Biotechnology and Government Funding: Economic Motivation and Policy Models

Michael S. Lawlor

The United States is clearly the world leader in the emerging field of biotechnology—the application of breakthroughs in biochemistry and molecular biology to new products and health care therapies. It is no exaggeration to say that this world leadership position is the result of the superiority of the human and physical capital of the U.S. science and technology base in the nation's university, government, and nonprofit labs. Most of this base has been nurtured and sustained since the end of World War II by the generous support of the American taxpayer. The economic and political motivations upon which the U.S. research system was designed and operates, the special features of the biomedical research community, its history up to the present era of tremendous advance, and some lessons that lie therein for public policy toward science are the subjects of this paper.

OVERVIEW OF R&D FUNDING

Figure 1 shows the total funding for research and development in the United States from 1953 to 1998 in both current and constant (1992) dollars. Concentrating on the constant dollar values, roughly four eras of total funding are evident from these data. From 1953 to 1970, there were large, sustained increases in research funding, led by federal government efforts that corresponded to the arms and space races. In the '70s, public support for both these goals waned. It is important to note, though, that while total funding stagnated in the 1970s, this decade also saw the advent of new biomedical initiatives, such as the federally sponsored "war on cancer," which laid the groundwork for much of the bioscience of today.

The third era of funding, in the 1980s, saw a brief resurgence of federal spending, mostly fueled by the Reagan administration's defense program, espe-

Figure 1
National R&D Funding, by Source, 1953–98

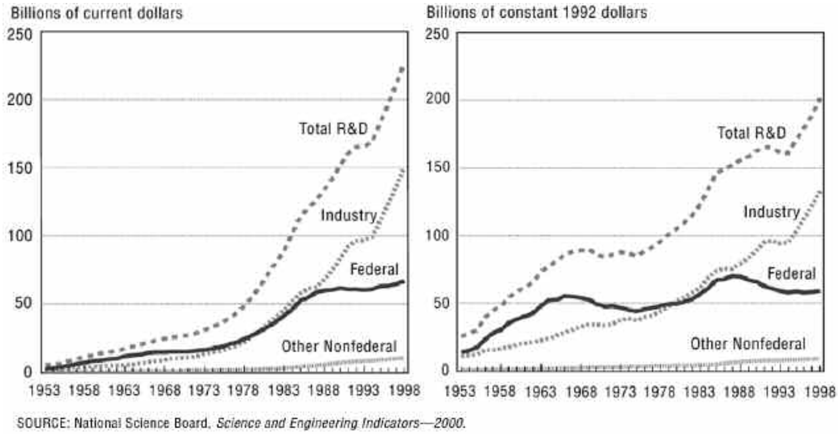
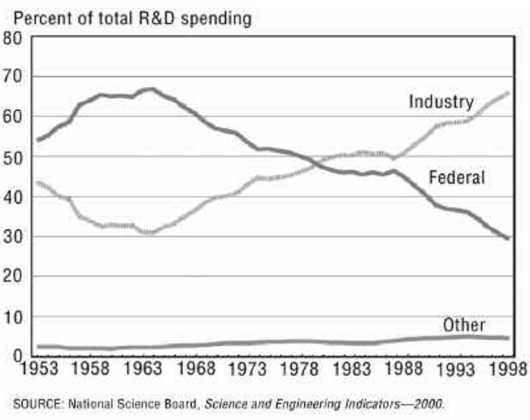


Figure 2
National R&D Expenditures, by Source of Funds



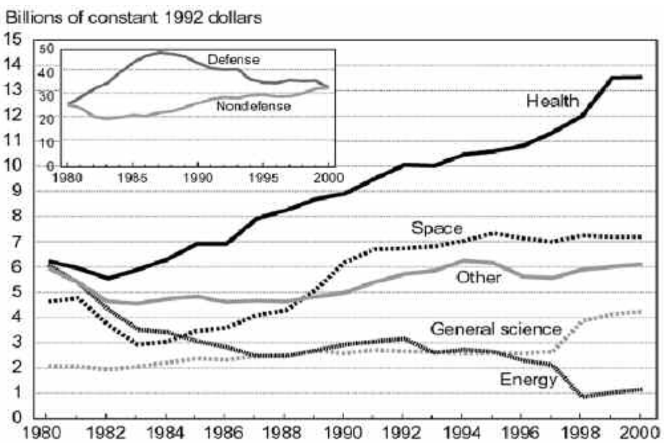
cially the effort to develop a space-based missile defense system. But the real story of the '80s is the rapid increase in private research expenditures. As can be seen in Figure 2, by the end of the decade, the federal role as the leader of funding had shifted to the private sector. Much of this was spent on drug discovery by the pharmaceutical industry. It was directed at the biological targets of the pregenetic biotechnological era that public basic science was then discovering. This research is largely responsible for most of the blockbuster drugs on the shelf today.

Finally, referring to Figure 1 again, a fourth stage in total national research and development spending began in the late 1980s with the end of the Cold War. The lack of any ambitious new nondefense initiative at this time saw total federal funding decline again. In terms of total federal government research spending, this decline has still not been reversed. Perhaps the recent military and biological defense spending increases called for by President Bush, in response to the threat of terrorism, may be the next large focus for public support of research spending. An important message to take away from this is the pervasive influence of current political interests, such as the Cold War science race, for instance, on the public funding of research and development activity. The variability of postwar public funding for science research is largely a story of changes in this political commitment.

Given the unpredictable nature of science, potentially *all* past federal science research has contributed to the biotechnology era. Consider, for instance, the fact that the techniques employed in the Human Genome Project were a complex combination of basic breakthroughs in theoretical biology, enabled by developments in imaging stemming from high-energy physics and kept track of by advanced computing technology (bioinformatics). Yet the original funding for the basic investigations that went into these seemingly unrelated advances, if they could all even be traced, came from sources originally thought to be unrelated to biomedical research.

Nevertheless, it is useful to see a breakout of public funding by category (*Figure 3*). First we should set aside defense research, much of which is directed

Figure 3
Federal R&D Funding, by Budget Function

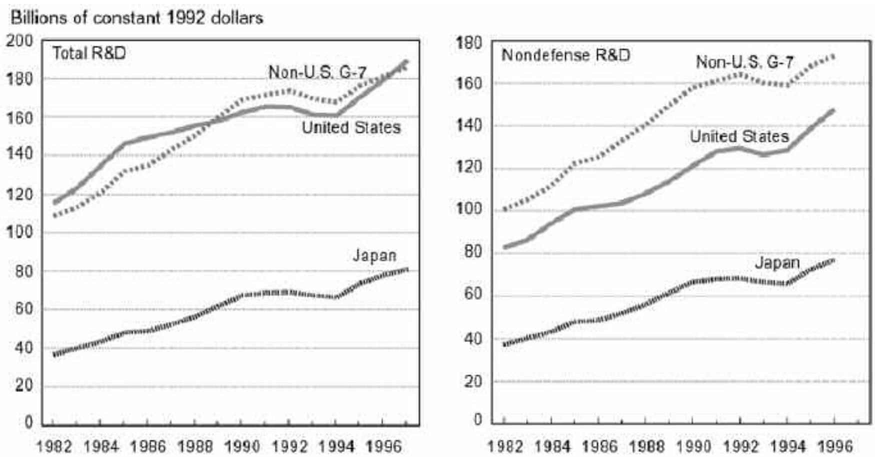


SOURCE: National Science Board, *Science and Engineering Indicators—2000*.

to weapons development, not to basic science issues at all. Aside from defense-related research, it is evident that most federal research funding is for "health" related activities. The majority of the funds in this category support the National Institutes of Health. If one were to further isolate the specifically biotechnology-related funding in the remainder of this breakout, it would span all the other categories shown in Figure 3, in addition to the obvious amount labeled "health." The majority of nonmedical, basic science training and research funding falls under the "general science" category (predominantly for the National Science Foundation). Additionally, various small programs that target specific biotechnology industries and/or types of technology are here included in the category "other" (for instance, the Department of Agriculture's research budget). Overall, because of the dominance of nondefense research by the health share, it has become customary to focus on the NIH budget when discussing biotechnology. By this measure, a good rough and ready indicator of the current health of publicly funded biotechnology research is the recent rapid increase in the NIH budget. If the proposal submitted by President Bush in April 2002 for the 2003 budget is passed by Congress, President Clinton's 1998 pledge to double the NIH budget over five years will have been met.

Finally, Figure 4 displays an international comparison of total U.S. science and technology expenditures. On a country-by-country basis, no single state comes close to the U.S. level of total spending. Japan, the closest, expends about half of the U.S. total. All of the non-U.S. G-7 countries combined spend an amount about equal to what the United States does. If we subtract defense

Figure 4
U.S. and Other G-7 Countries' R&D Expenditures



SOURCE: National Science Board, *Science and Engineering Indicators—2000*.

commitments though, an area in which none of these countries really competes, the United States does not stand out quite so dramatically. We are outspent on total nondefense research and development when compared with the whole group of our fellow G-7 partners. But we still outspend any one country by a large amount. This does not tell the whole story though, because for reasons discussed below, we also get more productivity—in terms of new breakthroughs, patents, marketable products, Nobel Prize winners, etc.—per dollar spent on research and development than any of these countries. Thus at present, the United States is the undisputed leader in almost every basic science area related to biotechnological research. Our universities, especially those with research-intensive medical schools, are the preferred place to train for a career in these fields. Every year sees a net inflow of talent from other countries of scientists wishing to work in these institutions. For these reasons, and despite the fact that much valuable research is conducted in Europe and Japan, all major international pharmaceutical companies feel the need to establish research relationships or laboratory locations to keep abreast of the new developments in the United States.

THE ECONOMIC MOTIVATION FOR PUBLICLY FUNDED RESEARCH

The basic economic motivation for public funding of scientific research lies with what economists call a market failure. The failure is caused by the degree to which the process of creating new scientific knowledge and technological innovation may be insufficiently appropriable—i.e., difficult to establish property rights to—to provide profit-seeking investment with sufficient rationale to pursue such research (Nelson 1959, Arrow 1962). At the root of this failure is the problem of the ease of spillover effects from new knowledge. Knowledge production requires real resources, and if the fruits of one's investment in those resources are freely available to anyone, then they make poor investment targets. Add to this the uncertainty, risk, and long-term nature of the knowledge production process and it is likely that many forms of research will not meet investors' minimum expected return hurdles. Even so, this is only a market failure of an important public good, one that requires public intervention, if the activity would also yield social returns greater than the cost of the investment in them.

Much empirical research by economists has established that this is in fact the case for investments in science. Two types of studies have been undertaken. At the microeconomic level, on an industry or case study basis, specific technological innovations have been demonstrated to display more benefits for the ultimate users of technology, consumers, than for the original innovating firms (Mansfield et al. 1977; Scherer 1982; Griliches 1992, 1995; Hall 1996; Jones and Williams 1998; and Lichtenberg's contribution to this conference). Thus the *public* rates of return on investment in the research to produce such new knowledge tend to be many multiples of the rates for *private* investors. This is because as the benefits spill over to other producers and consumers, the private investor is not compensated. A second type of study, at a macroeconomic level, consistently finds that the rate of productivity growth of the whole economy is importantly linked to the invention and adoption of new technology. (See Ruttan 2001, ch. 2 and Steil, Victor, and Nelson 2002, ch. 1 for useful summaries of this literature.) Here the proposed linkage is both the effect on productivity of the spread of new ways of doing things across industries and products and the increased skill of a workforce trained in the new technology. Note that this evidence also indicates that the investment value of new scientific knowledge is greater for society in general than for any one firm. Thus both types of evidence combine in an argument that the private sector can be expected to underinvest, relative to what would be an optimal level for society, in the types of scientific research for which the difficulty of appropriating specific new knowledge is substantial.

To move closer to a socially optimal level of investment in research, then, requires that the government intervene in some fashion. One such intervention could be the establishment of a government-regulated system of property rights on intellectual "inventions," such as the patent and copyright laws. This has been vigorously pursued in the United States since the time of the founding fathers. (See Grabowski's contribution to this conference.) A second possible policy could be to subsidize private research efforts by a tax credit. Research-intensive industries in the United States have lobbied for this incentive for decades, and since the 1980s it has become a permanent feature of our corporate tax code. Nevertheless, economists generally view tax incentives as a weak and ineffective tool, due to the undifferentiated incentive it presents to all kinds of research and development efforts. The problem is that it is difficult to target just the kind of basic research for which there is a market failure, and much applied and developmental research that could attract sufficient private funding on its own also ends up being subsidized. This is also inefficient from a social point of view. Thus the most direct and effective tool available to governments to fund research that is expected to be socially beneficial, but that is not likely to be done by the private sector, is to fund it directly. A long-term program of such funding also has the beneficial effect of keeping in place a system that will be uninterrupted over the long-run cycles of private funding. Providing infrastructure to nurture the cumulative and unpredictable nature of research programs, and the institutionalization of training grounds for reproducing the next generation of scientists, are additional benefits of this system.

SCIENCE VERSUS TECHNOLOGY, BASIC RESEARCH VERSUS APPLIED

Implicitly, we have assumed above that *basic* research into *scientific* questions represents the appropriate target of public research expenditures. Why?

Generally because such research is so broadly defined and so generally applicable and/or difficult to write into a legally binding patent application that it cannot be protected from spillover effects in sufficient degree to make it attractive to private investors. *Applied* research into *technology* would, in this framework, be such research as can be adequately appropriated to encourage private investment. But this tells us nothing essential about the qualities of these two types of activities that can be identified independently of what private initiative will or will not fund. Since, particularly at the basic science level, one cannot know in advance what scientists pursuing a particular line of research might have discovered or produced unless we let them try, there will always be a difficulty attached to identifying the correct (optimal) amount of total research spending. Additionally, public policy is faced with a need for ranking research goals to provide for the allocation of public funds between particular lines of research. Thus to some extent basic research will always depend on a degree of confidence—perhaps even bordering on "faith"—in the possible future life-enhancing usefulness of what must remain at some level the unforeseeable results of scientific research.

Nevertheless, the distinction between bioscience and biotechnology plays an important role in both investors' minds and in thoughtful public policy. Investors are reasonably suspicious of the probability of commercial success of an early and uncertain line of research. Policymakers, beholden to their constituencies, often want to direct funds to areas of greatest public interest or concern. Thus here is a good place to briefly review attempts by scholars to draw theoretical distinctions between the activities of science and technology research. We shall see that though this effort has added insight into the process of scientific research that is useful and interesting, the distinction is a shifting and slippery one to maintain in practice.

The most common view of the essential distinction between science and technology is based on the intended use of the new knowledge that is being pursued by research. By this view, science is new knowledge intended for knowledge's sake alone. Alternatively, technology is the "useful" application of new ideas for commercial, military, clinical, etc., uses. With regard to basic science activity, this captures something of the element of curiosity often proclaimed by scientists as the crucial element of research that has led to new breakthroughs (see Kornberg 1997). A more economic extension of this distinction was put forward by Dasgupta (1987). He distinguished between the alternative incentive systems involved in the production of each type of knowledge. Scientific discovery, situated largely in nonprofit settings and conducted by academic scientists, is motivated by the "rule of priority," according to Dasgupta. She who is first wins in this contest. A notable aspect of this system is that its focus on early achievement also serves to encourage rapid and complete disclosure of new knowledge. Thus this system advances the social function of the diffusion of new ideas. Technology, in Dasgupta's view, is motivated quite differently. A profit-oriented firm that employs scientists to develop new clinical products, for instance, is motivated by the "rents" that can be appropriated from the new knowledge. It is not in the interest of the firm to see a rapid dissemination of its new knowledge. Private knowledge production, alternatively, encourages secrecy and hoarding of information.

An interesting feature of the current biotechnology era, where academic science and commercial development fluidly intermix, is the degree to which these distinctions have been breaking down. Most new biotechnology is already a mix of what Ruttan (2001, 536) calls "doing science" and "doing technology" years before it ever hits the marketplace. (Indeed, most biotechnology has yet to reach the marketplace!) Both the fundamental *idea* of the structure of DNA and the useful *method* of gene splicing have been integral to the development of molecular biology, for instance. Thus the distinction between scientific ideas and technological applications of them is more of interactive feedback loop. New ideas often lead to new technology that itself aids the next stage of discovery. Moreover, today the dual feedback loop between bioscience and technology extends quite far into the development stage, where new product development is itself a scientific endeavor. Consider, for example, that the average biotechnology start-up firm is a small group of scientists and laboratory technicians trying to develop a commercially viable prototype of a previous scientific result.

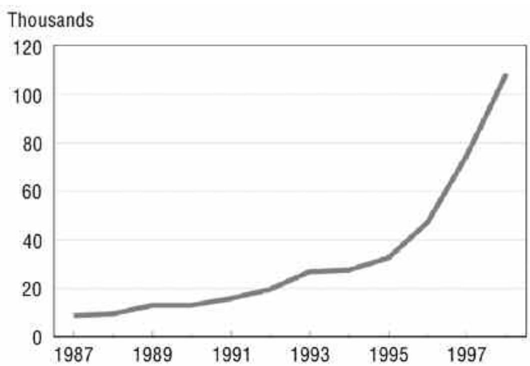
The same blurring of lines affects Dasgupta's taxonomy. Academic researchers who are winning the priority prize have also been patenting their discoveries and starting new commercial ventures to bring them to market. (See Darby's and Zucker's contributions to this conference.) For instance, Cohen and Boyer's gene-splicing technique, developed in a university lab, became the basis upon which the most commercially successful biotechnology firm to date, Genentech, was founded. This was the original model for the now numerous academic-science-entrepreneur firms that have sprung up in the biotech field. This cross-fertilization between basic science and technological development has also spread to the patenting process. Not only are many scientists and universities patenting the results of their research with greater frequency, but also many patent applications are citing scientific publications in their applications to establish both prior knowledge and the rule of priority. Figure 5 demonstrates this increasing link between new technology and new science in the rapid increase of references to scientific paper on applications for new patents since the mid-1980s. Another aspect of the breakdown of Dasgupta's distinction is the growing controversy over the clash of academic and commercial interests in disseminating the results of scientists who are also commercially funded or have a vested interest in future commercial applications. Thus not only are the worlds of science and technology increasingly intermixed, so are the motivations and roles of researchers in academic institutions and private industry laboratories.

One important public policy lesson of the ambiguous results academic investigation reveals about the distinction between science and technology is that there may be an additional role for public funding in certain cases of what might seem to be applied research. The rationale in this case concerns the possibilities that in relatively new technological areas there may be an additional market failure as firms find the difficulties of translating new laboratory science results into industrially viable technology too risky for private investment hurdles. In many cases, as biotechnology firms today are finding, for instance, established firms like large pharmaceutical companies find it an intolerable risk to nurture such new technologies as their own research investments. This is why the pooling of risk and consequent benefits of portfolio diversification through the characteristics of the venture capital fund have become so important in biotechnology.

But even venture capital may not be willing to assume all of the risk of wholly new science for which there is as yet no technology. Crossing this "death valley" of lack of funding along the way from laboratory science to engineering viability is a major hurdle today for many bioscience firms. Part of the problem is that certain types of premarket, generic, process technologies will possibly become commonly used by other firms in ways that are difficult for the original investor to lay claim to. But just as often it is the uncertainty of success in ramping up a basic science result to an industrial scale. An instructive historical example of this difficulty can be seen in the World War II–era attempt to produce penicillin. Penicillin mold was originally identified as an antibiotic by Alexander Fleming in 1928. Then followed a decade of work by British scientists at Oxford University in isolating the essential agent, producing it in labora-

Figure 5

Number of Citations on U.S. Patents to Scientific and Technical Articles, 1987–98



SOURCE: National Science Board, *Science and Engineering Indicators—2000.*

tory quantities, and proving its clinical efficacy in small numbers of risky experiments on patients. Only when the war arrived and it was expected that a successful antibiotic would save thousands of lives did the effort to industrially produce the product receive attention. When it did, the British turned to America for help. What turned out to be the crucial technological breakthrough came from agricultural scientists working for the U.S. Department of Agriculture on fermentation technology in Peoria, Illinois. The expertise of the agriculture scientists and engineers in the seemingly unrelated area of fermented food production led to an economically viable process by minimizing the ratio of "feedstock" input of mold to output of finished penicillin in industrial scale fermentators. (See Bud 1993, 103–7.) It was largely from these publicly funded results that the technological problem of penicillin was solved. This process then became the basis for a vast commerce in a wide spectrum of commercial antibiotics after the war.

Though some have called for more of this type of effort in the biotechnology field (Tassey 1999), already there is evidence that the U.S. government has been moving in the direction of providing some funding for just such generic technology development. For one, since the mid-1980s, it has been the policy of the federal government to encourage the transfer of any federally funded research to the private sector. This encouragement may occur in the form of cooperative research agreements (CRADAs) by which federally funded laboratories are authorized to establish research links for their own profit with commercial firms using their results. Similarly, all federally funded scientists are now authorized and encouraged to patent the results of their research by the opportunity for the scientists and the institutions to which they belong to share the royalties such patents might generate in the private sector. More directly, the Department of Commerce's National Institute of Standards and Technology has initiated a small-scale program of directly funding research into the development of a new generic process for emerging high-technology industry. This Advanced Technology Program (ATP) has launched projects on such questions as laboratory reproduction of stem cells, regeneration of human tissue, and the possible growth of insulin-producing cells in the pancreases of diabetics (Martin et al. 1998). Its mission is to investigate the feasibilities of such enabling technologies and then turn them over to the private sector for further use. If they can avoid, as they seem to be carefully doing, the problem of favoring particular firms, this small program has the potential to help bridge a crucial gap in the move of biotechnology from public science to viable commercial products.

POLITICAL AND SOCIAL MOTIVATION FOR PUBLICLY FUNDED RESEARCH

As our brief overview of public funding for scientific research in the previous section suggests, the market-failure rationale from economics has not been the prime mover of science policy in the United States. Indeed, throughout history it has been much more likely that political considerations such as national prestige, military security, and social needs have been the main motivators of public funding for scientific research. There is no reason to expect that this will change in the near future. Since it is particularly the long-term nurturing of the broad basic science base that has produced the United States' competitive edge in biotechnology, it is instructive to understand how this system was founded and what qualities are responsible for its many successes.

In fact, it is something of a historical fluke, born of the political conditions of the 1940s, that the United States established what is an internationally unique system of noncentralized, government-funded, but largely university-performed, basic research in science and technology in the postwar era. That fluke is the story of what has come to be called the Vannevar Bush-inspired era of national science policy.

Vannevar Bush, formerly the dean of the MIT School of Engineering and then the president of the Carnegie Foundation, was selected by President Roosevelt in 1941 to head the Office of Scientific Research and Development. His task was to harness the skills of the academic science community for the war effort. The spectacular successes of this effort in the war—including, to name just three of many possible examples, the creation of a feasible synthetic rubber to replace the natural supplies cut off by the Japanese, the mass production of penicillin, and the creation of the atomic bomb—convinced Bush that the same type of work should be harnessed for peacetime needs in the postwar era. In 1945 he authored a Carnegie Foundation report, *Science: The Endless Frontier*, which laid out a plan for establishing a permanent federal science policy. Bush's report was couched in the inevitable military rhetoric of its era, with accounts of logistical needs, personnel available and needing to be trained, chains of command, budgets, and a plan of action that would have made a field general proud. No doubt this added to his report's enormous influence. But more important is the vision that his plan put forward. It called for an ambitious and comprehensive National Research Foundation, which would support primarily basic research in the life sciences, physical science, medicine, and what he called "basic military research," meaning research prior to actual weapons development. (He no doubt had atomic energy in mind.)

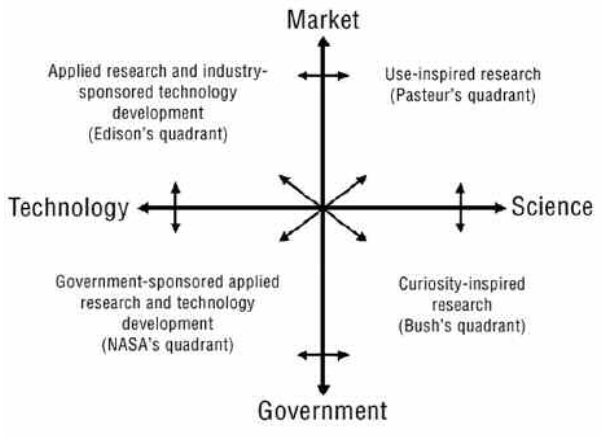
All of this research was to be funded at the federal level and performed largely by state and private university scientists. Most important for Bush, the scientists themselves would control the allocation of the funds. This would be accomplished, he suggested, by a peer review system by which proposals would be granted to projects and individuals deemed both capable and scientifically promising by other scientists. Yet though Bush made glowing comments on the potential applied social uses of scientific knowledge, he implicitly seemed to reject the rate of return reasoning we have just outlined as the economic argument for public funding. In rejecting the "investment" criterion, as he called it, he articulated the humanistic argument still heard today, that scientists do their best work when motivated by curiosity alone, not practical application. Curiously, though, like the economics argument this led him also, for different reasons, to reject funding for any applied research. His objection was that too much political or commercial direction of scientific research would inhibit the free play of idle curiosity. Thus he did not envision federal support for industrial product development, and he wanted actual weapons development to be the responsibility of the armed forces separately. Also, curiously, his discussion of medical research (Bush 1945, appendix 2) only briefly mentions clinical research.

It is fair to say that Bush's vision of a science establishment innocent of other interests was politically naïve. Bush's historical role was to use his enormous influence to lobby for perhaps as much freedom for science from political, commercial, or military control as it has been given anywhere, anytime in history. In this he was largely pitted against the forces arrayed behind Senator Harley Kilgore of West Virginia, who sought a more centralized control of government-funded scientific research (see Kleinman 1995). Though Bush is often credited with being the architect of the postwar federal policy, it is important to note that his was not an unqualified political success. First of all, his advocacy of noninterference with scientists by either defense, social, or commercial interests was not to become a complete reality. It would be more correct to say that the purest example of the Bush model has been the National Science Foundation, founded in 1950. The NSF has stridently avoided attempts by Congress over the years to direct or widen its mission to applied research and any outside interference with its peer review system. Yet, possibly because of the NSF's sponsorship of this pole of pure curiosity-driven science, the NSF's budget has remained relatively small throughout the postwar era. It has, for example, received only a fraction of the NIH's funding.

In fact, the creation of a separate vehicle for biomedical and clinical research at the NIH is itself an example of the only partial success of Bush's ideal. Additionally, the military establishment was not about to hand over the direction of its research program to a group of scientists. Consequently, the Department of Defense's own applied weapons development projects, working largely with commercial defense contractors and the Atomic Energy Commission, often focused on big projects like the Oak Ridge facility, which are examples of Kilgore's favored centralized, state-controlled research policy. Later, when space exploration became a serious concern of the government, it also was organized along similar lines—as a centrally controlled, explicitly mission-based, applied research project.[1]

Bush's vision, then, is just one of many ways the government can and does fund science. Figure 6 (borrowed from Ruttan 2001, 537, and altered for this paper) illustrates, both conceptually and by reference to actual examples, a con-

Figure 6
Possible Interactions Between Basic Science and Applied Technology and Between the Market and Government



SOURCE: Adapted from Ruttan 2001, 357.

tinuum of possible combinations of ways that the government, the market, applied technological work, and new scientific knowledge might be organized and interact. In the upper quadrants of this diagram, there are purely applied attempts, based mostly on trial and error, by commercial "inventors" like Edison to invent new products. Alternatively, it is possible that investigation of a practical problem, like Pasteur's work on alcohol fermentation, might inadvertently lead to significant new scientific knowledge, such as the identification of the role of microorganisms in organic processes. The government has also been known—sometimes spectacularly successfully, as in some defense technology, agricultural science, and the space race; sometimes dismally, as in alternative energy research in the '70s—to organize, fund, direct, and either disseminate or use the skills and methods of science to meet a predetermined social need. This is illustrated in the lower left quadrant. Finally, Bush's vision is illustrated in the lower right quadrant. In this model, the government funds basic research but otherwise leaves its direction to the curiosity of the funded scientist.

How does this discussion relate to the current biotechnology era? First, recall that the major player in the fundamental developments of bioscience has been the NIH. In light of our discussion of the pervasive role of political considerations in generating support for science, the NIH represents a highly successful compromise model. It broadly represents the motivations of the public by its system of twenty-five institutes organized around body systems (e.g., the National Heart, Lung, and Blood Institute) and diseases (e.g., the National Cancer Institute). Moreover, as illustrated in Table 1, there is a rough and ready concordance between the nation's major health threats and the relative proportions of the NIH budget devoted to them. Yet within each institute, and in accordance with the Vannevar Bush vision, an extensive peer review system sorts out the particular researchers and projects that will be funded.

It would be a mistake to say that NIH policy is perfect. That is an unachievable goal for any public policy. There has continued to be debate in both the political and scientific communities about the proper balance between NIH funding of basic science and more applied clinical activities. But in broad perspective, considering both its successes and in its more realistic (compared with Bush's utopian ideal of science funded by the taxpayer but run only by scientists) political model, it is a fine example of a good policy that trumps a theoretically "best" one. Policymakers should be mindful that its success is based on so delicate a balance of social and intellectual forces. It is this system we have to thank for the efforts that have made the United States the world leader in biomedical science.

Table 1
Top Ten Diseases and Conditions by Level of NIH Funding, Fiscal Year 2000

Disease or condition	NIH funding
Cancer	$3.86 billion
HIV/AIDS	$2.01 billion
Heart research	$1.42 billion
Mental disorders	$853 million
Digestive diseases	$731 million
Drug abuse	$697 million
Diabetes	$525 million
Eye diseases	$485 million
Alzheimer's disease	$466 million
Smoking	$393 million

SOURCE: National Institutes of Health.

NOTE

[1] A nice illustration of the political and organizational tensions that surround the methods of public research fund allocation is recounted by Ruttan (2001, 568, note 23), who attributes the following comment to former Surgeon General Jesse Steinfeld: "If the space program had been conducted by NASA on an investigator-initiated project basis, we might now have 60,000 space scientists, each 80 miles on the way to the moon." Steinfeld's comment was made in light of his efforts to focus more of the NIH budget on disease-oriented clinical research, as opposed to basic science. Though amusing and true enough about the space race, we should be careful to note that it doesn't tell the whole story. The space race had a relatively stable goal in mind (put a man on the moon) and was working with relatively known scientific tools (rocket technology and planetary physics, etc.). Thus a centrally controlled crash program was feasible but, of course, not guaranteed. It is not clear that we know enough yet about cancer, for instance, to justify putting all of our scientific eggs into one basket.

REFERENCES

Arrow, K. J. (1962), "Economic Welfare and the Allocation of Resources for Invention," in *The Rate and Direction of Inventive Activity* (New York: National Bureau of Economic Research).

Bud, R. (1993), *The Uses of Life: A History of Biotechnology* (Cambridge: Cambridge University Press).

Bush, V. (1945), *Science the Endless Frontier: A Report to the President by the Director of the Office of Scientific Research and Development* (Washington, D.C.: U.S. Government Printing Office).

Dasgupta, P. (1987), "The Economic Theory of Technology Policy: An Introduction," in *Economic Policy and Technological Performance*, ed. P. Dasgupta and P. Stoneman (Cambridge: Cambridge University Press).

Griliches, Z. (1992), "The Search for R&D Spillovers," *Scandinavian Journal of Economics* 44: 29–41.

——— (1995), "R&D Productivity: Econometric Results and Measurement Issues," in *Handbook of the Economics of Innovation and Technological Change*, ed. P. Stoneman (Oxford: Basil Blackwell), 52–89.

Hall, B. H. (1996), "Private and Social Returns to Research and Development," in *Technology R&D and the Economy*, ed. B. R. Smith and C. E. Barfield (Washington, D.C.: Brookings Institution Press), 148–55.

Jones, C. I., and J. C. Williams (1998), "Measuring the Social Return to R&D," *The Quarterly Journal of Economics*, 1119–35.

Kleinman, D. L. (1995), *Politics on the Endless Frontier: Postwar Research Policy in the United States* (Durham, N.C.: Duke University Press).

Kornberg, Arthur (1997), “Support for Basic Biomedical Research: How Scientific Breakthroughs Occur,” in *The Future of Biomedical Research*, ed. C. E. Barfield and B. L. Smith (Washington, D.C.: American Enterprise Institute and The Brookings Institution).

Mansfield, E. et al. (1977), *The Production and Application of New Industrial Technology* (New York: Norton).

Martin, S. A., D. Winfield, A. Kenyon, J. Farris, M. Bala, and T. Bingham (1998), *A Framework for Estimating the National Economic Benefits of ATP Funding of Medical Technologies* (Research Triangle Park, N.C.: Research Triangle Institute). Available at www.rti.org/publications/cer/6715-001.pdf.

Nelson, R. R. (1959), “The Simple Economics of Basic Scientific Research,” *Journal of Political Economy* 67: 297–306.

Scherer, F. M. (1982),”Inter-industry Technology Flows and Productivity Growth,” *Review of Economics and Statistics* 64: 627–34.

Ruttan, V. W. (2001), *Technology, Growth and Development: An Induced Innovation Perspective* (New York and Oxford: Oxford University Press).

Steil, B., D. G. Victor, and R. Nelson, eds. (2002), *Technological Innovation and Economic Performance* (Princeton, N.J.: Princeton University Press).

Tassey, G. (1999), *R&D Trends in the U.S. Economy: Strategies and Policy Implications. A Planning Report of the National Institute of Standards and Technology* (Washington D.C.: National Institute of Standards and Technology, U.S. Department of Commerce). Available at www.nist.gov/director/prog-ofc/report99-2.pdf.