appendix B

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Appendix D

Additional References

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