SCIENCE INNOVATION

Assessing the Impact of Science Funding

Quantifying the outcomes of investment in science is not an easy task.

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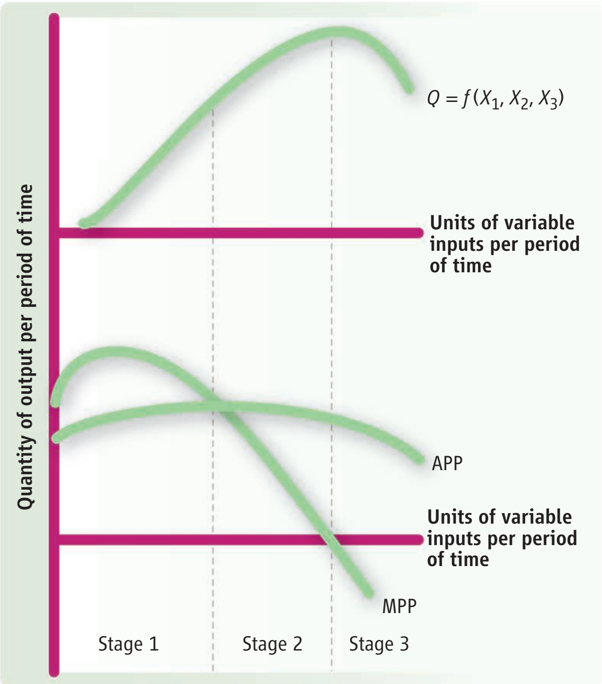
Science supporters were rightly excited by the passage of the American Reinvestment and Recovery Act (ARRA, i.e., the stimulus package). Headlines in *Science* (*1*) and *Nature* (*2*) rejoiced at the new value placed on science as a basis for economic growth and associated job creation. Indeed, federal investment was at least partly based on a belief that the result would be more competitive firms and more, and better, jobs—and soon! (*3*). That belief was bolstered by advocacy groups: For example, a report by the Information Technology and Innovation Foundation (ITIF) estimated that an additional \$20 billion investment in research in the stimulus package would create ~402,000 American jobs for 1 year.

Within 2 years, the public will want to be informed about the impact of the stimulus on the economic recovery. Were the estimates accurate? How can they be validated? And, in the longer term, what were the impacts of the reinvestment strategy on scientific knowledge, economic growth, and job creation? But we should also want to be informed about questions that go beyond the immediate accounting issues raised by ARRA. For example, what deeper understanding did we gain about the mechanisms whereby knowledge is created and how it contributes to both economic and social outcomes? Given the global nature of both economic and scientific activity, how did the science investments of other countries affect the United States? What new measures and indicators were developed to measure those contributions, and how can they be used to inform future investments and the response to future economic downturns? Answers to these questions will need to be based on theory and empirical evidence, as well as conveyed in a manner that is understandable. Some insights can be drawn from research into the science of science and innovation policy (SciSIP) (*4*).

Much of the public discussion about the "science stimulus," consistent with the apparent precision of the ITIF estimates, suggested that the outcomes of scientific investments were both certain and tied to economic growth. It is true that science policy in the United States and abroad is largely predicated on such beliefs. The United Kingdom's *Innovation Agenda* identifies basic research as critical to productivity and employment growth (*5*), as does the Organization for Economic Cooperation and Development's (OECD's) innovation strategy (*6*). Saudi Arabia has invested \$6 billion to set up a new science and technology university (*7*), and the Japan Science and Technology Agency has made investment in basic research a cornerstone of its economic strategy (*8*). Certainly, there are a number of anecdotes that make the case that science investments create jobs. For example, four researchers at the University of California at San Diego have been credited for the vibrant growth of San Diego, creating more than 40,000 jobs in life sciences and over 12,800 in electronics (*9*). The emergence of Google has been traced to National Science Foundation support of one of its founders, Sergey Brin, who was an NSF Graduate Research Fellow, and a \$4.5 million Digital Library Initiative grant from NSF to Stanford that helped support early Google prototypes.



A standard approach to linking inputs and outputs that has been used to study innovation. Output (Q) is shown as as a linearizable function of inputs (X_1, X_2, and X_3). The efficiency of different stages of production is described by the relationship between average physical product (APP) and marginal physical product (MPP).

However, much of the research in science policy is cautious about the impact of science investments—consistent with Congressional Budget Office expectations that increased spending for basic research and education would have very wide ranges of expected impacts and might affect output only after a number of years. Cross-national evidence also suggests that investment in science, while often successful, is not a guarantee of short-term economic growth and job creation. The U.S. experience of the past decade, in which more than three-quarters of post-1995 increase in productivity growth could be traced to science investments (*10*), was not duplicated in all other countries. For example, massive investments in university and government research institutes had little short-term impact on Japan's economic growth and "demonstrates that science, technology, and innovation policy cannot compensate for adverse framework conditions (e.g., dysfunctional financial systems)" [(*11*), page 8]. Similarly, Sweden, despite having invested heavily in research and development (R&D), has employment that is still below the precrisis level in 1990 despite a population growth of more than 5% (*12*). In sum, we do not understand the mechanisms through which investments in R&D, and their immediate products (knowledge and technologies) interact with other aspects of societies and economies.

Understanding the reasons for these cross-national differences is important not only for answering questions about the impact of the "science stimulus" and guiding policy deci-

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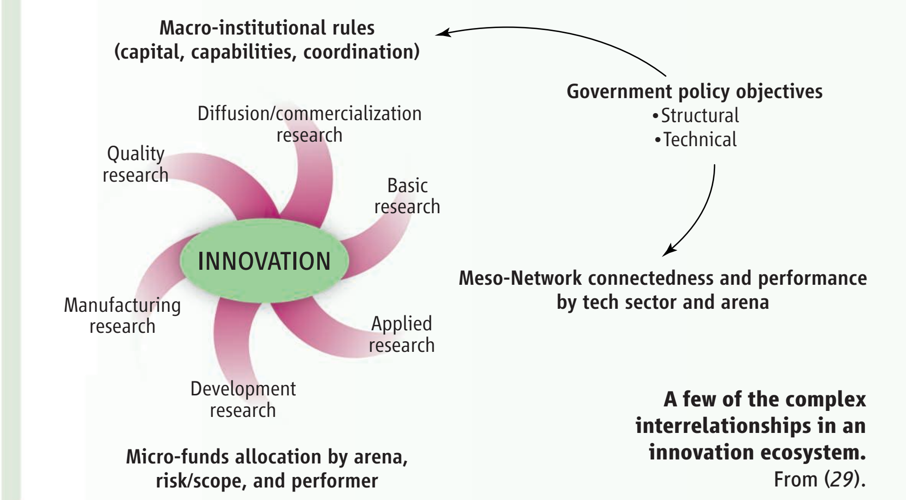
sions but also for responding to a fascinating scientific challenge. Similar policy-related challenges have resulted in scientific advances in the past. Jim Heckman's analysis of the econometric issues associated with labor policy not only earned him the Nobel Prize in 2000 but also guided government policy in training (*13*); Vernon Smith's research in alternative market mechanisms not only earned him the Nobel Prize in 2002 but also guided the design of broadband communication spectrum auctions and allocating landing slots at airports.

The challenge in the field of SciSIP is greater than in many policy areas for a number of reasons. The relation between science and innovation is nonlinear in nature, with complex outcomes that can vary substantially by discipline and be subject to considerable time lags. The units of analysis can similarly be quite complex, ranging from the individual to project teams to organizations to political systems: As a result, relevant research takes place in separate disciplines such as economics, sociology, political science, and psychology. This complexity has created a substantial empirical challenge: Because the creation and transmission of knowledge and technologies result from complex human and social interactions, new ways need to be developed to capture data on those interactions, and new data need to be developed to characterize the eventual outcomes. Finally, a related and equally interesting scientific challenge is how best to convey the results of scientific analysis to policy-makers and the public. Even the terms "innovation," "science," "technology," and "research and development," used interchangeably in the popular press, mean very different things to the scientists who study the science and innovation enterprise.



A few of the complex interrelationships in an innovation ecosystem. From (*29*).

The Scientific Challenge

The ITIF estimate of job creation in the opening section of this essay was derived from the Bureau of Economic Analysis's RIMS II model: a linear model linking science investments to economic outcomes. The basis is an input-output model of spending flows (*14*) in which spending on the RIMS II category of "scientific research, equipment, and facilities" directly generates scientific and construction jobs and indirectly generates jobs in service areas such as restaurants through a multiplier effect. This approach functionally equates the impact of science to that of building a football stadium or an airport: The impact is derived from the demand side and depends on the amount of spending on bricks, mortar, and workers.

Although this set of estimates was based on the most readily available and widely used models at hand, it is unlikely to do full justice to the long-term impact of science investments. Deeper insights can be derived from using a production function framework in which economic value is determined by the amount of physical capital, labor, materials (including land), and energy devoted to producing a good and to the efficiency with which these factors are combined (see chart, page 1273). Early work by Robert Solow, for which he received the 1987 Nobel Prize, described how these factors combine to generate productivity growth and increase welfare. Later work by Jorgenson and others (*10*) used an enhanced production function approach to decompose the sources of productivity growth: The source of the finding that information-technology–related increases in total factor productivity (i.e., innovation) explained more than three-quarters of the post-1995 increase in U.S. productivity growth. And a production function framework also provides the insight that the impact of science investment on jobs is more likely to create jobs for skilled than for unskilled workers, because skilled workers in the production function are complements for technological advances; unskilled workers are substitutes (*15*).

It is difficult to expand the production function framework to encompass the nonlinear and complex nature of value creation in the knowledge economy. Innovation is nonlinear because the demand side and the supply side of ideas are inextricably intertwined. Innovation also involves the interrelationships of human beings and social structures and processes. Thus, the term "the ecology of innovation" is often used to emphasize the nonlinear set of relationships at the micro, meso, and macro levels (see figure, above).

A good illustration of why it is critical to understand the complex nature of innovation when making science investments is provided by NIH's initial approach to funding biopharmaceutical research, particularly monoclonal antibodies and antisense technologies. NIH invested heavily in a research base, assuming that the resulting knowledge would draw entrepreneurs and venture capital and produce new drugs. However, as in many applications, technology has separate components, including a generic technology base, supporting infratechnologies, and proprietary market applications. Investment can occur at any of these points. Because this particular technology demanded substantial "proof-of-concept" (alternatively, "generic") technology research and such a technology platform was not initially provided, the results of the initial investments were disappointing. In the case of antisense (a subset of RNA technology), first-generation chemistry yielded only one small-market drug over a 15-year period. Subsequent investments have been much more fruitful (*16*). This anecdote illustrates that understanding how the venture capital component of our national innovation system is organized and works can be critical to ensuring that science investments achieve their full impact.

Understanding the ecology of innovation is important for answering the questions outlined in the introduction. The recovery part of ARRA was, by its nature, intended to have a short-term stimulative effect on job creation, but describing the impact of the reinvestment part of the stimulus is likely to take much longer. Research suggests that the time lags from initial investment to discovery, as well as the lag from patent to implementation, can take many years, or even decades. In other words, the science investment needs to generate an "aha" moment or an idea that has value; structuring that investment so that the ideas move beyond the initial

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research project is difficult (*17*). Translating that "aha" moment into an innovation also might require a well-functioning team or organization (*18*, *19*), a well-functioning patent system (*20*), a well-developed firm ecosystem (*21*), or appropriate university links to industry (*22*). The time lags can be substantial. Recent productivity growth in agriculture, for example, was based on research investments in the 1800s (*23*). Biotechnology commercialization was based on scientific findings dating from the 1950s. The Internet revolution that bore fruit in the 1990s was based on scientific investments in the 1970s and 1980s.

And, of course, a focus on economic value alone may also understate the true returns of investments in science. Indeed, one strand of research is attempting to develop a public value mapping of science outcomes: outcomes that are public, nonsubstitutable, and oriented to future generations and that capture dimensions such as competitiveness, equity, safety, security, infrastructure, and environment. The research is based on key ideas: (i) It is possible to identify public values, including ones not well captured by economic constructs; (ii) just as one can assess market failure, "public value failure" occurs when neither the market nor the public sector provides goods and services required to achieve designated public values; and (iii) innovation can be characterized not only in terms of contributions to economic growth and productivity but also in terms of the public values achieved (*24*).

Answering the Questions

Although there is a global interest in answering the questions, a recent Science of Science Policy roadmap, as well as researchers at a recent Science of Science Policy workshop concluded that the United States needs a major intellectual investment to permit further deep analysis of the impact of science investments (*25*). Some illustrations of those investments are identified below.

The passage of the ARRA and similar legislation in other countries provides one such opportunity for analysis. NSF's Science of Science and Innovation Program issued a RAPID (www.nsf.gov/pubs/2009/nsf09034/nsf09034.jsp) call for proposals to mobilize the research community to assess the effects of ARRA both on the ecology of innovation and on the science and engineering enterprise. The portfolio of funded research from that call should provide new insights into many of the scientific questions posed above as the research is completed.

Other examples of major investments also exist. The roadmap noted that the U.S. scientific data infrastructure is oriented toward program administration rather than empirical analysis. It currently does not allow science investments to be coupled with the associated scientific and technological, social, and economic outcomes (*25*). A number of U.S. research awards have been made to develop a pilot data infrastructure that provides information about where and to what purpose science tax dollars are spent. Some of these awards go beyond the use of administrative and survey data and both use and develop cyber tools to capture data on and about scientists, their interactions, and the related scientific and economic outcomes.

In addition, there is the potential to expand the current science data infrastructure, which has some of the elements necessary to fully inform the analysis of science investments. Grants.gov provides a unified portal to find and apply for federal government grants. Research.gov and science.gov provide information about research and development results associated with specific grants, and a consortium of federal agencies provides R&D summaries (www.osti.gov/fedrnd). Open.gov and data.gov are being implemented to promote citizen participation in government decision-making by making government data available online, in keeping with President Obama's vision (*26*). A mechanism that built on these and other initiatives could couple science investments with outcomes in a systematic fashion. It could also engage the scientific community and the public in an ongoing dialogue to describe and amplify knowledge about these outcomes.

Of course, the answer to the questions about the return on investments in science will not be contained in one number. A related intellectual investment is to advance understanding of how to convey complex answers about the impact of science investments to the public. Emerging visualization techniques seem to be more effective than tables and digital slide presentations at communicating the ways in which science investments bear fruit across a range of topics and disciplines. However, although visual representations are intuitively appealing, it is not clear what they convey: The scientific foundations upon which they are based are not fully developed. U.S.–funded research is thus moving beyond the science of simple mapping to leverage the science of visual analytics which has hitherto been used to "make sense" and describe the impact of terrorist, rather than scientific, networks. Just as John Snow used maps in 1854 to identify the waterborne source of cholera, researchers in the field are combining "the art of human intuition and the science of mathematical deduction to perceive patterns and derive knowledge and insight from them" (*27*).

Conclusion

The ARRA was intended to both promote recovery and make new investments in the American economy. Answering questions about the impact of the stimulus has two parts: short term and long term. Short-term estimates of the recovery aspect of the "science stimulus" do not properly convey the complexity of the process. And although the reinvestment aspect reflects a long-term bet that investments in science will bear more fruit than investments in stadia, and science still has a long way to go to provide full clarity in what those outcomes will be, a number of steps are being taken to ensure better answers in 2 year's time.

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