Directorate for Engineering Advisory Committee Meeting

National Science Foundation
Alexandria, Virginia
October 23-24, 2018
Room 2030

ENG AdCom Members Present:
Dr. Darryll Pines (chair)
Dr. Tilak Agerwala
Dr. Pedro Alvarez
Dr. Gilda Barabino
Dr. Curtis Carlson
Dr. Hossein Haj-Hariri
Dr. Bruce Horn
Dr. Leah Jamieson
Dr. Mary Juhas
Dr. Kenneth Lutchen
Dr. Sarah Rajala
Dr. Maxine Savitz
Dr. Susan Smyth
Dr. Gregory Washington
Dr. Yannis Yortsos

ENG Senior Staff Present:
Dr. Dawn Tilbury (Assistant Director)
Dr. Filbert Bartoli
Dr. Linda Blevins
Dr. Richard Dickinson
Dr. Don Millard
Dr. Sohi Rastegar
Dr. Mihail Roco
Dr. Robert Stone (incoming)
Dr. Mary Toney
Dr. Kon-Well Wang (incoming)

Not present:
Dr. Barry Johnson

Tuesday, October 23, 2018

The meeting convened at 11:45 a.m.

CALL TO ORDER

Dr. Darryll Pines, chairman of the NSF Directorate for Engineering (ENG) Advisory Committee (AdCom), welcomed everyone to the meeting. Members and ENG leadership introduced themselves. The members approved the minutes of the Spring 2018 meeting.

DIRECTORATE FOR ENGINEERING REPORT

Dr. Dawn Tilbury, Assistant Director for Engineering, introduced new ENG staff. She reminded the committee of NSF and ENG current and recent budgets. She discussed the change in core research programs to no proposal deadlines. She described the findings of the National Academies report on harassment and NSF steps to counter harassment. She summarized ENG activities among the 10 Big Ideas, areas for future NSF investment at the frontiers of science and engineering, which have offered opportunities for funding and partnerships since the last meeting. She provided updates on the new generation of Engineering Research Centers, investments in advanced manufacturing and artificial intelligence, new efforts in workforce development, and other investments in research and education. She closed by noting the contributions of NSF-funded engineer Frances Arnold, who was recognized with a Nobel Prize.

Discussion
Dr. Pines mentioned a December workshop at the University of Maryland to refine the curriculum for the pilot high school engineering course.

Committee members asked if ENG supports RAPID projects related to disasters such as wildland fires, like it supports research related to hurricanes; ENG has not awarded many in this area, but it depends on the research questions.

Members discussed harassment reporting and timing under NSF's new steps to stop harassment.

NSF BUDGET UPDATE

Ms. Caitlyn Fife, Division Director of the NSF Budget Division, gave an overview of U.S. budget revenue and spending, which can either be discretionary or mandatory. She described the President's FY 2018 request for NSF and Congress's appropriation, the President's FY 2019 request and the potential funding timeline. NSF plans to submit the President's FY 2020 request on February 4, 2019. She explained that in the past NSF has received full funding at different points during the year, and NSF focuses on managing whatever budget and funding it has.

Discussion
Advisory Committee members asked if there are dollar amounts associated with initiatives, and Ms. Fife explained that justifications are on NSF website for the Presidential request level. NSF may get additional funding or guidance from Congress.

PERSPECTIVE FROM THE DIRECTOR'S OFFICE

Dr. Tilbury introduced **Dr. Fleming Crim**, NSF chief operating officer, and **Mr. Brian Stone**, NSF chief of staff. The committee introduced themselves.

Dr. Crim introduced his history with NSF. He described NSF's budget situation and the House and Senate marks. He highlighted parts of the White House R&D priorities memo that relate to NSF. The Foundation participates in many interagency activities through the White House Office of Science and Technology Policy (OSTP) and committees of the National Science and Technology Council (NSTC) to advance areas such as artificial intelligence (AI), quantum science and engineering, STEM education and entrepreneurship. NSF also participates in international activities; for example, the NSF Office of International Science and Engineering is running MULTIPLIER expeditions in various parts of the world. Regarding harassment, NSF's concern stems from its mission to advance science and engineering, which requires contributions from diverse people. NSF appreciates community input on the new term and condition and asks universities to be our partners as we do more in the future.

Dr. Pines thanked NSF for its leadership. He said the number of college-ready U.S. students is decreasing, with a commensurate decrease in STEM-interested students. Fewer overseas applicants to graduate programs is affecting enrollment, education and research. How does NSF see these trends? Dr. Crim said that bringing students into STEM education is a continuing concern of NSF's that could see layered possible responses. Education research is making a difference, but we look for changes in a shorter time-horizon. Inclusion and diversity activities, such as the NSF INCLUDES program, are essential. The international enrollment decline in science and engineering is a nuanced problem, due to concerns

about security and intellectual property. These concerns and open science and engineering research are important to NSF, and he encourages communities to share their perspectives on these issues.

Dr. Kenneth Lutchen sees opportunities in data science, sensing, and engineering. In the new era of convergence, how can engineering build a diverse and inclusive workforce in these areas? The community needs to both excite and prepare students, and activities such as the high school engineering pilot will help. Dr. Crim replied that advisory committee members are in a good position to see the problem and own it. NSF programs can provide leverage.

The committee asked about NSF's next steps for stopping harassment. Dr. Crim described the partnership between NSF and universities. Title IX and sponsored research offices have not necessarily worked closely together in the past, but they are now. Once universities realized NSF is interested in supporting students and research, not pulling grants, they were very positive. Regarding training, NSF requires it as part of responsible conduct for research. NSF policy already says a university must have an ethics program in place, and NSF will strengthen this language to ensure that faculty get training too. It is necessary for both research excellence and public trust. NSF is holding internal discussions and planning community discussions about doing more. While NSF has been leading in this area, we recognize that others have wisdom and coordinate closely with other agencies.

Dr. Yannis Yortsos remarked that technology is changing rapidly, industry wants results quickly, and students are getting recruited after a couple of years. He asked how NSF will support research in this environment. Dr. Crim responded that the short industry timelines point to the importance of NSF's contribution of fundamental research in the precompetitive space. Students working with a company on a precompetitive research project will be well-prepared for their careers. One strength of NSF is to bring various experts together to solve new and challenging problems, and NSF is building more and stronger connections across the agency to support convergence and interdisciplinary research.

Committee members asked how NSF budgets are determined. Dr. Crim explained that budget allocations within NSF are a result of opportunities, needs, and advocacy. Many NSF priorities have additional investments through core programs. Currently, AI and quantum research have many supporters, and we need to find where NSF can make a significant, unique impact. NSF coordinates with OSTP and NSTC, as well as other agencies. NSF also nurtures international collaborations, even in AI and quantum, involving centers of excellence as well as bottom-up collaborations. NSF focuses on compelling research opportunities and may look at impacts on society and national needs, rather than responding to cyclical changes in the workforce or student enrollment.

Dr. Gilda Barabino asked about NSF INCLUDES and measuring its impacts. Dr. Crim noted that assessment is built into INCLUDES, and NSF has an evaluation and assessment unit. NSF looks at the people served and affected and is careful not to distort outcomes because of what we measure.

ARTIFICIAL INTELLIGENCE AND ROBOTS

Dr. Ken Goldberg, William S. Floyd Jr. Distinguished Chair in Engineering, University of California, Berkeley, wants to push back on conventional wisdom about AI and robots. While media and policy-makers give them lots of attention, today there are fewer than one robot per 100 workers. Research about people and robots working together has a long way to go. Despite instances of robots beating people at games or of deep learning combined with distributed computing, these are very different than

robots working in human environments such as roads, operating rooms, or community centers, which are higher dimensional, dynamic, and, most importantly, have a huge amount of uncertainty.

Soon advances such as 5G networks and the Internet of Things will come together in cloud robotics, and robots will not have to carry all computing and memory on board. Tech companies have announced major new initiatives in cloud robotics, and universities have started to combine cloud and local/edge computing, and gateway computing between the two.

One integrative application is surface decluttering in homes, offices, and other places. Robots will identify objects and where they go and them put them there, for example, to keep the floor clean for senior citizens and to organize and retrieve inventory for e-commerce. While grasping and manipulation are easy for humans, they are still very difficult for today's robots, especially if the object is unknown. Challenges remain in everything from sensor design to fundamental understanding of friction.

To achieve "universal picking," physics, perception, and control must combine. While computer vision offers super-human perception and can classify images, grasping has not made such progress. One approach involves a network of models of various objects that are labeled by where to grasp them. The system looks at potential grasp points, considers uncertainty, generates probability of success for a particular grasp, then formalizes that. The system can be trained with synthesized data sets of objects and synthesized bins of objects for picking; however, computer vision cannot see some characteristics of objects, such as rigidity or softness. While humans can perform 400-600 picks per hour, the robotic system can perform only 200 per hour.

Today, people understandably have automation anxiety. Jobs will change, some professions will go, and new ones will be created through AI and robotics. Instead of a singularity in our future, what about multiplicity, with humans and machines collaborating? Multiple AI classifiers could be combined to produce a better one, similar to using cognitive diversity to make a collective IQ that is greater than an average of individual IQs.

We will have a shortage of workers, not jobs, as our population ages. What can we do about it? A century ago, steam engines and automation came to farms, and progressive educators began the high school movement. Similarly, multiplicity will change how we teach the next generation, with a focus on creativity (diversity, variety, collaboration, innovation). AI can expand human thinking.

Discussion

Dr. Gregory Washington asked what happens when work such as inventory picking reaches human levels. Dr. Goldberg replied that technology will advance slowly, and the demand for pickers is huge, so these tools will not necessarily put people out of work. These jobs are hard, and robots can support humans by reducing the physical and cognitive loads. To reach human levels will take a very long time, and there are always things that robots cannot handle. It's not an either–or situation with robots.

Dr. Tilak Agerwala agreed with the hypothesis that humans and computers can interact with each other to solve problems that neither can solve by themselves, and he supported the notion of cognitive diversity. How would you go about conducting a social science experiment to prove these? Dr. Goldberg responded that, while he does not do much human-subjects work, this is an understudied area. Measuring how a group of people with AI tools would fare against people without tools or against tools alone has been done in areas like chess, but the results are not clear yet. Could an AI tool manage collaboration to make sure all participate? To make that future happen will require intentional work. Dr.

Lutchen added that there is a big gap between our imagined future and what is about to happen, and fear can get in the way of what we can constructively do in the meantime.

Dr. Curtis Carlson asked what fundamental paradigms could take us to next level with investment. Dr. Goldberg noted that interest in AI ebbs and flows, and because some AI claims are exaggerated now, we may soon face a correction. We still need to understand the fundamental science and limitations, and similarly, we need to understand the expandability of AI.

Dr. Yortsos asked whether all engineering students, or another set of students, should have these mindsets. Dr. Goldberg noted that engineers must have people skills. Human decision-making is affected by emotions and feelings and ethics; robots are different and can help make human decisions better.

Dr. Leah Jamieson can envision interaction between robots and humans, and she asked what tools and interfaces would facilitate that. Dr. Goldberg said this would be a good area for NSF to pursue and facilitate. NSF calls for proposals can change a researcher's thinking and can guide the research community to help empower the broader community and workers at all levels.

REAL-TIME LEARNING AND DECISION-MAKING WORKSHOP REPORT

ENG Program Director Tony Kuh introduced the NSF-funded workshop on real-time learning and decision-making held in February 2018. The workshop was motivated by multiple challenges: the proliferation of data in engineered systems, combining data across engineering systems, making decisions in real time, and convergence. The goal was to discuss common research areas from complementary perspectives and fields, such as power and energy systems, autonomy systems transportation, information systems, and other dynamic systems. The workshop resulted in 40+ position papers, an NSF Dear Colleague Letter for Real-Time Learning and Decision-Making in Engineered Systems (Real-D), and ideas for NSF Big Ideas. The workshop underlined the importance of combining physical models with data-driven approaches.

Discussion

Dr. Lutchen asked about systems in healthcare and home monitoring that look for patterns in real-time data but may not have a reason or an explanation for the pattern. Patterns could provide insights into disease processes to help create a better physical model. Dr. Kuh responded that every application needs domain knowledge behind the physical model. Some domains might have a good physical model and associated data, and others might have just data.

Dr. Mary Juhas asked how women and speakers of color were engaged in the workshop. Dr. Kuh replied that organizers contacted many people who could not make it. While no women were keynote speakers, women were speakers in the workshop.

Dr. Pines noted that some application areas could use data to inform the model, predict faults, and model the faults. Dr. Kuh agreed that real-time learning can improve diagnosis and maintenance.

DISCUSSION OF ENGINGEERING ROLE IN ARTIFICIAL INTELLIGENCE

Advisory committee members agreed that, if we do AI right, it could make fantastic contributions to fluid dynamics, the design of engineered systems, and many other areas. Engineering has a role in AI,

and AI has a role in engineering – although there are misperceptions about it in academia and industry. AI technologies are convergent, and getting the right people together is one of the major challenges.

Combining AI and engineering can greatly improve our quality of life; amplify, augment and complement human intelligence; and enhance security and economic competitiveness. While there is hype about AI, it is mostly about the technique of deep learning, and there are many other promising approaches.

The focus needs to be on ways humans and computers can work together. AI systems can help with decision-making or diagnoses by telling us probabilities or certainty behind possible answers; this way the human decision-maker remains in the loop. We need research on how and why AI systems work or do not, especially when they can have powerful consequences and societal impacts. Legal and ethical issues must be part of the research, and they are components of many NSF programs related to AI and human-machine collaborations.

NSF INCLUDES UPDATE

Dr. Don Millard, acting Division Director for the Division of Engineering Education and Centers, stated that this is the time for Engineering to get engaged in NSF INCLUDES and make an impact. He described the program's elements and history. NSF INCLUDES supports a range of design and development launch pilots and involves more than 750 partners of various kinds. **Dr. Sylvia James**, acting Deputy Assistant Director for the Directorate for Education and Human Resources, described awards from FY 2018, including a coordination hub led by SRI and five NSF INCLUDES alliances. They asked the committee what would attract new members from engineering to NSF INCLUDES and what engineering deans can do. They also asked how NSF can share what the Engineering Research Centers are doing. The community has an opportunity to align abilities, set challenges, and take advantage of NSF support.

Discussion
Dr. Maxine Savitz asked how engineers from industry and the professional societies are incorporated into the engineering alliance. Dr. Millard noted that the January 2018 Summit brought together NSF-funded centers to discuss broadening participation, and their leads in this area who work with industry partners are planning a workshop togethers. Also, the April STEM Funders meeting has a day devoted to industry. Dr. James added that NSF INCLUDES does not limit who partners are — they could be industry, professional organizations, or other groups.

Dr. Juhas praised the student focus and asked about the role of faculty, who can serve as role models and leaders. Are ADVANCE projects involved? Dr. James replied that some ADVANCE projects were in the NSF INCLUDES design and development launch pilots, and NSF hopes to see that number increase. Dr. Millard noted that the ENG broadening participation program has funded resources to support faculty, and the new NSF INCLUDES report has lessons learned that are relevant.

Dr. Carlson asked about NSF INCLUDES metrics. Dr. James described the role of the Directorate for Education and Human Resources in evaluation and assessment. Each NSF INCLUDES alliance has an evaluation component, and the hub performs that function for the whole program.

OFFICE OF EMERGING FRONTIERS AND MULTIDISCIPLINARY ACTIVITIES (EFMA) OVERVIEW

Dr. Sohi Rastegar, EFMA office head, introduced the people of the office and its programs. The Emerging Frontiers in Research and Innovation program invests in research that is transformative and

interdisciplinary, addresses national needs, and supports areas when engineering can take on a leadership role. EFFI research topics change periodically and are developed with community input; EFMA has a call for FY 2020 topic ideas open now. He described the Research Experience and Mentoring Supplements program to broaden participation and the Germination of Research Ideas for Large Opportunities and Critical Societal Needs program to cultivate a risk-taking and impact-driven research culture. In summary, EFMA serves as an incubator for potential future research areas.

EFMA COMMITTEE OF VISITORS (COV) REPORT

Dr. Leah Jamieson thanked the committee for their excellent work. She described the period and scope of the COV review. EFMA and its signature Emerging Frontiers of Research and Innovation (EFRI) program are comprehensive, effective, transparent, and inclusive in their merit review processes. The COV gave kudos to the EFRI topic selection process and two-step review process for proposals. Proposal reviews varied in quality and often did not comment on data management plans. Regarding reviewers, the COV found EFMA reviewer pools to be diverse and well-qualified, and they need NSF encouragement to address Broader Impacts. Program management in EFMA is thoughtful. The COV sees Germination as an avenue for faculty development and would like the program to expand and be more stable. Regarding the award portfolio, the COV suggested using outreach to improve the its balance and found the investments to be absolutely relevant to national priorities and the NSF mission. The Directorate can seek ways to leverage EFMA programs for continued impact.

Discussion
Committee members suggested following investigators and students long-term to understand impacts related to the original goals of EFRI. NSF can study how well programs offer a career path from high school to diverse people.

The Engineering Advisory Committee voted unanimously to accept the EFMA COV report.

The meeting adjourned for the day at 5:50 pm.

Wednesday, April 18, 2018

The meeting resumed at 8:30 a.m.

Dr. Tilbury explained that the upcoming advisory committee reports on recent activities are from the ENG subcommittee and from NSF-wide committees.

ADVISORY COMMITTEE LIAISON REPORTS

Dr. Tilak Agerwala, liaison to the **Advisory Committee for Cyberinfrastructure** (ACCI), said one challenge for cyberinfrastructure is to keep up with rapid changes in science and engineering research and in the technological landscape. ACCI continues to build on community input; recommendations from their request for information are in the report, CI2030: Future Advanced Cyberinfrastructure. Scientific domains and data science methodologies need tight integration, and they affect and grow from each other. To do so effectively, we need many types of bridges between them, from reproducibility to sustainability. These were the main topics at the fall ACCI meeting. The NSF Office of

Advanced Cyberinfrastructure will be doing more research on cyberinfrastructure itself; see their core research solicitation, NSF 18-567.

Dr. Pedro Alvarez, liaison to the **Advisory Committee for Environmental Research and Education** (AC-ERE), said that at tomorrow's AC-ERE meeting, they will discuss urban systems research, which is connected to prior NSF initiatives and several NSF Big Ideas. A healthy environment goes hand in hand with a healthy economy, and we want to show how environmental research strengthens national security and economic competitiveness. They issued a request for information asking, "What are the major environmental research priorities with the greatest potential to contribute to economic growth and competitiveness and/or national or human security and wellbeing?" Other discussion topics will be actionable research topics, which balance the discovery-driven culture of science and the innovation-driven culture of engineering, and cyberinfrastructure needs for environmental research.

Dr. Gilda Barabino, the liaison to the **Committee on Equal Opportunities in Science and Engineering** (CEOSE), said that the top item on the committee's agenda was the National Academies' sexual harassment report. Marcia McNutt framed the meeting discussion, and CEOSE discussed how NSF is responding to recommendations. The NSF Office of Diversity and Inclusion discussed Title IX and how it relates to NSF policies. The committee discussed NSF INCLUDES and the best methods for evaluation and assessment. The committee also discussed ways to better support minority-serving institutions and NSF's various programs. A draft of the CEOSE biennial report to Congress is due in January 2019, with submission to NSF in February. Future directions include: supporting people with disabilities, curating knowledge, using a systems approach, closing the achievement gap, incorporating global perspectives, integrating STEM with art, harnessing the full potential of minority-serving institutions, managing cultural shifts, increasing faculty diversity, training the next generation, and creating an ADVANCE-like program for under-represented minorities.

Dr. Juhas, liaison to the **Subcommittee for the Small Business Innovation Research/Small Business Technology Transfer Program** (SBIR/STTR), explained that the subcommittee is holding its next meeting in November, and she looks forward to the meeting and sharing information after that.

Discussion
The committee expressed interest in the idea of an ADVANCE-like program for under-represented minorities. They suggested that CEOSE use the history of ADVANCE as a guide and people would have that knowledge. The Society for Women Engineers has a program for under-represented women postdocs and junior faculty.

DIVISION OF ELECTRICAL, COMMUNICATIONS AND CYBER SYSTEMS (ECCS) OVERVIEW

Dr. Fil Bartoli, ECCS division director, introduced the division's current organizational structure, priorities, program clusters and special funding opportunities. Many emerging research areas supported by the division will help address major societal challenges and NSF Big Ideas (such as Quantum Leap). Creating a secure quantum communication network is an ECCS moonshot, in terms of both science and workforce development. Another important, interdisciplinary area is real-time sensing, learning and decision-making, which could radically transform critical infrastructure, manufacturing and healthcare.

Discussion
The committee noted that another quantum moonshot is understanding quantum biology, as seen in bird navigation, for example.

Many curriculum and training issues for quantum are the same for AI. Workshops and opportunities to train throughout one's career are important. At the same time, diverse students need access to these fields, specialized career advice, and understanding of leadership prospects in industry and government.

Dr. Carlson asked about international competition and coordination in these areas. Dr. Bartoli said the international landscape is not homogeneous but has very significant efforts from countries who are historical allies and have industrial partners. Focusing on broad moonshots helps NSF organize programs and form alliances in a coherent way, as NSF has with the NSF Big Ideas.

Dr. Pines asked about interagency collaborations in quantum engineering research. Dr. Bartoli explained that NSF has had such collaborations, and they will continue, especially if the National Quantum Initiative Act is established.

Dr. Carlson asked, when major investments are found around the world, what does it mean to be a winner? It may mean you can attract the best talent in the world and support their collaboration. Powerful teams are transformative.

ECCS COMMITTEE OF VISITORS (COV) REPORT

Dr. Carmen Menoni and **Dr. Rashid Bashir**, co-chairs of the ECCS COV, described the scope of the review and thank members of the COV. On merit review, the COV suggests strengthening transparency and substance for Broader Impacts, implementing more standardization for incorporating ad hoc reviews, and offering more than one submission window. On selection of reviewers, ECCS performs well and rigorously manages conflicts of interest. The division could use a more formal process to train reviewers and rate their work, and study hybrid panel further. On program management, program directors are excellent and benefit from attending research conferences; program budgets could increase, especially while the number of faculty is growing. On portfolio balance, the scope was appropriate and effective; minority and women researchers fare well in core programs but not necessarily in solicitations. The COV encourages moonshots and participation in national priorities. Other ideas were to consider implementation of regular brainstorming with external experts; a systematic approach to organizing workshops; a CCC-like initiative at the division level; placing at least one permanent program director in each program for continuity. The found a continued struggle with the definition and use of the Broader Impacts merit review criterion, but the issue is broader than one division.

Discussion
The committee asked about the diversity of ECCS panels. Dr. Menoni responded that review panels were diverse of gender, expertise, geography, and small versus large institutions. What the COV discussed was the broad scope of submissions, but there are still some pockets that fall short. So, the COV recommends using ad hoc reviewers more frequently and formally incorporating ad hoc reviews into the final decision process and analysis. Usually the ad hoc reviewers are invited separately, and their reviews not always part of the panel discussion.

Dr. Yortsos remarked that there are some commonalities between the EFMA and ECCS reports, and those generic things could be addressed at the directorate level. Dr. Menoni added that the COV tried to emphasize issues around Broader Impacts, which are difficult to evaluate and not well understood by the community. Dr. Rashid noted that the quality of individual review varies, the quality of panel summary is good, and the final analyses are great. Reviewers need examples and other tools to evaluate Broader Impacts.

The Engineering Advisory Committee voted unanimously to accept the ECCS COV report.

NSF BIG IDEA: QUANTUM LEAP

Dr. Rastegar, **Dr. Saúl González Martirena**, senior advisor in the NSF Division of Physics, and **Dr. Irene Qualters**, senior science advisor in the NSF Directorate for Computer and Information Science and Engineering, introduced the NSF Big Idea Quantum Leap (QL) with goals in fundamental science, creating devices and technologies, and understanding natural and engineered quantum systems. NSF's investment asks ambitious questions concerning quantum science and engineering, such as: How many qubits can we entangle? What can we learn from quantum systems? How can we galvanize the community?

Now, we are at an opportune moment to pursue QL because of recent scientific findings, international interest, and openings for collaboration. NSF is a good fit for this effort due to its mission and its approach, which involves community, convergence, and collaboration. Prior NSF investments include a quantum computer Ideas Lab, the Quantum Information Science and Engineering Network triplets, the EFRI ACQUIRE investment in secure quantum communication systems, and others. Next steps will involve continued participation in the national conversation, workshops, and investments in research and capacity-building.

Discussion
Advisory Committee members encouraged NSF to invest in quantum science and engineering infrastructure to promote development of expertise within US universities and strengthen the Nation's scientific leadership. Dr. González replied that NSF historically has invested in larger centers, including a few in quantum with infrastructure. The need for infrastructure is another reason NSF is collaborating with other agencies. Dr. Qualters noted that US infrastructure will help students, but they will also benefit from exposure to ideas outside the US. Dr. Rastegar added that NSF center and infrastructure programs not targeted for quantum can also serve as sources for funding.

Dr. Savitz asked how NSF will coordinate and avoid duplication among universities and government agencies. The QL team responded that NSF coordinates at all levels and in many ways, such as joint workshops and memoranda of understanding, cross-agency working groups, OSTP interactions, and others, and similar coordination is performed with the industry sector.

Dr. Barabino asked what concrete steps can ensure the emerging field of quantum science and engineering will be inclusive, when related fields such as physics and electrical engineering do not engage large numbers of women and under-represented minorities. The QL team suggested that current NSF mechanisms for broadening participation can be implemented as part of QL, for example, to offer student research opportunities or build an INCLUDES group in quantum. Quickly building capacity in quantum will be a challenge. NSF and other agencies have been encouraged to think of the whole spectrum of quantum workforce, not just researchers, and that could open opportunities for a lot of participation.

Committee members anticipate challenges in the quantum science and engineering curriculum. A degree program in quantum science will have trouble competing with other hot areas and will take too long to develop. Specialized concentrations might work better and attract more US students. NSF may

consider investing in innovative ways for learning with connections to industry for all the Big Idea topics. Industry is not necessarily looking for PhDs; they are looking for master's and bachelor's degrees.

HAS THE QUANTUM REVOLUTION ARRIVED?

Dr. Edo Waks, professor of electrical and computer engineering at the University of Maryland, began by explaining the differences between quantum and classical computers, and the differences present new opportunities for design and performance. Massive parallelism and quantum algorithms can make computers faster at calculations. Already there are more than 100 quantum algorithms archived on NIST's quantum zoo website. Many of these were derived by theorists without the benefit of an actual quantum computer. Until recently, quantum computers had only a few bits to serve as their building blocks, and now the field is rapidly accelerating using different types of platforms. But there is a long way to go: quantum computers are at a stage similar to mechanical computers of 1880, when computers were large, unscalable, and unreliable. We cannot yet build digital quantum computers. We are at the basic research phase of the quantum computer; however, it has gone from being a physics question in 1990 (does it work?) to an engineering question in 2018 (how to achieve large-scale systems integration?).

Quantum engineering challenges are many. Quantum computing needs error-correction built in. We need to move from analog to digital quantum computers. Quantum "wires" that preserve quantum properties are another challenge. Promising advances are happening in photonics, atomic-photonic integration, and quantum materials. The next question is device integration, of sources, emitters, memories made of different materials, to achieve quantum computing on a chip. Quantum technologies will require new fabrication methods that are scalable.

Is the US falling behind? The question arose following Europe's $1B euro investment and China's $10B investment. The US is making very strong efforts, but no matter what we do in the foreseeable future, NSF must play a strong role. Quantum is still basic research, some of it is hard and not esteemed. Quantum needs interaction between different fields and investment in basic research.

Discussion

Dr. Agerwala asked, regarding quantum simulation versus general-purpose computing, IBM Q seems to be approximately 20 qubits and is offered in the cloud. IBM says achieving 50 qubits is not far off. Are these examples general-purpose computing? Dr. Waks replied that so far these do not have error correction. The 50-qubit computer could in principle become a general-purpose computer if IBM builds in error correction.

Will quantum sensing have a bigger impact sooner than quantum computing? Dr. Waks responded that it could have. A quantum sensor theoretically can collect signal more accurately, but we still do not have one that can outperform classical sensors. In the future, he envisions quantum sensors talking to quantum computers that could network for a quantum internet of things.

Dr. Rastegar noted that so-called "dirty work" is basic research. Tackling fundamental problems that industry will not is the realm of government support. Dr. Waks added that heat from ion traps was creating noise, and a detailed NIST investigation of where the heat was coming from enabled it to be reduced little by little. Their concerted effort took a long time but is now making a huge payoff.

Dr. Yortsos asked about the quantum landscape when it comes to leadership. Are foreign investments paying off? Dr. Waks replied that, when it comes to leadership in this field, the US (at places like Google, IBM, Yale, Stanford, and Maryland) has made some of the biggest advances. We have the advantage of smart people, but whether that will continue is uncertain. Some people have moved to Europe because of funding, but it is unclear if this is a significant trend. In some areas, the competition is in Europe.

Dr. Juhas asked whether US and European quantum researchers might be persuaded to work China. Dr. Waks said that many of his students come from China. While in the past most wanted to stay in the US, these days there are opportunities in China that make them consider a return much more seriously. He does not see US and European students moving there but that could change.

DISCUSSION ON ENGINEERING DIRECTORATE ROLE IN QUANTUM ENGINEERING

Advisory committee members discussed the roadmap for quantum information science (QIS) research. The engineering of QIS and the application of QIS to engineering are both important, and we have an opportunity to establish a virtuous cycle. The research agenda should have both aspects. Comparing AI and QIS, AI has a more obvious roadmap, yet there are many opportunities for quantum, and discoveries can affect roadmap as they happen. Not being involved would be a huge mistake.

Regarding facilities for quantum research, access to materials and facilities are too expensive to build and run by single investigator. There may be one place where certain materials are grown and perfected. Also, some necessary facilities just do not exist, so it is important to encourage people to build new facilities and make them available to the community. NSF can help establish these facilities through partnerships with states, industry, and other agencies.

The committee discussed industry involvement in certain areas and how to ensure it is happening where it is needed. Google and many other companies are looking at it as a way to position themselves for thefuture, and even some venture capitalists are looking long term.

Workforce development is needed at all levels. New graduate students coming out of undergraduate programs need to know the fundamentals. Usually quantum mechanics and basic physics are not part of electrical engineering. Much of the quantum workforce now is coming out of physics.

For the faculty workforce, are there things that NSF can do to diversify graduate students in this field? Are there programs to encourage domestic students to go into graduate school in this area? NSF can look beyond large universities and programs, strengthen smaller ones with long-term support, and attract students with the promise of jobs.

ROUNDTABLE ON STRATEGIC RECOMMENDATIONS FOR ENGINEERING

Dr. Pines opened the session with a discussion on strategic visioning for engineering. **Dr. Tilbury** summarized the visioning session from last time and encouraged the advisory committee to give advice. The Engineering Directorate set up a visioning working group, led by Dr. Rastegar.

Dr. Rastegar said the working group has been considering input from the advisory committee and began planning a workshop for stakeholders in 2019 to get feedback on next steps. One challenge is to find a convening group that can reach the whole engineering community. The workshop's expected outcomes are to learn research priorities and gain consensus on the potential body's characteristics.

Dr. Jamieson said this activity could complement NSF's project with the National Academy of Engineering on the role of professional societies in engineering education.

Committee members suggested asking for research priorities by discipline, to ensure that no discipline is left out. Dr. Rastegar said they will ask for priorities but maybe not by discipline. ENG wants ideas that will galvanize entire community and move beyond their discipline. ENG can ask each society what they see as the grand challenges and what will impact society — and what requires fundamental research for engineering. Challenges are different in core engineering topics like manufacturing compared to interdisciplinary topics like AI and quantum. What can the engineering community own and lead? The directorate can ask what an engineering Big Idea would be, with room for others to join.

Committee members suggested that industry participate in the workshop and offered to connect ENG with leaders of industry to invite.

The committee agreed that ENG should hold the visioning workshop and wants to contribute to it.

CLOSING REMARKS AND WRAP-UP

Dr. Pines and **Dr. Tilbury** thanked the committee members and the NSF team. The committee thanked Dr. Pines for his leadership. The committee chose to meet again on April 17-18, 2019.

The meeting adjourned at 12:30.