Unlocking Our Future

Toward a New National Science Policy

A Report to Congress

by the House Committee on Science

September 24, 1998

Gingrich, Ehlers to Unveil National Science Policy Study Press Release

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Report Overview

The notion of state support for scientific research has existed for centuries; Francis Bacon called for such funding as far back as the early 1600s, and some monarchs and nobles responded to his call. It was not until 1862, however, when the Land Grant Colleges were established, that the United States began to organize and provide federal support for its science and engineering enterprise. Even so, it took until the outbreak of World War II for the Nation to fully grasp the benefits of substantial federal support for scientific research. It was at the culmination of that war, fresh from its lessons, that Vannevar Bush wrote his seminal document *Science: The Endless Frontier*.

The political consensus necessary to build today's science and engineering enterprise was forged largely by the Nation's needs and priorities in the period following the second World War, when the threat of total destruction by nuclear weapons was frighteningly real. Under these circumstances, the exigencies of the Cold War made science politically unassailable.

Recent geopolitical changes will have tremendous ramifications for the scientific enterprise. We are now blessed to live in a time of relative peace. Today, threats from rogue nations or individuals wreaking terror have replaced the fear of utter annihilation by the former Soviet Union. While we must remain ever vigilant and militarily strong, the need to maintain economic strength has taken on primary importance today. We now recognize more clearly than ever that economic strength facilitates not only a strong defense, but promotes other societal needs, such as social and political stability, good health, and the preservation of freedom.

The growth of economies throughout the world since the industrial revolution began has been driven by continual technological innovation through the pursuit of scientific understanding and application of engineering solutions. America has been particularly successful in capturing the benefits of the scientific and engineering enterprise, but it will take continued investment in this enterprise if we hope to stay ahead of our economic competitors in the rest of the world. Many of those challengers have learned well the lessons of our employment of the research and technology enterprise for economic gain.

A truly great nation requires more than simply economic power and the possession of military might, however. In a truly great nation, freedom triumphs. Diversity is not just tolerated, but celebrated. The arts flourish alongside the sciences. And strength is used not to conquer, but to assist. Economic stability brings more than a high standard of living in the purely material sense. It also promotes quality of life in the broadest sense.

Pursuing freedom requires confidence about our ability to manage the challenges raised by our increasing technological capabilities. Americans must remain optimistic about the ability of science and engineering to help solve their problems—and about their own ability to control the application of technological solutions. We must all possess the tools necessary to remain in control of our lives so that fear of the unknown does not slow down the pursuit of science. Science and engineering must be used to expand freedom, not to limit it.

As a nation, we have much to be proud of. But we ought always to be seeking to improve. Science and technology can play important roles in driving this improvement. These beliefs—that we can do better and that improvement can come, at least in part, through a strong science and technology program—are reflected in the vision that has guided the Committee on Science in formulating this policy study and in writing this report:

The United States of America must maintain and improve its pre-eminent position in science and technology in order to advance human *understanding of the universe and all it contains, and to improve the lives, health, and freedom of all peoples.*

The continued health of the scientific enterprise is a central component in reaching this vision. In this report, therefore, we have laid out our recommendations for keeping the enterprise sound and strengthening it further. There is no singular, sweeping plan for doing so. The fact that keeping the enterprise healthy requires numerous actions and multiple steps is indicative of the complexity of the enterprise. The fact that we advocate not a major overhaul but rather a fine-tuning and rejuvenation is indicative of its present strength. It is also not something the Congress or even the federal government can do on its own—making these mid-course corrections will require the involvement of citizens and organizations from across the nation.

Strengthening the scientific and engineering enterprise

Our recommendations focus on improving three major areas. First, science—including understanding-driven research, targeted basic research, and mission-directed research—must be given the opportunity to thrive, as it is the precursor to new and better understanding, products and processes. The federal investment in science has yielded stunning payoffs. It has spawned not only new products, but also entire industries. To build upon the strength of the research enterprise we must make federal research funding stable and substantial, maintain diversity in the federal research portfolio, and promote creative, groundbreaking research. Our challenge is actually twice as difficult as that which faced Vannevar Bush in 1945: we must maintain his legacy of excellence in groundbreaking research for which our science enterprise has become known, but in addition we must also take steps to explain the benefits of that research and make its results and benefits broadly known and available.

The role of the private sector is just as important in maintaining the overall scientific and engineering enterprise. The federal government's role in the application of research is naturally limited by the need to allow market forces to operate, but it is important that we ensure that the context in which technology-based industries operate is as conducive to the advancement of science, technology, and economic growth as possible. Because State-based economic development partnerships are far better suited to take on a greater role in this area, we have described some of their unique skills and outlined some of the ways they are already doing so.

Third, our system of education, from kindergarten to research universities, must be strengthened. Our effectiveness in realizing the vision we have identified will be largely determined by the intellectual capital of the Nation. Education is critical to developing this resource. Not only must we ensure that we continue to produce world-class scientists and engineers, we must also provide every citizen with an adequate grounding in science and math if we are to give them an opportunity to succeed in the technology-based world of tomorrow—a lifelong learning proposition.

New roles and responsibilities for science

While acknowledging the continuing need for science and engineering in national security, health, and the economy, the challenges we face today cause us to propose that the scientific and engineering enterprise ought to move towards center stage in a fourth role: that of helping society make good decisions. We believe this role for science will take on increasing importance, particularly as we face difficult decisions related to the environment. Accomplishing this goal will require, among other things, the development of research agendas aimed at analyzing and resolving contentious issues, and will demand closer coordination among scientists, engineers, and policymakers.

With the conduct of science today often transcending national borders, it is increasingly in our national interest to participate in international scientific collaborations. When it is, we should look to become involved. Not only will our participation reap direct benefits to our own research, but it will help spread the scientific ethos of free inquiry and rational decision-making worldwide and help us realize our vision of improving the lives, health and freedom of all peoples.

Finally, science must maintain a solid relationship with the society that supports it. In this report, we have not only suggested ways in which the scientific enterprise itself can be strengthened, but also ways to fortify the ties between science and the American people. Whether through better communication among scientists, journalists, and the public, increased recognition of the importance of mission-directed research, or methods to ensure that, by setting priorities, we reap ever greater returns on the research investment, strong ties between science and society are paramount. Re-forging those ties with the American people is perhaps the single most important challenge facing science and engineering in the near future.

Engaging in an ongoing process

We make no claim to have all of the answers or possess the ability to identify all of the steps necessary to reach our vision. Instead, this report attempt to lays out, in broad strokes, the problems we must address and constitutes the beginning of a lengthy process that we must all engage in together.

Finally, we recognize that as important as science and technology are, they are not ends in themselves. Neither science nor technology are panaceas for our Nation's or the planet's most troubling problems. Neither can guide morality nor substitute for idealism. Instead, science and technology are among the many tools to be used in building an even stronger Nation and safer planet.

I. Background and Introduction

A. The Speaker's Charge

On February 12, 1997, the Speaker of the United States House of Representatives, Newt Gingrich, sent a letter to House Committee on Science Chairman F. James Sensenbrenner, Jr. outlining a charge to the Committee to develop a long-range science and technology policy for the Nation. Excerpts of that letter follow:

> *The United States has been operating under a model developed by Vannevar Bush in his 1945 report to the President entitled* Science: The Endless Frontier. *It continues to operate under that model with little change. This approach served us very well during the Cold War, because Bush's science policy was predicated upon serving the military needs of our nation, ensuring national pride in our scientific and technological accomplishments, and developing a strong scientific, technological, and manufacturing enterprise that would serve us well not only in peace but also would be essential for this country in both the Cold War and potential hot wars.*
>
> *With the collapse of the Soviet Union, and the* de facto *end of the Cold War, the Vannevar Bush approach is no longer valid. Appealing to national pride in the sense that "Our science is better than your science" is no longer meaningful to the American public. The needs of our military mission today are far different, and the competitions we are engaged in now are less military and largely economic. Science today is an international enterprise, and we must assume a leadership role in guiding international science policy.*
>
> *I know that Vern [Ehlers] has discussed science policy with many academic and scientific leaders from across the country and has received a positive response from the scientific community. I believe it would be a powerful role for Vern to lead, with your advice and support, the House in developing a new, sensible, coherent long-range science and technology policy.*

B. Committee Actions

In addressing the Speaker's challenge, Science Committee Chairman Sensenbrenner asked Vernon Ehlers, the Committee's Vice Chairman, to lead a Committee study of the current state of the Nation's science and technology policies. Mr. Ehlers was also charged with outlining a framework for an updated national science policy that can serve as a policy guide to the Committee, Congress and the Nation.

A number of different approaches were used to gather input for the study: seven[1] hearings were held before the full Science Committee, two roundtable discussions were convened, and a web site was set up, through which the public could participate. In addition, interactions between the scientific and science policy communities and the Committee were facilitated by the speeches and other public appearances made by Mr. Ehlers and the Chairman, and in meetings between interested parties and the Congressman, staff, or both. All of these exchanges were crucial to gathering input into the important issues facing the national scientific enterprise.

C. A Vision for the Future

Where there is no vision, the people perish.

Proverbs 29:18

The hopes of a nascent Nation and her people were elegantly simple: life, liberty and the pursuit of happiness. In the centuries since the blood of our ancestors was shed in pursuit of those ideals, the Colonies that became the United States were transformed from aspiring Nation into the world's single greatest power. And yet, the original ambitions maintain their import to this day, as freedom must be vigilantly protected, good health is not ensured and prosperity is not yet enjoyed by all. Thus pursuit of the same basic objectives as those of our Nation's forefathers continues to propel us forward.

Our Nation continues to grow and develop in the context of a world that has witnessed vast changes. Today, no nation's economy can remain isolated; commerce links us all. Once-feared plagues have been rendered virtually obsolete while equally lethal ones have arisen. Our explorations range from the depths of the Earth's oceans to the hostile surfaces of our moon and neighboring planets, and our observations extend to the far corners of our universe and the interior of the atomic nucleus. Weapons capable of unfathomable destruction can be wielded from opposite sides of the globe by the touch of a button. Information is nearly instantaneously available and can be accessed from anywhere on the planet—and even from the reaches of space. Human impact on the planet, if left unchecked, may threaten the very resources we depend on for life. These changes tie the fate of all of humankind more closely together than perhaps ever before.

Facing tomorrow's challenges demands that we be armed with the power that is gained by knowledge and manifested in ingenuity. More than ever before, it will be our ability to gain a better understanding of our universe and all it contains, and to channel that understanding into solutions, that will enable us to realize the ideals our Nation holds sacred—and that others may aspire to. For the United States of America, continued leadership in science and technology will enable us to pursue the discovery and innovation that leads to better lives, improved health, and greater freedom for all peoples, as the advances generated and stimulated by science do not remain bound by geographic borders. A vigorous and sustainable American science and technology enterprise may be our most important legacy to future generations. This conviction is reflected in the following vision statement, which forms the foundation of this document and guided the Committee's work:

> *The United States of America must maintain and improve its pre-eminent position in science and technology in order to advance human understanding of the universe and all it contains, and to improve the lives, health, and freedom of all peoples.*

D. Science in Context

The scientific enterprise in the United States represents one of our country's greatest strengths. It is an enterprise characterized by intricate interrelationships between governments, industry, and universities. It draws strength from the American eagerness to innovate, our entrepreneurial spirit, and a research and technology base of considerable depth and strength. However, this enterprise cannot be expected to remain strong without attention. We must ensure that its components are functioning well, and that the interactions between the various players in it are productive.

Understanding the workings of the overall scientific and technology enterprise benefits from an awareness of the nature and practice of science itself. Science is fundamentally an inquiry-driven process; curiosity is at its core. It is a process of learning and discovery, not simply an accumulation of facts. Scientists seek to unlock the secrets that Nature holds, and since these secrets are closely held, only the clever and persistent questioner elicits answers. Thus pursuit of scientific understanding requires both intellectual dexterity as well as independence of thought. Although technology often finds its urging in necessity rather than curiosity, it requires no less resourcefulness and creativity in its pursuit.

These underpinnings in motive—curiosity versus need—have led to the designation of science as either "basic" or "applied." In the simplified versions of these descriptions, basic research is performed by academic researchers in search of knowledge, and applied research is carried out by inventors or industry researchers in pursuit of new and better products. These are artificial distinctions, as producing a new product, whether it is a microchip or a vaccine, often requires an understanding of underlying scientific principles. Similarly, insight into how or why something works often demands new tools. Thus the relationship between so-called basic and applied research is far from simple; it is instead complex, dynamic and interdependent.*

> *While recognizing the intricacy of the relationship between basic and applied research, the terms, however inadequate, have become part of the scientific vernacular and are therefore useful. To be clear, the term "basic" research in this document refers to research that is driven largely or entirely by the desire to better understand a given system or property, and is used interchangeably with terms such as "fundamental" or "understanding-driven" research. "Applied" research describes research that is done largely or entirely with the goal of perfecting a process or product.

Vannevar Bush's writings in *Science: The Endless Frontier,*[2] which despite being more than 50 years old are still largely recognized as the basis for the Nation's existing science policy, reinforced the simplified demarcation between basic and applied research. Dr. Bush implied a linear relationship between them, with basic research directly giving rise to applied research and product development. Interestingly, Bush's own experiences as an inventor, engineer and researcher suggest that he understood the subtleties of the relationships between fundamental research and its development into applications far better than he allowed in his report. He was, in fact, a co-founder of technology-based companies while a researcher at MIT and, perhaps most importantly, directed the Office of Scientific Research and Development during WWII. In this latter position, he was responsible for bringing together scientists—mostly university researchers accustomed to pursuing their own curiosity—with engineers and technicians to develop the tools that helped win the war, such as radar, the proximity fuse and the atomic bomb. He was thus well aware of the synergy that can exist between basic and applied science.

The linear model describing the relationship between basic and applied research nevertheless made for an appealingly simple policy prescription, one that has become Dr. Bush's greatest legacy to science in the U.S. It was Bush who, recognizing the downstream benefits of science performed in the laboratory, suggested emphatically in *Science: The Endless Frontier* that the federal government facilitate this research by funding both researchers in the Nation's colleges, universities and National laboratories, and the costs of training the next generation of scientists. He indicated in his report that this research be done in support of three major goals: improving national security, health, and the economy.

The Bush Report and the subsequent influx of federal dollars into the Nation's research universities shaped the scientific enterprise dramatically. Before WWII, most scientific research pursued in American universities was funded by the universities themselves, by charitable foundations, or by private industry. Federal funding for university research was restricted largely to agricultural research, done primarily in the Nation's land grant colleges. Science performed in the United States in this first mega-era of science policy was of high quality, but it was done on a small scale, and often with scant funding.

In the Bush-shaped, post-WWII era, the federal government funded an increasing share of research in the Nation's universities. These universities became centers of research excellence and the training grounds for future scientists and engineers unrivaled in the rest of the world.

Science—and science funding—during this second mega-era was affected greatly by the Cold War. Bush did not write his document with the intention of it being a Cold War manual; it was written in the brief window between assured victory in WWII and the onset of the Cold War. Nevertheless, the Cold War had an indelible effect on the scientific enterprise, as it provided a compelling rationale for research funding. Indeed, federal research dollars poured into science and technology during this period. The entire enterprise grew; greater numbers of research universities sprung up, more graduate students were trained to become scientists, and entire industries based on new technologies were founded. By 1961 the military-industrial complex had grown so powerful that President Eisenhower warned in his Farewell Address of the potential danger its dominance could have. He also expressed concern that either the scientists or the policymakers would become co-opted by the other.

The end of the Cold War had a profound impact on the Nation's research and development enterprise, and brought with it the end of the second mega-era of science policy. Without the backdrop of the Soviet military threat or the race to conquer outer space, convincing and often-used justifications for federal research funding became less compelling. Since then, the budgetary pressures exerted on research funding have grown. Today, while overall economic prospects appear favorable, growth of federal entitlements such as social security, health care and welfare threaten to overwhelm the federal budget and constrain discretionary spending—including funding for science—even further.

Our national experiment of federal funding for scientific research, however, has yielded enormous payoffs. In addition to fueling discoveries that save and improve lives, federally funded research represents an investment in the purest sense of the word, as it delivers a return greater than the initial outlay. Regardless of whether the relationship between basic and applied research is linear or more complex, the fact remains that the government's investment in fundamental research has yielded real dividends in every discipline—from astronomy to zoology.

For example, research on the molecular mechanisms of DNA, the so-called "blueprint of life," led to recombinant DNA technology—gene splicing—which in turn spawned an entire industry. Experimental and theoretical studies of the interaction of light with atoms led to the prediction of stimulated emission of coherent radiation, which became the foundation of the laser, a now-ubiquitous device with uses ranging from the exotic (surgery, precise machining, nuclear fusion) to the everyday (sewer alignment, laser pointers).

We are currently in the third mega-era of science policy. In this time of global commerce and communication a strong economic foundation will be paramount in achieving the vision of improving the lives, health and freedoms of our Nation's citizens. A fragile national economy poses potentially grave ramifications. Without a strong economy, the national defense may be compromised. Basic health care may be limited, and biomedical research becomes a luxury. And without a strong economy, all citizens face far greater obstacles to partaking in the benefits of progress.

Science, driven by the pursuit of knowledge, and technology, the outgrowth of ingenuity, will fuel our economy, foster advances in medical research, and ensure our ability to defend ourselves against ever more technologically-advanced foes. Science offers us an additional benefit. It can provide every citizen—not only the scientists who are engaged in it—with information necessary to make informed decisions as voters, consumers and policymakers. For the scientific enterprise to endure, however, stronger ties between this enterprise and the American people must be forged. Finally, our position as the world's most powerful nation brings opportunities as well as responsibilities that science and its pursuit can, and should, address.

This report seeks to outline the steps needed to bring about these goals from a national, not simply a federal government, perspective. That is, the science policy described herein outlines not only possible roles for federal entities such as Congress and the Executive branch, but also implicit responsibilities of other important players in the research enterprise, such as States, universities and industry. We believe such a comprehensive approach is warranted given the highly interconnected relationships among the various players in the science and technology enterprise.

In taking this broad view, our goal is to outline general principles and guidelines and to point out the importance of applying the discoveries from fundamental science to our daily lives and our needs. What our country needs now is not a complete re-structuring of our scientific enterprise, but instead an evaluation of our Nation's science and technology policies, and a determination of what changes are required to ensure the long-term health of this enterprise.

E. Toward an Updated National Science[¥] Policy

[¥] In general, the term "science" in this report is used in its broadest form, and unless stated otherwise, should be interpreted as including the physical, natural, life and social sciences, mathematics and engineering

The prevalence of science and technology in today's society is remarkable. Transportation, communication, agriculture, and medicine are but a few of the sectors of our society that have felt the impact made by advances in research and developments in technology. Yet rarely, if ever, do we stop to contemplate the system that fosters these changes that so greatly shape our society: the scientific and engineering enterprise.

This enterprise is much like any other massive, complex system. It has tremendous inertia and can keep functioning in the absence of any apparent direction. Indeed, as with any highly successful venture, it is tempting simply to stand back, admire its success, and assume it will maintain a steady forward course on its own. To do so, however, would be a mistake. No entity as vast, interconnected, and diverse as the science and engineering enterprise can successfully operate on auto-pilot perpetually.

As stunning as the gains from this enterprise have been, continued rapid advancement in many scientific and engineering fields suggests times of even greater progress lie ahead. Dramatic developments in communication, information and computational technologies alone promise to revolutionize our lives even further. Advances in these fields will change the way science is performed and expand its capabilities dramatically. They will influence the ways we teach and learn—perhaps even the way we think. Our scientific adventures are far from over.

America has, however, no intrinsic title to the dividends that science can bring; these proceeds must be earned. Past gains can be passed on to succeeding generations, but future progress requires continuous effort. The poor performance of our Nation's school-age children in math and science and the ineffectiveness of post-secondary science and engineering programs in engaging the interest of more of our Nation's youth are among the significant warning signals we ought to heed if we are to maintain our status as the world leader in science and technology.

If we adopt complacency in addressing the changes faced by the scientific enterprise in this country we risk our pre-eminence as a nation. Change in our democratic system, however, must not—indeed cannot—come from any one authority. The continued search for solutions and their eventual execution will require an ongoing commitment from all sectors of the science and engineering enterprise. Outlined herein are problems that need to be addressed, and, in many cases, possible solutions. This report constitutes the beginning of a process of addressing change, not the end.

We find ourselves at an opportune time to address necessary changes. We have witnessed the benefits that have come from our earlier investments in science and technology. New discoveries in a diverse number of fields promise great advances. Our economy is strong. It is at times like this that we must look to the future.

Three basic components of the scientific enterprise require strengthening if we are to ensure its success into the 21st century and thus realize our goals of improving the lives, freedom and health of all peoples. First, as discussed in Part II, *Ensuring the Flow of New Ideas*, we must ensure that the well of scientific discovery does not run dry, by facilitating and encouraging advances in fundamental research.

Second, we must see that this well of discovery is not allowed to stagnate. That is, discoveries from this well must be drawn continually and applied to the development of new products or processes, (Part III, *The Private Sector's Role in the Scientific Enterprise*), to solutions for societal or environmental challenges (Part IV, *Ensuring that Technical Decisions Made by Government Bodies are Founded in Sound Science*), or simply used to establish the foundation for further discoveries.

Finally, we must strengthen both the education system we depend upon to produce the diverse array of people—from scientists and engineers to technologically-proficient workers and informed voters and consumers—who draw from and replenish the well of discovery, as well as the lines of communication between scientists and engineers and the American people. These goals are outlined in Part V, *Long Term Sustainability of the Research Enterprise: The Importance of Education and Communication*.

The national needs that drove Vannevar Bush's vision for the role of science and technology in society are still compelling, and, as set out in the preceding section and implicit in the entire report, they remain a powerful force behind the need for a strong and sustainable scientific enterprise. Recent times have seen the emergence of a fourth rationale, as environmental threats have taken on increased urgency. Because greater scientific understanding of environmental issues is critical in addressing them properly, investment in research aimed at informing important decisions, such as whether and how to deal with specific environmental concerns, will be increasingly important. Thus four goals (national security, health, the economy and decision-making) constitute the foundation for this report and its recommendations.

II. Ensuring the Flow of New Ideas

A. The Importance of Understanding-driven Research

You rarely find the most important things by deliberately looking for them.

Joshua Lederberg, (1925-), 1958 recipient of the Nobel Prize in Medicine

[1995]

New scientific ideas form the foundation of the research enterprise. Without them, development would be stifled; our economy would stall. Hope for those with dreaded diseases would fade, and our defenses would be vulnerable. Yet the breakthroughs that form this foundation cannot be predicted or summoned upon demand. Instead, important discoveries often come from unexpected avenues.

Consider the work of Stanley Cohen and Herbert Boyer some 30 years ago, when they were among the many scientists experimenting on DNA. Like a number of other researchers in the young field of molecular biology, they were asking fundamental questions about the nature of genetic material. They were working independently of each other, trying to answer questions about such odd-sounding things as bacterial enzymes and mini-chromosomes called plasmids. A fortuitous meeting, however, led to a collaboration that precipitated a revolution in the field: the discovery of recombinant DNA technology. The technique they pioneered is now a staple of the life scientist's toolbox and made genetic engineering—and hence the biotech industry and many of the medical discoveries of today—possible.

At about the same time, an entirely different scientific discipline yielded an equally unanticipated but important discovery. Ronald Rivest, Adi Shamir and Leonard Adleman were engaged in research on computational complexity, a sub-discipline of theoretical computer science. Their pursuit of abstract mathematical concepts led them, however, to the foundation for public key encryption, a mathematics-based methodology that can be used to protect electronic information. Today, many years later, their discovery is felt profoundly, as encryption not only protects from prying eyes the e-mails we send, but also has made the burgeoning realm of electronic commerce viable by ensuring the confidentiality and security of internet-based financial transactions.

The scientists involved in these diverse pursuits had more than their scientific curiosity in common. Their quests for knowledge were all funded, at least in part, by the U.S. government. The above examples of basic research pursuits which led to economically important developments, while among the most well known, are hardly exceptions. Other instances of federally funded research that began as a search for understanding but gave rise to important applications abound. In fact, a recent study determined that 73 percent of the applicants for U.S. patents listed publicly-funded research as part or all of the foundation upon which their new, potentially patentable findings were based.[3]

The researchers described above might never have made their discoveries were it not for funding from the federal government. No company or private investor would have funded their scientific inquiries because, at the time, no payoff other than the gain of knowledge could have been foreseen.

New discoveries that will lead to equally important future breakthroughs are being performed in laboratories across the country today. It may take 5, 20, even 50 years before we derive the payoffs from some of this research, but once the returns are realized, we will wonder how we could ever have considered *not* funding it. Such 20-20 vision comes only with hindsight, of course. At the time a decision to fund a particular project is made, no guarantees exist.

Investment in basic research involves a willingness to take risks for eventual gain; for every revolutionary discovery there are other lines of research that yield far less momentous results. Such is the nature of basic research. The results carry the potential to lead to important or unexpected advances, but no assurances. Were a particular outcome of any given research project known in advance, the project would not truly be basic in nature.

James S. Langer, Professor of Physics at the University of California at Santa Barbara, summed up the essence of this point in an e-mail contribution to this Science Policy Study. "History tells us," he wrote, "that even the greatest scientists could not consistently point out the most profitable directions for research or predict the implications of their own discoveries. Newton spent a large part of his career studying alchemy. Einstein devoted the second half of his life to problems that we now know could not be solved without modern discoveries in elementary-particle physics. Bardeen grossly underestimated the importance of his invention of the transistor, as did most major U.S. industrial corporations at the time…While I am certain that we shall see remarkable scientific advances in the near future, I am equally certain that we cannot trust scientists, engineers, or public policy experts to predict where those advances will occur or in what ways they will have their greatest impacts."

The scientist or engineer pursues basic research in order to understand more about our universe and all of its creatures. While we may draw other benefits from these explorations—improvements to health, the economy, national security, our quality of life—we must not lose sight of the fact that the pursuit of knowledge alone is a worthy endeavor.

1. The basic research investment

The quick harvest of applied science is the usable process, the medicine, the machine. The shy fruit of pure science is understanding.

Lincoln Barnett, (1909-1979) American writer

[1950]

It is in our best interests as a nation to enable our scientists to continue to pursue fundamental, ground-breaking research. Our experience with 50 years of government investment in research has demonstrated the economic benefits alone associated with this investment. Economists' estimates as to the effect of technology on the growth of the Nation's economy vary, depending, in part, upon whether they are calculating private or public rates of return. A report from the Committee for Economic Development,[4] in citing a 1993 study,[5] estimated a consensus rate of return to private firms from investments in research at 20-30 percent. The Congressional Budget Office concluded recently that the public rate of return from research ranges from 30 to 80 percent;[6] a 1992 study[7] cited in a report from the Progressive Policy Institute[8] indicated that 49 percent of economic growth could be attributed to technological progress.[9] Regardless of the actual figures, few economists disagree that the federal investment in research pays real economic dividends. One need only consider the effect on the economy of the biotech and high-tech industries, both of which owe much of their success to advances in basic research, to understand the tremendous benefit to the economy that basic research expenditures can bring.

In his appearance before the Committee, Mr. George Conrades, the President of GTE Internetworking and a trustee of the Committee on Economic Development (CED), affirmed the CED's belief in the importance of the federal investment in basic research: "America's long-standing endowment of basic research has been overwhelmingly successful, providing American society with not only new knowledge but also the practical benefits of economic growth and improvements in the welfare of its citizens…Because federal support is essential for a thriving basic research enterprise, the long-term federal budget outlook is critical. Basic research should be a high priority in federal budgets in the decades to come."[10]

Other countries, such as Japan[11] and South Korea,[12] have recognized the success of American science and the downstream benefits that government funding of basic research bring and have begun to surpass the U.S. in funding expressed as a percentage of the Gross Domestic Product. If we are to retain our technology-based economic edge in the future, we must not allow this investment to dwindle. Funding of basic research today will be a major determinant of future economic strength. We have the resources to make this investment, and we owe it to succeeding generations to use them.

> **Because the scientific enterprise is a critical driver of the Nation's economy, investment in basic scientific research is a long-term economic imperative. To maintain our Nation's economic strength and our international competitiveness, Congress should make stable and substantial federal funding for fundamental scientific research a high priority.**

2. Making choices in the face of limited federal resources

The above recommendation comes with the recognition that, notwithstanding the short-term projections of budget surpluses, the resources of the federal government are limited. In fact, the discretionary portion of the federal budget, which must fund all of the government's programs and operating expenses, including defense, has shrunk to approximately one-third of the overall budget. This is down from nearly two-thirds in 1962, and the decrease is due to the growth of non-discretionary spending for federal entitlements and interest on the national debt. Besides making research funding a higher priority, making room for any future increases in spending for scientific research means controlling entitlement spending and reducing the federal debt.

The resources of the federal government will always be limited in that there are always greater numbers of worthwhile projects than there are dollars in the treasury to fund them. Our challenge, now and in the future, will be to maintain a steady flow of understanding-driven scientific and engineering studies even in the face of limited federal resources. Meeting this challenge means that priorities for spending on science and engineering by the federal government will have to be set. While it is clear that industry does fund a substantial amount of basic research, and that the federal government has funded, and in certain circumstances should continue to fund, research of a more applied nature, industry cannot be expected to fund research that has no guarantee of practical applications. Therefore, major funding for basic research must come from the federal government.

> **Because the federal government has an irreplaceable role in funding basic research, priority for federal research funding[‡] should be placed on fundamental research.**
>
> [‡] The phrase "federal research funding" requires clarification. This term is used throughout the report to refer to the roughly $35 billion spent by the federal government on research and development that does *not* include the Department of Defense's weapons development accounts. The 1995 National Research Council report's *Allocating Federal Funds for Science and Technology*, (the "Press Report") definition of a "Federal Science and Technology budget" should be considered synonymous with the use of the phrase "federal research funding" in this document.

3. The role of the individual investigator in the research enterprise

There is only one proved way of assisting the advancement of pure science—that of picking men of genius, backing them heavily, and leaving them to direct themselves.

James B. Conant (1893-1978)

[1945]

The primary channel by which the government stimulates knowledge-driven basic research is through research grants made to individual scientists and engineers. Typically, these funds go to professors who lead a university-based research team, but in some cases, researchers in non-profit research centers, hospitals or even in industrial settings or federal laboratories receive this type of funding for basic research projects. These investigators are critical to the effort to carry out creative, innovative, fundamental research that expands the boundaries of scientific understanding.

To obtain these grants, the researchers must vie for the limited federal funding available in a competitive process that is based on peer review. In his testimony, Mr. Conrades underlined the important role these scientists play in the scientific enterprise "...we revere the important role of the individual investigator, particularly the academic researcher who we believe to be at the core strength of the U.S. research enterprise as they compete for federal monies."[13] Direct funding of the individual researcher must continue to be a major component of the federal government's research investment, as it is the ideas generated by individual scientists that are in large measure responsible for the creative directions that basic research takes.

> **In order to facilitate basic research, the federal government should continue to administer research grants that include funds for offsetting indirect costs and use a peer-reviewed selection process, to individual investigators in universities, non-profit research centers, hospitals, and some industrial laboratories for support of investigator-driven, non-commercial research. Other federal agencies should consider increasing the use of this method of supporting and encouraging research.**

4. Stimulating innovation in basic research

Creativity, or scientific risk-taking, is critical to opening up new avenues of research and bringing about exciting advances. Yet, as the research enterprise—and the number of scientists within it—has grown, competition for peer-reviewed grants has become fierce. If limited funding and thus intense competition for grants causes researchers to seek funding only for "safe"—that is, incremental—research instead of research that challenges the status quo or pushes the boundaries of conventional wisdom, the research enterprise as a whole will suffer.

Indications that truly innovative research may be being stifled were presented by another witness before the Committee, Dr. Michael Doyle, Vice President of the Research Corporation, a private foundation dedicated to providing grants to scientists for pursuit of research. In describing the Research Corporation's Research Innovation Awards program, which was designed to fund young faculty for pursuit of innovative scientific projects that did not necessarily follow upon their prior work, Dr. Doyle stated that the program funded far fewer applications than it had originally intended to because most were not significantly innovative. "There was an unexpected uniformity in evaluations which suggested that we were dealing with a systemic problem rather than an isolated occurrence. Our interpretation of this is that 'innovation' presents considerable risk to a new faculty member concerned with obtaining the necessary resources to establish a research program."[14]

He went on to state that, "With federal funding sufficient to support only those proposals having the highest rankings, those with lower rankings but higher levels of innovation are left unfunded." A similar view was offered by Dr. Homer Neal, Professor of Physics at the University of Michigan. "Numerous forces exist that will tend to blunt the efforts of those who dare to propose radically new ventures…The emphasis on paradigm conformity for faculty [is one example] of how we can gradually lose some of the creativity that we have long cherished as a mainstay of our technological success."[15]

Many of the e-mail contributors to the study summed up the situation far more bluntly. Said one such commentator, Suzanne Rutherford, a post-doctoral fellow at the University of Chicago: "There are no rewards for risky science. It is too important to publish."

Stifling the creativity so important to the progress of science poses significant dangers to the long-term health of the research enterprise and must be avoided. Particular care should be taken in ensuring that scientists in the early stages of their research careers are able to capitalize on the energy and vitality their new ideas bring to the overall research enterprise. Identification of scientists who show tremendous potential—even when many of their ideas are unorthodox—should also be pursued, and funding for these particularly gifted scientists provided.

> **Because innovation and creativity are essential to basic research and must be encouraged, the federal government should consider allocating a certain fraction of grant monies specifically for the pursuit of particularly creative, groundbreaking research. This will require development of a system for reviewing these grant applications that depends on peer-review but takes into account the speculative nature of the proposed research.**

5. Maintaining diversity in the basic research portfolio

The practice of science is becoming increasingly interdisciplinary, and scientific progress in one discipline is often propelled by advances in other, often apparently unrelated, fields. For example, who would have thought that nuclear physics research (the study of the inner workings and properties of the atomic nucleus) and data gathering techniques developed for experiments on elementary particles (quarks and such) would lead to a device that has advanced the boundaries of biomedical research and health care? Yet both of these lines of inquiry led ultimately to Magnetic Resonance Imaging (MRI), a tool now used in laboratories and hospitals around the world both to conduct basic biological research and also to diagnose illness. Such cross-over between fields is yet another example of the unexpected payoffs that can come from basic research.

In some cases, a scientific advance may languish in obscurity for a significant length of time before it abruptly surfaces in the context of some new, unexpected development. For example, the (largely unsuccessful) search for a viral basis for human cancers led to the discovery of a unique category of viruses with unusual characteristics, called retroviruses, in the 1970s. It was not until many years later that a member of this class of viruses took on great significance as the probable cause of AIDS. Suddenly, the earlier body of work on what had seemed to be an interesting but not particularly practical avenue of study enabled the fight against AIDS to progress far faster than it would have had the earlier work not been pursued. In an example which illustrates an even greater lag time between initial discovery and eventual application, Boolean algebra was developed in 1854, but did not find widespread application until the development of modern computers.

Funding across a wide range of disciplines is important to the strength of the overall research enterprise. However, the current popularity of certain fields, primarily health-related ones, threatens to undercut funding in other disciplines. As Mr. Conrades stated in his testimony, "While federal and public priorities will require that some research areas and disciplines receive more funding than others, it is important for policymakers to recognize the imperative of an overall balance in the portfolio of federal basic research…The current trend to concentrate more and more federal money on health research while neglecting other areas of science and engineering is shortsighted."[16]

> **It is important that the federal government fund basic research in a broad spectrum of scientific disciplines, including the physical, computational, life and social sciences, as well as mathematics and engineering, and resist overemphasis in a particular area or areas relative to others. In addition, while excellence within a particular discipline must continue to be encouraged and supported, changes in the peer review process that make it easier to obtain funding for inter-disciplinary research should be developed.**

B. Science for Society

Concern for man himself and his fate must always form the chief interest of all technical endeavors . . . Never forget this in the midst of your diagrams and equations.

Albert Einstein (1879-1955)

[1931]

Understanding-driven research makes up an important, but limited, segment of the federal government's overall research portfolio. Much of the research funded by the federal government could more accurately be called "targeted basic research." This term describes research that is largely basic in nature but is done with a sense that some downstream use may exist—but is not done in direct pursuit of a specific application. This targeted basic research occurs in the mission-oriented national laboratories and federal agencies, and is also pursued by many of the scientists funded by individual federal grants.

More than one witness pointed out the tenuous distinction between purely understanding-driven basic research and targeted basic research in testimony before the committee. Said Claude Barfield, Director of Science and Technology Policy Studies at the American Enterprise Institute, "While much science is conducted out of curiosity and the desire to explore the unknown, it is also true that a great deal of scientific research since 1945 has been targeted to particular problems and applications—indeed, it is striking that it is precisely in the areas where the federal government has targeted scientific resources that the United States has emerged with technological predominance—high-end electronics, pharmaceuticals, genetics and aeronautics."[17]

Mr. Conrades underscored this point in his written testimony. "A common misperception is that fundamental research is conducted in an ivory tower, with no regard for practical benefits. On the contrary, a consistent virtue of U.S. basic research has been the pursuit of fundamental knowledge with a sharp eye out for downstream applications."[18]

Government agencies such as the National Aeronautics and Space Administration (NASA) and the National Institutes of Health (NIH), and cabinet level departments—Defense and Energy, for instance—employ science in pursuit of their missions. As such, a great deal of the science that is performed in or funded by these agencies or departments is driven at least as much by the overarching goals of the agency or department as it is by the research interests of an individual researcher. Although this research is typically basic in nature, in that no immediate or even short-term objective is sought, it is nevertheless performed with long-term, overriding goals in mind.

The Department of Defense has been highly successful in funding targeted basic research, to the betterment of both the national defense and science as a whole. Its mission, which is arguably more straightforward than many of the other agencies and departments that fund science, is first translated into specific priorities. Funds for basic research that are aimed at addressing these goals—targeted basic research—are allocated in the form of competitively-selected, peer reviewed "6.1"[19] research grants over 50 percent of which go to individual university researchers.[20] The researchers funded by these grants do high-quality, innovative research that often leads to advances important for all of science and, equally importantly, to the development of civilian technologies.

At the same time, the Department of Defense and its in-house researchers are able to draw from the results these scientists produce and, upon further development or refinement, turn them into new advances for protecting national security. The Internet, which was originally a Defense

Advanced Research Projects Agency (DARPA)-sponsored project sparked by the military's need for advanced field communications, is one example of targeted basic research sponsored by the Defense Department that paid off for science as a whole while furthering the Department's objectives at the same time. That the Defense Department's 6.1 research grants have been successful in stimulating high-quality fundamental research is indicated by the fact that these grants provided funding for 66 Nobel prize winners *before* they won their prizes.[21]

1. Research with a mission

Research within federal government agencies and departments ranges from purely basic, knowledge-driven research, to targeted basic research, applied research and, in some cases, even product development. Research in the Department of Defense, for example, spans this entire spectrum. The Defense Department decides upon certain 6.1 projects to pursue further, with selected projects receiving "6.2" research funding. This research, which is generally applied in nature, is done primarily in industry and in-house defense laboratories. It bridges the gap between the basic "6.1" research and "6.3" research, which is in essence product development. This multi-step process provides a clear mechanism for establishing priorities based in part upon the success or failure of earlier steps.

Other departments and agencies do not necessarily require an equally formal structure for prioritizing, and, of course, most of the other agencies and departments do not produce products and so do not need to proceed as far down the research spectrum. However, in all mission-oriented departments and agencies, once overall missions have been clearly identified, research priorities that reflect the relative importance of specific areas of study need to be set. The infrastructure needs necessary for carrying out essential federal R&D programs must then be assessed consistent with the agency's or department's mission and priorities.

In some cases, Congress may decide to pursue an independent review of these objectives. A Congressional review of this type for the National Institutes of Health's research program is currently underway.[22] Concerns have been raised that funding for particular NIH programs may be based more on the strength of a particular advocacy group's voice than on scientific merit. One consequence of this is that the flexibility NIH needs to set research priorities has been reduced, potentially shutting off promising avenues of research in other areas. Although federal funding for health research continues to grow, there is still a limited amount of money available, meaning that some promising research goes unfunded. To ensure that the money we spend is used wisely and to the greatest effect, Congress and the NIH need to change the way health and medical research priorities are set. The Congressional review now in progress, as well as a recently-completed report from the Institute of Medicine,[23] are examples of attempts to address this problem.

> **In general, research and development in federal agencies, departments, and the national laboratories should be highly relevant to, and tightly focused on, agency or department missions, and must focus on essential programs that are well-managed, long-term, high-risk, non-commercial, and have great potential for scientific discovery. Furthermore, once this focus is established the emphasis must be placed on performance of the research function, with a conscious effort to minimize administrative and auditing expenditures.**

2. Maximizing efficiency, accountability and success in the federal research enterprise

Scientists alone can establish the objectives of their research, but society, in extending support to science, must take account of its own needs.

John F. Kennedy (1917-1963)

[1963]

While Congress appropriates money for various federal research programs, it is the taxpayers of this country who actually pay the bills. Science cannot ignore this fact and hope to operate successfully. Vannevar Bush recognized this, and so even while he championed the merits of curiosity-driven research done by independent researchers, he nevertheless recognized that this research ought to be done with overarching goals in mind. He outlined three such goals: defense, the economy, and health.

Witness testimony reflected the current relevance of this point. Mr. Jim McGroddy, a former Vice President for Research at IBM, pointed out that, "Science has also benefited, both in the quality of science itself, and most certainly, in its ability to contribute to Bush's three goal areas, by a number of mechanisms which couple the science to its larger societal goals. When science is effectively managed, via a collaborative effort of the scientists themselves and their supporting and benefiting constituencies (or their surrogates), we get the best of both worlds."[24] Mr. Conrades made a similar point: "Like any far-reaching enterprise that comprises hundreds of institutions and thousands of workers, America's basic research establishment must constantly renew itself in response to changing conditions in global economic, political, and scientific markets. This enterprise must also recognize the legitimate expectations of the society that supports its efforts."[25]

The basic research enterprise in this country is as dependent on the taxpayers who finance this effort as it is on the scientists who carry out the actual research. In order to maintain the public's support for science in an era of limited funds for research, an emphasis on both maximizing the return on the taxpayer's investment and the setting of research priorities is necessary. While it may be paradoxical that the research that is most important for the federal government to fund is the most difficult to explain to the American people, maximizing success, efficiency and accountability within the federal government's research programs are critical to sustaining support for the basic research enterprise.

2a. Maximizing efficiency within the national labs

The national laboratories are a unique national resource within the research enterprise. They offer an environment that is highly conducive to interdisciplinary research as they are unencumbered by the artificial lines of separation that divide universities into departments. In addition, they have access to large, expensive equipment that would be difficult for a university department—and impossible for the individual investigator—to afford. Finally, security procedures that would be difficult to employ in other settings allow them to carry out classified research relevant to national security needs.

The rapidly expanding field of computational science represents one area in which the resources available in our national laboratories may thrust these centers to the forefront of a new scientific paradigm. Scientific hypotheses are usually pursued—and tested—by experimentation, but there are some scientific questions of such large scale that they cannot be adequately broken down into testable components. Some of these questions pose challenges that cannot be ignored. For example, our decision to cease nuclear weapons testing has meant that we must devise new ways of determining whether our aging nuclear stockpile is stable and thus safe—without actually performing the ultimate physical test: detonation. Computational science is a potential solution to this dilemma, and the national laboratories are at the forefront of developing the techniques and tools that will enable the massive computational power necessary. Similarly, determining which nuclear fusion process holds the most promise for future electric power generation, and designing a reactor to contain the process and extract the power requires extremely complex and difficult calculations. Again, computational modeling techniques provide a possible answer.

Nevertheless, concerns that national laboratories are not pursuing their mission either effectively or efficiently have made them the subject of numerous efforts to reform and improve their management and operations, most notably, in the 1995 "Galvin Report" *Alternative Futures for the Department of Energy National Laboratories*.[26] Suggesting that current management systems were stifling creativity and innovation and not providing effective high-level focus on the operations of individual laboratories, the Galvin Report recommended an approach—"corporatization"—that would enable individual research laboratories to operate more effectively. This process, which would involve the creation of a new not-for-profit R&D corporation, would be implemented with the goal of reducing unnecessary overhead and management inefficiencies. While the Department of Energy did establish the Laboratory Operations Board in response to the Galvin Report, unfortunately, no progress has yet been made on implementing more fundamental reforms.

> **A national laboratory not involved in defense missions should be identified for participation in a corporatization demonstration program. A private contractor should be selected to take over day-to-day operations of the lab, and the Department of Energy should be required to slash duplicative overhead requirements at headquarters that might otherwise limit the ability of the laboratory to take full advantage of private sector management techniques.**

2b. Maximizing accountability through the Government Performance and Results Act

Sensitivity to societal needs such as health, defense and jobs is one way in which the scientific enterprise should be accountable to the American people. But the federally funded research enterprise also has the obligation to ensure that the money spent on basic research is invested well and that those who spend the taxpayers' money are accountable to them. The Government Performance and Results Act[27] was developed for the purpose of providing such accountability across all of the federal government.

Application of the Results Act to the mission-directed research taking place inside the national laboratories and federal agencies is akin to the practice in the business world of using "roadmaps" that were developed earlier in order to detail overall goals and estimated timetables to measure success of a research program. When scientific or engineering research is performed in the context of attaining a particular goal or mission it is very important that some measure of research performance accountability be used to gauge whether the research program is effective. As Mr. McGroddy said in his testimony, "Science is not so different from other human activities that it cannot benefit from external inputs, from management. And science is too critical…for it to be shortchanged in…the wisdom with which we manage this critical resource, this large investment."[28]

It is vital that application of the Results Act to federal science projects not result in a *loss* of efficiency by overwhelming scientists with burdensome bureaucratic obligations and distracting them from their research efforts. Equally important is the need to maintain flexibility in the scientific pursuit of mission goals. Science often takes unexpected turns and researchers must be able to follow these unanticipated bends in the road to follow new, potentially more rewarding paths. We cannot simply apply the Results Act to science in the same manner it is applied elsewhere in the government. If in implementing the Results Act we allow government officials to ignore the judgment of scientists, we will have failed in the underlying goal. In order to apply the Results Act to science programs in an effective way, scientists themselves must be involved in establishing the actual framework through which the Results Act can work.

> **Government agencies or laboratories, especially those pursuing mission-oriented research, should employ the Results Act as a tool for setting priorities and getting the most out of their research programs. Scientific research programs not meeting these goals should be eliminated or decreased in order to enable new initiatives in promising areas of scientific research.**

Applying the Results Act to understanding-driven basic research is even more complex, as the payoffs stemming from basic scientific research are often realized far downstream from the time the research is performed, and scientific progress is often most profound when research reveals wholly unexpected results. It is the very nature of fundamental scientific inquiry that not every experiment will succeed though some few will succeed spectacularly. As in an investment portfolio, it is never apparent at the outset which individual investment will pay off. Thus, the determination of whether the nation’s basic research investment is successful requires a balanced research portfolio, a long-term view and a tolerance for less-than-perfect success rates.

> **In implementing the Results Act, government bodies that distribute investigator-driven grants such as NIH, NSF and the Department of Defense, should measure success in the aggregate and not on the basis of individual research projects, perhaps by using a "research portfolio" concept.**

2c. Maximizing success through research partnerships

Effective partnerships among various entities in the research enterprise can be a valuable means of leveraging the federal government’s research investment. This view was summarized by Dr. Lewis Branscomb, former Director of Research at IBM and Professor Emeritus at Harvard University, at a hearing devoted entirely to the subject of partnerships. "If we truly believe in lean government, in leveraging private talent and capital, in knowledge infrastructure to make America the most attractive and productive place in the world for research-based innovation, partnerships will be an increasingly important tool," he said.[29]

Research partnerships can take on many different forms. As Dr. Branscomb said of the various combinations of research partnerships, "They are found among all combinations of the three most important types of research institutions: universities, industrial laboratories, and ‘national’ laboratories. If you imagine a triangle with each type of research institution at the vertices, there are important links among each pair." Dr. Branscomb continued by describing the central role that the government plays in these interactions due to its role in funding research: "Sometimes, you will want to imagine government—both federal and state—agencies in the center of the triangle, using their influence and resources to encourage the various links in the triangle."

While different partnership combinations have different requirements, a few basic principles for the structuring of successful research partnerships were identified over the course of this Study. First, participants should have common goals and complementary skills, and should understand and accept the others’ priorities. Second, the partnership must be based on a shared interest in the research that will be performed and provide each participant with meaningful results. Finally, participants must set explicit outcome goals and procedures before the collaboration begins. Finally, trust and communication between partners is critical to success and must be cultivated.

(1) Cooperative Research and Development Agreements (CRADAs)

Partnerships between federal agencies or national laboratories and industry and/or universities are often formalized in the form of CRADAs. Dr. David Mowery, a Professor at the University of California at Berkeley, stated in his testimony that "Federal agencies and research laboratories have signed hundreds of CRADAs since the late 1980s; between 1989 and 1995, the Department of Energy alone signed more than 1,000 CRADAs."[30]

CRADAs are an effective structure for partnerships. They serve a dual purpose by helping to leverage federal research funding and allowing research conducted by federal agencies to benefit more quickly the U.S. economy through technology commercialization by the private sector. To ensure that private funds are being used appropriately to leverage federal research funds, research sponsored through CRADAs must assist agencies in fulfilling their mission.

During the hearings, issues were raised about the difficulty of negotiating intellectual property rights among CRADA partners and the appropriateness of foreign-owned subsidiaries participating in CRADAs. The latter is an issue of significant importance since, according to Dr. Branscomb, "Foreign direct investment in American research establishments is the most rapidly growing sector of U.S. research."

> **When the research effort involved in a CRADA fulfills a legitimate mission requirement or research need of the federal agency or national lab, these partnerships should be encouraged and facilitated. Within that context, Congress should continue to review and fine-tune the CRADA process to ensure that it benefits both the pursuit of scientific knowledge and U.S. competitiveness and that partnership selection is open, fair and appropriate.**

(2) University/industry partnerships

As universities seek ways to leverage their federal research dollars and companies look for opportunities to capture basic research results without building up expensive in-house research programs, partnerships between university researchers and industrial entities have become more prevalent.

The potential benefits to universities from partnerships with industry were outlined by MIT President Charles Vest in his testimony before the Committee. "Over the longer term, collaborations can have a transforming effect on the ability of institutions to attract high quality faculty, to encourage faculty and their students to interact more closely with industry, and to design curricula and academic programs better attuned to the needs of industry and the challenges we face as a Nation."[31]

Nonetheless, a number of challenges must be addressed if universities and industry are to collaborate effectively. First, universities must not lose sight of their ultimate aim of teaching students and performing basic scientific and engineering inquiry. As Dr. Vest stated, "Universities should work synergistically with industry; they must not *be* industry. Unless universities retain their culture, base of fundamental research, and educational mission, they will not have value to bring to the partnership."

Second, university researchers who benefit from federal funds should not be discouraged from publishing or otherwise disseminating their research results—a practice critical to furthering the pursuit and dissemination of scientific knowledge—due to proprietary claims to these results made by their industry partners. This point was underscored by Dr. Mowery, who noted, "Unbalanced policies, such as restrictions on publication, raise particular dangers for graduate education, which is a central mission of the modern university and an important channel for university-industry interaction and technology transfer."

Finally, private sector entities that partner with universities should not view their university partners as full-fledged substitutes for their own research programs. There is a concern that the amount of basic research done in private sector labs has been steadily declining, and university partnerships should not become excuses to dismantle "in-house" research activities.

Dr. Branscomb summed up these points when he described the importance of evaluating the motives of potential partners in a collaboration between universities and companies. "If the universities value the partnership as a means of exposing faculty and students to leading-edge technical issues that are driving innovations of benefit to society, and are not basing their expectations primarily on revenues from patents, a stable, productive relationship may endure. If the firms see universities as sources of new ideas and as windows on the world of science, informing their own technical strategies, rather than viewing students as a low-cost, productive source of near term problem-solving for the firm, they too will be rewarded."

> **University-industry partnerships can be mutually beneficial and provide benefits to the participants and the research enterprise as a whole that could not be realized within the same time frame were the two entities to work in isolation of each other and should therefore be encouraged. However, the independence of the institutions must be protected and their differing missions respected.**

(3) International collaborations

Although science is believed by many to be a largely individual endeavor, it is in fact often a collaborative effort. In forging collaborations, scientists often work without concern for international boundaries. Most international scientific collaborations take place on the level of individual scientists or laboratories. For example, two or more laboratories may agree to work together by providing complementary approaches to a scientific problem. Or individual scientists themselves may travel to other countries to work in another researcher’s lab as a professor on sabbatical, for example, or for all or part of post-doctoral or graduate training. Or, they may take advantage of breakthroughs in communication technology, by sharing ideas and research—and even using distant experimental equipment by remote control—via the Internet.

International collaborations are not limited to those that take place on the level of the individual scientist or laboratory, however. The U.S. government participates in a number of larger scale collaborations. According to the testimony of Ms. Caroline Wagner, a Senior Analyst at RAND’s Critical Technologies Institute, "Ten agencies dedicate significant portions (more than $1 million each) of their federal R&D budgets to international cooperative activity. These are, in descending order of spending: NASA, the Department of Defense, the Agency for International Development, the National Science Foundation, the Departments of Energy and Health and Human Services, the Smithsonian, the Environmental Protection Agency, the U.S. Department of Agriculture, and the Department of Commerce."[32]

One rationale for entering into international science collaborations is that the costs of large scale science projects, such as colliders for high-energy physics research, can be shared among the participating countries. Homer Neal, a physicist at the University of Michigan, said in his testimony, "With the demise of the SSC (Superconducting Super Collider), and the message we have received that the expense associated with our field is now sufficiently high that most subsequent projects should be international in scope, many American university physicists have joined one of the two approved LHC [Large Hadron Collider] structures."[33]

Dr. Bruce Alberts, President of the National Academy of Sciences, underscored this point. "Some research facilities are so expensive that international collaboration is necessary in order to make them affordable. In order for the U.S. to be able to capitalize on discoveries made elsewhere and facilities located elsewhere, we must have world-class researchers who maintain constant communication and work frequently in collaboration with the best scientists in other countries."[34]

The justifications for participation in international science projects go beyond those of cost-reduction for large programs. As Dr. Alberts pointed out, "The U.S. can benefit scientifically through increased international cooperation because many scientific and technological advances are made in other countries. A growing fraction, already over half, of all scientific articles have foreign authors."

> **In general, partnerships involving U.S. participation in international science and space exploration should be pursued only when they serve to further science and are in the national interest. The U.S. should enter into such co-operative arrangements with foreign governments only when entry reduces the cost of undertaking research projects and missions the U.S. government would likely pursue unilaterally, enables the U.S. to pursue research projects and missions that it would not pursue otherwise, or enhances the capability of the U.S. to use and develop scientific research for the benefit of its citizens.**

Dr. Neal described one example of a successful international collaboration: the European Organization for Nuclear Research (CERN) in Geneva, Switzerland. "[It] is perhaps the most successful international laboratory in the world…The Laboratory has a management structure that ensures that only high quality scientific projects are embarked upon, that all projects are continually reviewed to check that they are on schedule and on budget, that basic services are provided for visiting scientists and students, and that the overall intellectual vitality of the Laboratory remains high."

Not all international collaborations have been so successful, however. In describing problems encountered during joint Russian-U.S. endeavors aboard the Russian Space Station (Mir), Admiral James Watkins, President of the Consortium for Oceanographic Research and Education, said in his testimony, "The precedent [Mir] sets, therefore, is one of our Nation appearing to lack the conviction of leadership in meaningful international collaborations…experiences with Mir to date could have at least been foreseen as one *possibility* and hence could have been agreed to as a legitimate basis on which the U.S. would extract itself from the agreement."[35]

The pitfalls illustrated by the Mir example and the current troubles with the project to build the even larger International Space Station underscore the need to develop criteria that Congress can use to determine whether or not the U.S. should enter into a particular international scientific agreement.

> **A clear set of criteria for U.S. entry into, participation in, and exit from an international scientific project should be developed. Both successful and less successful ventures should be analyzed to develop these criteria.**

Because large-scale international science projects often take place over many years, the annual appropriations cycle in Congress can result in unstable funding for these projects. This affects the ability of the U.S. to act as a dependable partner in these agreements. As Admiral Watkins put it in his opening statement, "We are viewed as an unreliable partner by the G-7 and those other allies eminently qualified to partner on large-scale and societally-meaningful basic research." This lack of reliability affects our ability to take part in scientific projects that, ultimately, have the potential to benefit greatly science and, in turn, our Nation.

> **The importance of stable funding for large-scale, well-defined international science projects should be stressed in the budget resolution and appropriations processes.**

Finally, because it is important that international science projects not appear to be simply foreign aid, proposed scientific facilities for projects where the U.S. is a major funder should not be located outside of the U.S. unless there is a compelling rationale to do so.

> **It must be recognized that, in projects with international participation, funding priority must be placed on the U.S.-based components when the U.S. is a major contributor of funds.**

C. New Roles and Responsibilities for American Science

Science and technology, and the various forms of art, all unite humanity in a single and interconnected system. As science progresses, the worldwide cooperation of scientists and technologists becomes more and more of a special and distinct intellectual community of friendship, in which, in place of antagonism, there is growing up a mutually advantageous sharing of work, a coordination of efforts, a common language for the exchange of information, and a solidarity, which are in many cases independent of the social and political differences of individual states.

Zhores Aleksandrovich Medvedev (1925-)

[1970]

America’s position as the world’s only superpower and its pre-eminence in science and technology suggest important new roles for U.S. science policy in the international context. As Dr. Alberts stated in his testimony, "International science and technology cooperation is also necessary in order to make progress on many common problems in environment, health, food, water, energy and other global challenges…It is greatly in our interest that wise and informed decisions be made by other countries and international organizations in addressing these common problems. We have a great opportunity to develop more rational decision-making in foreign countries through working with the scientific organizations in those countries, so as to help them become more respected and involved in advising their governments."

Democracy itself may be furthered through science. Dr. Alberts made this point as well. "In a world full of conflicting cultural values and competing needs, scientists everywhere share a powerful common culture that respects honesty, generosity and ideas independent of their source, while rewarding merit…Knowledge is power, and diffusing it much more widely across the globe also provides a strong force that favors democracy."

For these changes to take place, however, a scientifically coordinated, coherent and informed State Department must be ready to help formulate scientific agreements and implement a framework for a worldwide approach to science and technology that is in America's interest. However, according to testimony of the witnesses, this scientific expertise and commitment is severely lacking within the Department of State:

Admiral Watkins, for instance, noted, "State Department involvement, understanding, and support today can offer the best hope of funding success tomorrow, but leadership there always seems to be lacking in both timely enthusiasm and technical qualifications…S&T [science and technology] counselors assigned to our embassy staffs worldwide are most often not given a serious role in deliberation on important foreign affairs matters that have significant technical content."

Dr. Alberts concurred with Admiral Watkins’ characterization of science within the Department of State. "Overall, U.S. international relations have suffered from the absence of a long-term, balanced strategy for issues at the intersection of science and technology with foreign affairs." Dr. Alberts noted, however, that the State Department had recently asked the National Academy of Sciences to undertake "a study on the contributions that science, technology and health can make to foreign policy and to make recommendations on how the department might better carry out its responsibilities to that end."

More than one witness suggested that the State Department take advantage of the technical expertise that exists within various agencies. "Each of the federal agencies that has large international programs or cooperative projects has [personnel who] include technical and program people as well as legal experts for [international] agreements," said Dr. Alberts. He continued by saying, "The State Department presently has an understaffed office to coordinate the substance of cooperation, particularly when it involves interests of diverse U.S. agencies with potentially differing interests."

According to Admiral Watkins, this lack of sufficient technological proficiency at the State Department has coincided with "an unannounced reorganization [that] has eliminated the State Department’s senior position for international science, technology and health, and redistributed those functions within a slimmed-down Department bureau that’s increasingly focused on global environmental issues. Yet, it is within this office…that much of the coordination of major S&T initiatives with other Nations should be routinely monitored and overseen in close coordination with the appropriate government agencies," according to Admiral Watkins.

Another witness, Dr. J. Thomas Ratchford, Director of the Center for Science, Trade and Technology Policy at George Mason University concurred in this observation, saying, "…in spite of successive attempts to upgrade science and technology as an important element of the policy-making apparatus of the State Department, science has receded slowly over the years as a factor in the foreign policy equation. More recently, resources devoted to science have been diverted for other purposes, especially the environment."[36]

It is interesting to note a parallel between the lack of appreciation currently afforded science within the State Department and that within the U.S. armed forces prior to WWII. Early in the Second World War, Vannevar Bush experienced tremendous frustration in trying to get the military to embrace scientific research as a major focus of its war effort. He eventually succeeded, of course, and by the end of the war the various service branches were competing with each other to establish research-granting programs. Today, the U.S. risks missing important opportunities because of the failure of the State Department to fully appreciate the role of science in its overall mission.

> **Mechanisms that facilitate coordination between various executive branch Departments for international scientific projects must be developed. The State Department should strengthen its contingent of scientific advisors—particularly within its Bureau of Oceans and International Environmental and Scientific Affairs, the focal point for foreign policy formulation and implementation in global environment, science, and technology issues—perhaps drawing on expertise in other departments or agencies to act as liaisons in the pursuit of international scientific projects.**

III. The Private Sector’s Role in the Scientific Enterprise

A strong, dynamic and sustainable basic research enterprise is but a foundation for progress. For the goals of our society (a vigorous economy, strong national defense and a healthy populace and environment) to be realized, a private sector capable of translating scientific discoveries into products, advances and other developments must be an active participant in the overall science and technology enterprise.

The U.S. has always been blessed with a vigorous industrial sector. Even before the end of WWII, when the federal government began funding basic research in the sciences and engineering on a grand scale, American corporations were successful in capturing both the fruits of the available intellectual capital in the world's universities, as well as the trademark ingenuity of the independent American inventor, and turning them into marketable products.

In doing so, these companies often engaged in substantial research efforts to develop fledgling technologies. For example, the Bell Laboratories of the middle of this century garnered a reputation as a corporate research facility that pursued truly ground-breaking research spanning the spectrum from basic to applied. In fact, the development of the transistor at Bell Labs, an invention that revolutionized the electronics industry and led to the development of radioastronomy, eventually led to the award of several Nobel Prizes.

Investment in basic research is always a bit of a gamble; not every research project will pay off. The rewards involved in taking a discovery and developing it can be enormous. But if the product is never realized, if its limitations cannot be overcome, or if it simply does not sell, the costs can be equally great.

For a technology-based company, the question is not really "Should the company do research?" but rather, "How much?" and "What kind of research should we focus on?" The needs of different companies vary greatly. Large, established companies often have greater resources available, but they may also have shareholders accustomed to regular dividends and unwilling to forgo them for the uncertain benefits of research that is more basic in nature, and therefore more risky. Such a company may decide to stick to exploration that is largely aimed at refining its existing products or increasing production.

For the small newcomer, pursuit of research that is far more risky may be the only way to break into a competitive market. Such young start-up companies must rely entirely on the initial capital provided by their investors to finance this research. Indeed, capitalization is the primary problem faced by many young companies. Some firms fold when the financial backing runs out with no product in sight. Others hit it big.

A company's size, however, is not necessarily an indicator of what type of research it will do. Certain big, highly successful companies maintain research divisions whose purpose is to push the boundaries of their research—and in doing so to risk more—to ensure the company stays ahead of, and innovates faster than, its competitors.

A. Stimulating Research in Industry

Today's technology-driven company must bridge the research gap between basic science and product development if it wants to remain on the cutting edge of the industry. This research, referred to as "mid-level" research by MIT President Charles Vest, is typically necessary to develop basic research results into an emerging technology and then into a marketable product.

Mid-level research has customarily been performed, and should continue to be done, in the private sector. The fruits of this research are proprietary; the company is the primary or even sole beneficiary of any new technologies. At the same time, the company must also bear the risk that the research project will not yield any profitable results. The heated competition generated by a global marketplace and shareholder emphasis on immediate returns have affected the ability of companies to engage in mid-level research, particularly that which leans more toward basic than applied.

Concern has been raised that companies are focusing their research efforts on technologies that are closest to being marketable—and hence are likely to be profitable sooner—instead of on projects which will require a more substantial research investment. This approach is of questionable long term sustainability. The deployment of industry scientists on research problems that address largely—or entirely—projects for which there are expected near-term payoffs suggests that these scientists will work on a series of short-term research projects and not be encouraged to take part in longer-term, more exploratory research. This would represent a clear loss for the overall research enterprise.

At the same time, the limited resources of the federal government, and thus the need for the government to focus on its irreplaceable role in funding basic research, has led to a widening gap between federally-funded basic research and industry-funded applied research and development. This gap, which has always existed but is becoming wider and deeper, has been referred to as the "Valley of Death." A number of mechanisms are needed to help to span this Valley and should be considered.

1. Capitalization of small companies

First, small "start-up" technology companies must be encouraged. These young companies often focus initially on a single, largely basic discovery as their ticket into a competitive market, frequently drawing directly from discoveries made in universities or national laboratories. While individually small, in the aggregate these companies provide one of the best hopes for bridging the research gap between the basic research funded by the government and the product development pursued by industry.

A large reservoir of funds is available for investing in promising young technology ventures.[37] Private sector capitalization of these small, dynamic companies is a major factor in determining their survival, as often they must operate in the absence of any revenues for extended periods and so are dependent on their original capital to pursue the research they hope will eventually lead to profitability. Because initial capital is so important to the entry of new technology companies, tax policies that encourage capital formation are extremely important. Additionally, it must be remembered that unnecessarily burdensome regulatory policies are another inhibition to private sector research and should be alleviated wherever possible.

> **Private sector capitalization of new technology-based companies should be encouraged through friendly tax and regulatory policies. Needlessly onerous regulations that inhibit corporate research should be identified and either mitigated or eliminated.**

2. The Research and Experimentation Tax Credit

The Research and Experimentation tax credit[38] is an effective means by which the federal government stimulates private-sector research. However, the tax credit is not permanent and must be renewed on a yearly basis by Congress in order to take effect. This has reduced its effectiveness, because companies are not able to plan on the existence of the tax credit from year to year, even though potential research projects—especially those that involve more basic than applied research—may last many times longer than the fiscal year. Making the tax credit permanent would almost certainly make long term research projects more attractive to businesses.

> **Extend the R&D tax credit on a permanent basis to provide a stable planning foundation for private firms and, in general, seek to implement tax policies that encourage capital formation.**

3. Partnerships for technology development

I have come across several types of associations in America of which, I confess, I had not previously the slightest conception, and I have often admired the extreme skill they show in proposing a common object for the exertions of very many in inducing them voluntarily to pursue it.

Alexis De Tocqueville (1805-1859)

Democracy in America [1835-1840]

Partnerships meant to bring about technology development share many elements with partnerships aimed at deriving research results, and in many cases these goals may overlap. For example, in the university-industry partner relationship, universities may gain access to technology necessary for further advances in fundamental understanding, while industry may be able to improve a technology in preparation for eventual sale of products. This type of symbiotic relationship is at the heart of successful partnerships, and partnerships such as these hold great promise both in disseminating the results of basic research efficiently and in stimulating research that spans the Valley of Death.

3a. Informal partnerships

Many of the most successful partnerships are those that remain uncodified and are based on the free movement of people between the public and private sector. As Dr. Branscomb said in his testimony, "The most powerful tool for effective diffusion of knowledge we know (is) the movement of young scientists, engineers, and doctors from their university setting to the commercial world, taking their tacit and codified knowledge with them…The university diffusion mechanisms are numerous and efficient: students graduating and going to industry, professors serving as consultants one day a week…"

> **These interactions and collaborations, which may or may not involve formal partnerships, are a critical element in the technology transfer process and should be encouraged.**

3b. State-based partnerships

State-based partnerships that tie together the efforts of state governments, industries, colleges, universities, and community colleges show great promise in bringing about significant stimulation of economic development and research within industry. State-based organizations have considerable advantages over the federal government in assisting in the commercial development of new technologies including their proximity to the firms that will actually employ new technologies, their close relationships with local university systems, and their ability to focus their efforts.

To learn more about how a state-based organization can assist interactions between academia and industry, the Committee heard from Mr. William Todd. As President of the Georgia Research Alliance, a private sector organization dedicated to improving the industrial competitiveness of the state of Georgia through partnerships between business, academia and the State government, Mr. Todd emphasized the important role that the state can play in enhancing technology development. "In my judgment," he said "the federal government could not have accomplished what the Georgia Research Alliance has in the last eight years. The primary reason is the inherent advantage of a private, non-profit organization in being flexible and entrepreneurial…The federal government can play a unique and critical role in joining the partnership of states, universities, and business by investing in basic research rather than 'national competitiveness' programs…State government in Georgia has an excellent track record in economic development programs in collaboration with private sector partners, and our business leadership has created realistic expectations about technology-based development coming from university laboratories."[39]

The critical role that the federal government plays in encouraging economic development in States through funding of basic research was recently affirmed by 51 Governors of States and U.S. territories in a letter sent to Members of Congress. "As governors we realize the benefits [of basic research] extend far beyond quality of life issues. The product of this research is, and will continue to be, a driving force behind a strong American economy. It creates jobs, increases productivity in the workforce, and provides the training ground for our country's next generation of highly skilled workers," they wrote.

In bringing the benefits of research to the American people, it is important that the different core competencies of States and the federal government are recognized and that each is encouraged to focus on what it does best. The federal government has an irreplaceable role in funding basic research. States, on the other hand, are far better suited to stimulating economic development through technology-based industry within their borders.

> **As the principal beneficiaries of technology-based industry within their borders, the States should be encouraged to play a greater role in facilitating the development of these industries, both through their support of colleges and research universities and by facilitating interactions between these institutions and the private sector.**

3c. Distribution of funding

There exists a strong correlation between the presence of major research universities and a flourishing technology enterprise within a given geographical area. California's Silicon Valley, Massachusetts' Route 128 corridor and North Carolina's Research Triangle are three of the most well-known examples of regions with a high density of thriving technology companies, all of which are located near and arose from major universities.

However, the absence of strong research universities in a number of states with currently under-developed R&D enterprises increases the obstacles to enjoying a thriving technology-based industrial sector. Historically, the federal government's investment in basic research has been concentrated in a small number of states with major research universities. In fact, as recently as 1995, nearly two thirds of federal research and development funding went to just 10 states.[40] All regions of the country ought to be able to share in the benefits of economic prosperity that flow from the fundamental research performed in universities.

To accomplish this goal, it is important that colleges and universities in those regions of the country that have traditionally received little federal research funding be able to compete effectively for peer-reviewed federal research grants. Two recent trends suggest that these less well-established research institutions will be increasingly well positioned to both compete for grants against, and collaborate with, researchers at more established research universities. First, modern communications technologies are making it easier for individual researchers to engage in collaborations, even across geographical boundaries. Furthermore, the oversupply, in some fields, of highly trained and motivated Ph.D.s seeking jobs in academia has resulted in the placement of extremely high-caliber faculty at less well-established research universities.

> **Major research universities should cultivate working relationships with less well-established research universities and technical colleges in research areas where there is mutual interest and expertise and consider submitting, where appropriate, joint grant proposals. Less research-intensive colleges and universities should consider developing scientific or technological expertise in niche areas that complement local expertise and contribute to local economic development strategies.**

4. Efficient dissemination of results from federally funded research to the private sector

Diffused knowledge immortalizes itself.

Sir James Mackintosh (1765-1832)

[1791]

Companies rarely have the resources to engage in purely exploratory research. Instead, they rely largely on government-funded research to open up new opportunities. However, to capitalize on and exploit the advances made in government laboratories and universities, private sector organizations must remain informed of developments in the realm of federally funded research.

The widespread availability and use of the Internet provides a means to address this issue. Internet-accessible, searchable databases that contain information about federally-funded research could allow those in the private sector to keep abreast of federally funded scientific developments in a relatively time and cost-effective manner. The RAND Corp's RaDiUS database[41] lists all research projects and programs underway in the federal government and thus provides a useful starting point for on-line dissemination of this information.

Most federally-funded university researchers—as well as many in the national laboratories and some in other government agencies or departments—already seek to publish their work in peer-reviewed, publicly available scientific journals. On-line databases that compile citations and abstracts from these journals—which provide a summary of the research results and conclusions—will allow interested parties to search published research papers by topic, author and other parameters to learn about new developments. The National Library of Medicine's PubMed database,[42] which was developed by the National Center for Biotechnology Information (NCBI) at the National Institutes of Health, serves this purpose for the biomedical sciences.

> **Consider expanding databases such as PubMed and RaDiUS to make them both comprehensive and as widely available as possible.**

5. Intellectual property protections

The patent system…thereby added the fuel of interest to the fire of genius, in the discovery and production of new and useful things.

Abraham Lincoln (1809-1865)

[1859]

Intellectual property protections are critical to stimulating the private sector to develop scientific and engineering discoveries for the market, as individuals or organizations must derive ownership of a scientific discovery—and thus be eligible for any future financial reward—in order to offset the risks involved in developing the discovery.

The Bayh-Dole Act of 1980,[43] which granted the licensing rights of new technologies to the researchers who discover them, has been the foundation of the government's role in intellectual property issues in science and technology. Universities have seen revenues rise due to technology licensing agreements made possible by Bayh-Dole, and this legislation has been critical in bringing about commercialization of technologies that would otherwise have remained undeveloped. Clearly, intellectual property protections and dissemination of scientific information are tightly linked, and the effect of one on the other must be carefully considered.

> **A review of intellectual property issues, both domestic and international, is necessary to ensure that an acceptable balance is struck between stimulating the development of scientific and engineering research into marketable technologies and maintaining the effective dissemination so important to the practice of science and economic development.**

B. Implications for Industry

When the well's run dry, we know the worth of water.

Benjamin Franklin (1706-1790)

[1746]

While the federal government may, in certain circumstances, fund research of a more applied nature, it is important that companies recognize the importance of the long-term investment that mid-level research—not simply product development—represents. When corporations post record profits in a robust overall economy, the resources necessary to make such investments are clearly available. Because periods of particularly strong economic growth do not last forever, it is imperative to seize the opportunity to invest in research that these periods of prosperity bring.

One strategy is to provide federal government assistance for commercialization of particular technologies. This idea is based on the belief that the government can correct the effects of market failures. This approach has been tried, usually unsuccessfully, in other countries. Ultimately, the market is the best selector of new technologies.

Beyond the risks of interfering in the market, there would also be potentially serious consequences for the scientific enterprise as a whole were the federal government to try to bridge the Valley of Death through direct federal funding. Not only would precious resources be taken away from basic research, creating a void no other entity could fill, but, given the magnitude of the Valley of Death, the federal government alone would not be able to provide enough funding to bridge this gap in any significant way.

> **The private sector must recognize and take responsibility for the performance of research. The federal government may consider supplementary funding for private-sector research projects when the research is in the national interest. Congress should develop clear criteria, including peer review, to be used in determining which projects warrant federal funding.**

IV. Ensuring that Technical Decisions Made by Government Bodies are Founded in Sound Science

Science and engineering provide more than the ideas for future products or the foundation for advances in manufacturing. They also provide the basis for making decisions as a society, as corporations and as individuals. While these decisions certainly affect important national, and even global issues, they also affect elements of our lives as basic as how we live and what we eat. For example, we turn to scientists and engineers for answers to questions such as "To what standards should cities' building codes be written?" Engineers, seismologists, geologists and materials scientists may all need to be consulted. Or, "Is the food on the dinner table safe to eat?" "Is a new drug ready for use by humans?" Epidemiologists, microbiologists and pharmacologists, among many others, must inform us.

Though many of these decisions affect our everyday lives, we tend to consider them only when there is a crisis: when buildings collapse in an earthquake, when *E. coli* in hamburgers kills children, when drugs cause dangerous side effects. While every individual must exercise his or her own judgment in making decisions—and be willing to accept responsibility for doing so—we nevertheless must of necessity rely on decisions made by our elected officials, regulators, and the courts for decisions that affect our society. When the decisions to be made involve technical issues, decision-makers must have access to and, to a large extent rely on, the advice and counsel of the scientific and engineering community.

Science can inform issues, but it cannot decide them. For example, scientists have told us that the New Madrid faultline in the Eastern U.S. will give rise, on average, to a magnitude 6.0 or greater earthquake every seventy to ninety years. But they cannot tell us whether states in this region of infrequent earthquakes should employ the same building codes as California does. Similarly, some research indicates that the use of fertilizers may have long-term effects on nearby bodies of water due to runoff. But science cannot tell us how we should balance the interests of the farmers who use the land and the fishers who depend on the water, or the interests of the customers who buy and consume the products of both.

To further complicate matters, in many cases science simply does not have all of the answers. This is likely to be true particularly when the issue involves very complex systems, as is often the case with environmental questions—a forest, lake or other ecosystem cannot be put in a test tube for experimentation. Conclusions drawn by scientists in these instances carry varying degrees of uncertainty, and different scientists may derive very different inferences from the available data.

It is at this point that legal and policy decisions become most difficult. Those on both sides of the issue level charges that the other side is doing "bad" science. Each side produces its own contingent of scientists who in turn put forth conflicting interpretations of the available data, if they even agree on that. Accusations are made that the other side's scientists "have an agenda" or are beholden to a particular stakeholder in the issue.

In fact, disagreements among scientists are nothing new; they are actually an integral part of the scientific process, and the means by which old hypotheses or theories are discarded and new ones accepted. The difference is that these disputes among scientists typically take place in the pages of scientific journals or in the presentation halls at scientific meetings, and not on the floors of Congress, in the Courts, or on the editorial pages of newspapers.

The emergence of environmental threats over the last half century has elevated environmental issues to a position of importance ranking alongside the need to protect our national security, improve peoples' health, and strengthen our economy. Mr. McGroddy acknowledged this in his testimony when he stated, "I know of no serious student of history who would today substantively revise (Vannevar) Bush's rationale or conclusions in any major way, other than perhaps to add a fourth area of impact, the improvement of our management of our environment." Properly managing our natural resources, ensuring clean air and clean water for every citizen, and preserving the planet for future generations are concerns shared by every American. The decisions that must be made in order to tackle these issues, however, are at times highly contentious. It is imperative that we focus scientific resources on questions relating to the environment if we are to make informed future decisions in this arena.

A. Bringing Legitimacy to Technical Policy Decisions

Science . . . warns me to be careful how I adopt a view which jumps with my preconceptions, and to require stronger evidence for such a belief than for one to which I was previously hostile. My business is to teach my aspirations to conform themselves to fact, not to try and make facts harmonize with my aspirations.

Thomas Henry Huxley (1825-1895)

[1860]

Uncertainty and debate may be implicit in the scientific process, but a lack of a clear scientific consensus on an important policy issue makes matters more difficult for decision-makers. However, there are steps that can be taken to better inform the scientific and technical decisions made by regulators, legislators and the courts.

1. Ensuring access to sound scientific data

Because there is no more contentious technology-based decision than one that is based on incomplete scientific data, we must commit sufficient resources at the federal and state levels to finding answers to scientific questions that promise to lie at the heart of *future* policy decisions. By committing resources early in the process, we decrease the likelihood that unsound decisions—decisions that end up costing far more down the road—are made. Whenever possible, research must precede policy, not the other way around.

As Dr. Roger McClellan, President and CEO of the Chemical Industry Institute of Toxicology, said in his testimony before the Committee, "Good decisions to protect and promote human health require sound scientific information. The development of sound scientific information requires time and resources to conduct research that is targeted to resolve issues. As simple as these statements are, all too often in the past they have not been heeded. The result has been that many past regulatory decisions have been undergirded by very uncertain science leading to decisions that are highly contentious."[44]

Research on a particular subject should not come to a stop once a policy decision has been made, an issue Dr. McClellan addressed in his testimony. "A mentality develops that we've set the standard, there isn't any need for any [more] research. Research [funding] goes down and then, about two years before the next review of the criteria document, there's a sudden realization [that] we've got to get more science…You have to have the time to create the science that's needed for credible decisions and (supply) the resources," he stated.

Applying forethought to funding decisions regarding research agendas that address areas of regulatory policy will likely come with some controversy, as decisions regarding the allocation of limited resources always are. However, making these difficult decisions before the regulatory process has gained unalterable momentum offers the opportunity to address complex questions, such as environmental issues, in a less highly charged atmosphere than that which exists when implementation of regulations precedes scientific consensus as to the nature—or existence of—a problem. Regardless of a policymaker's or regulator's views on an issue, it should go without saying that each ought to agree that more conclusive evidence on a controversial subject should be sought.

> **To address the relationship between regulations and sound science, at the earliest possible stages of the regulatory process, Congress, the Executive branch, and the technical advisors for each must work together to identify future issues that will require scientific analysis. Sufficient funding for these research agendas must then be provided and should not be overly concentrated in regulatory agencies.**

B. Protecting the Integrity of Science Performed in Support of Decision-making

For science to play a meaningful role in legal and policy decisions, the scientists performing the research needed to answer questions posed by policy or law must be seen as honest brokers with the proper expertise to render advice. One simple but important step in facilitating an atmosphere of trust between the scientific and the legal and regulatory communities is for scientists and engineers to engage in open disclosure regarding their professional background, affiliations and their means of support.

1. Open disclosure

Disclosure should not be used as a way to exclude particular scientists simply on the basis of their affiliations, as has happened in past debates. Rather, it should allow for broader participation and shift the focus of the debate to the science itself. In addressing this subject, Dr. McClellan expressed concern that, "we sometimes move and exclude individuals who are employed in the private sector from participation in certain deliberations as panel members because of their employment…We need to go beyond that [and] look at the credentials of the individual…their training, their experience…their publications in the peer reviewed arena, how have they interacted with their fellow scientists."

> **Scientists and engineers should be required to divulge their credentials, provide a resume and indicate their funding sources and other affiliations when offering expert advice to decision-makers.**

2. The importance of peer review

It is not permitted to the most equitable of men to be a judge in his own cause.

Blaise Pascal (1623-1662)

1670

That the scientific opinions these experts offer is seen as sound, credible and objective by those who rely on it depends on far more than the establishment of the scientist's credentials. It depends on the ability of the science itself to stand up to challenges from other experts. In the scientific community, a scientist's work is judged to be sound when it passes judgment upon critical review and testing by other scientists who work in the same field or are otherwise familiar with the subject matter being investigated.

The first step in this process, peer review to determine whether a scientist's results should be published, imposes a strict standard for initial acceptance by the scientific community. Upon submission of an article describing a new scientific result and any conclusions regarding it, the paper is given to a small group of other scientists who are familiar with the subject matter and have been selected by the journal's editor for anonymous review. Only if the article, its data and conclusions pass muster with this group is the article accepted for publication in any respected (peer-reviewed) scientific journal. Papers that have not been subjected to the peer review process are likely to be viewed with some degree of skepticism by other scientists. Note that peer review applies to more than just publication. Hiring and tenure decisions often rely on peer review, and the grant application process is wholly dependent on it.

Because the peer review process is critical in bringing about acceptance of new scientific results and encouraging discussion among scientists, expanding the peer review process to include the science and science-based decisions made in federal agencies will help improve the credibility of the science conducted or supported by these agencies. Regulations should not be made on the basis of science that does not stand up to the rigors of the peer review process.

> **In all federal government agencies that pursue scientific research, but particularly in those that formulate regulations, standardized peer review procedures should be developed and used.**

C. Accepting Scientific Uncertainty

All we know is still infinitely less than all that still remains unknown.

William Harvey (1578-1657)

[1628]

Peer review for publication is only the first step in the acceptance of a scientific theory or conclusion. Publication of the new results, and the scientists' conclusions or theories based on those results, constitute the beginning, not the end, of the scientific process and the search for understanding. Publication allows other scientists to compare their own results with those of the published researchers, and to attempt to replicate the results of others—both extremely important steps in validating new discoveries or theories.

The initial peer review process does not result in a stamp of scientific certainty, as there is often still disagreement over published conclusions or even over the data the conclusions were based on. These disagreements do not necessarily indicate that bad or sloppy science was done. Instead, the scientific debates that these disputes stimulate often lead to further clarification or advances in the field and therefore are an integral part of the process of science. As Dr. Lindley Darden of the University of Maryland wrote in an article entitled *The Nature of Scientific Inquiry*, "Publishing a plausible hypothesis plays the important role of placing it in the marketplace of scientific ideas…Individual scientists consider [alternative explanations] prior to publishing and choose the one that is best supported by the evidence they have at the time. Publication then allows the wider scientific community to continue the same process."[45]

As Dr. Darden points out, even the best scientists can be wrong on a particular point. For example, Enrico Fermi, Linus Pauling and Francis Crick—three of the most important scientists of this century (all of whom won Nobel prizes)—have all, at one time or another, published theories that later turned out not to be correct. In doing so, however, these scientists did anything *but* a disservice to their disciplines. Rather, their erroneous conclusions served to drive the science in those fields to a completely new level as other scientists tested—and subsequently rejected—their theories. Uncertainty is a fundamental aspect of the scientific process, and this is particularly true in rapidly developing fields of study.

Dr. Dennis Barnes, President of the Southeastern Universities Research Association, summed up the importance of the constant evolution of thought in the process of scientific discovery when he paraphrased the Austrian zoologist Konrad Lorenz in his testimony: "It is a good morning exercise for a research scientist to discard a pet hypothesis every day before breakfast. It keeps him young." Dr. Barnes then commented, "[Lorenz] explained perfectly the nature of scientific inquiry: constant examination and re-evaluation, a never-ending process of correcting errors and pushing back the frontiers of knowledge."[46]

Independent replication of scientific results and the attention scientific debate stimulated by uncertainty brings to a particular issue mean that scientific results do not remain forever in limbo. Eventually, scientists generate enough new data that they are able to shed light on previously uncertain findings. Still, this constant progress and initial uncertainty in the scientific process has repercussions for the policy process, which should not remain static in the face of changing scientific understanding.

> **Decision-makers must recognize that uncertainty is a fundamental aspect of the scientific process. Regulatory decisions made in the context of rapidly changing areas of inquiry should be re-evaluated at appropriate times.**

A particularly ominous threat to scientific freedom that would undermine the entire scientific enterprise are lawsuits brought against researchers and universities claiming damages because a researcher did not pursue a particular line of inquiry or published results that were later found to be in error. Researchers must be free to exercise their scientific judgment about which research paths to pursue without worrying that, if at some later date their hypotheses or conclusions turn out to be incorrect, they may be sued. This would have a chilling effect on scientific research, as Dr. Barnes made clear in his testimony. He said, "I think that there is no doubt about the inhibiting influence [of lawsuits] on the free performance of research…Researchers will be more cautious about making bold hypotheses, universities will need to scrutinize more carefully the research conducted by their faculty, and the cost of defending against such suits, whether or not they are actually pursued, will be another overhead burden on research."

D. Risk Assessment

To resolve effectively the problems regulatory agencies seek to address, regulatory decisions must not only be based upon a sound technical foundation, they must also make sense from a practical standpoint. The importance of risk assessment—the process of identifying and quantifying potential risks and of making decisions about how to deal with these risks through comparing various options and potential outcomes—has too often been overlooked in making policy. We must accept as a society that we cannot reduce every risk in our lives to zero, and should instead determine where to deploy our limited resources to greatest societal effect.

As Dr. John Graham, Founding Director of the Harvard Center for Risk Analysis said in his testimony, "The science of risk analysis can help regulatory organizations make better decisions…the failure to perform sound risk analysis can lead to poor decisions that can harm public health and safety."[47]

Dr. Graham went on to described an exercise one of his graduate students had undertaken to demonstrate the application of risk assessment to regulatory policy across the U.S. government. "[She] estimated that…she could save 60,000 more lives per year than we're currently saving at no increased cost to either taxpayers or the private sector, simply by reallocation. There are enormous opportunities for reallocation of resources to save more lives." Clearly, ignoring the broader picture in making specific policy decisions is not in the public's overall best interests.

> **Risk analysis must be used in the regulatory decision making process. Comprehensive risk analysis within and among regulatory agencies should be standard practice. Efforts to communicate information about various risks to the public in understandable terms, perhaps by using comparisons that explain risks in the context of other, more recognizable ones, should be undertaken.**

E. Science in the Judiciary

All three branches of our democratic system are faced with decisions that depend on science; the judicial system is no exception. Supreme Court Justice Stephen Breyer recently stated in a speech at the American Association for the Advancement of Science's (AAAS) 1998 meeting that the law "increasingly requires access to sound science…because society is becoming more dependent for its well-being on scientifically complex technology."[48] Indeed, whether it is new advances in forensic technology, such as DNA 'fingerprinting' in criminal proceedings, or questions of cause and effect in civil cases, such as those involving breast implants, science and technology play an important role in the courtroom.

The scientific discourse in a trial is usually highly contentious. As Dr. Mark Frankel, Director of the Scientific Freedom, Responsibility, and

Law Program at the American Association for the Advancement of Science, said in his written testimony, "The primary way that we educate judges and juries on complex scientific matters is through the use of expert witnesses, almost always retained by the parties to the litigation, airing their differences in an adversarial setting. Serious reservations have been expressed about this approach, however, some by judges themselves…what often occurs is that experts from both parties are pitted against one another, with lawyers on each side trying to destroy the credibility of the other party's witness. Such tactics are not likely to enlighten either judges or juries about the validity of a scientific methodology or of the conclusions drawn from disparate data."[49]

In a landmark 1993 decision that could change this focus from undermining the credibility of the other side's scientific expert to the merits of the science itself, the Supreme Court ruled in a civil case, *Daubert v. Merrill Dow Pharmaceuticals, Inc.,*[50] that "federal judges must act as gatekeepers in order to exclude unreliable evidence from the courtroom" according to Dr. Frankel's testimony.

With the possibility that, in accordance with the *Daubert* decision, increasing numbers of judges will avail themselves of independent, qualified scientists to assist them in addressing complex scientific and technical questions, the identification of these experts promises to be an increasingly important step in the judicial process. In his testimony, Dr. Frankel described a demonstration project the AAAS hopes to implement that would aid judges in this process: "On receiving a request from the court, the project will seek to clarify the specific technical issue on which the expert is expected to advise and what role the expert will play in the litigation. With the assistance of a Scientific Selection Panel and at the end of a rigorous search, the project will provide the court with a slate of at least three possible experts. In some cases, the court may decide to appoint a panel of experts, in other instances, a single expert will suffice." Dr. Frankel also stated that Justice Breyer had specifically endorsed the AAAS demonstration project.

> **Efforts designed to identify highly qualified and impartial scientific experts to provide advice to the courts for scientific and technical decisions must be encouraged.**

F. Addressing the Fractured Nature of Science Policy Decision-making at the Federal Level

Decisions about science policy are made in a large number of Congressional committees and subcommittees, which can impede the progress and coordination of important projects. In his testimony, Admiral Watkins gave voice to his frustration in dealing with 9 federal agencies and 47 Congressional committees and subcommittees in his work on oceanographic projects.

Having to answer to so many different committees and agencies is an understandable outgrowth of the extent to which science and engineering touches almost all aspects of our lives, but it clearly makes it much more difficult to effectively manage complex technical programs. While it might at some point in the future make sense to consider lessening the number of committees and agencies with significant influence over large, complex technical programs, at a minimum Congress and the Executive Branch should improve their internal coordination processes to more effectively manage, execute, and integrate oversight over these kinds of programs. While the Office of Management and Budget can fill this role in the Executive Branch, no such mechanism exists in the Congress.

> **In those cases where two or more Congressional committees have joint jurisdiction over or significant interest in large, complex technical programs, the affected committees should take steps to better coordinate their efforts. Wherever possible, the affected committees should consider holding joint hearings and perhaps even writing joint authorization bills.**

V. Sustaining the Research Enterprise—the Importance of Education

Knowledge is power.—Nam et ipsa scientia potestas est.

Francis Bacon (1561-1626)

[1597]

No element of the R&D enterprise is as important as the people who comprise it. Advances that save and improve lives or help secure against potential aggressors do not simply spring forth from the vast landscape of new scientific discoveries. They must be identified from among this crowded field and then molded, refined, and promoted by an extraordinarily diverse complement of talented, dedicated people. These people are our most important national scientific asset, and we must continuously and diligently nurture succeeding generations of people equally talented and dedicated.

We do this largely through education. We depend on our schools, colleges, and universities not only to turn out scientists and engineers, but also to turn out the people who play the myriad other roles in the scientific enterprise that are equally important, if less visible.

For example, for every scientist who makes a potentially useful discovery in the lab, there must be those in the private sector who recognize the significance of the finding and act on it, providing or attracting capital, making research and production facilities available, providing marketing, management, and legal assistance, and so on. People with skills in these areas who also have some scientific or engineering training are relatively rare and thus highly valued. The industry scientists and engineers who must then transform a novel discovery into an eventual product must be aided by technicians and other highly-skilled employees. Once the new product is ready for the market, other workers must produce these new goods, often in factories or other workplaces that are themselves driven by technology.

The ramifications for society and for the environment of new technologies must also be considered. Again, these decisions do not happen spontaneously, but are made by people. Regulators help determine whether new products, such as medications, or new technologies, such as airbags, are safe. Lawmakers must balance the sometimes competing interests of various entities within the R&D enterprise, as well as those of their constituents. And finally, every citizen in our free-market democracy must be able to make educated and responsible decisions as a consumer and voter.

Each member of society plays a part in the scientific enterprise. Whether a chemist or a first-grade teacher, an aerospace engineer or machine shop worker, a patent lawyer or medical patient, we all should possess some degree of knowledge about, or familiarity with, science and technology if we are to exercise our individual roles effectively. Our educational system—from preschools to research universities—is currently not up to this challenge. We have much work to do.

In a technology-driven economy, jobs that require a scientific or technology background will gain increasing importance for our economy. We must ensure that we instill in younger generations the motivation and desire to obtain those jobs as well as the fundamental skills and knowledge to be able to perform them. Those who hold such knowledge control a precious resource—intellectual capital—of which we must ensure a plentiful reserve.

A. Improving Science and Math Education at the K-12 Level

Our K-12 education system serves three main purposes: it is responsible for preparing future scientists and engineers for further study in college and graduate school; it provides a foundation for those who will enter the workforce in other capacities; and it provides scientific and technical understanding so that citizens may make informed decisions as consumers and as a citizens. To achieve these goals, schools must be able to develop curricula that are rigorous, develop critical thinking, and impart an appreciation of the excitement and utility of science.

There are, however, growing indications that science and math education in too many of our Nation's schools is letting down our students. The most recent evidence of this is from the Third International Math and Science Study (TIMSS),[51] which measured American students in the fourth, eighth, and 12th grades against comparable students in other countries. The study, which is the most comprehensive study ever done on the subject, was carefully designed and administered to provide a fair and accurate assessment of the scientific and mathematical understanding of each participating nation's students.

For the U.S., TIMSS revealed some serious problems. Although U.S. fourth graders did relatively well in both math and science, eighth graders sunk to the middle of the pack. By twelfth grade, the last year of mandatory schooling, U.S. students were among the very worst in the world, and in some areas, such as physics, were dead last.

The changes needed to improve math and science education in the U.S. are extensive enough to warrant further examination beyond this Science Policy Study, and the Science Committee intends to continue this effort. There are, however, a few principles that have been identified as crucial to addressing this issue. They are discussed below.

1. Improved science and math curricula

It is nothing short of a miracle that the modern methods of instruction have not yet entirely strangled the holy curiosity of enquiry.

Albert Einstein (1879-1955)

Coursework in science must convey the excitement of science to capture and maintain the interest of students. Children are naturally inquisitive. We must build on this natural curiosity and encourage it, not squelch it by teaching science as just an accumulation of facts and figures, as it so often is.-Science curricula should involve hands-on experimentation, allowing children to experience the thrill of learning how the world around them works. As Bill Nye, the host of the television program *Bill Nye the Science Guy,* said in his testimony, "A teacher doing a demonstration is one thing, but a student doing it for her or himself is another. There is nothing more empowering."[52]

Other curricular issues, particularly those affecting grades seven or eight, the years when our students' test scores start their downward plunge, and higher must also be addressed. Specifically, we must seek to avoid a problem identified in the TIMS study, that is, that science and math curricula in the U.S. are overly broad and insufficiently thorough. Dr. William Schmidt, the U.S. chairman of the TIMSS project and a professor at Michigan State University, described these curricula as "a mile wide and an inch deep," in his testimony.[53] American students, he explained, are exposed to an extremely broad range of facts and topics, none of which they learn very well.

Keeping the interest of these students for science and math remains important at the high school level, as many students make the decision to pursue science or engineering during these years. In fact, many colleges require students to declare the engineering major at the freshman level. Thus if students get "turned off" to math and science at the high school level, this decision often becomes irreversible. To prevent this from happening, it is vital that high school students get a sense of how their math and science courses can lead to interesting and challenging technical careers before they decide to withdraw from the world of science and engineering.

It is precisely for this reason that high school engineering design competitions like JETS (Junior Engineering Technical Society) and FIRST (For Inspiration and Recognition of Science and Technology) have been established. By exposing high school students to the practice of engineering in an exciting manner, these programs provide compelling, hands-on reasons to study math and science in high school. As Michael Peralta, the Executive Director of JETS, testified, "JETS provides high school students with an opportunity to "try on" engineering before they select a college major. JETS' task is to develop a larger and better prepared pre-college talent pool and to encourage these students to consider engineering, science, mathematics or technology as a career path."[54] The results of these programs can be remarkable. In the case of East Technical High School in Cleveland, a school located in the center of Cleveland's most impoverished public housing project, school officials credit the FIRST program with beginning their turnaround from being slated for closure to becoming the "Lighthouse School" for math and science in the Cleveland School District.

We must also to expect more from our Nation's students with respect to math and science. Curricula that contain rigorous scientific content must be developed and applied; children must have an adequate grounding in science knowledge. As a society, we seem to have lowered our expectations as to how much scientific and mathematical understanding the average citizen should have. We learned from the TIMSS project that most of the rest of the world holds their students to a higher standard. We must disavow the notion that not every student can master science and mathematics—that the subjects are "too difficult" for some, or that only students with innate ability can tackle math and science. Our children will not be able to sustain the accomplishments of previous generations unless they are prepared to compete with their peers in the rest of the world. Their preparation starts in the Nation's classrooms.

> **Curricula for all elementary and secondary years that are rigorous in content, emphasize the mastery of fundamental scientific and mathematical concepts as well as the modes of scientific inquiry, and encourage the natural curiosity of children by conveying the excitement of science and math must be developed and implemented.**

2. Teacher training, recruitment, and retention

Recruitment of qualified K-12 math and science teachers should be pursued far more aggressively. A number of states now require middle and high school teachers to possess a college degree in a specific subject area other than education, but many teachers still teach subjects in which they may not have had extensive training. For example, only 41 percent of high school mathematics teachers (and just 7 percent of middle school math teachers) possess an undergraduate degree in mathematics.[55] Of course, a lack of formal scientific training does not in and of itself disqualify one from teaching science or math well. There are teachers with limited science backgrounds who have, through determined self-education, become thoroughly versed in their subject matter. But as long as there are not enough talented teachers able to take the time to do this, science and math education will continue to suffer.

It seems reasonable, therefore, to suggest that those with backgrounds in science and math who also have an affinity and aptitude for teaching be allowed—indeed, encouraged—to pursue this line of work. Currently, many of those with training or educational backgrounds in math and science are dissuaded from teaching by the need for substantial additional schooling to gain a teaching credential. To address this, a number of States around the country have begun to implement credential programs that allow people with backgrounds in science, math, or engineering to learn teaching methods and to obtain their teaching credential on an accelerated schedule. States offering these programs are to be applauded.

Whether possessing a college or graduate degree in science, math or engineering or not, teachers should be required to undergo periodic training and professional development. This is especially important for science teachers because of the continually changing nature of the subject matter. By staying current with new ideas and trends, science and math teachers can increase their value to their students and communities.

> **Programs that encourage recruitment of qualified math and science teachers, such as flexible credential programs, must be encouraged. In general, future math and science teachers should be expected to have taken college courses in the type of science or math they teach, and, preferably, to have a minor. Ongoing professional development for existing teachers is also important.**

Another disincentive to entry into the teaching profession by those with those with a science, math, or engineering degree is the relatively low salaries K-12 teaching jobs offer compared to alternative opportunities. With the fierce competition for technically skilled workers, it is time that school districts consider paying science and math teachers competitive wages both to attract new teachers and, just as importantly, to retain current teachers of outstanding ability.

> **To attract qualified science and math teachers, salaries that make the profession competitive may need to be offered. School districts should consider merit pay or other incentives as a way to reward and retain good K-12 math and science teachers.**

3. Research in education

Currently, the U.S. spends approximately $300 billion a year on education and less than $30 million, 0.01 percent of the overall education budget, on education research.[56] At a time when technology promises to revolutionize both teaching and learning, this miniscule investment suggests a feeble long-term commitment to improving our educational system.

The revolution in information technology has brought with it exciting opportunities for innovative advances in education and learning. As promising as these new technologies are, however, their haphazard application has the potential, in the worst case, to affect adversely the classroom and the learning process. Research is needed to determine how these promising new technologies can best be adapted to the classroom, and particularly to math and science teaching.

> **A greater fraction of the federal government's spending on education should be spent on research programs aimed at improving curricula and increasing the effectiveness of science and math teaching.**

B. College and Graduate Math, Science and Engineering Programs

Undergraduate education programs suffer from some of the same problems as K-12 education in that the standards that students are held to are not always very high, and often students are not exposed to coursework that captures their attention. Many in the workforce, including most K-12 teachers, are formally exposed to math and science for the last time during their college years. Others who plan to pursue further study in math and science must have a solid foundation in order to succeed at the graduate level. Thus our expectations of these students and curricula issues at the undergraduate level need to be addressed. Education research at this stage must also be considered, as professors, while experts in their fields, are often not exposed to, or familiar with, teaching pedagogy.

Courses that are aimed at non-science or engineering majors that nevertheless employ a rigorous treatment of the subject must be provided. David Billington, a Professor of Engineering at Princeton University, has designed such a course, which has proven to be very popular. It highlights important engineering advances of the last two centuries by placing them in historical and social context, and lays to rest the notion that a rigorous treatment of complex technical concepts need be dry and boring. Dr. Billington's description of one of the lessons of the course, the contribution of steamboat inventor Robert Fulton, illustrates this: "By performing the same simple algebra that Fulton himself used in his patent application, our students relive the thrill of discovery as Fulton himself did. In light of modern understanding, they also learn about Fulton's mistakes and how he nevertheless developed a workable steamboat. This understanding can only be conveyed through numbers, but the numbers do not lose rigor by being simple."[57]

By most measurements, our graduate programs in science and engineering are, as David Goodstein, Vice Provost and Professor of Physics at Cal Tech University, said in his testimony, "the jewel in our crown, the only part of our system of education that the rest of the world admires."[58] Indeed, citizens from a number of other countries flock to our graduate schools for training at the Ph.D. and post-doctoral level. The attraction of these students to U.S. science and engineering programs, however, helps mask a situation with serious long term implications for the U.S.—the apparent lack of interest or preparation many of our own students seem to have for careers in science or engineering.

Much blame has been placed on a K-12 educational system that does not sufficiently excite or educate students in math or science and discourages further pursuit of them. While, clearly, there is much to be improved at the K-12 level, we must not be tempted to ignore problems at higher educational levels and the effect the overall economic picture has on students' choices. Today's American students will go where they perceive the opportunities to be. Earl Dowell, Professor of Engineering at Duke University addressed the decrease in the number of students entering into science and engineering graduate programs in his testimony: "The decline has come in part because the economy is generally doing well and since engineering and science are demanding courses of study, some students may perceive that a good job awaits them even without a degree in science or engineering."[59] We must address the question of why American students do not apparently view science and engineering careers as providing sufficient incentives if we are to encourage students to pursue study in these areas that are so important to our Nation's economy and our citizen's lives.

Medical training involves a period of post-college training not unlike that for Ph.D. researchers in the sciences in terms of length, and requires similar preparation. However, in general, the practice of medicine provides far higher salaries than does scientific research. This contrast may explain, at least in part, why medical schools continue to attract large numbers of qualified students while Ph.D. programs must turn increasingly to foreign-born students to make up for declining enrollments.

1. Bringing flexibility to graduate training programs in science and engineering

Part of the problem may be that students perceive training in science and engineering, particularly at the graduate level, as narrow preparation for a career they are not likely to pursue. At many institutions, Ph.D. training in the sciences focuses students narrowly on training for a research career, particularly one in academia.[60] But a number of witnesses and other contributors to the Policy Study pointed out that only a fraction of these students will actually follow the academic research career path due to a limited number of available positions and a far greater pool of potential candidates.

The fact is a majority of Ph.D. graduates in science and engineering take jobs outside of academia. A consequence of this mismatch between the focus of training in graduate school and the available career options at the other end has had a negative effect on student interest in graduate science and math programs. "The students are bitterly disappointed when they find out that the jobs that they want aren't there," Dr. Goodstein said, "and their disappointment seeps down through the ranks, turning younger students away from science."

Apparently, this effect is already being felt. According to Dr. Goodstein, "Around 1970, the fraction of the top students in our college and universities who decided to go on to graduate school started to decline, and it has been declining ever since. Our best students, in other words, proved their worth by reading the handwriting on the wall." In physics, for example, the number of American students deciding to pursue a Ph.D. education has dropped by approximately 27 percent just in the last six years.[61] What has allowed this precipitous decline to go largely unnoticed has been the steady influx of foreign students who have filled the vacated slots. Finally, recent surveys have indicated that a significant fraction of newly graduated Ph.D.s would not get their Ph.D. if they had to do it all over again.[62][63]

Of real concern is the possibility that the pessimism graduate students experience will trickle down to pre-graduate science and engineering education as well. Recent statistics do indeed indicate such a trend, at least in certain fields. Undergraduate enrollments in physics are at their lowest levels since the Sputnik era[64] and enrollments in mathematics and computer science majors are down.[65]

Similar patterns are seen in engineering. The number of college freshmen declaring the engineering major declined by 19 percent between 1983 and 1996.[66] This tepid interest comes at a time when many employers are in such stiff competition with each other for recently-minted engineers that they are offering signing bonuses—on top of attractive salaries—for recent graduates of undergraduate engineering programs, as Dr. Earl H. Dowell, Dean of Mechanical Engineering and Materials Science at the Duke University School of Engineering explained to the committee. Furthermore, employers are petitioning the Congress to increase the number of visas granted to technically trained immigrants.

There appears to be a serious incongruity between the perceived utility of a degree in science and engineering by potential students and the present and future need for those with scientific training in our society. This disconnect is mirrored in the narrow focus of science programs when viewed against the increasingly broad roles that those with scientific training are needed to play in our economy and our society. For example, in business, whether in finance, consulting or management, those with backgrounds in science and engineering will be increasingly sought for their analytical abilities and knowledge of technology-based industry.

Similarly, the legal profession needs those who understand science and technology, not only for addressing patent and intellectual property issues but also for evidentiary analysis in both civil and criminal law. An extraordinarily wide range of career options—journalism, communication, policy and ethics being just a few examples—will be open to those with backgrounds in science and engineering. Bachelors and graduate education programs must adapt to these changing circumstances if we, as a Nation, are to maintain the preeminence of our scientific enterprise and attract the very best and brightest students to pursue studies in science and engineering. To do so, students must be convinced that this education will provide them with broad, attractive career options.

The testimony of Catharine Johnson, a Ph.D. student in Biological Chemistry at Johns Hopkins University, is a case in point. She said, "The American system of graduate education produces highly trained scientists and engineers of unparalleled quality. Changes in both the global and our national economy, however, are expanding the role of science in commerce and society. Thus, our system of graduate education must continue to educate pre-eminent scientists, but also must generate scientists educated to fulfill these new roles. Scientists working outside of research and academia, who interface with all facets of our culture, help demystify both science and scientists, and diminish the gulf between the scientific establishment and the public. The current system of graduate education, however, is too narrowly focused on training specialists in a market that increasingly needs generalists. We must…better prepare young scientists to fully participate in the challenging opportunities that lie ahead."[67]

Graduate education in the sciences and engineering must strike a careful balance between continuing to produce the world's premier scientists and engineers and offering enough flexibility so that students with other ambitions are not discouraged from embarking on further education in math, science or engineering.

The National Research Council (NRC) Committee on Science, Engineering, and Public Policy (COSEPuP) made this suggestion in their 1995 report, *Reshaping the Graduate Education of Scientists and Engineers*.[68] The Chairman of the COSEPuP project, Phil Griffiths, testified to the rationale behind some of their recommendations, which were based in part on interviews with industry employers of Ph.D. scientists. "Here is a typical comment to our committee from a representative of a multinational corporation," he said. "…Skills like project management, leadership, planning and organizing, interpersonal skills, adaptability, negotiation, written and oral communication and solid computer knowledge are critical. If you walk on water technically but can't explain or promote your ideas and your science, you won't get hired. If you do get hired, your career will stall."[69] We must ensure that students are educated for success in a workforce that demands far more than research skills.

The engineering field has begun to address these issues in a formal manner by establishing a new engineering degree accreditation program, a process described by Dr. Dowell in his testimony. Individual academic institutions and the NSF have also made some progress in addressing education and training issues for other graduate programs in math and science.

However, the situation of post-docs has been largely ignored, as a recent report by the Association of American Universities (AAU) pointed out.[70] The concern that the postdoctoral appointment has become a "holding pattern" for those seeking academic positions that are increasingly difficult to obtain, and the lack of consistent standards and expectations for postdoctoral education noted in the recent AAU report need to be addressed.

Finally, we must also ensure that the opportunities that promise to unfold for those with an education in science and engineering are available to all citizens. Today, women and some minorities are underrepresented in many scientific and engineering fields. This represents a tremendous under-utilization of our Nation's resources.

On May 13, 1998, in an effort to address the relative lack of women in the fields of science, engineering and technology development, the Committee on Science passed H.R. 3007,[71] the Advancement of Women in Science, Engineering, and Technology Development Act. The bill creates a Commission to identify the underlying causes for the gender imbalances found in fields such as engineering and computer science, and make recommendations to address these causes.

> **While continuing to train scientists and engineers of unsurpassed quality, the higher education process should allow for better preparation of students who plan to seek careers outside of academia by increasing flexibility in graduate training programs. Specifically, Ph.D. programs should allow students to pursue coursework and gain relevant experience outside their specific area of research. Changes in the current academic culture, which often appears to undervalue non-research careers by students, must be encouraged to bring about these modifications.**

2. The link between education and research at the graduate level

Talented graduate students provide the right mix of agitation and skepticism that feeds new ideas, and the energy to explore them. They are a significant source of innovation and in that sense indispensable for the research enterprise.

Paul Berg (1926-), 1980 recipient of the Nobel Prize in Chemistry

[1996]

Research and education at the graduate level are tightly linked. The training of scientists and engineers in the U.S. occurs largely through an apprenticeship model in which a student learns how to perform research through hands-on experience under the guidance of an experienced researcher—the student's thesis advisor. In many fields, students continue this training in post-doctoral study. A result of this link between education and research is that students and post-doctoral researchers are responsible for actually performing much of the federally funded research done in universities. Thus, these students and post-docs represent a key component of the overall research enterprise.

Dr. Vest underscored the link between education and research in his testimony: "…education—especially graduate education—is an explicit goal of any research partnership that has a federal component…The United States has forged the efficient and productive arrangement of conducting its long-term fundamental research and its graduate education in university research laboratories. We take this arrangement nearly for granted, but it is *the* essential ingredient in our world leadership in science and engineering." Indeed, most of a Ph.D. student's time is spent not in classes, but performing research. This gives the student hands-on training and experience and at the same time generates data that form the basis of the advisor's scientific publications.

This connection between research and graduate education must be maintained as a critical element in the success of our graduate schools to turn out top-quality scientists and engineers. However, the actual mechanisms by which this link occurs can and should be addressed. Typically, a Ph.D. student's research is funded by federal grant money controlled by the student's thesis advisor, making the student directly dependent upon his or her advisor for support. In contrast, many post-doctoral fellows seek and obtain their own funding for their research projects (through a competitive grant process based on peer review). Extending to greater numbers of deserving graduate students[§] this increased control over their own financial resources for their research projects should be considered, as allocating the financial resources exclusively to the faculty places the focus on the needs of the advisor, not the student. The potential thus exists for the student's graduate experience to be dominated by the faculty member's need to generate publishable research results—and not the student's own scientific and professional development.

§Limited funding of this type *is* currently available. For example, both the NSF and the Howard Hughes Medical Institute (HHMI), a private, non profit organization that is a significant funding source for research in the biomedical sciences, offer competitively-awarded grants to graduate students.

> **Mechanisms for direct federal funding of post-docs are already relatively common. Expansion of these programs to include greater numbers of graduate students in math, science and engineering should be explored.**

3. Masters of science programs

Unlike the case in engineering, the Masters degree in the sciences is viewed by many of those in academia as a ‘consolation prize’ for students unable or unwilling to fulfill the requirements of the Ph.D. Yet, ideally, such programs would allow students to pursue an interest in science without making the long commitment to obtaining a Ph.D., and thus attract greater numbers of students to careers in science and technology. Students with Masters of science degrees would be qualified to contribute in numerous important ways to the overall science and technology enterprise.

> **More university science programs should institute specially-designed Masters of Science degree programs as an option for allowing graduate study that does not entail the commitment to the Ph.D.**

4. Length of time spent in training for a scientific career

The length of time involved in graduate training in the sciences and engineering is a clear disincentive to students deciding between graduate training in the sciences and other options. The median length of time required for a Ph.D. in the sciences is now between 6.4 and 7.4 years, depending on the field.[72] In most fields, additional years of postdoctoral research are required. It is not unusual for this added training to last another 3-6 years, making 10 years spent in training not at all uncommon.

Ms. Johnson emphasized the choices from the student’s view, saying, "Science promises an interesting career of intellectual challenge, but it is not alone in this respect. There are significant disincentives, however, for pursuing science. During the extensive training period—and remember, it’s nearly a decade after college and before getting a real job—during that period, we accrue no pension. We are granted poor benefits. Usually we do not contribute to Social Security. And, most importantly, we earn just above minimum wage…In order to recruit and retain young scientists, graduate studies must better compete with other interesting, satisfying, and lucrative professional options…We need to reduce the opportunity costs for pursuing advanced degrees in science and math."

> **Universities must be encouraged to put controls on the length of time spent in graduate school and post-doctoral study, and to recognize that, especially in a competitive economy, they cannot effectively attract talented young people without providing for adequate compensation and benefits during their training.**

C. Communicating Science

If we do discover a complete [unified] theory [of the universe], it should in time be understandable in broad principle by everyone, not just a few scientists. Then we shall all, philosophers, scientists, and just ordinary people, be able to take part in the discussion of the question of why it is that we and the universe exist. If we find the answer to that, it would be the ultimate triumph of human reason—for then we should know the mind of God.

Stephen William Hawking (1942-)

[1988]

One of the ironies of our modern age is that although our society depends on science as never before, what scientists do remains an enigma to most people. As any nonscientist who has tried to wade through a scientific journal knows, the language of science is virtually incomprehensible to the layman. While these journals are not written for a general audience—nor should they be—they are perhaps the clearest example of the widening chasm between scientists and the rest of society.

If we are to maintain public appreciation and support for our scientific enterprise, a way to translate the benefits and grandeur of science into the language of ordinary people is sorely needed. Scientists have wonderful stories to tell, yet too often they get told poorly, if at all. Educators and journalists have a role to play in communicating the achievements of science, but scientists must recognize that they, too, have a responsibility to increase the availability and salience of science to the public.

1. Building bridges between scientists and journalists

Literary intellectuals at one pole—at the other scientists . . . Between the two a gulf of mutual incomprehension.

Sir Charles Percy Snow (1905-1980)

[1959]

We cannot rely on an improved math and science education system alone to provide Americans the knowledge they will need to navigate effectively today's highly technical job market and make well-informed policy choices. The expanding base of scientific information means that to remain scientifically literate we must engage in continual learning. Mr. Jim Hartz, former co-host of the *Today Show*, and Dr. Rick Chappell, Director of Science and Research Communications and Adjunct Professor of Physics at Vanderbilt University, said in their (combined) written testimony, "There has been an outright explosion of new scientific knowledge just in our lifetimes. No one person can know it all. Many scientists, themselves, say they are hard put to stay up with cutting-edge research in their own specialties."[73]

To bring accurate, relevant information from the front lines of science to the pages of newspapers and into peoples' living rooms via television, journalists and scientists must be willing and able to communicate with each other. This does not always come easily. Mr. Hartz and Dr. Chappell, with their individual perspectives from journalism and science, respectively, sized up the basic problem this way: "Scientists complained that reporters didn't understand many of the basics of their methods, including peer review, the incremental nature of science, and a proper interpretation of statistics, probabilities and risk. Conversely, journalists complained that scientists get wrapped up too much in the jargon about such matters and fail to explain their work simply and cogently." The result of this apparent impasse is that good, important stories may go begging for lack of communication.

Most Americans get information on scientific advances from their local print and broadcast media. While many major papers do a credible job of covering science, and some even have science sections, many local news outlets often do not have the wherewithal to devote precious resources to science stories that are often difficult to write and may not attract a wide audience. Ms. Deborah Blum, a Pultizer Prize winning science journalist formerly with the *Sacramento Bee,* made the point in her testimony that readers do indeed respond to science articles when they are done well. But she also noted that writing these stories requires mutual trust between the scientist who is the object of the story and the journalist who writes it.[74]

The advice of Ms. Blum as to how to improve communication between scientists and the press was representative of the advice of other witnesses before the committee. She said, "I believe that at least an entry level science writing course should be required of journalism school graduates. We also need . . . training workshops at existing newspapers, magazines, television stations, radio stations . . . [S]ome programs should also be designed for editors." She also advocated more training in communications for scientists. "I would argue that we should eventually require every person majoring in science to take a science communication course, to be taught that communicating with the public is part of the job description. . . . [Scientists] know very little about the culture of journalism—what makes a story, how to talk to reporters."

Clearly, the gap between scientists and journalists threatens to get wider. Closing it will require that scientists and journalists gain a greater appreciation for how the other operates.

> **Universities should consider offering scientists, as part of their graduate training, the opportunity to take at least one course in journalism or communication. Journalism schools should also encourage journalists to take at least one course in scientific writing.**

2. The importance of communication in maintaining support for science

As important as bridging the gap between scientists the media is, there is no substitute for scientists speaking directly to laypeople about their work. In part because science must compete for discretionary funding with disparate interests, engaging the public's interest in science through direct interaction is crucial.

All too often, however, scientists or engineers who decide to spend time talking to the media or the public pay a high price professionally. Such activities take precious time away from their work, and may thus imperil their ability to compete for grants or tenure. Even for those who prove adept at public communications, the price among a scientist's peers is often great.

University of California at San Diego Professor Dr. Stuart Zola, a scientist who has successfully negotiated the public speaking circuit, testified to the importance of getting institutional backing for such efforts. "[I]t is critical that institutional officials, at the highest level, recognize the importance of communicating science to the public, and encourage faculty to speak to the public about science and scientific issues."[75]

Public speaking is one of the best ways for scientists and engineers to reach the public and share their enthusiasm for their work and educate the public about it. Efforts can include speaking at local civic clubs and other organizations, working with teachers in local schools, and inviting interested groups, such as students, into their laboratories. Without these efforts, support for science may erode.

> **Scientists and engineers, particularly those with an aptitude for public speaking, should be encouraged to take time away from their research to educate the public about the nature and importance of their work. Those who do so, including tenure-track university researchers, should not be penalized by their employers or peers.**

3. Keeping the public abreast of publicly-funded research

Research sponsored by the Federal government should be more readily available to the general public, both to inform them and to demonstrate that they are getting value for the money the government spends on research. Agencies that support scientific research have an obligation to explain that research to the public in a clear and concise way.

The roles of the specialized RaDiUS and PubMed databases in disseminating information to the scientific community were mentioned earlier in this report. Few comparable systems, however, exist for getting information to the general public.

The National Research Initiative (NRI) at the U.S. Department of Agriculture's Cooperative State, Education, and Extension Service does a credible job of making scientific information available to a wide audience. It distributes what is calls Research Highlights, newsletters featuring competitive research sponsored by NRI that has been published in a peer-reviewed journal. The newsletters are written in plain English and describe the results of the research and its impact on U.S. agriculture. These reports serve a useful purpose and could serve as a model for other agencies interested in making the results of their research more readily available.

> **Government agencies have a responsibility to make the results of federally-funded research widely available. Plain English summaries of research describing its results and implications should be prepared and widely distributed, including posting on the Internet.**

Summary of Recommendations

New ideas form the foundation of the research enterprise. It is in our interests for the Nation's scientists to continue pursuing fundamental, ground-breaking research. Our experience with 50 years of government investment in basic research has demonstrated the economic benefits of this investment. **To maintain our Nation's economic strength and international competitiveness, Congress should make stable and substantial federal funding for fundamental scientific research a high priority.**

Notwithstanding the short-term projections of budget surpluses, the resources of the federal government are limited. This reality requires setting priorities for spending on science and engineering. **Because the federal government has an irreplaceable role in funding basic research, priority for federal funding should be placed on fundamental research.**

The primary channel by which the government stimulates knowledge-driven basic research is through research grants made to individual scientists and engineers. Direct funding of the individual researcher must continue to be a major component of the federal government's research investment. **The federal government should continue to administer research grants that include funds for indirect costs and use a peer-reviewed selection process, to individual investigators.** However, if limited funding and intense competition for grants causes researchers to seek funding only for "safe" research, the R&D enterprise as a whole will suffer. **Because innovation and creativity are essential to basic research, the federal government should consider allocating a certain fraction of these grant monies specifically for creative, groundbreaking research.**

The practice of science is becoming increasingly interdisciplinary, and scientific progress in one discipline is often propelled by advances in other, seemingly unrelated, fields. **It is important that the federal government fund basic research in a broad spectrum of scientific disciplines, mathematics, and engineering, and resist concentrating funds in a particular area.**

Much of the research funded by the federal government is related to the mission of the agency or department that sponsors it. Although this research is typically basic in nature, it is nevertheless performed with overriding agency goals in mind. **In general, research and development in federal agencies, departments, and the national laboratories should be highly relevant to, and tightly focused on, agency or department missions.**

The national laboratories are a unique national resource within the research enterprise, but there are concerns that they are neither effective nor efficient in pursuing their missions. A new type of management structure for the federal labs may provide one solution and deserves exploration. **To that end, a national laboratory not involved in defense missions should be selected to participate in a corporatization demonstration program in which a private contractor takes over day-to-day operations of the lab.**

We also have the obligation to ensure that the money spent on basic research is invested well and that those who spend the taxpayers' money are accountable. The Government Performance and Results Act was designed to provide such accountability. **Government agencies or laboratories pursuing mission-oriented research should employ the Results Act as a tool for setting priorities and getting the most out of their research programs. Moreover, in implementing the Results Act, grant-awarding agencies should define success in the aggregate, perhaps by using a research portfolio concept.**

Partnerships in the research enterprise can be a valuable means of getting the most out of the federal government's investment. Cooperative Research and Development Agreements (CRADAs) are an effective form of partnership that leverages federal research funding and allows rapid commercialization of federal research. **When the research effort involved in a CRADA fulfills a legitimate mission requirement or research need of the federal agency or national lab, these partnerships should be encouraged and facilitated.** Partnerships between university researchers and industries also have become more prevalent as a way for universities to leverage federal money and industries to capture research results without building up in-house expertise. **University-industry partnerships should, therefore, be encouraged so long as the independence of the institutions and their different missions are respected.**

International scientific collaborations form another important aspect of the research enterprise. While most international collaborations occur between individuals or laboratories, the U.S. participates in a number of large-scale collaborations where the costs of large scale science projects can be shared among the participants. **In general, U.S. participation in international science projects should be in the national interest. The U.S. should enter into international projects when it reduces the cost of science projects we would likely pursue unilaterally or would not pursue otherwise.** Our experience with international collaborations has not been uniformly successful, as our participation in Mir and the International Space Station demonstrate. **Therefore, a clear set of criteria for U.S. entry into, participation in, and exit from an international scientific project should be developed.**

Large-scale international projects often take place over many years, requiring stable funding over long periods. The annual appropriations cycle in Congress can lead to instability in the funding stream for these projects, affecting our ability to participate. **The importance of stability of funding for large-scale, well-defined international science projects should be stressed in the budget resolution and appropriations processes.**

It is also important that international science projects not appear to be simply foreign aid in the guise of research. **To that end, when the U.S. is a major contributor of funds to projects with international participation, funding priority must be placed on the U.S.-based components.**

America's pre-eminent position in the world suggests new roles for U.S. science policy in the international arena. To take advantage of these opportunities, the State Department must broaden its scientific staff expertise to help formulate scientific agreements that are in America's interest. The evidence suggests that the State Department is not fulfilling this role. **Mechanisms that promote coordination between various Executive branch Departments for international scientific projects must be developed. The State Department should strengthen its contingent of science advisors within its Bureau of Oceans and International, Environmental, and Scientific Affairs and draw on expertise in other agencies.**

A private sector capable of translating scientific discoveries into products, advances and other developments must be an active participant in the overall science enterprise. However, there is concern that companies are focusing their research efforts on technologies that are closest to market instead of on mid-level research requiring a more substantial investment. **Capitalization of new technology based companies, especially those that are focused on more long-term, basic research, should be encouraged. In addition, the R&D tax credit should be extended permanently, and needlessly onerous regulations that inhibit corporate research should be eliminated.**

Partnerships meant to bring about technology development also are important. Well-structured university-industry partnerships can create symbiotic relationships rewarding to both parties. **These interactions and collaborations, which may or may not involve formal partnerships, are a critical element in the technology transfer process and should be encouraged.**

Partnerships that tie together the efforts of State governments, industries, and academia also show great promise in stimulating research and economic development. Indeed, States appear far better suited than the federal government to foster economic development through technology-based industry. **As the principal beneficiaries, the States should be encouraged to play a greater role in promoting the development of high-tech industries, both through their support of colleges and research universities and through interactions between these institutions and the private sector.**

The university community, too, has a role in improving research capabilities throughout its ranks, especially in states or regions trying to attract more federal R&D funding and high-tech industries. **Major research universities should cultivate working relationships with less well-established research universities and technical colleges in research areas where there is mutual interest and expertise and consider submitting, where appropriate, joint grant proposals. Less research-intensive colleges and universities should consider developing scientific or technological expertise in niche areas that complement local expertise and contribute to local economic development strategies.**

To exploit the advances made in government laboratories and universities, companies must keep abreast of these developments. The RAND Corporation's RaDiUS database and the National Library of Medicine's PubMed database serve useful purposes in disseminating information. **Consider expanding RaDiUS and PubMed databases to make them both comprehensive and as widely available as possible.**

Intellectual property protections are critical to stimulating the private sector to develop scientific and engineering discoveries for the market. The Bayh-Dole Act of 1980, which granted the licensing rights of new technologies to the researchers who discover them, has served both the university and commercial sectors reasonably well. **A review of intellectual property issues may be necessary to ensure that an acceptable balance is struck between stimulating the development of scientific research into marketable technologies and maintaining effective dissemination of research results.**

While the federal government may, in certain circumstances, fund applied research, there is a risk that using federal funds to bridge the mid-level research gap could lead to unwarranted market interventions and less funding for basic research. It is important, therefore, for companies to realize the contribution investments in mid-level research can make to their competitiveness. **The private sector must recognize and take responsibility for the performance of research. The federal government may consider supplementary funding for private-sector research projects when the research is in the national interest. Congress should develop clear criteria, including peer review, to be used in determining which projects warrant federal funding.**

Science and engineering also provide the basis for making decisions as a society, as corporations and as individuals. Science can inform policy issues, but it cannot decide them. In many cases science simply does not have the answer, or provides answers with varying degrees of uncertainty. If science is to inform policy, we must commit sufficient resources to get the answers regulators need to make good decisions. **At the earliest possible stages of the regulatory process, Congress and the Executive branch must work together to identify future issues that will require scientific analysis. Sufficient funding to carry out these research agendas must be provided and should not be overly concentrated in regulatory agencies.**

For science to play any real role in legal and policy decisions, the scientists performing the research need to be seen as honest brokers. One simple but important step in facilitating an atmosphere of trust between the scientific and the legal and regulatory communities is for scientists and engineers to engage in open disclosure regarding their professional background, affiliations and their means of support. **Scientists and engineers should be required to divulge their credentials, provide a resume, and indicate their funding sources and affiliations when formally offering expert advice to decision-makers.** The scientific opinions these experts offer also should stand up to challenges from the scientific community. **To ensure that decision-makers are getting sound analysis, all federal government agencies pursuing scientific research, particularly regulatory agencies, should develop and use standardized peer review procedures.**

Peer review constitutes the beginning, not the end, of the scientific process, as disagreement over peer-reviewed conclusions and data stimulate debates that are an integral part of the process of science. Eventually, scientists generate enough new data to bring light to previously uncertain findings. **Decision-makers must recognize that uncertainty is a fundamental aspect of the scientific process. Regulatory decisions made in the context of rapidly changing areas of inquiry should be re-evaluated at appropriate times.**

Aside from being based on a sound scientific foundation, regulatory decisions must also make practical sense. The importance of risk assessment has too often been overlooked in making policy. We must accept that we cannot reduce every risk in our lives to zero and must learn to deploy limited resources to the greatest effect. **Comprehensive risk analysis should be standard practice in regulatory agencies. Moreover, a greater effort should be made to communicate various risks to the public in understandable terms, perhaps by using comparisons that place risks in the context of other, more recognizable ones.**

The judicial branch of government increasingly requires access to sound scientific advice. Scientific discourse in a trial is usually highly contentious, but federal judges have recently been given the authority to act as gatekeepers to exclude unreliable science from the courtroom. More and more judges will seek out qualified scientists to assist them in addressing complex scientific questions. How these experts are selected promises to be an important step in the judicial process. **Efforts designed to identify highly qualified, impartial experts to provide advice to the courts for scientific and technical decisions must be encouraged.**

In Congress, science policy and funding remain scattered piecemeal over a broad range of committees and subcommittees. Similarly, in the Executive branch, science is spread out over numerous agencies and departments. These diffusive arrangements make effective oversight and timely decision making extremely difficult. **Wherever possible, Congressional committees considering scientific issues should consider holding joint hearings and perhaps even writing joint authorization bills.**

No factor is more important in maintaining a sound R&D enterprise than education. Yet, student performance on the recent Third International Math and Science Study highlights the shortcomings of current K-12 science and math education in the U.S. We must expect more from our Nation's educators and students if we are to build on the accomplishments of previous generations. New modes of teaching math and science are required. **Curricula for all elementary and secondary years that are rigorous in content, emphasize the mastery of fundamental scientific and mathematical concepts as well as the modes of scientific inquiry, and encourage the natural curiosity of children must be**

developed.

Perhaps as important, it is necessary that a sufficient quantity of teachers well-versed in math and science be available. **Programs that encourage recruitment of qualified math and science teachers, such as flexible credential programs, must be encouraged. In general, future math and science teachers should be expected to have had at least one college course in the type of science or math they teach, and, preferably, a minor. Ongoing professional development for existing teachers also is important.** Another disincentive to entry into the teaching profession for those with a technical degree is the relatively low salaries K-12 teaching jobs offer compared to alternative opportunities. **To attract qualified science and math teachers, salaries that make the profession competitive may need to be offered. School districts should consider merit pay or other incentives as a way to reward and retain good K-12 science and math teachers.**

The revolution in information technology has brought with it exciting opportunities for innovative advances in education and learning. As promising as these new technologies are, however, their haphazard application has the potential to adversely affect learning. **A greater fraction of the federal government's spending on education should be spent on research programs aimed at improving curricula and increasing the effectiveness of science and math teaching.**

Graduate education in the sciences and engineering must strike a careful balance between continuing to produce the world's premier scientists and engineers and offering enough flexibility so that students with other ambitions are not discouraged from embarking on further education in math, science, or engineering. **While continuing to train scientists and engineers of unsurpassed quality, higher education should also prepare students who plan to seek careers outside of academia by increasing flexibility in graduate training programs. Specifically, Ph.D. programs should allow students to pursue coursework and gain relevant experience outside their specific area of research.**

The training of scientists and engineers in the U.S. occurs largely through an apprenticeship model in which a student learns how to perform research through hands-on experience under the guidance of the student's thesis advisor. A result of this link between education and research is that students and post-doctoral researchers are responsible for actually performing much of the federally-funded research done in universities. **Mechanisms for direct federal funding of post-docs are already relatively common. Expansion of these programs to include greater numbers of graduate students in math, science and engineering should be explored.**

Increased support for Masters programs would allow students to pursue an interest in science without making the long commitment to obtaining a Ph.D., and thus attract greater numbers of students to careers in science and technology. **More university science programs should institute specially-designed Masters of Science degree programs as an option for allowing graduate study that does not entail a commitment to the Ph.D.**

The length of time involved and the commensurate forfeiture of income and benefits in graduate training in the sciences and engineering is a clear disincentive to students deciding between graduate training in the sciences and other options. **Universities should be encouraged to put controls on the length of time spent in graduate school and post-doctoral study, and to recognize that they cannot attract talented young people without providing adequate compensation and benefits.**

Educating the general public about the benefits and grandeur of science is also needed to promote an informed citizenry and maintain support for science. Both journalists and scientists have responsibilities in communicating the achievements of science. However, the evidence suggests that the gap between scientists and journalists is wide and may be getting wider. Closing it will require that scientists and journalists gain a greater appreciation for how the other operates. **Universities should consider offering scientists, as part of their graduate training, the opportunity to take at least one course in journalism or communication. Journalism schools should also encourage journalists to take at least one course in scientific writing.**

As important as bridging the gap between scientists and the media is, there is no substitute for scientists speaking directly to people about their work. In part because science must compete for discretionary funding with disparate interests, engaging the public's interest in science through direct interaction is crucial. All too often, however, scientists or engineers who decide to spend time talking to the media or the public pay a high price professionally, as such activities take precious time away from their work, and may thus imperil their ability to compete for grants or tenure. **Scientists and engineers should be encouraged to take time away from their research to educate the public about the nature and importance of their work. Those who do so, including tenure-track university researchers, should not be penalized by their employers or peers.**

The results of research sponsored by the Federal government also needs to be more readily available to the general public, both to inform them and to demonstrate that they are getting value for the money the government spends on research. **Government agencies have a responsibility to make the results of federally-funded research widely available. Plain English summaries of research describing its results and implications should be prepared and widely distributed, including posting on the Internet.**

Endnotes:

[1] **(1) The Role of Science in Making Good Decisions, June 10, 1998**

(2) Communicating Science and Engineering in a Sound-Bite World, May 14, 1998

(3) The Irreplaceable Federal Role in Funding Basic Scientific Research, April 22, 1998

(4) Math and Science Education Part II: Attracting and Graduating Scientists and Engineers Prepared to Succeed in Academia and Industry, April 1, 1998

(5) International Science, March 25, 1998

(6) Defining Successful Partnerships and Collaborations in Scientific Research, March 11, 1998

(7) Math and Science Education 1: Maintaining the Interest of Young Kids in Science, March 4, 1998

Other Science Committee hearings on K-12 education:

(8) Science, Math, Engineering, and Technology (SMET) Education in America - Collaboration and Coordination of Federal Agency Efforts in K-12 SMET Education, October 29, 1997

(9) The Third International Mathematics and Science Study (TIMSS) - A comprehensive analysis of elementary and secondary math and science education, October 8, 1997

(10) Science, Math, Engineering, and Technology (SMET) Education in America - What are we trying to teach, to whom, and for what purposes?, September 24, 1997

(11) The State Of Science, Math, Engineering, And Technology Education in America, July 23, 1997

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