Testimony of
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Before the
Subcommittee on Research and Technology
Committee on Science, Space, and Technology
U.S. House of Representatives

May 8, 2019

"A Review of the National Science Foundation FY 2020 Budget Request"

A Celebration of Science

"The activity of science being necessarily performed with the passion of hope, it is poetical."
– Samuel Taylor Coleridge, letter to chemist Humphry Davy

The race to the Moon, the invention of the internet, the sequencing of the human genome, the quest to observe gravitational waves, the ambition to take a picture of a black hole – these scientific and engineering pursuits have revolutionized our understanding of the universe, our world, and ourselves. We know that all of these big projects are great achievements – but as scientists, as explorers, as innovators, we also know that they are milestones, not endpoints. They each spawned whole new avenues of discovery research, innovation, and invention.

Bold, inspirational, question-driven science and engineering projects like these are built on the bedrock disciplinary research that is a core of the National Science Foundation's mission. At the same time, such breathtakingly ambitious projects bring together researchers from across disciplines, challenging them to do something entirely new through a creative collision of ideas and expertise. In the process, we push the frontiers of science and engineering (S&E), producing new knowledge and new technologies that in turn spur new disciplinary and interdisciplinary research, fueling a powerful circle of curiosity, effort, and achievement. Only the federal government can ignite such endeavors, because they require a strategic long-term commitment to ideas with enormous potential – and the freedom to fail. Yet history has shown that taking these risks has paid off time and time again, with all sectors of our "knowledge ecosystem" – universities, government laboratories, industry – contributing to and benefiting from these visionary projects.

The 2017 Nobel Prize-winning discovery of gravitational waves is a recent example of a project that required long-term strategic planning and a commitment to patient investment. We often think of the Laser Interferometer Gravitational-Wave Observatory (LIGO) as a physics or astrophysics breakthrough. In reality it succeeded by drawing on many fundamental disciplines: not only physics, astronomy, and math, but also computer science, engineering, and materials research. LIGO moved from the realm of theory to research and development to construction only because the researchers developed and leveraged new technologies that made what was previously impossible possible. And this was an all-hands-on-deck project for the science, technology, engineering, and math (STEM) workforce, from PhD research scientists to expert engineers to skilled technical workers and skilled craftsmen who built and continue to maintain the instruments, particulate controls, and ultra-high vacuum equipment.

The lesson I take from LIGO, the Moon landing, the invention of the internet, and the Human Genome Project is that government leadership and willingness to take risks lets us do, create, and discover things that would have remained undone, unmade, and undiscovered without taxpayer investment. And when our scientific and elected leaders convey a spirit of adventure and excitement and belief in the national importance of this work, they inspire people to join these projects and students to see the wonder of STEM.

It would be easy to look at the triumphs of the last century and conclude that the best discoveries and innovations are in the rear-view mirror. I draw the opposite conclusion. By building on that knowledge and technology we can ask and answer questions that were in the realm of idle speculation even a decade ago. CRISPRs, AI, multi-messenger astronomy, genomics, big data, and quantum information systems are all right now opening broad new frontiers of science and engineering.

On top of that there are structural reasons to think that the best of science and engineering lies ahead of us. Before NSF was founded, S&E research was focused on using new discoveries to develop technologies used toward victory in World War II. In *Science - the Endless Frontier,* Vannevar Bush presented a vision for a new model, in which individuals with advanced degrees working at elite universities performed government-supported research. Since then, our national S&E ecosystem has changed and grown. Today, unlike at the turn of World War II, it involves many more actors, with differing motivations and expertise. Private corporations, non-profit foundations, many types of higher education institutions, including minority serving institutions, and federal agencies all fund activities with goals that are sometimes complementary, but also sometimes in competition with one another. In areas such as AI and quantum computing, all of these actors have their own reasons for pursuing the innovations that derive from fundamental research. The key is to not waste valuable resources on duplication of effort and to leverage the competitive advantages of our unique ecosystem. To this end the NSB supports OSTP Director Kelvin Droegemeier's idea to undertake a regular assessment of the status of the nation's R&D enterprise. In doing so, the federal agencies, including NSF, can more accurately identify opportunities and gaps in our nation's basic research portfolio.

The Board has also been thinking expansively about the future – about what we need to do now to enable the transformative research of tomorrow. As it has been almost 15 years since the NSB last published a vision for the future of fundamental S&E research, we are developing a *Vision 2030* to guide NSB actions and priorities over the next decade. While as Niels Bohr said, "It is very difficult to predict, especially the future," the exercise is an important part of strategic planning. International partnerships, collaboration and competition, research integrity, role of AI and big data, and the state of STEM education and the workforce rank high on the NSB's list of critical topics for exploration.

OSTP's proposed assessment, the Administration's five-year strategic plan for STEM education,[1] NSB's *Vision 2030,* NSF's 2022-2026 Strategic Plan, the NSF 2026 Idea Machine, and the work of this Committee will all help develop our strategy for this new era of discovery. We have an opportunity to demonstrate that the U.S. is determined to retain its position at the vanguard of science and innovation. To succeed in today's increasingly competitive, technological, knowledge-intensive world, we must celebrate our public commitment by renewing our support for the fundamental science and engineering that has been a core element of US security and prosperity in the last century. This commitment would entail strengthening our assets – a diverse, flexible STEM-capable workforce, state-of-the-art research facilities, world-class educational institutions, an innovative private sector, and forward-thinking policymakers – to help the nation prosper in the new global knowledge-intensive economy. And crucially, all of us – political leaders and S&E practitioners alike – must ensure that all Americans can participate in and benefit from advances in science and technology, and we must communicate clearly about the value of our S&E enterprise to the country and its citizens.

What do we need to do to enable transformative research?

> *"The great driver of scientific and technological innovation [in the last 600 years has been] the increase in our ability to reach out and exchange ideas with other people, and to borrow other people's hunches and combine them with our hunches and turn them into something new. …Chance favors the connected mind."*
> – *Steven Johnson,* Where Good Ideas Come From: A Natural History of Innovation

Last year when my predecessor testified before this Committee, she highlighted that the 2018 *Science & Engineering Indicators* report confirmed a trend that we have observed for several years now: that while the U.S. remains a major global player in S&E, other countries have seen the benefits of investing in research and education and are following our example. The world of S&E, historically centered around the U.S., Western Europe, and Japan, is increasingly multipolar. Emerging economies, particularly of China and other countries in the Asia/Pacific region, are becoming major actors and near peers. These trends are expected to continue as more nations recognize that investments in research and development (R&D) translate into economic growth and create jobs. Congress recognized this and responded in FY 2019. The Board expresses its deep appreciation to Congress for demonstrating strong, bipartisan support for

[1] *Charting a Course for Success: America's Strategy for STEM Education*. The National Science and Technology Council, December 2018.

fundamental research. Now, as we look forward to FY 2020 and beyond, we ask: what does S&E leadership mean in this new context? What does it mean for U.S. S&E policy? In this competitive global landscape, what do we need to do now to continue to enable truly transformative research?

The answers are not easy, but the solutions are not unknown. There is no silver bullet, but there is wide agreement on many things. This Committee had an excellent hearing in March on U.S. leadership in science. All witnesses, again and again, echoed the same needs and the same themes. They highlighted the need for a strategy, a plan for prioritizing our focus and exploiting our many competitive advantages. We need predictable, sustained investment in the fundamental research that is intertwined with our nation's economic growth and we need to be cognizant of the investments of other nations who are trying to emulate our robust S&E ecosystem. We must diversify our STEM-capable workforce as, according to the Census Bureau, by 2042 our country will be a majority-minority nation. Thus, we must utilize the abilities and creativity of *all* our citizens, in all demographics and at all education levels, while continuing to welcome talent from across the globe. This means improving STEM education here in the U.S., for example by giving everyone the opportunity for hands-on learning starting at an early age. We must provide our citizens with the problem-solving skills needed for the lifelong learning that is now required to adapt and thrive in a rapidly changing job market, one often driven by advances in S&E.

What would a renewed national commitment to fundamental research look like?

Steady, predictable, federal funding for fundamental research commensurate with the growth of our knowledge-intensive economy.

In 1960, government spending on R&D was 1.69% of our GDP.[2] Today, that number has fallen to only about 0.7% as the economy has grown.[3] As we said last year when we came before this Committee, this is particularly challenging for our leadership in S&E. China is set to soon surpass us in gross R&D expenditures.[4] While business sector investment in R&D has recently grown faster than the government's, the lion's share of business sector investment has been on the applied side. The federal government provides almost half of all basic research funding, with the business sector providing 27%.

Within the realm of basic research, there are significant differences in the scope and time horizons of research funded by private business and that funded through federal agencies. Industry research often focuses on targeted goals likely to reap an acceptable return on the investment within a relatively short time horizon, or offer essential competitive advantages, for instance in AI. For early phase basic research it can take decades for a breakthrough to blossom into the next great innovation – and again: predictions are hard, if not impossible. The government is uniquely able to invest in curiosity-driven research over a long-time horizon.

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[2] National Science Board. *Science and Engineering Indicators 2014*, Appendix Table 4-1.
[3] National Science Board. *Science and Engineering Indicators 2018*, Figure 4.3.
[4] National Science Board. *Statement on Global Research and Development (R&D) Investments*. NSB-2018-9, 2018.

History has shown that such investments are an essential part of our innovation ecosystem, setting the stage for the directed research of the mission agencies and the private sector.

At NSF, things have changed significantly even in my time on the Board. As recently as 2000, NSF's funding rate for grant proposals was 33% (total submitted proposals: 29,508). In FY 2017, the funding rate was 21% (total submitted proposals 40,678). Going unfunded were $1.6 billion in proposals rated better than "Very Good."[5] Funding those grants is the difference between our current funding rates and the historical norm of ~30%. It is also the difference between a researcher's ability to secure funding to pursue promising ideas without excessive administrative burden in the form of constant proposal writing – and the search for a new career. Furthermore, individual investigator proposals are only one component of NSF's mandate to promote the progress of science. As described in two NSB reports to Congress in 2018, significant challenges exist in large facility operations and maintenance (O&M) and mid-scale research infrastructure.[6] While NSB applauds the initial response to those reports in the FY 2020 request, we remain mindful that we cannot hope to continue to be preeminent in S&E, and compete with the world's best, if we are leaving potentially game changing ideas on the table for others to find.

Development and implementation of a long-term strategy for our S&E enterprise.

As the participants in your March hearing on U.S. leadership in science articulated, we need to formulate a strategy that considers everything from national needs to competitive advantages to technological opportunities. We need an enduring commitment to S&E leadership. An effective plan, built on a holistic evaluation of our national research portfolio, would help us match our strategic priorities with our investments. China has declared its intent compete in AI, quantum computing, and 5G wireless systems; NSB endorses the Administration's efforts, including in this Budget Request, to make the U.S. a leader in these areas. But this is only one part of a long-term committed strategy: many other things, including Congressional buy-in, private sector partnerships, and support for basic research are also essential for success.

For its part, NSF has identified ten Big Ideas as agency-level strategic priorities, detailed in the Budget Request. These Big Ideas include preparing for the Future of Work in a world with AI, Harnessing the Data Revolution, and the Quantum Leap, an investment exploiting quantum interactions to produce novel materials and next-generation information technologies. These are in coordination – not competition – with our disciplinary investments, ensuring that NSF welcomes the best ideas of scientists and engineers *and* that the agency is more than the sum of its parts. The Big Ideas and our new Convergence Accelerators build from disciplinary bedrock to tackle new questions and discovery spaces that are inherently transdisciplinary. They focus on frontiers where we need to draw on expertise from the disciplines and bring researchers together in new ways. In turn, the insights gained from these interdisciplinary efforts feed new ideas, tools, and techniques back into the core disciplinary research. As scientists and engineers in the

[5] Report to the National Science Board on NSF's Merit Review Process, Fiscal Year 2017, preliminary draft.
[6] National Science Board. *Study of Operations and Maintenance Costs for NSF Facilities* and *Bridging the Gap: Building a Sustained Approach to Mid-scale Research Infrastructure and Cyberinfrastructure at NSF*. 2018.

"innovation agency," the NSB commends Director Córdova for experimenting with our own structures, and not being risk averse.

NSF has long sought a balanced portfolio, one that recognizes and embraces the knowledge that transformational discoveries often grow out of repeated "dead-ends." The only real failure in research is when you stop learning. Our portfolio, and this Request, balances large, long-term investments like LIGO with awards to individual investigators and small teams that can nimbly pursue innovative, out-of-the-box research. Affording them the time and space to think creatively and experiment – including by reducing administrative burdens – is just as important for long-term success as the marquee discoveries that captivate and delight us all.

This Request also balances a robust portfolio of facilities and infrastructure at multiple scales with awards to the researchers who depend on the observations and data they produce. The challenge for our long-term strategy is to balance the facilities that we use today with the need for new cutting-edge facilities to further our knowledge tomorrow. We know that investment in scientific infrastructure at all scales is essential to U.S. competitiveness in S&E – but we also know that the cost of frontier-busting facilities will continue to increase. This will place a premium on balancing not only the portfolio mix between existing and new facilities, but also the balance between unilateral and partnership funding models. These issues became very clear in NSB's 2018 research infrastructure-related reports to Congress. As the agency engages in strategic planning for its facilities portfolio, NSB and NSF are working together to ensure that NSF is positioned to provide the future research infrastructure needs of the U.S. scientific community for decades to come. For all of these efforts, NSB has been working closely with the Chief Officer for Research Facilities – a partnership that has proved to be invaluable. The Board thanks Congress for recognizing the need for this position and creating it in the American Innovation and Competitiveness Act (AICA).

To continue the great legacy of American innovation and fulfill the potential to reach even greater heights, any successful long-term strategy must include a commitment to develop the domestic human capital that exists in every classroom across the country. STEM education across all demographic groups and geographic regions, beginning in primary school and continuing across all levels of education, is essential to the maintenance of economic prosperity in an ever-increasingly technological world. Ensuring that all Americans are STEM-capable is an ambitious goal, and one which requires the effort of many partners across government at all levels, working together with the private and non-profit sectors. For its part, NSF has embraced this challenge through numerous programs, including one of its Big Ideas, NSF Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science (INCLUDES); the Established Program to Stimulate Competitive Research (EPSCoR); and the Advanced Technological Education (ATE) program. These and other programs operate within both the Directorate for Education and Human Resources (EHR) and the S&E research directorates.

Understanding the U.S. STEM workforce, and what is needed to ensure that this workforce is inclusive and leverages the ability and curiosity of all our people, has been a NSB priority for several years. In our 2015 report, *Revisiting the STEM Workforce*,[7] we focused on "big picture" concepts including the breadth of the STEM workforce, the existence of multiple segments within the workforce each with its own story, and the fact that STEM knowledge and skills enable multiple, dynamic career pathways. The Board's 2018 policy brief, *Our Nation's Future Competitiveness Relies on Building a STEM-Capable U.S. Workforce*,[8] expanded on these themes and placed additional emphasis on the skilled technical workforce (STW) and on the need to attract demographic groups historically underrepresented in STEM. We have complemented these broadly-themed reports with more detailed examination of segments of the STEM-capable workforce, as we did with our 2017 statement and infographic, *SEH Doctorates in the Workforce*,[9] that focused on the career trajectories of S&E doctoral holders. The next installment in the Board's examination of the nation's S&E workforce is our forthcoming report on the Skilled Technical Workforce. We hope that this report, which is based on 18 months of NSB activities and stakeholder engagement, will complement and inform the recent work on the STW of both Congress and the Administration, in the context of our national conversation about preparing American workers for the jobs of today and tomorrow.

Leading the way in developing and implementing policies to strengthen our national scientific enterprise by improving its practice.

As the participants in your March hearing testified, maintaining S&E leadership is simultaneously becoming more challenging and more critical. In many ways, we need to rethink what "leadership" means. If we continue to rely only on historical "by the numbers" measures such as amount invested in R&D, number of STEM doctorates produced, and the number of scientific articles published, we will lose. As the Board noted last year based on data from *Science and Engineering Indicators 2018*, we are at a pivotal moment in our history as other nations, including China, invest more, aggressively compete for talent, and aspire to define the future of science and engineering.

At the same time, scientific practice and norms are evolving due to new concerns from within – the research community – and without – the new global landscape. We have an opportunity to define leadership as something more than a "numbers game" – to make it about *values*. To begin with, we must embrace our traditions of openness and transparency that have drawn the world's best to our universities and laboratories for decades and continue to show why the land of the free remains the gold standard for fostering intellectual curiosity and research collaboration. This does not mean naivete – we need to protect our national security. The Board strongly affirms[10] the principle behind President Reagan's National Security Decision Directive 189: "our

[7] National Science Board. *Revisiting the STEM Workforce*. NSB-2015-10, 2015.
[8] National Science Board. *Our Nation's Future Competitiveness Relies on Building a STEM-Capable U.S. Workforce*. NSB-2018-7, 2018.
[9] National Science Board. *SEH Doctorates in the Workforce*. 2017.
[10] National Science Board. *Statement of the NSB on Security and Science*. NSB-2018-42, 2018.

leadership position in science and technology is an essential element in our economic and physical security. The strength of American science requires a research environment conducive to creativity, an environment in which the free exchange of ideas is a vital component."

Foreign-born individuals have long been major contributors to our S&E enterprise – as of 2015, over half of our doctoral-level S&E workforce, and a majority of first-year, full-time S&E graduate students in the natural sciences and engineering are foreign-born.[11] At the same time, we must be aware that the world's best minds have choices today that did not exist as recently as 20 years ago in selecting a place to study, perform research, and innovate. Other nations are actively courting globally-mobile talent, sometimes aggressively enough to violate U.S. government policies. Even as we work to broaden and enlarge the pipeline for domestic talent, it is important to continue to encourage the influx of curious, creative, and ambitious young researchers from overseas. At the same time, we should work together with our universities and research laboratories to improve institutional and community awareness of security concerns, ensure adherence to conflict of interest and commitment policies, and strengthen and clarify the necessary security and reporting requirements.

Beyond the issue of openness and transparency, our researchers should aspire to the highest standards and our institutions should exemplify those values. We should strive for results that can be reproduced, demand zero tolerance for fabrication and theft of intellectual property, and cultivate a culture of scientific practice free from harassment and welcoming to all. NSF has led the way in demanding its grantees comply with standards against sexual harassment, and other federal agencies and organizations have begun to emulate the NSF model. NSF and its Inspector General actively enforce research integrity and grants management standards. The U.S., and NSF, can continue to lead the world by setting examples about the responsible conduct of research and by promoting a healthy research environment – in short, by exporting American values.

Inspire the next generation of researchers by speaking with one voice about the value of fundamental discovery research.

When the U.S. was faced with the challenge of Sputnik, Congress chartered this committee as the Committee on Science and Astronautics. Not long thereafter, President Kennedy boldly set a course for the Moon. This call, backed up by the necessary investment, was answered in less than a decade. It is that same sense of national purpose that we need today to remain a leader in the global S&E enterprise. This year we celebrate the 50th anniversary of humanity's first steps on a new world and make plans to return. Today, this journey is joined by myriad, diverse scientific and engineering challenges that also motivate us. Now opportunities, competition, and excitement arise from science and technological advances everywhere, in every field, in research and industry and academia and business.

[11] National Science Board. *Science and Engineering Indicators 2018*. NSB-2018-1, 2018.

Meeting today's challenges requires our national leaders in academia, government, and the private sector to speak together about the importance of fundamental research, reminding ourselves and our fellow citizens why science and engineering matters and about the endless benefits each and every one of us have gained from government investment in fundamental research across all fields. As a member of the NSB for over a decade, it has been my pleasure to witness the example this Committee has set in modeling the standard for bipartisan support in an area of national importance.

As scientists, as policymakers, we are constantly asking the question: how do we get more young people into STEM? Here is one answer: we *inspire* them. My generation was inspired by President Kennedy's quest for the next frontier. Americans are still inspired when their nation asks them to rise to the challenge of audacious goals, solve real problems, and make a difference in the world. Meeting this challenge can be done while learning and doing exciting things: exploring the universe, unlocking the mysteries of the genome, designing faster, safer airplanes, developing technologies to mitigate climate change, and feeding the world. We can call on the curiosity and passion of our citizens and of people from around the globe to help us build the future here, in the U.S. – if we are willing to speak with one voice to celebrate science and engineering, and to back that voice up with a clear commitment and a long-term strategy. We can say to our citizens and to the world: *great ideas are born here.*

NSB and the FY 2020 Request

> *"I am certain that after the dust of centuries has passed over our cities, we, too, will be remembered not for victories or defeats in battle or in politics, but for our contribution to the human spirit."*
> *– President John F. Kennedy*

The Board applauds Director Córdova and her team for their accomplishments during this budget-constrained time. NSF has balanced the various demands on its financial and human capital to chart a course for impactful science that serves the country. The Administration's FY 2020 budget request will enable NSF to make outstanding contributions to the national S&E enterprise.

NSB has been an active partner with NSF management as the Foundation has navigated the evolution of science and engineering over its 70-year history. The increase in the cost of research amid the years of modest budget growth since 2000 have placed a premium on strategic leadership. The need to balance the bottom-up priorities expressed by the science and engineering communities with the agency's strategic imperative is a necessity. The Board has endeavored to offer sound counsel and strategic guidance in recent years through its publication of reports on topics ranging from the STEM workforce to administrative burdens to large facility O&M to mid-scale research infrastructure investments.

Our current priorities include continuing to partner with the Director and her team – including the Chief Officer for Research Facilities – to finish addressing the issues raised in the 2018

reports on NSF's research infrastructure. As mentioned, we are concluding our examination of the Skilled Technical Workforce. We are also working with NSF to make significant improvements to the annual Merit Review Report, and to reimagine *Science and Engineering Indicators,* in order to make both of these reports more timely and accessible for stakeholders. Finally, NSB is drafting a *Vision 2030* to help us plan for the long-term future of fundamental science and engineering research at NSF and for the nation.

As I have previously stated, Director Córdova has charted an excellent course forward for NSF building the Big Ideas and highlighting the importance of convergent research, while fully committing to continued investments in individual investigators, disciplinary research, major research facilities, mid-scale infrastructure, and the latest research instrumentation. NSB looks forward to continuing to work with the Director and her team to realize the full potential of these innovations.

Thank you for the opportunity to testify today, and for your continued support of NSF. I will be pleased to answer any questions you may have.

Diane L. Souvaine

Biography

Computer Science and Mathematics
A.B. c.l., English & Mathematics, Harvard University
M.A.L.S., Mathematical Sciences, Dartmouth College
M.S.E., Electrical Engineering & Computer Science, Princeton University
M.A., Computer Science, Princeton University
Ph.D., Computer Science, Princeton University

Dr. Diane L. Souvaine, Professor of Computer Science and Adjunct Professor of Mathematics, has been a member of the Tufts University faculty since 1998. She served as Vice Provost for Research from 2012-2016, Senior Advisor to the Provost from 2016-2017, and Chair of the Department of Computer Science from 2002-2009.

Prior to Tufts, Dr. Souvaine was a member of the Rutgers University faculty for 12 years. During her tenure at Rutgers, she served for 2.5 years in the Directorate of NSF's Science and Technology Center for Discrete Mathematics and Theoretical Computer Science (DIMACS), a groundbreaking academic/industry collaboration of Princeton, Rutgers, Bell Labs and Bellcore. DIMACS is tasked with both the theoretical development of mathematics and computer science and their practical applications.

Dr. Souvaine's research contributions range from solving challenging problems in computational geometry to practical application across disciplines. Her work extended the results of straight-edged computational geometry into the curved world. Visibility, triangulations and geometric graphs represent another focus of Dr. Souvaine's research as does the application of computational geometry to statistics. Her research led to consulting engagements with corporations such as Exxon Chemical Research, IBM and Pfizer.

Elected Chair in 2018, Dr. Souvaine is in her second term on the National Science Board to which she was appointed in 2008 and 2014. She previously served as Vice Chair from 2016-2018, has chaired NSB's Committee on Strategy and Budget and its Committee on Programs and Plans, and served on its Committee on Audit and Oversight, all of which provide strategic direction, and oversight and guidance on NSF projects and programs.

In addition to her scientific and policy contributions, Dr. Souvaine is dedicated to increasing diversity and advancing women and underrepresented groups in mathematics, science, and engineering and works to enhance pre-college education in mathematics and computational thinking.

Dr. Souvaine is a Fellow of the American Association for the Advancement of Science (AAAS) and of the Association for Computing Machinery (ACM), and was a 2005-2006 Fellow of the Radcliffe Institute for Advanced Study. Among many other accomplishments, she was the recipient of the 2008 Lillian and Joseph Leibner Award for Outstanding Teaching and Mentoring.