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The End of the Age of Physics

When human life lay grovelling in all men's sight, crushed to the earth under the dead weight of superstition whose grim features loured menacingly upon mortals from the four quarters of the sky, a man of Greece was first to raise mortal eyes in defiance, first to stand erect and brave the challenge. Fables of the gods did not crush him, nor the lightning flash and the growling menace of the sky. Rather, they quickened his manhood, so that he, first of all men, longed to smash the constraining locks of nature's doors. The vital vigour of his mind prevailed. He ventured far out beyond the flaming ramparts of the world and voyaged in mind throughout infinity. Returning victorious, he proclaimed to us what can be and what cannot: how a limit is fixed to the power of everything and an immovable frontier post. Therefore superstition in its turn lies crushed beneath his feet, and we by his triumph are lifted level with the skies.—Lucretius, *On the Nature of the Universe*

The age of physics came to an end on October 21, 1993, when the U.S. Congress canceled funding for the Superconducting Super Collider, a $10 billion-plus project whose scientific goals were to reproduce the conditions of the very earliest stages of the big bang and determine the origin of mass in the universe. To its supporters, the collider was many things: it was the ultimate physics experiment, an opportunity to develop a "final theory" that could unify all known laws of physics; it was a testament to humanity's quest for knowledge and enlightenment and a laboratory for the education of America's next generation of physicists; it was a further demonstration of American preeminence in science and technology as well as a potential source of technological innovation that could yield great economic and practical value; and it was a sizeable public works project that would create thousands of jobs and bring billions of dollars to the Texas economy. But despite these justifications, despite the political support that they engendered, and despite the $2 billion that the federal government had already spent on construction, the collider was canceled. Today, fourteen miles of the planned fifty-four-mile circular tunnel beneath the ground of Waxahachie, Texas, is all that remains of the project, a subterranean monument to the fifty-year period where physics reigned supreme in American science and technology policy.

Many explanations have been offered for the demise of the Superconducting Super Collider (SSC), all of which probably contain an element of truth. Highly publicized cost overruns and poor project management at the Department of Energy created political vulnerability just at a time when a beleaguered Congress was looking to make symbolic, if not significant, cuts in federal spending. This vulnerability was reinforced by the political impotence of the Texas congressional delegation and by a conspicuous lack of consensus about the value of the SSC within the scientific community itself. Foreign governments, whose support and cooperation were supposedly a cornerstone of the project, proved willing to contribute little more than rhetoric on the SSC's behalf. Ultimately, and most importantly, the proponents of the SSC failed to convince Congress and the public that the project was crucial to the future of science and the nation.

And yet, five years earlier Congress would never have killed a major physics research program with as high a profile as the SSC's. Physics was the discipline that helped win World War II, and physics helped to keep the Soviet Union at bay throughout the Cold War. Physicists were the most influential scientists in the nation, garnering Nobel Prizes, advising presidents, and making the discoveries that allowed the United States to lead the world in technological innovation. Physicists even acted as the conscience of the nation by spearheading the opposition to a nuclear arms race that they had unwittingly unleashed. Embodied by the benevolent image of Albert Einstein, physicists represented the intelligence, ingenuity, and wisdom that brought peace and prosperity to America in the twentieth century, and the SSC represented the type of fundamental investigation into nature that physicists had long promoted as the key to progress in modern society.

By the early 1990s, however, several historical trends had undermined the special political treatment long enjoyed by physicists. Perhaps most important was the end of the Cold War and the consequent disappearance of the principal political rationale for support of physics research in America—national defense. Another factor was the protracted anemia of the American economy and the apparent inability of the nation to translate scientific and technological progress into economic growth. Also implicated was the rising political appeal of other scientific disciplines, especially biomedical research, which seemed to offer more to society than physics did. Each of these trends was a harbinger of a new and evolving government research agenda. While the SSC lost its mandate, other major science programs were thriving, including the Human Genome Project; special government initiatives in manufacturing technology, high performance computing, and biotechnology; and the federal research program on global climate change.

Despite such changes, the policies, programs, and attitudes that were institutionalized during the age of physics still exert a profound influence on the nation. The mushroom clouds over Japan cast a long shadow, and while this shadow darkened the prospects of world peace, it also symbolized the imagination, potential, and potency of all modern science. The promise of science and technology, borne out so tangibly and spectacularly during World War II, translated into a tremendously expanded role for government in promoting science and technology in the United States after the war. Federal funding for research and development grew from less than $2 billion per year in the early 1950s to more than $70 billion per year in the early 1990s.[1]

Yet the past fifty years have shown that the linkage between scientific progress and societal well-being is highly attenuated. While federally funded research and development (R&D) has historically been justified by its promised contribution to human welfare, the fulfillment of this promise seems increasingly elusive. Knowledge and innovation grow at breathtaking rates, and so does the scale of the problems that face humanity. Science-based revolutions in areas such as communication and information technologies, agriculture, materials, medical technology, and biotechnology are accompanied by global weapons proliferation, population growth, concentration of wealth, declining biodiversity and loss of habitat, deterioration of arable land, destruction of stratospheric ozone, and the potential for rapid changes in the earth's climate. These opposing trends may appear to have little possible connection to one another, but they create at the very least an arresting counterpoint, a fundamental paradox of modern culture.

Nevertheless, advocates of publicly funded science—not only researchers themselves but also politicians, bureaucrats, university administrators, corporate executives, special-interest groups, and many private citizens—base their advocacy on the premise and promise that more scientific knowledge and technological innovation will lead to the solution of society's most serious challenges. This line of argument uniformly assumes a causal linkage between progress in science and technology and progress in society. As Nobel Prize–winning physicist Leon Lederman suggests: "What's good for American science . . . is good for America."[2]

The perspective adopted throughout this book is that government support for R&D must ultimately be justified by the creation of societal benefits. Modern society is obviously dependent in many ways on science and technology, and the federal government has helped to create the world's most advanced system of research and development in response to this dependence. But the R&D system is therefore a political entity, itself dependent upon government decision-making processes and public approval for its own well-being. In this context of dependence, and in light of the growing complexity and magnitude of challenges to humanity's long-term welfare, the assertion of causality between progress in the laboratory and progress in society may therefore be viewed as an unproven—although extremely powerful—political argument invoked by researchers and research advocates to sustain public support. Upon such arguments the research system is built.

This book is a critique of the foundations of United States science and technology policy at the end of the age of physics and a portrayal of the R&D system in its political setting. It is not a critique of science and technology per se,* nor is it a discussion of the byzantine and frequently capricious political process through which policy is implemented. Rather,

*The word "science" as used in this book refers to a body of existing and prospective knowledge, not to the technical activity of scientific research or the epistemological foundathe goal here is to reveal and evaluate the assumptions and interests that underlie the current system and that justify the government's role in supporting and promoting research and development. These assumptions and interests help to shape the complex relationship between scientific progress and the common good.

Science and Technology Policy

In 1995, the U.S. government spent almost $73 billion on science and technology programs. How much money is this? It is considerably less than was spent on the military ($276 billion) and on interest on the national debt ($234 billion) and considerably more than was spent on education and training programs ($56 billion), administration of the judicial system ($18 billion), foreign aid ($13 billion), and pollution control and abatement ($6 billion). Fifty-four percent of the science and technology budget was devoted to military projects; the rest was distributed throughout the gamut of civilian research and development fields ranging from space exploration and energy supply to biomedical studies and agriculture.

The total realm of government-funded science and technology activities is loosely encompassed by the term "federal research and development system." The processes through which this system is designed, promoted, funded, administered, and evaluated are encompassed—equally loosely—by the term "science and technology policy." Together, these terms offer a convenient and unavoidable rubric for the full range of activities that determine the shape, size, and direction of publicly funded science and technology in America. The "system" is in fact pluralistic; balkanized might be a more precise description. It is made up of many competing elements, including congressional committees and federal

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tions of science. This perspective is external to the laboratory and reflects a social consensus that treats the validity of the scientific method as proven.

As a matter of taxonomy, the word "science" is meant to encompass all of the natural sciences—for example, physics, chemistry, biology, astronomy, earth sciences—but to exclude the social sciences. References to or discussions of the social sciences will be explicitly identified. Engineering is subsumed by the term "technology," although engineering activities are a component of both "research" and "development."

agencies fighting amongst themselves for greater influence over budgets and programs; national weapons laboratories desperately trying to justify their continued existence in the post–Cold War world; universities seeking to establish or maintain world-class facilities; and individual scientists conducting research and competing for research funds. The "policy process," which determines the structure of the system, is perhaps best characterized as the total of the tactics and strategies employed by these various competing elements as they strive to further their own interests. This process sounds unsystematic and Darwinian, and in many ways it is.

Traditional science and technology policy covers the R&D trinity: basic research, applied research, and development. Basic research is the investigation of natural phenomena; it is often referred to as "pure science" because it is supposedly carried out independently from any consideration of practical utility. The popular (and often apocryphal) imagery of science—Archimedes shouting "Eureka!" in his bathtub, Galileo dropping things off the Leaning Tower of Pisa, Fleming accidentally discovering the penicillin mold—is the imagery of basic research. Applied research is the effort to use existing knowledge to solve particular problems—for example, determining the medical utility of penicillin. Development is concerned with making the products of applied research usable by society—for example, by devising techniques for mass production of penicillin. The boundaries between these various activities are often diffuse, but as a whole they encompass the jurisdiction of science and technology policy. In recent decades, between 50 and 60 percent of the federal R&D budget has been spent on technology development, predominantly for military programs administered by the Pentagon. Most research programs, in contrast, are focused on nonmilitary goals and are administered by a variety of federal agencies, including the National Institutes of Health, National Science Foundation, National Aeronautics and Space Administration, and the Department of Energy.

Because the federal government supports almost half of the nation's R&D activities (private corporations support most of the remainder), the tortuous policy process by which government research priorities and spending levels are determined is the single most important factor controlling the overall makeup of the nation's R&D system. How much will be spent on energy research and how much on medical research? Within the energy research budget, how much is allocated to solar power and how much to nuclear power? How much should go for applied research on nuclear reactors and how much for basic research in high-energy physics? These types of questions are the ultimate responsibility of politicians and bureaucrats. As with all areas of government expenditure, however, various interest groups try to influence the way that R&D programs are funded and administered. The principal interest group in this case is the research community itself—especially the scientists and engineers who carry out federal R&D programs—although, once again, the term "community" in fact comprises a diverse group with diverse and often competing interests. Still, researchers can be distinguished from other participants in the R&D policy process by their technical expertise. They know how to set up laboratories and research programs, they understand the potentials and limits of their work, and they possess comprehensive knowledge in their particular fields of endeavor—knowledge that is often far too technical in nature for nonscientists to grasp fully. Many of the same scientists and engineers who coordinated technical activities for the government during World War II were later called upon to design the postwar R&D system. In fact, for the past fifty years, the government has depended upon the advice of researchers in formulating and implementing federal science and technology policy.

As a political matter, the government spends over $70 billion a year on R&D not because it cares about the abstract pursuit of knowledge but because policy makers and the public believe that progress in science and technology creates societal benefits, both tangible and intangible. Military preparedness, economic growth, medical care, adequate energy resources, and national prestige are among the most important benefits said to accrue from the new knowledge and innovation that come from the R&D system.* Because the principal political justification for R&D funding is public benefit, the basis for science and technology policy can be thought of as a social contract under which the government provides

*The value of science as a cultural activity—a source of intellectual liberation, spiritual enlightenment, and aesthetic satisfaction—is incalculable, but it is not a principal motivation for government support of research and development and is therefore generally beyond the scope of this book.

support for R&D activities in return for a product—knowledge and innovation—that contributes to the common good.

Policy Goals and Policy Myths

But how is public benefit created from the laws of nature? The remarkable success of physics derives principally from its capacity to isolate particular phenomena and describe them in terms—usually mathematical—that are applicable to a large number of situations. The archetypal example is Newton's laws of motion, three basic principles that are valid at scales varying from interstellar to molecular and are applicable to such apparently disparate phenomena as heat and temperature, electric and magnetic forces, celestial mechanics, and motion due to the earth's gravity. Similarly, four simple equations derived by James Clerk Maxwell in the 1860s successfully unified and described all electromagnetic phenomena and thus set the stage for the electronics revolution a century later. The beauty and strength of these sorts of simplifying relationships is that they create a view of the world that is uniform and invariant—a world that is independent of context and therefore describable and predictable.

By reducing natural phenomena to a series of ideal, universal relationships and controlling the environment in which these phenomena occur, scientists and engineers are able to extract practical utility from the laws of nature. It is through such a reductionist approach to creating and applying knowledge that the natural sciences—physics, biology, chemistry, and their various offspring—have made their greatest impact on society. Thus, for example, a physicist can derive an equation to describe the behavior of an electron moving through a uniform electric field in a vacuum. Such ideal conditions are not easily found in nature, but a physicist can create them in the laboratory. The result is a cathode ray tube, and one of the linear descendents of the cathode ray tube is television. Similarly, physicists know, through Einstein's theory of special relativity, that the destruction of atomic mass liberates huge quantities of energy. Fortunately, this conversion occurs naturally on earth only in very small doses. However, by concentrating relatively small amounts of highly unstable elements such as uranium 235 and bombarding the uranium with neutrons, physicists are able to achieve very large and selfsustaining mass-to-energy conversions indeed, and the result is nuclear weapons.

When a new process or product emerges from the laboratory, it undergoes a profound transition—from well-behaved, insular idea or object to dynamic component of a complex interactive social system. Once imbedded in that social system, the new idea or innovation may produce effects that are completely surprising. When a television is turned on, a series of intrinsically predictable electromagnetic processes occurs inside the television that always leads to the generation of a visual image on the screen. But nothing else about the television is predictable or immanent because all of its other attributes derive not from the physical laws that allow it to operate but from the context in which it is used: when, where, and by whom it is turned on; what is being broadcast; how the viewer is affected by the program; what activities the viewer chose to forego in making the decision to watch; how this decision affected others who interact with the viewer (a sports-hating spouse on Superbowl Sunday, for example); how the total number of viewers influences the economic prospects of companies that are advertising at that particular time.

On one hand there are laboratories and on the other, the outside world of human beings. An idea or product in the laboratory often evolves rapidly into something entirely different once it moves into society. But society, too, will undergo change as it responds to and absorbs the knowledge and innovation transmitted from the laboratory. No one anticipated the overwhelming impact of television—just a modified cathode ray tube—on global culture. Or of the telephone, which in its early days was viewed as little more than a replacement for the telegraph, useful only for point-to-point communication, like two cans and a piece of string. Computers were considered by their earliest designers to have application for a narrow range of scientific calculations and no commercial market appeal whatsoever.[3] Nuclear power, on the other hand, was to be the miracle that would provide electricity to the world at virtually no cost.[4] The societal value of science and technology is created at the interface between the laboratory and society; it is inherent in neither alone. There is no a priori link between the structure of physical reality and the manner in which society applies its scientific understanding of that structure.

And this is where politics collides with the natural world to define the fundamental dilemma of science and technology policy. Effective political justifications for government support of R&D are based primarily upon the promise of social benefit. But the societal consequences of scientific and technological progress are not inherent in the natural laws that researchers seek to uncover and exploit. The laws of nature do not ordain public good (or its opposite), which can only be created when knowledge and innovation from the laboratory interact with the cultural, economic, and political institutions of society. Modern science and technology policy is therefore founded upon a leap of faith: that the transition from the controlled, idealized, context-independent world of the laboratory to the intricate, context-saturated world of society will create social benefit. And society has obviously been willing to take the leap, as the annual $70 billion in public expenditures on research and development—or any visit to a hospital, electronics store, or guided missile cruiser—will attest.

An examination of the political rhetoric used to justify and explain the structure of the R&D system yields a number of powerful and oft-heard arguments that underlie and rationalize the leap of faith. Much of this book will be devoted to a discussion of these arguments. They are the basis for postwar science policy, and as such they have proven sufficiently resilient and compelling to ensure the political acceptability of the publicly funded R&D system. These arguments are characterized here as "myths" because they are widely subscribed to and commonly repeated, even though they are not derived from well-developed empirical or theoretical foundations. They are, at root, expressions of ideology and tools of political advocacy, accepted and expressed as truth. They guide the behavior of scientists and policy makers alike. Five such myths are identified and discussed in the following chapters:

1. The myth of infinite benefit: More science and more technology will lead to more public good.
2. The myth of unfettered research: Any scientifically reasonable line of research into fundamental natural processes is as likely to yield societal benefit as any other.
3. The myth of accountability: Peer review, reproducibility of results, and other controls on the quality of scientific research embody the principal ethical responsibilities of the research system.

4. The myth of authoritativeness: Scientific information provides an objective basis for resolving political disputes.
5. The myth of the endless frontier: New knowledge generated at the frontiers of science is autonomous from its moral and practical consequences in society.

These myths reflect the frame of reference of the laboratory. They are the starting point for political debate and thus are not subjected to scrutiny or analysis. Broad acceptance of the myths in the political realm can be attributed to three factors. First, the myths are wielded by a research community that possesses significant political legitimacy and enjoys high societal prestige, in large part because of the great and conspicuous progress of science and technology during this century. Second, the experience of rising standards of living in industrial society over the past two centuries is at least partly consistent with the assertion of causality between public welfare and progress in science and technology. Third, the political interests of the R&D community may overlap with the political interests of other groups, such as the manufacturing sector, the military, and even elected officials, who are thus willing to support or even co-opt the myths. Each of these considerations will be recurrent themes in coming chapters.

Because the overriding political rationale for government support of R&D has been the creation of public benefit, the myths of science and technology policy can be evaluated in this same context. But how are the criteria for such an evaluation established? Indeed, how can such general terms as "public benefit" be usefully defined? Myths of course serve a vital function in any society, by simplifying complex processes and making them comprehensible, and by encapsulating broadly held sentiments and thus creating a unity of vision and a shared sense of community and purpose. Thus, the question here is not simply the degree to which the policy myths are "true" or "false" but what ends they serve and how they affect the policy process and society at large. Just as the R&D community both defines and portrays itself and its interests through its particular myths, so are the broadest interests of society given definition, consistency, and resilience through shared civic myths of a higher order: "that all men are created equal; that they are endowed by their Creator with certain inalienable rights; that among these are life, liberty, and the pursuit of happiness." Such myths may be idealized and unachievable, and their interpretation may change with time, yet they embody particular goals toward which progress can be measured: to "establish justice, insure domestic Tranquility, provide for the common defense, promote the general Welfare, and secure the Blessings of Liberty to ourselves and our Posterity." Furthermore, the myths may define concrete standards from which society should not deviate: freedom of speech, of religion, of the press, of public assembly. Thus, the higher-order civic myths, in defining the fundamental, shared aspirations of society, create a framework within which the myths of science and technology policy can be understood and assessed.

The political effectiveness of the policy myths does not require that all scientists and engineers subscribe to them uncritically. However, the leading voices of the R&D community explicitly proffer these myths in their efforts to explain and justify the operations of the R&D system. In this sense, the public articulation of the myths represents the way that this community wishes to be viewed by the rest of the world, and it presumably represents, in a general manner, the way that the community views itself. For this reason, the presentation and analysis of policy myths in this book is based on the words chosen by leaders of the R&D community to portray themselves to the outside world and to each other. These words are found in newspapers and popular magazines, on the editorial and letters pages of scientific journals, in speeches and congressional hearings, and in the reports and publications of professional societies and other organizations that represent the interests and expertise of scientists and engineers. Such sources are explicitly nontechnical in nature; they are the public voice of science and technology. This is the voice heard by the rest of society.

Although much scholarly work in the social sciences over the past several decades has been devoted to analysis of the science-technology-society relationship, most of that work is of an academic nature that is not directly applicable to political debate; nor does it affect public perceptions about R&D. The scholarly literature is for the most part, therefore, separate from my principal concern here, which is to address the terms of political debate and public perception head-on. In fact, some of the myths still adhered to by natural scientists and policy makers alike have been assessed (and often debunked) in the social sciences literature;[5] what matters here, however, is that the myths remain powerful in the policy arena, that they are still part of the policy rhetoric, and that they have a palpable influence on policy decisions and thus on human welfare.

Beyond the Age of Physics: Science, Technology, and Reality

It is perhaps no coincidence that the end of the age of physics comes at a time when the human perspective has become truly global. Is the reductionist approach to understanding reality a suitable basis for confronting the problems of an increasingly interconnected world? What start out as concrete scientific and technological solutions to particular challenges—food production, birth control, energy supply, infectious diseases, transportation—are later revealed as interlocking components of a global society. Improvements in human health lead to exploding population; stronger and more durable materials and tools allow more efficient depletion of natural resources; greater industrial productivity generates more waste; techniques for increased food production introduce new toxic materials into the soil and water and reduce genetic variability of seed stocks. Further advances in science and technology will help to mitigate these problems, and they will also create new problems of their own. Context that is stripped away in the laboratory reasserts itself with a vengeance when a new process or innovation interacts with political, economic, and cultural systems. At the science-society interface, the distinction between solutions and problems may become fuzzy, as short-term scientific and technological contributions to human welfare often create unanticipated long-term problems. This trend is well known.

The history of human culture can be viewed as a history of crises, overcome in many cases with the help of technology—crises of demography, of resource supply, of environment, of economics, of military confrontation, of epidemic disease—but all such crises, with the exception of the Pleistocene ice age, were limited in their consequences by the finite scope and reach of society. Greece fell, but Rome rose; Europe maundered in the Dark Ages while Aztec, Mayan, Islamic, and Chinese cultures variously thrived. This long-term equilibrium may be a source of modern optimism—we have seen, and surmounted, serious challenges before.

Prophets of doom have come and gone; humanity's reach still expands. But there is something new on the scene: a quantum leap in the scale of human activities and human problems, a leap made possible by science and technology, with implications that can no longer be contained by political or geographic boundaries, or even by the natural systems that sustain life.

As the potency of science and technology grows, and the global interdependence of society deepens, the need to view scientific and technological progress in its human context becomes ever more urgent. Humanity's ever-increasing capacity for manipulation of nature at a fundamental level implies an accelerating potential for complex and even chaotic results at a societal level. No major product of the R&D system finds its way into society without in some way influencing or altering the economic, political, environmental, or even moral composition of life. Globalization of communication, of markets, of conflict, of environmental impacts, of culture, has magnified the nonlinear consequences of the research and development process and increased the opportunity both for major societal gain and for large-scale disaster.

The survival value of a linear policy perspective—where progress in science is viewed simply as the precursor of progress in society—will continue to diminish as the potency of science and technology increases. An essential responsibility of science and technology policy, therefore, must be to compare the promises made on behalf of the R&D system—promises that derive their legitimacy from the policy myths—with the system's actual performance in society, and to modify the promises and the myths on one hand, and the system on the other, to create greater consistency, a more realistic level of expectations, and an increased capacity to achieve societal goals. A new perspective must emerge in which science and technology are understood to be agents of context alteration, not merely simple steps upon which humanity seeks to ascend above the latest array of crises. Is the impact of the internal combustion engine on society best understood in terms of the thermodynamics of combustion, the average number of vehicle miles traveled each year, the contribution of the automotive industry to the national economy, the curve of rising carbon dioxide content in the atmosphere, the geopolitical struggle for control of oil resources embodied by the 1991 Persian Gulf War, or the effect of the commuter culture and the increased mobility of the individual on the structure and psyche of the American community? Understanding the implications of progress may become as important to the future of humanity as progress itself.

What follows is an attempt to illuminate and assess the foundations of post–World War II science and technology policy through an examination of the fundamental myths that have guided policy making for half a century (Chapters 2–6) and a discussion of some of the less familiar and more troubling economic and political ramifications of the research and development system that is constructed upon these myths (Chapters 7 and 8). This analysis will point the way toward some alternative approaches to science and technology policy, aimed at encouraging the development of stronger linkages between the publicly funded R&D agenda and the long-term goals and obligations of society (Chapter 9). The leap of faith that spans the chasm between laboratory and reality must be replaced with a bridge, lest, at the end of the age of physics, we look down and realize that there is nothing underneath our feet.