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What If Congress Doubled R&D Spending on the Physical Sciences?

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Executive Summary

Many business, academic, and scientific groups have recommended that the Congress substantially increase R&D spending in the near future. President Bush's American Competitiveness Initiative calls for a doubling of spending over the next decade in selected agencies that deal with the physical sciences, including the National Science Foundation. We consider the rationale for government R&D spending in the context of globalization and as an investment in human capital and knowledge creation with gestation times far longer than federal funding cycles. To assess the impact of a large increase in R&D spending on the science job market, we examine the impact of the 1998–2003 doubling of the National Institutes of Health (NIH) budget on the biomedical sciences. We find that the rapid increase in NIH spending and ensuing deceleration created substantial adjustment problems in the market for research and failed to address long-standing problems with scientific careers that are likely to deter many young people from choosing a scientific career. We argue that because research simultaneously produces knowledge and adds to the human capital of researchers, which has greater value for young scientists because of their longer future career life span than for older scientists, there is a human capital–based reason for giving awards to younger researchers relative to equally competent older researchers.

In his 2006 State of the Union Address President Bush announced the American Competitiveness Initiative—a program that promised to spend substantial federal moneys to redress perceived U.S. weaknesses in science and technology. One of the centerpieces of the initiative was a commitment to double basic R&D spending over the next decade at the National Science Foundation (NSF), the Department of Energy's Science Core programs, and the National Institute of Standards and Technology. Another component called for $4.6 billion in R&D tax incentives, intended to induce greater R&D spending by private firms. Much of the president's proposal was based on the National Academy of Sciences' 2006 *Gathering Storm* report, which called for large increases

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in federally funded R&D in physical sciences, among other policies, to keep the United States in the forefront of science and technology.

Congress responded to the Competitiveness Initiative by authorizing increased R&D spending, indicating that it desired to increase R&D support. But Congress did not appropriate the funds. Failure to appropriate the money reflected partisan disagreements in Washington and the greater importance of other budgetary and political considerations. The result was a modest change in federal spending for R&D in the physical sciences and stagnant federal support of R&D overall that reduced spending in real terms. Congress did, however, extend tax incentives for corporate R&D spending.

Between 2000 and 2006, many studies and reports called for improvements in the country's capacity in scientific and technological activity (Freeman 2006) by increasing R&D spending and investing more in science and engineering education. The call for increased resources for science and engineering was based on a widespread belief that "solutions to many of the challenges facing society have their roots in our scientific understanding, where technology increasingly drives the global economic engine, and where many other nations are gaining rapidly in scientific and engineering capabilities" (NSF 2007a, 1). Business leaders, particularly in high-tech sectors, were worried about increased foreign competition and the decline of comparative advantage in the R&D-intensive sectors of the economy. The science community decried a decreased rate of funding basic research proposals that "may be negatively impacting the academic research community, resulting in increased workload and diminished S&E capacity" (1). The National Institutes of Health (NIH) complained that it could not support as many high-quality research proposals as in the past, and the NIH and NSF reported that their peer review systems were overburdened with a growing number of research proposals. The military and defense establishment, whose hires are often limited to U.S. citizens, feared that not enough citizens and residents were choosing science and engineering careers.[1]

Given that most analysts recognized that the career incentives for entering science and engineering were too low to attract more U.S. students, nearly all studies favored educational initiatives to improve science in schools as well as spending increases to boost demand for scientists and engineers. The National Academy of Sciences' Board of Life Sciences recommended that NIH "take steps to provide PostDocs and early-career investigators with more financial support for their own research and establish programs for new investigators and staff scientists among other mechanisms" (NAS 2005, 1). The American

Academy of Arts and Sciences (2008) report on alternative models for funding the sciences called for funding directed at young investigators and at risky projects that could have high payoffs.

The widespread support for increasing the U.S. investment in science and engineering, particularly in the physical sciences, makes it likely that in the near future Congress will substantially boost R&D spending.[2] There are precedents for a surge in R&D spending to meet perceived national opportunities or needs. In 1998 a bipartisan coalition in Congress pressed the Clinton administration to increase the R&D budget substantially, with particular emphasis on the NIH. The coalition favored a doubling of NIH spending over 10 years, but the administration chose an even more rapid increase—a doubling in the budget over the next 5 years. In 2003 the Bush administration completed the doubling but then kept the budget roughly stable in nominal terms. Earlier, the Soviet Sputnik spurred a huge increase in federal R&D spending between 1956 and 1962. There have been smaller bursts of financial support for particular programs deemed of special national interest in given time periods such as the War on Cancer, Apollo, and the Nano-Technology Initiative.

How do large concentrated increases in R&D spending affect the market for research and the careers of scientists and engineers? How might the government best structure an increase to produce a bigger sustainable research system? Will increased spending improve the job market for young scientists and engineers and attract more Americans into the fields as many hope it will do?

This paper examines these questions. It reviews some of the evidence on the state of science and engineering that motivated the Competitiveness Initiative and the diverse reports that called for increased R&D spending. Then it assesses the doubling of the NIH budget from 1998 to 2003 and the ensuing deceleration in spending, focusing on the adjustment problems that result from rapid acceleration and deceleration of spending. The NIH doubling experience provides a warning sign of what might happen in the future to the physical sciences if funding increases for the NSF and the other agencies that support the physical sciences in the same manner that funding increased for NIH.

On the basis of this analysis, we consider ways for the federal government to boost R&D spending more efficiently in the future. Our main conclusions are as follows:

1. Increased R&D spending may not by itself resolve problems with the American scientific research endeavor. More funds may be necessary but

not sufficient to improve the opportunities for young researchers and to place basic research onto a long-term sustainable growth path. The way the funds are allocating and the time pattern of changes in funding are also important.

2. One-time surges in spending, which produce a deceleration after the surge, have sizable adjustment costs. Instead of making "doubling" spending a goal, policy makers could determine a desired ratio of R&D to GDP and increase funding smoothly to attain that goal. Agencies and universities could use "bridge funding" or stabilization policies to buffer research activity from rapid changes in spending.

3. The response of researchers to the incentives built into the number and size of research grants offered determines the effects of spending initiatives on research activity. When a funding agency increases the number and value of research grants, researchers submit more proposals, increasing the amount of research, along a supply curve. When an agency reduces the number of awards, in the short run researchers also respond by making multiple submissions. This stresses the peer review process and stability of the research market. Funding agencies have to balance changes in the number and value of grants carefully to reduce the adjustment costs of changes in budgets.

4. Viewing research grants as investments in the human capital of the researcher as well as in the production of knowledge, funding agencies could support proposals by younger researchers over equivalent proposals of older researchers. The reason is that younger researchers, by which we mean those with 20 or so years of likely future research careers, are more likely to use their increased human capital in future research because they have a longer career ahead of them than older researchers close to retirement.

I. Understanding the Concern

The Background

The U.S. share of science and engineering activity around the world is declining (see table 1 for an overview). This decline is inevitable as the rest of the world catches up to the United States in higher education and R&D. In 1970, with just 6% of the world's population the United States had 30% of the world's college students and graduated about 40% of science and engineering PhDs. By 2005, as countries around the world invested heavily in higher education, the U.S. share of college

Table 1
Declining U.S. Shares of World Science and Engineering Activity

Measure of Activity	Early Period	Later Period
College enrollments	30% (1970)	13% (2005)
Science and engineering undergraduate degrees	~20% (1970)	~9% (2004)
PhDs in science and engineering granted	40% (1970)	15% (2010)
R&D	~50% (1970)	~35% (2003)
ACS chemical abstracts	73% (1980)	40% (2003)
All science articles	39% (1988)	29% (2005)
All citations	36% (1992)	30% (2002)

Sources: College enrollments: Freeman (2008), based on tertiary enrollments from United Nations Educational, Scientific, and Cultural Organization, Institute for Statistics (http://stats.uis.unesco.org/unesco/TableViewer/tableView.aspx?ReportId-167, table 14), Montreal. Science and engineering undergraduate degrees: 2004 from NSF (2008, app. table 2-37), excluding social sciences; 1970 estimate from Freeman (2008). PhDs granted, R&D, and American Chemical Society chemical abstracts: Freeman (2006). Science articles: NSF (2007b, 2008, table 5-34). Citations: NSF (2008, app. table 5-38), where 2002 refers to articles written in 2001–3 cited by 2005 articles (%); 1992 refers to 1991–93 articles cited by 1995 articles.

enrollments had fallen to 13%. The U.S. share of the world's science and engineering graduates is, moreover, below its share of all graduates because science and engineering attract larger proportions of students overseas than in the United States. At the doctorate level, the U.S. share of science and engineering degrees fell to 20% in 2000 and is expected to reach 15% in 2010. The United States contributed about half of the world's R&D spending in the 1970s, but this dropped to about a third by 2003.

Partly in response to the growth of scientific and engineering talent around the world, the multinational firms that undertake most industrial R&D increasingly invest in R&D outside the United States as well as in the United States. The large number of science and engineering graduates in China and India combined with the lower wages in those countries makes them attractive sites for multinational R&D facilities. In 2004 China reported that multinationals had established over 750 R&D facilities, whereas in 1990 they had none. In 1991 the United States spent 13 times as much on R&D as China. In 2003 it spent only 3.4 times as much (Freeman 2006).

About 60% of basic research in the United States is conducted in universities, largely funded by the federal government.[3] The major federal funding agencies for basic research in the physical sciences are the NSF, Department of Defense, Department of Energy, and National Institute of Standards and Technology; the NIH is the main funder of basic research in the biological sciences. The NSF supports over 50% of the federal nonmedical fundamental research at U.S. colleges and universities. From 1990 to 2006 the share of R&D funded by the federal government fell from 40.5% to 28.4%. Compared to GDP, federal R&D fell from 0.112% to 0.073%.[4]

As the U.S. share of scientists and engineers and R&D worldwide has trended downward, so too has the U.S. share of scientific publications and citations. Data from the Chemical Abstracts Services show that in 1980 the United States had 73% of papers in the field, whereas in 2003 U.S. researchers had only 40% of the papers (Freeman 2006). The U.S. share of science articles published fell from 39% in 1988 to 29% in 2005, and the U.S. share of citations dropped from 36% of articles written in 1992 to 30% of articles written in 2002.

Given the demography of the world, the United States cannot maintain the dominance in science and technology that it enjoyed in the last half of the twentieth century. It can, however, be a leading center of excellence of basic R&D if it invests more in R&D and makes science and engineering careers attractive to young Americans and to immigrant scientists and engineers.

Why Care?

The calls for increased federal spending on basic science and related policies are motivated by economic and national security concerns. On the economic front, there is widespread belief that the United States is more likely to maintain production and jobs in high-tech sectors if the country pioneers scientific advances than if other countries pioneer those advances. The growth of high-tech employment in Silicon Valley and in university-based locations of scientific excellence suggests that innovation, production, and employment in high tech occur largely in areas with excellence in science.[5] Since leading-edge industries have the fastest long-run productivity growth, pay higher wages to most workers,[6] and offer spillovers of knowledge to other sectors, there is global competition for these industries. Advocates of increased federal spending for basic R&D also argue that the more basic R&D performed in the United States, the more likely it is that the country will attract industry in research-intensive sectors.[7]

To take the argument a step further, many analysts note that the United States' comparative advantage in global markets lies in high-tech, research-intensive industries. Were the United States to lose comparative advantage in those sectors, it would have to sell goods or services with lower technological content on the global market and compete with countries with similar technology and low wages. The gains from trade would lessen and wages would fall for American workers.

In terms of national security, proponents of increased U.S. investment in science and engineering note that current "technologies for counterterrorism and homeland security are outcomes of earlier US investments in science, technology, and education" (Jackson 2003, 1) and argue that science and technology offer the best defense against terrorist threats. The National Security Agency and various Defense Department laboratories and contractors hire only U.S. citizens for critical research tasks, which makes them particularly sensitive to the supply of citizens in the relevant fields. The science and engineering workforce in security areas has become top-heavy with older workers, which will create large replacement demands for citizen researchers.

A More Critical Assessment

Economic analysis provides some support for these arguments but also offers some caution about how much weight to place on them. For reasons of *knowledge spillovers* and *economic competitiveness*, investments in basic research can pay off in ways that justify major public investments.[8] But to determine whether the United States is currently at, below, or above the socially optimal level of public spending on basic research is not an easy task. In a global economy, where other countries are also investing in basic and applied research and where major U.S.-owned firms have become "global firms," it has become more difficult to assess the optimal level of public support for basic research than it was in the past.

Knowledge Spillovers

Economists focus on knowledge externalities as the main reason for public spending on research. Because of the public-good nature of knowledge, the benefits of research "spill over" to other agents and are only partially captured by the person or firm that originally invested in it. The result is that the private market will invest less in R&D than is socially optimal, giving a strong rationale for government spending on R&D in various ways. A large body of evidence shows that knowledge spillovers are statistically and economically significant.[9] Such spillovers are the foundation of modern growth theory (e.g., Romer 1989; Aghion and Howitt 1990).

While knowledge has always moved across international boundaries,[10] the spread of higher education and transfer of technology by multinational firms from advanced countries have made R&D more international than ever before (Freeman 2006). If knowledge spread instantly across boundaries, the rationale for government subsidies to research would decrease in favor of global subsidies.[11] In reality there is some localization or "stickiness" to research so that the country or region within a country that does the research disproportionately benefits from the spillover. But modern communication such as the Internet and falling transport costs appear to have reduced this advantage (Griffith, Lee, and Van Reenen 2007), weakening the spillover justification for R&D subsidies. By a similar logic, the growth of an international labor market for scientists has meant that many U.S. universities attract postdocs and faculty from the international market, reducing the necessity of using U.S. taxpayers' money to train the next generation of scientists and engineers.

Economic "Competitiveness"

Firms compete in the marketplace: when one firm does better, it is often at the expense of other firms. Countries do not "compete" in the same sense. While there are situations in which one country's gain is another country's loss (see, e.g., Baumol and Gomory 2004), the benefits of R&D-induced or other innovations that improve productivity in one country are likely to flow to persons in other countries as well. Given the public-good nature of R&D and trade in goods and services, the expansion of modern scientific and technological activity in the world should improve the lives of people worldwide regardless of the location of the innovative activity. If a medical scientist in China, India, the United Kingdom, or anywhere else finds a cure for cancer, we will all benefit. If a German innovation lowers the price of household goods and services, we will all benefit. If scientific advances and innovations overseas lead foreign firms to set up production facilities in the United States or if U.S. firms exploit overseas innovations to produce in the United States, this will create jobs as well as better products.

At the same time, countries can use publicly funded R&D to boost their strategic position in some sectors, potentially creating comparative advantage that would not exist without public support (e.g., in the commercial airline market). Strategic trade theory has models in which R&D subsidies can help countries attract and retain rent-generating R&D-intensive sectors (e.g., Brander and Spencer 1985).[12] At the same time, the

Table 2
Rationale for Government Support of R&D

Justification for Taxpayer Support of R&D Spending	Basic Research (Federal Grants, Largely to Universities)	Applied Research (e.g., R&D Tax Credits)	What Is the Impact of Globalization on the Rationale?
Knowledge spillovers	Yes	Some	Probably weakens rationale
Economic competitiveness	None/little	Yes	Probably strengthens rationale

fall of transportation costs and entry barriers makes multinational R&D more internationally mobile. For example, "footloose" R&D may be able to move more quickly to jurisdictions offering a more favorable tax regime for R&D (see Wilson [2008] for evidence of this in the U.S. context). By making it easier to attract R&D, this sharpens the case for subsidizing science on economic competitiveness grounds.

These arguments are summarized in table 2. In our view, knowledge spillovers are the strongest argument for R&D subsidies, especially for basic research compared to applied research. Nonetheless, globalization has probably weakened the case for such subsidies, whereas it has strengthened the case for subsidies to applied research. There are two caveats to this assessment. First, if basic research is complementary to applied research, then subsidies to basic research could "crowd in" more applied research. There is evidence on this from the positive local effects of university research (e.g., Jaffe 1989). But at some point basic and applied research are substitutes; in terms of federal subsidies, for example, spending more on one means cutting back funding on the other. Second, the normative argument for strategic R&D subsidies is weakened by the fact that other countries may respond to U.S. subsidies with their own subsidies. Countries' competing in subsidizing R&D to attract high-tech firms is like an auction for multinational R&D. The main winners of this auction are likely to be multinational companies and their shareholders rather than taxpayers.

The U.S. Position in Innovation

While the U.S. share of world R&D and the science and engineering workforce have fallen as other countries have invested higher education and research, the United States remains the world leader in scientific and technological competence. The United States spends more on

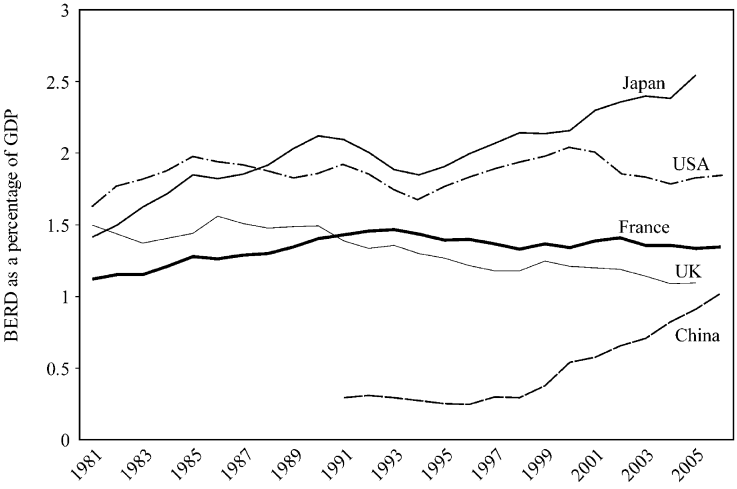

Fig. 1. Business enterprise research and development (BERD) as a percentage of GDP in selected countries. Source: OECD.

R&D in total dollars and has more scientists and engineers doing research, basic and applied, than any other country. The ratio of R&D to GDP in the United States is higher than in other major advanced countries except for Japan (NSF 2008, app. table 4-35). Despite the European Union's "Lisbon Agenda" push to raise the R&D/GDP ratio to 3%, the large countries in the European Union continue to fall far short of the U.S. level of 2.6% in 2005.

European countries have increased government investment in R&D relative to GDP, but European firms invest a much smaller share of revenues on R&D than U.S. firms, which have raised their R&D budgets even as the federal government has invested less. Figure 1 shows the position of R&D performed by business as a proportion of GDP in several major countries since 1981. The U.S. business R&D to GDP (BERD) ratio has remained broadly stable, rising modestly from 1991 (1.5%) to 2006 (1.7%). It exceeds all the other major nations except Japan. In contrast, Chinese business R&D has come from nowhere in the 1980s to over 1% of GDP today. This illustrates both the remarkable catch-up by China and the fact that China remains less R&D intensive than the United States.

How has the United States done in the R&D-intensive high-tech industries? Table 3 shows that from 1980 through 2003 the United States did well by several measures of innovativeness and production in high

Table 3
U.S. Shares of USPTO Patents, Shares of World High-Tech Output, and Trade Balance in Manufacturing

Measure	1980	1990	2000	2003
U.S. first-name inventor share USPTO patent applications (%)*	55	55	56	53
U.S. first-name inventor share EPO patent applications (%)*	27	27	26	23
U.S. share of world gross revenue in high tech (%)	28	25	38	39
U.S. share of world value added in high tech (%)	25	25	40	42
U.S. share of world exports in high tech (%)	30	23	18	15
U.S. share of world imports in high tech (%)	13	18	20	17
U.S. trade balance in high tech ($billions)	+34	+27	−40	−90

Source: NSF (2008), tables 6.31 and 6.32 for USPTO patent data, tables 6-41 and 6-42 for EPO patent data, tables 6.8 and 6.9 for value added, and tables 6.14 and 6.15 for total revenue, exports, and imports.

Note: High-technology manufacturing industries as classified by the OECD include aerospace, communications equipment, office machinery and computers, pharmaceuticals, and scientific instruments. Value-added revenue excludes purchases of domestic and imported materials and inputs. Constant dollar data for foreign countries are calculated by deflating industry data valued in each country's nominal domestic currency with a sector-specific price index constructed for that country and then converted to U.S. dollars on the basis of average annual exchange rates.

*Patent statistics refer to 1985 as the first year rather than 1980 and 2005 (USPTO) and 2006 (EPO) as the last year rather than 2003.

tech. The share of U.S. Patent Office (USPTO) patent applications going to first-named U.S. persons remained roughly constant from 1985 to 2005, whereas the share of European Patent Office (EPO) applications going to first-named U.S. persons fell only slightly. In high-tech manufacturing[13] the U.S. share of world gross revenue and of value added rose during the 1990s boom and remained high through the early 2000s. In the global economy, where firms outsource parts of activities to different places in the world, the most meaningful measure of U.S. economic activity relative to other countries is value added. The U.S. share of world value added in high tech rose from 25% in 1990 to 42% in 2003.

Where U.S. performance has been less impressive is in the balance of trade. In 1980 and 1990 the United States ran a large balance of trade surplus in high tech, which partially counterbalanced the country's trade deficit in other goods. The trade balance in high tech turned negative in 2000 and has gone more negative since, along with the rest of the country's balance of trade (Weller and Wheeler 2008).

Since patents and production depend on past scientific advances, it is possible that the positive picture of U.S. performance in high-tech science-intensive sectors shown in table 3 reflects the advantages of

U.S. investments in R&D in past years. From this perspective, the call for increased federal R&D spending and the investment in science and engineering workers is more of a preemptive warning than a response to any economic disaster. Given that research is exploration of the unknown with payoffs in the future, this is arguably the appropriate way to interpret the Competitiveness Initiative and plethora of calls for additional R&D spending.

II. The NIH Doubling

Background

To see how a potential future rapid increase in R&D spending on the physical sciences might affect researchers, we examine the 1998–2003 doubling of the NIH research budget and the subsequent deceleration of NIH funds.[14] Figure 2 displays the level and percentage change in NIH funds from 1995 through 2007. From 1998 to 2003 the NIH budget grew by double-digit amounts in nominal terms, which raised annual NIH spending from about $14 billion to $27 billion. In constant conumer price index (CPI) dollars, real research funding increased by 76%. In the decade prior to the doubling (1987–97), real NIH funding deflated by the CPI increased by only 40% (NSF 2004, table 1H). Thus the doubling raised NIH spending by twice as much in 5 years as it had done in the previous decade. From the Biomedical R&D Price Index (BRDPI), which rose more rapidly than the CPI, the doubling increased spending by 66%.

When the doubling ended, the Bush administration recommended a rapid deceleration in NIH funding, which Congress largely followed. The rate of increase in spending dropped in nominal terms to 3% in 2004, to 2.2% in 2005, to −0.1% in 2006, and to 0% in 2007. From the CPI deflator, real NIH spending was 6.6% lower in 2007 than in 2004; it is expected to fall 13.4% below the 2004 peak by 2009 (Garrison and McGuire 2008). From the BRDPI deflator, real spending was down 10.9% through 2007. The drop in the real NIH budget shocked the agency and the bioscience community since it undid much of the extraordinary increase in funding from the doubling. NIH director Elias Zerhouni said that even in "the worst scenario, people really didn't think that the NIH budget would go below inflation" (quoted in Couzin and Miller 2007, 357). The NIH responded first by reducing the number of grants awarded and then by reducing the amounts of grants. For the postdoctorate researchers trained during the doubling period and for the young

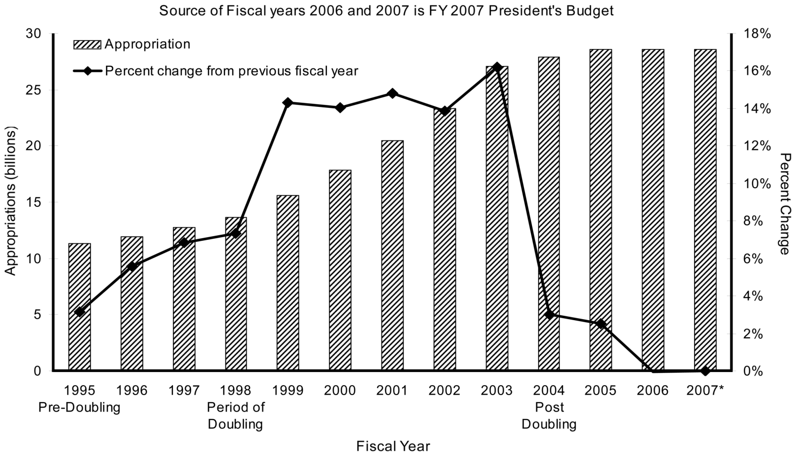
Source of Fiscal years 2006 and 2007 is FY 2007 President's Budget

Fig. 2. The acceleration and deceleration of NIH spending under the "doubling goal"

researchers who obtained their first independent research grants during the doubling, the deceleration created a career crisis. For principal investigators with NIH support, it also posed major problems, as the probability of continuing a grant and making a successful new application fell and as the size of grants shrank. Research labs were pressured to cut staff. At NIH, which is the single-largest employer of biomedical researchers in the country, with over 1,000 principal investigators and 6,000–7,000 mostly PhD researchers, the reduced funding led to a contraction in the number of principal investigators by 9%. "A completely new category of nightmare" was the description given by a researcher in the National Institute of Child Health and Development, which was especially hard hit (*Science*, March 7, 2008, 1324). Others in the scientific and university community also reacted with dismay or horror. Typical examples follow:

> The marvellous engine of American biomedical research that was constructed during the last half of the 20th century is being taken apart, piece by piece. (Robert Weinberg [founder of Whitehead Institute], *Cell* 126 [July 14, 2006], 10)

> Without effective national policies to recruit young scientists to the field, and support their research over the long term, in 10 to 15 years, we'll have more scientists older than 65 than those younger than 35. This is not a sustainable trend in biomedical research and must be addressed aggressively. (NIH Director Zerhouni, http://www.president.harvard.edu/speeches/faust/080311_NIH.html).

Most of the scientific community views the doubling as having significantly increased the rate of biomedical knowledge creation above what it otherwise would have been. But the effects of the doubling may have been muted because of the adjustment costs associated with such a rapid increase (see below). If, moreover, labor supply is inelastic, the increase in funding will show up in the short run in higher wages for scientists rather than an increase in research (Goolsbee 1998), though in the long run the higher wages will presumably attract more talent into science. Given the international mobility of scientists, moreover, increased spending is more likely to prompt migration into the United States of overseas scientists and postdocs than in the past.

Still, it is hard to find clear evidence that the doubling raised scientific output. Sachs (2007) noted that the number of biomedical publications from U.S. labs grew at a steady rate after 1999. The share of U.S. science and engineering articles in the biological and medical sciences from 1995 to 2005 (NSF 2007a, app. table 5-36) did not tilt toward these areas despite their increased share of the nation's basic research budget. Using a regression discontinuity design that compared the publications of scientists who just succeeded in obtaining an NIH grant with the publications of those who just failed to obtain a grant in the period 1980–2000, Jacob and Lefgren (2007) found only a small impact of receiving an NIH grant on research output, though one that is larger for younger than for older scientists. To be sure, without a well-specified counterfactual of what would have happened without the doubling or with some adjustment in the numbers of articles for their quality, we cannot rule out the possibility that the funding in fact spurred more and better science. Still, the data are consistent with the notion that by increasing spending quickly in a short period, NIH did less to increase scientific production than it might have done if it had increased spending more evenly over time.

Our analysis highlights two problems with the NIH pattern of increasing R&D spending: the front-loading of the increase in a short period of time and the allocation of the increase between the size and number of grants and between younger and older researchers. We consider the economics of each problem in turn.

Big Push versus Gradual Change

In general, a rapid acceleration in spending followed by a rapid deceleration is an inefficient way to get to a permanently higher level of research activity and stock of research scientists. To see why this is so, we apply the classic accelerator model of investment in physical capital to increasing R&D. We treat the stock of research by the "perpetual inventory formula" $K_t = I_t + (1 - \delta)K_{t-1}$, where K is the number of scientists engaged in research, I is the number of newly trained scientists (postdocs) who enter into research, and δ is the proportion of scientists who leave research each year for retirement or other reasons. In this model, K_t is the stock of activity in year t, I_t is the flow of new activity, and δ is the depreciation rate. The values of K and I are related to the number of trained scientists or new scientists by a fraction θ, which measures the proportion who work in academia doing basic research. The rest are engaged in other activities—working in industry or government—or teaching, doing administration, and so on.

In the accelerator model of investment, an increase in the demand for output induces firms to seek a higher capital stock to meet the new demand. This increases investment spending quickly. When firms reach the desired capital stock, they reduce the rate of investment sharply. Analysts of business cycles have long used this model to explain the greater volatility of investment than of consumption spending that contributes to cyclical fluctuations in the economy. In the case of basic R&D, assume that society wants to increase the stock of research activity from K^{OLD} to a new desired level of K^{NEW}. The goal is to increase the stock of research activity, not to "double" or otherwise increase the flow of spending. While it may attract public or political support by making the increase in spending the goal, it is the sustainable stock of research activity that presumably contributes to national output.

The optimal path to attaining a higher stock depends on the costs of adjustment, which will include such things as disruptions to labs, the hiring of new staff, the purchase of new equipment, and so on. Most empirical studies find evidence that adjustment costs for R&D are substantial compared to other forms of investment (Hall 1992; Himmelberg and Peterson 1994; Bond and Van Reenen 2008). We assume that the costs rise more than proportionately with the size of the change in any period. Building one new R&D lab involves disruption; building five new labs at the same time is likely to be more than five times as disruptive.[15] Many models of adjustment use a quadratic cost curve to measure this more than proportionate rise in cost. If adjustment costs take any convex form of this type, the ideal adjustment path is a slow incremental movement to the new desired level. This would mean increasing R&D incrementally to reach K^{NEW} rather than increasing it in a sudden burst.

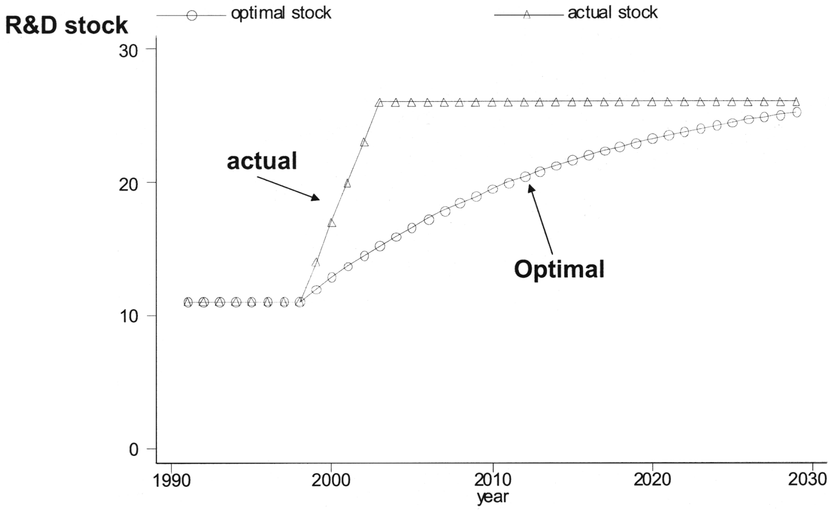

Fig. 3. Comparison between doubling research and the socially optimal path of increase. This compares a stylized version of the doubling of NIH funding to an optimal path when adjustment costs are convex.

Figure 3 shows the difference between the optimal relatively smooth adjustment to the new level of K and adjustment that more closely mirrors the NIH doubling. At the start of the period, investment is just equal to the depreciated old capital (e.g., the flow of new postdocs exactly balances the retiring older scientists so that $I_t = \delta K_{t-1}$). The line of circles shows the ideal increase to the new level K^{NEW}. The line of triangles is closer to what actually happened. The area in between determines the inefficiency of the system. The inefficiency means that society could have greater total R&D activity in the long run if it increased spending more gradually. With quadratic adjustment costs, the inefficiency can be substantial.[16]

The way biomedical research works, with senior scientists running labs in which postdocs and graduate students perform most of the hands-on work, much of the adjustment costs fall onto young researchers. An increase in R&D increases the number of postdocs hired and the number of graduate students that principal investigators seek to attract to their labs. Parallel to the rapid rise of investment when demand for output rises in the accelerator model of physical capital, the number of postdocs/graduate student researchers grows sharply with increased R&D. The benefits or costs of the adjustment fall disproportionately

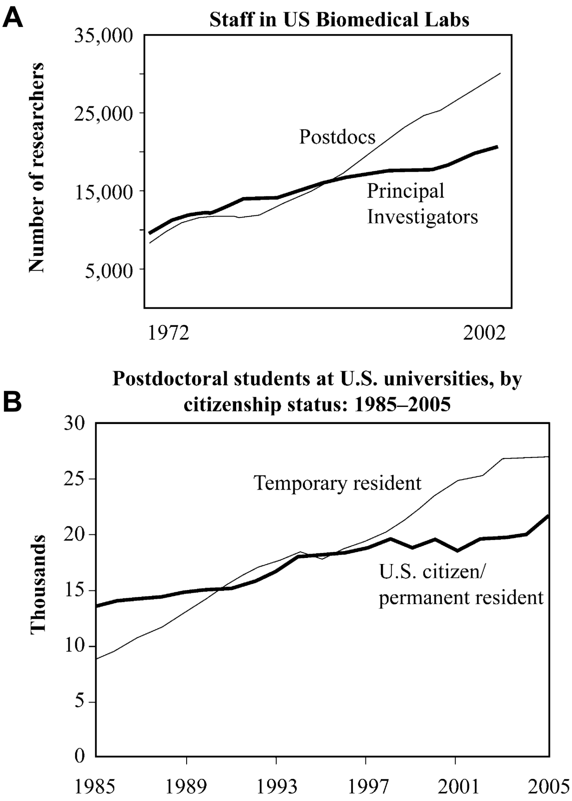

Fig. 4. Increase in the ratio of postdocs to principal investigators in U.S. biomedical labs and the increase in foreign-born postdocs compared to U.S. postdocs. *A*, Postdocs compared to principal investigators. *B*, U.S. versus foreign-born postdocs. Sources: NSF, Division of Science Resources Statistics, Survey of Graduate Students and Postdoctorates in Science and Engineering (WebCASPAR database: http://webcaspar.nsf.gov), app. table 2-34; NSF (2008).

on the new entrants into the market. On the benefit side, increases in demand should raise the pay and job opportunities more for new graduates than for older scientists. On the cost side, young persons trained during an upsurge in spending will compete with a larger supply of young biomedical researchers after the upsurge, when there are likely to be no greater or even fewer independent research opportunities than when they were attracted to the field.

Figure 4*A* shows that during the doubling period the number of postdocs increased rapidly whereas the number of principal investigators barely changed. Figure 4*B* shows that much of the increase in postdocs during the doubling period came from foreign-born PhDs, of whom about half were trained outside the United States.

Even before the doubling there was a sizable increase in the number of postdocs in the United States. The number of postdocs began increasing rapidly in the early 1980s (Garrison and McGuire 2007, slide 28), producing a major imbalance between the number working in academic labs and the number of tenure-track academic jobs to which they could aspire. In 1987 the ratio of postdocs to tenured faculty in the life sciences was 0.54—or approximately one postdoc for every two faculty. By 1999, the ratio of postdocs to tenured faculty had risen to 0.77. The situation did not change much in the doubling period. The number of full-time senior faculty in the life sciences grew by 13% (NSF 2008, app. table 5-19) and the number of postdocs in biological sciences grew by 18% (NSF 2007b, table 49). In the 1970s about three-quarters of postdocs obtained academic jobs, but no more than 20%–30% of the increased number in the 2000s can expect positions in academic research. The vast bulk of postdocs will end up in nonacademic research jobs. The slowdown of NIH spending after the doubling led to effectively no growth for either senior faculty or postdocs.

In sum, the rapid acceleration and deceleration of NIH spending created problems for researchers and potential researchers. In considering any future increases in federal support for basic research, policy makers could focus on the rate of scientific activity relative to GDP rather than on increasing the rate of spending over a short period. The most efficient policy is to move slowly to the desired level of R&D, minimizing as far as possible adjustment costs, rather than following a "feast then famine" spending policy. In our conclusion we offer some suggestions as to how to do this in a world in which Congress sets budgets annually.

Internal Organization of Biomedical Research

At the heart of the American biomedical science enterprise are the R01 grants that the NIH gives to fund individual scientists and their teams of postdoctorate employees and graduate students. The system of funding individual researchers on the basis of unsolicited applications for research support comes close enough to economists' views of how a decentralized market mechanism operates to suggest that this ought to be an efficient way to conduct research compared, say, to some central planner mandating research topics. The individual researchers choose the most promising line of research on the basis of "local

Table 4
Applications, Awards, and Success Rates for RO1 and Equivalent Grants, by Status of Applicant

	1980	1998	2003	2006	2007
Potential first-time awardees:					
Applications	8,515	6,817	8,377	9,399	…
Awards	1,903	1,484	1,720	1,384	1,663
Success rate	22.3	21.3	20.5	14.7	…
% of successful with original proposal	86	61	49	34	28
% of successful with first amendment	13	29	38	40	41
Experienced (previously funded) applicants:					
Applications	7,404	13,666	16,325	19,822	…
Awards	3,240	4,782	5,730	4,677	
Success rate (%)	43.8	35.0	35.1	23.6	

Source: http://grants.nih.gov/grants/new_investigators/Workforce_Info09072007.ppt (09-7-2007), app. A table.

knowledge" of their special field. They submit proposals to funding agencies, where panels of experts—"study sections" in the NIH world—give independent peer review, ranking proposals in accordance with criteria set out by funding agencies and their perceived quality. Finally, the agency funds as many proposals with high rankings that it can within its budget constraints.

On the funding side, there is also competition. There are nongovernment funders such as the Howard Hughes Foundation, a major supporter of independent researchers, and many medical foundations focused on particular diseases or issues, as well as the NSF and other government agencies. The NIH itself, moreover, is a diverse institution with a variety of programs, institutes, and centers that make their own research support decisions. With many groups seeking to support research and many scientists seeking support for their research, the level of competition would seem to be sufficiently broad and wide to yield good economic outcomes.

Still, in the market for biomedical research, NIH is the 800-pound gorilla. For most academic bioscientists, winning an NIH R01 grant is critical to their research careers. It gives young scientists the opportunity to run their own lab rather than to work in the lab of a senior researcher or to have to abandon research entirely. For scientists who have an NIH grant, winning a continuation grant is often an implicit criterion for obtaining tenure at a research university.

Table 4 provides a statistical overview of the RO1 granting process from 1980, when it was relatively easy for biomedical scientists to obtain grant support, through the 1998–2003 doubling period and through

2007. It presents data for two groups of applicants for research awards. The first group consists of "potential new awardees"—researchers who had not previously applied for an NIH grant.[17] Because postdocs rarely apply for the RO1s, potential first-time awardees are primarily newly hired assistant professors in research universities.[18] The second group consists of experienced researchers, those who had previously been funded by NIH. They may be applying for a continuation grant or possibly a new grant to undertake a project that differs from what they had been working on.

In 1980 the agency received more applications from potential new awardees than from experienced researchers but gave more awards to previous awardees than to new investigators. It funded 44% of experienced applications versus 22% of applications from new investigators. As the stock of researchers increased in the 1980s and 1990s, the number of submissions from previous awardees increased. By 1998 the agency had fewer submissions and gave fewer awards to new researchers than in 1980, whereas it had more submissions and gave more grants to experienced researchers.

During the doubling period, the number of applications from both potential new awardees and experienced researchers increased significantly, and the NIH gave more grants to both. The deceleration in the funding of the NIH produced a sizable drop in the number of grants awarded from 2003 to 2006 even as the number of submissions increased, again with the percentage changes being larger for the potential awardees. In 2006 the NIH trimmed the amounts it gave for continuing grants by 2.35% despite inflation and used the funds saved to increase the number of grants to new researchers, though the number of awards still remained below the number in 2003. It did this in an effort to keep new researchers with high-quality proposals in research activity.

The rows in table 4 referring to success rates of potential first-time awardees with their original proposal or with a first amendment show another change in the research process: a marked drop in the percentage of applicants who gain a grant with their original submission.[19] In 1980, 55% of awardees who succeeded in gaining support did so on their first submission compared to 28% of awardees in 2007. Increasingly, researchers gain awards after amending the submission to meet with objections or suggestions of the panel that reviewed their proposal. The sum of the percentages for success with the original proposal and the first amendment also drops over time, implying that the NIH asked for second or

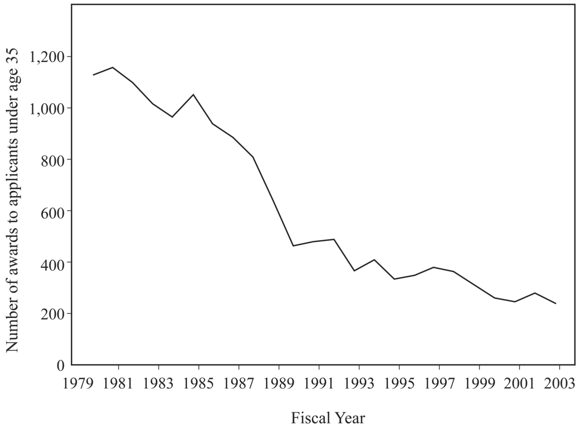

Fig. 5. Number of persons younger than 35 years old getting RO1s

third submissions before giving a grant. This means that projects were delayed for perhaps a year.

While it is common to refer to new RO1 awardees as "young researchers," the term is a misnomer. Because R01s generally go to scientists who are assistant professors or higher in their rank and the length of postdoctorate jobs has grown over time, the average age of a new recipient was 42.9 in 2005, up from 35.2 in 1970 and 37.3 in the mid-1980s. According to the numbers in figure 5, in 1980, 22% of grants went to scientists 35 and younger, but the proportion trended downward so that in 2005, just 3% of grants went to scientists 35 and younger. By contrast, the proportion of grants going to scientists 45 and older increased from 22% to 77% of R01s. Within the 45 and older group, the largest gainers were scientists aged 55 and older.

Part of this change is associated with an aging of the science workforce, but most of it is due to the changing organization of research, which gives older investigators substantive advantages in obtaining funding and places younger researchers as postdocs in their labs. When we take account of the distribution of PhD bioscientists by age, the relative odds of a younger scientist gaining an NIH grant compared to someone 45 and older dropped over 10-fold. We do not attribute this pattern to the doubling of research moneys since it reflects a longer-run trend. But we note that the NIH did not use the extra moneys to improve career prospects for graduate students or postdocs. The result is considerable malaise among graduate students and postdocs in the life sciences as well as among senior scientists concerned with the health of their field (NRC 1998; NAS 2005; American Academy of Arts and Sciences 2008).

Research Grants for Younger Scientists?

Should the country be concerned about the small, declining share of grant moneys that goes to younger scientists and to the increased number of years that it takes them to obtain independent research support? In terms of economic analysis, there are three reasons for believing that the concentration of research support on older scientists has deleterious effects on research productivity.

The first is the possibility that scientists are more creative and productive at younger ages. Measured by numbers of papers, there is evidence that productivity falls with age in at least some fields (Lehman 1953; Zuckerman and Merton 1973; Simonton 1988; Levin and Stephan 1991) and that productivity in research institutes is lower when the average age of researchers is higher (Bonaccorsi and Daraio 2003). Jones (2005) finds that major breakthroughs in science and innovations occur primarily when scientists or inventors are in their 30s or 40s, but that in recent years the greater investment in knowledge to get to the frontier has meant that the age at which people make their great contributions has increased. To the extent that younger scientists are more likely to undertake breakthrough research when they have their own grant support rather than when they work as postdocs in the labs of senior investigators and are more likely to undertake such work than older scientists, concentrating research support on the older group reduces the productivity of research and the payoff from government funding.[20]

The second reason is that supporting scientists earlier in their careers will increase the pecuniary attractiveness of science and engineering to young persons choosing their life's work. It will do this because the normal discounting of future returns makes money and opportunities received earlier more valuable than money and opportunities received later. If students who consider science careers had a better chance to become independent investigators in their 30s rather than in their 40s or 50s, we would expect the number who chose science to be higher than it is today.[21]

The third reason relates to the likely use of new knowledge uncovered by researchers. A research project creates two outputs. It produces research findings that are public information. But it also increases the human capital of the researcher, who knows better than anyone else the new outcomes and who probably has better ideas of how to apply them to future research or other activities than other persons. Assume that an older researcher and a younger researcher are equally productive and accrue the same additional knowledge and skills from a research project. Then because the younger person will have more years to use the new knowledge, the social payoff from funding the younger person will be higher than from funding the older person. Just as human capital theory says that people should invest in education when they are younger because they have more years to reap the returns than if they invested when they are older, this line of thinking implies that it would be better to award research grants to younger scientists than to otherwise comparable older scientists.

In sum, economic analysis lends some support to the views of the scientific community that society would likely get more "bang for its research buck" if the internal structure of research funding was more favorable to younger researchers than it is.

III. Funding Agency and Researcher Behavior

Funding agencies and researchers interact in the market for research grants. An agency with a given budget must decide how to allocate the budget between the number of grants and the sizes of grants, presumably with the goal of maximizing research output. Should it give fewer large grants or more small grants? Should it favor new research submissions, whether from younger or experienced researchers, or continuance of existing grants from experienced researchers? The effect of these decisions on research output depends in turn on how researchers respond to changes in the dollar value and number of potential research awards.

Table 5 shows that during the doubling, NIH increased the average value and number of awards, particularly for new submissions (which includes new projects proposed by experienced researchers as well as projects by new investigators). With the success rate of awards stable at roughly 25%—a proportion that the agency views as desirable to support on the basis of the quality of proposals—the number of awards increased proportionately to the number of submissions.

From 2003 to 2006, when the budget contracted in real terms, the NIH maintained the value of awards in real terms and reduced the number of new awards by 20%. With the number of new submissions growing, the result was a large drop in the success rate. In 2007, the

Table 5
The Reduced Chance of Getting NIH R01 Grants and the Increased Number of Submissions Needed to Get an NIH Grant

	1997	2003	2006	2007
New submissions:				
Submissions	14,814	18,738	22,150	20,651
Awards	3,476	4,526	3,612	3,961
Success rate (%)	23.5	24.2	16.3	19.2
Success rate for original submission (%)	18.7	17.0	7.9	8.4
Proportion winning on original submission (%)	55	51	32	28
Average number of submissions per award	1.6	1.7	2.0	2.1
Average value of award	$217,348	$345,426	$359,911	$382,782
Continuation grants:				
Submissions	5,510	5,785	6,830	6,586
Awards	2,624	2,858	2,388	2,468
Success rate (%)	47.6	49.4	35.0	37.5
Success rate for original submission (%)	47.5	40.2	25.7	25.2
Proportion winning on original submission (%)	44	61.8	41.8	36.8
Average number of submissions per award	1.4	1.5	1.8	1.9
Average value of award	$261,662	$357,103	$374,288	$386,507

Source: Office of Extramural Research, NIH, "Success Rates for NIH Type 1 Competing Research Project Applications" (http://grants.nih.gov/grants/award/success.htm), Excel file, by amendment status.

NIH squeezed the budgets of existing projects and raised the number of new awards. The data on continuation grants for existing projects show a similar pattern: increases in the number and amount awarded during the period of doubling and reductions in numbers awarded relative to submissions afterward.

Although its budget increased more modestly in the early and mid-2000s, the NSF faced similar decisions regarding the allocation of budgets between the number and average size of awards (amount per year and duration) and between new and previously funded investigators. Responding to a 2001 Office of Management and Budget concern that NSF researchers spent too much time writing grant proposals instead of doing research, the NSF decided to increase the amount of research awards while holding fixed or reducing the number of awards. Giving larger grants to a smaller proportion of researchers would, in the NSF's eyes, "minimize the time [principal investigators] would spend writing multiple proposals and managing administrative tasks, providing increased stability for supporting graduate students" (NSF 2007a, 5). Table 6 shows that, consistent with this, the NSF increased the mean dollar value of awards from 1997 to 2006 by 72% (from $78,223 to $134,595) compared to a 13% increase in the number of awards. The

Table 6
National Science Foundation Research Proposals and Awards, 1997–2006

	1997	2006
Competitive proposals	19,935	31,514
Competitive awards	5,961	6,708
Funding rate	30%	21%
Proposal submitted per principal investigator receiving one award	1.7	2.2
Average mean award size	$78,223	$134,595

Source: NSF (2007a, figs. 2–4).

number of research proposals grew rapidly over the period, presumably in part because of the increased dollar value of awards, but also possibly because of the greater ease of submitting proposals through the NSF's fast-track system. In any case, the success rate for funding dropped from 30% to 21%, which our analysis suggests would spur additional applications. In 2006, the NSF funded 62% of highly rated proposals, whereas in 1997 it had funded 76% of such proposals. Proposals that were highly rated but ultimately declined represented $2 billion in requested research support in 2006 (NSF 2007a).

How did researchers respond to these changes in the allocation of funds between amounts and numbers? What can we learn from those responses to guide agency decisions about the division of any future large increase in R&D spending and the inevitable ensuing deceleration in the rate of spending?

Researchers responded to the NIH doubling by submitting more proposals to the agency. While NSF spending increased more modestly in the late 1990s and early 2000s, the NSF saw an increase in proposals as well. Given higher grant awards and the increased numbers of awards (with roughly constant funding rates), the growth of submissions reflects standard economic supply behavior: positive responses to the incentive of more and higher-valued research awards. What about responses to declines in research support?

If researchers submitted a single proposal to agencies, we would expect reduced numbers or sizes of awards that lower the expected value of a submission to lead them to make fewer submissions. But the fact that researchers can submit more than one proposal to funding agencies alters their potential supply behavior, at least in the short run. Some researchers could submit more proposals in periods of low numbers of awards in the hope of improving the chance they will gain at least one award and thus be able to continue their research work.

Table 5 shows that this is what happened in NIH after the doubling period. The average number of submissions per new award granted and per continuation awards granted rose sharply from 2003 to 2007 after changing only modestly during the doubling period. By 2007, NIH awardees were putting in roughly two proposals to get an award. Data in the table on the proportion winning awards on an original proposal tell a similar story: fewer investigators gaining awards on original proposals, inducing them to amend proposals in response to peer review reports to increase their chances of gaining a research grant.

The data for the NSF in table 6 tell a similar story. The number of research proposals submitted per principal investigator before receiving one award increased by 1.7 in 1998–2000 to 2.2 in 2004–6. The statistics underlying the averages in the table show that the proportion of principal investigator awardees making a single submission dropped from 59% to 51%, whereas the proportion of principal investigators making three or more submissions increased from 18% to 26%. The notion that by giving fewer large grants the NSF would reduce the time spent writing multiple rewards turned out to be largely wrong. Faced with the risk of losing support and closing or contracting their labs, principal investigators made multiple submissions.

In appendix B we present a simple model of researcher behavior consistent with this form of behavior. The model gives researchers the option of submitting zero, one, or two proposals to a funding agency. We assume that each researcher wants only a single grant to conduct his or her work. In this situation, the very best researchers submit one application (since they are virtually assured of getting support), but some researchers choose to submit two proposals because they judge their chances of winning as lower but still above the costs of developing a proposal. A third group decides against making a proposal. When the value of awards increases, a larger proportion of scientists make bids and a larger number make two bids, and conversely when the value of awards decreases. The interesting behavior occurs when the number of awards granted changes. An increase in the number of awards increases the number of researchers who apply as the chances of winning increase. But when the number of awards decreases, the model says that it is likely that a larger proportion of applicants will put in two bids. Some highly able scientists make additional proposals because they are uncertain that they will gain an award and maintain their lab. The result is an increase in the average number of proposals from researchers who ultimately gain an award and a research grant process that consumes a larger fraction of researchers' time. In addition, the increased proportion of potential grantees writing multiple grants means that they have less time to peer-review the proposals of their colleagues. This puts a strain on the whole system.

It is possible that this process by itself discourages some young persons from going on in science. Who wants to spend time writing proposal after proposal with modest probabilities of success? It may also lead to more conservative science, as researchers shy away from the big research questions in favor of manageable topics that fit with prevailing fashion and gain support from study groups.

While our analysis deals with only some of the decisions facing research granting agencies and researchers, it highlights a key point about the research process: that funding agencies need good knowledge of the likely behavior of researchers to allocations of funds in order to get the most research from their budgets. Conceptually, there is an optimal division of budgets between numbers and values of awards and between new and continuing grantees that depends on the response of researchers. From NIH experience with the doubling and ensuing cutback in funds and NSF experience with increasing the size of awards while barely changing the numbers, the agencies have presumably learned enough about researcher behavior that they would respond differently to future increases in R&D budgets than they have in the past.

IV. Conclusions

This study directs attention to how policy makers might best undertake any future sizable increase in R&D spending, of the type envisaged for the physical sciences by the American Competitiveness Initiative. We have noted that globalization affects traditional justifications for government funding of R&D as a public good. Increasing spillovers of knowledge across national borders reduces the ability of any country to recoup the benefits of basic R&D and thus weakens the public-good argument for greater U.S. spending. But at the same time, the greater international mobility of high-tech research-intensive industries that are drawn by strong basic research in an area argues for larger support of basic R&D than in the past. We have made no effort to quantify these two effects.

Our analysis stresses that future increases in research spending should be seen in terms of increasing the stock of sustainable activity rather than in attaining some arbitrary target (i.e., doubling) in a short period. There are virtues to a smooth approach to higher (or lower) levels of spending, which are particularly important for R&D, as distinct from most other forms of investment, because it takes considerable time to build up human capital, which then has a potentially long period of return. Since Congress determines budgets annually, the question becomes how either the Congress can commit to a more stable spending goal or how agencies and universities can offset large changes in funding from budget to budget.

We have two suggestions here. The first would be for research grants to contain an extra "stabilization" overhead with the stipulation that universities or other research institutions place those payments into a stabilization fund to provide bridge support for researchers when R&D spending levels off. The second is to assign some of the R&D tax credits that boost applied research to a basic research fund that would provide smooth funding for basic research. There is considerable evidence that fiscal incentives for R&D affect firm's R&D behavior.[22] On the basis of current evidence, however, it is difficult to assess the outcome of these two suggested ways to change the mode of funding basic research.

Third, our analysis highlights the importance of funding agency decisions about the division of research budgets between younger and older researchers and between numbers of awards and sizes of awards. Because younger investigators have longer careers than equally competent older investigators over which to use the newly created knowledge, human capital analysis gives a reason to tilt grant spending toward younger scientists. In addition, given multiple applications and the overstretch of the peer review system, it might increase efficiency for agencies to add program officers and find ways to deal more efficaciously with proposals, as indeed both the NIH and the NSF have begun to do.

In sum, if there is to be a new surge in research budgets, there are pitfalls to avoid from the NIH doubling experience and different ways agencies could allocate funds that might get more research output for the dollars spent. Additional research funding spent more efficaciously could attract and retain the young scientists on whom future progress depends and improve the flow of the new science that can help the U.S. economy and contribute to the solution of the diverse problems that threaten global well-being.

Appendix A

Additional Data

Table A1
Success and Funding Rates of First-Time and Previously Funded Applicants: Fiscal Years 1980–2006 (R01 Equivalent: R01, R23, R29, R37)

	Potential First-Time Awardees						Experienced (Previously Funded) Applicants					
Fiscal Year	Applications	Awarded	Success Rate (%)	Applicants	Awardees	Funding Rate (%)	Applications	Awarded	Success Rate (%)	Applicants	Awardees	Funding Rate (%)
1980	8,515	1,903	22.3	7,949	1,859	23.4	7,404	3,240	43.8	6,093	2,992	49.1
1981	8,694	1,818	20.9	8,097	1,766	21.8	8,739	3,482	39.8	7,100	3,253	45.8
1982	8,106	1,598	19.7	7,523	1,572	20.9	9,937	3,628	36.5	7,868	3,361	42.7
1983	7,568	1,650	21.8	6,948	1,607	23.1	9,776	3,777	38.6	7,797	3,498	44.9
1984	7,440	1,637	22.0	6,870	1,612	23.5	9,934	3,887	39.1	8,085	3,627	44.9
1985	7,784	1,845	23.7	7,013	1,809	25.8	11,138	4,341	39.0	8,917	4,021	45.1
1986	7,305	1,683	23.0	6,661	1,658	24.9	11,302	4,328	38.3	9,105	4,004	44.0
1987	7,077	1,657	23.4	6,388	1,629	25.5	11,151	4,744	42.5	9,066	4,364	48.1
1988	7,774	1,780	22.9	7,083	1,741	24.6	11,565	4,329	37.4	9,404	3,989	42.4
1989	7,752	1,621	20.9	7,068	1,590	22.5	11,629	3,782	32.5	9,430	3,547	37.6
1990	7,838	1,394	17.8	7,201	1,371	19.0	11,997	3,371	28.1	9,685	3,146	32.5
1991	7,279	1,560	21.4	6,652	1,539	23.1	11,902	3,932	33.0	9,653	3,679	38.1
1992	7,200	1,473	20.5	6,625	1,451	21.9	12,602	4,262	33.8	10,247	3,988	38.9
1993	8,124	1,269	15.6	7,408	1,246	16.8	13,465	3,690	27.4	10,831	3,458	31.9
1994	8,832	1,453	16.5	7,932	1,425	18.0	14,337	4,269	29.8	11,180	3,931	35.2

(continued)

Table A1
Continued

	Potential First-Time Awardees						Experienced (Previously Funded) Applicants					
Fiscal Year	Applications	Awarded	Success Rate (%)	Applicants	Awardees	Funding Rate (%)	Applications	Awarded	Success Rate (%)	Applicants	Awardees	Funding Rate (%)
1995	7,968	1,420	17.8	7,217	1,399	19.4	14,712	4,514	30.7	11,458	4,173	36.4
1996	7,017	1,356	19.3	6,395	1,336	20.9	14,043	4,419	31.5	11,171	4,102	36.7
1997	6,967	1,484	21.3	6,313	1,453	23.0	13,654	4,751	34.8	10,862	4,413	40.6
1998	6,817	1,545	22.7	6,161	1,505	24.4	13,666	4,782	35.0	10,978	4,400	40.1
1999	7,333	1,596	21.8	6,592	1,561	23.7	14,802	5,515	37.3	11,834	5,063	42.8
2000	7,479	1,642	22.0	6,741	1,596	23.7	14,750	5,466	37.1	11,719	4,998	42.6
2001	7,494	1,629	21.7	6,691	1,580	23.6	14,545	5,361	36.9	11,625	4,975	42.8
2002	7,632	1,612	21.1	6,862	1,574	22.9	14,640	5,222	35.7	11,673	4,815	41.2
2003	8,377	1,720	20.5	7,380	1,680	22.8	16,325	5,730	35.1	12,647	5,243	41.5
2004	9,413	1,578	16.8	8,147	1,528	18.8	18,241	5,457	29.9	13,863	4,999	36.1
2005	9,365	1,475	15.8	8,195	1,441	17.6	19,175	5,014	26.1	14,410	4,631	32.1
2006	9,399	1,384	14.7	8,180	1,354	16.6	19,822	4,677	23.6	14,766	4,350	29.5

Table A2
NIH Changes in Numbers of Grants and Dollar Support (Report Date: February 12, 2008)

		Research Grants	
Fiscal Year	Total Amount Awarded	Number of Awards	Award Amount
2007	$21,263,805,742	47,181	$20,415,899,325
2006	$23,182,959,918	46,797	$20,154,363,154
2005	$23,410,118,044	47,345	$20,206,478,806
2004	$22,900,576,587	47,464	$19,607,812,023
2003	$21,866,798,411	46,081	$18,461,462,170
2002	$19,074,464,796	43,520	$16,830,194,185
2001	$16,784,681,877	40,666	$14,907,921,291
2000	$14,791,024,329	38,302	$13,002,656,762
1999	$12,855,628,060	35,870	$11,228,665,952
1998	$11,179,749,719	33,703	$9,801,789,027
1997	$10,456,030,704	32,109	$9,046,542,619

Appendix B

Modeling Researcher Responses to Short-Run Changes in Numbers of Awards: A Simple Model of Scientist Behavior

A. Individual Behavior

There are a pool of L potential researchers who submit either zero, one, or two research bids.[23] If they submit, they have a probability p of winning an award. This will be a function of researcher quality, z, and the number of awards made available by the government, N, so $p = f(z, N, \cdot)$ and is increasing in both arguments. Let us assume that the support of the distribution of researcher quality is [0, 1]. A researcher is allowed to accept a maximum of only one award at a time (so if he wins two, he can take only one). Winning an award gives value to the researcher (funds) of V, and losing is normalized to zero. The cost of putting a bid together is c.

The net utility of submitting one bid is $u(1)$:[24]

$$u(1) = pV - c.$$

The net utility of submitting two bids is $u(2)$:

$$u(2) = [1 - (1 - p)^2]V - 2c = p(2 - p)V - 2c.$$

A scientist will not submit a bid if $u(1) < 0$, that is, $p < c/V$.

Define the benefit-cost ratio as $\beta = V/c$ and the threshold probability as $\widetilde{p} = 1/\beta$. Thus if $p < \widetilde{p}$, the researcher will choose not to bid.

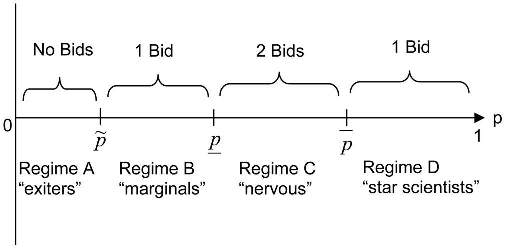

Fig. B1. General model. The term p is the probability of winning an award; the three cutoff probabilities define the thresholds. See the text for details.

When will the scientist put in two bids? This will occur if $u(2) > u(1)$. This condition can be written as

$$-\beta p^2 + \beta p - 1 > 0.$$

This quadratic form has two solutions that define two more threshold values of p:

$$\underline{p} = \frac{1}{2}\left[1 - \sqrt{\left(1 - \frac{4}{\beta}\right)}\right] \quad \text{and} \quad \bar{p} = \frac{1}{2}\left[1 + \sqrt{\left(1 - \frac{4}{\beta}\right)}\right]$$

subject to the regularity conditions that the value of β must allow p to be defined on the (0, 1) support (e.g., $\beta > 4$).

These three thresholds define scientist behavior over four regimes (see fig. B1):

A. $p < \tilde{p}$: researcher will bid zero.

B. $\tilde{p} < p < \underline{p}$: researcher will make one bid.

C. $\underline{p} < p < \bar{p}$: researcher will make two bids.

D. $\bar{p} < p$: researcher will make one bid.

The intuition is the following. In regime A, the probability of winning is too low to cover the costs (in expected terms). In regime D, "star scientist," the probability of winning is so high that there is not much benefit from a second bid. In regime C, the chances of winning are not quite so high, so the researcher finds that it pays to take out a second ticket. In regime B, it is worth making a bid, but because these scientists are on the margin ("marginal quality") of not bidding, they do not find that it is worth the cost of two bids.

Comparative statics in β. If the value of the award rises (β up), then this will change the thresholds: $\tilde{p}$ will fall, $\underline{p}$ will fall, and $\bar{p}$ will rise. This means that (*a*) there will be a larger number of bids and (*b*) there will be a larger number of scientists making two bids.

B. Equilibrium

There are M bidders, L potential bidders, and a total number N of awards available. In a rational expectations equilibrium, the probabilities have to adjust so that the number of awards given out equals the expected ex ante probability of success integrated across all scientists. In our simple case,

$$M \int_0^1 p(z, N) dp = N.$$

Since p and M are now endogenous, we must solve the model in terms of the exogenous variables z and N. We can define thresholds analogous to $\tilde{p}$, $\underline{p}$, and $\bar{p}$ in the space of researcher quality ($\tilde{z}$, $\underline{z}$, and $\bar{z}$). These can be written as functions of the benefit-cost ratio, β, and the number of potential awards.

Comparative statics in β. If the number of awards falls, all the thresholds shift to the right. The probability of winning a bid will fall, so fewer scientists will submit any bids. Similarly, if the number of awards rises, then the thresholds shift to the left and there are more bids.

In terms of the numbers making two bids, this depends on the functional forms and the magnitude of the change in N. The following seems like a reasonable description of the doubling and postdoubling period, however. During the doubling period the thresholds all shift to the left, but the proportion of (potential L) scientists in regime C who make two bids stays the same ($\bar{z} - \underline{z}$).

Compare this to the postdoubling period. We keep $\bar{z} - \underline{z}$ the same, but all thresholds have moved to the right, so there is a smaller margin of scientists in regime D. This means that of all the winning bids, the proportion of scientists submitting two bids has increased; that is, $(\bar{z} - \underline{z})/(1 - \tilde{z})$ is larger.

The intuition is clear. During the postdoubling period, many of the "star scientists" during the doubling period can no longer feel confident in winning an award, so they put in two bids to increase their probability of a successful draw.

Endnotes

We would like to thank Scott Stern, Walter Schaffer, Rolf Lehming, and seminar participants at the Innovation Policy and the Economy Washington, DC, conference for helpful comments. The Economic and Social Research Council through the Centre for Economic Performance and the Sloan Foundation through the Science and Engineering Workforce Project have generously funded the research.

1. An alternative to broad-based incentives to increase supply would be for military and defense sectors to attract more U.S. citizen scientists and engineers by raising their pay, which would reallocate more citizens to those jobs even if the number of U.S.-born scientists did not change.

2. Indicative of the concern and pressure to increase the national investment in science, in the first week of May 2008, 450 educators, lobbyists, government officials, and business leaders met in Washington to keep the issue and Competitiveness Initiative in the forefront of policy makers (Mervis 2008).

3. According to NSF (2007b, table 2), the United States spent $63.6 billion on basic research in 2006, and $36.9 billion was in colleges and universities, of which $24.5 billion was funded by the federal government (66%; http://www.nsf.gov/statistics/nsf07331/pdf/tab2.pdf).

4. U.S. R&D increased by 6% in 2006 according to NSF projections (NSF 2007b), projected; 1990 figures from NSF (1995).

5. Zucker, Darby, and Brewer (1998) show that there are clusters of biotechnology activity around "star researchers" in nearby universities. Similarly, U.S. states with greater supplies of university graduates have been in the forefront of the "new economy" (Progressive Policy Institute 2002). For evidence on the aggregate impact of R&D on productivity, see Griliches (1998) and Jones and Williams (1998).

6. Earnings of production and nonsupervisory workers in the three highly R&D-intensive sectors—aerospace, chemicals, and computers and electronic products—averaged $20.00 per hour compared to $15.97 per hour for production and nonsupervisory workers in the country as a whole (http://www.bls.gov/web/empsit.supp.toc.htm#historical).

7. The idea that other parts of the value chain locate close to R&D is widespread. This may be much less true in today's more globalized world since the value chain can increasingly be disaggregated. For example, in pharmaceuticals, drug discovery may occur in the United States, but clinical trials may be located in eastern Europe and drug manufacturing in India.

8. There may be other market failure justifications, such as imperfections in financial markets.

9. For a classic survey, see Griliches (1992); for more recent evidence, see Bloom, Schankerman, and Van Reenen (2006).

10. See Keller (2004) for a survey and Griffith, Harrison, and Van Reenen (2006) for recent evidence.

11. More generally, the rationale for country support depends on the relative rate of diffusion of knowledge within a country and across countries. If diffusion rates increase proportionately, the social vs. private margin for national investments would be stable.

12. Convincing empirical evidence of the quantitative importance of these strategic R&D competitions is rare. Those that have studied it generally find that the strategic R&D competition effect is dwarfed by the knowledge spillovers effect (e.g., Bloom et al. 2006).

13. This is defined by the Organization for Economic Cooperation and Development (OECD) to include aerospace, communications equipment, office machinery and computers, pharmaceuticals, and scientific instruments.

14. The experience of the NIH doubling is more relevant to a future increase in R&D than the doubling of federal R&D spending following the Sputnik. In that

period the supply of science and engineering workers was primarily domestic, so that the increase raised salaries greatly, inducing more native students to enter the field and increase supply in the future (Freeman 1975). Today, with the international market in science and engineering workers, supply is more elastic so that increased spending will likely have a greater impact on quantities than wages.

15. Adjustment costs come in many forms. They include the construction of new R&D labs, recruitment and training of new staff, and systemwide adjustment costs, which we discuss shortly.

16. If R&D spending were mainly an irreversible fixed cost, then the optimal adjustment path in fig. 3 would not be smooth adjustment, but rather a sudden shift closer to the actual change. This is unlikely to be a good description of adjustment costs, however, especially at the aggregate level. Also note that our analysis ignores any possible advantage to producing new research earlier than later beyond the standard discounting of future benefits, for instance, through spillovers over time that improve the productivity of future research. If there are such gains, they must eventually suffer from diminishing returns so that rising adjustment costs dominate the calculation on the margin where the decision about funding is made.

17. Applicants are considered new investigators if they have not previously served as the principal investigators on any Public Health Service–supported research project other than a small grant (R03), an Academic Research Enhancement Award (R15), an exploratory/developmental grant (R21), or certain research career awards directed principally to physicians, dentists, or veterinarians at the beginning of their research career (K01, K08, and K12). Current or past recipients of Independent Scientist and other nonmentored career awards (K02, K04) are not considered new investigators.

18. While the NIH has no restriction against postdocs applying for research grants, its Web site states that "before you seek an independent research grant, [you should] Hold a Ph.D. or M.D. Have a faculty-level position, usually assistant professor or higher. Have a publication record in the field in which you are applying. Work in a research institution that will provide the resources, e.g., equipment and lab space, you will need to complete the project. … You will also need preliminary data for an R01" (http://www.niaid.nih.gov/ncn/grants/new/new06.htm). Universities have general rules guiding the level of investigator that may apply for independent funding and about the resources they will provide to help in the grant process.

19. Much like journals, study groups can choose to accept or reject new submissions outright or ask for a revision of the original submission.

20. But there is no analysis of whether working in someone else's lab affects productivity nor that older scientists with the same productivity as younger scientists in fact make less use of the knowledge created. The faster knowledge changes in a field, the less importance the shorter future working life of older scientists will have on the probability that they will use this knowledge less than younger scientists. In addition, there may be offsetting factors beyond human capital considerations that argue in favor of older scientists, for instance, if older scientists transmitted their knowledge more rapidly to students than younger scientists dids.

21. Freeman (2005) and Freeman, Chang, and Chiang (2005) show substantial responsiveness of young persons to NSF Graduate Research Fellowships. It is hard to imagine that if they offered $30,000 awards 20 years into the future, they would apply for the fellowships as much as they have.

22. See Bloom, Griffith, and Van Reenen (2002) for international evidence or Hall and Van Reenen (2001) for a survey focusing on U.S. evidence. Hall (1993) examines policy in the 1980s.

23. For simplicity we cap the maximum number of bids at two but consider a larger number of bids in the extensions below.

24. The model assumes risk neutrality. If we incorporate risk aversion, the same basic intuitions come through.

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