

Increasing benefits & reducing social costs of technological innovations

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abstract

Technological innovation is a double-edged sword. It can help solve major problems, such as how to treat cancer, and can be an engine of economic growth, but it can also cost jobs, such as when automation replaces people. Both aspects raise issues that have major but so far little-recognized policy implications. One such issue is that new technologies are now taking the place not just of routinized jobs but of more complex positions. Another is that many government policies meant to foster needed innovation are based on an outmoded understanding of how innovation occurs and thus are not as effective as they could be. As behavioral scientists who study technology and innovation, we offer insights into addressing both issues.

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Core Findings

What is the issue?

Technological innovations, like artificial intelligence (AI) or vastly more powerful computer chips, are automating production control systems. While this is yielding significant benefits for society, governments must manage this innovation to provide safety nets for labor replaced by automation. The innovation process itself is not linear, and innovation policy should be designed accordingly.

How can you act?

Selected recommendations include:

- 1) Revising policies that unduly constrain the recombination of extant knowledge and technology for new applications
- 2) Emphasizing procedures and incentives that allow technologies to be put to new uses over time

Who should take the lead?

Behavioral science researchers, policymakers in technology, science, innovation

Technological innovations—especially in the ways people communicate with one another and exploit data—are profoundly affecting society in positive and negative ways. They have resulted in the creation of the ever-changing Internet and advances in medicine, and they are fueling the rise of new businesses and new kinds of jobs. Yet they are also costing jobs in many fields. In this article, we focus on the need to minimize the downsides of technological innovation while enhancing the development and adoption of the radical advances that benefit society. In particular, we examine two issues that have not received much public notice but have major policy implications.

First, computers are now able to take the place not just of workers who perform routine tasks but of people who handle more complex responsibilities, such as recognizing patterns in data from business logistics, retail sales and services, and even radiology. In addition, information technologies increasingly permit work that was previously performed by individuals in full-time jobs to be done by independent contractors who receive no health care, unemployment, disability, or pension benefits. As employment across a wide range of occupations becomes more uncertain, many people will have to change jobs more often over the span of their careers than has been true in the past. What should be done with an excess labor force that is made up of highly skilled workers who are unlikely to find jobs providing the income they had before? And how can a safety net be provided for Americans whose health insurance or retirement accounts may not be portable from job to job?

Second, given that technological innovation remains important for the health of the economy and other realms, the federal government should foster it as effectively as it can. Studies show, however, that the processes that encourage the development and adoption of game-changing innovations are more complex than the people creating government policies and practices consider. Innovations do not follow a simple set of stages that begins with research and ends with small-scale testing and large-scale commercialization. Instead, the

process typically involves nonlinear interactions and feedback at all stages of technology development, as well as across different streams of people working cooperatively or competitively on their own aspects of the technology, from the science of the initial concept to the marketing of the final product. This realization has several important implications for how government agencies should manage the processes involved in innovation.

So far, the problems of displaced high-level workers defy easy resolutions. But behavioral science does suggest broad policy recommendations that should enhance the government's ability to nourish useful technological innovation.

Technology's New Effects on the Workforce

In 1965, William Faunce argued that all production systems consist of four components: a power system, a system for transforming raw materials, a transfer system for moving objects in space, and a control system that coordinated the other three. He claimed that the first industrial revolution automated power sources, while the second brought automation to systems for transforming and transferring materials and goods. He also predicted that computers would automate control systems. Today, society is well along the path that Faunce forecasted.¹ Many key innovations in the last 15 years—particularly those enabled by artificial intelligence (computer software that learns from experience and can make predictions based on patterns in complex data) and vastly cheaper, more powerful chips—have indeed made automated control possible in manufacturing² as well as in service industries.

At one time, the introduction of new technologies created jobs for people who managed their use. But the opposite is often true now: technological innovations pull humans out of control positions and replace them with intelligent machines,^{3,4} leaving skilled workers with fewer options for earning a reasonable income.

Several well-known examples illustrate how the trends that Faunce predicted¹ have come

to pass. Through the online retailer Amazon, consumers can now easily order and pay for goods via sophisticated computational devices that can be activated from nearly any computer or smartphone. Once Amazon's computers receive the order, they instruct robots to retrieve the ordered goods from shelving in a warehouse, which then move those goods to a mailing station, where a human touches the items for the first time—picking them up off the cart and sending them to other machines to prepare for shipping.⁵ The smart grid is another example. Embedding microprocessors in the electrical grid allows utilities to automatically monitor electricity use, alter the amount of electricity flowing from one point to another, and charge a variety of rates for electricity depending on when the electricity of consumed—all without the intervention of meter readers and other workers. Self-driving cars are yet another case in point. They depend on sensors and microelectronic controls to replace the control previously exerted by human drivers. Vehicle manufacturers have begun to experiment with self-driving trucks,⁶ which threaten the livelihood of truck drivers. In 31 of America's 50 states, the most common form of employment is as a truck, delivery, or tractor-trailer driver.⁷

Although it is difficult to predict how many people and which jobs are likely to be affected by advanced control technologies, recent studies provide some estimates. Frey and Osborne combined information on what various forms of artificial intelligence are currently capable of doing with data on the skills involved in 702 occupations (drawn from O*Net) to estimate the percentage of jobs that would be affected by computerized control technologies.⁸ The occupations they examined ranged from the most cognitively complex to the most manually intensive. Their estimates suggested that 47% of U.S. employment would be at risk over the next two decades.⁸ The occupational categories most at risk, according to Frey and Osborne's analysis, are service, sales, office and administrative support, production, transportation, and materials handling.⁸ Frey and Osborne's analysis indicated that automation based on machine

“it is unclear what percentage of the labor force is actually capable of learning high-level STEM skills”

learning will render obsolete additional jobs with midlevel wages and thereby further exacerbate income inequality.

Few Good Solutions

Many observers have emphasized the need to train more people in STEM (science, technology, engineering, and mathematics) fields, both to provide alternative forms of employment and to enhance desired kinds of innovation.⁹ This approach to employment policy has several flaws, however. First, it appears that many programs designed to make people more employable in a postindustrial economy focus less on technical skills and more on basic social skills needed to land a job, such as writing résumés and interviewing well.^{10,11} Second, it is unclear what percentage of the labor force is actually capable of learning high-level STEM skills. The emphasis on high-level skills is crucial because mounting evidence indicates that advances in artificial intelligence will soon make it possible for computers to make inferences currently performed by humans who do fairly sophisticated STEM work.^{12–14} Witness, for example, recent research indicating that pattern-recognition software and intelligent machines do a higher quality and less costly job than human radiologists do in interpreting scans taken to diagnose certain disorders.^{15,16}

Given that jobs may continue to be scarce or to convert from full time to freelance, the U.S. Government Accountability Office and others have called for decoupling the American social safety net from specific employers so that people can take their health insurance or retirement accounts with them from job to job.^{17,18} So far, however, progress in that direction has been slow.

Improving Innovation

Government Participation Is Critical

At the moment, prospects for enhancing the benefits of technological innovation are much brighter than for minimizing the social harms it unleashes. For policymakers, a key question is: What should be the government's role in facilitating innovation, including developing and operating the *innovation infrastructure*—the collection of systems and entities that incubate the creation of radically new products, procedures, and services and facilitate their commercial success?¹⁹

There is no question that government has to be involved. Many studies have found that government plays a critical role in building innovation infrastructures (also known as *ecosystems*), because the private sector alone does not have the required resources, legitimacy, capabilities, or market incentives to do so.^{20–22} But the government cannot perform the job alone; joint public–private collaboration is required to build a successful innovation infrastructure.^{23,24} This infrastructure includes (a) institutional arrangements that regulate, set standards for, and legitimize a new technology; (b) mechanisms for public funding of basic scientific research and knowledge bases and for the education and training of workers; (c) systems for developing markets, educating consumers, and generating demand; and (d) private businesses that conduct proprietary research and carry out product development, manufacturing, and distribution with the aim of making a profit.

Many studies have found, for instance, that commercialization of a technological innovation is a collective result of many actors in public- and private-sector organizations who engage in developing these complementary infrastructure components over extended periods of time.^{20,25–28} Some actions are helpful; others are not. For example, government regulations and costly and slow review and approval processes can constrain innovation, as businesspeople in various industries complain,²⁹ but government funding of basic research enables technological

innovations. Studies of biotechnologies³⁰ and cochlear implants²⁴ document that government-funded basic research in universities and government laboratories predated by 20 to 40 years the proprietary appropriation of this public knowledge for commercial development.

Programmatic government funding and investment have also been critical in building innovation infrastructures that support the development of more traditional, physical infrastructures—such as the interstate highway system, built in the 1950s and early 1960s, and hydroelectric power systems, built in the 1930s. Both of these systems were part of the New Deal's attempt to eliminate mass unemployment. Today, again, major infrastructure projects carried out by the private sector with government contracts seem to be an attractive way to promote innovation and put people to work in jobs at multiple levels.

Policies That Encourage Innovation

Behavioral science suggests a need to reexamine the process by which innovations and the infrastructures that support them develop. In 1944, President Roosevelt asked his science advisor, Vannevar Bush, how wartime investments in science might contribute to peacetime society. In response, Bush's 1945 report, *Science: The Endless Frontier*, laid out the government's first formal innovation policy, outlining a bold new vision of how federally funded basic research could and would solve the nation's—and the world's—problems of disease, hunger, poverty, and national security.³¹

Besides specifying the federal government's role in supporting innovation, Bush defined the innovation process itself—creating a language that still dominates public and private sector understandings of the process—as a set of distinct linear stages moving from research (both basic and applied) to development, then demonstration, and finally deployment.³¹ Basic research, with the goal of advancing fundamental knowledge, raises possibilities for new technologies; applied research tests the possibilities and improves on the best candidates. Development comes up with the actual products or processes

that can be put into practice. Demonstration, as the term suggests, represents the activities associated with installing, running, and monitoring the performance of these products or processes. Deployment (or diffusion) is the successful culmination of the process: the manufacturing, selling, installing, using, and maintaining of a new technology across a broad market. Even today, corporations manage their research and development with stage-gate processes that follow this linear model, and the federal government allocates funds with these stages in mind.

Over the past 50 years, though, studies^{20,23,25,32–36} have shown that innovations rarely originate with inventions in basic research, nor do they follow this linear sequence of events. Instead, most innovations are more complex than government policies and practices imply. The innovation process typically involves multiple feedback loops by which the downstream activities of development and deployment generate both new problems and new knowledge that change the agendas of the upstream stages of research and development. These feedback loops may take place within a single stream of scientific or technological development, but they can also take place across multiple streams.

Historically, the federal government's largest impacts on economic development, national security, and public health and welfare came through funding and support (through investment and procurement) that directly brought new science and technology all the way to industrial production and use.²⁰ Considerable innovation also occurred in downstream activities through learning by doing and learning by using.³⁶ For example, the Internet's properties and uses have continually shifted in response to emergent opportunities that were not initially anticipated. Similarly, the American system of manufacturing (the foundation of mass production), which grew out of efforts to build armories, arose through the coevolution of machine tools, manufacturing methods, and firearm design that took place throughout the 1800s. Other examples of nonlinear effects can be seen in the development of the steel industry, antibiotics,

and the space program, all of which required federal involvement. Thus, projects provide more value—in terms of knowledge generated and social benefit—when the government is involved in all aspects of innovation, including basic research as well as initial deployment.

Given these findings, federal policies need to be designed so that knowledge and resources developed in downstream industrial efforts can more readily inform and support upstream scientific efforts. To achieve this goal, the federal government should

- help to establish long-term, technology-specific collaborations between industry, academia, and government focused on advancing science and practice aimed at grand challenges, such as climate change, and
- solicit and fund collaborative research projects that connect university and industry researchers and expose early-career scientists to the knowledge, resources, and challenges of industry.^{37,38}

Because many innovations represent the combination of science and technologies developed across multiple streams,³⁹ policymakers should also support efforts that integrate existing streams of science and technology instead of funding only efforts aimed at inventing or discovering new knowledge. The wisdom of this approach becomes evident when one realizes that American agricultural productivity benefited dramatically in the late 19th century from the integration of several parallel processes: the development of new crop breeds, the use of mass-produced agricultural harvesting equipment, and the federally funded development of rail transportation. Likewise, modern smartphones are built on independent and interdependent advances in semiconductor, radio, GPS, software, and Internet science and technology. Today, smartphones are playing a central role in the emergence of innovations in the collection, analysis, and use of big data files containing information on millions of activities and transactions in all segments

47%

US employment at risk from automation over the next 20 years



in 31 states the most common job is a truck, delivery, or trailer-tractor driver

1945

the year the Roosevelt Government published *Science: The Endless Frontier*, the first Innovation policy

Ways for Policymakers to Enhance Innovation in the United States

PROBLEM: Technological innovation is an ongoing process of nonlinear development and interactions, wavering from a set of consistent steps. How can policymakers help manage this process to ultimately maximize both its potential profits and its social benefits for society?

SOLUTION: Provide incentives for communication at all levels of technological development: among researchers in different labs and fields; among industry, academia, and government; among agencies within the government; among international entities; and among laypeople and experts.

PROBLEM: The private sector alone has neither the resources nor the capabilities to develop the innovation infrastructures necessary to facilitate commercial success. This leaves the government to play a critical role in building innovation infrastructures. What can policymakers do to successfully support the private sector in developing the necessary infrastructure for innovation?

SOLUTION: Support efforts to integrate existing streams of science and technology by funding and encouraging knowledge sharing and learning across basic and applied research, development, demonstration, and deployment activities.

PROBLEM: Innovations rarely originate from only one source; rather, they are influenced by many different technologies' streams of ideas during the process of development. What steps can government take to influence innovation in the context of these complex and interacting feedback loops?

SOLUTION: Provide incentives for devising new uses for existing technologies and hasten the repurposing by enabling downstream industrial efforts (when technologies are already being commercialized) to readily provide feedback to upstream activities (such as basic research and early development of technologies).

PROBLEM: Innovation is a significantly more complex process than some government policies and private sector practices reflect. How can governments correct potentially inaccurate knowledge of managing innovation while also increasing the likelihood of success in the complex innovation process?

SOLUTION: Develop training programs for people charged with managing innovation. Teach managers how to cope constructively with conflict and competition among actors; to facilitate convergence on policies, regulations, standards, and platforms that underlie technological innovation; and to engage actors from many realms in the innovation processes.

of society. To better foster the integration of existing streams of science and technology, the government could

- fund promising university and industry programs that focus on bridging previously disconnected research streams (for example, data analytics and agriculture; nanotechnology and energy efficiency; and microbiology, food production, and infant nutrition) to address specific problems, and

- revise established policies that unduly constrain the recombination of extant knowledge and technologies for new applications (such as problematic policies in the domains of research funding, intellectual property rights, and resource management).

At the same time, any policies for innovation should emphasize procedures and incentives that allow technologies to be put to new uses over time.³⁷ Government-led efforts in the development of physical infrastructure, such as highways and communication systems, have been most successful when the government was open to new uses and repurposing. History shows that, whether targeted at specific, scaled end goals (for instance, the interstate highway system was originally meant to facilitate unencumbered military movement across the country) or launched to facilitate exploratory development (for instance, ARPANET, which evolved into the Internet, was meant to test ways for computer users to interact), innovation infrastructure efforts characterized by openness and malleability can do more than create direct value: they can enable further developments. As in natural ecosystems like oceanic reefs, it takes some time for communities to emerge around such platforms, but once the communities take hold, the supported diversity can be vast. In fact, the benefits to society can dwarf the vision of early proponents and far exceed the expected returns that were used to justify the initial investment. Thus, procedures that foster diverse uses should be considered in designing innovation infrastructures.

Managing Innovation Processes

A review of the research literature indicates that most innovations, particularly the large and complex ones, are neither predictable nor controllable by a single actor.⁴⁰ Moreover, behavioral science studies of the innovation process suggest that much received wisdom about managing innovation is questionable, including the value placed on business plans, budgets, and administrative review procedures.³⁵ Nevertheless, the government can help to increase the odds of innovation success by designing and carrying out training programs that will teach innovation

managers, both in and out of government, skills and practices that have been found to increase the prospects for success. (One example of a training course in managing innovation and change is available from the University of Minnesota at <http://z.umn.edu/ahvmgmt6050>.)

“the benefits to society can dwarf the vision of early proponents”

Skills that innovation managers should have include the following:

1. Managers need to learn ways to cooperate, compete, and conflict constructively with different stakeholders involved in building various components of an infrastructure for innovation, ensuring that they promote, rather than inadvertently interfere with, the innovation process. As A. P. Usher powerfully illustrated in his 1954 history of mechanical inventions, innovations are not produced by the inventive act of a single entrepreneur at a discrete point in time. Instead, the innovation process involves an accretion of numerous events in building infrastructures that require entrepreneurial roles by many public- and private-sector actors over extended periods of time.²⁵ These public- and private-sector actors both cooperate and compete with each other as they build the infrastructure needed to support a technological innovation. A recent well-known example is the development of an intranet and, subsequently, the Internet through many interactions among public- and private-sector actors performing numerous roles in the areas of research, financing, regulation, standards, and maintenance of the technological advances.
2. Managers must learn negotiating skills for adapting to periods when stakeholders diverge on policies, regulations, standards, and platforms that underlie technological innovation. Research shows that convergence on these aspects is critical to success.^{41–43} Convergence depends on clarifying intellectual property and processes for sharing and codevelopment, as well as on ongoing adaptations, as the underlying sciences, technologies, industry structures, and regulations coevolve over time.
3. Managers have to devise ways to enable various stakeholders to participate in and work together on innovations. Infrastructures need engaged participation from people in the public, private, and not-for-profit sectors, although the specific ways people contribute will vary and change over time. *Engaged participation* means that people participate voluntarily because they realize that they benefit from doing so. In a 2016 book, Dougherty illustrated the profound need for cooperation in the highly complex process of drug discovery, which can involve interactions among thousands of people.²³ Through interactions in which information or perspectives are shared, these individuals, each with a partial image of a complex problem, can collectively construct a representation that works and outstrips the capacity of any single individual. As noted by Taylor and Van Every in their book *The Emergent Organization: Communication as Its Site and Surface*, “Out of the interconnections, there emerges a representation of the world that none of those involved individually possessed or could possess.”⁴⁴
4. Government innovation managers, in particular, need to also develop incentives for more cooperation in the development of innovations. The current system of government incentives for research and development encourages just the opposite: competition and incremental science. For example, many universities and research laboratories fund their research positions through National Science Foundation and National Institutes of Health grants, and funds for a common kind of grant—the R01, which pays for circumscribed projects—are always scarce.³⁸ Consequently, researchers in competition for the same pool of scarce funds tend to avoid helping one another, such as by not sharing

“These guidelines are not merely theoretical”

enzymes or mice, yet such sharing would save time and effort. Consider the importance of mice for many of these individuals: when applying for an R01 grant, an investigator must already have the major tools for the proposed project (such as a genetically modified colony of mice) at the ready. It can take 2 years to develop a colony that breeds true to the needed attribute, however. That stumbling block makes the risk of doing something exploratory extremely high, so scientists often resort to study designs that will allow them to use the mice (or enzymes, or drugs, and so on) they already have available. Clearly, government incentives are needed to encourage collaboration between researchers over longer time periods, which would enable more radical, less incremental research.

These guidelines are not merely theoretical. The government is putting them into practice in some of its innovation activities. A good example is the federal Big Data Research and Development Initiative.^{45–48} It started in 2012 with attempts to put into practice key dimensions of behavioral science understanding of nonlinear innovation systems. It organized regional innovation hubs focusing on distinct needs (including health care, coastal hazards, manufacturing, agriculture, and education in addition to precision medicine, finance, energy, and smart cities) of specific regions of the country, as well as cross-sector collaborations to leverage public–private–nonprofit partnerships. The initiative also provides incentives to make public and private data more widely accessible to researchers and entrepreneurs and includes integration efforts to connect data sources that have been fragmented.

CancerLinQ is one project involved in the initiative. It is an effort to assist oncologists in improving cancer treatment by collecting the data on the care of cancer patients that is

stored in electronic health records.⁴⁹ Such information would be very hard to pull together if only competing, private-sector entities were involved. A second example is funding for the Amazon Web Services (AWS) cloud, which is a private platform, to provide public access to the largest data set on human genetic variation, developed through the 1000 Genomes Project. Few researchers have the computing power or storage capacity to house the data set; AWS uses the cloud to provide infrastructure for data analysis at enormous scale. The AWS project also typifies the initiative’s use of international public–private collaborations, bringing together researchers and institutions from several countries.^{50–52} Finally, the initiative explicitly promotes the broad participation that catalyzes innovation by engaging with civic groups and other grass-roots organizations.

Conclusion

We have focused here on two issues related to technological innovation that have significant long-term costs and benefits to society. First, technological innovations in control systems and information technology are replacing many jobs or shifting them so that they are performed by independent contractors with no health care, unemployment, disability, or pension benefits. The affected workers need a safety net.

Second, contrary to old ideas, research shows that innovations do not follow a linear sequence of stages, beginning with basic and applied research and moving downstream through development, demonstration, and diffusion. We explored several important implications of this understanding for innovation policy as well as for how government agencies themselves manage their own innovation processes.

We suggest that policymakers convene meetings to discuss the public policy implications of technological innovations with relevant stakeholders in the public, private, and nonprofit sectors; the involvement of all these parties is crucial to the success of any plans intended to minimize the negatives and enhance the positives of the technological trends facing the nation today.

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