At the Foundation of the Foundation: Basic Research at the NSF

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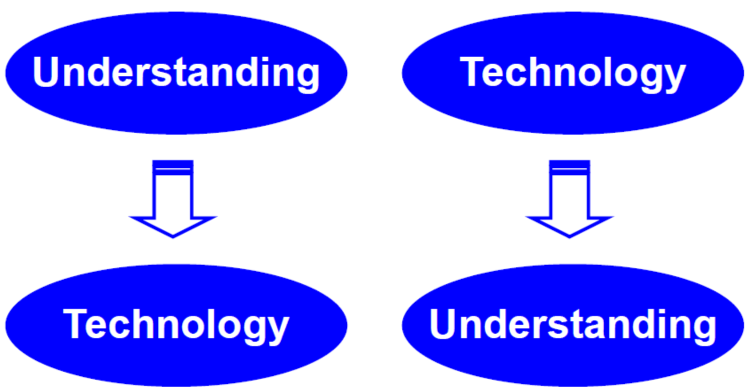
Reaffirming and strengthening America's role as the world's engine of scientific discovery and technological innovation is essential to meeting the challenges of this century. – President Barack Obama, November 23, 2009

Half our economic growth in the last half-century has come from technological innovation and the science that supports it. – President William Clinton, December 16, 1997

Research, including in the biological sciences, that yields epoch-making advances requires time horizons that often are impossible for businesses, with their inescapable attention to quarterly results. – George Will, January 02, 2011

I. Introduction

In science and technology, 'to understand' is a powerful concept. Understanding forms the foundation for all technological development. There is a symbiotic relationship between fundamental understanding and the technologies that underpin the Nation's economy, security and the health and well-being of our society. Basic understanding and technological development represent two sides of the same coin.



Just as breakthroughs in basic research lead to significant advances in technology, technological developments often yield new directions in basic research that result in a deeper understanding of the fundamentals. Think about the new questions and insights that emerged with such technological breakthroughs as the design of the scanning tunneling microscope, next generation sequencing machines, and nanomanufacturing. These technologies become the fuel for further fundamental insights which in turn feed new technological development. ***Basic research[1] and technological development are interdependent aspects of a discovery ecosystem***.

Given this interdependency***, it is imperative that our Nation maintain a balanced research portfolio between mission-oriented research and basic research focused on the pursuit of knowledge and understanding***. Across the range of federal agencies that support research and development, most have a mission-oriented mandate reflected in their titles: Department of Energy; National Institutes of Health; Department of Defense; Environmental Protection Agency; and Homeland Security. While the National Science Foundation has a mission, it is unique among US technology agencies in that it is not explicitly a "mission agency." We feel strongly that the National Science Foundation *must maintain and enhance* its focus on expanding understanding, and on pushing out the frontiers of human knowledge through the promotion and funding of basic research. Otherwise, our Nation may lose its preeminent role in developing the technologies that fuel a vibrant economy, maintain our national security, and enable the health and well-being of our society

A snapshot of the U.S. economy today would show a number of key areas driving growth and opportunity. They come under headings like biotechnology, multimedia, medical imaging, environmental technologies, polymers, materials, decision theory, educational technologies, sensors, and opto-electronics, not to mention high-speed computational and communications technologies such as the internet. All have deep roots in the support of fundamental research. The technologies are the result of steady and stable federal support for the instruments and insights needed to extend the frontiers of basic science and engineering.

Breakthroughs in fundamental research hold the key to future economic success. A wealth of evidence testifies to the impressive returns generated by these investments. One ground-breaking study funded by the NSF and published in the Fall 1997 issue of the journal *Research Policy,* found a rapidly growing linkage between industrial innovation and scientific research. The study examined patents in key areas of industrial technology, including biomedicine, chemistry, and electrical components. It found that nearly three-fourths of the research papers cited by U.S. industry patents are what the study termed "public science" – papers authored at universities, government laboratories, and other public and non-profit centers. Furthermore, the research underlying the cited papers was found to be heavily supported by the NSF and other federal agencies.

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[1] In this paper we take the definition for "basic research" that is set forth in the Organization for Economic Cooperation and Development's *Frascati Manual*, 6th Edition (2002), Chapter 4, page 77: "***Basic research is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundation of phenomena and observable facts, without any particular application or use in view."*** (http://www.tubitak.gov.tr/tubitak_content_files/BTYPD/kilavuzlar/Frascati.pdf).

These latest findings add to an already compelling body of evidence on the contributions of fundamental science and engineering to economic growth, productivity and innovation. The Council on Competitiveness affirmed the need for a stronger national investment in science and engineering in its recent report, *Going Global: The New Shape of American Innovation*. The report reflects the consensus findings of CEOs, R&D managers, and top officials at 120 leading corporations, universities, and national laboratories:

> *"For the past 50 years, most, if not all, of the technological advances have been directly or indirectly linked to improvements in fundamental understanding. Investment in discovery research creates the seed corn for future innovation."*

The NSF must claim responsibility for cultivating the seed corn for future innovation. Investments in furthering our fundamental knowledge base should not only continue, but indeed must be enhanced.

II. The Tangible Benefits

The case for strong funding for basic research can be divided into two parts: the tangible benefits and the intangible benefits. Both parts of the argument are important, and we will begin with the tangible benefits.

It makes sense to place the tangible benefits of basic research in a broader economic context, a context that can be summed up succinctly as "jobs and wages in a global economy." Wages are dramatically lower in booming countries like China and India. Whereas twenty years ago the concern was the loss of manufacturing jobs to countries with lower blue-collar wages, the question now is whether our economy can also absorb the loss of knowledge-worker jobs. With modern telecommunications, much of what a knowledge worker produces can be readily shipped across borders via the internet or teleconferencing. Given the increasing ease of outsourcing basic-level knowledge work, there are powerful economic forces tending to drive the wages in US, China and India into equilibrium. Considering the population disparity between the nations, the question we must ask ourselves is "why should we expect Asian wages to rise to US standards, rather than US wages to dramatically fall?"

A national goal then should be to foster policies that drive the relative wage scales out of global equilibrium, away from a vast level playing field at an elevation much lower than where we are today. What is the needed unbalancing force – what is the heat-flow, to use a physicist's analogy – that will disrupt equilibrating trends and keep global wage scales tilted in the direction we in the US prefer? The answer looking into the future is very much as it has been for some time. We must maintain and grow our lead in the most cutting-edge technologies, the highest of high tech, at the top of the value-added food chain. It is not a matter of simply encouraging more Americans to get basic bachelors-level education in engineering. That train long ago left the station. "Store-front universities" in India turn out upwards of one-quarter million bachelors in engineering annually, more than three times the rate of US universities, and the gap is rapidly growing. In China, the number is again much larger. Where we still hold the lead is in cutting-edge research and development. ***Maintaining our lead in advanced R&D is the key to our future prosperity.*** Otherwise, the US will inevitably face the prospect of seeing transformative technology being developed by other countries, which are even now investing greater amounts in basic research. It should be emphasized that keeping our "edge" in advanced technology is not just beneficial economically – meeting many key societal needs in health, environment and energy also relies, now and in the future, on our being as far out on the edge of the technology curve as possible.

What needs to be done to maintain our cutting-edge lead? Part of the necessary work can be accomplished by federally-funded research that directly targets immediate short- and mid-term societal needs, but ***the engine that drives the long-term success of technology development is basic research***. It is fashionable to use the term "high-risk" to describe basic research, but we emphasize that, paradoxically, the real danger to our society lies precisely in neglecting the high-risk part of a balanced research portfolio, and allowing the world's greatest scientific power to atrophy. As a speculative example, think of jet engines for commercial airliners. There's a market for more reliable, more fuel efficient engines. There is an ongoing industrial research effort making use of computational fluid dynamics to squeeze another *two percent* efficiency out of turbine blades. This sort of work was once done in the US – now it is done predominantly in India. Where the US aerospace industry can still compete is, for example, in the development of radical new materials or design concepts. But, innovation of the most dramatic, disruptive form relies on better fundamental understanding, and improved understanding is the immediate goal of basic research.

> *But technological progress cannot continue without the input of basic research and the conceptual breakthroughs it makes possible. In order to reduce knowledge to practice, one must have the knowledge in the first place. Science is the raw material that applied research and engineering refine into their products.* – Nathan Myhrvold, former CTO of Microsoft.

The all-important generation of knowledge can be effected through two complementary approaches. On the face of it, to obtain knowledge relevant to the solution of a particular societal problem, the natural thing to do is to fund mission-specific research in a conscious effort to confront the problem. Indeed this approach has had many important successes. What history has often shown, however, is that very often our most important advances, important economically, medically, militarily, were enabled by knowledge that was generated from the inquiries of research motivated originally only by the desire to push out the frontiers of knowledge. These discoveries form the framework of an innovation ecosystem, in which more focused research can flourish. A few examples follow:

a) *The laser*. Now essential to telecommunications, data storage, microsurgery and materials processing, the laser grew out of a gradual increase in understanding of stimulated emission, an abstruse concept dating to early work by Einstein. After the initial demonstration in 1960, the laser developed into a tool of basic research through the 1970s. When the commercial application of lasers and laser optics caught fire in the 1980s, U.S. companies benefited immensely from their ready access to a pool of researchers who had real understanding of the principles of laser technology, and the majority of the lucrative optics industry moved from Japan and Europe to the US.

b) *MRI (magnetic resonance imaging)*. MRI evolved from NMR (nuclear magnetic resonance), developed in the US by atomic physicists wanting to understand the inner workings of sub-atomic structure. MRI has grown into an important tool both in medical imaging and in molecular biology.

c) *Advanced image processing and adaptive optics*. Many of the most important ideas were developed by astronomers motivated by the need to see deeper into the Universe. Adaptive optics was a concept originally developed in astronomy that would remove the distorting influence (turbulence) of the earth's atmosphere on images obtained by ground-based astronomical telescopes, and was subsequently used by the Defense Department for high-resolution observations of satellites launched by other nations. Recently, this basic research concept is being used to study and characterize the human retina *in vivo*, something that has never before been possible; newly-developed medical adaptive optics instruments are now making important discoveries about the retina and the eye.

d) *Liquid crystals*. The original fascination with liquid crystals was based on investigation of the vast diversity of structural phases of condensed matter and the critical phenomena accessible in liquid crystals. The realization that liquid crystals could find use in LCD displays came much later.

e) *Positron emission tomography*, commonly known as PET scans. The discovery of positrons, first introduced by Dirac as a sort of mathematical sleight-of-hand, grew out of a desire to understand sub-atomic physics. The grant proposals of that day did not mention that positrons would eventually be used as the basis for function-sensitive imaging, as a means to visualize hidden tumors.

f) *Developments in mathematical number th*eory, which even its most enthusiastic practitioners were hard pressed to think of a use for, now form the basis of modern cryptography, essential for commerce and for our national security.

In concluding this section, we wish to reiterate that it is the cutting-edge basic research investment in fundamental science and engineering that provides the basis for the many technologies which we have come to take for granted, and this investment will continue to fuel the development of the new advanced technologies of the future. Such technologies will be instrumental to solving key problems presently facing our society, including energy, food and clean water. They will also continue to improve our quality of life, as for example the cell phone, GPS, and the ubiquitous transistor have done in the recent past.

III. The Intangible Benefits

Future Generations

Cutting-edge innovation will only be accomplished by cutting-edge innovators. Where will they come from? Consistent with the multi-decade time horizon of this white paper, the answer is, "from today's elementary schools." What policy changes can be made to reverse the increasing trend of our best and brightest young minds being diverted to industries that merely reshuffle existing wealth rather than create new national wealth through technological innovation? What will fire those young imaginations?

Children thrive on hands-on experiments that help explain natural phenomena. Chemical reactions that convert two substances into a new material spur the mind into thinking about other possibilities. Peering into the galaxy through a telescope opens a panorama of questions. Hearing about and experiencing basic scientific discoveries is the driver that propels many students into science and engineering disciplines.

The key that energizes and excites young people to think about the future and what it can bring is the thought of exploring new frontiers. Young minds are inquisitive; they ask questions about the world around them and demonstrate an enthusiasm for new discoveries that should be encouraged and nurtured.

Reaching Out to the Public

Promoting public interest in science is another role of the NSF. Basic research into the mysteries of the Universe, the origins of life, and the forces of nature produce scientific results that are interesting and accessible to everyone. They do not come with a political agenda in the way that applied science topics like energy and the environment do. They do not require that one choose sides or believe a certain viewpoint. Revealing the basic working of the natural world around us, whether that is through incredible images of stars being born taken by the Hubble Space Telescope or the intricate view of a strand of DNA, inspires everyone, not just scientists.

When people are interested in science, they are willing to think about it, learn about it and talk about it. ***A scientifically literate society is a goal that is paramount if we are to thrive in the 21st century***. The best way to interest young people in a scientific career (often to do applied science!) is to expose them and the broader community to the grand ongoing adventure that is basic scientific discovery; to make them realize how much there is yet to be learned.

IV. Concluding Remarks and Recommendation

Support for basic research is an essential part of the NSF, and is provided through the efforts of Directorates and Divisions throughout the Foundation. However, there are ways in which the priority given to that part of the mission may tend to dwindle over time, in comparison with initiatives that have more immediate and tangible payoffs. The payoffs of investment in basic research and its infrastructure are often realized on the timescale of decades rather than months or years*,* but ***investment in basic research is critical to the continued health of the national ecosystem for research and innovation.***

Every organization is subject to mission drift. Reassessing and reaffirming core commitments is an inevitable and periodic necessity. Such reassessment serves not only to define the sense of purpose held by the organization itself, but also the view of the organization held by those outside it. In the case of the NSF, there is little doubt of its commitment to basic research, but it is fair to say that there is a widespread feeling in the research community that the "growing edge" in NSF-sponsored activity lies in program-oriented research. The perception among many in the community is that funding for basic research has remained flat in real terms, while other areas have seen real growth. A purposeful effort to restore balance would have a salutary effect on the research community and on the decision-making priorities of NSF staff and panels.

No amount of lip service to the importance of funding "high-risk" or "disruptive" proposals can undo the dollars and cents message that is sent by Congress and OMB when all funding increases are tied to initiatives specific to short-term societal needs. This message is not lost on a creative young scientist contemplating a new research direction, and wondering how to get it funded. To be fair to both the OMB and Congress, they are unlikely to give the NSF anything the NSF is unwilling to ask for.

Increased support explicitly directed for basic research will send the clear signal that the NSF, and the federal government as a whole, sees basic research as an integral component of the national research enterprise, and will be an opportunity to rearticulate the many reasons for that. In particular, it will offer an opportunity to prioritize research that takes convincing steps in new and unexpected directions, and thus will encourage the research community to explore such directions more fully. ***A reaffirmation of the importance of basic research is a precondition for the emergence of the new insights and paradigms that will be necessary to confront the challenges we face in the 21st century, in an era of fierce global competition.***