Correction

COLLOQUIUM

Correction for "Creativity and collaboration: Revisiting cybernetic serendipity," by Ben Shneiderman, which was first published February 5, 2019; 10.1073/pnas.1807200116 (*Proc Natl Acad Sci USA* 116:1837–1843).

The author notes that, on page 1840, left column, second full paragraph, lines 4–5, Jeffrey Heer should have been included in the list of speakers, along with Maneesh Agrawala, Alyssa Goodman, Katy Börner, Fernanda Viegas, and Jonathan Corum.

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Creativity and collaboration: Revisiting cybernetic serendipity

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creativity | collaboration | disciplinary integration | cybernetic serendipity

The Sackler Colloquium "Creativity and Collaboration: Revisiting Cybernetic Serendipity" was held at the building of the National Academy of Sciences in Washington, DC on March 13–14, 2018 (www.nasonline.org/Cybernetic_Serendipity). This Sackler Colloquium celebrated the 50th anniversary of the famed art exhibit "Cybernetic Serendipity" by reconsidering how disciplinary partnerships could more reliably produce breakthrough discoveries and powerful innovation (Fig. 1). The organizer's ambition was to redirect the history of ideas, restoring the Leonardo-like close linkage between art/design and science/engineering through widespread use of internet-enabled creativity and collaboration.

Abraham Lincoln founded the US National Academy of Sciences in 1863 by way of an Act of Congress. The National Academy of Sciences Congressional Charter stipulated a nongovernmental advisory organization of scholars whose role was to "investigate, examine, experiment, and report upon any subject of science or art."

That charter, which combined "science and art" came at a time in which those disciplines were seen as closely related, maybe still infused with the spirit of Renaissance thinkers, such as Leonardo da Vinci, whose brilliant integration of art, design, science, and engineering produced astonishing breakthroughs and bold creations that have endured for 500 y. Leonardo's training as an artist enabled him to make more accurate medical drawings, see the movement of bird wings, understand the dynamics of flowing water, and much more.

Leonardo's integrative style inspired 19th century scientists, engineers, designers, and artists, such as Charles Darwin, Louis Pasteur, James Audubon, Ada Lovelace, Samuel Morse, and others who gracefully wove together these diverse disciplines. However, during the 20th century the pressures for specialization and the emphasis on rational thinking methods pulled the sciences away from the arts. This split led to C. P. Snow's controversial essay that portrayed the gulf between what he called the "two cultures" (1). He encouraged closer connections between the two cultures, but many critics wondered how to more reliably ensure that human values and societal needs guided science and engineering.

The thirst for and opportunities to be gained from a broader vision began to emerge, maybe with the work of Buckminster Fuller, whose concept of "comprehensive anticipatory design science" was inspirational to many. Fuller's geodesic domes, support for educational technology, and global environmental visions demonstrated the kind of integrated thinking, which is easy to trace back to Leonardo. Buckminster Fuller, who was awarded the Presidential Medal of Freedom for his contributions, was a firm believer in the power of individuals to produce large changes.

Fuller may have been the catalyst for historic changes that began to raise the profile of design thinking, a research method that is sensitive to human values, devoted to advancing human needs, and protective of the planetary environment. His prominent advocacy of well-designed technology to advance human welfare and address societal needs surely contributed to the formation of the National Academy of Engineering in 1964, 101 y after the establishment of the National Academy of Sciences.

To study the changes of interest in science, engineering, art, and design I used the Google Ngram Viewer (https://books.google.com/ngrams), which provides search capabilities for the frequency of words over time across 20 million English language books (Fig. 2). I was startled to find that design has grown so dramatically in its importance during the past century. The emergence of

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Fig. 1. Poster announcement for National Academy of Sciences' Sackler Colloquium on "Creativity and Collaboration: Revisiting Cybernetic Serendipity."

design is not due to Steve Jobs and Jony Ive, but they were part of a larger movement.

Design is more than a way to make nicer brochures and better consumer products. Design is more than a component of engineering, as in chip design or structural design. Design is a fresh way of thinking about how we shape human experiences and our environment through better services that improve business, widely used mobile devices that weave families together, and potent web-based resources that give access to information. Designers teach a fresh way of thinking that calls for heightened sensitivity to human needs, greater empathy for the people who use technology, and increased willingness to engage with stakeholders as partners and participants. Designers also raise awareness and appreciation for diversity: old and young, men and women, novices and experts, people from different cultures, and people with varied abilities and disabilities.

I see design as such a vital discipline that I propose the creation of a National Academy of Design by the year 2065, just 101 y after the establishment of the National Academy of Engineering and 202 y after the establishment of the National Academy of Sciences. Design thinking, infused with art, science, and engineering, is increasingly shaping the world by way of products and services, as well as novel research methods and innovative social structures.

How This Sackler Colloquium Emerged

This Colloquium began when Jill Sackler requested that the National Academy of Sciences hold a Sackler Colloquium to

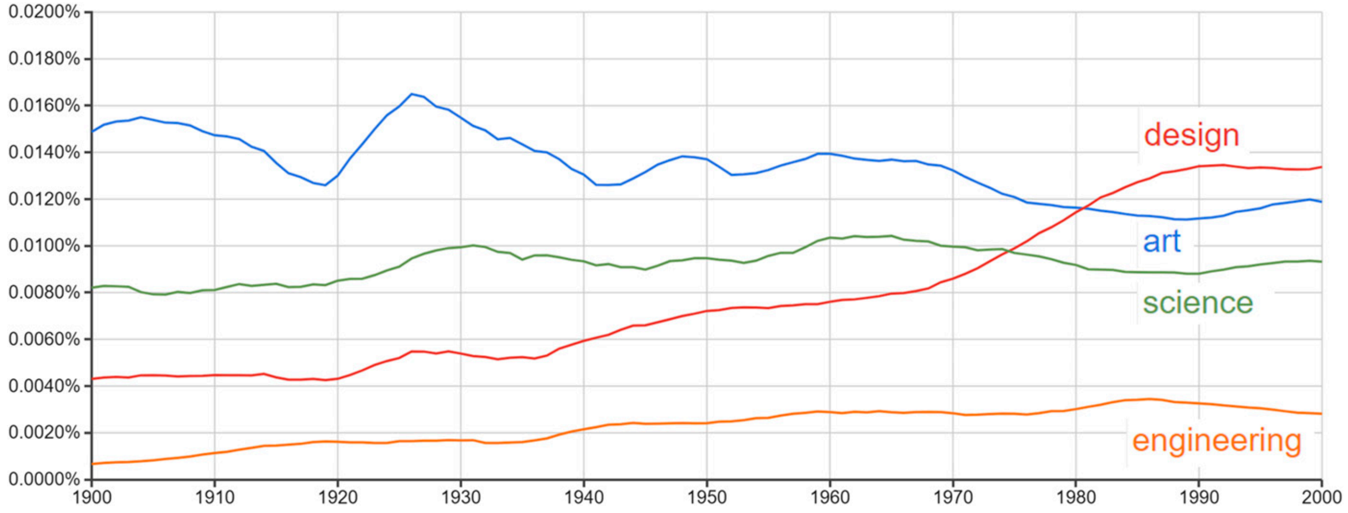

Fig. 2. Frequency of word occurrences in the 20M English books in the Google Ngram Viewer.

celebrate the 50th anniversary of the famed exhibit "Cybernetic Serendipity," which was held in London in 1968 (www.nasonline.org/programs/sackler-colloquia/completed_colloquia/cybernetic-serendipity-background.pdf). That influential exhibit, seen by 60,000 people, was organized by Jasia Reichardt. "Cybernetic Serendipity," which opened in a time of political turmoil and rapid technological advances, celebrated the innovative ways that artists and technologists worked together to create entrancing art, sculpture, music, animations, videos, and much more. The goals of the contributing artists and technologists were to delight, surprise, and sometimes annoy audiences with their creations.

This Colloquium uses the historical framework of the "Cybernetic Serendipity" exhibit to look at how the context has changed. This forms the foundation for asking questions of how collaboration and creativity is impacting practice and research today. How should we reenvision research policy and educational structures to maximize the impact of partnerships with design, art, and humanities? How can we productively engage business, government, and nongovernmental organizations as research and educational partners?

We recognized that valuable work has been and continues to be done by many organizations with similar goals, such as: Alliance for the Arts in Research Universities (a2ru, https://a2ru.org/), Ars Electronica (https://ars.electronica.art/about/en/), Art & Science Collaborations, Inc. (asci.org/), Association of Science-Technology Centers (https://www.astc.org/), Innovation Collaborative, https://www.innovationcollaborative.org/council.html), ISEA International (formerly Inter-Society for the Electronic Arts, www.isea-web.org/), Leonardo/The International Society for the Arts, Sciences and Technology (Leonardo/ISAST, https://www.leonardo.info/), National Art Education Association (https://www.arteducators.org/about), and the National Science Teachers Association (https://www.nsta.org/about/). However, we believe that this Sackler Colloquium represents a new and substantial effort in the National Academy of Sciences, which complements the public outreach efforts of the Cultural Programs of the National Academy of Sciences (www.cpnas.org).

The Organizing Committee, which included Maneesh Agrawala (Stanford University), Alyssa Goodman (Harvard–Smithsonian Center for Astrophysics), Youngmoo Kim (Drexel University), and Roger Malina (University of Texas-Dallas), set out a bold vision for this Colloquium:

> Our ambition is to redirect the history of ideas, restoring the Leonardo-like close linkage between art/design and science/engineering. We believe that internet-enabled collaborations can make more people more creative more of the time.

This goal of restoring integrative ways of thinking drove the deliberations of the Organizing Committee, which worked hard to select, invite, and engage with our dream team of exceptionally strong speakers. Because we sought broad attendance, we wanted to enable participation from those who could not afford the full registration fee. We thank the Simons Foundation for stepping forward to support the reduced registration fee for those who requested it.

Overview of the Events

This Colloquium began with the March 12, 2018 Student Fellows Symposium, which brought together 54 graduate students from across North America. They were chosen from almost 200 applicants who represented an astonishingly broad range of disciplines. This Student Fellows Symposium, organized by Profs. Liese Zahabi and Molly Morin, gave the students a chance to present their work to each other in a spirited day filled with energetic discussions. This first-ever Student Fellows Symposium, sponsored by the Sackler Foundation and Google, brougtht youthful energy and fresh thinking to our events, helping to support our goal of substantive and sustainable change.

There were also three art exhibits organized by J. D. Talasek, who heads the Cultural Programs of the National Academy of Sciences, featuring the work of remarkable artists: Paul Brown (www.cpnas.org/exhibitions/archive/process-chance-and.html), Luke Dubois (www.cpnas.org/exhibitions/archive/r-luke-dubois-love-in-the.html), and Neri Oxman (www.cpnas.org/exhibitions/archive/aguahoja.html).

Agenda. The main Sackler Colloquium on "Creativity and Collaboration: Revisiting Cybernetic Serendipity," was held on March 13–14, 2018 with a diverse set of speakers representing fresh ways of thinking about the integration of art, design, science, and engineering. The thoughtful opening talk by Jasia Reichardt described emerging art and technology communities in Paris, Tokyo, and London. On day 1 there were two sessions and an evening Keynote; then on day 2 there were two sessions (Fig. 3).

The power of art and design were featured in the first session (Roger Malina, Patrick McCray, Curtis Wong, Sara Diamond) in which speakers took inspiration from the 1968 exhibit of "Cybernetic Serendipity" and made a powerful case for the value of design thinking. The speakers showed potent examples of design excellence and reported on the benefits of, to quote Sara Diamond, "artists and designers working in concert with STEM [science, technology, engineering, math] disciplines in order to act as transformative social, economic, environmental, and cultural agents."

The second session on information visualization demonstrated how design thinking combined with a deep understanding of human perceptual abilities enables the creation of novel interactive information visualization tools (Maneesh Agrawala, Alyssa Goodman, Katy Börner, Fernanda Viegas, Jonathan Corum). The speakers demonstrated how interactive exploration, when combined with statistical methods and embedded in modern information visualization tools, lead to more effective analyses. Researchers in every field can use interactive information visualization tools for: more effective detection of faulty data, missing data, unusual distributions, and anomalies, deeper and more thorough data analyses that produce profounder insights, and richer understandings that enable researchers to ask bolder questions.

Visualization examples included ice flow patterns across Antarctica, dynamics of galaxy formation, and machine learning with deep neural nets. In addition, data-driven story-telling is revolutionizing journalism while empowering a new generation of software-savvy artists and designers to help us understand the world around us.

The evening keynote speaker was Smithsonian Secretary David Skorton, a respected scholar, visionary thinker, and inspirational leader. His talk "Branches of the Same Tree," based on a quote from Albert Einstein, emphasized the unity of diverse disciplines. He described the thinking behind the recent report on integrating humanities and arts with the sciences, engineering, and medicine (www.nap.edu/24988) (2).

The third session presented an early briefing on the National Academies report "The Integration of the Humanities and Arts with Sciences, Engineering, and Medicine in Higher Education: Branches from the Same Tree" (2) (David Skorton, Youngmoo Kim, Tom Rudin, Laurie Baefsky, Pamela Jennings, Robert Root-Bernstein). This major report (2), compiled by a diverse and distinguished committee over a 2-y process, highlights opportunities in higher education to give students more diverse backgrounds and skills, while also raising awareness of the ethical issues surrounding their work. Further perspectives on how art and design benefit science and engineering included evidence on the strong relationship between arts and crafts activities and high levels of research accomplishment (Robert Root-Bernstein, John Maeda, Robert Semper).

The fourth session showed how the transformative power of design coupled with internet-based access enables an historic shift to greater participation and collaboration (Jennifer Preece, Laura Trouille, Julia Parrish, Niki Kittur, Zeynep Tufekci). Teamwork is the new normal, and the evidence is strong that teamwork produces better research. In the past 60 y, science and engineering research paper authorship has gone from primarily single authors to 90% coauthor teams, sometimes including more than 1,000 authors. The internet-based teamwork tools, such as video conferencing, shared documents, and open datasets, appear to have accelerated the pace of collaboration and the quality of the work. Evidence from citation analysis shows that teamwork produces stronger papers that attract more citations and have greater impact.

New forms of crowdsourced research, such as citizen science, enable projects that collect and analyze large datasets. New forms of social media research enable the gathering of vast amounts of data about human behavior, as well as the chance to study evolving trends, track emerging influential leaders, and understand the dynamics of controversy. However, the dark side of social media needs to be acknowledged, understood, and controlled so as to develop methods that reduce the impact of cyber-bullying, cybercriminals, fake news, hate groups, oppressive governments, and terrorist organizations. Every researcher needs to take responsibility for the ways in which their work is used, while doing what they can to counter unanticipated negative impacts.

Four Paths to Collaboration. Many of the talks give examples of how the integration of art, design, science, and engineering actually takes place. Our thinking emphasized the benefits to science and engineering researchers from collaborating with and

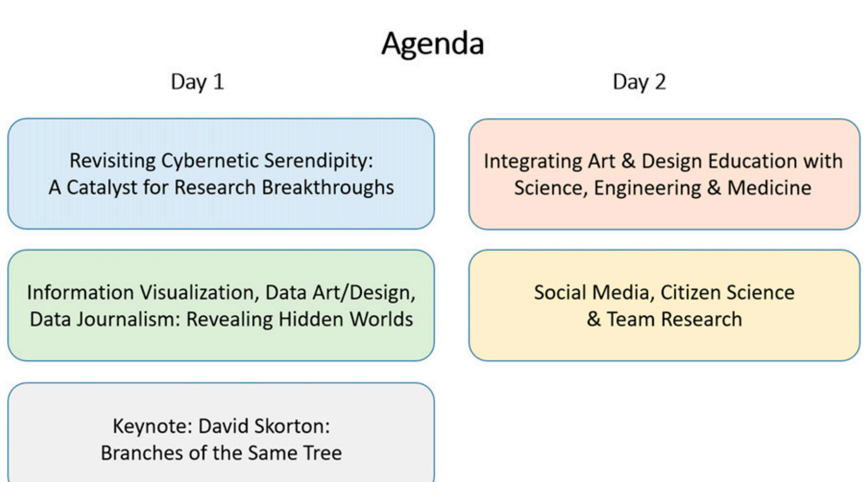

Fig. 3. Agenda for the National Academy of Sciences Sackler Colloquium "Creativity and Collaboration: Revisiting Cybernetic Serendipity."

learning from artists and designers. I think there are four paths to productive collaborations, as described below.

Perceptual training and skills of artists, musicians, dancers, and designers serve scientists and engineers well. Musically trained physicians not only hear more when using stethoscopes and chest percussion than nonmusicians, but make more accurate diagnoses (3, 4). Similarly, visual arts training improves their ability to read X-rays and other radiological images and to perceive external symptoms of disease (5–7). Pasteur's training in portraiture probably helped him understand the chirality of molecules: that is, their left- and right-handed versions (8). Chemistry Nobel laureate Dorothy Crowfoot Hodgkin attributed her ability to comprehend the complexities of transforming X-ray crystallographic data into meaningful 3D models of proteins to her early training as a graphic artist (9). Training as artists helped Leonardo da Vinci, James Audubon, Mary Leakey, and others to see more clearly, draw more accurately, and notice what others missed. Robert Root-Bernstein's review of Nobel Prize winners found them to be polymaths who frequently were proficient in producing art, sculpture, music, literature, poetry, theater, and so forth (10).

Innovative visions of artists and designers put demands on scientists and engineers. A famous example is Karlheinz Brandenburg, whose passion for music and sound drove his foundational research, which led to the creation of the widely used mp3 audio format, igniting the digital music revolution, and thereby opening up new directions for computing algorithms research. Bell Labs hired artist Lillian Schwartz specifically because her demands for new techniques drove the development of novel software and hardware that had much broader uses (11). Similarly, computer games, Hollywood animations, and the current interest in virtual reality forced rapid development of new software, advanced chip designs, and improved interactive capabilities.

Playful, exploratory, iterative, and divergent methods of art and design expand the range of thinking of scientists and engineers. Maybe the double-diamond method of repeated divergent and convergent design thinking should play a greater role in the education of scientists and engineers (12). Courses that combine arts and engineering students at the University of Georgia and the University of Colorado, Boulder, for example, loosen up the engineers to explore wider ranges of possibilities, methods, and materials while teaching the artists how to use problem constraints to better define the nature of design challenges. These students also have transformative aesthetic experiences that redefine how they perceive natural and human-made phenomena (13–16). Creative practitioners of today increasingly combine art, design, technology, science, engineering knowledge, and skill in practice-led research processes, known widely as "practice-based research" (17). Some creative practitioners make contributions to scientific and engineering research (18). The Wellcome Trust's long-term broad-based effort of 118 projects that supported collaborations of artists and scientists demonstrated the benefits of such partnerships (19).

Products of art and design, such as paintings, sculpture, music, or film can directly inspire scientists and engineers. Leonard Shlain shows numerous examples of parallel developments in art and physics, suggesting that art inspired science (20). Einstein claimed that the architectonics of music underpinned the insights that led to his theory of general relativity (21). A Miro painting inspired Yuri Verlinsky to invent the first technique for preimplantation genetic diagnosis, a means of screening embryos created by in vitro fertilization for genetic defects (22). An Escher print stimulated Nadrian Seeman to produce the first DNA-based nanotechnologies (23, 24). Buckminster Fuller helped two groups working on spherical viruses to see how his geodesic dome principles could be used to explain virus capsid structures (25, 26). Did a Kandinsky painting, a Calder mobile, or a Stravisnky symphony open up fresh possibilities for 20th century researchers? Do the works of Basquiat, Annie Leibovitz, Trevor Paglen, or Liz Lerman inspire 21st century researchers?

These four paths to collaboration need further discussion and refinement to clarify the ways in which they work, so that academic leaders can create the environments that produce more frequent successful partnerships, such as the inspiring examples from the network for Science, Engineering, Art, and Design (https://seadexemplars.org/). Several approaches appear promising. One is for researchers and educators to disseminate knowledge on the historical and contemporary exemplars described in the above examples. This could inspire young scientists to develop and integrate the skills and knowledge they acquired from their avocations with their formal training. A second is for academic leaders to develop hybrid courses that actively teach methods of disciplinary integration to mixed groups of students who, not incidentally, will also teach each other. A third would be for educators to teach generalizable "tools for thinking" (27), such as imaging, abstracting, patterning, modeling, playing, and the creative process (28). Most importantly, instructors who lead students to see that breadth of training is as important as depth of training will do much to accelerate creativity and innovation.

Special Feature Papers. The memorable presentations during this Sackler Colloquium led to spirited discussions, which gave the authors feedback to refine their talks into a strong set of papers.

Jasia Reichardt's talk laid the foundation for the event by giving a detailed history of the events leading up to the 1968 London exhibit "Cybernetic Serendipity."

Jeffrey Heer's paper (29), "Agency plus automation: Designing artificial intelligence into interactive systems," breaks new ground by offering ways of using machine automation in support of human agency. Across examples of data cleaning and transformation, exploratory data visualization, and natural language translation, Heer's fresh strategy is to support creative work through interfaces that richly integrate computational assistance while keeping the user in control.

Sara Diamond reports (30) on her observations from several decades of efforts to encourage art, design, and STEM collaboration, first at The Banff Centre and then as President of OCAD University (formerly the Ontario College of Art and Design). Her second theme, which will bring fresh insights to many readers, is to describe Indigenous methods and knowledge as they support education and research. Diamond's many case studies and lessons provide a guide to others who seek to follow the successful transformation of her university.

Katy Börner, Andreas Bueckle, and Michael Ginda (31) present a data visualization literacy (DVL) framework that can be used to guide the design of DVL teaching and assessment. The authors' clear call for raising data visualization literacy is gaining momentum in many disciplines, where the new generation of commercial and research tools are dramatically changing the ways research and education are conducted. The paper presents a set of exercises and assessments that can be used to measure and improve DVL. Börner et al. argue that students across all scholarly disciplines will be empowered if they are literate in interpreting and in creating data visualizations for personal and professional purposes.

David Skorton (32) summarizes the issues that arose in the 3-y-long National Academy of Sciences, Engineering, and Medicine study, which led to the report on "The Integration of the Humanities and Arts with Sciences, Engineering, and Medicine in Higher Education: Branches from the Same Tree" (2). The key finding in the report is that "integration of the arts and humanities into STEM courses and curricula" is "associated with positive student outcomes, including higher order thinking, creative problem solving, content mastery of complex concepts, enhanced communication and teamwork skills, and increased motivation and enjoyment of learning" (2).

Aniket Kittur et al. (33) summarize a large body of their work on using crowdsourcing and artificial intelligence methods to support analogical invention. By separating process from mechanism, they were able to produce more effective distributed innovation by: (*i*) breaking fixation on surface features, thereby finding structurally similar analogs in distant domains; (*ii*) scaling up the process of finding analogs in large idea repositories; and (*iii*) coping with complex real-world problems.

Youngmoo Kim et al. (34) describe arts and STEM integration projects at Drexel University's Expressive & Creative Interaction Technologies Center. The authors describe collaborations with off-campus arts organizations and presents survey and interview data to characterize the outcomes and impacts.

Jennifer Preece et al. (35) describe community-driven environmental projects as an emerging form of citizen science. These locally led small groups who have physical meetings, facilitated by mobile applications and web sites, take on projects that directly benefit their communities. Based on the authors' experience with Anacostia Watershed community-driven environmental projects, the authors provide six guidelines for technology and social design.

Julia Parrish et al. (36) provide an in-depth data analysis of factors leading to the high levels of continuing participation and high levels of data quality in Parrish's 17-y-long citizen-science project. The authors' Coastal Observation and Seabird Survey Team has had more than 5,000 participants who walked beaches to collect, identify, and measure bird carcasses, thereby providing invaluable data about changing patterns of bird behavior and migration.

Laura Trouille, et al. (37) present a series of case studies exploring the integration of machine learning into the Zooniverse, an online citizen-science platform supporting over 120 projects with 1.7 million participants around the world. They investigate the tensions that arise when designing a human–machine system serving the dual goals of carrying out research in the most efficient manner possible while empowering a broad community to authentically engage in this research, including safeguarding opportunities for serendipitous discovery.

Robert Root-Bernstein et al. (38) report on the role of arts, crafts, and design avocations in promoting creative thinking among 225 STEMM (STEM + Medicine) professionals. Tantalizing results, such as the correlation of metal- and woodworking avocations with patent production, suggest that increased training for STEMM students could be an effective way to improve their outcomes.

Conclusion

The organizers of this Sackler Colloquium have worked hard to make it more than a memorable moment of inspiration. We hope it can trigger profound discussions and build powerful new relationships that bind our disciplines. Then we, our colleagues, and our students can ask new and important questions that lead to positive changes. We hope these fresh ways of thinking will lead us to bold discoveries and breakthrough innovations that empower people, improve society, and preserve the environment. The speakers' videos are posted on the online at https://www.youtube.com/playlist?list=PLGJm1x3XQeK140JC2g7EzGO2NEK3a2I4l.

This special feature in PNAS presents papers from many of the speakers. In addition, Studio International will publish all of those papers and related essays in ways that will reach broader audiences.

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