Quantum materials R&D forges ahead

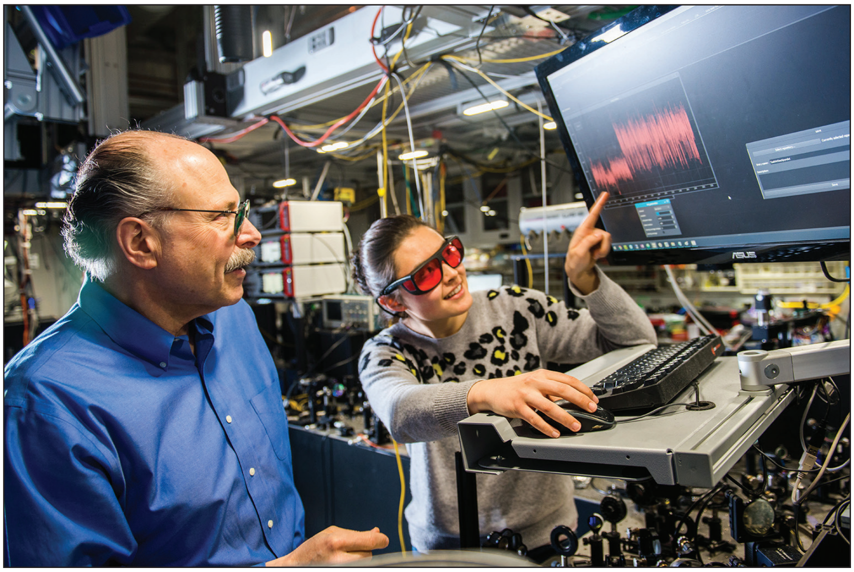
Despite the funding and safety protocols that have slowed down R&D in various scientific fields except for COVID-19-related work this year due to the current COVID-19 pandemic, federal governments around the world have kept quantum projects on-track.

"'Quantum' has not slowed down—there were a lot of research initiatives announced this summer and [our project] is a program to support quantum education," says Emily Edwards of the University of Illinois at Urbana-Champaign, co-principal investigator of Q2Work, a program funded by the US National Science Foundation.

Anna Grassellino, director of Fermilab's Superconducting Quantum Materials and Systems Center (SQMS), and David Awschalom, director of Argonne National Laboratory's Next Generation Quantum Science and Engineering Center (Q-NEXT), each began receiving funds for their quantum centers. The US Department of Energy announced this summer that they will provide USD$625 million over five years to fund five National Quantum Information Science Research Centers, including SQMS and Q-NEXT.

In the UK, Dominic O'Brien, director, and David Lucas, principal investigator, head up the UK Quantum Computing & Simulation Hub, which began its five-year program at the end of 2019. The Hub is a collaboration of 17 universities and more than 25 industrial and government partners and is led by the University of Oxford. The current Hub was preceded by the Networked Quantum Information Technologies Hub (NQIT), which ran from 2014 to 2019.

The UK focuses its quantum initiative on technology, launching the UK National Quantum Technologies Programme in 2013. From 2014 to 2019, UK Research and Innovation invested £120 million (~USD$156 million) for four quantum technology hubs managed by the Engineering and Physical Sciences Research Council. The four hubs then received £94 million (~USD$122 million) for the next five years comprising the second phase.



David Awschalom, a physicist at the University of Chicago and Argonne National Laboratory, reviews data from a quantum information experiment with a graduate student in his laboratory. Credit: University of Chicago.

Tadashi Sakai, R&D manager of Q-LEAP's (Quantum Leap Flagship Program) Quantum Metrology & Sensing, a 10-year program in Japan commissioned by the Government of Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT), says, "Following the government's state of emergency [due to COVID-19], we were forced to refrain from activities for about two months. During that time, we stopped experiments. It is now back to almost normal activity levels."

In its FY 2020 budget highlights released earlier this year, MEXT includes ¥3.2 billion (~USD$30 million) for its Q-LEAP initiative. This represents an increase by ¥1 billion (~USD$9.5 million) from FY 2019 and exemplifies Japan's 10-year Fifth Science and Technology Basic Plan known as Society 5.0 (approved by the Japanese Cabinet in January 2016). In Society 5.0, the government's emphasis is on an "inclusive society" that values knowledge and information, versus the capital-intensive society of the 20th century.

When the Q-LEAP initiative was adopted in 2018, it focused on three general areas: quantum information technology (quantum simulator, quantum computer), quantum metrology and sensing, and the next-generation laser.

These are just a few examples of the quantum science megaprojects that have taken off globally.

"Quantum has been funded before for computing, Internet, sensors, but has never been pushed to this level of bringing together academia and all the stakeholders," Grassellino tells *MRS Bulletin*, referring to the US initiative. "I see this is important now to accelerate [R&D]. Either we're going to be serious about it or progress is going to be too slow."

Since the US government signed the US National Quantum Initiative Act into

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law at the end of 2018, it has authorized just over USD$1.2 billion for the first five years (starting in fiscal year 2019), spread across the National Institute of Standards and Technology (USD$80 million), the National Science Foundation (NSF) (USD$10 million), and the US Department of Energy (DOE) (USD$25 million). All three already have quantum programs in place (see *MRS Bulletin*, doi:10.1557/mrs.2019.49).

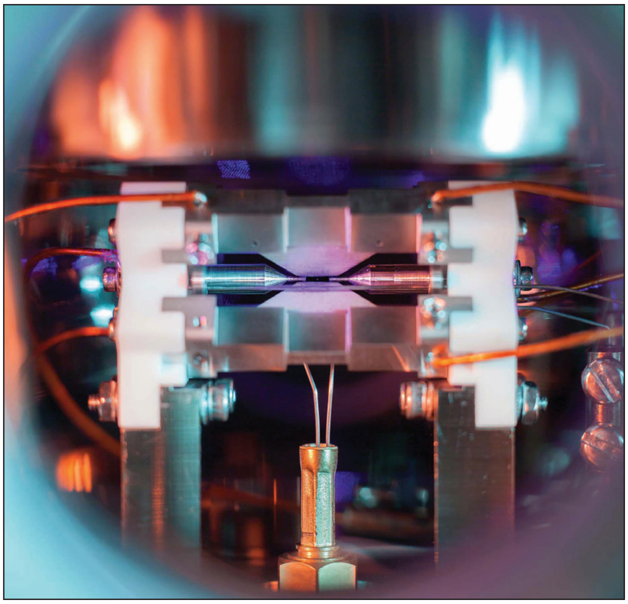
This summer, the White House Office of Science and Technology Policy (OSTP) partnered with DOE to further quantum materials education and research.

In response to the OSTP/DOE partnership, Awschalom tells *MRS Bulletin*, "When this intriguing opportunity arose, our team began to identify the most important challenges of quantum information science that could not be easily addressed by a single group and that, if overcome, would revolutionize the field."

One of the challenges they chose to address is developing the science and technology to control and distribute quantum information across distances ranging from microns to kilometers. "We felt that if you don't produce these types of quantum connections it will be difficult to develop many practical quantum technologies. When you build quantum sensors you need to connect them to quantum machines within an ecosystem that is entirely quantum mechanical," Awschalom says.

To build a communication network, researchers need to link quantum sensors and computers together, he says. For example, a significant level of quantum communication is required to build a quantum supercomputer. "We realized that in order to create and control quantum information with these quantum connections you need the appropriate materials as a basis to build the technology, and that meant we need to create foundries," Awschalom says.

In order to create standardized, characterized high-quality materials for quantum science and technology, Q-NEXT will focus on scaling synthesis and integration of qubits for both semiconducting- and superconducting-based materials for quantum devices and systems. To do so, the Center will create two national quantum foundries, one for solid-state materials at Argonne National Laboratory west of Chicago, and one for superconducting materials at the SLAC National Accelerator Laboratory in California. "The foundries will produce well-characterized quantum materials and devices to support the broad national quantum initiative for the community," Awschalom says.


Oxford-built ion trap with a single strontium ion-qubit held at the center. Credit: David Nadlinger, winner of the UK science photo competition 2018.

Awschalom and his team developed the plan for these foundries working alongside 10 industry partners of Q-NEXT. He likens the materials that these foundries will deliver to the wafers that today's semiconductor companies use to fabricate their own devices. "We need quantum factories that will enable the development of quantum science and technology from sensing to communication to computing. This capability is currently lacking in the United States," he says.

At the Quantum Computing & Simulation Hub in the UK, researchers are concentrating on a wide range of computing and simulation platforms including ion trap and silicon processors, superconductors, diamond nitrogen-vacancy (NV) centers, cold atoms, and photonics. On the software side, they are focused on applications, algorithms, architecture, verification and benchmarking, and on the fundamentals of quantum computers.

O'Brien says, "At present there is no clear winning platform that will ultimately lead to a widely usable quantum computer." Taking a broad view also has other advantages, he tells *MRS Bulletin*: "Working across platforms allows you to learn from one platform to another. For example, error reduction is a challenge for all of the computing platforms and there may be techniques which cross over."

Lucas says, "With the current 1% error rate, we're unable to achieve a quantum computer….We need a large number of qubits to tolerate a high error rate." He tells *MRS Bulletin* that the more mature approaches are superconducting qubits and trapped-ion qubits. For the superconducting platform, such as used by Google and IBM, it may be easier to scale up the system. With trapped-ion qubits, as used by Honeywell and IonQ, he says, "there are fewer qubits under good control, but they are higher precision qubits."

Other consortiums focus on one platform. "The Flagship Project of Q-LEAP Quantum Metrology & Sensing aims at ultrasensitive magnetic sensors using diamond, and focuses on diamond's NV defect control," says Sakai of the Tokyo Institute of Technology. The advantage for this platform in developing solid-state quantum sensors is that spin coherence is good at room temperature and quantum states can be initialized and read out by light.

At Fermilab's SQMS Center, the focus is on the superconductivity platform. "The key problem that we try to overcome is quantum coherence for the lifetime of the qubit," Grassellino says. "The lifetime fully depends on how long

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the photon can live inside of a cavity or the transmon qubit before the quantum state gets destroyed or the photon gets absorbed. That depends on the material we use."

The superconducting two-dimensional transmon qubit is being used by Google and IBM where the qubit lifetime lasts for tens of microseconds. "We'll be building a quantum computer using the 3D [three-dimensional] superconducting architecture," Grassellino says, which is based on their ultrahigh-quality-factor (ultrahigh-q) 3D resonator. One of the major partners in the consortium is Rigetti Computing. "From Rigetti, we'll receive hundreds of qubits that Fermi will distribute to the different research groups," she says, from which they will be able to analyze materials properties. At Fermilab, researchers will insert the Rigetti qubit inside their 3D device to study how they will preserve the lifetime of the quantum state inside the cavity.

"Our vision after five years is to be a national user facility," Grassellino says. "One of the things we want to build is a materials test bed where materials to be employed for quantum can be started in the most sensitive environment."

Another outcome of Q-NEXT, says Awschalom, is a quantum devices database. "The database will be available to the scientific community and will serve as a collection of benchmarks and references for different materials of relevance to quantum technology," Awschalom says. "It will serve as a resource for both theorists and experimentalists who will have access to the latest materials and device performance parameters and references."

In 1992, when Awschalom received the Outstanding Young Investigator Award from the Materials Research Society (MRS), he presented a talk on "Spin dynamics and tunneling in quantum magnetic systems" (see the award announcement in *MRS Bulletin*, doi:10.1557/S0883769400041129). At the time, quantum science was just barely entering the materials research realm. "I think what's changed are advances in our understanding of the underlying science, materials research, and measurement techniques that are relevant to quantum technology. Taken together, these accomplishments have pushed forward new ways to create and control quantum states in broad classes of materials," Awschalom says. "More mature quantum systems have emerged that are driving science and technology, enabling scientists and engineers to prototype devices and identify powerful materials platforms."

"To build a national resource focusing on pristine materials for quantum science and technology is an extraordinary opportunity for the national labs, universities, and industries—we all need access to these materials," he says.

O'Brien and Lucas at the UK Hub agree. The UK initiative incorporates the technology component. "Research in universities and national labs has matured to a point of more and more industry interest and investment interest with no sign of progress slowing down," Lucas tells *MRS Bulletin*.

At the Hub, specific mechanisms are in place to work with industry. Events are held at which early-career researchers can learn about career opportunities in quantum information science. Similarly the DOE centers are developing workforce programs that introduce students to research opportunities in industry.

Scientist Alex Romanenko holds up a small superconducting radio-frequency (SRF) cavity in Fermilab's Quantum Laboratory. Fermilab specializes in SRF cavities for particle physics and is now extending their applications into the world of quantum science. Credit: Reidar Hahn, Fermilab.

Quantum education

Education and training the quantum workforce is another part of the US National Quantum Initiative. In the OSTP/NSF announcement of the National Q-12 Education Partnership, NSF Director Sethuraman Panchanathan says, "Through close collaboration with academia, industry, and partner agencies, the National Q-12 Education Partnership will increase the technical literacy of students, expanding inclusion and broadening participation for a future workforce that will bring benefits to all of us."

Earlier this year, a workshop was convened on behalf of the Interagency Working Group on Workforce, Industry and Infrastructure under the National Science and Technology Council Subcommittee on Quantum Information Science to which were invited 25 researchers and educators spanning the range of quantum disciplines and educational outreach specialists. The goal of the workshop, sponsored by NSF, was to develop key concepts for future quantum information science learners.

Among the materials researchers who participated in the workshop are Tina Louise Brower-Thomas, executive director and PI for Howard University and education director for the Center for Integrated Quantum Materials, and Christopher Richardson of the

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Laboratory for Physical Sciences at the University of Maryland.

"'Quantum state' is a mathematical representation," says Brower-Thomas, "but it's based upon a physical system—that could be an atom, it could be a trapped ion, for example—but even to get to the quantum state you have to consider the material."

What Brower-Thomas and Richardson both point out is the importance of bringing in the language of various disciplines in order to develop key concepts for quantum information. "My work at MRS as part of the quantum staging group was also helpful at the workshop," Richardson says. "In the MRS quantum staging group we are focused on creating a community at MRS for researchers working in materials for QIS [quantum information science] and quantum materials. This experience was also helpful at the workshop because it has provided opportunities for me to discuss QIS concepts with a broad range of materials researchers. These discussions have helped me understand how non-QIS experts build their understanding of QIS concepts."

By bringing in the range of disciplines involved when developing the key concepts, says Brower-Thomas, "high-school teachers keep in mind how diverse the field is."

"We don't want to lose anyone," she says. "We don't want to lose people who are chemists, engineers, physicists; we want everyone who has an interest in STEM [science, technology, engineering, and mathematics] from different backgrounds to see themselves in these terms, in these ideas, when they're taught by their high-school teachers."

Furthermore, Brower-Thomas—who is also co-director of Diversity & Culture of Inclusion for a new NSF Engineering Research Center: The Center for Quantum Networks—says it is important that she represented Historically Black Colleges and Universities (HBCUs) at the workshop. She says HBCUs produce the largest number of graduates from underrepresented groups in STEM who go on to receive their PhD degrees. "These are our future professors, the people who will be engaging the broader audience and getting young folks involved or interested. If they don't see someone who looks like them who's doing the work, they may not have in their mind that this is something they could contribute to."

Edwards agrees. When she and co-principal investigator Diana Franklin, from the University of Chicago, put in their proposal to develop "Q2Work," increasing women and minority representation at the college level was part of their goal. Their proposal was accepted last summer and the program is facilitating the National Q-12 Education Partnership.

The Q2Work website will serve as an aggregator of QIS education resources. Furthermore, their project will convene workshops with stakeholders who will develop steps to incorporate QIS education into existing standards of learning and curricula.

As they are just now at the beginning stages of contributing toward the development of the quantum education community, Edwards tells *MRS Bulletin* that their program can work on growing a quantum workforce that is inclusive and diverse. "Since QIS is young then we have a chance, as a community," she says, "to consider issues of inclusion and diversity and learn from the efforts of other fields, such that we can grow this diverse workforce successfully."

Judy Meiksin

EU announces European Green Deal €1 billion investment

The European Commission has launched a €1 billion (~USD1.2 billion) call for research and innovation projects that respond to the climate crisis and help protect Europe's ecosystems and biodiversity. The Horizon 2020-funded European Green Deal Call is expected to spur Europe's recovery from the coronavirus pandemic by turning green challenges into innovation opportunities.

Mariya Gabriel, Commissioner for Innovation, Research, Culture, Education and Youth, says, "With innovation at its heart, this investment will accelerate a just and sustainable transition to a climate-neutral Europe by 2050. As we do not want anyone left behind in this systemic transformation, we call for specific actions to engage with citizens in novel ways and improve societal relevance and impact."

Given the urgency of the challenges it addresses, this Green Deal Call aims for clear, discernible results in the short- to medium-term, but with a perspective of long-term change. There are fewer, but more targeted, larger and visible actions than previous calls, with a focus on rapid scalability, dissemination, and uptake.

The projects funded under this call are expected to deliver results with tangible benefits in 10 areas, including clean, affordable, and secure energy; industry for a clean and circular economy; energy and resource efficient buildings; and sustainable and smart mobility.

The call includes opportunities for international cooperation in addressing the needs of less-developed nations, particularly in Africa, in the context of the Paris Agreement as well as the UN Sustainable Development Goals.

The deadline for submissions is January 26, 2021, with selected projects expected to start in autumn 2021. □

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