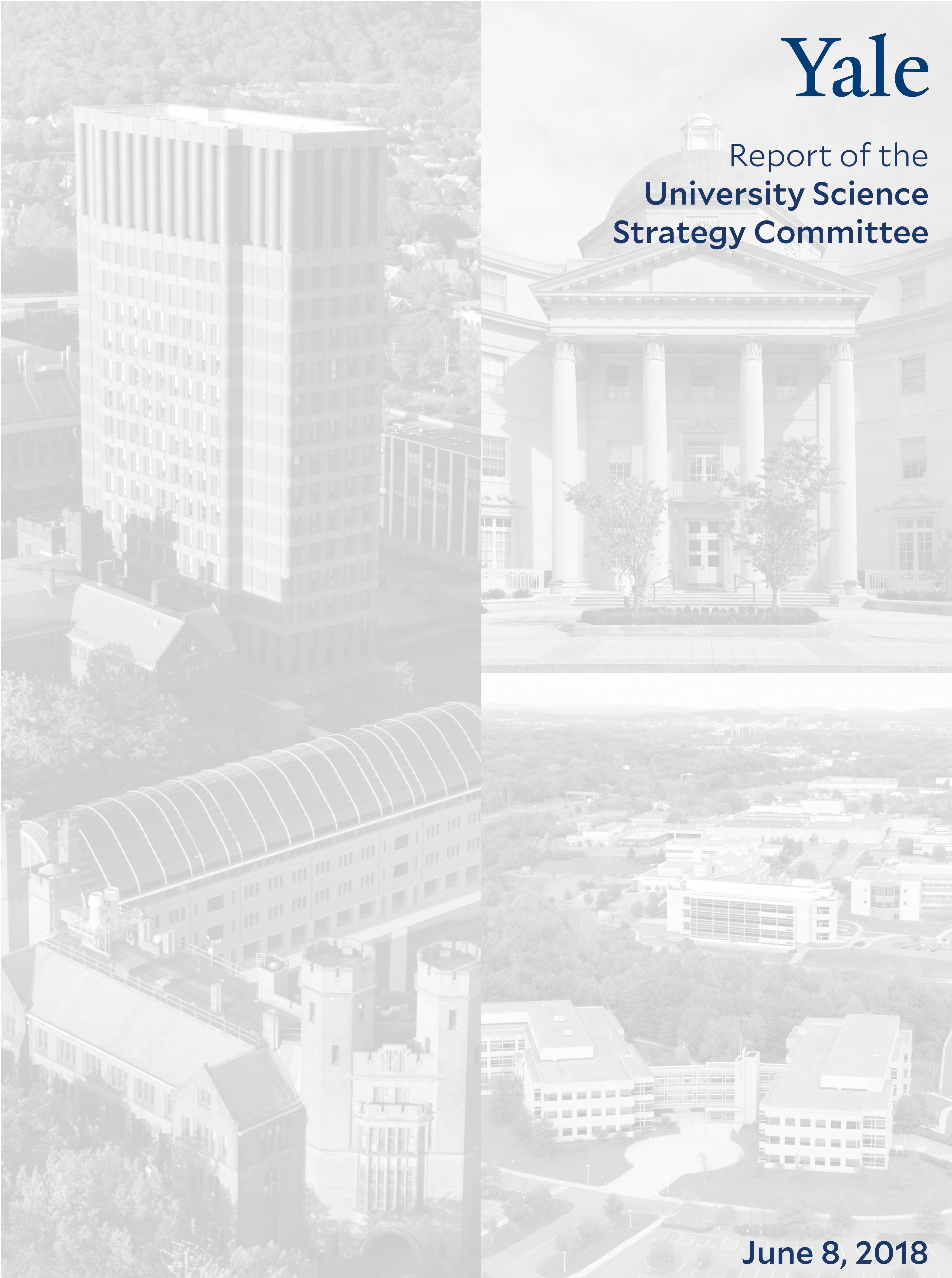

Yale

Report of the University Science Strategy Committee

June 8, 2018

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Recommendations

Executive Summary

President Peter Salovey, in November of 2016, identified science as a top academic priority for Yale University. Science can change - and improve - the world. Tomorrow's leaders need a solid grounding in science, technology, engineering, and mathematics (STEM) so they can understand the world and shape its future. Yale must invest strategically in these areas to remain a great research university and meaningfully contribute to addressing the world's present and future challenges.

To better define that goal, the University Science Strategy Committee (USSC) was charged to develop a strategic plan for STEM at Yale that could be implemented in the coming decade. We were asked to identify changes to organizational structures that will support excellence in science and engineering and to recommend a prioritized set of 'big ideas' for new investment. We were asked to dream big, realizing that Yale will not be able to do everything that we could imagine. We were also asked to prioritize the ideas and make difficult choices among many excellent possibilities.

The USSC took its charge seriously. We devoted significant time to gathering information and conducting our deliberations. To accomplish our charge, we solicited input from the community broadly, both at departmental and individual faculty levels. Each science department or school was invited to prepare a self-reflection for consideration by the USSC. We also solicited recommendations online from all science and engineering faculty in the University and held one-on-one interviews with faculty and deans. During the 2017-18 academic year, we organized over a dozen faculty panels in which we invited colleagues to guide us to the scientific frontiers of their respective disciplines. In this format, we met with over 100 faculty members who have primary appointments in almost 50 departments and five schools. We also attempted to identify the scale of the resources needed for each of the ideas and to project their annual cost if implemented. A similar process was followed during the consideration of several cross-cutting investments and structural recommendations.

The USSC gave careful thought to the criteria it should use for evaluation of the ideas. We established two overarching criteria, Impact and Feasibility, as well as a series of questions that we used to consider each of the ideas. No single question served as a litmus test for evaluation of any idea, but these questions provided a framework for considering how to prioritize them.

Based upon this process we recommend **five ideas for top priority investment**. For each of these five ideas, which are listed in their order of priority, we offer a set of recommendations for implementation. We also identify a second set of **five additional priority ideas**. Each of these ten areas is highly interdisciplinary and integrative - and implementation should include, where appropriate, scientists, engineers, mathematicians, and clinicians. These ideas were selected for their impact and feasibility at this time, but they do not represent a comprehensive list of the many areas of excellence at Yale. We recognize that not all excellent science fits into a short list of ideas, therefore we recommend **four areas for cross-cutting investment** that will support all STEM fields. We also recommend **ten changes to organizational structure** that will improve support for science and engineering at Yale. Science is a dynamic enterprise. These cross-cutting and organizational changes will allow Yale to better realize its current and future scientific initiatives.

Our recommendations are as follows:

Four Cross-Cutting Investments

Graduate Student Support:

Graduate students help drive discovery through the research that they conduct within the training environment of their faculty mentors. Graduate students are the future of scientific innovation. We recommend a major investment in the funding of STEM graduate education to ensure sustained scientific excellence at Yale.

Diversity across the STEM Pipeline:

Improved diversity and inclusion is critical to our society. Science is no exception. Diversity leads to improved outcomes for laboratories, academic departments, and even individual publications. We recommend initiatives that will allow Yale to further promote and nurture diversity in all our scientific enterprises.

Instrumentation Development:

The development of new tools and measurement techniques is an essential component of the scientific process, allowing researchers to open entirely new avenues for investigation. We recommend that Yale develop high-capacity centralized instrumentation and engineering facilities to serve as intellectual "hubs" for instrumentation development.

Core Facilities:

State-of-the-art core facilities are crucial for innovation across the University. Research in every laboratory is dependent upon these services. We recommend making strategic investments to better organize, coordinate and support the University cores.

Five Ideas for Top-Priority Investment

Integrative Data Science and its Mathematical Foundations:

We recommend a University-wide Institute for Integrative Data Science and its Mathematical Foundations. The world is currently undergoing a data revolution. The confluence of the volume, speed, and availability of data is transforming information and knowledge production. Harnessing data streams from sensors, instrumentation, medicine, and the internet, among other sources, will require developing algorithms, machine learning techniques, and innovative mathematical models to enable new understanding and predictive power.

Quantum Science, Engineering and Materials:

We recommend expanding the existing Yale Quantum Institute into a University-wide initiative in the areas of science and technology associated with quantum-mechanical phenomena and materials science. This research arena, which has emerged in the 21st century, is a frontier of fundamental knowledge about how the universe works. The "Quantum" is rapidly becoming a

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radically new source of practical technologies. As part of this initiative, we recommend the construction of a new building for the physical sciences with Quantum Science, Engineering and Materials as its major focus.

Neuroscience, from Molecules to Mind:

We recommend an integrated Neuroscience Institute that unites research across the Yale School of Medicine (YSM) and Faculty of Arts and Sciences (FAS). By integrating knowledge across scales, from molecular and cellular neuroscience to organismal behavior and cognition (systems neuroscience), the Institute will facilitate new fundamental insights into the function of the mind, the development of the brain and the causes and cures of neural disease.

Inflammation Science:

We recommend a new Institute of Inflammation Science to focus on the inflammatory basis of both homeostasis and disease. Inflammation has emerged as a key factor in diseases that are the leading causes of death in the United States. This initiative will explore the full extent of the interplay among inflammation, organ systems, the immune system, environmental factors, and genetics.

Environmental and Evolutionary Sciences:

Human-accelerated changes in the environment present one of the greatest challenges of the 21st century. We recommend an Institute in Environmental and Evolutionary Sciences that has the goal of modeling environmental changes and understanding how organisms evolve in response to a rapidly changing Earth that will help us conserve ecosystems.

Five Additional Priority Ideas

The ideas above constitute the top priority recommendations. The Committee gave serious consideration to many others. The USSC endorses efforts underway in the following areas, and would support additional investment if additional resources were available.

Climate Solutions:

Climate change is a defining issue of our time. One of the most overwhelming challenges in addressing climate change is to identify practical mechanisms to capture CO2 directly from the ambient atmosphere and to sequester it.

Computer Science:

New opportunities are arising at the intersections of computer science and other fields – referred to broadly as "CS+X," where X can range from Biology, Engineering, Law, and Medicine to Business, Economics, Music, and beyond. The success of artificial intelligence will greatly increase the fraction of our world controlled by information systems and augment human interaction with technology.

Conquering Cancer:

Cancer remains a leading cause of death in the United States. The grandest challenge in cancer research is to develop and apply new patient-specific therapeutics so that all patients can be cured. Opportunities abound at Yale to integrate advances from other strategic areas within cancer research.

Precision Medicine:

Medicine is entering a new era in which the acquisition and interpretation of vast quantities of data from human populations will enable individually-tailored medical care. The integration of clinical and genetic information promises to transform our understanding of human biology and the treatment of disease.

Regenerative Medicine:

Regenerative Medicine seeks to repair, replace, or regenerate cells, tissues, and organs. It exploits advances in genomics, biomaterials, immunobiology and mechanobiology, and advanced cell therapies (particularly stem cells), and it can be enhanced by high-resolution medical imaging and computational modeling.

School of Engineering and Applied Sciences (SEAS)

The USSC was not tasked to provide a strategic plan for any individual school or department, but we emphasize that engineering and applied sciences will play a vital role in implementing many of these ideas. To make this possible, SEAS must be fully integrated into the fabric of the University, across all three of Yale's campuses. We offer ideas for an Engineering +X strategy for the future of SEAS.

Ten Recommended Changes to the Organizational Structures that Support Science

- Build improved mechanisms for interdisciplinary faculty appointments
- Increase computing and data management support
- Provide more organized support for large grant submissions
- Enhance support for professional scientists
- Increase input for well-coordinated space planning in the sciences and engineering
- Offer faculty development training in leadership
- Better support for commercialization and entrepreneurship
- Improve research communications and dissemination
- Increase connections with Brookhaven National Laboratory
- Improve support for clinical trials research

Additional scientific ideas of interest are briefly described in Appendix #1.

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Acknowledgments

The Committee is grateful to the many members of the Yale community who assisted in this process. We thank those who prepared departmental self-reflections and individual faculty who provided input to the Committee in response to our requests. We are particularly indebted to Daniel Bennett, Tamara Chiba, Katherine Haskins, Melissa Hey, Angie Hofmann, Roopa Narasimhaiah, Zandra Ruiz, Jeremy Toyn and Tammy Wu, who helped create initial drafts for sections of this report. We thank Sara Epperson for staffing the Committee and Kelly Locke for managing the Committee's many administrative needs.

University Science Strategy Committee Members

Committee Chair:

Scott Strobel, Henry Ford II Professor of Molecular Biophysics & Biochemistry and Chemistry (FAS/YSM)

Committee Faculty Members:

Daniel A. Colón-Ramos, Associate Professor of Cell Biology and Neuroscience (YSM)

Alison Galvani, Burnett and Stender Families Professor of Epidemiology and Ecology & Evolutionary Biology (YSPH/FAS)

Steven Girvin, Eugene Higgins Professor of Physics and Applied Physics (FAS)

Arthur Horwich, Sterling Professor of Genetics and Pediatrics; HHMI Investigator (YSM)

Jay Humphrey, John C. Malone Professor of Biomedical Engineering (SEAS/YSM)

Akiko Iwasaki, Waldemar Von Zedtwitz Professor of Immunobiology and Molecular Cellular & Developmental Biology; HHMI Investigator (YSM, FAS)

Mark Lemmon, David A. Sackler Professor of Pharmacology and Molecular Biophysics and Biochemistry (YSM/FAS)

Scott Miller, Irénée duPont Professor of Chemistry (FAS)

Anna Marie Pyle, William Edward Gilbert Professor of Molecular, Cellular & Developmental Biology and Chemistry; HHMI Investigator (FAS)

Peter Schiffer, Professor of Applied Physics and Physics (FAS)

David Skelly, Frank R. Oastler Professor of Ecology at the School of Forestry and Environmental Studies and Ecology and Evolutionary Biology (FES/FAS)

Daniel Spielman, Henry Ford II Professor of Computer Science, Statistics & Data Science, and Mathematics(SEAS/FAS)

Paul Turner, Elihu Professor of Ecology and Evolutionary Biology (FAS)

Additional Committee Members:

Tim Pavlis, Associate Vice President for Strategy & Analytics

Patricia Pedersen, Associate Vice President for Development, University Director of Corporation & Foundation Relations

Introduction

In November 2016 President Salovey stated that building strength in science is a major priority in the University's academic strategy. To identify major ideas for strategic new investment in science and engineering, Provost Polak organized the University Science Strategy Committee (USSC) (See Committee charge in Appendix #2). Our committee was convened in February 2017 and met regularly through May 2018. The USSC met almost 60 times over a 16-month period totaling more than 90 hours.

We were charged to engage broadly with the University community to identify big ideas in which additional new resources would have a maximum impact on the overall quality of science at Yale. Ideas that would enable us to create new knowledge and unlock discovery toward a better world. We were asked to create a strategic plan on a scale of $50 to $150 million per year in new scientific investment. Through seeking the best ideas across all fields, we were urged to dream big, realizing that Yale would not be able to do everything that we could imagine. We were also asked to prioritize the ideas and make difficult choices among many compelling possibilities. We anticipate that the recommended scientific themes will provide focus for the next development campaign and guide the University's strategic thinking for new investments in science and engineering at Yale.

The Committee was kept at a moderate size to keep the discussions manageable and efficient. Given the University-wide scope of its charge, the small committee size required that the Committee's members were not representative. The Provost explicitly discussed this with the Committee during the initial charging meeting. Members were asked not to consider themselves as members representing their own department or school, but rather to take a holistic view of STEM at Yale and to conduct their deliberations accordingly. The ideas under our consideration had to be big enough and broad enough to garner support from the whole Committee. We were encouraged to think beyond the boundaries that may exist between departments and between schools.

The USSC process offered a rare opportunity for Yale to consider its academic future across a broad spectrum of the scholarly enterprise. The outcome of this process is a set of recommendations for significant new investment in the sciences and engineering.

We also considered the resources that support the broader scientific enterprise at the University. Recognizing that not all excellent science at Yale fits into a short list of ideas, we recommend **four areas for cross-cutting investment** that will support all STEM fields, which include support for graduate students, development of the diversity pipeline, support for the creation of new instrumentation and investments in core facilities.

We recommend **five ideas for top priority investment** and lay out a set of recommendations for implementing each of them. We also identify a second set of **five additional priority ideas** where we endorse initiatives that are underway on campus.

One theme that emerged repeatedly in our deliberation process was the imperative that Yale have robust strength in engineering and applied sciences. Producing a detailed strategy for an individual School or Department was beyond the scope of our charge. However, during the course of our deliberations we gathered information about the School of Engineering and Applied Sciences that would be useful for the articulation of that strategic plan and offer some observations below.

We also offer recommendations for **ten changes to organizational structures** that would improve how science and engineering is implemented at Yale. We were struck that science at Yale is often constrained, not by the quality or quantity of good ideas, but by our structural support for science and the ability of our community to organize itself around those ideas. These organizational changes are meant to ensure that the culture of science at Yale reduces the barriers to pursuing our ever-evolving sense of scientific possibility.

The Committee sought to identify recommendations that are actionable, though we recognize that the timing of these actions will, of necessity, be variable over the coming years. Some of these recommendations can be acted upon in the near future, but many will require that funds be obtained and that space be renovated or constructed prior to implementation. We have provided recommendations for space resources that can be applied to these priorities.

Although the scope of our charge was broad, in one particular way it was constrained. We were not tasked to consider how our science recommendations would interface with programs in the University beyond STEM. We are aware that strategic planning efforts are underway for the Social Sciences and the Humanities. It is clear that several of the priorities that we identified will find synergistic convergence with initiatives in these other disciplines. We have noted some of the anticipated convergence points within our report, and recognize that Yale's strength in these other disciplines can provide unique advantages when harnessed together with science and engineering.

A particular challenge of our work was that not every excellent idea could be ranked as a top priority. It was noted in the charge to the Committee that we should "dream big." If Yale could easily implement everything we identified as exciting, we had not dreamed big enough. We did our best to predict the future in anticipating where the University should invest. We have made our best bets, but we also recognize what a tricky business such forecasting can be and how limited today's knowledge will seem tomorrow. For this reason, we recommend that the University evaluate the development of each of these scientific areas carefully and revisit the strategic planning process for other emerging fields on a regular cycle.

This report begins with a summary of the deliberation process we followed to reach our recommendations. This summary is followed by full descriptions of each of the cross-cutting investments, the scientific ideas, and the organizational structural changes we prioritized. These recommendations represent the consensus opinion of the Committee, and we hope the University will find them helpful in implementing a strategic plan for science and engineering in the coming decade.

Respectfully,

University Science Strategy Committee

Daniel Colón-Ramos
Associate Professor of Cell Biology and Neuroscience

Alison Galvani
Burnett and Stender Families Professor of Epidemiology, Professor of Ecology and Evolutionary Biology

Steven Girvin
Eugene Higgins Professor of Physics and Professor of Applied Physics

Arthur Horwich
Sterling Professor of Genetics and Professor of Pediatrics

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Jay Humphrey
John C. Malone Professor of Biomedical Engineering; Chair, Biomedical Engineering

Mark Lemmon
David A. Sackler Professor of Pharmacology; Co-Director, Cancer Biology Institute

Tim Pavlis
Associate Vice President for Strategy and Analytics

Anna Pyle
William Edward Gilbert Professor of Molecular, Cellular, and Developmental Biology and Professor of Chemistry; Director, Division of Biological Sciences

David Skelly
Frank R. Oastler Professor of Ecology; Director of the Peabody Museum of Natural History; Professor of Ecology and Evolutionary Biology

Scott Strobel
Henry Ford II Professor; Department of Molecular Biophysics and Biochemistry; Vice President for West Campus Planning and Program Development; Deputy Provost for Teaching and Learning Yale University

Akiko Iwasaki
Waldemar Von Zedtwitz Professor of Immunobiology and Molecular, Cellular and Developmental Biology

Scott Miller
Irénée duPont Professor of Chemistry

Patricia Pedersen
Associate Vice President & Director, Corporate and Foundation Relations

Peter Schiffer
Vice Provost for Research and Professor in Applied Physics

Daniel A. Spielman
Henry Ford II Professor of Computer Science; Professor of Statistics and Data Science; Professor of Mathematics

Paul Turner
Acting Dean of Science, and Elihu Professor of Ecology and Evolutionary Biology

USSC Deliberation Process

Given the scope of our charge, the USSC undertook an extensive process for collecting and considering input from multiple stakeholders across the University. We viewed our role as being a conduit to collect and organize the many excellent ideas that are emerging across the University.

We began our work by reviewing recent examples of strategic planning documents prepared by other universities. We consulted with faculty who served on those strategic planning efforts to understand best practices for how they approached their deliberation process. We gained a University-wide perspective from which to consider potential ideas at the broadest possible scale by reviewing internal institutional data. These data established the relative strengths of schools, programs, and departments throughout the University.

We broadly solicited input from the community, both at the departmental and faculty level. Each science department or school was invited to prepare a self-reflection for consideration by the USSC (the full text of the invitation is included as Appendix #3). In this request for input, we asked the units to consider a series of questions: What are the big ideas that will define new directions for your field over the next ten years? How should Yale be contributing in those areas? What are the strengths of your unit at Yale, and which of those strengths would you identify as unique comparative advantages versus other institutions? Are there other unique strengths in the University that we should take more advantage of? What are other institutions doing that you admire? What structural or organizational changes would maximize the impact of our investments in science and engineering? In addition to unit input at the department and school level, we also solicited recommendations from all science and engineering faculty in the University by inviting them to respond to an online survey with prompts similar to the five questions listed above and an open text field. Based upon these solicitations we received responses from over 40 departments and schools and input from almost 120 individual faculty. The result was a merged document exceeding 300 pages, which included hundreds of ideas across many scales and fields.

Further input was sought through interviews and discussions with thought leaders from across the campus. The USSC chair met individually with over 40 faculty. He also met with the FAS/YSM Biological Tenure Appointments Committee, the FAS Physical Science Tenure Appointments Committee, the FAS Science and Engineering Chairs Committee, and the YSM Chairs and Directors. In cases where new ideas emerged, faculty were asked to provide a short description of the idea for consideration by the full Committee.

In the late spring of 2017, while the USSC awaited responses to the departmental self-reflections, we held meetings with President Salovey and Provost Polak. We also held a full-day retreat where we met the Deans responsible for the sciences. These meetings gave us a perspective on what University leadership views as the future of science and engineering, both on the global stage and within the University. This allowed us to understand strategic initiatives underway at various schools and to identify themes that cut across individual units. Based upon the input from these various sources, the Committee identified about 70 ideas for further consideration.

The USSC gave careful thought to the criteria it would use for evaluation. This process gave us the opportunity to see beyond the boundaries of individual departments and schools and to see ideas that were emerging in multiple places across the University. We took seriously the challenge outlined in the charging letter that we would hear many excellent ideas that would be worthy of support, but that we must prioritize among many excellent possibilities. We were told that “this will require the Committee to make difficult choices” and we certainly felt this during our deliberations. To undertake such a prioritization, it was necessary to define principles for making such choices. After extensive discussion, we established two overarching criteria we used to evaluate each of the ideas: Impact and Feasibility.

For Impact, we formulated the following questions: Is the idea worth reaching for? Is it a problem that is important? Does it have a promised benefit for humanity or for science? Does it create novel interactions beyond a single department? Is it a theme that re-occurs across fields? It is broader than a single field? Is it beyond "business as usual?" Is it an area of significance in which we can't afford to be weak? Is it likely to remain relevant over time? Does it contribute support broadly or would it only benefit a few? Does it contribute to teaching efforts? Does it have a sufficient degree of uncertainty?

For Feasibility, we also formulated a set of questions: Do we have strength in this area upon which to build? Do we have strength in related areas? Do we have leadership in place? Is the idea of the correct scope? If it is interdisciplinary, does it align incentives with related disciplines? Do we expect it to have a positive cost/benefit tradeoff?

No single question served as a litmus test for evaluation of any idea. Different Committee members gave different weight to each of these criteria in their prioritization, but these questions provided the framework through which the ideas were considered.

Each idea was discussed by the USSC and independently scored by each member of the Committee. Based upon these preliminary rankings, about a dozen ideas were selected for further consideration. To further inform our deliberations, we convened faculty panels and invited thought leaders from across the University to meet with the full Committee and describe the scientific frontiers of their respective disciplines. Each of the 90-minute panels was composed of six to nine faculty members. In this format, we met with almost 100 faculty who have appointments in almost 50 departments and five schools. Each panelist was invited to present a vision for the future development of their discipline in relation to the USSC's charge (Appendix #4). Prior to meeting with the USSC, each panel was convened at least once. During these pre-meetings, one member of the Committee described the charge of the USSC and facilitated a discussion among the panelists. This allowed faculty to communicate their ideas with each other prior to communicating them to the Committee.

The panelists were asked to address the following questions in their remarks:

1. *What is the vision for the "big idea?"* What is it? What impact would it have on the world and Yale? Consider benefits for students, other scholars and humanity.
2. *What are Yale's comparative advantages in this area?* Who is working in this area or related fields at Yale today? What are other institutions doing? Consider what factors might give Yale a comparative advantage over others.
3. *Who would need to be involved?* If it crosses disciplinary boundaries, what will be required for them to work effectively together?
4. *What are the key uncertainties associated with the idea?* Consider both the intellectual risks inherent in the idea as well as execution risks of Yale's ability to lead in this area.
5. *What resources would be required?* Consider the talent needed, as well as logistical requirements such as space, equipment and other resources.

These panels provided a venue for the Committee to hear detailed discussions of each idea, to ask probing questions about its impact and feasibility, and to think more deeply about how each idea fits within the University's scientific landscape. The panels also provided a forum for both the Committee and the panelists to consider how the scientific ideas are strengthened by interdisciplinary interactions across

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departments and schools. This last point is a valuable strategic benefit of conducting a University-wide process, in contrast to plans developed at the level of the individual school or department.

Based upon input from the panels, white papers for each of the ideas were drafted, reviewed and edited by the Committee. The USSC held a series of Committee-member-only meetings to discuss each idea and the content of the white papers. These conversations explored whether we had defined the right borders for the individual ideas, whether particular ideas should be merged or split, and if the impact and feasibility of each idea merited prioritization.

In parallel with this process, we estimated the resources needed for each of the ideas and calculated their annual cost if fully implemented. Key cost drivers include the cost of staff, students, faculty, equipment and the capital and operating expenses needed for space (new or renovated, purchased or leased). These estimates were included in our discussions and considered relative to the cost targets that were provided to the Committee in our charging instructions.

The scientific ideas were prioritized by an iterative vote in which each member of the Committee ranked the ideas using the rubric described above. Committee members recused themselves from voting on ideas that directly affected their departments or research areas. The ranks were tabulated and discussed, and the Committee voted again after hearing the input of others. This process was repeated until there was a consensus across the Committee that we had identified the highest priority ideas, and subsequent voting no longer changed the prioritization.

A similar process was followed for the cross-cutting investments and structural ideas. They were listed and voted on by the Committee to create a short list. Each was discussed in greater detail and ranked through the iterative process described above. The criteria of Impact and Feasibility were applied to these recommendations and weighed against the cost of implementation. We note that for the structural recommendations, the costs of implementation are often measured less in dollars than in administrative time and attention.

The following ideas and recommendations emerged as a result of these deliberations.

The USSC is certain that not all excellent science at Yale will fit into a single short list of ideas, and that important science will emerge from all quarters of the University. Therefore, we recommend four areas for cross-cutting investment that will support all STEM fields.

Cross-cutting Investments

Graduate Student Support in STEM

A strategic investment in STEM graduate education is recommended to ensure sustained scientific excellence in the coming decades.

Science and engineering graduate students are major drivers of scientific discovery through the research that they conduct in partnership with their faculty mentors. Graduate students are the future of scientific innovation. Achieving solutions to the world's biggest challenges, including those outlined in the Top Priority Ideas (see below), will require nurturing the imagination, curiosity and problem-solving abilities of young investigators through graduate education. Graduate school is the critical period in a student's academic career when they translate their passions into intellectual pursuits and learn to be producers of knowledge and creators of ideas.

Independent of the topic we were exploring, the USSC repeatedly heard that, to be competitive in STEM fields, Yale must attract and train the best graduate students in the world. Yale must do so across all scientific and engineering disciplines. In addition to the intrinsic benefits of an excellent graduate program for advanced training, two other benefits were repeatedly communicated to the USSC: that access to exceptional graduate students will help attract and retain the best faculty, and that strong graduate programs are vital to undergraduate education, both for teaching and training. As a result, the USSC concludes that sustaining and promoting excellence in graduate STEM education is a matter of great consequence to the vitality of science and engineering research across the University.

Yale is uniquely positioned as a premier institution to demonstrate best practices for graduate education. Graduate science education at Yale has a distinguished history almost as long as that of the University, and science has been an integral part of the academic mission since graduate education was introduced in 1847. In 1861 Yale conferred the first Ph.D. degrees in the United States, one of them in physics. In 1863 Yale awarded the first American doctorate in engineering. Yale also conferred the first Ph.D. on an African-American scientist in 1876. Since that time, the Graduate School of Arts and Sciences has carried on the tradition of pioneering education as a pillar of the scientific enterprise at Yale. The combined program in the Biological and Biomedical Sciences created in 1996 was among the first to transcend departmental boundaries and afford students a novel flexibility in pursuing their interests. Many institutions have emulated this program.

Based upon our discussions with the Dean of the Graduate School and faculty across multiple programs in the University, the USSC identified three goals that are needed to better support graduate student training in STEM fields at Yale.

1. Provide a funding model that is stable, sustainable, equitable, and appropriate to the needs of supporting the most talented graduate students, with regard to both the duration of support and the size of the student population.
2. Attract and educate the best students in the world without constraint on nationality or agency-specific funding restrictions.
3. Promote a uniform structure across the University that increases the fluidity of students across departments and programs, raising the likelihood of interdisciplinary research and discovery.

Currently, graduate students in the sciences and engineering are supported throughout their degree programs by a patchwork of fellowships, University funding, training grants, and research grant funding. The formulations differ from year to year and there are drastic differences from department to department. University funding is front-loaded into the early years when students are taking classes and developing research projects. However, by the third or fourth year (and in some cases even in the second year), a graduate science student is typically funded through faculty grants, through fellowships, or a combination of both.

The current system relies heavily on external funding sources, which puts significant burdens on faculty to raise the requisite funds and further limits the number of students who can be supported. This has become particularly problematic because scientific research and training in higher education has long depended on extensive and sustained federal funding, but over the last few years, the federal funding pipeline has become seriously constrained, and is no longer as reliable a source of support as it was in the past. For example, in spite of significant faculty effort, there has been a 29% drop in the number of federally funded training grant slots in the University over the past 10 years (143 in 2007/08, 102 in 2017/18). Importantly, federally funded slots place restrictions that limit participation and training of international students.

The USSC recognized that there is a notable gap in the funding sources for graduate science education at Yale, namely endowed funding for student support. Current endowment support for science and engineering graduate students is modest relative to the size of the programs. University funds are particularly important for the recruitment of international students who are not eligible for federal training grant or fellowship support. We conclude that a lack of sufficient sources of sustained income for graduate education and training will be a major barrier to the advancement of science and engineering at Yale unless additional sources of support are identified.

We also discovered an important issue regarding the number of graduate slots in the various programs. The system of allocating graduate student slots is exceptionally complex with calcified quotas for each program that were defined many years ago. Although the number and distribution of science and engineering faculty has evolved over the past 30 years, the size and distribution of the graduate students has remained largely unchanged over that same period. This attention to historic disciplinary boundaries hinders the development and growth of emerging fields at Yale, particularly in the physical sciences and engineering, as well as at interdisciplinary and interdepartmental interfaces, such as those identified in the Science Strategic Priorities (see below). The USSC concludes that the fixed size and distribution of graduate student slots in STEM is a serious barrier to advancing excellence in science at Yale. More flexible slot allocation models should be developed that consider faculty size, grant funding, productivity and track record of student training to account for future changes in scientific fields.

The USSC makes the following recommendations to support STEM graduate education at Yale University:

- Build an endowment to provide three full years of support to all science and engineering graduate students that is independent of faculty research grants and irrespective of nationality. This will reduce funding pressure on faculty and increase the ability of students to explore new areas of research with high potential for major impact.
- Link the number of science and engineering graduate students to a level that is dynamically commensurate with the faculty size and research productivity of the individual programs. Incremental steps that can be implemented toward reaching this goal include:

- Provide an incentive for supporting students on research grants by rebating back to faculty a percentage of tuition and stipend paid from research grants (similar to the 9/9 program for faculty salary recovery in some schools).
    - Expand all annual University fellowships from nine months of support to twelve months of support.
    - Include incremental funding of graduate programs when endowing faculty chairs that increase the size of a department or school.
    - Reward students and departments that are successful in external competitions such as the NSF Graduate Research Fellowship Program, NIH fellowships, and training program grants.
- Improve overall funding packages for students by adding relocation expenses as well as funds for conference travel and research.
- Ensure recruitment of excellence from across the globe, including nations that are not traditionally considered for graduate recruiting.
    - Establish relationships with leading global institutions. These faculty led-partnerships with peer institutions, modeled after the Yale-China program, would be facilitated by Yale's Office of International Affairs and aimed at identifying and recruiting the best talent, particularly in nations that are not traditionally considered for graduate recruiting.
    - Create or extend institutional Post-baccalaureate programs to identify promising international students, particularly from regions underserved by science. The program would bring these students to campus to work with faculty during an internship, allowing evaluation of their potential as research scientists and graduate students and extending Yale's global impact in the training of future scientists, regardless of background.
- Accelerate efforts to enhance student diversity by expanding the Summer Undergraduate Research Fellowship program (SURF), the Post-Baccalaureate Research Experience Program (PREP) and the Emerging Scholar programs (see ***Diversity*** below).
- Establish one or more coordinated programs that encourage interdisciplinary research, similar to the successful BBS program in the biological sciences: for example, an interdepartmental graduate program in environmental research involving Ecology & Evolutionary Biology, Environmental Engineering, Forestry & Environmental Studies, Geology and Geophysics or similarly a program across the Physical Sciences (see ***Quantum*** below).

Cross-cutting Investments

Diversity across STEM at Yale

Strategic planning, improvements in campus climate, and resource investments are needed for Yale to leverage diversity and excellence in the sciences.

STEM fields should be accessible to all scholars regardless of background. However, these fields often reflect societal challenges, falling short of being truly inclusive and lacking gender and racial/ethnic diversity. Without active intervention, this status quo is self-perpetuating due to implicit bias, non-inclusive recruitment practices, and shortfalls in the training of the next generation of diverse scholars. Organizations such as the NIH and the NSF have placed significant emphasis on the creation and cultivation of diversity and inclusion. As eloquently noted by Francis Collins, director of the NIH, "*The inescapable conclusion is that we are missing critical contributors to our talent pool*."

Indeed, diversity and inclusion has been shown to improve the performance of an organization and to inspire scientific innovation through greater depth and scope of ideas, alternative perspectives, methods, and approaches. Science is an increasingly collaborative process that advances through contributions from teams that include faculty, postdocs, graduate and undergraduate students, residents, and staff. This is the science talent pipeline where diversity and inclusion needs to be developed and fostered. Multiple studies have shown that greater gender and racial/ethnic diversity leads to improved outcomes for laboratories, academic departments, and even peer reviewed publications. Maximizing the ability of all scholars, including those at Yale, to thrive in the sciences, requires the development and support of diversity efforts throughout the scientific talent pipeline.

Diversifying the scientific pipeline at Yale:

A key element of Yale's mission statement is its commitment to an "ethical, interdependent, and diverse community of faculty, staff, students, and alumni." Yale has established several programs of national prominence to promote diversity at many steps of the talent pipeline, from high school students in the New Haven area to faculty diversity recruitment efforts. The USSC surveyed these programs and met with the program directors. We were impressed with many of these initiatives and there is evidence of their positive impact. We offer four observations based upon these discussions:

1. There are challenges specific to the STEM fields, where diversity and inclusion significantly lags behind that in other disciplines.
2. Greater coordination is needed between the programs and initiatives that have been implemented at various levels across the University.
3. To increase their impact, a campus-wide strategic plan for diversity at all levels of the organization needs to be articulated.
4. University-wide diversity efforts need to be integrated into mission crucial aspects of university life, such as faculty and leadership searches as well as graduate student recruitment.

We offer a partial overview of programs that are in place on campus and challenges that need to be overcome to nurture diversity in STEM fields at Yale.

Diversity at the K-12 level:

Yale has undertaken significant efforts to promote STEM outreach training for K-12 students in the New Haven area. The Yale Pathways to Science Program is an effective STEM outreach program in partnership with the New Haven, West Haven, and Orange public schools. Pathways coordinates outreach and education efforts geared to K-12 populations across Yale and allows middle and high school students to take part in engaging demonstrations, lectures, and laboratory visits to learn about cutting-edge advances in science. Pathways initiatives include science-based after-school programs with a proven track record of placement in selective undergraduate institutions. Of particular significance, the Pathways program has maintained a best-in-class longitudinal database of its roughly 1,500 student participants, providing a valuable tool to track and evaluate the program's effectiveness. Currently, ~45% of Pathways students identify as Black or Hispanic. The percentage of Black or Hispanic students in the greater New Haven region is 70-80%. Greater awareness of Pathways as a resource for faculty and students interested in outreach, as well as support for programs that successfully serve a representative sample of New Haven school children could further increase the impact and visibility of this program.

Diversity at the undergraduate level:

The Science, Technology and Research Scholars (STARS) Program has served as Yale's flagship program to support women, minority, economically disadvantaged, and other historically underrepresented students in STEM since 1995. Data collected over two decades clearly demonstrate that STARS improves the retention and performance of its participants. STARS students are almost nine times more likely to persist in science than students at large. STARS is complemented by the Summer Undergraduate Research Fellowship (SURF) and the Post-Baccalaureate Research Experience Program (PREP) Programs, which help provide graduate-level research experiences to a diverse group of undergraduate students. An institutional plan is needed to provide sustained support and continue development of these important programs.

Diversity at the graduate student and postdoctoral level:

Yale works to promote diversity in graduate enrollment, participates in dedicated recruitment efforts at Historically Black Colleges and Universities, Hispanic Serving Institutions, and Tribal Colleges and Universities, and provides financial support for Emerging Scholars from diverse backgrounds. Despite these efforts, most STEM graduate departments at Yale have low participation among underrepresented minorities. Beyond targeted recruitment efforts, and based on successful STEM recruitment programs at other research intensive institutions, we recommend programs that power meaningful relationships with minority-serving institutions through faculty exchanges, research collaborations and other targeted approaches for STEM fields. Postdoctoral positions are also an important step along the career path for young scientists, particularly for those interested in academic positions. Across the country, men tend to occupy a majority of postdoc positions, even in fields with gender balance in graduate programs. Yale should work to identify barriers to under-represented groups in postdocs and pilot new policies to address issues that become evident.

Diversity at the faculty level:

In November 2015, Yale announced a $50 million partnership between the Office of the Provost and the FAS and professional schools to promote excellence and diversity of its faculty. In addition to the Emerging Scholars initiative mentioned above, this includes funds for visiting scholars, faculty development offerings, and resources to complement the recruitment of faculty that could enrich the excellence and diversity of the University. While the Faculty Excellence and Diversity Initiative has contributed resources to support the recruitment of fifty ladder and ladder equivalent faculty university-wide over the past two years, diversity within the professoriate in STEM fields remains a significant challenge.

Faculty diversity in STEM is a nationwide issue, but there are institutions and programs that have shown success in attracting and recruiting diverse scholars and promoting inclusive environments through cluster hiring, faculty peer mentoring and support, and tangible rewards for faculty that engage in mentoring and service. In addition, studies show that major inroads could be made, particularly in the sciences, for programs focused on the Ph.D.-to-faculty transition. Other programs, such as the NIH-IRACDA and the HHMI Hanna Gray Fellowship, have found success at improving diversity in the academy by investing in diversity at the postdoctoral level. These programs include mentor training for both the mentor and the fellows and professional development for the transition into a faculty position.

In order for Yale STEM programs to fully leverage the body of exceptional and increasingly diverse talent of tomorrow's students, postdocs, faculty, and staff, the University must promote the integration of best practices in recruitment and retention across all STEM departments. These efforts must implement strategies that address challenges that are specific to STEM fields.

The USSC makes the following recommendations to recruit, develop and retain diverse community of STEM researchers:

- Coordinate existing STEM diversity initiatives within a single administrative home that has broad responsibility for strategic planning across the entire diversity pipeline. This would include not just faculty diversity, but all aspects of diversity and inclusion in the STEM pipeline. The most logical base for this responsibility would be with the Deputy Provost for Faculty Development and Diversity within the Office of the Provost. This position need not run all the programs, but it should have authority for strategic planning for the full pipeline.
- Continue investment in early stage diversity programs, including outreach efforts to local middle and high schools, research and mentoring for undergraduates and graduate students, the Dean's Emerging Scholars Initiative, and the Presidential Visiting Fellowships.
- Continue investment in programs designed to help undergraduates from underrepresented groups advance in the sciences, such as the Summer Undergraduate Research Fellowship (SURF) and the Post-Baccalaureate Research Experience Program (PREP) Programs.
- Establish and maintain productive relationships with minority serving institutions. These relationships should be purposeful and resourced for success, including coordinating mechanisms to bring students for summer research, internships and post-baccalaureate periods and promoting faculty exchanges and student-centered research collaborations.
- Recruit senior scientists and administrative leaders committed to diversity, who, through their influence and status, will improve the culture of inclusion in STEM fields.
- Tailor efforts to address specific challenges related to the recruitment of postdocs and to the transition from a Ph.D. to a faculty position in STEM fields. Consider establishing, emulating or supporting the development of programs that are successful in the recruitment of postdocs from diverse backgrounds, such as programs that secure time for teaching (similar to IRACDA) or provide resources for student and mentor pairs (like the Hanna Gray Fellowships).
- Make the Presidential Visiting Fellowships within the Faculty Excellence and Diversity Initiative more applicable to STEM fields by providing research space and resources to talented diverse scientists who would develop independence while having "insider access" to the STEM networks of the university.
- Implement recruitment, hiring and retention practices and policies that increase representation in the STEM faculty ranks, including cluster hires.

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- Reaffirm and continually improve mechanisms to assess and evaluate the impact of efforts to increase diversity in STEM. All efforts should incorporate best practices and evidence-based strategies and should be designed to integrate ways of monitoring and assessing progress.
- Ensure that the University-wide infrastructure to promote scientific innovation and entrepreneurship, such as the Office of Cooperative Research, Tsai CITY, the Blavatnik Fund for Innovation, and the Center for Biomedical and Interventional Technology, is inclusive and supportive of diversity.
- Provide mechanisms that allow faculty to conceptualize, implement and measure interventions that improve diversity in STEM. Being Human in STEM and Yale Ciencia are two examples of faculty-initiated programs that have allowed faculty, students and staff to design, implement and evaluate innovative programs in research inclusion, mentorship and education.
- The decline in the proportion of female scientists in the STEM fields begins during the postdoc-to-faculty transition, and continues through to becoming full professors. Lack of access to affordable and local childcare is a major reason behind this decline. To attract and retain the brightest female scientists, Yale should provide more opportunities for affordable on-campus day care and after-school childcare programs at all levels of the scientific career ladder. This serves as a specific example to the general concept that University should establish processes that systematically evaluate and address historical and institutional barriers that disproportionately affect under-represented groups in STEM.

Cross-cutting Investments

Instrumentation Development

Strategic investment in instrument development is needed to enable the novel measurements at the frontier of discovery across STEM fields.

The history of science reveals that many great discoveries have been enabled by innovative instruments. The development of new tools and measurement techniques continues to be an essential component of the scientific process, allowing researchers to push the boundaries of observation and open entirely new avenues for investigation. From the earliest refracting telescopes to today's mass spectrometers and atomic force microscopes, new instruments that enable us to observe and measure novel phenomena for the first time are among the most powerful drivers of scientific progress. The 2017 Nobel Prizes for both Physics and Chemistry, awarded for the detection of gravity waves and the determination of high-resolution structures for biomacromolecules using cryo-electron microscopy, respectively, stand as powerful reminders that instruments remain essential in answering the most enduring and important questions in science.

Over the past century, Yale researchers have been at the forefront of efforts to develop groundbreaking scientific instrumentation and new measurement devices. These efforts span both the geographic footprint of the University and its full spectrum of intellectual interests and academic departments. These vital research instruments have led to remarkable advances in science and medicine, but today's most pressing scientific questions require us to look further – in and around the furthest galaxies, at the smallest microscopic scales beyond the diffraction limit of light, or deep within our cells –using new and improved instrumentation.

Given the importance of instrumentation to discovery, the institutions that lead the way in the development of new instruments are able to attract an outsized share of grant funding for research and lead in the national and international research communities. This has recently been emphasized by the National Science Foundation, which listed mid-scale instrumentation and research infrastructure as one of the 10 "big ideas" for future NSF investments. Thus, a renewed focus on the design and development of new and cutting-edge instrumentation and measurement tools at Yale represents both a critical need and an outstanding strategic opportunity.

Yale is well-positioned to address this need. It has a manageable size, enjoys a close proximity to Brookhaven National Laboratory and other institutions on the East Coast, and includes a variety of faculty with an interest in developing new scientific instruments, devices, and tools. As a result, the USSC concluded that greater investment in instrumentation and measurement would pay significant dividends. In our laboratories of physical chemistry, for example, state-of-the-art, one-of-a-kind instruments simultaneously perform optical spectroscopy on gas phase molecular ions to reveal previously unseen molecular structures. The newly renovated Wright Laboratory, which not only houses new research laboratories, but also our highly-coveted machine shops for the development of unique devices, is a bustling hub of instrumentation development. Even at the undergraduate level, our Center for Engineering Innovation and Design is a hotbed of both focused fabrication of novel tools for measurement and observation, as well as a center for tinkering and incubation of next generation prototypes.

The development of new instrumentation at Yale has typically been driven by the scientific needs of specific projects, funded by individual grants, and "siloed" (i.e., carried out with access to, or knowledge of, the full array of resources available on campus). Long-term instrumentation projects are traditionally driven by research scientists, postdoctoral scientists, and, to a lesser degree, students, who graduate and move on to their own initiatives and careers. Naturally, students and postdoctoral scientists do not provide long-term continuity, and in our present culture, individual research scientists do not form a broader community or environment outside their immediate research group. Where necessary expertise exceeds that available at Yale, the design of specific individual components is often outsourced to freelance contract-based employees. Freelance employees are costly, unpredictable, and lack accountability for the broader and longer-term goals of the project (i.e., the design of an entire instrument, instead of just a single circuit).

The USSC views this ad hoc approach to instrumentation development as insufficiently strategic. Instrumentation is a key structural area in which the University should make a thoughtful investment to strengthen science and engineering at Yale across all scales. To maximize the collaborative and synergistic impact that is possible through instrumentation innovation, we envision a series of changes to strengthen the design, development, and optimization of cutting-edge measurement technologies and emerging scientific devices on Yale's campus. This includes institutional recommendations to build a culture of innovative thinking at the intersection of science and engineering, as well as direct investments in the search for new and innovative scientific tools. These facilities should build community while offering proximity and instrumentation support, with a professional staff and specialized resources. They should offer a range of machining and prototyping equipment, computing resources, design and interaction space, and a flexible, expanded, supervised "tinkering space," where people could bring ideas and challenges in instrumentation. A commitment to instrumentation research will help inspire the founding of spin-off companies and will make Yale a more attractive home for research. An increase in first-in-class devices developed at Yale would lead to increased grant revenue, and in some cases, a decreased reliance on commercialized "off the shelf" technology - driving innovative science more broadly at Yale. Royalties from particularly successful technologies are also a possibility. The design of new instrumentation will unquestionably play a central role in the training of undergraduates, graduate students, and postdoctoral researchers at Yale.

The USSC makes the following recommendations to support the development of novel instrumentation at Yale University:

- Build or expand one or two high-capacity centralized instrumentation and engineering facilities (in the form of core or shared research support facilities) to serve as intellectual "hubs" for instrumentation development at Yale. The instrumentation hub(s) must support projects beyond a single department or school. They must truly be University centers for instrumentation development.
- Establish a single point of contact for all campus instrumentation-development resources and improved coordination of core instrumentation facilities and capabilities across campus (see ***Core Facilities*** recommendation below).
- Initiate a review of on-campus resources and professional expertise in fields relating to instrumentation, such as computer programming, computer-aided design (CAD), computer engineering, computer modeling, electrical engineering, electronics systems design, mechanical engineering, machining, fabrication, and optics.
- Assess the need for long-term support personnel in these areas.
- Increase the staffing of its instrumentation facilities, filling gaps identified by the review of available on-campus professional expertise, adding full-time, non-tenure track slots for professional scientists, engineers, and machinists with a clear oversight structure and management plan consistent with a University-wide resource.

- Establish, promote, and sustain a campus culture of innovation in instrumentation.
    - Initiate seed funding programs at the faculty and student/postdoc levels for proof-of-concept and pre-commercialization instrumentation development. This includes seed funding for instrumentation-related work, "pitch contests" for instrumentation, and RFP-driven grants to individual researchers working on novel measurement devices and approaches.
    - Establish seminars, conferences, workshops, and "brown bag" lunches for faculty, postdoctoral fellows, and research scientists whose interests include the development of new instrumentation.
    - Create a University-wide "Instrumentation Day" to raise awareness of the high-profile instrumentation research on campus and to spark new collaborations.
- Integrate the instrumentation development process into education at Yale for undergraduate and graduate students.
    - Students and junior scientists should be given maximal exposure to the instrumentation design and development process.
    - Development of cross-disciplinary courses and workshops on instrumentation and technical topics that go beyond the expertise of a single department or unit.

Cross-cutting Investments

Core Facilities

Core facilities play a critical role in innovation and interdisciplinary science that justifies increased coordination and strategic investment.

Yale makes a substantial investment in core facilities that support the research and education missions of the University. The quality of these facilities is highly variable, and they span all scales of the University. There are University-wide cores, cores that support individual schools, cores that support individual departments, and some that support clusters of faculty laboratories. The funding mechanisms of these are equally variable, with support coming from internal and extramural sources, but all involve some level of cost recovery from users.

The USSC repeatedly heard about the importance of modern and highly functioning core facilities, and the important role they play for innovation and interdisciplinary science across the University. Particularly in the life sciences, we learned that the sophistication of many fundamental technologies has grown to the degree that leading-edge work is now well beyond the reach of individual laboratories or departments. The availability and quality of core facilities are also increasingly prominent factors in recruitment and retention of faculty, and in the review of research proposals. Based upon the input received, we made an effort to identify areas where incremental core investment is needed to advance science on our three campuses. Through that analysis, we discovered several things about organization of the cores at Yale that may be leading to underperformance on a University-wide level relative to the scale of our investment and relative to the efforts of our peers.

- There is no overall campus-wide strategy or source of funding for core investment.
- There is relatively little coordination between the different schools in the development of emerging core technologies.
- Many existing cores have emerged through expansion of local, home-grown, efforts – resulting in a patchwork of services that suffers both from scientific gaps and overlapping/competing service areas.
- Growing out of the lack of coordination, each core has had to develop its own solutions to address basic processes such as scheduling, sample tracking, order processing, staff training, billing, negotiating service contracts, etc.
- The communication of core services to the user community through web sites or other internal communication is disorganized, reflecting both the patchwork organization of our cores and the absence of overall University strategy.
- There is no central inventory of what core services are available at the University, how they can be accessed, what they cost, what are their capabilities, or who to contact.
- In almost every case, cores run a deficit. The magnitude of the required subsidy is a source of concern both for the users and those responsible for running the cores.
- In several key areas, cores lag behind the current state-of-the-art, limiting Yale science and forcing Yale scientists to seek facilities at other universities or forgo good ideas.
- In many cases the cores lack a strategic plan and funding to upgrade their equipment and services.

- In some other important areas, core facilities do not have the capacity to meet the needs of Yale laboratories and/or are not cost effective.

Through our analysis of the Cores at Yale, the USSC also identified features that have led to particularly successful core facilities across our campus and at other institutions. Not every successful Core has all these features, but we observed that these represent best practices.

- Significant faculty involvement in the form of advisory committees and/or faculty director leadership to provide vision, expertise and the innovation necessary to support and advance current and future leading-edge technologies.
- Dedicated, highly qualified staff whose salaries are underwritten at least partially by central support to provide continuity of their employment.
- Substantive consultation is provided at no cost to users, with comprehensive guidance to both internal and external facilities.
- Cores keep abreast of the most current developments in their respective technology, and tailor these developments according to the needs of the community. Development is considered a cost of operation.
- Resources are available for upgrading and replacing equipment from internal or external funding sources.
- Groups of faculty and staff are willing to write successful project and equipment grants to help support the core infrastructure.

All of the priority scientific ideas in the biological and physical sciences (see below) depend upon effective core support. Modern 'precision' biology is technology driven, requiring collection and analysis of 'omics' data on a large scale. 'Next-generation' technologies will define all current and future advances in Precision Medicine, Cancer, Regenerative Medicine, Neuroscience, and Immunology and Inflammatory Disease. Yale's leadership in these areas will depend critically upon improved and expanded leading-edge Core facilities with continued investment and development. The USSC recommends against making incremental technology investments specific to individual institutes or departments. Rather, as outlined below, Cores at Yale should be considered as part of a larger infrastructure of 'next-generation' support for all of biological science that will also serve to bridge departments, institutes and schools.

Yale's current biological cores represent most – if not all – required technologies at some scale or generation, yet we also recommend greater investment is these resources. Leadership in the big ideas recommended by the USSC, and across the life sciences, will require substantial expansion of this infrastructure and timely adoption of next-generation technologies. One exemplar of the impact this can have is provided by the Yale Center for Genome Analysis (YCGA), which allowed Yale to be at the forefront of whole exome sequencing and to perform the world's first genetic whole exome diagnosis of a chronically ill infant. YCGA brought leading-edge high throughput genomic analysis technologies under one roof to provide a centralized Yale resource for large scale genomic studies, with substantial faculty involvement, space, resource and personnel commitment – and a significant technology development component. It also included a significant central financial investment. Development of YCGA was a necessary step in the evolution of next-generation DNA sequencing technologies at Yale, superseding several cores across the University that employed outmoded methods. YCGA is a model for how the University should adopt other burgeoning technologies and analytical methods that lie at the heart of modern life science and medicine, including transcriptomics (RNA analysis), mass spectrometry (proteomics and metabolomics), genomic perturbation (CRISPR), biostatistics/bioinformatics, imaging/image analysis, and single cell biology.

Excellent core facilities are equally essential for Yale to be at the forefront of research in the physical sciences. The Yale Clean Room and Yale Institute for Nanoscience and Quantum Engineering (YINQE) nano-fabrication facilities are essential for the fabrication of samples used in sophisticated devices ranging from chips for optical signal processing to superconducting qubits for Yale's quantum computing effort. Sample characterization via scanning electron microscopy, transmission electron microscopy, atomic force microscopy and other techniques is an equally vital service. YINQE users come from many different departments and areas of research. Another example is the Chemical and Biophysical Instrumentation Center (CBIC), which is a vital resource for chemists and biologists interested in high-quality NMR, X-ray, optical, mass spectrometry and various other biophysical measurements. All of these cores have achieved their success through the efforts of expert and dedicated staff working in cooperation with faculty committees. But even in these best-case examples, there continues to be a need for instrumentation upgrades, adoption of new technologies, and better communication and coordination across the University of its core services.

We offer the following recommendations to improve and expand the support services provided through the University's cores. These recommendations apply to all the science Cores on campus.

- Create a position in the Provost's office that has responsibility for overall coordination and integration of the Cores at Yale.
- Establish strategic oversight committees (SOCs) for Yale Cores in the life sciences and physical sciences, each comprising 5-8 faculty who represent the highest level of science. Charge the committees with formally evaluating core technologies and aligning Core development with current strengths, respective needs, and strategic interests of the University – noting that Cores should not strive to be comprehensive, but should be excellent and well-staffed.
- Conduct an inventory of all Cores available across the University on all three campuses – including the types of services offered, equipment available, staffing, pricing, reporting lines, extent of cost supplementation, and other practices. This information should be analyzed for redundancies, gaps, and inefficiencies in the Core services, and for quality.
- Make information about Cores accessible through a prominent, well-designed, and continuously updated website that is visible externally.
- Establish simple, standardized and publicized procedures for appropriate core use by external entities.
- Survey the faculty for their use of Core services, what work they do in-house and what they choose to send to facilities at other universities. Seek faculty input to identify gaps in Core services or emerging services that should be considered for future Core support.
- Guided by the strategic oversight committees and the Provost's office:
    - Establish centralized Yale Cores in areas of greatest impact, associated with recruitment of a faculty-level scientific director with expertise in advancing the relevant technologies, as well as investment in appropriate instrumentation and professional staff.
    - Invest in staffing and instrumentation in strategically important developing cores at the School and/or Department level, ideally in association with faculty recruitment.

- Recognize technology development as an important aspect of all Core facilities, and include this requirement in the funding model.
- New services or equipment should be added to the Cores as identified based upon the Core review described above. For example, several faculty across many fields expressed a need for greater Data Science consultative support (for example see ***Precision Medicine*** and ***Cancer*** below). Pending the results of the Core assessment, a Data Science core is likely to be an area that warrants investment.
- Scale back or eliminate redundant services, where possible, based upon the Core review.

The USSC recommends **five ideas for top priority investment**. The nature of each idea, Yale's current strategic position with respect to that idea, and specific recommendations for implementation are described below. For each of these five ideas, we recommend creation or expansion of an institute, or an analogous academic structure. Variability in the current organizational landscape for each field creates significant variability in what an "institute" means in each case, but we have used that classification here for purposes of simplicity.

Top Priority Idea:

Integrative Data Science and its Mathematical Foundations

How will the data revolution transform intellectual inquiry, accelerate scientific discovery and promote human sustainability?

The world is currently undergoing a data revolution comparable to the industrial revolution in its potential impact. That revolution began with technological innovations, which were broadly and rapidly applied to myriad inventions, ultimately shaping the course of societal development. We are at an equivalent moment today. The confluence of the volume, speed, and availability of data is transforming information and knowledge production. Not a single aspect of society today will be left untouched by the data revolution. We are fundamentally changing how we generate insights and how we approach understanding the world.

Data Science is a rapidly coalescing discipline. It is inspired by recent scientific and engineering advances in computing power, the ability to collect data sets of immense size and diversity, and algorithmic advances in machine learning and artificial intelligence that enable powerful analyses and inferences. Data Science facilitates the integration of multiple types of data across different scales and applications to other fields with the goal of accelerating discovery and improving our lives. A new mathematics of data must be developed to meet this challenge, advancing the mathematics of modeling complex systems and evolving it into a modern (as yet little explored) data-informed regime. Data streams from sensors, instrumentation, the clinics, and the internet demand innovations in mathematical models and algorithmic tools to make possible new understanding and predictive power never before imagined.

Yale's rich tradition in the theory and methods of data analysis and scientific computation sets it apart as a leader at the innovation frontier for the advanced tools and techniques that this torrent of complex data will require. With the right organizing principles and structures to enable collaboration, Yale can leverage this strength to energize and transform the university landscape in the data age.

Mathematical foundations of data science: Machine Learning, modeling, and methodologies

The successful application of Data Science will require its integration with current analytic techniques and the strengthening of its mathematical foundations. Many techniques of Machine Learning have succeeded by being "agnostic" towards their source of data, whereas many scientific analyses succeed by the analysis of carefully constructed models. Modeling, whether based on simple regressions, complex networks, conservation laws, or differential equations, can greatly facilitate inference from data. In turn, machine learning tools can help identify significant features needed to improve existing models and define new ones. This combination of machine learning algorithms and modeling will be used in scientific simulation to improve prediction and aid efforts in explanation and design. Across the spectrum of research and discovery, an emerging dialectic between model-driven and data-driven discovery gives rise to a new "feedback loop" in the discovery process. Models drive data acquisition and data-driven inference refines the models.

The intertwining of these approaches illustrates another central intellectual challenge of integrative Data Science. While many techniques of machine learning appear to work well in certain applications, there is often insufficient understanding of *why* they work, when they are wrong, and how they fail. The more powerful and central to society these algorithms become, the more we run the risk that their failures will have catastrophic repercussions. Without deeper understanding, we cannot validate the robustness of their predictions and this fact constitutes the overarching challenge of the data age.

We expect that innovative mathematical theory will be necessary to achieve rigorous analysis of machine learning algorithms. Deep mathematics has been central to the development of our understanding of complex data. Examples abound of deep mathematics playing a crucial role in development of such algorithms, such as ensuring little information is lost in the projection of data to lower dimensional spaces, or producing theorems that facilitate data recovery with sparse information, or how to use topology and diffusion to cluster and interpolate similarity in massive "point clouds" and networks where large scale structure plays a critical role. Yale has been a leader in the development of these techniques, tools, and theorems, and it should continue to lead with this strength at the interface of mathematics and data.

Incorporating machine learning methods into mathematical modeling - currently in huge demand for studying complex scientific problems across the sciences and engineering - will require development of rigorous techniques and tools. To lead in this development, Yale should build on its great strength in the areas of pure and applied mathematics, statistics, and theoretical computer science. Each will play a role in the advance of these fields, with ideas and methods drawn from areas ranging from probability, analysis, topology, combinatorics, graph theory, and the analysis of algorithms.

Integrative Data Science encompasses the entire life cycle of data

Integrative Data Science is not just about "big data". It encompasses study of the entire data life cycle from acquisition to interpretation and action. The data life cycle presents a broad range of demanding challenges, all of which are essential for successful exploitation of data. This life cycle includes:

- Understanding how data are gathered and the issues that arise in data collection;
- Knowledge of what data sources are available and how they may be synthesized;
- The storage, annotation, curation, management, and transformation of data;
- Statistical inference, machine learning, artificial intelligence, and the design of algorithms and computing systems that enable these tasks;
- Mathematical research on effective tools and techniques from a range of disciplines to understand high-dimensional, complex, or sparse data sets;
- Presentation and visualization of data and the results of data analysis;
- Use of data analysis to make decisions and set policy;
- Appropriate protection of privacy and the elimination of bias in the entire process.
- Development, analysis and refinement of mathematical models that explain the data

The need for method development in inference, machine learning, artificial intelligence, and algorithms appears throughout the data life cycle. Each new challenge presses the need for deep theoretical advances, from data processing, to scientific reproducibility, to interpretability, including an increasing need for a theoretical understanding of 'why it works' and what lies within the 'black box.' The latter questions are of great societal importance as more and more aspects of our lives become affected and even controlled by algorithmic decisions. Moreover, such understanding can ensure our use and understanding of data for the public good.

Integrative Data Science with many applications

The data revolution offers a contemporary opportunity to transform science. There are great intellectual challenges in the development of Data Science and its integration broadly into the physical and life sciences, engineering, health care, medicine, humanities, law, and business. Yale's compact campus and collegial atmosphere create an ideal setting in which to dissolve the traditional barriers between technology development and subject matter expertise – an essential ingredient to enable the novel multidisciplinary collaborations needed to harness the data revolution and accelerate scientific discovery.

Most of the great developments of Data Science have been motivated by real problems; indeed, Data Science quickly becomes circular without subject-specific data sets and goals. The following areas provide grand challenges in Data Science applications that will both improve our world and yield new methodological and scientific discoveries. These grand challenges also integrate seamlessly with other big ideas in our science strategy recommendations (see below).

1. Biomedical science and precision medicine– Can we tailor healthcare for each individual?

Healthcare is a national priority, with spending in the U.S. of over three trillion dollars per year. Despite extensive health records and the availability of individual genetic data, routine medical risk assessments and treatment decisions rely largely on minimal information such as age, gender, and body mass. There is tremendous potential to improve medical decisions and health outcomes by integrating and analyzing these additional extensive data sources. Yale has an outstanding track record in the biomedical sciences, and has invested heavily in this area for many decades. Biomedical experts and their collaborators in Data Science at Yale seek to leverage the extensive collection of patient data – the "data lake" acquired from patients in the Yale-New Haven Health (YNHH) system – to advance biomedical science and to educate the next generation of students. Of particular value are the health records of many patients who have visited the health system over extended periods. The resulting longitudinal data are a unique asset made possible by the leading role of YNHH in the New Haven area and the State of Connecticut. The challenges to overcome in this area include how to automatically interpret medical records and how to find patterns in these giant data sets. The future will be the synthesis of these data to provide precision medicine – individualized diagnosis and treatment.

2. Environmental science – Can we save the planet?

The effective management of Earth's natural resources and health in the face of ongoing global change represents one of the greatest challenges of our time. There is immense need for science and engineering to support environmental management, decision-making, and policy. The need is not just to test scientific hypotheses, but for the development of data-driven recommendations and products that have the potential to inform society. For example, Yale produces the Environmental Performance Index, informing world leaders at the World Economic Forum (based in Geneva). Moreover, international science policy organizations have tasked the scientific community with providing novel, highly data-intensive and spatially-explicit climate models. In addition, Yale has expertise in the organismal, theoretical and applied science of our planet. This expertise presents huge opportunities to develop data-driven discovery and data interpretation recommendations at the interface of science and policy.

3. Neuroscience – Can we determine how the brain works?

The challenges of Neuroscience are intimately linked to those of Data Science. Advances in brain imaging technology, including those achieved at Yale, provide immense amounts of information about which parts

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of the brain are active during various cognitive tasks, as well as how neurons are connected and which individual neurons are firing within the brain. Analyzing these data to find correlations and to discover how these activities lead to cognition is a daunting computational problem. Like genomic sequence data, the vast storage requirements for movies of brain and neuron activity will be challenging. Moreover, analyses of these data will be orders of magnitude more resource-intensive than storage, and will require significant advances in Data Mining, Machine Learning, and mathematical modeling.

4. Social science – Can we transform the field through data-rich "hard science?"

Social science is now entering a "golden age" of understanding people's preferences and behaviors. The digitization of human history, the availability of extensive databases of government, corporate, and social actions, and the continuous data streams produced by internet browsing and smart phones allow unprecedented studies in Sociology, Psychology, Political Science, Linguistics, Anthropology, and Economics. These data sources are allowing these fields to become increasingly quantitative and predictive. Insights extracted from such data have the potential to deepen our understanding of the connections that people make and the information that they share, thus enabling the development of interventions that can enhance our society and advance our health, security, and civic life. To maintain Yale's strength in these disciplines, researchers in these fields will benefit from collaborating with experts in Data Science. This work will complement Yale's considerable strengths in qualitative social science.

5. Basic science – How will new tools of inference transform scientific inquiry?

Scientific progress increasingly depends on the robust integration of computation, mathematics, and modeling into fields such as biology, chemistry, geology and astrophysics. The duality between mathematical modeling and data analysis has become a central new dynamic in each of these fields. Integration of Data Science and modeling requires foundational methodological training, interdisciplinary thinking, and field-specific expertise – a combination that is possible only through extensive and productive collaborations among teams of investigators. In addition to the growing need to incorporate mathematical modeling and data-driven approaches into scientific pursuits, this changing landscape in the sciences emphasizes the need to ensure that appropriate education and training programs exist for undergraduate and graduate students as well as faculty. Indeed, Yale must work to provide an environment that inspires scientists at all levels to leverage mathematics and Data Science to address the grand challenges of science.

Many other areas of excellence at Yale stand to be improved by collaboration with data scientists, from astronomy and astrophysics to materials science, management, and the humanities. Determining how to use data responsibly will also require the combined efforts of data scientists who understand what is possible, and political scientists, philosophers, and lawyers who think about what is desirable. Leveraging existing strengths, Data Science will thrive at Yale and play a vital role in its future.

We offer the following recommendations for developing an Institute for Integrative Data Science and its Mathematical Foundations:

- *Organizational Structure*: Establish a University-wide Institute for Integrative Data Science and its Mathematical Foundations to facilitate integration of Data Science and mathematical modeling research across the University. This Institute should offer membership to and facilitate interactions among faculty in the Department of Statistics and Data Science, Mathematics, Computer Science, Engineering and relevant faculty in domain areas, including those affiliated with the Center for Biomedical Data Science in YSM.

- The Institute should play a consultative role in faculty recruitment across the University and should be vested with a combination of full slots and half slots for faculty appointments in various departments (see below).
- The Institute should provide administrative infrastructure to facilitate and govern the funding of cross-departmental and cross-disciplinary efforts that span diverse departments, schools, and initiatives across the campus.
- The Institute should integrate and involve Yale faculty in cross-campus research programming, industry collaboration, and broader regional university consortia.
- The Institute should maintain close connections with the Yale Center for Research Computing, which would be charged with providing hardware and technical support for much of the research in this realm.

- *Faculty and Students*: Expand by at least a dozen the number of faculty in Data Science, machine learning, and mathematical modeling and foundations across the University.
  - Hires should include core areas such as algorithms; mathematical methods of Data Science; mathematical modeling; machine learning; deep learning; vision and imaging; computational biology; natural language processing; computational social sciences; high performance computing, distributed and large-scale computation, and cloud computing; privacy, security and fairness; visualization and communication.
  - Faculty appointments should be primarily in the departments of Statistics and Data Science or Mathematics in the FAS. Joint faculty appointments within YSM, FAS or elsewhere in the University should be distributed across other relevant departments and institutes specific to subject matter expertise. Connections to ***Neuroscience***, ***Environment and Evolution***, ***Cancer*** and ***Precision Medicine*** (see below) are domain areas for which particular attention should be given.
  - As faculty are added, there should be a commensurate increase in the size of the relevant graduate programs.
  - Creative ways should be identified to bring the best researchers to Yale, not just from academia, but also from industry where some of the most important fundamental research is being carried out today. This may include creating positions analogous to “Professor in the Practice” or sabbatical positions to allow researchers from industry to teach and work at Yale for a defined period.
- *Space*: Identify space for the co-location of the Statistics and Data Science and Mathematics departments with sufficient room for expansion. Include hoteling space for visiting faculty and students from other departments to collaborate. One location that meets many of the criteria is Kline Biology Tower, assuming that it is completely renovated for this purpose following the relocation of the MCDB department from the building.
- *Funding*: The University should create clear and viable pathways for its top faculty to compete for outward-facing, federally- and/or privately-funded institutes in the foundations of Data Science (see Center Grant Support recommendation below).
- *Education*: As faculty are added, the University should significantly expand its courses to include advanced machine learning, algorithms, large-scale computing courses, and applications in key fields.

    - Focus attention on introductory courses that emphasize mathematical foundations and principled understanding of tools and methods.
    - Support the creation of intensive short-term training opportunities in the technologies of Data Science. These could take the form of week-long workshops. Such programs would make Yale a destination for training in Data Science.

- *Infrastructure*: Storage and computational infrastructure is vitally important for handling large amounts of data. The University should support data storage and management resources oriented towards data-intensive disciplines (see ***Data Management*** recommendation below). These resources could take the form of a new Core facility, in analogy to other facilities that support research at the university.

Top Priority Idea

Quantum Science, Engineering, and Materials

Can we harness the power of the quantum?

The science and technology associated with quantum-mechanical phenomena have emerged in the 21st century as a new frontier of fundamental knowledge about how the universe works. All aspects of "Quantum" are rapidly becoming a radically new source of practical technologies. Many of the most famously perplexing and counterintuitive aspects of quantum mechanics do not represent limitations on our ability to understand and control the world around us, but rather–surprisingly–a powerful new set of resources that can be exploited to remarkable advantage in applications at the cutting edge of many disciplines.

One of the key insights that has opened this frontier is that information plays a fundamental role in our understanding and analysis of physical systems. As a result, we have realized that physical systems can control information in a much more powerful fashion than had previously been conceivable. The quantum information perspective has given us a completely new way to teach quantum mechanics that truly ignites students' imaginations.

The scientific and technological resources emerging from these insights are not specific to subatomic particles or isolated physics experiments. Rather, they apply broadly to all physical systems and phenomena (e.g., molecules, liquids and solids; light, sound, heat, motion; electricity and magnetism) and are now being studied and exploited in ever-larger and more complex systems, relevant to a much wider range of science and engineering. This 'second quantum revolution' is resulting in transformational advances in astronomy, cosmology, physics and applied physics, chemistry, materials science, electrical engineering, biology and biomedical engineering, computation, and communication. Importantly, this progress not only enables, but is enabled by, remarkable advances in new materials and in the manipulation of atoms and materials at the atomic and nanometer scale. In order for Yale to excel in Quantum, we need to build both directly in support of quantum science and engineering and in the broader areas associated with materials – only through excellence in both will Yale be able to excel in quantum technology.

We envision three closely related and mutually supporting pillars of intellectual activity in Quantum.

1. Quantum Computation, Communication, and Data Security

Can we build the ultimate computer? Quantum information, the study of the information content of quantum systems, has futuristic potential applications in information security, data science, machine learning and computation. The creation of revolutionary quantum computers—able to carry out extremely difficult computations (e.g., detailed predictions of molecular and material properties, quantum-enhanced machine learning and database manipulations), possibly far beyond the scales that will ever be achievable with ordinary high-performance computers—is on the horizon, enabled by novel materials and nanoscale engineering.

Can we enhance privacy through the power of the quantum? Quantum information can be transmitted but, paradoxically, cannot be copied. This means that future quantum technologies could enhance information security and privacy. Preliminary examples of this technology have already been deployed in small private networks, but the development of these ideas to transform worldwide information security will take place in academic quantum science and engineering labs in the coming decades.

2. Quantum-Enabled Sensors and Measurement Techniques

Can we detect the tiniest signals from distant galaxies and from individual living cells? Devices whose operations are based on quantum principles include not just computers and communication channels, but also the potential for radically new measurement devices and sensing techniques able to focus on tiny signals and (partially) ignore noise. Such 'quantum-enabled' devices and sensors, enabled by deep understanding of materials and device engineering, are beginning to even surpass the standard limit expected from naïve application of the famous Heisenberg uncertainty principle.

These advances are enabling the development of new research tools in physics, engineering, cell biology, neuroscience, astronomy, and beyond. Examples currently under development include: nanoscale sensors of temperature and magnetic field for measuring the structure and dynamics of individual cells and potentially individual molecules; single-photon detectors to receive light from remote planets, stars and galaxies as well as weak fluorescence signals from biological tissues; sensors for gravity, both real world (detection of underground structures and mineral deposits) and fundamental (gravitational waves); 'table-top' quantum experiments to detect new particles even more massive than can be created at the world's largest colliders; and possibly to detect dark energy, the mysterious force causing the expansion of the universe to accelerate.

3. Quantum Materials

Can we design and synthesize materials that were never before possible? A room-temperature superconductor? An anti-cancer molecule? A catalyst to turn pollutants into useful products? A new material for solar cells?

Advances in materials science, and quantum science in particular, will lead to greater understanding of many-electron systems, and thus to new abilities to understand, measure, design, synthesize and predict the properties of novel solids, as well as to create completely new artificial materials that do not naturally occur. These new capabilities will advance both fundamental science and practical applications in fields such as solar energy, catalysis, magnetism and drug design. The ability to design 'picomaterials' in which atomic placement is controlled with picometer resolution fundamentally depends on understanding the quantum world, as does the ability to measure and characterize the results of picometer-level changes in structure. In turn, strong control of materials enables the design and fabrication of quantum devices and sensors.

This moment in the history of Quantum is special in that a virtuous cycle is underway, in which new ideas in each of the three pillar areas summarized above are feeding back to bring advances to the others. For example, materials scientists are embedding single-atom defects into optical materials in search of the best possible properties for quantum sensing. Development of new quantum measurement and sensing methods is intimately related to the development of devices used as quantum bits ('qubits') for computation, and the resulting computers in turn will help predict and develop better materials properties for manifold applications. This synergy will provide a path for rapid growth in the field. A second example is that ideas from quantum information theory have already improved the accuracy of atomic clocks and enabled nuclear magnetic resonance (NMR) spectroscopy on small groups of individual nuclear spins – a capability that may someday allow us to directly determine the structure of a single molecule, with revolutionary impact on biology and medicine. Other ideas about the information content of quantum states have shown us how to dramatically improve current algorithms for solving the equations of quantum mechanics on ordinary computers. This in turn is beginning to have an impact on theoretical studies of quantum materials and molecules. Finally, a local example is the use of new optical clocks that are helping Yale astronomers in their search for exoplanets orbiting distant stars.

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Yale and the future of Quantum

We envision developing Yale's Quantum efforts into an overarching umbrella program encompassing multiple disciplines. The goal of this program will be to build on Yale's foundational strengths in one of the most important new intellectual frontiers of our lifetime, and to knit these strengths into a unified enterprise that establishes Yale as the internationally recognized center of excellence in Quantum.

Leading this dramatic blossoming represents an opportunity to do something unexpected and explicitly forward-looking that will make a serious statement for and by Yale—a statement that will enhance our ability to recruit top students and faculty and to build technologies with major impact in the world. It will also make Yale the place that is addressing the enormous governmental and corporate interest and concern in workforce development for this field.

The foundation for a world-leading program already exists at Yale and has been recognized with the formation of the Yale Quantum Institute. The University has pillars of excellence in a wide range of departments that can feed into a comprehensive program in Quantum, including in:

- *Quantum computing and quantum information*: Physics and Applied Physics have world-class theory and experimental programs in superconducting quantum circuits that already make Yale the world-leading center for the dominant technology platform in quantum information processing. The first electronic quantum computer was built at Yale, as was the first successful quantum error correction architecture on any technology platform.
- *Materials Science*: Yale has substantial and diverse strengths in materials science spanning Chemistry, all of the SEAS Departments, Applied Physics, Physics, and the West Campus Energy Sciences Institute. Connections to Brookhaven National Laboratory are also strong in support of this area.
- *Quantum-enabled detectors and sensors*: Yale has strong groups in Electrical Engineering, Physics and Applied Physics in this area and is a world-class center for opto-mechanics (the use of quantum light to control and sense quantized mechanical motion).
- *Table-top precision quantum experiments* studying both the microscopic world and the structure of the universe. The Physics Department (the Wright Laboratory in particular) have several superb experimental programs in this area.
- *Quantum condensed matter theory*: Physics and Applied Physics have substantial strengths in the quantum theory of many-electron systems and the study of the entanglement and topological properties of matter. This provides an important intellectual bridge between properties of quantum materials and certain powerful types of quantum error correction in quantum information processing.

These existing exceptional local strengths can be leveraged to recruit outstanding talent in complementary areas. Strong interdisciplinary hiring will help multiple departments (e.g., Physics, Applied Physics, Electrical Engineering, Mechanical Engineering and Materials Science, Chemistry, Computer Science) accelerate their evolution, and modernize and strengthen their research and teaching portfolios.

By enhancing synergy and interactions among faculty, students, and postdocs in diverse departments, Yale has great potential to be the first institution to establish a comprehensive university-wide research and education program in Quantum Science, Engineering and Materials that will advance the frontiers of knowledge and train the next-generation workforce for this burgeoning field. Such a program would be unique among our peer institutions. It would be highly attractive to students (and prospective students) by providing a meeting ground and common language for them to communicate across disparate departments.

To advance Yale's efforts in Quantum Science, Engineering and Materials, we offer the following recommendations:

- *Organizational Structure*: Expand the scope of the existing Quantum Institute into a University-wide Quantum Initiative at a scale that will attract international attention and will place Yale in a position of broad intellectual leadership. The expanded Quantum Institute should create a powerful ecosystem that initiates, enables and sustains both fundamental and applied advances in this burgeoning field and develops the underlying science and engineering disciplines, and materials research.
- *Faculty and Students*: Expand the faculty size in Quantum-related science and engineering departments through strategic hiring. We recommend the use of a pool of half-slots available to departments willing to commit a half-slot to make a hire in Quantum-related fields. We also recommend a subset of full slots be made available for pairs of departments willing to make joint hires in partnership.
    - Key areas for faculty hiring include quantum computer science, quantum materials science, quantum electrical engineering, quantum sensors for real-world applications (particularly in biology and medicine), quantum information theory approaches to fundamental questions about the universe (e.g., gravity, space-time and black holes), and materials science - in a way that builds on the natural intellectual synergies relevant to quantum technologies (e.g., superconductors or topological insulators).
    - As faculty are added, there should be a commensurate increase in the number of graduate students in the relevant host department.
- *Space*: Create a central intellectual hub for the Quantum Initiative, built on the foundation of the existing Yale Quantum Institute, by expanding its intellectual scope to fully include all three pillars discussed above and by expanding its physical scope to include modern high-quality space to house cutting-edge experiments and outstanding new hires.
    - Construct a new building for the physical sciences with the Quantum Initiative and Materials Research among its major foci, and with a goal of occupancy within ten years (by the year 2028). This building should be designed at a scale to support approximately 25 faculty labs, to house core facilities for materials research and nanoscale research and device fabrication, and to allow an expansion of SEAS in this and related areas.
    - In the period before such a building is available, the University should make maximum use of space available on West Campus, particularly in space committed to the Energy Sciences Institute, and in Becton to house incremental faculty hires in this area.
- *Core facilities*: Expand, upgrade and modernize the core facilities and cleanroom that support the Quantum Initiative and the physical sciences (see ***Core Facilities*** recommendation above). This includes nano-fabrication, lithography, instrumentation for materials characterization, high performance computing and modern high-performance electronics expertise.
- *Education*: Create a multi-departmental graduate program in Quantum (perhaps similar to the Biological and Biomedical Sciences umbrella program in the biological sciences and medicine) with a modest number of core introductory courses in a coordinated curriculum common among Physics,

Chemistry, Applied Physics, Electrical Engineering, Mechanical Engineering and Material Science, Computer Science, and other interested departments. Create an undergraduate program in Quantum Engineering (perhaps focusing on quantum computing and information, quantum signal processing, sensing, transduction, devices and measurements) involving Physics, Applied Physics, Electrical Engineering, MEMS, Computer Science and other interested departments.

Top Priority Idea

Neuroscience, from Molecules to Mind

How do the brain and the mind function?

What is a memory? When thinking about a loved one…how is that represented at a cellular and a molecular level? How is our brain biology established so that we can perceive the world around us, and what happens in neurodevelopmental disorders like autism and mental retardation? In devastating diseases like Alzheimer's, where humanity is slowly drained through the loss of memories, what is it that is being damaged and how can it be repaired? Understanding the nervous system will reframe how we think about cognition, memory and mental disease. Answers to these questions remain some of the great intellectual challenges of our time, and Yale is uniquely positioned to lead in answering them.

How does a brain self-assemble during development? A healthy human brain has ~100 billion neurons and over 80 trillion synaptic connections: more neurons than there are stars in the Milky Way. Proper wiring of these 100 billion neurons is necessary for the normal functioning of the human brain, and erroneous connections lead to neurodevelopmental disorders and disease. How the interconnectedness of 100 billion cells that underpin human behavior is coordinated during development is a grand challenge to understand.

What are the bases for complex human thought, emotion, language, and social behavior? Today, we view the brain as the core element of human identity, and understanding it has broad implications ranging from medicine to law. Abstract thinking, language and social behaviors are some of the most distinctive aspects of being human. While many neuroscientists study the human brain and cognition, understanding what makes brains unique is not typical of neuroscience research institutions. Understanding the conserved traits necessary for brain function, as well as the traits that make different animal brains unique is a fundamental question in neuroscience that, if developed here, will uniquely position Yale in the field.

What goes wrong in neurodevelopmental, neurodegenerative, and psychiatric diseases? As many as 100 million Americans are afflicted by at least one of the more than 1,000 known neurological diseases. The economic burden of these diseases is estimated to be over $800 billion. As the population continues to age, these numbers continue to increase. Many of these diseases lack modifying therapies or cures. Yale is well-positioned to build on the formidable strength of its basic research and clinical departments to shed new light on the fundamental mechanisms that underlie neurodevelopmental, neurodegenerative and psychiatric diseases. This could be done by linking existing strengths and fostering collaborative relationships that translate this knowledge into impactful treatments of diseases and disorders of the brain and the nervous system.

Neuroscience is composed of many disciplines that work across multiple scales, ranging from psychology to structural biology. These disciplines use distinct approaches to address the same fundamental questions, and until recently, the approaches could not be cross-referenced because of differences in the scale of the problems being examined. Advances in molecular, cellular and functional brain imaging, remarkable progress in whole-genome sequencing and gene editing techniques, plus innovative methods in theory, modeling, machine learning, and statistics, have changed the way neuroscientists analyze and understand complex brain functions across scales. These advances have opened new opportunities to address the grand challenges in neuroscience—the key to which is bringing these diverse fields together.

Vertical advances in science result from the collision of traditionally separate fields, catalyzed either by the integration of multidisciplinary approaches that produce new knowledge or by the development of new tools that allow conceptual reframing of fundamental problems. The neurosciences are about to experience such a vertical leap, and Yale should position itself to lead.

Raising Yale's profile in the neurosciences

Yale boasts some of the world's leaders in the fundamental biology of the nervous system as well as neuropsychiatric disorders, nervous system development, neurosurgery, cognition, learning and memory, genetic discovery, and much more. Yale leads both in the development and implementation of emerging technologies—imaging in particular, including functional MRI for real-time brain imaging and super-resolution microscopy for discovery at molecular scales. Yale therefore has, distributed across a broad footprint, all the necessary ingredients to catalyze integrative approaches with transformative consequences for our understanding of cognition and perception, memory and plasticity, and the genetic and cellular mechanisms that underlie nervous system disease and dysfunction.

Yet, the current organization of neuroscientists at Yale is not aligned with these exciting opportunities. It is instead arranged based upon the history of the field at Yale. Therefore, as good as we are individually, Yale lacks a single integrative entity in the neurosciences. This gap puts Yale at a competitive disadvantage in research, clinical activity and funding. There is a need to better organize ourselves, to establish a nucleating entity in neuroscience that will drive innovation and push the boundaries of neuroscience research – which in turn will help attract government support and philanthropic contributions. To address this critical shortcoming, Yale should integrate the outstanding (but dispersed) intellectual, academic, and clinical resources across the neurosciences on campus into a broader organizational framework, the Yale Neuroscience Institute.

Examples abound of the problems that can be addressed by such an integrated approach to Neuroscience. An explanation of network and cognitive dysfunction in Alzheimer's Disease will require input from scientists with expertise in molecular, cellular, systems, genetic, structural biological, immunobiological, imaging, psychiatry, and pharmacology. Understanding the causes of neurodevelopmental disorders like autism will similarly require input from scientists in molecular genetics, cellular biology, developmental biology, physiology and cognition. Both of these examples are representative of how challenges in neuroscience need to be addressed, and how they will require coordination across scales, and research that crosses traditional disciplinary boundaries to achieve the necessary outcomes.

Neuroscience at Yale, broadly conceived and interdisciplinarily organized, would be ideally positioned to address the biggest questions in Neuroscience. What are the mechanisms of neurological disease and dysfunction? What is the bases for neurological development, learning, memory, and plasticity? What constitutes cognition and perception? What is unique about the human brain? How can machine learning and artificial intelligence inform us about our own learning and our own intelligence?

To advance University-wide efforts in Neuroscience, we offer the following recommendations:

- *Organizational Structure*: The University should establish a single, integrated Neuroscience Institute to serve as a "home" and intellectual convening point for the neurosciences at Yale across all its scales and disciplines.
    - The Yale Neuroscience Institute must be interdisciplinary and cross-campus, integrating research in the biomedical sciences, clinical programs, psychology, engineering and data science. It needs to incorporate Yale's strengths in neurological, neurodegenerative, neuropsychiatric, and neurodevelopmental diseases as well as imaging from molecule to mind.

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- The governance structure of this Institute should consist of a director or a small number of co-directors that represent basic and clinical science, the various schools, and the different levels of neuroscience inquiry (molecules to minds). The director(s) would be advised by a steering committee that further broadens representation.
    - Context for the framework of the Institute could be drawn from existing successful centers with a split academic/translational research mission, such as the Yale Cancer Center, with its strong focus, clear administration, support mechanisms, core facilities, and physical space.
    - The Institute should include faculty from multiple departments across FAS, YSM, including the departments in which neuroscience-related research is taking place. A subset of these faculty would be physically housed within Institute space.
- *Space*: The University should identify a dedicated space of sufficient size to house 35-40 research groups. There should also be sufficient space to convene students and faculty from the larger neuroscience community to participate in Institute functions.
    - The space should be located between the Medical School and Central Campus to facilitate cross-communication between basic science faculty and researchers in clinical departments.
    - Faculty who are physically housed within the Institute should have primary appointments in FAS and/or YSM departments. The Institute should not be the domain of a single school or department.
    - Given the large scale of neuroscience research underway at Yale, not everyone engaged in neuroscience research needs to be, should be, or even can be, physically co-located.
    - The Institute space should include seminar rooms, meeting spaces, core facilities and hoteling offices needed to convene the larger neuroscience community.
    - There is a need for vivarium space to support the neuroscience research enterprise, and this space should be in close proximity to the Institute space.
- *Faculty*: We recommend that the University perform a comprehensive review of its faculty strengths in the Neurosciences and identifies areas where faculty appointments could bolster current weakness or capture future opportunities. Three potential areas of interest are: theoretical neuroscience, disease modeling, and artificial intelligence/machine learning (see ***Data Science*** above).
    - New hires should address these opportunities using currently committed hiring resources and/or incremental slots.
    - Faculty hired into the Neuroscience Institute should have faculty appointments in FAS and/or YSM departments. Faculty hired into any incremental slots should be identified through a joint search committee process.
- *Students*: The Institute should become the home for the INP (Interdepartmental Neuroscience Program). An exceptionally deep pool of quality students applies to the INP. Given the quality of the student pool, the number of faculty in neuroscience, and the high placement rates of graduating students, an increase in the INP size is justified, possibly by as much as twice the current size.
- *Core facilities*: We recommend facilitated, expanded and improved access to key core facilities, including new and existing cores that support the research enterprise and promote collaborative interactions (see ***Core Facilities*** recommendation above).

- *Education*: The Neuroscience Institute should be a home for interdepartmental teaching and training initiatives at the undergraduate, graduate, and postdoctoral levels.
    - We recommend that Yale continue to promote the new undergraduate Neuroscience major, utilizing the resources of FAS and YSM faculty for its instruction and research training. The convening role played by this Institute will be a strong asset to the teaching initiative.
    - Graduate trainees would benefit from the opportunity afforded by the Institute to engage in research across scales from molecules to the mind and establish collaborations between faculty.

Top Priority Idea

Inflammation Science

What is the connection between inflammation and chronic disease?

Inflammation is broadly defined as the body's reaction to harmful changes or events. It is a defensive response to any threat to homeostasis, including infection and tissue damage. Inflammatory response is governed primarily by the immune systems and serves to eliminate the harmful agents and restore homeostasis. Over the past 20 years, inflammation has emerged as a key factor in the diseases that comprise the top causes of death in the United States: cardiovascular disease, cancer, respiratory diseases, stroke, Alzheimer's disease, obesity, diabetes, and kidney diseases. While runaway inflammation is a major driver of these illnesses, a precise and thorough understanding of inflammation science has yet to emerge. Despite volumes of research, the full extent of the interplay among inflammation, organ systems, the immune system, environmental factors, the microbiota (the community of microorganisms that reside within the body) and genetics remains unknown. Establishing a foundation in inflammation science is therefore one of the most exciting scientific and health frontiers of today.

Acute inflammation occurs in response to injury or infection, when the immune system dispatches white blood cells to the affected site, resulting in redness and swelling or symptoms such as fever. However, the concept of inflammation extends far beyond acute responses to infection and injury. Inflammation can become chronic or systemic over time – as in responses to stressors such as environmental toxins, an unhealthy diet, excess fat, autoimmune reactions, aging, and persistent acute inflammation – resulting in chronic disease. The purpose of the inflammatory response is to remove or sequester the source of the disturbance, to adapt to the abnormal conditions and, ultimately, to restore tissue functionality. It has recently become clear that inflammation is fundamentally involved in all aspects of medicine.

Harmful effects arise as a result of chronic inflammation in excess of what can be handled by the body's intrinsic stabilizing and protective processes. Recent evidence also suggests that the progression of, and susceptibility to, many diseases are modulated by shared molecular and cellular mechanisms that are profoundly affected by extrinsic factors such as diet, genes, and the microbiota. Taken together, this provides both a challenge and a remarkable opportunity. Identifying the core shared rules and specific roles of these essential factors, the mechanisms by which they work and their interdependence will lead to new paradigms in human biology and leaps in our understanding and treatment of disease.

The picture that emerges from the current understanding of inflammation is that it is not just a specialized defense reaction, but rather it is a fundamental biological process that affects every aspect of human physiology. Each organ system can operate in either a normal (homeostatic) or an inflammatory mode, the latter providing the defense against, and adaptation to, the challenges that elicited the inflammatory response. Just as the endocrine and the autonomic nervous systems coordinate the homeostatic functions, the immune system orchestrates the inflammatory mode of function of every organ system. This new perspective departs from the traditional view of inflammation as a specialized defense reaction to infection and injury. Instead, inflammation is a fundamental mode of function of physiological systems, which is an alternative to the homeostatic mode of function. Because the two states of physiological systems are largely incompatible, inflammation has the potential to drive pathological states.

This perspective provides a framework for investigating these associations, and it calls for an integrated new scientific domain that combines currently disconnected biological disciplines. The goal of this initiative would be to develop this new interdisciplinary approach to inflammation and human diseases - combining studies of gene regulation, cell communication and tissue organization, neuroendocrine control

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and systemic homeostasis and stress adaptations on cellular, tissue, and organismal levels. It will address the fundamental pathophysiological processes underlying aging and chronic diseases, including cancer, neurodegeneration, cardiovascular and metabolic diseases. Research in this area will include:

- Basic biology of inflammation as revealed by underlying gene regulation and cellular and tissue architecture
- Physiology of inflammation and its effects on neuroendocrine control and systemic homeostasis
- Host-microbe interactions, from infectious disease to commensal microbes
- Relationships between inflammation and age-associated illnesses, including cancer and neurodegeneration
- Inflammatory processes that lead to chronic diseases such as cardiovascular diseases, obesity and metabolic syndrome

Substantial progress in our understanding of inflammation will require a research structure focused on the breadth and interdisciplinary nature of the challenge. The overarching model for inflammation science spans components of immunobiology, cell biology, pathology, physiology and structural and molecular biology, and integrates aspects of diverse fields such as systems biology, biochemistry, computer science, bioengineering, neuroscience, and microbiology. Dissecting inflammation's complex effects on tissues requires knowledge of neurobiology, cardiology, cancer biology, metabolism, and digestive diseases. Work to understand the unique profile of inflammatory factors in autoimmune diseases will be crucial, as will expertise in human genetics—to identify contributing genetic variations. Ultimately, understanding the fundamental mechanisms involved in inflammation will provide new targets for therapeutic and improved patient care.

Why Yale? Strength in Immunobiology

Yale already has unmatched strength, position, intellectual capital, and potential for impact in this area. Our comparative advantages include broad expertise and clear leadership in inflammation and immunobiology. In 1988, Yale was one of the first universities in the country to create a Department of Immunobiology devoted specifically to the study of the immune system. It is now the top-ranked immunology department in the country In 2006, the Human and Translational Immunology Program was founded to accelerate the application of discoveries in the field of immunology to the study of the human immune system and the treatment of diseases. Yale researchers have made unique seminal contributions to the molecular, cellular, and genetic underpinnings of immune system function and development, and their translation to human health. Breakthrough discoveries at Yale include:

- Discovery of the innate immune system
- Creation of innovative mouse models for human disease, including reconstitution of mice with a functional human immune system
- New vaccine strategies based on tissue-resident memory T-cells
- New understanding of human autoimmune diseases, based on their underlying genetic architecture and immune regulatory networks
- Implementation of immune check-point inhibitors for cancer therapy

With its community of scholars who are renowned for working collaboratively, Yale is now poised to transform research on some of the most devastating diseases of our day. It is the best place to create a research team dedicated to the study of inflammation. Yale has a unique opportunity to leverage these strengths toward understanding the underlying cause of a broad range of human diseases.

Inflammation sits at the intersection of a number of traditional academic disciplines and several independent departments and units. The establishment of a Yale Inflammation Science Institute would position us as a leader in research on inflammation and inflammatory diseases, a field that is ripe for transformative discovery. The Institute would boast a carefully selected faculty representing the most creative and original scientists in specific relevant fields, along with associate members, fellows, visiting scientists, and access to professionally managed research support facilities. Yale has an unparalleled opportunity to redefine the concept of inflammation itself and will be poised to transform research on some of the most devastating diseases of our day.

To advance University-wide efforts in Inflammation Sciences, we offer the following recommendations:

- *Organizational Structure*: Establish an interdisciplinary Yale Inflammation Science Institute dedicated to studying the fundamental principles of inflammation and its roles in a broad range of human diseases.
- *Faculty and Students*: The Institute would be organized around several major research themes, led by about 12 principal faculty members who represent the most creative and original scientists in the relevant field, and who would be engaged in close collaborations with Associate Faculty members.
    - Institute Faculty would be drawn from both those already at Yale and new hires to the University. Appointment in the Institute will be driven by the scientific need for specific fields and/or approaches, targeting the outstanding scientists with a demonstrated record of constructive interactivity.
    - Associate Faculty members. The Institute should also serve as an organizing center for multiple Associate Faculty, who will retain research space within their primary academic departments. Associate Faculty will conduct basic or clinical research in fields related to the Institute's core mission, such as cancer, metabolic disorders, neurodegenerative diseases, and cardiovascular diseases.
    - Visiting scientists. The Institute should provide a venue for visiting scientists (with terms of visit ranging from one week to a full sabbatical year) who are involved in collaborative studies and who will enrich the intellectual diversity of the Institute.
    - As faculty are added, there should be a commensurate increase in the number of graduate students in the relevant host departments.
- *Space*: Physical co-location of key faculty and resources. The physical co-location of the Institute's personnel and scientific resources will be essential to promoting collaboration and ensuring access. The proposed Institute will require the identification of suitable space most likely within YSM.
- *Core facilities*: The Institute will have access to technology platforms (see ***Core Facilities*** recommendation above) including imaging, genomics, proteomics, computational science, mass spectrometry, and bioinformatics.
- *Education*: The Institute will create a unique, multi-departmental advanced course in Inflammation Science to provide key interdisciplinary student training in this field.

Top Priority Idea

Environmental and Evolutionary Sciences

How are organisms evolving in response to a rapidly changing Earth and how can that understanding be used to save species and conserve ecosystems?

Human-accelerated environmental change presents one of the greatest challenges of the twenty-first century. The Earth is speeding through a transformation on a planetary scale so profound that a new epoch, the Anthropocene, has been proposed. Major impacts include global climate change; the rapid loss and redistribution of biodiversity; the spread of vector-borne diseases; deforestation and land degradation; over-exploitation of natural resources; alteration of biogeochemical cycles; and the rapid evolution of organisms ranging from microbes to vertebrates. These far-reaching changes harm the functioning of natural ecosystems and, ultimately, will impair the Earth's ability to support life.

At the same time, unprecedented technological advances in genomics, high-throughput phenotyping, remote sensing, and big data analytics are leading to radical changes in our perspective on the interactions between organisms and the environment. These new technologies have enabled the integration of scientific thinking across environmental and evolutionary sciences, creating a dynamic new scientific discipline. The situation is analogous to advances in precision medicine. Precise and detailed genetic information about individual organisms can likewise be interpreted in the context of tailored ecological analyses, and this is revealing that evolutionary changes and ecological changes are reciprocally related across the entire range of temporal and spatial scales, including (most surprisingly) at the very smallest times and distances.

An extraordinary opportunity now presents itself to accelerate away from the old worlds of descriptive ecology and evolutionary biology toward a new scientific era of mechanistic and predictive understanding. New ways of thinking and new technologies are revolutionizing the research landscape:

- Evolutionary principles are being used in new contexts such as the conservation of species and ecosystems.
- Genomic methods are now increasingly available for many species – not just model organisms.
- Routine genotyping of tens of thousands of single nucleotide polymorphisms can be used to reconstruct phylogenetic relationships between species that date back many millions of years, or to reconstruct the evolution of a single species over the past several decades in response to environmental change, or even to elucidate the parentage of individual organisms.
- Interventions that manipulate organisms in natural environments are now enabled by CRISPR and Gene-drive technologies, which will be used, for example, to stop the spread of invasive organisms, or for conservation efforts to save species at the brink of extinction.
- Remote sensors – orbiting in space and placed in terrestrial and aquatic habitats – provide a vast and diverse stream of precise data on environmental variables and even individual organisms (e.g., migration paths of individual birds), making it possible to achieve mechanistic insights based on differences between individuals.
- High-throughput phenotyping encompasses many methods to characterize differences in the structure and function of organisms, from metabolomics to 3D imaging. Conveyor-belt automation to monitor large numbers of samples and infrastructure for mega-data storage and computational analysis have become a reality.

- A “big data explosion” is now occurring in organismal biology due to the growing volumes of genomic data and automatic sensor data. New computational methods, such as machine learning, are being developed to analyze and synthesize this flood of new data.

Yale’s exceptional potential to spearhead this new science

Yale has a deep and influential history stemming from the pioneering work of G. Evelyn Hutchinson, who is widely regarded as “the father of ecology,” and Yale is well-positioned to harness cutting-edge technological advances to unify the evolutionary and environmental sciences. Yale has major thought-leaders and experimentalists in this area already, as well as a basic foundation of the necessary infrastructure on campus:

Many excellent faculty members in FAS, including those in the departments of Ecology & Evolutionary Biology, Geology & Geophysics, and Environmental Engineering, as well as in Forestry & Environmental Studies are uniquely positioned to bridge the ecology-evolution gap, and have already developed innovative research programs at this intersection utilizing a wide range of cutting-edge technologies. This is illustrated by four short examples.

1. *Carbon recycling from fallen trees by fungi*: The decay of dead trees represents a major contribution to the carbon cycle. Predicting the rate of wood breakdown by combinations of >100,000 fungal species found in the Northeast may seem intractable. However, the opposite is true. Interactions between fungi yield predictable outcomes due to the ways that these organisms cope with environmental stressors and community interactions. Molecular genomics for fungal identification and rapid fungal phenotyping are essential to this research. Predictability emerges in wood breakdown rates, microbial biodiversity, and, most importantly, in carbon recycling rates. These findings have been incorporated into the Earth System Models of carbon cycle-climate feedbacks.

2. *Rapid evolution of keystone species*: A fish called the “alewife” demonstrates how the rapid evolution of a single “keystone” species can have large-scale impact on the environment. Alewife populations have evolved rapidly in response to environmental change: changes in their foraging morphology and behavior alter their predation of zooplankton, changing entire food webs and primary production. This research now informs the conservation and management of aquatic resources across the Northeast.

3. *Macroscale eco-evolutionary feedbacks*: The past may provide insights into the precipitous changes of the Anthropocene. Major transitions in the Earth’s geological history include mass extinctions, atmospheric oxygenation, ice ages, and dramatic episodes of rapid evolution. Plankton with calcium carbonate shells suddenly appeared about 200 million years ago, creating a deep-sea reservoir of carbonate that can buffer periodic large emissions of carbon dioxide. Outsized volcanic events triggered two of the largest mass extinctions in the history of life before the evolution of calcareous plankton – but not afterward – thanks to their buffering effect on the carbon cycle. Understanding such eco-evolutionary feedbacks on a macro-scale has the potential to predict key tipping points that may be imminent in the current epoch.

4. *Evolutionary clues for organism engineering*: The quest to engineer C4 photosynthesis, which is a more efficient form of photosynthesis than C3 photosynthesis, in rice and other crops seeks to enhance the productivity of these important food plants even under the stress of drought and heat, and thus to adapt our agricultural systems to climate change. Studies of leaf structures across many grass species revealed the unanticipated finding that key anatomical components of C4 metabolism evolved prior to C4 photosynthesis. This has provided the conceptual framework

necessary to engineer C4 photosynthesis in rice: first engineer the required anatomy, then introduce the C4 genes.

Yale has made significant investments in facilities and specialist expertise that are essential to this new enterprise in Environmental and Evolutionary science. The Yale Institute for Biospheric Studies has created centers for spatial analysis to support environmental and organismal monitoring using remote sensors. The Peabody Museum has made enormous investments to mobilize museum specimen records that allow us to track spatial and temporal changes over the past century. The Peabody is also actively assembling a new informatics team to address the challenges in rapid data capture, machine learning, and other advances. The Yale School of Forestry & Environmental Studies (FES) is internationally known for its excellence and serves as a locus for research on local, regional and global environmental issues. The Environmental Engineering program encompasses the scientific assessment and development of engineering solutions to environmental problems affecting land, water, and air. Collectively this provides Yale with a unique community of scholars who can drive innovative ideas and new approaches in the field - uniquely fusing evolutionary biology and ecology to make far better predictions about the World spanning from the microscale to the planetary scale.

To capitalize on University-wide efforts at the interface of Environmental and Evolutionary Sciences, we offer the following recommendations:

- *Organizational Structure*: Establish an Institute of Environmental and Evolution Sciences – possibly the G. Evelyn Hutchinson Institute – to newly integrate the environmental and evolutionary sciences. This Institute will:
    - Unite environmental and evolutionary sciences across lower Science Hill, including Forestry and Environmental Sciences, Geology and Geophysics, Ecology and Evolutionary Biology, and also relevant segments of Environmental Engineering, Anthropology, Psychology, and the Yale School of Public Health.
    - Support collaboration among faculty and students across these departments and schools
    - Facilitate access to big data and new analytical techniques
- *Faculty and Students*: Expand the size of the faculty in Environment and Evolution through strategic hiring.
    - We recommend the identification of a pool of 4-5 half-slots that are allotted to the Institute and made available to departments or schools willing to commit an equivalent resource to hire in this area.
    - As faculty are added, there should be a commensurate increase in the number of students in the relevant graduate programs.
- *Space*: The University should identify dedicated space sufficient to house at least six research groups across multiple departments and schools. There should also be sufficient space to convene students and faculty from the larger Environment and Evolution community to participate in Institute functions.
    - The space should be located at or near the base of Science Hill, in close proximity to the relevant departments and schools. One potential location is a renovated Osborn Memorial Lab following the move of the MCDB department from OML into the new Yale Science Building.

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  - The faculty who are physically housed within the Institute should have primary appointments in FAS, SEAS and/or FES departments. Physical co-location with the Institute should not be specific to a single school or department.
  - Given the large scale of environmental and evolutionary research underway at Yale, not everyone doing this research needs to be, or even can be, physically co-located.
  - The Institute space should include seminar rooms, meeting spaces, core facilities and hoteling offices needed to convene the larger community.

- *Core Facilities*: We recommend further investments in Core facilities to support research at this interface (see ***Core Facilities*** recommendation above). This would include access to high-throughput phenotyping, equipment and analytical expertise that would allow us to fully exploit the "big data explosion" in organismal biology, rapid phenotyping capabilities and diagnostic tools that are specifically relevant to addressing environmental problems.
- *Education*: The Institute will serve as an intellectual home and 'collision space' for students bridging disciplinary divides and integrating new technologies. We envision the development of a laddered series of courses for sophomores, juniors and seniors that would culminate in the completion of a senior thesis within the Institute. Earlier courses would focus on intellectual themes relevant to Institute research programs as well as the mastery of techniques that will prepare them for their own research projects.

The USSC identified a second set of five additional priority ideas. The nature of each idea and Yale's current strategic position with respect to that idea are described below. We do not offer specific recommendations for investment in these ideas, but we would support additional investment if additional resources are available.

Additional Priority Idea

Climate Solutions

Science has demonstrated that the Earth's climate is changing drastically. Can we identify solutions?

Climate change is a defining issue of our time. No aspect of life on Earth is untouched by the effects of climate change, from human health and the economy to the sustainability of global natural environments. Science has done much to reveal the seriousness of the issue. The past four years were the hottest years on record. Arctic sea ice is declining, and at a rate even faster than predicted. The two strongest El Niño events on record happened in 1997 and 2015. Precipitation patterns are shifting, causing drought conditions in some regions, flooding in others. The frequency of high-category tropical cyclones, such as Hurricanes Harvey and Irma in 2017, have increased and are projected to increase further, and will become more damaging with rising sea level. Heat waves will become more intense and long lasting, possibly rendering areas of the globe seasonally or permanently uninhabitable.

The most recent international climate accord, the UNFCCC Paris Agreement of 2015, set a warming target of no more than 1.5 degrees Celsius above the pre-industrial era. Anything more than that is considered to be, inevitably, catastrophic. With greater than 400 ppm CO_2 in the atmosphere, we are entering climate conditions last seen on Earth 3 million years ago, long before modern humans arose. Plenty of life thrived in conditions during that time, but humans are ill-adapted to that environment. The IPCC was therefore tasked with finding ways to hold the temperature increase under two degrees Celsius, and modeled more than a thousand possible scenarios. Roughly one hundred of these scenarios would limit warming to below two degrees, and almost all of those (108 out of 116) required negative emissions, meaning not just slowing emissions but offsetting them and reducing atmospheric CO_2.

It is incumbent on major research institutions to offer leadership by aggressively studying and developing mitigation approaches to reduce CO_2 levels, while also devising adaptation approaches to changes in global and regional environmental conditions. Universities should not focus on one single solution, but must take a multipronged approach. Multiple solutions, not one alone, will be required given the scope and variable impacts of global climate change. However, efforts to mitigate and adapt can only be meaningful if informed by state-of-the-art climate and environmental science, as many questions remain relating to how Earth's climate and ecological systems respond to both natural and anthropogenic drivers.

Climate and environmental science and the solutions roadmap

The climate system has many complexities, and future change will create winners and losers based on geography, population, economy and agricultural activity. Developing successful mitigation and adaptation strategies is predicated on an expanded and improved knowledge of the climate and environmental systems at local, regional, and global scales. In short, we have to refine our understanding of what we are mitigating and adapting to. We also need to understand the response of the climate and biosphere to any aggressive strategies that may be proposed.

The precision of predictions of future impacts at regional scales - at which solutions will be devised - are still very much a work in progress. In particular, much work remains to understand the response of the climate and ocean to increased CO_2 levels. More knowledge is needed in areas such as the effect of clouds and aerosols, as well as both marine and terrestrial sources and sinks of CO_2. Moreover, we are still far from a detailed understanding of the effect of climate change on weather and climate extremes, as well as tipping points for the ocean and cryosphere. Not only are improved climate models required, but a greater understanding of past climate is necessary, through paleoclimatological studies that can provide information about extreme states as well as historical data on climate sensitivity to large changes in CO_2 levels. Furthermore, we need a much more detailed understanding of how anthropogenic climate change, both with the status quo and with aggressive mitigation strategies, will impact different parts of the world. The contribution of climate and environmental science at Yale can better explain and forecast these regional differences.

Can we mitigate climate change? Negative emissions, carbon capture and long-term storage.

The negative emissions goal inevitably requires carbon capture from the atmosphere. Carbon capture is reasonably well-developed for extraction of CO_2 from power plant emissions. To offset current levels of atmospheric CO_2, however, carbon will need to be captured directly from the ambient atmosphere. Atmospheric CO_2 capture remains a frontier of technology and a highly challenging problem. Some examples include "wind-mills" doused in amines that react with CO_2 in passing air, and membrane separation of atmospheric nitrogen to increase CO_2 concentration. Developing a variety of ambient capture strategies, using integrative insights from chemistry, engineering and atmospheric science, remains a critical component to successful mitigation strategies.

Once captured, CO_2 must also be stored. Carbon storage or sequestration technology can involve injecting captured carbon into subsurface reservoirs, such as saline aquifers and coal seams. However, the CO_2 remains trapped as an aqueous solution or in a supercritical "liquid" state, which can potentially leak. Permanent storage by reaction of CO_2 with "mafic" minerals (found in many volcanic geological settings) includes storing carbon as carbonate minerals such as limestone and dolomite. This approach remains an active area of research and is a scientific and technological holy grail. Other means of carbon capture and storage involve iron fertilization of iron-deficient parts of the ocean. Given the vastness of the ocean and its potential as a CO_2 reservoir, such capture and storage approaches may be an important component in the mix of possible solutions. Another approach for combined carbon capture and storage is the targeted use of natural biogeochemical processes within aquatic and terrestrial ecosystems and the atmosphere. All of these mediations of carbon storage remain frontiers in science.

Despite the abundance of research and evidence that Earth's climate is undergoing dramatic change, there is still much inertia and even intransigence by society and governments to take action. Relative to efforts in other crucial fields, such as in human health, there has been far from sufficient determination to counter climate change. Thus, this is a both a scientific and a public policy problem. There is need for partnership with scientists, engineers and social scientists to find climate solutions.

Climate solutions at Yale.

Given the importance of finding Climate Solutions, the USSC is enthusiastic about a Climate Solutions initiative at Yale. The feasibility of identifying solutions to carbon capture and sequestration challenges makes a Climate Solution initiative one of significant risk. We have excellent faculty working on public perception and communications about climate change, climate modeling, and social policy around climate change. The identification of carbon capture and carbon sequestration technologies will rely upon the recruitment of senior faculty leadership to move this idea forward, as well as significant investment in facilities for the types of science and engineering required. Furthermore, governmental reluctance to acknowledge the problem of human induced climate change means that the research will require significant funding from non-governmental sources. A broad approach to environmental and climate

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sciences, which also includes the ***Environment and Evolutionary Sciences*** recommendation above, could include exploration and expansion of our footprint in this field.

Additional Priority Idea

Computer Science

How can Yale help define and shape our increasingly computational world?

Over the past 40 years, computers have become essential tools in almost every form of human endeavor. Our lives are shaped by sophisticated computation in countless, almost invisible, ways - in fields ranging from engineering, medicine, and science to mass communication and journalism, to law, international relations, and finance. Recently, a more profound change has taken place. Sophisticated computational techniques, including artificial intelligence, machine learning, formal verification and cryptography are transforming the world and, critically, reshaping the ways in which we generate new knowledge and carry out research.

Three emerging trends are fundamentally transforming the field of computer science:

- The success of artificial intelligence: In the last decade, the fields of artificial intelligence (AI) and Machine Learning have made significant advances that have enabled amazing technologies such as speech recognition, computer translation, and self-driving automobiles. We anticipate that further advances in these fields will greatly increase the fraction of our world controlled by information systems and augment human interaction with technology. Decisions and discoveries will be made by humans collaborating with computers.
- New "vertical" research themes: Computer Science is increasingly becoming organized around "vertical" research themes that cut across the largely historical distinctions between theory, AI, systems, and applications. These new vertical themes include robotics, the Internet of Things (IoT -- the growing network of internet-equipped devices in homes, businesses, laboratories and industries), smart cities, cyber-physical systems, connected health, and blockchains (decentralized, encrypted transaction records) with smart contracts.
- New cyber entities and emerging challenges: The vertical themes spawn many novel cyber entities (e.g., computer programs, systems, devices, data sets, etc.) that present both challenges and opportunities. The application, safety, and social implications of these new entities will require research breakthroughs in key CS research areas, including cyber security, resilience, fairness, and privacy. Computer science must help address the ramifications of computing advances on society, the law, and the economy.

Computer Science is a critically important academic discipline. However, meeting the emerging opportunities and challenges in the field (which involve human, physical, biological, and social entities, as well as a large variety of computing components) will require close coordination among diverse academic research communities, industries, the government, and policy makers. There is a severe shortage of qualified computer scientists at all levels (from bachelor's to Ph.D.), and the competition from industry and within academia for qualified people is fierce. Success in computer science—both in its application to the pursuit of knowledge and in training the next generation of leaders—requires investment in new types of interdisciplinary researchers who can work across multiple traditional fields. Because CS is now at an inflection point, it will be critical for Yale to take advantage of today's emerging opportunities to shape and lead a robust computer science program.

Many new opportunities are arising at the intersections of computer science and other fields – referred to broadly as "CS+X," where X can range from Law, Medicine, or Business to Economics, Biology, Engineering, Music or Quantum Computing. Majoring in CS+X typically entails a program of study that combines a strong grounding in Computer Science, a strong grounding in another discipline, and advanced coursework or independent project work that combines the two disciplines. Establishing programmatic expertise in specific CS+X areas is a natural fit for a liberal arts university such as Yale, with unparalleled breadth of scholarship in the social sciences, humanities, law, and medicine. By investing in computer science and leveraging these strengths, Yale is uniquely positioned to lead in select targeted fields, including:

- **CS+Social Sciences** (e.g., CS+Psychology, CS+Economics, CS+Politcal Science or CS+Law)
  As robots and computational devices proliferate, it becomes increasingly crucial that we understand how they should interact with humans. This is studied in the field of Human-Computer Interaction, which lies at the interface of Computer Science with Psychology. As we ask computers to assist in activities such as driving and to make decisions that impact human lives, we must decide how Artificial Intelligence and other computational decision systems should function and be regulated. As our lives become increasingly digital - and attacks on computer systems become increasingly sophisticated - establishing trust in information and identities also becomes a technological challenge. Blockchains, cryptocurrencies, cryptography and cyber security, involving research in Computer Science, Economics, and Law, address these challenges. By investing in faculty, research, and teaching at these critical junctions, Yale and its Department of Computer science will be uniquely positioned to help shape these fields and establish domains of eminence.
- **CS+Biological Sciences and Medicine**
  Computation is permeating every field of biology and medicine. The increasing power and scale of biomedical data has necessitated large-scale computational analysis, spawning the field of bioinformatics that aims to design analytical methods and software tools to aid in interpreting and understanding massive collections of biological data - and more recently the field of computational biology, which seeks to develop predictive models of the dynamics of biological systems across a wide range of scales from molecules to cells to organs and organisms. In addition, computation is essential for modern imaging techniques and underpins emerging techniques in molecular and developmental biology, where it is now possible to analyze RNA, DNA or proteins from millions of individual cells across thousands of dimensions.
- **Artificial intelligence and machine learning** (see ***Data Science*** above)
  The fruits of artificial intelligence and machine learning research play a vital role in all these efforts. They include: the computer vision and image processing techniques that allow robots to sense the world or help clinicians to diagnose disease and plan treatments, the algorithms that allow robots to accomplish desired motions, the speech recognition tools that allow us to talk with computational devices, the language processing tools that allow computers to gain knowledge from text, and the data mining algorithms that permit discovery from biomedical data.

Computer Science at Yale

The USSC emphasizes the important role of CS in a Yale education. Over the past decade, CS has become one of the most popular subjects of study in the Ivy League, drawing large numbers of students and majors. Yale College's class of 2019 boasts 116 computer science majors, making computer science the fifth largest undergraduate major. In addition to the expansion of CS majors, the number of students seeking training in CS is also expanding. The number of enrollments in CS courses has increased more than three-fold over the past decade. Additional student and faculty engagement in CS learning has taken place in the form of student-organized Hackathons, coding camps for undergraduates, graduate students, postdocs and faculty, and other forms of peer-to-peer learning. The CS environment has also provided a fruitful environment for innovation and experimentation, including the introduction of Undergraduate Learning Assistants (ULAs) to the Yale ecosystem.

In recognition of these trends, Yale has made a commitment to an expansion of the Computer Science faculty. This expansion is still in its earliest stages. In 2015, the University announced a plan to increase the department from its historical size of 20 primary and fully joint ladder faculty (plus 6 non-ladder FTEs) to an intermediate size of 25 ladder faculty (plus an increased number of non-ladder FTEs), with possible further growth to 30 ladder faculty as strength in the department is established.

USSC endorses Computer Science's plan to expand its faculty by seizing the intersectional opportunities represented by a "CS+X" approach. In conjunction with this commitment to increase the number of primary faculty, faculty with secondary appointments have been added to the CS community through hiring in adjacent departments, most notably in Electrical Engineering and Statistics and Data Science. We also see interesting opportunities for hiring in the area of Quantum Computing that are worth exploring (see ***Quantum*** above). Efforts to strategically invest in computer science research and education will allow Yale to gain strength in this important area of 21st century knowledge. They will also boost science and other pursuits across campus, and help educate the next generation of leaders in fields ranging from the social sciences, to medicine, to law.

Additional Priority Idea

Conquering Cancer

How can we harness the "omics" revolutions to conquer cancer?

Cancer is one of the greatest challenges of our time. 40% of Americans will be diagnosed with cancer in their lifetime, and cancer remains a leading cause of death in the United States. With recent exponential progress in targeted therapies, in harnessing the body's own immune system to kill cancer cells, and in understanding genetic predisposition to cancer, there are now unique opportunities to discover new approaches for conquering cancer.

Although our ability to describe cancer is now quite advanced, conquering this complex disease requires an understanding at multiple levels and scales – from molecules to communities. We need to understand differences between cancers at different sites, in different patients, and in different societies. Only then will it be possible to reduce cancer incidence and suffering through interventions at the population, familial, individual patient, sub-tumor, single cell, and molecular levels.

Unfortunately, most current cancer therapeutics are relatively blunt tools. Surgery removes what can be seen (and accessed) of a patient's tumor. Chemotherapy and radiation therapy kill rapidly dividing cells with some selectivity – but with substantial side-effects and toxicity. New targeted therapies – although specific – have limited application and inevitably meet with resistance. Similarly, the new class of immuno-oncology agents (checkpoint inhibitors) that are now transforming cancer care only benefit a minority of cancer patients who cannot currently be identified prior to treatment.

The grandest challenges in cancer research are to develop new stables of patient-specific therapeutics so that all patients can be cured, and to match patients to these therapeutics. Advances in these directions will require progress with emerging and new technologies that allow cancers (and cancer patients) to be assessed simultaneously at molecular, cellular, immunological, physiological, genetic, microbiotic, and behavioral levels. Systematic acquisition of very large quantities of molecular, cellular, and patient care data – and its integration to establish biological interpretation and clinical action – will then be needed to drive new understanding and developments in cancer care and treatment.

Harnessing world class basic cancer research from molecules to man

Basic and clinical scientists at Yale are at the vanguard of understanding genetic, epigenetic, immunological, and biochemical changes that drive (or allow) cancer formation and progression – areas that will dominate cancer research in the coming years. Comprehending and engaging with these changes will illuminate paths to developing new analytical tools and technologies, new data resources, and new animal and "disease-in-a-dish" models of cancer that will spawn hitherto unimagined genetically- and molecularly-driven therapeutic approaches and diagnostic tests. So too, Yale is home to world-leading molecule designers and builders who make chemotherapeutic intervention possible. Harnessing these discoveries and inventions will require development and refinement of new cutting-edge technologies, and development of key core facilities to integrate them into cancer research and clinical trials.

- New CRISPR-based approaches to genome editing are revolutionizing cancer research, allowing rapid generation of specific somatic genetic changes in cells and advancing our ability to make complex experimental animal models of cancer.
- New technologies for studying tumors cell-by-cell (rather than as cell populations) are transforming our understanding of tumor heterogeneity, make-up, and evolution as well as the immune microenvironment of tumors. The ability to study the individual cells that make up a tumor (and its

microenvironment) – and how they differ in treatment response – is revolutionizing models of tumor initiation, development, and progression.

- The influence on cancer development of our microbiota is only now being realized, alongside startling revelations about how the composition of the microbiota affects response to treatment, metabolism of drugs, and metabolism (or production) of carcinogens.
- Cancer immunotherapy has shown great potential, but current therapies represent only the tip of the iceberg. Yale has a unique combination of strengths in immunology and clinical cancer research that can be leveraged to further advance this field – in which Yale already plays a leading role.
- Tremendous gaps between available data and biological interpretation and clinical action are being exposed as quantities of molecular and patient care information increase – including routine bioinformatic analyses of patient samples and collection of increasingly complex and informative clinical data available in electronic medical records. Closing this ever-increasing gap, and exploiting the burgeoning data to drive new science and medicine, will require complex and advanced computational and theoretical approaches.

Cancer Research at Yale

Yale has a history of firsts in all areas of cancer research – in basic science and its translation to the clinic. It was the birthplace of cancer chemotherapy, still the mainstay of cancer treatment. Yale established the first tumor registry – a core resource for clinical, epidemiological and laboratory investigations in cancer. Yale investigators developed the first genetically modified mice for studies of human disease. The first genetic diagnosis based on human DNA sequencing was also made at Yale, and Yale investigators pioneered the science and clinical application of immune checkpoint inhibition in cancer therapy. With a superlative record of high-impact research, the Yale Cancer Center (YCC), which unites research across 30 University departments and 286 Yale faculty with a vast range of expertise and interests, brings together outstanding faculty in immuno-oncology, cancer biology, signal transduction, cell biology, genetics, immunology, and dedicated disease experts who cross disciplines for clinical impact.

We endorse the ongoing investments into the interdisciplinary and translational efforts of the YCC and the creation of the Cancer Biology Institute on the West Campus. We also recommend further investment in a suite of core facilities (see ***Core Facilities*** above) that are needed to leverage recent developments in biological research for conquering cancer.

Additional Priority Idea

Precision Medicine

How can we exploit clinical and genomic "big data" to predict and individually improve each person's health trajectory?

Medicine is entering a new era in which the acquisition and interpretation of vast quantities of data from human populations is not only beginning to enable individually-tailored medical care, but is also opening previously inaccessible avenues for understanding the biology of health and disease. Electronic medical records give access to high quality phenotypic data, including medical history, family history, environmental exposures, and medication use. DNA sequence data give access to the underlying genetic information that encodes and influences phenotypes. This integration of clinical and genetic information promises to transform our understanding of human biology, and to boost discovery for diagnosis, individualized treatment, predictive medicine, and disease prevention.

Historically, personalized medicine began with blood transfusion, involving the assignment and matching of blood groups between donors and recipient patients. Now, the most visible recent development is individualized cancer therapy. For example, if a non-small cell lung cancer tumor is positive for the PD-L1 protein, it can be treatable with specific antibodies, known as checkpoint inhibitors, which enable the immune system to eliminate the cancer. Underscoring the broader significance of this approach to medicine, in 2016 the NIH announced initial funding *"to inform efforts to accelerate the understanding of individual differences that play a role in health, with the goal of informing better prevention and treatment strategies tailored for each person."* Although there has been a remarkable pace of medical progress along these lines, there remains vast unexplored territory in understanding human biology and disease. For example, of the ~20,000 genes of the human genome, genetic variants in only 57 genes are currently considered to be "medically actionable," that is, potentially targetable by therapeutics. Therefore, the grand challenge ahead is to comprehensively identify and functionally explain all individual genetic variants that correlate with human health and disease. These discoveries will have major scientific, medical, and economic impact.

There is a need for scalable, automated, and predictive algorithms for Precision Medicine. A top priority toward linking genetic data with human biology and disease is the need for generating algorithms that will derive novel insights from the vast amounts of multidimensional data entailed in the Precision Medicine enterprise. This will require intellectual expertise and innovation in data science and full participation of experts in this rapidly evolving field. Clearly, assistance will come from Machine Learning, Artificial Intelligence, and mathematical models, and the contributions of leading investigators in those areas will be essential (See ***Data Science*** above). At the same time, patient privacy and data security will remain paramount. Thus, a growing need for collaborative teams of big data scientists will confront biologists and clinicians engaging in the Precision Medicine enterprise.

Personalized Medicine at Yale

In 2009, Yale investigators developed exome sequencing, the small subset of the genome that encodes for protein function, selectively capturing and sequencing the exomes of expressed genes at high efficiency and low cost. The utility of this technology was demonstrated by performing the first genetic whole exome diagnosis of a chronically ill infant, identifying a homozygous defect in a bicarbonate/chloride exchanger of the kidney. In other studies, family pedigrees with the highest and lowest values of blood pressure were studied by exome sequencing, identifying a variety of kidney channels and transporters implicated in renal salt processing, thus establishing salt handling as a primary element responsible for blood pressure variation.

A major investment in 2010 established the Yale Center for Genome Analysis (YCGA), one of the first CLIA/CAP-certified facilities for diagnostic DNA testing of human samples, providing state-of-the-art low-cost sequencing and data processing, and leadership in developing new technologies for genomic analysis. YCGA is a University-wide resource used by over 400 Yale investigators, and has the capacity to annually sequence 10,000 human genomes at the exome level in high-priority areas including prenatal medicine, newborn disorders (e.g. congenital heart disease), and cancer. The enormous accumulation of exome, and recently, whole genome data, places Yale scientists in an ideal position to make informative and often unanticipated observations about the genetic differences between individuals. Such valuable information provides the basis for creative biological hypotheses, allowing our investigators to ask crucial scientific questions about human health and disease.

A major asset is Yale's close partnership with the Yale New Haven Health System, which, as part of its role in healthcare provision and clinical trials, collects a comprehensive array of electronic health records. These data are maintained in a standardized, research-compatible form via Epic, and include content that is particularly valuable for biomedical discovery. Moreover, the Health System serves a diverse population, reflecting the varied demography of Connecticut and the nation as a whole, providing insight into population-level heterogeneity in disease risk and treatment outcomes. In many cases, medical information has been collected repeatedly from the same individuals over time, providing longitudinal data. Thus, the combination of YCGA sequencing capability with the strong local medical record system, and the demography of the New Haven area, place Yale in a uniquely advantageous position to push genomic discovery in medicine to new limits.

The USSC endorses the ongoing efforts in this area, and sees increasing investments in Data Science and improvements in clinical trial support, both described elsewhere in this report, as critical factors in developing our leadership in this field.

Additional Priority Idea

Regenerative Medicine

Can we develop regenerative medicine to create ultra-personalized therapies and non-invasive medical procedures?

Regenerative Medicine seeks to repair, replace, or regenerate cells, tissues, and organs to improve the human condition. This is increasingly critical due to our aging society and advances in general surgical and trauma care. Many individuals now survive severe injuries and require sophisticated follow-up reconstructive or reparative procedures. Regenerative Medicine builds upon modern developments in genomics. It develops and uses novel biomaterials. It exploits advances in immunobiology and mechanobiology. It relies increasingly on advanced cell therapies, particularly stem cells. It can be enhanced by high resolution medical imaging and computational modeling. Regenerative Medicine has significant promise to produce manifold biological discoveries as well as to transform clinical care via a personalized approach to medicine and surgery. It also has tremendous potential both to generate ex vivo patient-specific models of disease that are useful for basic science research or drug screening and to engineer biosensors that can detect biological or chemical threats. Regenerative Medicine thus has tremendous potential to build on and advance basic science, engineering, and clinical care.

Regenerative medicine has already yielded an array of cutting-edge approaches for restoring cellular and tissue function to improve human health. The FDA has approved applications ranging from artificial skin to tissue engineered blood vessels. Additional exciting outcomes are arising from autologous stem cell therapies (derived from a patient's stem cells). These are combined with novel biomaterials-based scaffolds to repair, replace, or regenerate tissue and organ function - using either sophisticated bioreactors to generate the biological implant or direct implantation in the patient to provide the precise microenvironment to promote restoration. Continued breakthroughs in genome editing, immunobiology, bioengineering, data science, computational technology, nanotechnologies, and personalized medicine promise to transform how we understand and treat aging, disease, and injury. Regenerative Medicine will continue to be an increasingly essential, integrative approach for achieving true advances.

Building on transformative discoveries in stem cell and developmental biology, Regenerative Medicine stands as one of the great frontiers of modern science. Recent advances in our fundamental understanding of the pathways involved in tissue repair and regeneration, combined with remarkable progress in adult stem cell biology, have enabled great progress in medicine. The discovery of induced pluripotent stem cells (iPSCs) has enabled remarkable stem-cell based research, including patient-specific disease modeling in a dish and screening for novel therapeutic agents for illnesses spanning cancer and macular degeneration to osteoarthritis and even organ transplantation. These breakthroughs are just beginning to translate to clinical practice and represent the first steps into an exciting and vast novel territory in medical science.

Regenerative Medicine at Yale

Yale already stands as a leader in fundamental allied areas, including genetics, immunobiology, and stem cells, as well as in the many clinical disciplines that will be impacted by Regenerative Medicine – from Pediatrics to Neurosurgery, Cardiology to Orthopedics, Dermatology to Pulmonary Medicine. Yale also has renowned basic scientists, bioengineers, material scientists, and clinicians who have made fundamental discoveries in tissue engineering and have realized first-in-human applications. Indeed, there are only two FDA-approved clinical trials for tissue engineered blood vessels in the US – one for treating a common congenital defect of the heart and one for treating end-stage renal failure patients. Both arose from multi-disciplinary research and development at Yale.

In addition to these allied strengths in fundamental research and clinical medicine, Yale already ranks among the most innovative institutions in the world in tissue engineering, nanomedicine, and regenerative medicine. These areas at Yale also benefit immensely from our strengths in physiological systems, including cardiovascular, musculoskeletal, neurological, and pulmonary. For example, the first RMAT (Regenerative Medicine Advanced Therapy) designation in the United States was awarded for a tissue-engineered artery (Human Acellular Vessel) that was developed by a Yale PI for use as an arterial bypass or reconstruction. This vessel is now in phase III clinical trials for treatment of end-stage kidney failure patients – this is only the second phase III trial for an engineered tissue in the United States. Additional efforts at Yale include tissue engineering of conduits for congenital heart surgery, engineering a replacement trachea or lung, engineered heart tissue for personalized diagnostics and treatment planning, and regenerative treatment of nerve fibers to relieve chronic pain. Regenerative Medicine thus has potential to impact many areas of clinical care through it significant translational potential.

In addition to the scientific and clinical impact of Yale Regenerative Medicine, the substantial attention garnered by these fields could have a major impact on students—these fields and their practical applications are major drivers of interest in the interface of life and physical sciences and engineering at undergraduate and graduate levels. Furthermore, Regenerative Medicine, including tissue engineering, nanotechnology development, and patient-specific cell-based therapies, has a strong potential for commercialization.

The USSC recognizes that Yale could leverage these ongoing strengths to become a leader in both the basic research that underlies regenerative medicine and its practical and clinical applications, particularly given allied strengths within clinical medicine at Yale.

Comments on the School of Engineering and Applied Sciences

The USSC was charged to consider big ideas that spanned science and engineering campus-wide. We were not tasked to develop a strategic plan for an individual school, department or cluster of departments. The Committee's membership was too diverse for such a task, and our key assignment was to identify cross-unit synergies and opportunities for interdisciplinary investment. Nevertheless, a consistent theme that was repeatedly emphasized throughout our deliberations, for all of these ideas and many others, was the need for Yale to have strength and intellectual coverage in areas of engineering and applied science. Consistent with this, many of the priorities we have identified will require significant engagement with engineers and applied scientists. For example, for Yale to advance research in quantum engineering, neuroscience, climate solutions, regenerative medicine, instrument design, and computer science will require cutting-edge engineering faculty.

The USSC reviewed the data that define the national rankings for each of Yale's schools and departments, including the five FAS departments that currently constitute the School of Engineering and Applied Science (SEAS). With two notable exceptions, most of these programs are not ranked as highly as those in the fundamental sciences. The causes for this current situation are complex, but the relatively small size and broad distribution of our engineering faculty is a factor. A second, and closely related, cause is the limited availability of quality space for both individual research laboratories and essential core facilities. This impacts our ability to recruit and retain excellent faculty in these areas.

A strategic plan for SEAS was developed about 10 years ago with input from faculty and alumni. Numerous aspects of that plan have been implemented, including creation of a highly successful Center for Engineering Innovation and Design for student instruction and the raising of funds to recruit ten senior faculty members to chaired positions (half of which have since been filled). As with all strategic plans, however, such plans need to be reviewed and updated. The recruitment of a new Dean to lead SEAS is an opportune time to undertake such a planning effort.

Although the USSC was not tasked to provide an updated strategic plan for SEAS, during the course of our own deliberations, we gathered information that would be useful for the articulation of that strategic plan and offer some observations here. The USSC emphasizes that engineering and applied science will play a vital role in implementing an overall strategy for advancing STEM across Yale. This is evidenced by the many specific intellectual and structural recommendations provided elsewhere in this report. Yale's investments in engineering and applied science will take place at a relatively small size compared to large state universities. Therefore, the Committee submits that engineering must be further integrated into the fabric of the University, across all three of its campuses. The space constraints on lower Hillhouse necessitate such a strategy, both for the short and the long term, even with the near-term construction of new physical sciences building that would house some SEAS faculty (see ***Quantum*** above). Integration of engineering into the recommendations of this report, as well as the emerging institutes on the West Campus, provides a pathway for growth and SEAS must find a way to capitalize on these opportunities.

The USSC is supportive of a concept suggested by several faculty during our deliberations, an Engineering +X strategy for the future of SEAS. In this model, SEAS would be viewed as having a hub and spokes structure across the University. There is a core center of Engineering on lower Hillhouse (the hub of SEAS) plus clusters of engineering faculty distributed in strategic research areas elsewhere across the campus (the spokes, or the +X). Examples of this structure are already in place. BME faculty are located in the Medical School as part of its emphasis on biomedical imaging. Faculty in the MEMS and CEE are associated with the Energy Science Institute on West Campus, and BME faculty are associated with the Systems Biology Institute, also on West Campus. This is a model that could find additional examples in the recommendations for strategic investments in ***Quantum Science***, ***Engineering and Materials*** (including the recommendation for a new building to house researchers in that field); ***Neuroscience*** (particularly theoretical neuroscience where network modeling is required); ***Climate Solutions*** (which will require full engagement with engineers); and ***Regenerative Medicine***, among others. It is also obvious that machine learning and artificial intelligence have a direct connection to SEAS, especially now that Computer Science has become part of the School. Although the USSC is not in a position to define what belongs in the hub of SEAS, our recommendations should help to define some of the key "Xs" where SEAS can make strategic emphasis. Implementing such a strategy for the growth of SEAS would have the benefit of integrating Yale's work in engineering and applied sciences with its work in the basic and clinical sciences, thus helping Yale's discoveries find application in the form of engineering solutions.

In addition to identifying scientific themes for incremental investment, the Committee was charged to think about how science and engineering is conducted at Yale. We identified **ten enhancements to organizational structures** that would improve the University's research enterprise. Each recommendation for a structural improvement will require some administrative attention and, in some cases, a financial investment. Each recommendation will enhance support for Yale's scientific enterprise and will enlarge the scientific impact of research within individual faculty labs, departments and schools.

Structural and Organizational Support for STEM Research at Yale

1. Interdisciplinary Faculty Appointments

The USSC was tasked with thinking about science and engineering across the University. Several of our recommendations involve cooperation and engagement between faculty in different schools. For these recommendations to be successfully achieved, Yale will need improved coordination of faculty hiring and greater flexibility in the nature of their appointments.

Science at Yale would be strengthened if there were greater interaction among the various schools and departments that are engaged in scientific discovery and education. The USSC frequently heard that faculty quality would benefit from engagement with other parts of the University for faculty selection, appointment and/or retention. We also regularly heard requests for greater flexibility in faculty leave policies to allow work with industry or national laboratories, as well as increased opportunities for academically-minded scientists and engineers working in such organizations to have association with the University. This is particularly important in the Data Science and Computer Science disciplines, where the fields are evolving rapidly and there are regular transitions of experts between industry and academia.

The systems of faculty hiring in the School of Medicine and the Faculty of Arts and Sciences are quite different. The YSM system allows considerably more flexibility than FAS. Unfortunately, the differences in these systems has led to significant differences in cultures around hiring in the two schools. Consequently, joint hiring efforts have been limited to a few departments and a small number of faculty. The necessary differences in teaching expectations and evaluations can also limit interdisciplinary interactions and instruction, noting that working together in the classroom can often initiate new research collaborations at the intersection of allied fields.

Although the USSC did not attempt to make specific edits to the faculty handbook, we recommend some themes that would benefit from administrative attention.

- The Deans of YSM, FES, YSN, YSPH, SEAS, and FAS should explore issues that are faced when making joint appointments. They should identify changes to policies that will facilitate making such appointments with minimal administrative challenges when the academic justification is strong. Issues that should be considered include questions of salary, space, and start-up resources, but also policies associated with tenure processes, teaching expectations, and service expectations.
- The Deans should incentivize department chairs to explore joint hiring and creative sharing of resources to enable such interdisciplinary hires.
- The Deans, particularly in FAS and YSM, should review their policies regarding faculty leave for research purposes in the sciences and compare their policies with those of peer institutions.

2. Computing and Data Management Support

The availability and accessibility of data are transforming the scientific enterprise. Many research programs require the acquisition and storage of large data sets, often with restrictions that protect the privacy of subjects or the intellectual property of the researchers or the sources of the data. Furthermore, funding agencies are now requiring data management plans, often with an expectation of open accessibility of data collected during sponsored projects. In addition to the impact of the changing nature of data, computational science and machine learning are having an outsized and increasing impact on all areas of science and engineering. Yale has made considerable strides in high-performance computing support for researchers in science and engineering who are expert in computation and data sciences. This support should be extended to research computing and data management support for researchers who do not need high-performance computing, but still need to work with complex computation and/or large and complex data sets. We offer the following recommendations:

- Expand the role of the Yale Computing Resource Center to develop support for computational science and big data efforts by non-expert researchers who need to leverage such tools in advancing their research programs. Areas of need include consultation/advice, specialty cloud services, secure environments for private or sensitive data, and temporary assistance in writing specialized code. This service could be considered a Core facility as suggested above (see ***Core Facilities***).
- Develop and maintain sufficient data management support structure to help faculty meet the evolving research and compliance needs in this arena. This could follow the recommendations proposed in the recent internally sponsored Research Data Strategic Initiative Group report, which outlines steps to help manage data by Yale faculty who may not have expertise within their own research groups.

3. Support for Large Grants

Large strategic grants, often known as center grants, have many benefits beyond the level of funding that they bring. Such grants, for example DOE Energy Frontier Research Centers, NSF Science and Technology Centers, NIH P41 Centers, or private foundation grants (e.g., Paul G. Allen Discovery Centers) or private-public partnership grants (e.g., NSF/Simons Foundation) bring national visibility and draw university researchers together around common themes, allowing them to attack more ambitious and impactful problems. Although certain Schools, notably YSM, have had significant success with such grants (P30, P50, and U54 grants), Yale has not had success as a lead institution in obtaining such grants when they require efforts across Schools, and many faculty feel that Yale should do better in these competitions. The USSC recognizes this deficiency and recommends that actions be taken to bring such funding mechanisms to Yale.

The preparation of proposals for large, inter-departmental or inter-school multi-investigator grants is substantial. It requires considerable project management support, as well as the preparation of numerous non-technical sections to address agency requirements. Yale is competing against other universities that have established central proposal development offices that support the preparation of such grant applications. These offices serve as expert surge capacity and project managers for large strategic grants. They support faculty principal investigators in ways that regular grants staff typically do not, and coordinate the efforts of multiple entities within the university. This allows the faculty to focus on scientific and strategic aspects of the proposals and reduces barriers to grant submission.

To facilitate the award of large center-scale grants to faculty across the University, the USSC makes the following recommendations:

- Yale should establish a central proposal development office to support the preparation of large multi-investigator or strategic proposals. The activities of this specialized office should focus on project management and administrative aspects of proposal-preparation, allowing the faculty leadership to concentrate on the technical and scholarly aspects.
- The Vice Provost for Research should actively work with the deans' offices of the various schools to encourage and support teams of researchers who aspire to develop center-scale grants.
- Consideration should be given to how to support and incentivize faculty who apply for and then obtain center-scale grants (e.g., consideration of relief from other duties, administrative support).

4. University Space Planning for the Sciences

The availability of high-quality laboratory, office and teaching spaces is a primary constraint on all research efforts. An improvement in physical space can have immediate effects on a program. For example, the renovation of the buildings housing the Chemistry Department has invigorated the faculty and students within that department. Similar effects resulted from the construction of the TAC building in the Medical School, and comparable outcomes are anticipated from the construction of the Yale Science Building on Science Hill. The availability of large amounts of high quality space on West Campus has also allowed strategic hiring for multiple departments across the University. By contrast, the limited availability of high-quality space will continue to adversely impact the ambitions of some departments in SEAS and in the Physics Department, and will likely require significant investments both for short-term and long-term solutions.

Any activity in the renovation, construction and utilization of space has downstream impact on subsequent space uses and needs. Space needs are also impacted by scientific developments and faculty recruitments. The USSC recognizes that almost all of its recommendations are dependent upon the availability of appropriate space and that the space adjacencies between departments and programs are key to innovation.

The ultimate authority for all space allocations resides in the Provost's Office. This provides efficiency and allows strategic decisions to be made with a broad view toward the University's needs. At the same time, a concern heard by the Committee was that there is insufficient faculty consultation in the decision-making process, which limits the flow of information to the Provost's Office to promote optimal decision making.

Given the critical nature of space for the development and implementation of any strategic plan, the USSC makes the following recommendations to provide faculty consultation in the big picture space planning process.

- The Provost's Office should restore the tradition of appointing faculty to a Research Space Planning Committee tasked with supporting the Provost's Office in campus-wide planning for large-scale renovations and building projects for science and engineering research. Such participation would be comparable to faculty participation on the Budget Advisory Group for resource allocation.
- The Research Space Planning Committee should support the Provost's Office in developing a 10-year plan for research space. This plan should be refreshed on a 3-4-year cycle, in order to reflect the

changing needs of the campus and unforeseen developments in scientific progress and available resources.

5. Support for Professional Scientists

Many faculty stressed the importance of professional scientists and engineers who support the research mission of the University. These members of the research ecosystem provide high-level support needed for ambitious programs that include such things as the development of complex computer code, extensive data collections, creation of advanced instrumentation and facilitating use of complex equipment by students, postdocs, and faculty. These staff are typically supported on soft money of relatively short duration. In most cases, central support is not available to allow such staff members to develop a cohesive career at Yale that spans multiple projects. As a result, Yale cannot attract the best professional scientists (who prefer more stable positions), and talent developed at Yale is lost when there are gaps in staff salary because a particular research program came to an end, another project was not immediately available, or a grant was not immediately renewed. It is also noted that such positions could help in the recruitment and retention of outstanding and diverse faculty whose spouse/partner is a professional scientist, engineer, or programmer.

The USSC recommends strategic central investment in professional scientists. These experts should be viewed as a critical human resource that supports the scientific enterprise, and we think that they should be developed, managed and supported in a way consistent with this important role. We see these ideas as being closely aligned with the recommendations for ***Core Facilities*** and ***Instrumentation*** that are described above. We offer the following recommendations to expand our support of professional scientists:

- Inventory professional scientist positions across the University and identify key skills and capabilities that justify supplementation of grant funding with central support.
- Develop standards for the employment conditions for professional scientists. This should include a promotion track and normalized reappointment schedules with the possibility of bridge funding for long-term employees who are typically supported on grants.
- Create more opportunities for career development, skills training and networking of the professional scientist community at Yale and across the New England region.
- Consider centralized management and bridge support of professional scientists to facilitate their stable employment at Yale through the timespan of multiple projects and grants, and the development of a community of such staff at Yale.

6. Junior Faculty Development Training

New Assistant Professors in STEM need to make a sharp and dramatic transition from full-time bench scientists into managers of a scientific enterprise while maintaining high academic standards. With little formal training in the managerial aspects of science, each Assistant Professor is expected to effectively utilize start-up funding; set up a research lab; recruit and supervise students and postdocs; develop a research portfolio; submit, secure and properly manage extramural grants; independently publish their scientific findings; and teach and mentor. They often do this in relative isolation, because any given department only hires a few junior faculty each decade. Difficulties inherent in the transition from bench work to principal investigator can create a significant sense of isolation. Easily avoidable mistakes can negatively impact career development.

About ten years ago, several junior faculty at a similar stage of their career in multiple YSM and FAS departments organized themselves. They collectively sought training in the managerial skills needed to successfully navigate the junior faculty period of their careers. They received practical advice in personnel, project and time management. Professional trainers and an organizational psychologist from the SOM were brought in to guide the group in retreats and in small group "question and answer" sessions that included University leadership. These interactions afforded the junior faculty a forum in which to compare notes and experiences with each other on how to navigate the many challenges of the job. Overall, the program not only helped faculty overcome specific managerial challenges, but also resulted in a robust and long-lasting peer network that facilitates excellence.

The USSC views these organized interactions as a best practice in faculty development. We recommend similar cohorts of junior STEM faculty be supported across the University as junior faculty continue to join our STEM departments. Such a program develops interdisciplinary peer networks while promoting the institutional aspiration of promoting faculty interaction across all three of Yale's campuses. We expect that participation will ease the transition to a principal investigator role, increase scientific productivity in the short and long term, and increase interdisciplinary interactions across the University. Specifically, we propose that the University:

- Support the creation of STEM junior faculty development cohorts on a 2 to 3-year cycle for management training and community building across schools.
    - Training should include the voluntary participation of entering faculty to career development retreats, junior faculty mentoring groups and professional coaching activities that could be organized by the faculty based on their needs, but facilitated and coordinated at the level of the University.
    - Participation should be facilitated at the level of the department but structured at the level of the University to maximize interdisciplinary interactions.
    - Participation should be encouraged and the potential benefits explained to entering faculty, but participation should not be a requirement.
- Training does not end once the junior faculty period is concluded. Faculty in STEM are stimulated by new opportunities and challenges, and this contributes to retention, and service to the institution. The USSC identified an opportunity for tenured faculty members with inclination toward leadership positions to develop management and leadership skills through formal courses at the SOM, mentorship and "fellows" programs within administrative offices. Such programs could be geared to provide special encouragement to members of underrepresented groups to become engaged in university leadership and STEM leadership in particular (see ***Diversity*** above).

7. Commercialization and Entrepreneurship

Commercialization of intellectual property that arises from Yale's research has the potential to bring benefits to the inventors and the University. The Office of Cooperative Research (OCR) is charged with protecting the intellectual property of the University's research enterprise, and to support its commercialization so that researchers' inventions can have maximal impact, and to assist faculty who have entrepreneurial ambitions. OCR has traditionally had a strong focus on biomedical efforts, particularly pharmacology, commensurate with the profile of Yale's research portfolio.

The USSC sees opportunities for commercialization to play an increasingly vital role in the full professional development of the University's STEM faculty and in support of the University's missions, and thus recommends improvements to Yale's approaches in this realm.

- Assess resources devoted to commercialization of intellectual property, including areas outside of the biomedical enterprise, and compare the resources with those of appropriately chosen peer institutions. Depending on the outcome of this assessment, the University should consider how to optimally support efforts in these areas and whether an increase in staffing is warranted.
- The USSC is concerned that Yale has not traditionally provides sufficient support for faculty interested in entrepreneurship, given its importance to many faculty members' career ambitions and to the local economy. Recent support from the Blavatnik Foundation is positively impacting this arena, and the efforts started with that funding should be continued and enhanced. The goal should be to provide adequate support to researchers from all fields whose professional goal is to have societal impact through entrepreneurship. OCR should engage faculty proactively. They should robustly communicate what programs exist to support faculty entrepreneurship. The Vice Provost for Research should review whether the existing structures are compatible with institutional goals in this arena.
- Yale should work with other local and regional stakeholders to explore the development of an incubator where faculty startup companies could be nurtured through the earliest stages of development. Such an incubator would build the community of entrepreneurship for Yale, and it could provide services such as marketing advice, legal support, and web design. It would also provide an opportunity to engage science and engineering faculty and other researchers with students from SOM and other programs.

8. Improve Research Communication

The communications landscape for the sciences is evolving rapidly. New ways of reaching audiences both on campus and beyond offer the opportunity to increase the impact of research. But the means and skills to effectively communicate via new media will need to be widely understood. The USSC recommends investments that will improve the way Yale scientists communicate with each other, and with the diverse audiences around the world.

Yale enjoys a high degree of collegiality among its faculty and staff. Greater collaboration between the faculty in each campus could be achieved through improved centralized communication. Better faculty communication would also be helpful to the administrative and compliance efforts that enable the scientific enterprise. There are few regular communication streams that focus on connecting researchers to each other and to relevant administrative efforts and external funding opportunities.

Regular meetings of diverse groups of researchers are routine at other institutions, but are less common here. They provide a relatively easy way to improve communications and collaborations across Yale. The annual "Day of Data" and the "Yale Science and Engineering Forum" are two examples of meetings that create connections among researchers at relatively low cost.

Yale would also benefit from a stronger research-focused web presence and centrally supported internal research communications that build awareness of research activities and structures within Yale and provide the impetus for taking advantage of the resources of the larger university.

The USSC heard the need for greater internal communication channels and skills for external communication. We offer the following recommendations:

- Initiate and support a strong and dynamic research web presence aimed at both internal and external audiences. This should include annual reporting on the size, scale, and impact of research at Yale, user-friendly links for internal staff, students, and faculty who conduct research at Yale, links to research news stories with appropriate connections to social media, and links to administrative functions and information that might be of interest to external stakeholders.
- Convene regular meetings of research leadership across the three campuses. This could include monthly gatherings of the relevant research deans of the different schools, quarterly gatherings of science chairs across all schools, or gatherings of researchers or research administrative staff with common interests.
- Initiate and maintain a system of routine messaging about research funding opportunities and administrative changes.
- Develop an online research expert profile system. These can be deeply valuable to a wide range of audiences, including campus administrators seeking expertise, development staff, corporate partners, as well as potential students and faculty.
- Foster opportunities for faculty and students to develop skills in science communication, recognizing the rapidly changing landscape for publication and other forms of research dissemination including social media, and the importance of clear articulation of research goals and findings for attracting funding.

9. Increase Connections with Brookhaven National Laboratory

Some universities with strength in the sciences benefit from a strong affiliation with one of the national laboratories. Brookhaven National Laboratory (BNL) is the US Department of Energy national laboratory that is geographically closest to Yale. Battelle Corporation and SUNY Stony Brook are primarily responsible for running BNL, but Yale is part of the governing board and both BNL and Yale would benefit from closer connections.

Several of our scientists have close collaborations with BNL researchers, but there is still considerable untapped potential for shared projects and the development of shared equipment. BNL staff could bring advanced teaching and mentoring expertise to our students, as well as research expertise to our campus. The facilities at both institutions could provide complementary strengths to the combined community. Such interactions would open new possibilities for external research funding and provide access to the high-end instrumentation that is only available at a national laboratory.

The USSC heard from several faculty, particularly those in the physical sciences, about the strategic opportunities that would be afforded through a stronger relationship with BNL. To achieve this goal, we offer the following recommendations.

- Convene a standing committee of faculty to identify opportunities for greater collaboration with BNL. Invite members of the BNL community also to participate. The focus should be on how to create long-term sustainable partnerships that extend beyond the involvement of specific individuals in either institution. This committee should also advise regarding administrative barriers to closer cooperation that will need to be overcome.
- Explore appropriate mechanisms for joint appointments of ladder faculty, non-ladder faculty, staff, and postdocs with BNL. These appointments could originate for current Yale or BNL employees.

- Develop a standard mechanism to support longer term visits of graduate students and postdocs to conduct research at BNL.

10. Improve Support for Clinical Trial Research

Yale's research in the biomedical sciences is making discoveries that can and do find important application in treating human disease. The significant growth of Yale's clinical practice makes research with clinical applications an increasingly important part of the University's research portfolio. Clinical trials research offers tremendous opportunities for translating basic scientific discoveries into direct impacts on human health, as well as the development of new research directions and advances in the treatment of patients.

Clinical trials involve a complex landscape of scientific research, regulatory permissions, privacy/ethical requirements, legal disclosures, financial interactions among multiple participants, and reporting. This complex landscape extends across federal (NIH, FDA, CMS, VA), state, and private (both non-profit and for-profit) entities. Clinical trials research is frequently not only cross-disciplinary but also multi-institutional, often with high visibility and impact on the general public. Within this complex landscape, it must support all missions of the University (including education, community service, and research).

The USSC heard from several faculty that the infrastructure to support clinical trials at Yale has not kept pace with these complex and ever-changing regulatory and administrative requirements, nor with the expanding importance of this type of research. The University should support and facilitate bench-to-bedside translation of scientific discoveries. Comprehensive administrative services that help move trials quickly from initial proposal through contract execution should be made available to all Yale investigators. The USSC recommends that the Yale School of Medicine, Yale School of Nursing, Yale School of Public Health, and relevant Departments in FAS, along with the Office of Research Administration, and in partnership with Yale New Haven Health System, redouble efforts to improve our capabilities in this area.

- The University should continue its review of current performance in clinical trial initiation and execution, compare metrics with those of competing institutions, and alter procedures to streamline processes as required.
- Based upon the review, one solution for consideration would be creation of a Clinical Trials Office that provides a one-stop-shop for infrastructure and operational support of clinical trials. The Office should provide assistance to both faculty and industry sponsors throughout the lifecycle of a protocol from inception to study closeout, including study coordination, fiscal services, protocol development, clinical research group support, and data collection and reporting.
- The University should maintain a standing high-level task force to continuously review processes around clinical trials to improve efficiency while maintaining the highest levels of compliance.
- As the number of clinical trials increases, the relevant compliance, contracting, and administrative staff should be increased proportionally to ensure that those processes do not unnecessarily delay the progress of the studies.

Appendices

Appendix 1: Other Ideas of Interest

The USSC identified almost 70 different ideas from among the documents submitted to us by the community. Among that list, we highlight here eight other scientific areas that captured our imaginations.

Exoplanets and the Search for Earth Analogs.

The discovery of Earth analogs and the search for life on those planets rank among astronomy's greatest quests. With the discovery of thousands of planets orbiting other stars, the scope of this field can now be stated: there are billions of undiscovered worlds in our galaxy alone. The next phase in the field of exoplanets is shifting toward their chemical characterization. How do planets form and evolve? What are they made of? Are they likely to have convective cores, plate tectonics and magnetic fields? What are the spectroscopic fingerprints of their atmospheres? Is there life on any of these planets? NASA and the European Space Agency are launching missions to measure exoplanet radii and obtain spectra of exoplanet atmospheres. Next generation ground based spectrographs will measure exoplanet masses with unprecedented precision (highlighted in ***Quantum*** and ***Instrumentation*** above). Yale has significant strength in this area and is in a position to open vibrant interdisciplinary collaborations among astronomers, geophysicists, biologists and statisticians.

The Microbiota and Symbiosis

The microbiota is the collection of microbes (bacteria, viruses, fungi) that live in and on larger organisms. In humans, interpersonal variations in the microbiota and the microbiome far exceed interpersonal genome variation. The composition of a person's microbiota has been implicated in a vast array of human diseases, including obesity or malnutrition, resistance to pathogens, cancer, and even behavior (highlighted in ***Inflammation Science*** and ***Cancer*** above). For example, in mouse models of autism, inflammation during pregnancy alters the microbiome transmitted to offspring, and these offspring exhibit repetitive and asocial behaviors. Mice that lack gut microbes, by contrast, do not exhibit these properties. In animal models, these microbiome-encoded properties are often transmissible between individuals by microbiotic transplantation, providing an avenue for experimental study and clinical intervention. All animals that have a gut carry out their biology in the context of microbial partners. The same is true for plants, which carry their own flora of microbial associations. The impacts of resident symbiotic microbiota across biology are just beginning to be explored. The biological and chemical characterization of the microbiome is in its infancy, and will require the engagement of biologists, chemists, biochemists and biosynthesis scientists. Yale is well-positioned to become a leader in both the omics and the function-oriented study of how the microbiome impacts biology, disease and therapy.

Structural Biology and the cryo-EM Revolution

Pictures of an object reveal much about its attributes and environment. Images of biomolecules are no different, providing powerful insights into the machinery that keeps viruses, cells and whole organisms running. Until recently, it has been difficult to obtain images of large biomolecules and to visualize them in their natural surroundings, but this has been transformed with advances in cryo-electron microscopy and tomography (cryo-EM and cryo-ET). Using cryo-EM, it is now possible to see the biomolecular machines that synthesize our genes, make our proteins, and move cargo around the cell. It is possible to capture images of these machines at different points in time, leading to molecular movies of cellular action. This technique has been extended further with cryo-ET, in which individual molecules and assemblies are imaged within a functional cell, thereby revealing the cast of characters involved in biological processes. These technologies are fast becoming the "eyes" with which investigators explore the frontiers of bioscience and medicine, and access to these methods will determine the pace of discovery by Yale scientists in many biological fields. Yale has invested in the instrumentation needed to capture these images and has made multiple hires of faculty to utilize these instruments. As cryo-EM and cryo-ET are applied to more and more areas of biology, Yale will need to keep pace with technological developments, faculty expertise and instrumentation capacity in this area.

Urbanization

The world is rapidly urbanizing. Over the next 30 years, the world's urban population will grow by about 2.5 billion, an addition of about 170,000 people per day. To accommodate this growing urban population, urban areas are expanding by 20,000 American football fields every day. Growth in urban areas involves the construction of buildings and roads, water and sanitation facilities, and energy and transport systems that are transforming the planet. Urban areas produce the majority of global greenhouse emissions, generate more than 75% of global economic output, and are home to more than 50% of the world's population. Urban development strategies are central to improving human health, expanding economic opportunity, reducing poverty, fostering vibrant communities, and creating resilient and dynamic towns and cities in which resources are more equitably shared. For cities to transition towards sustainability, we need to develop scalable solutions that are based on sound evidence, good design and the best science. Forestry and Environmental Studies has identified Urbanization as a key strategic priority allowing Yale to help solve urban challenges and create more sustainable urban futures.

Global Health

Health quality is directly related to economic and social development, as good health is paramount to economic growth and political security. Global health research saves lives, improves economies, and enhances national security. Pandemic outbreaks, non-communicable disease burden, and climate change are among the many problems that have a dramatic impact on human and planetary health. Investing in basic and translational global health research saves millions and has high return on investment. From vaccine development and infectious disease modeling, to medical device innovation and health system emergency preparedness, more than 150 Yale faculty are engaged in global health-related science, in New Haven and with partners around the globe. The new Yale Global Health Institute brings together expertise from multiple schools (YSM, YSN, and YSPH). This Institute will allow Yale to take discovery science to real-world application by fostering innovation and scientific translation with partners around the world.

Imaging and Image Analysis

Richard Feynman advised biologists to '*...just look at the thing!*' to answer their fundamental questions. This advice applies equally to doctors, astronomers, geologists, neuroscientists, and chemists. Looking at '*the thing*' requires both innovation in image-collection methods and technologies and in processing, analysis and interpretation of the images - whether the subject is a biological machine, a cell, or a far-off galaxy. Yale has a history of innovation in imaging and image analysis from electron microscopy to astronomy, and a wealth of imaging expertise across disciplines. By forging interdisciplinary collaborations among scientists imaging very different subjects - both with one another and with mathematicians and data scientists - Yale has the opportunity to drive the development of approaches to view our universe and its components in unprecedented ways (highlighted in ***Instrumentation*** and ***Data Science*** above).

RNA Biology

Although proteins were once thought to do all the major work within a cell, it is increasingly evident that RNA carries a substantial portion of the workload. While certain RNA molecules (such as mRNA) contain genetic information, most RNAs are non-coding molecules that function as structural scaffolds, enzymes and cellular signals. Indeed, the vast majority our genome encodes RNA molecules that regulate diverse aspects of life and growth in an organism. Efforts to understand the mechanisms of these processes are driving an explosion of knowledge about biology, and with that knowledge, powerful new technologies and therapies are emerging. For example, it is now possible to cure devastating degenerative diseases with short RNA molecules that reprogram muscle development. RNA-based technologies can recode entire genomes and turn genes on or off with precision and control. RNAs that mimic viruses can unmask tumor cells and enable the human immune system to clear cancer. Yale has great interdisciplinary strength in RNA biology, including the receipt of two Nobel Prizes in this area. The Yale Center for RNA Science and Medicine provides a structure for community and collaboration for this important area of research.

Science of Cultural Heritage

Yale's museums and libraries host cultural heritage collections that stand among the greatest of any university in the world. There are over 13 million items in the Peabody museum alone, with millions more in the Yale Art Gallery, the Yale Center for British Art and the University's Libraries. These objects come in every imaginable medium and form. Understanding the materiality of these works and specimens through scientific analysis serves the humanities by providing scholars essential and fundamental tools to interpret the origins and histories of the object. The humanities in turn serve science by providing context and meaning of the work at hand. Decoding art and artifacts unlocks vivid insights into human experience, expression, and creativity. Cultural material and scientific collections are non-renewable resources. Their exhibition and study exact a price, as do efforts for remediation and restoration. Minimizing this price requires methods to interrogate the nature and condition of objects. Analysis of the functional and expressive properties of cultural materials has the potential to catalyze research across many branches of science, including proteomics, climatology, photochemistry, computer science, and data science as well as economics, cognitive science, and history (highlighted in ***Computer Science***). Scientific inquiry into the materiality of cultural objects animates Yale's collections of art and artifacts and demonstrates a world integrally interwoven, connected, and evolving.

Appendix 2: Charge for the University Science Strategy Committee

From Provost Ben Polak
January 31, 2017

President Salovey has identified the sciences as a top academic priority for Yale (see *November 21, 2016 email re: University Priorities and Academic Investments*). This committee will play a key role in giving shape to this priority. It will create a strategic plan for STEM at Yale. While the immediate task of the committee is to provide a set of priorities, it also has the opportunity to define science at Yale for decades to come.

Initially, I am asking the committee to "dream big," unconstrained by resources or realism. If we were able to do everything the committee recommends, I would not consider that a success, but rather an indication that we have not dreamed big enough. But understanding that we will not be able to do everything comes with a second (and harder) task. I ask the committee to prioritize its ideas. This will require the committee to make difficult choices.

What would constitute a compelling vision of science for the community of Yale students and faculty, today and in the future? What are the big ideas that we should be considering? Big ideas might be areas of science, either contained within a single department or extending across the university. This committee is well-situated to identify initiatives that cross traditional boundaries. Other ideas might involve the way we organize ourselves as a scientific community, the way we fund graduate students, or the way we teach.

What are the principles that might guide us? First, the committee should consider Yale's comparative advantages. It is easier to build on strength than on weakness. But there may be specific areas where Yale cannot afford to be weak, and hence where we might need also to build. And we must always maintain focus on our core mission: teaching, research, and practice.

I ask that the committee

1. Develop a list of approximately 4 – 8 big ideas, listed in order of priority. Please assess each idea in terms of impact, resources required (funding, space, faculty, etc.), feasibility, and comparative advantage.
2. Develop prioritized lists of ideas that could be accomplished at current levels of resources, as well as those that would be possible with an additional $50m, $100m, and $150m in annual expenditures.
3. Make suggestions about organizational structures and behaviors that could support excellence in STEM at Yale.

Finally, I ask each member of the committee not to think of themselves as representing their particular area, school, or department but instead as representing Yale, to take a long-range and university-wide view. I appreciate the creativity, wisdom, and institutional citizenship that this will require, and I thank each of you in advance. I look forward to working with you – and learning from you – on this important undertaking.

Appendix 3: Letter to Solicit Input from Departments

From: Scott Strobel
Friday, January 27, 2017

Dear Colleagues,

I write to request your assistance in developing a University-wide science strategy plan for the coming decade. President Salovey has identified science as a top University priority. President Salovey asked Provost Polak to assemble a University Science Strategy Committee and the Provost has asked me to serve as the committee chair. As was announced on Wednesday, the other members of the committee are Daniel Colon-Ramos (YSM), Alison Galvani (Public Health), Steve Girvin (FAS), Art Horwich (YSM), Jay Humphrey (SEAS/YSM), Akiko Iwasaki (YSM), Mark Lemmon (YSM), Scott Miller (FAS), Anna Pyle (FAS), Dave Skelly (FES), and Dan Spielman (SEAS/FAS).

Our charge is to "dream big" as we envision the future of the sciences and engineering (STEM) at Yale, both areas where we have strength that can be further strengthened and areas where we cannot afford to be weak. Input from leaders across the sciences at Yale will be crucial to this process. **As a first step, we respectfully invite you to provide the committee with a brief "self-reflection" document that provides input for your School, Department or Institute**. This is not meant to be a lengthy or time-consuming exercise, so we are keeping the timeline fairly short. We request that you return your self-reflections by March 27. There will be time to flesh out ideas further in a later stage of the process in summer and fall 2017.

Here are a few general guidelines to assist you: First, the goal of this committee is to identify actions that will broadly strengthen science at Yale. We are not tasked with thinking about the strengths of individual departments, programs, or schools in isolation. Therefore, we ask that you pay particular attention to priorities in your field that have a broader impact on the University, including ways that your unit makes inter-disciplinary connections. Second, we aspire to understand the frontiers of work in your field, even if these are not currently reflected in your department; so please keep a broad perspective. Third, please give thought to your teaching mission (of all categories of students) in addition to the research mission of your unit. Finally, we ask that you identify areas where Yale has a comparative advantage – i.e., things that we do well – or could do well - compared to other institutions. These unique strengths provide a solid foundation upon which we can build further.

The format of your document is flexible, but we ask that you keep it brief. Please aim for fewer than five pages. We do not want this to be an onerous task for you - or for the committee, which will be reviewing more than 30 of these reports. There will be opportunity to follow up in greater depth at a later stage.

One implication of the charge to the committee to "dream big" is the expectation that if we have done our job well, we will identify more worthy and exciting ideas than it will be possible to implement. If we can easily accomplish everything in the strategic plan, then we failed to think big enough. We must also have a sense of what possibilities we will have to postpone or forgo if we choose to pursue a particular opportunity. It will be necessary to make choices. A key objective for our committee is to identify priority areas for investment over the next decade. However, we also seek to do something more durable. No strategic plan can specify all of the University's future initiatives in an area as broad and dynamic as the sciences. Instead, we intend to also articulate guiding principles that reflect what distinctively defines science and engineering at Yale, as well as develop a framework for prioritizing the necessary trade-offs. In addition, we seek to identify the enablers that must be in place to allow science at Yale to thrive.

With that as background, we ask that you consider the following questions as you prepare the analysis of your unit (*Note: your "unit" refers to your school, department, or institute as appropriate*):

1. What are the big ideas that will define new directions for your field over the next ten years?
2. How should Yale be contributing in those areas?
3. What are the strengths of your unit at Yale, and which of those strengths would you identify as unique comparative advantages versus other institutions? Are there other unique strengths in the University that we should take more advantage of?
4. What are other institutions doing that you admire?
5. What structural or organizational changes would maximize the impact of our investments in science and engineering?

Please let me know if you have any questions. Thank you so much for giving your time and recommendations to this planning process.

Sincerely,

Scott Strobel

Henry Ford II Professor
Howard Hughes Medical Institute Professor
Department of Molecular Biophysics and Biochemistry
Department of Chemistry
800 West Campus Drive
West Haven, CT 06516

Appendix 4: Charge Letter to Panelists

Dear <<Panelist Name>>,

I write to ask for your participation in a panel discussion with the University Science Strategy Committee (USSC) to provide your perspective on the area of <<insert area>>. The panel will be comprised of about six faculty members who also have expertise in this area. <<insert name>>, a member of the USSC, will moderate this discussion and will set up a time to meet with you and the other panelists in advance of the conversation. At that pre-meeting, [insert first name] will provide instructions for the panel format, a summary of the committee's deliberations on this area to date, and guide a preview of the discussion among the panelists. I will provide you the panel membership in advance of these meetings after I have received confirmation of people's willingness to participate. Your panel will be scheduled during the months of October and November. Additional panels on other topics will be held in early 2018. Please let me know if you are willing to participate in this forum by responding to this email at kelly.locke@yale.edu by Friday September 22. We will then work with you to schedule the pre-meeting and the panel in the next few weeks.

President Salovey has identified the sciences as a top academic priority for the future of Yale (see his November 21, 2016 email re: University Priorities and Academic Investments). The USSC has been tasked by the Provost to create a University-wide strategic plan that will guide future scientific investment at Yale. To quote the charging document: "Initially, I am asking the committee to "dream big," unconstrained by resources or realism. If we were able to do everything the committee recommends, I would not consider that a success, but rather an indication that we have not dreamed big enough. But understanding that we will not be able to do everything comes with a second (and harder) task. I ask the committee to prioritize its ideas. This will require the committee to make difficult choices."

The USSC committee was constituted in January 2017. During the Spring 2017 semester, the USSC solicited broad input from the University community through a variety of sources, including input from individuals, departments and schools. The committee received hundreds of ideas across all fields of science. We have narrowed this input to a list of approximately a dozen themes that could potentially provide the elements of the strategic plan. The committee next needs to better understand each of these research areas in order to complete the prioritization work that we have been tasked to accomplish. This is where we need your help.

Each panel will meet with the full USSC to share your vision for what this big idea could be, what impact it could have on both Yale and the world, and to discuss what you think would be required for us to seize the opportunity should this area be moved forward. This is not an invitation to solicit resources for your department, school or center. To guide your planning for this discussion, please consider the following questions:

What is the vision for the "big idea?" What is it? What impact would it have on the world and Yale? Consider benefits for students, other scholars and humanity.

What are Yale's comparative advantages in this area? Who is working in this area or related fields at Yale today? What are other institutions doing? Consider what factors might give Yale a comparative advantage over others.

Who would need to be involved? If it crosses disciplinary boundaries, what will be required for them to work effectively together?

What are the key uncertainties associated with the idea? Consider both the intellectual risks inherent in the idea as well as execution risks of Yale's ability to lead in this area.

What resources would be required? Consider the talent needed, as well as logistical requirements such as space, equipment and other resources.

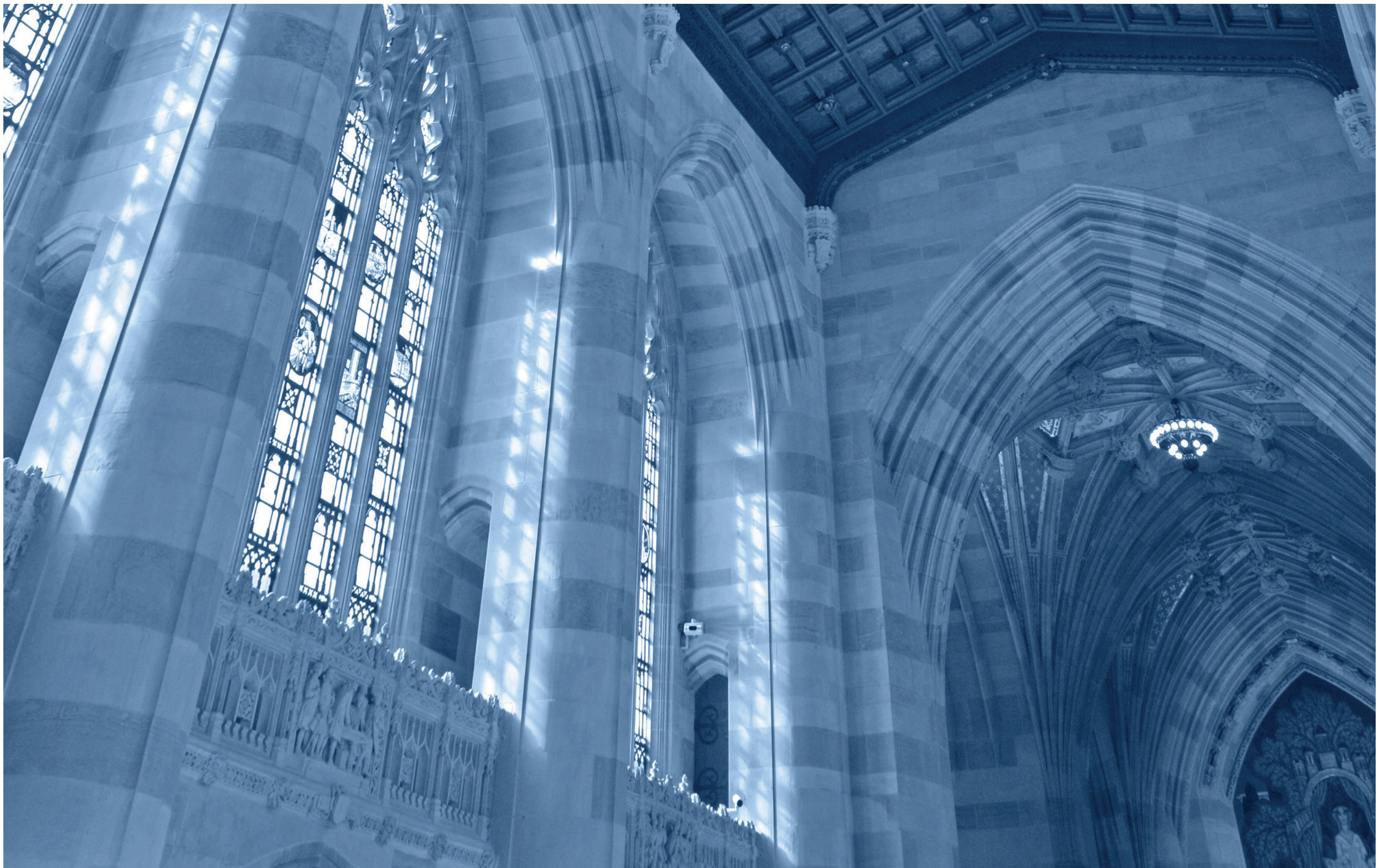
To further guide your preparation, I encourage you to look at the strategic planning document generated by the School of Engineering at Stanford. We are modeling our own process based upon this document in. It can be found at: http://soefuture.stanford.edu/

Thank you for considering this invitation to provide direct input to the committee and I look forward to hearing from you.

Sincerely,

Scott Strobel

Henry Ford II Professor of Molecular Biophysics and Biochemistry
Chair University Science Strategy Committee



Report of the
University Science Strategy Committee

Yale