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21ST CENTURY BIOLOGY

Chairman Lipinski, Ranking Member Ehlers, and committee members: I am James P. Collins, Virginia M. Ullman Professor in the School of Life Sciences at Arizona State University (ASU). I am also an Affiliated Scholar in the Consortium for Science and Policy Outcomes at ASU. Prior to returning to Arizona State University, I served in the Federal Government during the George W. Bush and Barack H. Obama Administrations as Assistant Director for Biological Sciences at the National Science Foundation (NSF) from October 2005 to October 2009. I am currently a consultant at NSF.

The biological sciences will flourish in the 21st century by sustaining strength in its core disciplines while simultaneously supporting research at the intersection of the natural, physical, and social sciences as well as engineering. Research at these disciplinary edges holds great promise for addressing problems in energy, the environment, agriculture, materials, and manufacturing. Interdisciplinary methods cut across disciplines to combine in powerful ways basic research with solving real world problems. Because today's students are tomorrow's problem solvers we must also integrate research and education to prepare the next generation to address 21st century challenges. But the problems confronting us are complex and will not be solved by business as usual: innovation must be a hallmark of both research and education in 21st Century Biology.

Sustaining disciplines while blurring their boundaries

Biology itself emerged as an interdisciplinary science late in the 19th century. At that time researchers from diverse areas such as physiology, natural history, and anatomy realized their research had a common theme and argued for uniting these largely separate areas of scholarship into the new discipline of biology focused on the study of life: How did life originate? Why are there so many species? How does heredity influence development of individuals? What organizes living systems from the complexity of a cell to the complexity of a forest?

Some late 19th and early 20th century life scientists also conceived of their research more within the realm of engineering. As the historian of science Dr. Philip Pauly argued, they thought that their research should be focused on controlling life. They envisioned manipulating, transforming, and even replicating living systems, in order to understand nature and also to help solve human problems. "Nature was raw material to be transformed by the power of the biologist" wrote Dr. Pauly (Pauly, P.J. 1987. *Controlling Life. Jacques Loeb and the engineering ideal in biology*. Oxford University Press, Oxford). Straight from the first decade of the 20th century this is a perspective that we can easily imagine finding in a 21st century discussion of synthetic biology or nanotechnology.

Throughout the 20th century the two great themes of understanding and controlling life wove together even as biology itself divided into sub-disciplines such as genetics, cell biology, ecology, and evolution. Discoveries such as the molecular structure of DNA advanced our basic understanding of genetics, and this knowledge was then applied through biotechnology to control living organisms such as genetically modified crops. Discoveries in embryology led to fertility treatments, while discoveries in ecology led to improved environmental quality. Yet until recently, the subdisciplines have not worked together as effectively as they might.

Two things stand out as we look to biology's 21st century future:

- First, more and more research questions require reintegrating biology's sub-disciplines, and the fields are making progress in carrying out that integration.

For example, systems biology seeks a deep quantitative understanding of the emergent properties of complex biological systems—properties such as resilience, adaptability and sustainability—through the dynamic interaction of components that may include multiple molecular, cellular, organismal, population, community, and ecosystem functions (after *A New Biology*. 2009. National Academies Press, Washington, DC: p. 61).

- The second thing we see is the biological sciences as a growing source of inspiration for and collaboration with engineering and the physical and social sciences.

A recent National Research Council report, *Inspired by Biology: from molecules to materials to machines* (2008. National Academies Press, Washington, DC), calls for three research strategies:

biomimicry or learning how a living system's mechanistic principles achieve a function and then replicating that function in a synthetic material; bioinspiration where a task achieved by a living system inspires making a synthetic system; and bioderivation which involves hybridizing a biological and artificial material. Developing these biologically inspired materials advances basic science, improves U.S. competitiveness, and addresses national challenges in materials and manufacturing. This sort of visionary research at disciplinary edges is transforming and selectively dissolving the boundaries of the life and physical sciences as well as engineering.

Biology in the 21st century is rapidly changing before our eyes as life scientists engage in innovative ways with many other areas of scholarship. Today's biologists conduct research in areas that did not exist as recently as ten or even five years ago: computational biology, systems biology, and sustainability science are examples. These interdisciplinary fields are emerging as a result of new questions, new tools such as sensors, new methods such as computational thinking, and new ways of conducting research especially in large group collaborations supported by new cyberinfrastructure.

At the Subcommittee's request I'll comment on the environmental sciences, which offer many promising research opportunities. Interdisciplinary research is advancing our basic understanding of challenges such as global change and global loss of biodiversity and suggesting ways in which we might mitigate these changes. NSF-supported sensing systems in the Long Term Ecological Research Network (LTER) and in the proposed National Ecological Observatory Network (NEON) are designed to gather enormous quantities of data continuously. These networks of sensors, computers, and people promise to transform how we test basic ecological theory and apply the results to environmental problem solving. Molecular methods are accelerating the description of new species, including the discovery of novel microbes that add to our basic understanding of the biosphere while serving as "bio-inspiring" sources of novel energy technologies. At NSF the new Dimensions of Biodiversity initiative is supporting just this sort of grand challenge research in which new knowledge is developed.

As this research matures, researchers will need new tools such as sensors that run on small, very long life power sources. New methods must include fast, highly accurate molecular techniques for indentifying species and efficient computer algorithms for analyzing, visualizing, and storing large quantities of data. Students entering these fields must be skilled in quantitative and computational methods, understand how to draw on multiple disciplines to address problems, and learn to do science in nationally and globally connected communities.

We must remember, however, that even as we envision biology as a way to address today's problems we cannot forget that today's "grand challenges" eventually will change. Our research institutions must remain agile and capable of responding to new and evolving problems that we cannot yet imagine. Part of the agility and capability needed must come from supporting researchers conducting basic research that generates new knowledge. In addition, the agility and capability needed must come from educating students and ourselves in innovative ways. Failing to do both of these things would cause the U.S. to lose out in two ways: first, we would not have the basic knowledge needed to respond to a future challenge and second, in the near term we fail to sustain ourselves as science and technology leaders. Research agencies and universities must be innovative and adaptable if "a new biology" envisioned in the recent NRC report by the same name is to be realized.

Innovation as a central feature of life science research and education

When I testified before this Subcommittee in October 2009, I observed that NSF was first and foremost an innovation agency with a long history of success in supporting research with far-reaching impacts on the U.S. economy and the well-being of all Americans (*Investing in high-risk, high-reward research*; available at: http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=111_house_hearings&docid=f:52484.pdf).

In particular I argued that, "The challenge for agencies like NSF that fund research done by other organizations is to create and sustain a culture of innovation in which the flow of information among its members creates an institutional culture and framework that stimulates, reinforces, and rewards creativity, and pervades the agency and guides its decision-making process." That remains true today for NSF, and in general creating and sustaining an innovation ecosystem is a wider challenge for our funding agencies, America's universities, and industry.

At the heart of this ecosystem is what we can call the process of discovery, which begins with an idea that is tested and developed by one or a few individuals. Increasingly, however, the testing is done by large groups that may or may not be in one place. Networks of computers unite investigators in problem solving efforts using what is called "the wisdom of the crowd." It is an approach that can be very effective in bringing together widely separated experts for solving problems rapidly. Crowd sourcing models, prediction markets, and prizes are modern components of the process of discovery (Collins, J.P., *Investing in high-risk, high-reward research*).

Innovation is not just an idea, but it is a process that links a few to many individuals. In a rapidly changing world the process of discovery itself is also changing rapidly, and our students must learn how to keep up. Modern biology curricula should expose students to this sort of thinking and more. Learning is the creative process by which new knowledge is discovered; learning is not memorization of facts as an end in itself. Too often students imagine biology as the latter, perhaps because it is commonly taught that way, but no characterization of the biological sciences could be further from the truth.

One innovative reform effort in biology curricula is called Vision and Change in Undergraduate Biology which is a joint effort of NSF and the American Association for the Advancement of Science or AAAS (http://visionandchange.org/). A second international effort focused on undergraduate curricula in general is emerging from an international consortium at the Wissenschaftskolleg zu Berlin/Institute for Advanced Study (Appendix I). Both are opportunities for the U.S. to assume a leadership role in shaping student learning and problem solving in the 21st century.

But as the saying goes, a vision (or idea) without resources is a mirage. Funding is needed for developing innovative ideas and here is where researchers/entrepreneurs turn to public and private sources for help.

NSF is one choice for U.S. researchers and educators. The Directorate for Biological Sciences advances transformative science by building on fundamental disciplinary strengths and also by encouraging high risk/high reward research. The directorate is experimenting with new methods of review such as crowd sourcing and prediction markets to support transformative science and learning at the interface of biology and many other disciplines. Experimenting with innovative methods for finding the best ideas to fund in research and education must be a central feature of NSF and other Federal agencies.

Especially as budgets tighten it is easy for any institution to be satisfied with sustaining what it does well. But the magnitude of some of the challenges and the need to respond quickly means that business as usual is not good enough. Agencies like NSF should be bold and adopt policies that foster innovation as they seek to fund high risk, high reward research—and education.

A central value at NSF is the integration of research and education. In response to a question from the Subcommittee I'll note that the NSF supports a wide range of programs from undergraduate REUs (Research Experiences for Undergraduates), to graduate IGERTs (Integrated Graduate Research and Training), and postdoctoral fellowships.

As contributors to the U.S. scientific enterprise students also need an understanding of the historical, philosophical, and ethical context within which research questions are asked and answered. Students must understand that knowledge is not a static set of facts but is always evolving within a historical and cultural context. We must instill in students an interest in and a healthy respect for the societal implications of their research because the best of them will make discoveries that will have huge implications for society.

The radical transformations enabled by modern technologies for generating and disseminating knowledge quickly and widely can be a great help in enabling the basic discoveries needed for understanding life and addressing real world problems. Much of the future will be about networks of investigators and networks of institutions.

Building coalitions among institutions

The Subcommittee asked me to comment on university-industry collaborations and coordination across U.S. Federal agencies. These topics are related: knowledge creation and use along with the best ideas to identify and fund research and education should not start or stop at the borders of one organization.

University-industry partnerships are increasingly a feature of the modern educational landscape. NSF funds major Science and Technology Centers that connect universities and colleges to private sector technology development. At the Subcommittee's request I have appended to this testimony examples of NSF activities at the intersection of federally funded basic research, the private sector, and universities (Appendix II).

In the best cases the relationship between a university and industry partner, or either of these with a Federal funding agency, should be a two-way process of learning. For example, the process of discovering marketable ideas within industry can be very innovative. In my last discussion with the Subcommittee I described how "The recent Netflix million-dollar prize competition is a compelling example of the successful use of crowd sourcing for technological discovery while also contributing to a culture of innovation." A recent *New York Times* (June 27, 2010: B1-B8) report described "proof-of-concept centers" to bridge university researchers studying basic problems to the business world. The report noted that "Rather than offering seed money to businesses that already have a product and a staff, as incubators usually do, the universities are harvesting great ideas and then trying to find investors and businesspeople interested in developing them further and exploring their commercial viability." Universities are acting as very early risk takers to help bridge the so-called "valley of death" separating people with ideas from people willing to invest in them.

As NSF fosters university-industry collaborations in biology the Foundation can learn best practices from this process. Institutions should be open to using great ideas wherever they are found.

Coordination across federal agencies is another way to build coalitions while also serving as a way to leverage the innovative ideas of several institutions. For example, the National Institute for Mathematical and Biological Synthesis is jointly supported by NSF's Directorate for Biological Sciences, Directorate for Mathematics and Physical Sciences, U.S. Department of Agriculture (USDA), and Department of Homeland Security. Two Nanotechnology Centers are supported by NSF's Directorate for Biological Sciences and the Environmental Protection Agency. The Plant Genome Research Program (PGRP) is an excellent example of coordination across Federal agencies. NSF, USDA, Department of Energy, National Institutes of Heath, and the U.S. Agency for International Development collaborate to support PGRP, which is an exceptionally effective National Science and Technology Council collaboration for fostering basic plant research and its translation to agriculture.

Institutional coalitions are not the answer to every challenge, but in selected cases they can be very effective ways to leverage resources and facilitate innovation.

Modern problem solving requires more than science and technology

In the U.S. National Research Council's *New Biology* report we see the central themes of biology's origins—understanding life, controlling life and a call for broad engagement with other disciplines—recast in new forms around contemporary problems. Modern science, engineering, and technology are full of breathtaking discoveries. It would be wrong, however, to conclude that scientists and engineers can solve all of the problems of food, health, energy, and the environment. Social scientists call questions in these areas "wicked problems" for a reason: they are full of complex, interdependent parts and solving one aspect of a problem often reveals or even creates other problems. Simply put, so-called wicked problems will not yield to only scientific or technological fixes.

America's best researchers and their students must engage in a process of discovery that transforms the way in which research is conducted and students are educated. If the changes needed are to occur at a sufficiently fundamental level it will also mean transforming our research institutions. Solving problems must not be limited by disciplinary or institutional borders. Global change and the global loss of biodiversity are part of a litany of important and pressing problems. Challenges such as these have the quality that the longer we delay addressing them the worse they become. The process of discovering solutions must include students as partners with our senior researchers. Because they are young, students have great energy to invest in realizing a future in which they have the greatest stake as planetary stewards. Agility and adaptability, which are available in great quantities in young people, will be indispensible qualities for problem solvers in a rapidly changing world.

I have envisioned a future for biology that has three elements: sustaining disciplines while blurring their boundaries; innovation as a central feature of life science research and education; and building coalitions among institutions**.** In combination these three elements are a vision for understanding how the life sciences will play a key role in addressing the great intellectual and social challenges of the 21st century. At the same time, we will sustain America's leadership in science, engineering, and technology innovation during the years ahead.

Once again Mr. Chairman, thank you very much for giving me the opportunity to testify on this very important subject. I would be pleased to answer any questions that you have.

Appendix I. Principles for Rethinking Undergraduate Curricula for the 21st Century: *A Manifesto* (From: Principles of curricular reform developed by a Wissenschaftskolleg zu Berlin/Institute for Advanced Study 2009-2010 working group and revised at the Workshop on "The University of the 21st Century," Wissenschaftskolleg zu Berlin/Institute for Advanced Study, June 5-6, 2010.)

The current crisis of the university is intellectual. It is a crisis of purpose, focus and content, rooted in fundamental confusion about all three. As a consequence, curricula are largely separate from research, subjects are taught in disciplinary isolation, knowledge is conflated with information and is more often than not presented as static rather than dynamic. Furthermore, universities are largely reactive rather than providing clear forward-looking visions and critical perspectives. The crisis is all the more visible today, as the pace of social, intellectual and technological change inside and outside the universities is increasingly out of step. While universities worldwide are undergoing many, often radical, structural transformations, ranging from the Bologna Process in Europe and the Exzellenzinitiative in Germany to the rapid expansion of universities in India and China, the accelerating decline of public investments in universities in the United States and elsewhere and an ever growing demand for university access everywhere, much less attention has been paid to university curricula. But for the university as a community of scholars and students, that is its central function and the key to its internal renewal. Universities are embedded in multiple institutional, economic, financial, political, and research networks. All of these generate pressures and constraints as well as opportunities. The curriculum, however, is the core domain of the university itself.

Here we present a set of eleven overlapping principles designed to inform an international dialogue and to guide an experimental process of redesigning university undergraduate curricula worldwide. There can be no standard formula for implementation of these principles given the huge diversity of institutional structures and cultural differences amongst universities but these principles, we believe, provide the foundational concepts for what needs to be done.

1. As a central guideline teach disciplines rigorously in introductory courses together with a set of parallel seminars devoted to complex real life problems that transcend disciplinary boundaries.

2. Teach knowledge in its social, cultural and political contexts. Teach not just the factual subject matter, but highlight the challenges, open questions and uncertainties of each discipline.

3. Create awareness of the great problems humanity is facing (hunger, poverty, public health, sustainability, climate change, water resources, security, etc.) and show that no single discipline can adequately address any of them.

4. Use these challenges to demonstrate and rigorously practice interdisciplinarity avoiding the dangers of interdisciplinary dilettantism.

5. Treat knowledge historically and examine critically how it is generated, acquired, and used. Emphasize that different cultures have their own traditions and different ways of knowing. Do not treat knowledge as static and embedded in a fixed canon.

6. Provide all students with a fundamental understanding of the basics of the natural and the social sciences, and the humanities. Emphasize and illustrate the connections between these traditions of knowledge.

7. Engage with the world's complexity and messiness. This applies to the sciences as much as to the social political and cultural dimensions of the world. This will contribute to the education of concerned citizens.

8. Emphasize a broad and inclusive evolutionary mode of thinking in all areas of the curriculum.

9. Familiarize students with non-linear phenomena in all areas of knowledge.

10. Fuse theory and analytic rigor with practice and the application of knowledge to real-world problems.

11. Rethink the implications of modern communication and information technologies for education and the architecture of the university.

Curricular changes of this magnitude and significance both require and produce changes in the structural arrangements and institutional profiles of universities. This is true for matters of governance, leadership, and finance as well as for systems of institutional rewards, assessment, and incentives; it is bound to have implications for the recruitment and evaluation of both professors and students as well as for the allocation of resources and the institutional practice of accountability. The experimental process of curriculum reform we hope to stimulate by offering these guiding principles will thus require the collaboration of scholars and educators willing to transform their scholarly and educational practices and of administrators willing to support experimentation and to provide the necessary structural conditions for it to succeed.

These principles are the conclusion of deliberations by a working group of scholars that met at the Wissenschaftskolleg zu Berlin during the academic year 2009/10. Participants represented diverse disciplines (from the natural and social sciences and the humanities), geographical origins (Europe, North America, and India) as well as career stages (from former university presidents to students). They invite their colleagues around the world to join in this effort of re-thinking and re-shaping teaching and learning for the university of the future.

Appendix II: Examples of NSF activities at the intersection of federally funded basic research and the private sector and universities. (from Collins, J.P. 2009. *Investing in high-risk, high-reward research*. available at: http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=111_house_hearings&docid=f:52484.pdf).

NSF-funded Centers are designed from the outset with built-in flexibility so that investigators can pursue innovative ideas within the context of a defined program of research. Examples are legion, and include the Mosaic web browser developed at NSF's National Center for Supercomputing Applications at the University of Illinois. NSF's creation of two Centers for the Environmental Implications of Nanotechnology (CEIN) in 2008 exemplify innovative networks that are connected to other research organizations, industry, and government agencies to strengthen our nation's commitment to understanding the potential environmental hazards of nanomaterials and to provide basic information leading to the safe environmentally responsible design of future nanomaterials.

The **Industry/University Cooperative Research Centers (I/UCRC)** program develops long-term partnerships among industry, academe, and government. Each I/UCRC contributes to the Nation's research infrastructure, enhances the intellectual capacity of the STEM workforce by integrating research with education, and encourages and fosters international cooperation and collaborative projects. For example, the NSF Industry/University Collaborative Research Center (I/UCRC) known as the Berkeley Sensor and Actuator Center conducts industry-relevant, interdisciplinary research on micro- and nano-scale sensors, moving mechanical elements, microfluidics, materials, and processes that take advantage of progress made in integrated-circuit, bio, and polymer technologies. This I/UCRC has developed and demonstrated a handheld device that allows verified diagnostic assays for several infectious diseases currently presenting significant threats to public health, including dengue, malaria, and HIV. The device uses a dramatically simplified testing protocol that makes it suitable for use by moderately-trained personnel in a point-of-care or home setting. The center has also created many spin-off ventures including companies in the areas of wireless sensor networks for intelligent buildings; MEMS mirror arrays for adaptive optics; and optical flow sensors for industrial, commercial, and medical applications.

The objective of the NSF **Small Business Innovation Research (SBIR)** program is to increase the incentive and opportunity for small firms to undertake cutting-edge research that would have a high potential economic payoff if successful. For example, in 1985, Andrew Viterbi and six colleagues formed "QUALity COMMunications." In 1987–1988 NSF SBIR provided $265,000 (Phase I 8660104 and Phase II 8801254) for single chip implementation of the Viterbi decoder algorithm. Qualcomm introduced CDMA (code division multiple access) which replaced TDMA (time division multiple access) as a cellular communications standard in 1989. This advance led to high-speed data transmission via wireless and satellite. Now the $78B company holds more than 10,100 U.S. patents, licensed to more than 165 companies. Another example - Machine Intelligence Corp. was supported by SBIR Phase I and Phase II awards to develop desktop computer software that could alphabetize words, a feat that previously had been accomplished only on supercomputers. When Machine Intelligence went bankrupt, principal investigator Gary Hendrix founded Symantec and continued the project. The line of research resulted in the first personal computer software that understood English, marketed as "Q&A Software." Q&A quickly became an extremely successful commercial product and remains a widespread commercial application of natural language processing. Symantec research supported by NSF SBIR eventually led to six other commercial products and contributed to 20 others. Now, Symantec is a leading anti-virus and PC-utilities Software Company valued at $12B with more than 17500 employees worldwide.

NSF launched the **Integrative Graduate Education and Traineeship Program (IGERT)** in 1997 to encourage innovative models for graduate education at colleges and universities across the nation that would catalyze a cultural change in graduate education – for students, faculty and institutions. IGERT was designed to challenge narrow disciplinary structures, to facilitate greater diversity in student participation and preparation, and to contribute to the development of a diverse, globally-engaged science and engineering workforce. The result has been a cadre of imaginative and creative young researchers. For example, an NSF-funded IGERT award to the Scripps Institute of Oceanography (NSF #0333444) supported a doctoral student who successfully modeled the extinction of the Caribbean monk seal and demonstrated the magnitude of the impact of over-fishing on Caribbean coral reefs. This research developed improved ecological models, which may influence environmental policy and ultimately lead to the preservation of species and ecosystems for future generations.