



Federally Supported Innovations: 22 Examples of Major Technology Advances That Stem From Federal Research Support

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The origins of many foundational technologies can be traced to at least an initial investment of United States federal research and development (R&D) support and funds.

INTRODUCTION

While a few innovators have celebrity status—Bill Gates and Steve Jobs come to mind—the creators behind most widely used technologies remain obscure. In fact, the origins of many foundational technologies can be traced to at least an initial investment of U.S. federal research and development (R&D) support and funds. The Second World War institutionalized this important federal role in R&D and resulted in remarkable advances in radar, electronics, jet aircraft and atomic power. The United States has depended on this rich ecosystem, supported with federal money, where many of the biggest innovations stem from the work of the community, rather than a lone innovator.

However, after years of relative stagnation, as of 2012 the federal government funded just 31 percent of U.S. R&D, but with declines by the private sector in basic research, it funds 60 percent of basic research in the U.S.¹ The federal contribution to R&D is complemented with private sector R&D funding which provides the other 69 percent—largely for development. As a result, in terms of R&D intensity, the United States is falling behind other countries with only 2.9 percent of GDP invested in R&D in 2009, in contrast with 4.46 percent in Israel and 3.93 percent in Finland. Sweden, South Korea, Japan and Denmark all invest a larger percentage of GDP on R&D than the United States.²

This report reviews the literature and evidence of the role of federal R&D funding on innovation. It then examines 22 cases of successful U.S. innovation that has stemmed from federal support for R&D. The bottom line is simple: if the United States wants to regain the world lead in terms of innovation (as a share of its economy) it will need to expand, not contract, federal support for R&D.

THE ROLE OF GOVERNMENT IN THE U.S. INNOVATION SYSTEM

The spillover effects of R&D tend to be profound for society. Over the last 130 years, U.S. per capita income has grown exponentially. The positive feedback, enabling exponential growth, comes largely from one area of the economy, technological advancement. Nobel Prize-winning economist Robert Solow studied factors of production leading to growth and found less than half could be explained using the common factors assumed at the time related to capital supply and labor supply. He found, instead, that technological and related innovation was the dominant factor—in the 60 percent range—in economic growth.³ Elaborating on Solow's work, economists such as Paul Romer,⁴ Zvi Griliches⁵ and Kenneth Arrow⁶ confirmed that technological progress was the critical missing factor. Succinctly put by William H. Press, “As a factor of production, technology produces wealth and produces more technological progress, enabling a virtuous cycle of exponential growth.”⁷ And the federal government has long played a critical role in enabling and supporting innovation.

Federal support for innovation dates back to the beginning of the republic. In 1797 the first U.S. armory opened in Springfield, Massachusetts. Instead of relying on private contractors to produce arms for the U.S. Army, the federal government took on the role of both producing and providing the market. The U.S. Armories would become the most advanced manufacturers in the country, producing gun parts to a level of standardization that made them interchangeable. This crucial industrial advance of “interchangeable

machine-made parts” was known as “armory practice.”⁸ Armory practice began to spread to other industries, starting in the sewing machine industry. By the 1850s production of machinery was a stand-alone industry, each factory no longer constructed its own machinery. The development of the armory practice and accompanying machine tool industry paved the way for mass production, epitomized by the Ford Model T.⁹

The military continued funding innovations that helped spur the U.S. economy. Defense contracts from the Navy and the Army provided the only market in the early development of computing. The Department of Defense (DoD) supported research on semiconductors and even subsidized the facilities of private industry. Vernon Ruttan concludes in his book, *Is War Necessary for Economic Growth?*, that without federal involvement in the computing industry, the industry’s development and commercialization would have been delayed well into the 21st century. The DoD investment and military procurement in the 1970s and 1980s drove the economic tech boom and high growth rate of the 1990s.¹⁰

Following the national shock resulting from the launch of Sputnik by the Soviet Union in 1957, a new agency was founded that has come to be known as DARPA, the Defense Advanced Research Projects Agency. DARPA was set up to invest in high-risk, high-payoff research, as a flexible non-bureaucratic agency focused solely on technology.¹¹ While DARPA funds research and development, it does not fund the commercialization of technologies. Yet the agency is in a unique position to help ensure innovations make it to the next stage by leveraging its connections within the larger U.S. Defense Department.

DARPA has been responsible for funding the early research into some of the most common consumer products. From the Internet to GPS, advanced materials to pharmaceuticals, DARPA has funded innovative ideas that serve the military and civilians alike. The recently founded ARPA-E (Advanced Research Projects Agency-Energy), intends to do for the energy sector what DARPA did for defense. Both seek to bring innovation to their market sectors (a number of technologies launched by DARPA funding appear in Part II).

Many of the technologies funded through the Department of Defense offer clear, concise narratives of economic and social gain from federally funded research. As the examples in Part II show, research funding from the Department of Energy (DOE), National Institute of Standards and Technology (NIST), National Science Foundation (NSF), National Space and Aeronautics and Space Administration (NASA), and the National Institutes of Health (NIH) has also played a critical role in supporting this country’s economic prosperity.

Growing Role of Universities

Since the 1920s, universities have been involved in patenting and licensing intellectual property.¹² However, following the Second World War and the corresponding increase in federal support for research conducted at universities, technology transfer to the private marketplace was limited by an ineffective system for licensing; as the federal government held the patent. In 1980, the Bayh-Dole Act was passed, leaving intellectual property in the hands of the research institution, which contributed to vastly increasing the commercialization of technology developed with federal funding.¹³

The research at universities and nonprofits is not restricted to the educational sphere; many of the results from research are commercialized, benefiting the U.S. economy directly.

Prior to the passage of Bayh-Dole, in the 1970s, technology transfer offices, which manage and license intellectual property at research universities, became widespread. Universities could patent and license their research, however, under the regulations of Institutional Patent Agreements, an agreement had to be made with each federal agency that provided funding.¹⁴ Since Bayh-Dole, technology transfer offices have more easily been able to facilitate the transfer of economically significant innovations to commercial markets.

The results have been impressive. A study by the Biotechnology Industry Organization (BIO) examined the economic benefits derived directly from the transfer of technology from universities to industry. The study looked at the years between 1996 and 2007 but did not account for product substitution effects. Licensing agreements accounted for somewhere in the range of \$47 to \$187 billion of U.S. GDP. An additional \$82 billion of GDP over the 12-year time period came from royalty rate yields at an estimated 5 percent. Additionally, the study estimates that, as a result of university licensing, 279,000 jobs were created and gross industry output increased from \$108.5 to \$457.1 billion.¹⁵ A follow-up study by BIO extended the period from 1996 to 2010 and included nonprofit research institutes with universities. The study found that technology transfer resulted in an impact up to \$836 billion in gross industry output, \$388 billion in GDP, and three million jobs.¹⁶

Technology transfer links many universities to new startups. In 2010 there were 651 spin offs from university research and in 2011 that number increased to 671.¹⁷ These start-ups are the direct result of federally funded research at universities. It is important to note that these start-ups are often incredibly innovative but they aren't doing the basic research. Federal funding for research does not place the government in competition with industry. Rather the government funds research that is more basic and doesn't have an immediate economic impact, complementing the more applied research and development performed by industry.¹⁸

As a result, the research at universities and nonprofits is not restricted to the educational sphere; many of the results from research are commercialized, benefiting the U.S. economy directly. A wide range of ideas, concepts, and techniques discovered during the course of research at universities are of use to industry.

Synergistic Effect of Private and Public R&D

Federal support for R&D is critically important in today's innovation system. This is because now most R&D funding in the private sector increasingly focuses on later stage development, resulting in a decline of industry basic research since the mid-1980s. As noted, while basic research is risky for private industry, generally taking much longer with less assured results, it increases the knowledge pool and can lead to breakthroughs—particularly for “radical” innovation as opposed to “incremental” innovation. The responsibility for basic research has largely shifted to universities, which now conduct 56 percent of all basic research, up from 38 percent in 1960.¹⁹

One economic sector where federal research funding has worked synergistically with industry is information technology (IT). A well-known infographic (see Figure 1 on the following page), often called the “tire tracks” diagram, shows the links between academic

and industry research in the creation of new IT industries. The diagram was first produced in a 1995 report from the National Research Council and was updated in 2012. The graphic shows eight IT sectors, all but one now part of a \$10 billion or more market. In none of the represented IT sectors was research conducted solely by industry.²⁰ Instead the diagram shows the strong early presence of academic research in all the sectors, but also more significantly, the interconnections between industry and academic research in each sector and between sectors.

In 2010, the IT sector grew by 16.3 percent and accounted for nearly 5 percent of U.S. GDP. Virtually all the sectors in the diagram show that at least a decade of research, often primarily academic, is needed before a market exists. In broadband and mobile there were over three decades of research before a \$1 billion market existed. What it does highlight is the need for consistent and sustained investment in research. Between 1976 and 2009, two-thirds of university research funding in electrical engineering and computer science came from the federal government.²¹ The outcome of basic research is not always readily apparent; it can often take decades before the full significance is recognizable.²²

IT Sectors With Large Economic Impact

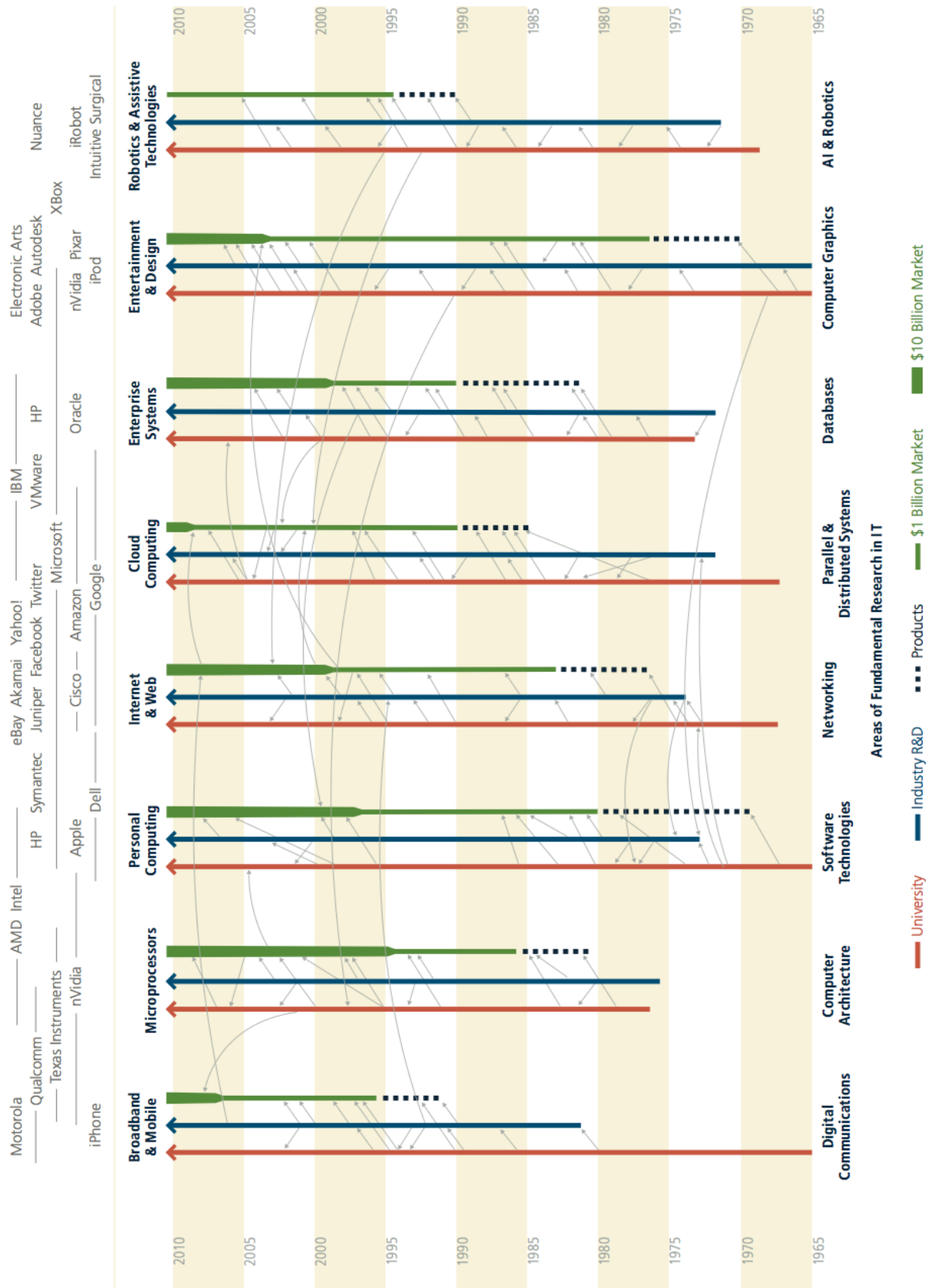


Figure 1: IT Sectors with Large Economic Impact

Source: National Research Council report *Continuing Innovation in Information Technology*²³

U.S. Innovation at Risk

This critical role of the federal government is now at risk. While private sector investment in R&D has continued to rise over the last few years, continued stagnation or cuts in federal funding could have long term ramifications on the innovation potential of the United States for years to come. Private sector investment in R&D increased from \$279 billion in 2010 to \$294 billion in 2011.²⁴ From 2010 to 2013 federal R&D spending fell from \$158.8 to \$133.2 billion, in constant 2013 dollars.²⁵ ITIF's report "Eroding our Foundation: Sequestration, R&D, Innovation and U.S. Economic Growth" notes that there are certain areas of R&D for which the private sector is unable or unwilling to support.²⁶ For instance, firms don't fund basic research because it is high risk—it doesn't readily translate into products in the short term. Firms are simply financially unable to address foundational research problems; research addressing basic and broad research questions lies outside the scope of most private investment. Shareholder demands for short-term profits limit the "knowledge spillover" of private R&D, limiting the societal benefit of research advances. As William H. Press frames the issue, for companies, the issue is about appropriability: "How well do the rewards flow back to the investor who actually takes the risk and puts up the money?"²⁷ Basic research spending is very unlikely to reward the original spender. However, the rewards from basic research remain huge and spread throughout society; it is a public good.²⁸ Without federal support of basic research, private industry will fail to fund this public good.

Moreover, state support of universities has decreased drastically in nearly every state, with the largest average reduction, 7.6 percent, occurring in 2011-2012.²⁹ The most widely noted effect of these cuts was tuition increases; these cuts, however, also affected state funding of university research. While states play a dominant role in supporting public universities and their buildings and infrastructure, they also play a modest role in research support. Between 2003 and 2008, state funding for university research, as a share of GDP, dropped on average by 2 percent. States such as Alaska and Utah saw decreases of 49 percent and 24 percent respectively.³⁰ Between 1989 and 2009 state and local government support for science and engineering research and development at all U.S. institutions dropped from 8.2 percent to 6.6 percent of total funding.³¹ While state funding has fallen drastically, federal funding has not filled the void. In fact, federal funding has not kept pace with competitor nations; the U.S. ranks 18th in the world in "percentage change in government-funded research performed in the higher education sector as a share of GDP," between 2000 and 2008.³² Industrial funding of university research is not significant either; the U.S. ranks 21st in university research funding by business as a percentage of GDP.³³

Although it is impossible to forecast which innovations won't occur, or will take much longer, because of declining research investments, it is very probable that the role of the United States as an innovation leader will decline as some of the next big innovations, and the new markets they create, take place overseas. As the following two sections will illuminate, the role of federal funding in game-changing innovations over the last 70 years has been pervasive. In a number of cases, including GPS and supercomputing, the federal government has played a dominant and leading role in their development, technology launch, and initial market creation. In other cases, small strategic funding has provided the push for innovations, like visible LEDs and the algorithm behind Google search, to get off

the ground. While we can't know what innovations won't happen, it is useful to look back and see how federal funding played a role in the development of so many innovations and products we take for granted today.

Spending caps, set by the Budget Control Act of 2011 (P.L. 112-25), have resulted in cuts to federal agencies that fund research, threaten the long-term ability of the United States to lead the world in innovation and as a result, grow our economy. The important role of federal government support of research has long been recognized. Both non-defense R&D and defense R&D spending have been studied thoroughly. The innovations resulting from federal R&D support are nothing short of amazing. Benefits of some of these investments are calculable. Others are more difficult to parse, including returns from investments in the combined mission at research universities, where federal money supports projects that perform the dual function of both research and education. Students play an integral role in university research and are also educated to later enter the workforce.

Over the long term, cuts in federal spending on research and development will result in lower long-term GDP growth and potentially an end of the historic trend of exponential growth. Sequestration, as proposed, would result in cuts of up to 9.4 percent for defense spending and 8.2 percent for non-defense spending, lasting for a decade, which according to estimates by the American Association for the Advancement of Science (AAAS) could result in a cut of a minimum of \$50 billion to all R&D from FY2013 to FY2017.³⁴ Between 2013 and 2021, ITIF estimates that the loss in GDP as a result of cuts to R&D will range from \$203 billion and \$860 billion. ITIF also estimates that 450,000 jobs will be cumulatively lost or not created.³⁵ This amounts to an unprecedented departure from the historic levels of growth in R&D spending, and also significantly reduces the innovative capabilities of the United States in the long run. The long-term costs of sequestration on R&D are difficult to project, however, the outlook from the Congressional Budget Office (CBO) of the effects of sequestration on the economy, as a whole, is not encouraging. In 2013 alone the CBO estimates that GDP growth will shrink by 0.6 percent and 750,000 jobs will not be created due to the overall mandatory cuts.³⁶ While the effects of sequestration were moderated for FY 2014 and FY 2015 by budget legislation at the end of 2013 (H.J.Res. 59), if nothing else changes sequestration will resume in full force after FY 2015.³⁷

22 CASES OF U.S. TECHNOLOGY INNOVATION THAT STEM FROM FEDERAL FUNDING

Information Technology

Google Search Engine

Two graduate students working on the Stanford Integrated Digital Library Project, supported with \$4.5 million in grants from NSF, came up with an idea for a new algorithm. PageRank, the algorithm, was the basis for a search engine they called BackRub. After first testing BackRub on equipment partially paid for by NSF, the two students sought private financing and founded the now ubiquitous company Google.

Funding from the National Science Foundation's Digital Library Initiative played a role in Larry Page and Sergey Brin developing a new algorithm, PageRank, which gave rise to the Google search engine.

Two graduate students at Stanford University, Larry Page and Sergey Brin, began work on an Internet search engine dubbed BackRub in 1996, as part of their academic research.³⁸ Two years later, after an infusion of \$100,000 in venture capital funds, they renamed their search engine Google and incorporated the company of the same name.³⁹ Today Google is a Fortune 100 company and the dominant force in internet search engines. As of January 23, 2014, Google's market value stood at \$387 billion.⁴⁰

The National Science Foundation's Digital Library Initiative supported Page and Brin's research. The \$4.5 million Stanford Integrated Digital Library Project—supported by NASA, DARPA, and several industrial partners, in addition to NSF—looked to reimagine how information would be collected and made available as digital repositories replaced traditional collections of books. Page and Brin created a new algorithm called PageRank to search through information posted to the internet.⁴¹ There were other internet search engines available, but the Stanford researchers thought they could do better. PageRank computed how valuable a page was likely to be by considering how many other webpages cited it, and the importance of each of those linking pages. PageRank rank helped BackRub return results that were usually more relevant to the searchers' interests.⁴² Soon BackRub transitioned from the academic world to the commercial world as Google, a name Page and Brin chose to indicate their confidence that they could search the entire World Wide Web ("Googol" is the very large number represented by 1 followed by 100 zeroes).

The company has branched out into advertising, social networking, email hosting, and operating systems for the mobile device market, while continuing to improve upon its core information search and retrieval, which still incorporates a version of PageRank. Google's search engine has also created a marketing industry based around search engine optimization, which aims to raise a webpage's ranking so it appears near the beginning of related searches.⁴³ Meanwhile federal agencies continue to support research on computer and information science and are actively exploring strategies for improving public access to quality information on the web.

GPS

In 1957, as Sputnik orbited the earth, researchers realized that satellites could be used to determine a location on earth. The Department of Defense would bring the idea of a global positioning system into operation by 1978. There were failures along the way: the first satellites failed to keep accurate time prompting the Department of Defense to turn to atomic clocks developed by NIST. DARPA would also play an important role, with efforts to create smaller lighter GPS receivers, which combined with the opening of the military GPS to civilian users, created a new market.

The Global Positioning System (GPS) uses a combination of ground stations, satellites and receivers to calculate a precise location nearly anywhere on earth. GPS receivers are now ubiquitous, found in nearly all cell phones and in many cars; however, this large consumer market developed around what was initially an exclusive military technology. The idea for GPS originated when researchers monitoring signals from Sputnik 1 were able to determine its orbit and realized that "an accurate position on the Earth [could be determined] from Doppler signals received from a satellite in a known orbit."⁴⁴

Driven by the demands of nuclear research, the U.S. National Labs worked with private companies to develop new supercomputers and to provide the requirements that shaped the field.

By 1959, the DoD-funded project TRANSIT, the first attempt at a positioning system, had begun. However, the six TRANSIT satellites designed mainly by the Johns Hopkins Applied Physics Laboratory, and built by RCA, were unable to keep accurate time. Satellite clocks need to be exactly synchronized to accurately calculate a position on earth due to the huge distance the signals travel; any time variations make this impossible. This major problem was later solved by the Navy's TIMATION program, which used atomic clocks. In 1973, the DoD brought the various programs together into one program, Navstar Global Positioning System.

The National Institutes of Standards and Technology was responsible for bringing atomic clocks to fruition. Isidor Rabi, a physics professor at Columbia and Nobel Prize winner, first proposed the idea for atomic clocks in 1945. Four years later the first atomic clock, using the ammonia molecule, was unveiled by NIST. In 1952, an apparatus, NBS-1, which measured the frequency of the cesium clock resonance was completed.⁴⁵ The atomic clocks in the TIMATION program used the rubidium standard, while the later clocks in the Navstar program used the cesium standard. The highly accurate clocks in the Navstar satellites were used to demonstrate Einstein's theory of relativity.⁴⁶ The theory of relativity predicts that the atomic clocks on the GPS satellites will run 38 microseconds faster per day per than those on earth, a change of time that if not accounted for would result in hugely inaccurate calculations of position within a few days.⁴⁷

By the end of 1978, enough satellites were in orbit for a limited GPS to operate.⁴⁸ After an attempt to limit the accuracy of civilian devices using the single GPS frequency in the mid-1980s failed, the DoD announced the broadcast of GPS on two different frequencies. One unencrypted frequency for civilian use, importantly helping improve airline safety, and the other frequency encrypted, for military use.⁴⁹ At the same time, DARPA worked to shrink the size of receivers from the standard 35 pounds. DoD receiver to a handheld device.⁵⁰ In July 1995, GPS became Fully Operation Capable. Modernization continues with a new generation of satellites launched starting in 2005. The ground stations have also been updated with new antennas, computers, and receivers.⁵¹ Federal research money continues to support further improvements in GPS technology, with DARPA currently funding positioning, navigation and timing (PNT) technologies to improve accuracy and providing locating services even if contact with satellites is lost.

Supercomputers

Supercomputing, from the beginning, has been the realm of national governments. Driven by the demands of nuclear research, the U.S. National Labs worked with private companies to develop new supercomputers and to provide the requirements that shaped the field. Today some of the fastest supercomputers in the world are located in U.S. National Labs.

During the Manhattan Project, teams of enlisted soldiers worked around the clock using punch card machines that filled multiple rooms to perform calculations to simulate explosions. The required calculations took between two and three weeks to complete. The need for a more efficient way to make those calculations wedded the history of

supercomputing to the National Laboratories responsible for the nuclear arsenal. Drawing on the early Whirlwind/SAGE computers at MIT funded by U.S. Air Force research for the first air defense systems, IBM created the 701, its first commercial computer, specifically to fulfill a defense need. Los Alamos National Lab received the first 701 in 1953.⁵² Nuclear research requirements played an important role in driving supercomputers forward, with the Lawrence Livermore National Lab providing the specification for the LARC supercomputer, which it received in 1960. The Los Alamos National Lab partnered with IBM to develop the Stretch design, the first was delivered in 1961 and four of the eight built were sold for nuclear research.⁵³

The next phase in the history of supercomputing was dominated by Seymour Cray. Cray began working for Control Data Corporation, leading the team that developed the Control Data 6600. Livermore Lab was the first to buy a 6600, which helped Control Data go on to sell more than 100.⁵⁴ Cray would leave Control Data in 1972 to set up his own company, Cray Research. His company's first supercomputer, the Cray-1, used memory chips that were slower than magnetic-core memories used in previous supercomputers. However, this led to an increased amount of memory to go along with improved processor speeds, meeting an important need for nuclear weapons laboratories. The company was unable to sell the Cray-1 until it made a deal with Los Alamos. The National Lab purchased it after an initial six-month loan, during which time it was tested.⁵⁵ Cray Research would become the dominant supercomputing company during the 1980s, eventually adding the oil industry and aircraft manufacturers to its customer base.⁵⁶

Supercomputing has largely remained the realm of national governments; in the United States, the maintenance of the nuclear stockpile without test detonations has driven their continued progress and purchase. The fastest supercomputer, the Tianhe-2 located in China, was measured at a speed of 33.86 petaflops.⁵⁷ The next two fastest are at Oakridge National Laboratory and Livermore, both of which use substantially less energy than the Tianhe-2, making them much more efficient.⁵⁸ The measurement of the speed of supercomputers, flops, was a result of the speed measurement requirements and purchasing power of the U.S. Department of Defense.⁵⁹ Supercomputing proved key to NIH's human genome initiative effort and increasingly plays a critical role in non-defense scientific applications. The growing importance of "big data" has resulted in more commercial uses of supercomputers.

Artificial Intelligence and Speech Recognition

Although some of the earliest work on artificial intelligence and speech recognition was started by private industry in the early 1950s, until products could be successfully commercialized the survival of these fields depended on federal funding from the Air Force and DARPA. Dragon Systems would commercialize a speech recognition program in the late 1990s drawing on years of research and participation in DARPA's SUR program. The iPhone assistant "Siri" would branch off from the DARPA-funded CALO project in the late 2000s.

Artificial intelligence (AI) has long captured people's imagination. Developments in the field have resulted in widely used, every day products. Claude E. Shannon's work, at Bell

From the 1960s onward, the majority of funding for artificial intelligence research has been provided by DARPA.

Laboratories and MIT, on information theory and how to create a program for a computer to play chess helped start research into artificial intelligence in the early 1950s.⁶⁰ Collaboration between Herbert Simon and Allen Newell led to the first successful artificial intelligence computer program, the Logic Theorist, in 1956, which was capable of solving numerous mathematical theorems. The funding for this program was provided by the Air Force, through RAND.⁶¹

From the 1960s onward, the majority of funding for AI research was provided by DARPA. One seminal DARPA program was Project Mac, begun in 1963 at MIT, an experiment in time-shared computing. Remote terminals were distributed around MIT's campus, giving each user the experience of personal computing.⁶² Of the 2.3 million dollars of funding for Project Mac, about two-thirds were allocated for AI research. By 1966, MIT professor Joseph Weizenbaum had finished writing the program ELIZA, which emulated natural conversation by responding and carrying on a conversation with the user. ELIZA was presented using the MAC time-sharing computer.⁶³ The next large AI project was the Strategic Computing Program (SCP), a ten-year, \$1 billion program funded by DARPA starting in 1983 that set ambitious AI goals, one of which was an autonomous vehicle.⁶⁴ The SCP led to relatively few direct commercial successes, but helped advance rule-based reasoning systems and the field of AI.⁶⁵

Bell Laboratories conducted some of the earliest research into speech recognition in the 1950s, but focused only on recognizing the spoken digits between zero and nine. The next big move forward came from the DARPA Speech Understanding Research (SUR) program, begun in 1971. Its goal was to create a system that could recognize 1,000 words. DARPA again funded speech recognition research through the SPC in the 1980s. Institutions such as Carnegie Mellon University (CMU), Stanford Research Institute (SRI) and MIT participated, as well as IBM and Dragon Systems. Funding continued in to the late 90s. The most notable software to emerge was from Dragon Systems, which was able to recognize continuous speech.⁶⁶

In 2003, DARPA began a new project called the Cognitive Assistant that Learns and Organizes (CALO). SRI was the lead research institute and the project received \$150 million over five years. One startup that broke off from SRI was Siri: "Siri offered the first mass-market assistant capable of understanding humans' natural speech patterns and assembling information from disparate parts of the Internet into a single, correct response."⁶⁷ In 2010, Siri was acquired by Apple, and now comes standard on all iPhones. Programs like Siri may mark the beginning of a change in the way we interact with computers.

ARPANET: Foundations of the Internet

First imagined by J.C.R. Licklider as a "Galactic Network" in the 1960s, ARPANET, a network originally consisting of five computers, went online in 1969 with research support and leadership from DARPA. Key follow-on developments and additions to ARPANET, while still a DARPA project, such as TCP/IP and email helped pave the way for today's Internet.

Through the development of ARPANET, a network originally consisting of five computers that went online in 1969 with DARPA's support, to subsequent innovations such as TCP/IP and email, federal support has played a catalytic role in the development of the modern Internet.

The Internet, compared to how we know it today, had a very humble origin, five interconnected computers. In 1967, Lawrence Roberts, working at DARPA, published a plan outlining a computer network he called ARPANET. Like his predecessor at DARPA—the earlier Internet and personal computing theorist J.C.R. Licklider,⁶⁸ who conceived of a “Galactic Network” in the early 1960s—Roberts was previously at MIT. DARPA, moving forward with the plan, contracted out the protocols and hardware to Bolt Beranek and Newman (BBN), a small technology firm in Cambridge, Massachusetts, allowing the computers to communicate with one another. BBN developed Interface Message Processors (IMPs), crucial hardware for packet switches or sending and receiving bursts of data. Packet switching offers a much more flexible transfer of data than circuit switching, which requires a dedicated point-to-point connection. The first IMP was installed at the Network Measurement Center at UCLA. By the end of 1969, ARPANET was up and running, connecting five computers at UCLA, BBN, Stanford Research Institute, UC Santa Barbara and University of Utah.⁶⁹

ARPANET continued to expand through 1972, with new software-based protocols and standards in place, supported by DARPA. In order to coordinate with other ARPANET users, Ray Tomlinson of BBN wrote a basic piece of software allowing users to send and receive messages.⁷⁰ This application was widely popular, anticipating today's email. By 1972, a host-to-host protocol called the Network Control Program (NCP), which controlled how messages were sent and received between hosts, was implemented throughout ARPANET. However, NCP had no end-to-end error control. This meant any reliability issues could bring down the entire network. Without a new protocol ARPANET could never expand into an open architecture network, a network of interconnected networks that were not all identical.⁷¹

Robert E. Kahn, at DARPA, set out to improve upon the NCP, working with Vinton Cerf, an assistant professor at Stanford. In 1973, they released a paper that described a new protocol called TCP/IP, which could deal with lost packets. DARPA led initial testing of TCP/IP, and by 1980 it was adopted as a defense standard. On January 1, 1983, ARPANET followed suit and switched. TCP/IP would thereafter go on to gain popularity until it became dominant. It is now the standard protocol, making the Internet as we know it possible.⁷²

NSF took over management of ARPANET in the 80s, creating NSFNET, which quickly spread through academic institutions. NSFNET first went online in 1986, connecting five university based supercomputer centers. Within the first year, which included the addition of ARPANET to the network, upgrades were required to manage the traffic. In 1987, a partnership between Merit Network Inc., IBM, MCI, the state of Michigan, and a consortium of Michigan universities received an award from NSF to make the necessary upgrades. The new network backbone was up and running in just eight months and connected over 170 campus networks.⁷³ Another important milestone occurred when the European Organization for Nuclear Research, known as CERN, introduced the World Wide Web, a system of interlinked hypertext documents, for Nuclear Research, in 1991. As the World Wide Web grew, browsers were needed to navigate it. One popular early browser was Mosaic. Marc Andreessen designed Mosaic while he was a staff member at the

NSF-supported National Center for Supercomputing. The development of personal computing, the World Wide Web and the Internet revolutionized the exchange of information and infused almost every form of commerce.⁷⁴

Closed Captioning

Closed Captioning was developed after three employees of the National Bureau of Standards (NBS, now NIST) found an unused part of the television-broadcasting spectrum large enough to transmit text. A fellow employee at NBS captioned a television episode in 1971 that successfully demonstrated the technology. By 1980, three national stations were broadcasting programming with closed captions.

While working at the National Bureau of Standards' Time and Frequency Division, Jim Jespersen, George Kamas and Dick Davis found an unused portion of the television signal. Their original intention was to transmit a time signal in the unused part of the spectrum. After that plan was abandoned Jespersen, Kamas, and Davis, found that the unused spectrum was large enough to transmit text.⁷⁵

Jespersen, Kamas, and Davis were able to hide the text from viewers unless they had a decoder. In 1971, another employee at the National Bureau of Standards captioned an episode of ABC's "The Mod Squad." This episode was shown as a demonstration of closed captioning at the National Conference on Television for the Hearing Impaired.⁷⁶

Following the successful demonstration, the Public Broadcasting Service and NBS worked to improve the encoding equipment, with PBS airing a closed-captioned news program at night. In 1975, PBS petitioned the FCC to reserve line 21 of the vertical blanking interval for closed captioning.⁷⁷ In 1979, a nonprofit, the National Captioning Institute, was founded in part with a federal grant to provide closed captioning, and by 1980, ABC, NBC, and PBS were broadcasting closed captioned programs (CBS would not broadcast with line 21 closed captions until 1984). Decoders were available to the public for purchase at that time. After 1990, all televisions larger than 13 inches were required to be capable of decoding the closed captioning signal.⁷⁸

Smartphone Technologies

Much of the technology found in today's smartphones is the result of both federal procurement and research grants. From driving the semiconductor revolution to supporting small research projects on touchscreens at the University of Delaware, federal money has played a key role in making the development of the smartphone possible.

The development of microchips—arrays of transistors connected to form reliable circuits—drove the semiconductor revolution. Although the microchip was developed by private laboratories at Texas Instruments and Fairchild Semiconductor, the buying power of the U.S government helped turn microchips into mass-produced, publicly-affordable, foundational technology. NASA and the U.S. Air Force were the first to buy thousands of chips per week to fuel their space exploration and missile projects, respectively, creating the initial market. Within a few years, several federal agencies began purchasing microchips to support their growing computing needs. Over time an industry for microchips was created,

From driving the semiconductor revolution to supporting small research projects on touchscreens, federal investment has played a key role in making the development of the smartphone possible.

including assembly lines for microchip mass production that would facilitate entry into the commercial market. It took only a few years for the cost of production of the microchip to be driven down by a factor of fifty. The market for semiconductor devices—recognized as a key driver behind the IT revolution and therefore of U.S. economic growth—was further advanced by the public-private partnership known as *Sematech*, which DARPA cost-shared for its first five years.⁷⁹ Microchips are a foundational component for smartphones, and allow the amplification of signals, physical movement of data and computational analysis. Consider this: “without these public investments, your iPod would cost \$10,000 and be the size of a room.”⁸⁰

University of Delaware research, supported by NSF grants and fellowships, developed a touch screen that was commercialized; it now provides a popular interface on cell phones and tablets. Wayne Westerman, a University of Delaware doctoral student, launched the company FingerWorks in 1998. His dissertation work on multi-touch surfaces was supported by the National Science Foundation’s funding of the University of Delaware’s *Experimental Program to Stimulate Competitive Research* (EPSCoR). After producing a line of tablets with multi-touch capacities, FingerWorks was bought by Apple, Inc., in early 2005. The technology is an essential feature of many popular smartphones.⁸¹

The federal government assisted many small technology companies early in their development. For example, early on Apple and Intel benefited from the U.S. government’s Small Business Investment Company program. The program offers critical early stage financing for small companies to fuel business growth.⁸² Of course, cell phone communications themselves stemmed from widespread use of radio during the Second World War to provide faster, larger-range, mobile communications. Postwar, even more reliable communications equipment was in demand from the federal government.⁸³ The needs of the U.S. military drove growth in radiotelephony, to which early mobile phone technologies owe their start.⁸⁴

Some progressive mobile telephone features already mentioned in this document include the Internet, whose foundation was laid by DARPA’s ARPANET, global positioning systems for maps navigation, and artificial intelligence with a voice-user interface, such as Siri on iPhone. These are all rooted in basic and applied research conducted by the U.S. government. Smartphone technology demonstrates the importance of both public and private research and development as a driver of American leadership in technological innovation.

Energy

The Shale Gas Revolution

Work performed at the National Laboratories provided key technologies necessary for hydraulic fracturing. DOE support of early demonstrations showed the feasibility of hydraulic fracturing in oil shales. Federal funding helped hydraulic fracturing develop in the early years when it was not commercially viable.

Beginning in the 1970s, federal investments in gas extraction technologies helped transition inaccessible shale deposits into a fast-growing component of the United States’ energy

Work performed at the National Laboratories provided key technologies necessary to the development of hydraulic fracturing, while federal funding helped hydraulic fracturing develop in the early years when it was not commercially viable.

portfolio,⁸⁵ which is moving the U.S. closer to a forty-year goal of energy independence. Although hydraulic fracturing of oil and gas wells occurred in the early twentieth century, fears that the United States natural gas resources were declining spurred government research to develop measurement methods of gas volume in nontraditional gas reservoirs, e.g., oil shales, tight sandstones. The U.S. Department of Energy's National Energy Technology Laboratory developed foam fracturing technology, oriented coring and fractographic analysis, and large-volume hydraulic fracturing. Jointly with industry, DOE completed the first horizontal shale well and developed the first public estimates of recoverable gas from shale fields in the United States.⁸⁶

Federal support for hydraulic fracturing included tax credits, public demonstrations and government-industry joint ventures such as the Gas Research Institute (GRI) and the Eastern Shales Gas Project. In 1977, the DOE successfully demonstrated massive hydraulic fracturing (MHF) in shales. This prompted Congress to promote production tax credits for institutions processing unconventional gas. Federal scientists and engineers worked closely with private companies to develop imaging technologies to aid in shale field mapping. The GRI successfully funded the first horizontal well in the Texas Barnett shale. This proved to be a cost-effective method of extracting gas from shale.⁸⁷

The DOE push for technological innovation, following the energy crisis in the early 1970s, vastly increased the speed of development. Today's new approach to the hydrocarbon economy provides some groundwork for policy proposals reducing greenhouse gas emissions, the use of oil in shipping and general dependence on foreign energy sources.⁸⁸ Although the early years of fracking were costly and challenging, full-scale commercial fracking was made possible through crisis-driven federal investment in basic and applied research, alongside public-private partnerships in technology development and demonstration. Compared with other nations with currently growing shale fracturing, the decades of strong public investment in R&D helped bring the United States back to the forefront of the natural gas hydrocarbon economy. Other countries with sizeable shale deposits are only just beginning to grow their shale-based energy sectors.⁸⁹

Seismic Imaging

Since 1921, the oil industry has used seismic imaging. It would take until 1967 for the next big breakthrough, 3D seismic imaging, to occur. However, 3D seismic imaging involved a massive amount of data processing, delaying its widespread use. The DOE National Laboratories provided computing power as well as new algorithms that solved some 3D imaging problems, and also developed 4D seismic technology. Seismic imaging advances have improved resource recovery for oil companies and may help make carbon sequestration possible.

Seismic imaging works much like radar. Signals are sent into the ground and the reflections are received and used to create an image. Seismic imaging has long been useful for identifying the location and size of underground oil fields and more recently has improved the efficiency of hydraulic fracturing. Seismological equipment was first used in 1921 to send beneath the surface of the earth to aid in the discovery of oil. Dynamite was used to send shock waves through the earth and the seismic reflections were recorded on a seismograph.

This experiment produced a 2D seismic survey; the first 3D seismic survey would not occur until 1967. In large part due to huge costs associated with the vast amount of data needed for 3D surveys, they were not common until the mid-1980s.⁹⁰ In 1988, the Department of Energy became involved with the Oil Recovery Technology Partnership, helping make improvements in seismic imaging technology.

The involvement of the National Laboratories provided the industry with a number of benefits. The oil industry was granted access to more computing power and seismic technology through the National Laboratories. The DOE also developed new algorithms to solve some 3D imaging problems, a multi-station borehole seismic receiver, and 4D seismic technology (time-lapse 3D imaging), all of which are now commercially available.⁹¹ These imaging advances were critical to the industry's success by making drilling for gas in shale efficient.⁹²

Advances in seismic imaging continue to play an important role in the current shale gas boom. Seismic imaging is now being used in early attempts at carbon sequestration. Michael Fehler and Di Yang, at MIT, have worked in collaboration with Lianjie Huang, from Los Alamos National Laboratory, on a new technique. Their double-difference technique compares differences in data rather than comparing models, which produces clearer images and reduces costs. The improved images help researchers to characterize and monitor CO₂ sequestered below the surface.⁹³

Visible LED Lighting Technology

While the earliest records of light emissions from semiconductors date from 1907, the first major milestone came in 1962. That was the year Nick Holonyak, while working at General Electric and receiving funding from the Air Force, created a red LED. The next big breakthrough came in the 1990s with the development of blue LEDs, which make the creation of white light possible. The Department of Energy's Next Generation Lighting initiative has helped fund development of brighter and more efficient LEDs, making them a cost competitive and energy efficient alternative to fluorescent and incandescent lighting.

The first recorded emission of light from a semiconductor occurred in 1907, when Henry Joseph Round noticed light near a metal point contact while working with silicon carbide (SiC).⁹⁴ From 1923 until the 1940s Vladimirovich Lossev would also work with extensively with SiC, although he was unable to advance the understanding of why light was emitted. After the World War II, work by Bardeen, Brattain and Shockley at Bell Labs led to a theoretical understanding, by 1948, of the p-n junctions inside semiconductors and explained the emission of light.⁹⁵

Research moved away from SiC and focused more on III-V compound semiconductors starting in the 1950s. By 1962, groups from RCA, GE, IBM and MIT Lincoln Labs had made infrared LEDs and lasers (GaAs lasers).⁹⁶ The breakthrough in visible-spectrum LEDs came from Nick Holonyak in 1962. Building off the work on III-V compound semiconductors, Holonyak would create the first GaAsP red LED. At the time Holonyak had been working at GE where he was under pressure to focus more of his efforts on Si-

The Department of Energy's Next Generation Lighting initiative has helped fund development of brighter and more efficient LEDs, making them a cost competitive and energy efficient alternative to fluorescent and incandescent lighting.

related (silicon-related) work, however funding from an Air Force contract helped offset the pressure from GE management.⁹⁷

Initially, visible LEDs were used as indicator lights replacing bulbs that burned out more frequently and used more power. LED displays began appearing in calculators and wristwatches in the 1970s.⁹⁸ As more colors of LEDs were developed they began appearing in signs and stoplights. The big breakthrough in LED lighting would come with the development of a blue LED, which when mixed with yellow appears white. Although companies like Cree, which received federal funding, were working on developing high efficiency and brightness blue LEDs, Shuji Nakamura of the Nichia Corporation would be the first to do so in 1994.⁹⁹ Work to develop brighter, cheaper, and more efficient white LEDs continues in a number of companies. The Department of Energy also provides funding to researchers as part of the Next Generation Lighting initiative.

LEDs, which use far less power than fluorescent and incandescent light bulbs, are now poised to acquire an ever-greater share of the lighting market and offer potential energy savings for the nation. In 2011, the U.S. Energy Information Administration estimated that residential and commercial lighting accounted for 461 billion kilowatt-hours of energy use, or 12 percent, of all U.S. electricity consumption.¹⁰⁰ LEDs use 75 percent less energy and last up to 25 times longer than incandescent lighting. Upfront costs of LED lighting are presently higher than the cost for comparable fluorescents and incandescent lamps and fixtures, but have begun to fall rapidly. By replacing all lighting with LEDs over the next 20 years, the DOE estimates the United States could save \$250 billion in energy costs.¹⁰¹

Health

Magnetic Resonance Imaging (MRI)

MRI developed out of early work at U.S. and U.K. universities on nuclear magnetic resonance. After Richard Ernst developed the basic technique for MRIs in 1975, new developments and techniques led to new uses for MRIs. In the 1990s, work at NIH resulted in Diffusion Tensor Imaging, expanding MRI usefulness in studying white matter in the brain. Both NIH and NSF have played a role in the long-term development of MRI, which allows enhanced diagnosis of disease and an improved ability to monitor treatments.

Magnetic Resonance Imaging came arose from earlier research on nuclear magnetic resonance. Important early figures in this research included Isidor Rabi, who worked at Columbia University, where in the 1930s he developed an apparatus that “succeeded in detecting and measuring single states of rotation of atoms and molecules, and in determining the magnetic moments of the nuclei.”¹⁰² In 1946, Felix Bloch, at Stanford University, and Edward Purcell, at Harvard, both found nuclear magnetic resonance (NMR), the phenomenon where nuclei absorb then readmit electromagnetic energy.¹⁰³ Over the next 25 years, many researchers developed NMR into a sensitive probe of materials properties. NSF investments supporting the development of NMR from 1955 until the 1990s totaled \$90 million.¹⁰⁴

*National Science
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million.*

Paul Lauterbur produced the first two-dimensional NMR image while working at State University of New York at Stony Brook in 1973. A year later Peter Mansfield, at the University of Nottingham, “filed a patent and published a paper on image formation by NMR.”¹⁰⁵ Richard Ernst developed the basic technique of today’s MR images in 1975, inspired while attending a talk by Lauterbur a year earlier.¹⁰⁶ All three won the Nobel Prize. MRIs continued to be improved; by the 1980s performing cardiac MRIs was possible as well as the imaging of congenital heart disease. The NIH has played a long-term role in the development of MRI.

Advances in the 90s led to new technologies based on the MRI, such as Diffusion Tensor Magnetic Resonance Imaging (DT-MRI). DT-MRI is able to measure the motion of hydrogen atoms. Water diffuses in specific patterns depending on the obstacles it encounters, for instance water diffuses in the direction of fibers in tissue with lots of fiber, like brain white matter. Unlike conventional MRIs, Diffusion Tensor Imaging can show the white matter in the brain, providing a new tool for studying concussions, schizophrenia, and Alzheimer’s. Peter J. Basser, James Mattiello, and Denis LeBihan invented DT-MRI while working at the National Institutes of Health.¹⁰⁷

Advanced Prosthetics

New materials and prosthetics with programmable chips appeared in the 1990s. The U.S. wars in Afghanistan and Iraq prompted an increased need for prosthetics. Recent research work supported by the U.S. Department of Veterans Affairs has advanced the field by merging robotics and prosthetics with the creation of an ankle and foot that mimics natural motion. DARPA has also stepped in, supporting research for upper-limb prosthetics.

In the United States today, there are approximately 2 million people who are missing a limb, with about 185,000 amputations occurring every year.¹⁰⁸ The number of major limb amputations performed on U.S. service members since the start of Operation Enduring Freedom in Afghanistan and the operations in Iraq stood at 1,493 at the end of 2012.¹⁰⁹ The use of prosthetics is not new, the first prosthetic appeared in ancient Egypt, but improvements have been slow. The development of movable prosthetics did not occur until the 1800s. More recent advances have moved beyond improvements of materials used (lightweight polymers instead of wood) to address function. Some prosthetics now work like functioning appendages.¹¹⁰ The German company Ottobock developed one of the first of these new types of prosthetics, called the C-leg. It uses hydraulics controlled by a microprocessor to mimic the user’s gait.¹¹¹ More recent innovations such as the iWalk BiOM have further merged prosthetics and robotics.

The BiOM is largely a result of work done by Hugh Herr, a professor at the MIT Media Lab. Herr has spent most of his life designing prosthetics. The BiOM came into existence through the Center for Restorative and Regenerative Medicine, which received a \$7.2 million grant from the VA and included scientists from Brown University, MIT, and Providence VA Medical Center. In 2007, the BiOM was licensed to the company iWalk; production began in 2011.¹¹²

A \$3.8 billion federal investment to launch the Human Genome Project has resulted in an estimated economic impact of \$965 billion between 1988 and 2012 alone in associated research and genomics industry sector activity.

The BiOM uses a battery and small motor along with springs to replicate the natural motion produced by the foot and ankle muscles and tendons. Prosthetic feet and ankles that use only passive springs require the user to expend 30 percent more energy.¹¹³ In addition the BiOM is programmable; ankle stiffness and amount of power can be adjusted.¹¹⁴ The design of the BiOM provides a more natural gait and helps reduce fatigue.¹¹⁵

By 2006, upper-limb prosthetic technology had lagged behind lower-limb prosthetics leading DARPA to launch the “Revolutionizing Prosthetics” program. By 2012, DEKA Integrated Solutions Corporation, a participant in the program, had completed a VA-funded optimization study and began seeking FDA approval for its Gen-3 Arm System. The DEKA prosthetic offers more dexterity, range of motion and control than traditional upper-limb prosthetics.¹¹⁶ Federal funding of new more advanced prosthetics continues. Building on the earlier work of “the Boston Arm,” a 1968 lightweight, powered artificial limb that used electrical brain signals to control its movement, some of the most cutting-edge research today concerns enabling the brain to directly control an artificial appendage.

The Human Genome Project

The project was jointly conceived and executed by the U.S. National Institutes of Health and the U.S. Department of Energy. The venture’s price tag was approximated at \$3.8 billion over the course of 15 years of DNA base sequencing. Federal grants to university-affiliated genome centers were critical to the project’s success, two years ahead of the scheduled 2005 completion date and under budget. The Project laid the foundation for a new generation of collaborative genomics research fueled by scientific curiosity and medical need.

The economic impact of the Human Genome Project (HGP) is enormous, an estimated \$965 billion between 1988 and 2012, in associated research and genomics industry sector activity, both directly and indirectly.¹¹⁷ However, in the 1980s, a time when biologists were sequencing one gene at a time, the possibility of sequencing the entire human genome remained only theoretically possible. An additional challenge was that there was no tradition of “Big Science” in biology as there was in physics, starting with the Manhattan Project, and later with space exploration, through the Apollo Project.

Two developments triggered the NIH to take more seriously scattered calls from the biology community to sequence the entire human genome. Firstly, Leroy Hood and Lloyd Smith of the California Institute of Technology invented the first automated sequencing machines in 1986 to facilitate more rapid analysis of DNA. Before this development, the sequencing of one DNA base maintained a price tag of \$10, and one scientist required a full day to sequence 50-100 bases. Hood and Smith revolutionized the sequencing process, enabling scientists to sequence 10,000 bases per day at a cost of little under \$1 per base. Secondly, the United States Department of Energy reapportioned \$5.3 million for a human genome initiative and created three genome research centers utilizing the national laboratories. With these technological and logistical advances, the National Research Council endorsed the Human Genome Project, recommending \$200 million in funding

per year over ten to fifteen years. The cost of the HGP was estimated to total \$3 billion by the time of completion.¹¹⁸

The National Institutes of Health maintained an interest in understanding biology for medical advances, while the Department of Energy, in light of the Manhattan Project, advances in nuclear technology, and its expertise in supercomputing, wanted to explore the human genome to identify mutations that nuclear radiation may cause. The two agencies banded together to submit a joint, five-year proposal as part of a concerted public effort to sequence the human genome, advance sequencing technologies, and make ethical considerations part of the HGP. The project progressed so rapidly that, in 1993, NIH and DOE set new goals for their project.¹¹⁹

HGP was formally launched in 1990, with most of the funding from NIH and DOE being distributed as grants to individual academic investigators at universities and research institutions around the United States, who shaped their pursuits to fit HGP goals. Genome centers were located at the Whitehead Institute (affiliated with the Massachusetts Institute of Technology), University of Michigan, Baylor College of Medicine, the University of California, San Francisco, and Washington University in St. Louis. In 1998, Celera Genomics, a private venture led by Craig Venter, previously an NIH scientist, sought to sequence the human genome more quickly and cheaply than the HGP. By using a shotgun approach, where random pieces from the genome are sequenced and then later assembled into the whole by a computer, Venter believed that Celera could complete the project in half the time of the HGP. HGP was concerned that Celera's business model necessitated that portions of the genome be patented, which prompted HGP to accelerate its efforts, resulting in one of the most famous and productive scientific competitions in history. In May of 2000, Jim Kent of UC Santa Cruz began writing the program that would assemble a draft of the human genome; he completed the 10,000-line program in four weeks. On the 22nd of June, NIH researchers released a draft of the human genome. This draft helped ensure that access to the human genome would be free and publically available.¹²⁰ The project drew to a close when the final draft was released in 2003; NIH's HGP was published in *Nature* simultaneously with Celera's in *Science*.

The project allowed more federal funding to pour into the determination of gene function, as well as research proposals exploring the genetic basis of thousands of diseases. A new area of research exploring the bioethical considerations was raised by the project. A rapidly developing class of genomic and bioinformatics research was also ushered in.¹²¹ The project exemplifies how NIH's commitment to basic research fuels subsequent public and private innovation. The United States spearheaded genome sequencing internationally and associated technologies primarily because of NIH and DOE investments. HGP spurred more than \$8 billion in subsequent federal funding in genomics-related research and opened new areas of study in medicine and biotechnology.

HIV/AIDS

The first American case of AIDS was identified in 1981. Within three years, hundreds of thousands of cases were reported across the nation. A majority proved fatal. The recognition of the HIV/AIDS epidemic as a national priority led to swift

federal measures supporting disease response, screening, research, prevention, and education widely across the United States. Research supported by NIH and expedited FDA approval led to the first antiretroviral drug, AZT, drastically increasing life expectancy for HIV patients.

In 1981, the United States Center for Disease Control and Prevention (CDC) reported a rare lung infection among five gay men in Los Angeles; within one week, doctors across the United States inundated the CDC with similar case reports. In the first six months, 270 cases of severe immunodeficiency were reported, and 121 of those individuals passed away. In the coming year diagnoses of similar cases were made among infants, women and other groups. The quickly spreading disease was labeled as acquired immunodeficiency syndrome (AIDS). Cities, blood banks and the U.S. Congress pursued rapid response and prevention measures in the new fight against HIV/AIDS.¹²²

Work into finding the cause of AIDS began worldwide. Luc Montagnier, at the Pasteur Institute in Paris, was the first to isolate the cause of AIDS; the virus LAV, renamed HIV in 1983. Early on, Dr. Robert Gallo, at the National Cancer Institute, was able to identify the cause of AIDS as a retrovirus. Gallo was able to isolate a retrovirus he called HTLV-III in 1984; a few months later Montagnier's and Gallo's retroviruses were confirmed to be the same. A year after the discovery of the virus, the FDA approved the first commercial blood test for HIV using ELISA, which identified HIV antibodies.¹²³

In 1986, the United States Health Resources and Services Administration (HRSA) established its first AIDS-specific health initiative. It provided funds to four of the country's hardest-hit cities in its first year: New York, San Francisco, Los Angeles, and Miami. These AIDS Service Demonstration Grants utilized community-based—rather than inpatient-based—case management approaches. Within five years, the program appropriated grants to smaller cities, towns, and rural communities across the United States. The grants helped community leaders provide many services for HIV-infected individuals, including viable options aside from inpatient care.¹²⁴

The first antiretroviral drug, zidovudine (AZT), was approved by the FDA in March of 1987. Jerome P. Horwitz first synthesized AZT in the early 1960s at the Michigan Cancer Foundation. The drug failed to treat leukemia in mice and was shelved in 1964. After the identification of the cause of AIDS, researchers at the Burroughs Wellcome Company began testing known compounds as possible treatments. Working with laboratories at NIH's National Cancer Institute, Duke University and the FDA, Burroughs Wellcome found that AZT inhibited HIV replication. Testing on animals started and with FDA permission, granted after only a week, human trials began on July 3rd 1985.¹²⁵ The U.S. Congress approved \$30 million in emergency funds to help get AZT to patients.¹²⁶

The HIV epidemic placed pressure on the FDA to ensure that new drugs reached patients without unnecessary delay. In 1987, a new class of drug was created which led the FDA to accelerate approval time from three years to two. The following year the FDA allowed the importation of unapproved drugs to treat life-threatening illnesses. The approval processes was again accelerated following pressure from the group AIDS Coalition to Unleash Power (ACT UP).¹²⁷

In 1990, the Comprehensive AIDS Resources Emergency (CARE) Act was signed into law. It remains one of the only disease-specific health programs in the United States. The Act identified services that could be used by people living with HIV/AIDS and also made awards available to clinics and other healthcare providers serving disenfranchised populations. Since the CARE Act is a discretionary budget program, rather than an entitlement, funding availability depends on the Federal budget.¹²⁸

When the CARE Act was implemented in 1991, the first year during which grants were appropriated, 156,143 people had perished from AIDS in the United States. Swift government action supporting a united force of governments, providers and communities spread a network of services for HIV-infected individuals across the nation.¹²⁹ Administrative actions such as mailing educational packets on HIV/AIDS to all American households improved public awareness of how the disease is contracted and promulgated preventive measures against HIV/AIDS across the nation.¹³⁰

The federal government's efforts have helped new treatments and tests become available and federal initiatives have furthered the general public's education and ensured wider access to treatment. Since the mid-1990s, the number of available drugs to treat HIV has increased. In 1995, FDA approval of Invirase, the first of a new class of drugs that attack the virus at a different stage, allowed for highly active antiretroviral therapy (HAART), the combined use of multiple class of drug. In the 1980s there was an assumption that the AIDS epidemic would require non-stop U.S. hospital construction to create enough beds for the dying; today through federally supported medical research advances, AIDS in the United States has become a treatable, manageable disease. Tens of thousands of AIDS patients are able to maintain productive lives despite their disease.

Mathematics

Reverse Auctions

Mathematical research, funded by NSF, into the classical “assignment problem” throughout the 1980s and early 1990s resulted in an algorithm that helps reduce costs and improve efficiencies in distributing assets. The system of reverse auctions leads the bidders to make lower bids to provide a service or materials, drastically lowering the price and more efficiently allocating resources. Both the Federal Communications Commission (FCC) and the General Services Administration (GSA) now make use of reverse auctions in cost-saving measures for taxpayers.

Pressure to cut costs has led federal agencies to turn to new methods such as the reverse auction to lower procurement costs. In a reverse auction, the sellers bid against each other, driving down the cost for the buyer. The FCC TV Incentive Auction will use a reverse auction to buy back part of the spectrum currently being used by television stations and make it available for sale to mobile broadband companies.¹³¹ In 2013, the General Services Administration announced the launch of a reverse auction platform that will be used when federal agencies need office products, equipment, and services.¹³²

A 1979 paper by Dimitri Bertsekas was the first to introduce the idea of a reverse auction. Bertsekas came up with a new algorithm to solve the classical assignment problem. The

Mathematical research funded by NSF into the classical “assignment problem” throughout the 1980s and early 1990s resulted in an algorithm that today serves as the basis for cost-saving reverse auctions operated by many government agencies.

algorithm matches buyers with sellers in a way that minimizes the costs for the buyers. Bertsekas and others would continue to refine this method throughout the 1980s and early 1990s, receiving funding from the National Science Foundation and other government agencies.¹³³

During the mid and late-1990s internet boom, numerous online companies were set up to manage reverse auctions. Glen Meakem started one pioneering company, FreeMarkets Inc., in 1995. Companies that used FreeMarkets, such as General Motors, Emerson Electric and Quaker Oats, were able to save over 15 percent with reverse auctions.¹³⁴ In 2004 FreeMarkets Inc. was sold to Ariba for \$493 million. By 2004 there was a push within the government for federal agencies to use cost saving methods such as reverse auctions.¹³⁵

Kidney Matching Program

Starting in the 1980s, Alvin Roth set out to solve practical problems by further developing early “matching” algorithms. With the support of the National Science Foundation, Roth and other researchers enabled a drastic increase in the number of kidney transplants from living donors from 19 in 2003 to 5,769 in 2012.

As of June 21st, 2012, 96,645 people in the United States were waiting for kidney transplants. In 2012, of the 16,812 kidney transplants to occur, 5,769 kidneys came from living donors.¹³⁶ This number is astonishing considering that there were only 19 transplants from living donors in 2003.¹³⁷ This drastic change occurred largely as a result of the efforts of a small group of economists to develop new algorithms to create satisfactory matches.

In 1962, David Gale at Brown University supported in part by a grant from the Office of Naval Research, and Lloyd Shapley, (at the RAND Corporation), published a paper entitled “College Admissions and the Stability of Marriage.” The paper noted the comparable goals of college admission and marriage. The authors proposed a new algorithm that achieved as many satisfactory and stable matches between partners as possible from the huge number of potential pairings, a concept that also applies matching students and universities.¹³⁸ From the 1980s on, Alvin Roth would build off Gale and Shapley’s theoretical work (the 1962 matching algorithm) and apply it to various practical problems.¹³⁹

Teaming up with Tayfun Sönmez and M. Utku Ünver, Roth set out to find a better method for matching kidney donors and recipients. Receiving funding from the National Science Foundation through the National Bureau of Economic research, they published a paper on the problem in 2004.¹⁴⁰ The paper proposed a system that would create compatible pairs (donor and recipient) by building a database composed of willing donors. However, since most people who donate a kidney are related to the person in need, the system depended on matching algorithms to ensure that when their kidney was donated, the donor’s relative received a compatible one in return. Roth would go on to help found the New England Program for Kidney Exchange, between 2004-2005, which put the system of matching donors into practice.¹⁴¹ The system devised by Roth, Sönmez, and Ünver is now used across the country, vastly increasing the number of kidney donations from living donors, which have a higher rate of success than those from deceased donors.

DARPA funding helped generate an algorithm which can solve certain integral equations faster than previously available methods and with much less computing power and which has use in civil aviation, semiconductor manufacturing, and health imaging.

Fast Multipole Method

The ability of radar to identify a plane by its signature had long eluded the military due to the large amounts of data involved. DARPA invested in the work of two mathematicians, Rokhlin and Greengard, to figure out how to create an algorithm to solve this problem. The Fast Multipole Method algorithm they developed now has many uses beyond just radar.

The Fast Multipole Method (FMM) is an algorithm that can solve certain integral equations faster than previously available methods and with much less computing power. The FMM is particularly useful for solving the problem of identifying a specific plane's radar signature. In computing a plane's radar reflection, a series of equations (Maxwell's equations) must be solved. These equations can be solved using Green's function, but it takes a prohibitively large amount of data. Each time, calculations must be made using source points and target points, requiring something along the lines of N^2 calculations for each set of points of which there are many on a plane. FMM approximates source points into one multipole field, drastically reducing the number of calculations to a manageable level.¹⁴²

Vladimir Rokhlin of Yale University and Leslie Greengard of NYU published a paper on the Fast Multipole Method that solved two-dimensional problems.¹⁴³ Louis Auslander, applied mathematics program manager at DARPA from 1989-1991, turned to Rokhlin and Greengard to find a solution for the radar identification problem.¹⁴⁴ Rokhlin and Greengard received funding from DARPA, AFOSR and ONR to conduct further research. In 1996, they released a paper detailing the use of FMM for three-dimensional problems.¹⁴⁵

The use of FMM vastly improved systems in place, increasing efficiency between ten and 1,500 times. Boeing employed FFM in the Joint Strike Fighter on board radar.¹⁴⁶ FMM has found many uses outside the military and is currently being used, in a slightly simpler form, by the semiconductor industry. As another example, it has also been used in computer simulations of blood flow, which may eventually expand understanding of blood clotting.¹⁴⁷

Education

SCALE-UP (Student-Centered Active Learning Environment for Undergraduate Programs) Learning Science Advances

Many introductory physics classes at major universities across the United States no longer use the traditional lecture format, but instead include more technology and hands-on learning, resulting in more success for students. SCALE-UP, with the support of NSF, has innovated the way physics and engineering are taught.

In August 2010 the University of Minnesota opened the Science Teaching and Student Services Building, complete with ten rooms that can be used for SCALE-UP. Students collaborate in hands-on SCALE-UP courses, supported by computer-rich interactive learning environments, and outperform those in traditional lecture based courses.¹⁴⁸ The rooms at the University of Minnesota can seat between 27 and 126 students.¹⁴⁹ Originally started at North Carolina State University (NCSU) in the mid-90s, more than 50 colleges and universities now use the SCALE-UP approach.¹⁵⁰

The NCSU SCALE-UP program, funded by the Department of Education, National Science Foundation and corporate partners, has its roots in earlier models. One of the first models to move away from lecture-based courses and to focus more on hands-on activities was Dickinson College's Workshop Physics. The 1987-1988 school year was the first that all introductory physics courses at Dickinson were taught using the Workshop format. With no formal lectures, learning occurs through activities and observations with computer-based work for enhancement. Dickinson physicist Priscilla Law was instrumental in developing the new curriculum. Law and her colleagues received major grants from the Department of Education and NSF.¹⁵¹ In 1993, Rensselaer Polytechnic Institute began an integrated lecture-laboratory format called Studio Physics. Studio Physics, which has been recognized with several national awards, brought technology into the classroom and focused more on group work and interactions with faculty.¹⁵² The SCALE-UP pilot, during the 1995-1996 term at NCSU, aimed to bring methods similar to studio physics to full introductory sized classes of 100 or more students.¹⁵³ Lessons from SCALE-UP are now being applied in the design of online and "blended learning" higher education courses.

Transportation

Civilian aviation

Although the first powered flight took place in the United States, the country's aviation industry struggled during the first few decades of the 20th century. Key actions to bolster private industry following the First World War kept the aviation industry afloat. The move to allow private companies to contract out mail routes was the first major step in the creation of the modern civilian aviation industry. In that period, aviation programs at the Army and Navy bolstered aircraft production, and the military and National Advisory Committee for Aeronautics (NACA, now NASA) supported extensive aeronautics R&D, serving both military and civilian sectors.

December 1903 marked the beginning of the era of powered flight, when the Wright brothers *Wright Flyer I* made a number of short flights at Kitty Hawk. Although the first powered flight occurred in the United States, the aviation industry would lag behind the rest of world until World War I.¹⁵⁴ The war saw a huge increase in military demand for aircraft from private companies. It also saw the government get directly involved in production, with the creation of the Naval Aircraft Facility in Philadelphia in 1917, to help meet demand and deter wartime profiteering. At the end of the war, government procurement of aircraft diminished and the market collapsed.¹⁵⁵

The Naval Aircraft Facility would drastically reduce its production of aircraft following the war, even though the facility was capable of meeting all the Navy's needs at the time. But continued production still lessened the number of planes the military procured from private industry. The Naval Aircraft Facility would switch to exclusively experimental design in 1922 after sustained pressure from private industry.¹⁵⁶ Two years earlier the National Advisory Committee for Aeronautics, the predecessor of NASA, began operating the Langley Aeronautical Laboratory and its first wind tunnel. NACA's research efforts helped moved the industry forward, and in 1927 developed, for example, a cowling that substantially increased engine efficiency.¹⁵⁷

The year 1925 would be pivotal for the aircraft industry, with important congressional action. The Lambert Committee released a report, noting that the aviation industry was entirely dependent on the government procurement for its survival.¹⁵⁸ The same year saw the enactment of the Contract Air Mail Act, which allowed companies to bid on some of the smaller Postal Service routes.¹⁵⁹ These private companies would begin carrying passengers on their routes, however the mail contracts provided up to 95 percent of revenues.¹⁶⁰ Military aircraft procurement was consciously designed to foster a strong group of aircraft production firms, to build and sustain an aviation private sector that would support military needs.¹⁶¹ The aircraft industry would continue to grow, leading to the breakup of companies into manufacturers and transportation. For example, United Aircraft and Transport Corp became Boeing Airplane Co., United Air Lines, and United Aircraft Co. The 300,000 aircraft produced during World War II put the aircraft industry on firm footing.¹⁶²

The early aviation industry was driven by the needs of the U.S. Army and Navy. Important decisions along the way insured its survival and provided the necessary base so that companies could expand into civilian commercial aviation. The massive production scale-up during the Second World War provided the needed push, coupled with federally funded R&D advances in such areas as aeronautical design and jet engines, leading the civilian aviation industry towards success.

Agriculture

Hybrid Corn

Throughout the 20th century corn yields consistently increased, the first time in history this has occurred. This rise was largely possible due to the work of D.F. Jones at the Connecticut Agricultural Experiment Station on hybrids. Traits that have been genetically modified are the most recent addition to the corn breeding process. The heartiness and yields of future corn may improve as a result of the NSF, DOE, and USDA funding of the corn genome.

Over the last century, improvement in crop yield has been vital for U.S. and world food security, with 32 percent of the world's corn produced in the United States.¹⁶³ At the beginning of the 20th century, corn yields began to steadily grow for the first time in history due to the breeding of hybrids. In a 1908 paper, geneticist G.H. Shull laid the groundwork for hybrid corn. Within 30 years hybrids would dominate American cornfields. Shull found that inbreeding corn led to deterioration of health and yield. However, when two lines of inbred corn were mixed to create a hybrid, the hybrid could have a higher yield than either of the initial lines of corn (prior to inbreeding).¹⁶⁴

D.F. Jones, working at the Connecticut Agricultural Experiment Station, in 1918 came up with double-cross hybrids, the mix of two different hybrids. In 1921 the first double-cross, the Burr-Leaming, was commercially released. The following decade saw the expansion of both state and federal hybridization programs, but it would not be until the 1930s that the use of hybrid corn became widespread. In 1962, 95 percent of the corn crop was hybrids, with a yield 20 percent higher than in 1930 on three-quarters the land.¹⁶⁵

In the 1960s the development of single cross hybrids, the result of crossing two inbred parents from one line, in part, led to even faster growing corn yields.¹⁶⁶ The 20th century saw corn yield increases of 50-60 percent due to the extensive breeding. The next advancement in corn was the addition of traits improved through genetic modification; the first created by Monsanto appeared in 1998 and by 2011 was present in 88 percent of corn.¹⁶⁷ Breeding and genetic modifications continue to hold the potential to further increase yields, and will be greatly assisted by knowledge of the complete corn genome which was published in 2009. The huge process of sequencing the corn genome (corn has 12,000 more genes than humans) was led by The Genome Center at Washington University School of Medicine in St. Louis. The project took four years and received \$29.5 million of funding from NSF, DOE and USDA. While genetically modified foods remain controversial in many parts of the world, the complete corn genome may help improve traditional breeding, leading to more drought resistance or corn with higher yields.¹⁶⁸

Lactose Free Milk

Lactose free dairy products are more common than ever and sales continue to increase; however, lactose free milk has only existed since the 1980s. Virginia Harris Holsinger, while working at the USDA Agricultural Research Service, developed a way to break down the lactose in milk. This innovative process now allows millions of lactose intolerant people to enjoy the nutritional benefits of milk.

In the United States, estimates of lactose intolerance range from 21 percent among Caucasian Americans up to 80 percent in Asian and Native American populations. Symptoms vary among individuals from discomfort and nausea to pain.¹⁶⁹ In 2013, the United States produced an estimated 200 billion pounds of milk.¹⁷⁰ The market for lactose free milk is expected to continue growing larger, after sales of lactose free dairy products doubled between 2007 and 2012.¹⁷¹

In the 1980s, the Agricultural Research Service, part of the USDA, began research to address the need for lactose free milk. Lactose intolerance occurs when an enzyme known as lactase is absent from a person's intestines. Lactase breaks down lactose, a complex sugar, into the simple sugars glucose and galactose.¹⁷² Chemist Virginia Harris Holsinger's work focused on breaking down lactose into simple sugars in milk prior to consumption. By adding lactase from non-human sources, like fungi, Holsinger was able to break down about 70 percent of the lactose to a level a satisfactory for the majority of lactose intolerant people.

The company, Lactaid, Inc., commercialized Holsinger's research. Lactaid introduced various other lactose free dairy products, building off Holsinger's work, in the 1980s and 1990s such as ice cream and cottage cheese. Lactaid Inc. and the Agricultural Research Company shared the 1987 Institute of Food Technologists' Industrial Achievement Award for the development of lactose free milk. In 1991, Johnson and Johnson purchased Lactaid.¹⁷³

CONCLUSION

The 22 examples in this report only begin to demonstrate the importance of federal funding to the innovative capabilities of the United States. Many of the innovations discussed support Vernon Ruttan's conclusion that without federal involvement, extensive and potentially prohibitive delays in the development and commercialization of innovations would occur. Such delays could have cost the United States the economic benefits of its first mover technology advantage. Although Ruttan was referring to the computing industry specifically, there is some support to extend this to other fields. Nick Holonyak offers a prime example: without funding from the Air Force to offset pressure from GE, the first GaAsP red LED may not have been developed when it was. Double-cross hybrid corn, which led to huge increases in yield using less land created a U.S. agricultural boom. Double-cross hybrids gained traction early on due to D.F. Jones's work while at the Connecticut Agricultural Experiment Station.

The work of economists Robert Solow, Paul Romer, Zvi Griliches and Kenneth Arrow has demonstrated the vital role of innovation for economic growth. New innovations rely on supporting research and development. Private industries in the United States have increasingly focused their money on the development stage, leaving the federal government to now support 60 percent of all basic research. Many of the most successful sectors of the U.S. economy, such as IT and biomed, have built upon federally supported basic research. Even beyond economic success, many federally supported innovations have improved quality of life, from the population's health through MRIs and antiretroviral combating HIV, to an abundance of food, to improved communications.

The budget constraints of sequestration, mitigated in FY14-15 through a temporary budget deal, are slated to resume following FY 2015, once again limiting federal support of research and development. The United States has long been the world leader in innovation, largely as a result of strong federal support for basic and applied science. Research continues in many fields with the potential for large societal payoffs, ranging from big data and advanced GPS technologies to energy-saving technologies like LEDs to the possibilities in biomed opened up through genome sequencing. Innovation will continue throughout the world, but without continued strong federal support, the possibility increases that this will increasingly occur outside of the United States with negative consequences for U.S. economic growth.

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