Assessing the Impacts of Changes in the Information Technology R&D Ecosystem: Retaining Leadership in an Increasingly Global Environment

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ASSESSING THE IMPACTS OF CHANGES IN THE INFORMATION TECHNOLOGY R&D ECOSYSTEM

Retaining Leadership in an Increasingly Global Environment

Committee on Assessing the Impacts of Changes in the Information Technology Research and Development Ecosystem

Computer Science and Telecommunications Board

Division on Engineering and Physical Sciences

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Preface

The sustained development of information technology (IT) over the past several decades has contributed significantly to nearly every aspect of the U.S. economy and society. This development has been fueled by the participation and cooperation of members of an ecosystem comprising academic, industry, and government IT research and development (R&D) performers and supporters. Concern has been growing, however, that the historically highly successful U.S. IT innovation ecosystem is at risk. In this period of intense global competition—reflecting, notably, the growing economic strength of India and China—the consequences for the United States of a less than vital IT R&D ecosystem could be quite severe.

To address these concerns, the National Science Foundation asked the National Research Council (NRC) to assess the impacts of changes in the IT R&D infrastructure. The statement of task for the study was as follows:

> This study will assess the changes occurring to the structure, processes and outcomes that have historically characterized the nation's long-term investment in information technology research and development. It will look broadly across academic, government and industry activities (including research, human resource and venture capital development), characterize issues and identify opportunities to sustain innovation. It will examine issues including the maturation of information technology research fields, economic processes of information technology research and production, international competition and collaboration (intellectual and economic), patterns of funding, and the structure of funding programs as they affect the innovation and human resources pipeline. The

> study will examine alternative strategies and develop recommendations on actions that could be taken by the public and private sectors, alone and in partnership, to sustain and improve the health of the relevant research fields, and the historic pattern of technical innovation and national economic and security benefits.

The Committee on Assessing the Impacts of Changes in the Information Technology Research and Development Ecosystem was appointed by the NRC and convened under the auspices of the NRC's Computer Science and Telecommunications Board. The members of the study committee were drawn from academia and industry (see Appendix A for biosketches of the committee members). Individuals on the committee have expertise spanning the areas of IT software and hardware research; IT education; the economic and business aspects of R&D and innovation; globalization and IT; IT issues, history, and policy; participation in the field; the use of IT in organizations; regional and thematic R&D consortia and centers; and venture capital.

The committee's goals for the study were to do the following:

- *Describe* the current IT-specific ecosystem through which innovative, market-creating information technologies and products are conceptualized, transitioned, and developed into new economic sectors and globally competitive products (i.e., "the next billion-dollar industries"). Identify this ecosystem's essential components and their dynamic interrelationships, the contextual forces that influence its health, and the nature of its products and contributions to the nation's economy and its society.
- *Assess*, considering both national R&D priorities and global competition, the ecosystem's current health in the United States, through the quantification of relevant "vital signs," especially with respect to the dynamics of industrial globalization, the sociology of new-industry creation brought about by innovation networks, the changing economics and funding sources for underwriting innovation, and the role of regulation in accelerating or impeding the commercialization of new ideas.
- *Identify* the role of emerging technology platforms—such as personal computers (PCs), Windows, and client-server processing in the 1980s; the Internet and the World Wide Web in the 1990s; and open-source software and Web 2.0 services and "mashups" (Web applications that combine data from multiple sources) in the first decade of the 21st century—that dramatically reduce the barriers to the deployment of new concepts and products.
- *Illustrate* this assessment with several case studies that highlight recent successes and failures of the current IT R&D ecosystem.
- *Formulate* policy recommendations aimed at enhancing the survival and increasing the agility of the U.S. technological and commercial

IT R&D enterprise through the appropriate nurturing and sustenance of its ecosystem.

Of necessity the committee had to limit its consideration of each of the many subfields of IT R&D, and the lack of discussion of any particular subfield is thus not an indication of the importance attached to it by the committee. In particular, this study did not devote significant attention to cybersecurity, which was the focus of the 2007 NRC report *Toward a Safer and More Secure Cyberspace*. That report calls for "a broad, robust, and sustained research agenda at levels which ensure that a large fraction of good ideas for cybersecurity research can be explored . . . commensurate with a rapidly growing cybersecurity threat" and observes that "a substantial increase in federal budgetary resources devoted to cybersecurity will be needed."[1]

In addition, because the committee focused on IT R&D ecosystem changes that occurred during the period from 1995 to 2007 and largely wrapped up its deliberations in mid-2008, it was not in a position to consider the implications of the 2008 global economic crisis, which was continuing to unfold as this report went to press. What was apparent in late 2008 was that several conditions—including a marked reduction in the availability of venture capital funds following losses in pension funds and endowments; a dramatic reduction in initial public offerings by technology companies and a decline in mergers and acquisitions; steep declines in consumer confidence; and significant layoffs and hiring cutbacks in IT firms and across the global economy—would all have adverse impacts on both investments made in and revenue earned by the IT sector. Those conditions will almost certainly also significantly affect the IT R&D ecosystem, undermining the partial recovery seen over the past couple of years, although the magnitude, duration, and enduring impacts of the downturn are not yet clear.

With the economic downturn have come prospects for additional federal stimulus spending in 2009, which has in turn prompted debate about the role that federal R&D investment should play as part of a stimulus package. This report underscores both the importance of the IT sector to the economy and the importance of R&D investment to the IT sector's health and growth. The committee was, of course, not in a position to consider what stimulus effect federal R&D spending would have or the relative merits of investment in R&D versus alternatives. Nonetheless, the committee believes that this report will be helpful to those setting

[1] National Research Council, *Toward a Safer and More Secure Cyberspace*, The National Academies Press, Washington, D.C., 2007, pp. 11-12.

priorities and otherwise structuring whatever additional investments in IT R&D are ultimately made.

Most importantly, the committee believes that the report's main message—that the need has never been greater for the nation to recommit itself to providing the resources required to fuel U.S. IT innovation, to mitigate unintended negative consequences of laws and regulations, and to remain a nation of leading innovators and users of IT—takes on even greater importance in light of the recent economic downturn.

The committee drew heavily on perspectives and other inputs gathered during three, day-long public workshops (detailed workshop agendas and lists of speakers are provided in Appendix B):

- *In Washington, D.C.:* The first study workshop and meeting took place at the National Academies Keck Center in Washington, D.C., on November 2-3, 2006. The focus was on the committee's receiving its charge and terms of reference and being briefed on an initial set of important perspectives on the IT ecosystem. In particular, the study committee received presentations on the federal agency view of the ecosystem, university and business perspectives on the state of R&D in the field, and an overview of the state of technology start-up activity in the Washington, D.C., area.
- *In Mountain View, California:* The second study workshop and meeting were held at the Computer History Museum in Mountain View, California, on February 23-24, 2007. The emphasis of this meeting was on gathering input from the Silicon Valley community and the greater academic and business community of the San Francisco Bay Area, one of the key cluster regions of the IT industry in the United States. The topics covered included perspectives on the emergence of the IT industry in China and India, changes in the IT R&D ecosystem as observed by leading journalists and writers on technology, the changing experiences of serial entrepreneurs and early-stage angel investors, and the thoughts of leading scholars who have studied the evolution of several industries in response to globalization and technology shifts.
- *In Boston, Massachusetts:* The third study workshop and meeting were held in Boston, Massachusetts, on April 19-20, 2007, to gain insights from the second-largest cluster of the IT industry in the United States. The topics covered included public policy aspects of the industry; the relationship between universities and both U.S.-based and international firms; perspectives on the development of the IT industry in Israel, Ireland, and Scandinavia; the emerging technology platforms for information technology and their impact on research and development; and workforce and social issues.

The committee deliberated and developed draft materials in working meetings held in conjunction with each workshop and held an additional working meeting on June 7-8, 2007 (in Menlo Park, California) to develop the study's recommendations and report outline. It worked on this report throughout the study period by e-mail and teleconference.

This study and report were made possible by sponsorship from the National Science Foundation. The committee is grateful to all of the workshop participants for their thoughtful presentations and discussion and appreciates the comments and constructive criticisms of reviewers of the draft report.

Eric Benhamou and Randy H. Katz, *Co-Chairs*
Committee on Assessing the Impacts of Changes in the
Information Technology Research and Development Ecosystem

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Roger D. Blandford, Stanford University,
Eric A. Brewer, University of California, Berkeley,
Daryl E. Chubin, American Association for the Advancement of Science,
Dixon Doll, DCM,
Shane Greenstein, Northwestern University,
Anita K. Jones, University of Virginia,
Robert E. Litan, The Ewing Marion Kauffman Foundation,
Peter Miller, Vanderbilt HealthTech Laboratory,
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Prabhakar Raghavan, Yahoo! Research,
Daniel A. Reed, Microsoft Research,
Anna Lee Saxenian, University of California, Berkeley,

Robert F. Sproull, Sun Microsystems,
Myron F. Uman, National Research Council (retired),
Andrew J. Viterbi, Viterbi Group, LLC, and
Irving Wladawsky-Berger, IBM Thomas J. Watson Research Center (retired).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Lewis M. Branscomb, University of California, San Diego. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Summary

The U.S. *information technology (IT)*[1] *research and development (R&D) ecosystem* was the envy of the world in 1995. (See Box S.1 for a discussion of the term and its origins.) That ecosystem—encompassing university and industrial research enterprises, emerging start-up companies and more mature technology companies, the industry that finances innovative firms, and the regulatory environment and legal frameworks—remains unquestionably the strongest such ecosystem in the world today. However, this position of leadership is not a birthright, and it is now under pressure. In recent years, the rapid globalization of markets, labor pools, and capital flows has encouraged many strong national competitors. During the same period, national policies have not sufficiently buttressed the ecosystem or have generated side effects that have reduced its effectiveness. This is particularly true of such areas as IT education, federal IT research funding, and the regulations that affect the corporate overhead and competitiveness of innovative IT companies. As a result, the U.S. position in IT leadership today has materially eroded compared with that of prior decades, and the nation risks ceding IT leadership to other nations within a generation unless the United States recommits itself to providing the resources needed to fuel U.S. IT innovation, to removing important roadblocks that reduce the ecosystem's effectiveness in generating innovation and the fruits of innovation, and to becoming a lead innovator

[1]In this report, the term *information technology* is used broadly to include computing and communications components, equipment, software, and services.

BOX S.1
Defining the Information Technology Research and Development Ecosystem

In this study, the term *ecosystem* is used in the sense first introduced by James F. Moore when he applied biological concepts to the world of business.[1] The concept of a national innovation ecosystem was further developed and refined by such scholars as Michael Porter and Scott Stern[2] and, more recently, Egils Milbergs.[3] The information technology (IT) research and development (R&D) ecosystem comprises IT researchers and scientists (and their institutions), IT businesses (both large and small), IT customers (consumers, businesses, governments), and powerful contextual forces such as regulatory and legal environments, the supply of financial and human and intellectual capital, the economic infrastructure, and the pressure of international competition, in the production of IT-based goods and services that create economic wealth, jobs, and societal benefits. See Chapter 1 in this report for further discussion of the U.S. IT R&D ecosystem, its elements, and interactions among them.

[1]James F. Moore, "Predators and Prey: A New Ecology of Competition," *Harvard Business Review* 71(3):75-86, May/June 1993.

[2]Michael Porter and Scott Stern, *The New Challenge to America's Prosperity: Findings from the Innovation Index,* Council on Competitiveness, Washington, D.C., 1999.

[3]Egils Milbergs, *Innovation Vital Signs—Framework Report,* Center for Accelerating Innovation, Washington, D.C., 2007.

and user of IT. Globalization is a broad and sweeping phenomenon that cannot be easily stemmed, let alone contained. If embraced rather than resisted, it presents more opportunities than threats to the U.S. national IT R&D ecosystem. The Committee on Assessing the Impacts of Changes in the Information Technology Research and Development Ecosystem was established under the auspices of the National Research Council's Computer Science and Telecommunications Board to examine these issues and make recommendations to strengthen the U.S. IT R&D ecosystem.

The period from 1995 to 2007 was marked by rapid and significant change in the U.S. and world economies. From the perspective of information technology, the United States enjoyed a strong industrial base, an ability to create and leverage ever new technological advances, and an extraordinary system for creating world-class technology companies—all of which have been the envy of the world. Yet over this period, the IT industry became more globalized, especially with the dramatic rise of the economies of India and China, fueled in no small part by their development of vibrant information technology industries. Ireland, Israel, Korea, Taiwan, Japan, and some Scandinavian countries have also developed strong niches within the increasingly globalized industry. Today, a product conceptualized and marketed in the United States might be designed to specifications in Taiwan, and batteries or hard drives obtained from Japan might become parts in a product assembled in China. High-value software and integrated circuits at the heart of a product might be designed and developed in the United States, fabricated in Taiwan, and incorporated into a product assembled from components supplied from around the world.

As the logical starting date for its study, the committee adopted 1995, a year that marked the emergence of the Internet as a commercial entity and the beginning of a period of turbulence in the IT sector. The technologies that developed around the Internet and the services that it enabled generated a period of euphoria characterized by exuberance, burgeoning enrollments in IT programs, rising valuations, the suspension of fiscal prudence, and a stock market in the stratosphere between 1995 and 2000. The period of the late 1990s witnessed the unusual convergence of three trends: the move to deregulate many parts of the nation's telecommunications system (with implications for network connectivity), the rise of the World Wide Web as a technology platform, and the commercialization of the Internet from what had been the government-funded, research-only National Science Foundation Network (NSFnet). These trends were most strongly embraced in the United States, and the U.S. IT ecosystem reaped many benefits.

The year 2000 is noted not only for the calendar problem faced by older computer systems but also for the realization that "the Emperor had no clothes" with respect to the plans of many Internet-based businesses. Greed turned to fear as the stock market dropped, the technology-heavy NASDAQ (National Association of Securities Dealers Automated Quotations) plummeted, and the boom turned to bust. Many of the fledgling firms born in the Internet euphoria failed. Both fledgling and established firms were driven to conserve cash in order to survive, and all sought lower-cost ways to continue to develop and manufacture their products. These events had the effect of accelerating the rise of Indian and Chinese IT industries.

This period was also marked by the spectacular bankruptcies of highly visible companies such as Enron Corporation and WorldCom. The regulatory response—notably the passage of the Sarbanes-Oxley Act of 2002 (Public Law 107-204), commonly called SOX—established new standards for U.S. public company boards, management, and accounting firms with respect to the visibility of and responsibility for the financial dealings within U.S. public companies. In the wake of the passage of SOX, these companies faced significant new requirements to implement and assess internal controls over financial reporting. For young IT companies seeking to go public in the United States, SOX Section 404 (pertaining to the certification of the integrity of the financial control structure of a firm) has proved disproportionately costly relative to the limited resources of these young companies.

Companies' emphasis on cost reduction over growth investments during this period fueled interest in outsourcing and offshoring.[2] Also, firms that might have sought capital in U.S. markets increasingly began to seek capital in overseas markets such as the London Alternative Investment Market (AIM), or sought to be acquired by larger companies—a trend that for some companies may have had as much to do with cost pressures as with the availability of capital in the United States.

These developments fueled a perception that jobs in the IT industry in the United States were being shed and that future prospects were bleak, even though this is not necessarily the case: according to a 2006 study of data from the Department of Commerce, there were more professional IT workers in the United States than ever before.[3]

The shock of September 11, 2001, refocused the nation on homeland defense and affected research priorities, and national attention and resources were redirected to combating new threats. The funding for IT research at the nation's universities underwent major shifts as the priorities of the Defense Advanced Research Projects Agency shifted and time horizons shortened. In the meantime, industry increased its support for university research.

Yet starting in 2005, the pendulum began to swing back in a positive direction, with the emergence of new technologies such as multicore processors, new programming languages and environments, Internet data centers, and new applications that capture the phenomenon of social networking. Technology companies once again were able to launch successful initial public offerings (IPOs), and funding for new ventures began returning to pre-boom levels. Enrollments in the IT fields in U.S. universities started to rise again.

Today, there are signs that the U.S. IT R&D ecosystem is in recovery. The continued global spread of IT and its overwhelmingly positive impacts on people's daily lives are quite evident in the developed world and increasingly so in the developing world. The widespread use of

[2]*Outsourcing* is the practice of purchasing work, formerly done in-house, from an outside vendor. *Offshoring* is the practice of moving work to developing nations.

[3]Association for Computing Machinery Job Migration Task Force, *Globalization and Offshoring of Software: A Report of the ACM Job Migration Task Force,* W. Aspray, F. Mayadas, and M. Vardi, eds., Association for Computing Machinery, New York, N.Y., 2006.

cellular telephones (now nearly 3 billion subscribers worldwide[4]) and the rising number of Internet users (more than 1 billion[5]) illustrates the size and scope of these developments. Today, "information at your fingertips" is largely a reality, made possible by leading Web sites such as Google, Yahoo!, and Microsoft Live. And Amazon, eBay, and many others have changed the way we shop and swap.

Notable recent technology IPOs such as Google (2004), Riverbed Technology (2006), and VMware (2007) indicate that great technologies and solid businesses can still attract investors. Venture investment in information technology has rebounded to the pre-boom levels. Active consideration is being given to ways of easing such frictions in the U.S. IT ecosystem as the unintended consequences of the Sarbanes-Oxley Act for small companies, and there is serious discussion of patent and intellectual property litigation reforms. Technology continues to evolve and even accelerate: radio-frequency identification, grid computing, dynamic Web pages, social networking and Web 2.0, open-source development, and the emerging shifts toward IT-enabled services represent exciting opportunities.[6]

Much remains to be accomplished in applying information technology for the benefit of humankind, in terms of improved health, better education, and more social opportunity. As other industries are becoming increasingly IT-intensive, information technology is intimately entwined with virtually all economic activity.

Given this context, this study was charged with answering some fundamental questions. Has the nation's ecosystem for IT R&D emerged as strong as it was before the boom and bust? Is it sufficiently healthy today to continue generating the innovative concepts, products, and services that have made the U.S. information technology industry the envy of the world?

The global landscape in 2007 is quite different from what it was in 1995. The globalization of the world's economy is a fact that cannot be ignored. India is a strong presence in software and services. China is the world's manufacturer. Moreover, those nations represent fast-growing markets for information technology products, and both are likely to grow

[4]International Telecommunication Union (ITU), "Worldwide Mobile Cellular Subscribers to Reach 4 Billion Mark Late 2008," Press release, ITU, Geneva, Switzerland, September 25, 2008.

[5]Computer Industry Almanac, "Worldwide Internet Users Top 1.2 Billion in 2006," February 12, 2007, available at http://www.c-i-a.com/pr0207.htm; accessed December 31, 2008.

[6]As this report was being prepared for publication in late 2008, a new major shock to the ecosystem came in the form of a global credit crisis. The duration and implications of the crisis are unclear, but decreased access to capital (both equity and debt) for young IT companies and decreased robustness of end-user markets are among the likely effects.

their IT industries into economic powerhouses for the world, reflecting both deliberate government policies and the existence of strong, vibrant private-sector firms, both domestic and foreign.

To thrive in this landscape, the United States should play to its strengths, notably its continued leadership in conceptualizing the idea-intensive new concepts, products, and services that the rest of the world desires and where the greatest increments of value added are captured. Toward this end, it is necessary for the United States to have the best-funded and most-creative research institutions; to develop and attract the best technical and entrepreneurial talent among its own people as well as those from around the world; to make its economy the world's most attractive for forming new ventures and nurturing small, innovative firms; and to create the environment that will ensure the deployment of the most advanced technology infrastructures, applications, and services in the United States itself for the benefit of the nation's people, institutions, and firms.

The findings and recommendations of the committee presented in the sections below are organized according to four broad objectives. The numbering of the objectives and the related numbering of the findings and recommendations reflect the logical flow of the committee's arguments, not necessarily temporal or other priorities. The objectives are as follows:

- *Objective 1*. Strengthen the effectiveness and impact of federally funded information technology research.
- *Objective 2*. Remain the strongest generator of and magnet for technical talent.
- *Objective 3*. Reduce friction that harms the effectiveness of the U.S. information technology R&D ecosystem, while maintaining other important political and economic objectives.
- *Objective 4*. Ensure that the United States has an infrastructure for communications, computing, applications, and services that can enable U.S. information technology users and innovators to lead the world.

These objectives are discussed in some detail below.

OBJECTIVE 1. STRENGTHEN THE EFFECTIVENESS AND IMPACT OF FEDERALLY FUNDED INFORMATION TECHNOLOGY RESEARCH

Measures of "research" generally fail to distinguish between exploratory research that leads to wholly new technologies and applications, and work that yields advanced prototypes and proofs of concept. University research is focused largely on the former and industrial research concentrates on the latter, which means that much of the feedstock for long-term innovation is to be found in the nation's universities. As a result, support for university education and research is essential to generating the stream of innovations that nourish the rest of the ecosystem. Measures to enhance the productivity of university research funding, as well as that of other R&D funding, would increase the payoff from these investments.

Information technology and its impact on the economy continue to grow in size and importance. According to estimates of the Bureau of Economic Analysis, for 2006 the IT-intensive "information-communications-technology (ICT)-producing" industries accounted for about 4 percent of the $13,247 billion U.S. economy but contributed more than 14 percent of real gross domestic product (GDP) growth.[7] (As a point of reference, federal funding in fiscal year 2008 for computer sciences research was around $3 billion, less than 0.025 percent of GDP.[8]) This substantial contribution to the economy reflects only a portion of the overall long-term benefits from IT research investments. It is in the nation's interest for these benefits to continue to grow and accrue.

Although the advances of information technology over the past 50 years have been truly breathtaking, the field remains in its relative infancy, and continuing advances over the coming decades can be expected as long as the IT R&D ecosystem's capacity to sustain innovation is preserved and enhanced. Among the impacts anticipated from advances in IT during the coming decades are, for example, safer, robotics-enhanced automobiles; a more scalable, manageable, secure, and robust "new Internet"; enhanced information storage devices for personal use with improved search and retrieval capabilities; personalized and collaborative educational tools for tutoring and just-in-time learning; and personalized health monitoring.

Current decisions about how the nation should make federal investments—both civilian and military—in basic IT research do not seem to reflect the full impact of IT on society and the economy. For example, data collected for the President's Council of Advisors on Science and Technology (PCAST) indicate that the United States lags behind Europe

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[7]Thomas F. Howells III and Kevin B. Barefoot, "Annual Industry Accounts: Advance Estimates for 2006," *Survey of Current Business*, Bureau of Economic Analysis, Washington, D.C., May 2007, Tables A, B, 1, available at http://bea.gov/scb/pdf/2007/05%20May/0507_annual_industry_accounts.pdf; accessed August 28, 2007.

[8]Intersociety Working Group, *AAAS Report XXXII: Research and Development FY 2008*, American Association for the Advancement of Science (AAAS) Publication Number 07-1A, AAAS, Washington, D.C., 2007, Table I-9, p. 57, available at http://www.aaas.org/spp/rd/rd08main.htm; accessed December 31, 2008.

and Japan in civilian funding for IT R&D.[9] Regaining a lead position will require aggressive action, including ambitious targets for increased R&D investment. The European Union and China—the latter a strong emerging competitor—have aggressive plans for strengthening their global positions in IT through substantial and increasing IT R&D investments. In its August 2007 report *Leadership Under Challenge: Information Technology R&D in a Competitive World,* PCAST noted that the European Union is pursuing the goal of strengthening its position in information and communication technologies through increased cooperative R&D investment (roughly $12 billion) through 2013.[10] The PCAST report also noted that by 2006, China's overall R&D spending had exceeded that of Japan and amounted to about 1.4 percent of its GDP—on a path to achieve a national goal of 2.5 percent of GDP by 2020.[11]

As China, Japan, and Europe aggressively increase their targeted IT R&D investment levels, it is appropriate and necessary for the United States to adjust its own federal IT R&D spending level correspondingly, just as individual businesses, following best practices, track their global competitors' business models in order to avoid falling behind in global market share. Increased federal investment in IT research would reflect the importance of IT to the nation's society and economy as a whole and would allow the United States to build and sustain the already large positive impact of IT on the economy.

The desirability of increased federal investment in IT R&D has also been recognized in the 2007 report of the National Academies, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,*[12] and, to some extent, by provisions in the subsequently passed America COMPETES Act of 2007 (Public Law 100-69).[13] Moreover, in its August 2007 report, PCAST found an imbalance in the current federal R&D portfolio in that more long-term, large-scale, multidisciplinary R&D is needed. PCAST concluded that current interagency coordination processes for networking and IT R&D are inadequate for meeting antici-

[9]President's Council of Advisors on Science and Technology, *Leadership Under Challenge: Information Technology R&D in a Competitive World,* Executive Office of the President, Washington, D.C., August 2007, Table 4.3.

[10]Ibid., pp. 13-14.

[11]Ibid.

[12]National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* The National Academies Press, Washington, D.C., 2007, Actions B-1 and B-4.

[13]The America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science Act (America COMPETES Act) became Public Law 110-69 on August 9, 2007.

pated national needs and for maintaining U.S. leadership in an era of global competitiveness.[14]

A strategic reassessment of national R&D priorities is needed—an analysis meriting the attention of first-tier scientists and engineers from academia, industry, and government. (According to a 2006 National Science Foundation study on R&D by funding sector, industry investments in R&D overall were more than double those of the federal government.[15]) A strong focus on IT will be important because of the unique role of IT within science and engineering.

Toward that end, a means of delivering to the highest levels of the U.S. government the best possible advice on the transformational power of information technology would help ensure that the nation invests at appropriate levels in IT research and that these investments are made as efficiently and as effectively as possible—in part through improved coordination for federal R&D investments. This advice could be provided in a number of ways, including the augmentation of the current presidential science and technology advisory structure, the establishment of a high-level IT adviser to the President, or the reestablishment of an IT-specific presidential advisory committee (such as the President's Information Technology Advisory Committee, which operated from 1997 to 2005).

Finding 1.1. A robust program of federally sponsored research and development in information technology (IT) is vital to the nation.

Finding 1.2. The level of federal investment in fundamental research in information technology continues to be inadequate.

Recommendation 1.1. As the federal government increases its investment in long-term basic research in the physical sciences, engineering, mathematics, and information sciences, it should carefully assess the level of investment in IT R&D, mindful of the economic return, societal impact, enablement of discovery across science and engineering, and other benefits of additional effort in IT, and should ensure that appropriate advisory mechanisms are in place to guide investment within the IT R&D portfolio.

[14]President's Council of Advisors on Science and Technology, *Leadership Under Challenge: Information Technology R&D in a Competitive World*, Executive Office of the President, Washington, D.C., August 2007, pp. 14, 37.

[15]National Science Foundation, *US R&D Continues to Rebound in 2004*, NSF-06-306, January 2006, available at http://www.nsf.gov/statistics/infbrief/nsf06306/; accessed December 31, 2008.

OBJECTIVE 2. REMAIN THE STRONGEST GENERATOR OF AND MAGNET FOR TECHNICAL TALENT

There is cause for concern that an undersized and insufficiently prepared workforce for the information technology industry will accelerate the migration of higher-value activities to other nations. This report does not address the entire array of technology-sector wage and job-security issues. However, without a workforce that is knowledgeable with respect to technology and that has sufficient numbers of highly trained workers, the United States will find it difficult to retain the most innovation-driven parts of the IT industry. Despite the demand for such workers, the number of students specifying an intention to major in computing and information sciences has dropped significantly in the past 6 years. The problem of declining enrollments in the computing disciplines (as compared with the projected demand) is compounded by the very low participation of underrepresented groups in IT.[16,17,18,19]

The United States should rebuild the national IT educational pipeline, encouraging all qualified students, regardless of race, gender, or ethnicity, to enter the discipline. Without sustained, amplified intervention, the United States is unlikely to produce an educational pipeline yielding a revived and diverse IT workforce over the next 10 years. To achieve the needed revitalization, the United States should pursue a multipronged approach: it should improve technology education at all levels from kindergarten through grade 12; broaden participation in IT careers by women, people with disabilities, and certain minorities, including African-Americans, Hispanics, and Native Americans; and retain foreign students who have received advanced degrees in IT. Immigrants have been especially significant in high-technology entrepreneurship; for at least one-quarter of the U.S. engineering and technology companies started between 1995 and 2005, mostly in software and innovation and in manufacturing-related services, at least one of the key founders was born outside the United States.[20]

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[16]National Center for Education Statistics, *Integrated Postsecondary Educational Data System (2005-06)*, U.S. Department of Education, Washington, D.C., May 1, 2007.

[17]S. Zweben, "Record PhD Production Continues; Undergraduate Enrollments Turning the Corner," *Computing Research News* 19(3):7-22, 2007.

[18]Bureau of Labor Statistics, *Current Population Survey, Annual Averages 2000-2006*, U.S. Department of Labor, Washington, D.C., 2006.

[19]College Board, *2006 College Bound Seniors: Total Group Profile Report*, 2006, available at http://www.collegeboard.com/prod_downloads/about/news_info/cbsenior/yr2006/national-report.pdf; accessed July 2, 2007.

[20]Vivek Wadhwa, AnnaLee Saxenian, Ben Rissing, and Gary Gereffi, "America's New Immigrant Entrepreneurs: Part 1," Duke Science, Innovation, and Technology Paper No. 23, January 4, 2007, p. 19, available at http://ssrn.com/abstract=990152; accessed December 26, 2007.

Finding 2.1. Rebuilding the computing education pipeline at all levels requires overcoming numerous obstacles, which in turn portends significant challenges for the development of future U.S. IT workforce talent.

Finding 2.2. The participation in IT of women, people with disabilities, and certain minorities, including African-Americans, Hispanics, and Native Americans, is especially low and is declining. This low level of participation will affect the ability of the United States to meet its workforce needs and place it at a competitive disadvantage by not allowing it to capitalize on the innovative thinking of half of its population.

Recommendation 2.1. To build the skilled workforce that it will need to retain high-value IT industries, the United States should invest more in education and outreach initiatives to nurture and increase its IT talent pool.

Finding 2.3. Although some IT professional jobs will be offshored, there are more IT jobs in the United States than at any time during the dot-com boom, even in the face of corporate offshoring trends.

Recommendation 2.2. The United States should increase the availability and facilitate the issuance of work and residency visas to foreign students who graduate with advanced IT degrees from U.S. educational institutions.

OBJECTIVE 3. REDUCE FRICTION THAT HARMS THE EFFECTIVENESS OF THE U.S. INFORMATION TECHNOLOGY R&D ECOSYSTEM

The committee is concerned that such factors as intellectual property litigation and corporate governance regulations have become sources of increased friction in the conduct of business in the United States and that such burdens can have the effect of making other countries more attractive places to establish the small, innovative companies that are an essential component of the ecosystem. The committee recognizes that these issues are not simple—for example, in the case of corporate governance, the dampening effects of increased regulation have to be weighed against the benefits of restoring and maintaining public confidence in equity markets. But the committee believes that it is vital to keep the United States attractive for new venture formation and to sustain the nation's unrivaled ability to transform innovative new concepts into category-defining products and services that the world desires; the committee emphasizes that in considering new measures or reforms in such areas as corporate governance or intellectual property litigation, the potential impacts on the IT R&D ecosystem should be heavily weighed.

Finding 3.1. Fewer young, innovative IT companies are gaining access to U.S. public equity markets.

Recommendation 3.1. Congress and federal agencies such as the Securities and Exchange Commission and the Patent and Trademark Office should consider the impact of both current and proposed policies and regulations on the IT ecosystem—and especially on young, innovative IT businesses—and consider measures to mitigate these where appropriate.

OBJECTIVE 4. ENSURE THAT THE UNITED STATES HAS THE INFRASTRUCTURE THAT ENABLES U.S. INFORMATION TECHNOLOGY USERS AND INNOVATORS TO LEAD THE WORLD

The United States has long enjoyed the position of being the largest market for IT; global demographics and relative growth rates suggest that this advantage is unlikely to endure. Fortunately, although a healthy domestic IT market is an important element of a healthy domestic ecosystem, market size is not the only factor in leadership. The environment fostered by leading-edge users of technology—including those who can leverage research, innovate, and create additional value—creates the essential context for technology's next wave and its effective application. In such an environment, all sectors of society (including consumers, businesses, and governments) exploit and make the best use of advanced information technology. The committee is concerned that the United States has lost its leadership in the use of information technology. In particular, the U.S. broadband infrastructure is not as advanced or as widely deployed as that in many other countries. Should this situation persist into the future, the United States will no longer be the nation in which the most innovative, most advanced technology and highest value-added products and services are conceptualized and developed.

Moreover, in addition to broadly fostering research and commercial innovation, government-sponsored R&D can help meet particular government demands. Although the government is no longer a lead IT user across the board, it continues to have an appropriate leadership role where federal agencies' requirements are particular to their missions and commercial analogues are scarce or nonexistent.

Finding 4.1. The most dynamic IT sector is likely to be in the country with the most demanding IT customers and consumers.

Finding 4.2. In terms of nationwide availability, use, and speed of broadband, the United States—the inventor of broadband technology—has been losing ground compared with other nations.

Recommendation 4.1. The United States should establish an ambitious target for regaining and holding a decisive lead in the broad deployment of affordable gigabit broadband services. Federal and state regulators should explore models and approaches that reduce regulatory and jurisdictional bottlenecks and should increase incentives for investment in these services.

Recommendation 4.2. Government (federal, state, and local) should foster commercial innovation and itself make strategic investments in IT R&D and deployment so that the United States can retain a global lead position in areas where it has particular mission requirements.

1

Defining the Information Technology R&D Ecosystem

In this study, the term *ecosystem* is used in the sense first introduced by James F. Moore when he applied biological concepts to the world of business. Referring to a business ecosystem, Moore wrote that it is—

> an economic community supported by a foundation of interacting organizations and individuals—the organisms of the business world. This economic community produces goods and services of value to customers, who are themselves members of the ecosystem.[1]

The concept of a national innovation ecosystem was further developed and refined by such scholars as Michael Porter and Scott Stern[2] and, more recently, Egils Milbergs.[3] This report focuses on the complex interrelationships among information technology (IT)[4] researchers and scientists (and their institutions), IT businesses (both large and small), IT customers (consumers, businesses, governments), and the powerful contextual forces such as regulatory and legal environments, the supply of financial and human and intellectual capital, the economic infrastructure, and the

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[1]James F. Moore, "Predators and Prey: A New Ecology of Competition," *Harvard Business Review* 71(3):75-86, May/June 1993.

[2]Michael Porter and Scott Stern, *The New Challenge to America's Prosperity: Findings from the Innovation Index,* Council on Competitiveness, Washington D.C., 1999.

[3]Egils Milbergs, *Innovation Vital Signs—Framework Report,* Center for Accelerating Innovation, Washington, D.C., 2007.

[4]In this report, the term *information technology* is used broadly to include computing and communications components, equipment, software, and services.

pressure of international competition, in the production of IT-based goods and services that create economic wealth, jobs, and societal benefits.

A healthy and vibrant IT R&D ecosystem is characterized by the following:

- The quality and quantity of intellectual property that it generates over time,
- The economic value of the businesses that it creates,
- The richness of the goods and services that it produces or enables,
- The number and quality of the jobs that it creates,
- Its ability to adapt to changing environmental conditions, and
- Its ability to collaborate with and compete against other IT R&D ecosystems around the globe.

Precise measurements along these various dimensions are not always practical or available, but a detailed examination of each reveals enough information to allow an educated opinion to be formed about the relative health of the U.S. national IT R&D ecosystem today, relative to the past, relative to other nations, and relative to this nation's own potential.

ANATOMY OF THE ECOSYSTEM

The national IT R&D ecosystem is complex, involving many actors and many types of relationships. When well tuned, it produces industry-leading innovative products and services that benefit virtually every aspect of our society and economy and generates returns that substantially justify the enormous financial risks incurred in the early stages of a technology cycle. To be sure, risks and returns are not evenly distributed. Some firms that incur large costs for technology and market exploration and make large investments in infrastructure will succeed (and reap large returns); others will not. Some incumbents will face dislocation costs as new entrants and new products succeed.

The early to mid-1990s—the years immediately preceding the period of interest (1995 to 2007) for this report—was a time of economic expansion led by IT-induced productivity enhancement when the U.S. IT R&D ecosystem was broadly perceived to be very healthy and competitive. To understand how parts of this system could drift out of kilter and how these local disequilibria could impact the output of the system as a whole, one must examine the anatomy of this ecosystem in terms of some of its key elements and relationships, as shown in Figure 1.1.

As Figure 1.1 shows, the ecosystem is populated with a number of actors, ranging from individuals (for example, students and researchers), to institutions (such as industrial and government laboratories), to

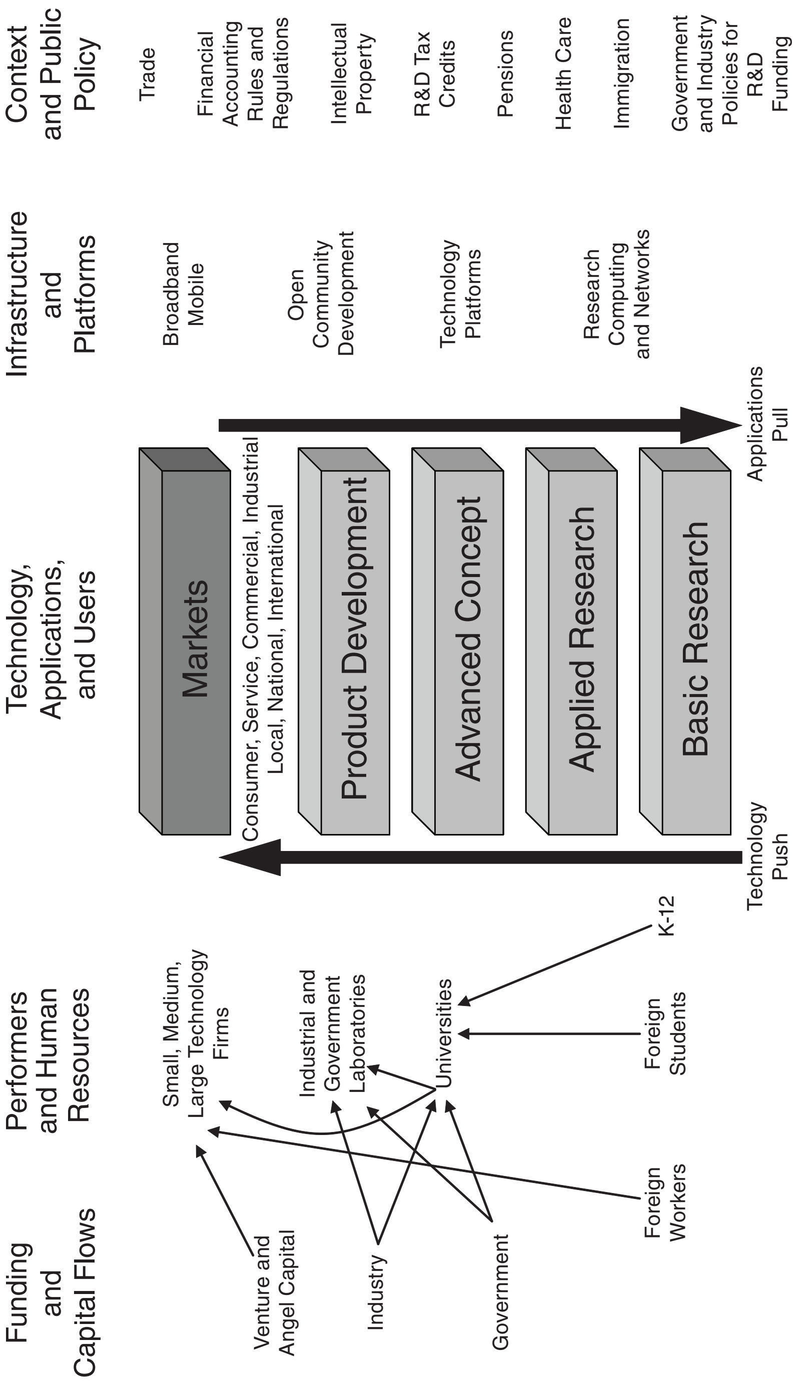

FIGURE 1.1 Some key elements and relationships in the U.S. information technology research and development (R&D) ecosystem.

governments. Several elements that are key to the committee's assessment of the impacts of changes on the IT R&D ecosystem are described in the following section.

SELECTED KEY ELEMENTS OF THE ECOSYSTEM

Research Universities

U.S. research universities carry out the majority of the fundamental and advanced IT research work in this country. They have been and continue to be one of the primary competitive assets in the IT R&D ecosystem. They attract the best research talent from around the world, including the most talented domestic and foreign students and faculty, and receive an increasing amount of attention and sponsorship from foreign firms. The largest and most significant source of research funding for research universities remains the federal government, through its key grant-making agencies (e.g., those agencies that participate in the Networking and Information Technology Research and Development program).

K-12 Schools, Colleges, and Universities

U.S. schools and colleges are the primary source of human resources for the nation's research universities. The quality of middle and high school science, technology, engineering, and mathematics education is a primary determinant of the strength and motivation of the cohorts of students that will attend U.S. universities in years to come.[5]

Innovative Start-up Firms

The entrepreneurial culture that characterizes much of American heritage and values has found fertile ground in the field of IT. The United States is home to the largest number of and most talented IT start-up firms, concentrated primarily in clusters such as in Silicon Valley and a number of other areas. These start-up firms are a major source of innovation and national competitiveness in the field of IT. In recent years, firms such as Google and Facebook have risen to prominence and wield significant influence in the Internet industry.

[5]Grades 5 through 8 are crucial years for cultivating or discouraging students' interest in STEM careers. Students begin losing enthusiasm for STEM fields in elementary and middle school. See, for example: J. Jovanovic and S.S. King, "Boys and Girls in the Performance-Based Science Classroom: Who's Doing the Performing?" *American Educational Research Journal* 35(3):477-496, Autumn 1998; and T.A. Greenfield, "Gender, Ethnicity, Science Achievement, and Attitudes," *Journal of Research in Science Teaching* 33(8):901-933, 1996.

A trend of immigrant-led high-technology entrepreneurship that was first documented for Silicon Valley has spread nationwide: for at least one-quarter of the U.S. engineering and technology companies started between 1995 and 2005, at least one of the key founders was born outside the United States. Almost 80 percent of these immigrant-founded companies were in two industry fields: in software and innovation and in manufacturing-related services.[6]

Medium-Size and Large Corporations

Successful start-up firms can rapidly grow into medium-size and large corporations. Historically, examples of IT start-ups that have become industry leaders include Microsoft Corporation, which is a leader in personal computer (PC) software; Intel Corporation, a leader in semiconductors; Dell, in PCs and peripherals; Cisco Systems, in networking and communications technologies; and Oracle, in database and enterprise software systems. Sometimes start-ups grow into very large companies that later on must adapt to changing markets and enter new ones. IT companies that have navigated this path include Hewlett-Packard Company, which adapted to become a leader in PC hardware, imaging, and printing; and International Business Machines Corporation (IBM), which now focuses on enterprise computing and services. Together, in late 2007, the firms listed in this paragraph had a market capitalization in excess of $1 trillion and employed almost 900,000 people.[7] Note that although only a few corporations participate directly in the IT industry by producing or selling IT components or solutions, virtually every corporation today uses IT products and services to deliver its own goods and services into the marketplace and contributes its own experience and innovation to the IT industry and the ecosystem in which it participates.

End Markets

One of the reasons why most IT firms need to have a strong presence in the United States is that this country (still) represents the largest IT market in the world. Industry sectors such as financial services, where the United States is particularly strong, are heavily dependent on the quality and performance of their IT infrastructure and tend to be early

[6]Vivek Wadhwa, AnnaLee Saxenian, Ben Rissing, and Gary Gereffi, “America’s New Immigrant Entrepreneurs: Part 1,” Duke Science, Innovation, and Technology Paper No. 23, January 4, 2007, available at http://ssrn.com/abstract=990152; accessed December 26, 2007.

[7]Together, the firms listed in this paragraph had 894,295 full-time employees worldwide and a total market capitalization of $1.09 trillion on September 27, 2007, according to information compiled from NASDAQ and New York Stock Exchange financial data, available at Yahoo! Financial data, http://finance.yahoo.com; accessed October 28, 2008.

adopters of new technologies. More recently, however, consumer markets, particularly in such segments as digital entertainment and communications, have become important IT markets. As the shift in the importance of consumer markets continues, the leadership of U.S. IT end markets may be challenged because of demographic considerations—for example, there are other nations whose markets are as large as those in the United States—or because of niche specializations in certain markets as in the case of computer games produced in Korea.

Private Capital

Start-up companies tend to receive their initial funding from private-capital sources such as angel investors (affluent individuals who invest their own funds in start-ups) and venture capital. The U.S. venture capital industry has led the world in the magnitude of the funds raised and deployed, as well as in the number of successful firms that it has enabled and the financial returns that it has generated for its investors.

In recent years, private equity firms have become more prominent in acquiring and recapitalizing medium-size and large IT corporations. These new owners have a natural focus on economic returns rather than on long-standing ties to particular sets of employees or certain locations. Thus, the increased prominence of private equity capital may tend to increase the movement of IT jobs and capabilities overseas, at least in the short term, in order to increase profits, reduce costs, or seek additional markets.

A recent empirical study prepared by the World Economic Forum on the impact of private equity investment on the behaviors of firms post-transaction considered such factors as the impact on investment in innovation and employment. It found that firms that undergo a buyout pursue inventions that are more economically important (as measured by patent citations). Increased patent citation rates indicate that innovation becomes more targeted post-buyout and that patent portfolios become more focused on core technologies. The same study found that the observed impact of private equity on employment was mixed, but private equity was seen to speed up the pace of acquisitions and divestitures: "private equity groups act as catalysts for change in the economy."[8]

[8]Josh Lerner and Anuradha Gurung, "Executive Summary," *The Global Economic Impact of Private Equity Report 2008*, World Economic Forum, p. xi; available at http://www.weforum.org/pdf/cgi/pe/Executive_Summary.pdf; accessed April 16, 2008. Companies tended to have workforce cuts in the years immediately before and after a buyout transaction, as well as adding some new jobs afterward, for a net decrease overall. The study did not look at jobs created in or transferred to other countries. The entire report is available at http://www.weforum.org/en/media/Latest%20Press%20Releases/PrivateEquity_PressRelease; accessed April 16, 2008.

Public Capital

The traditional and ideal trajectory of a successful IT start-up firm includes the milestone of a public stock offering along the way. The U.S. stock markets have attracted the largest numbers of IT start-up initial public offerings. The liquidity and vitality of U.S. markets have helped fast-growing IT firms gain access to the financial capital that they require to fund their growth. In recent years, other markets have developed that offer access to public capital (both debt and equity) on competitive terms, in both Europe and Asia. These markets have improved, but they are not yet comparable to the NASDAQ (National Association of Securities Dealers Automated Quotations) in depth, breadth, or quality.

Regulatory and Legislative Bodies

The U.S. regulatory and legislative environments have a significant influence on the quality and transparency that IT firms demonstrate, as well as on the administrative overhead and other sources of friction that they must deal with in their operations. Enlightened regulations and laws can be a major source of national competitive advantage when their rigor supports the quality of the market and provides a stable rule of law for contracts and investments. Conversely, the U.S. IT R&D ecosystem can be hampered by regulations and laws that have not kept pace with technological advances or whose benefits do not outweigh the costs. There is a balance to be struck between disclosure, honesty, and transparency that can increase investor confidence on the one hand and, on the other, regulatory burdens that can retard markets and chill the flow of capital to worthy firms.

Global Context

The U.S. IT R&D ecosystem has been materially transformed in recent years by globalization. Markets, financial flows, access to human resources, and intellectual property are now global phenomena. As a result, an assessment of the U.S. IT R&D ecosystem and measures taken to strengthen it must reflect the ecosystem's interactions with those of other nations.

RELATIONSHIPS AND INTERACTIONS AMONG MAJOR ACTORS IN THE ECOSYSTEM

The complexity of the U.S. IT R&D ecosystem precludes exhaustively enumerating (or drawing) the relationships and interactions among the major actors shown in Figure 1.1. The most important of these for the purposes of this study are the following:

- A large fraction of the graduate students recruited and graduated by U.S. research universities come from overseas.
- The funding for IT research in U.S. research universities comes primarily from the federal government and secondarily from private sources, of which foreign corporations represent a small but growing percentage.
- IT companies (small, medium-size, and large) must access global markets to design, manufacture, and sell their products and services. A growing percentage of employment in IT research and development is overseas for a variety of reasons, including market access, access to cutting-edge knowledge and consumers, and lower-cost trained personnel.
- The creation of intellectual property in the field—whether formally protected or not—is the primary basis on which IT firms get started and continue to grow and compete over time. The flow of entrepreneurial talent out of universities into young start-up firms is particularly vital in the U.S. IT R&D ecosystem. The collaboration between U.S. universities and small, medium-size, and large IT firms enables the rapid productization and commercialization of the most promising discoveries. It is critical that the ability to connect intellectual property to markets be kept vibrant and efficient.
- Access to financial capital at different stages of growth is one of the important characteristics of the U.S. market that has made it competitive since the dawn of the IT industry. These various capital flows are now far more complex and far more global.

These topics are discussed in the following chapters.

2

Information Technology: The Essential Enabler for the Information Society

THE IMPORTANCE OF INFORMATION TECHNOLOGY

The economic contributions of information technology (IT) are not in question. Put simply, IT is the enabling technology of the 21st century. The effective use of IT is now recognized as a major component of economic growth and innovation in other areas of society and the economy. As the President's Council of Advisors on Science and Technology acknowledged in its 2007 assessment of the federal networking and IT research and development (R&D) program:

> IT leadership is essential to U.S. economic prosperity, security, and quality of life. . . . It is difficult to overstate the contribution of [networking and information technology] to America's security, economy, and quality of life. . . . The cumulative effect of these technologies on life in the United States and around the world has been profound and beneficial.[1]

Since 1995, the networking and information technology industries have accounted for 25 percent of U.S. economic growth, measured as real change in gross domestic product (GDP), despite representing only 3 percent of GDP.[2]

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[1]President's Council of Advisors on Science and Technology, *Leadership Under Challenge: Information Technology R&D in a Competitive World,* Executive Office of the President, Washington, D.C., August 2007, pp. 1, 5.

[2]Ibid., p. 9, citing National Research Council, *Enhancing Productivity Growth in the Information Age: Measuring and Sustaining the New Economy,* The National Academies Press, Washington, D.C., 2007.

Advances in IT and its effective use can be expected to continue to drive economic and social gains and are key to future innovation and growth. IT is diffused throughout the economy: it is critical to or supports production in all sectors. IT underpins all fields of scientific and engineering endeavor—from basic and applied research to product development, sales, and distribution (see also the discussion of pervasive IT in Chapter 3).

The Economic Case: The Contributions of IT to the Economy

Although economists had debated the exact nature of its impact, the permanent, positive contribution of IT to economic output and growth is now unquestioned.[3] Previous difficulties in capturing the impact of IT in the national income and product accounts had been expressed in Nobel Prize-winning economist Robert M. Solow's often-quoted statement in 1987: "You can see the computer age everywhere but in the productivity statistics."[4] In economics circles, this was known as the Solow productivity paradox. However, improvements in how the national income and product accounts are constructed have convincingly revealed IT's fundamental contributions to output and growth.[5] The paradox is resolved.

In the past decade, worker productivity increased dramatically owing to investments in information technology and, perhaps more importantly, to the effective use of that technology by firms.[6] Jorgenson points out that "the development and deployment of Information Technology is the

[3]For a resolution to the economic debate about whether the effect of IT was a positive but temporary "shock" to the economy or a permanent improvement, see Dale W. Jorgenson, "Information Technology and the U.S. Economy" (President's Address to the American Economic Association, January 6, 2001), *American Economic Review* 91(1):1-32, March 2001. See also the statement by Alan Greenspan, Chairman, Board of Governors of the Federal Reserve System, before the Joint Economic Committee, U.S. Congress, June 14, 1999: "Innovations in information technology—so-called IT—have begun to alter the manner in which we do business and create value, often in ways that were not readily foreseeable even five years ago." See http://findarticles.com/p/articles/mi_m4126/is_8_85/ai_55671973; accessed March 24, 2008.

[4] Robert M. Solow, "We Had Better Watch Out," *New York Review of Books*, July 12, 1987.

[5] These improvements began with a revision in 1999 that started treating software expenditures as an investment rather than as an expense to be written off against current income. See Dale W. Jorgenson, Mun S. Ho, and Kevin J. Stiroh, *Information Technology and the American Growth Resurgence,* MIT Press, Cambridge, Mass., 2005.

[6]Jason Dedrick, Vijay Gurbaxani, and Kenneth Kraemer, "Information Technology and Economic Performance: A Critical Review of the Empirical Evidence," *ACM Computing Surveys* 35(1):1-28, March 2003.

foundation of the American growth resurgence."[7] His capital-investment/capital-services analysis starts with the technology-driven pattern of relative decreases in quality-adjusted semiconductor prices over time. The precipitous fall in semiconductor prices flows through to falling prices for computers, software, communications equipment, and IT services, which in turn reduce the cost of all kinds of sophisticated products, from aircraft to automobiles. Jorgenson also notes the pervasive nature of IT and that the impacts of IT investments are broadly felt throughout the economy, "altering product markets and business organizations."[8]

Yet the impact of information technology goes well beyond its yielding of cost reductions in traditional products and productivity gains in the services sector. IT intersects with other sectors and disciplines and is no longer so self-contained: it is pervasive. According to Apte and Nath, "information workers" now account for as much as 70 percent of the U.S. labor force and contribute over 60 percent of the total value added in the U.S. economy.[9] Information "processing" by workers represents a growing component of the GDP, and it is predicated upon information technology.

For example, financial analysts use search engines and databases to collect information about investments, retrieve it for analysis with spreadsheets and other modeling tools, and communicate their results to other workers by way of electronic mail and Web sites. At the firm level, integrated supply chain management allows greater communication and coordination between customers and their suppliers, enabling the former to find the lowest-cost supplies subject to delivery constraints, reduce their inventories, and increase their overall production efficiency. These capabilities yield direct benefits to consumers, and not simply in terms of reduced costs. For example, it is now possible for a consumer to purchase a custom-built vehicle with specified color, trim, and other options, and to track its progress through production to dealer delivery.

Brynjolfsson offers an interesting comparison between two major retailers in their use of IT.[10] By investing in more IT per worker, one of these competitors has also enabled a more decentralized decision-making process, pushing purchasing decisions to lower-level workers. This com-

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[7]Dale W. Jorgensen, "Information Technology and the U.S. Economy," *American Economic Review* 91(1):1-32, March 2001.

[8]Ibid.

[9]U. Apte and H. Nath, "Size, Structure, and Growth of the U.S. Economy," Center for Management in the Information Economy, Business and Information Technology (BIT) Working Paper, December 2004, available at http://www.anderson.ucla.edu/documents/areas/ctr/bit/ApteNath.pdf; accessed October 28, 2008.

[10]Erik Brynjolfsson, "The IT Productivity GAP," *Optimize,* Issue 21, July 2003, available at http://ebusiness.mit.edu/erik/Optimize/pr_roi.html; accessed October 28, 2008.

bination of technology and business process has contributed to higher levels of productivity and business value for that firm.

Brynjolfsson also observes that from 1995 to 2005, productivity in the U.S. economy grew by more than 3 percent per year, essentially twice the rate of the preceding 20 years. This growth rate persisted through the recession of the latter part of this period, when productivity grew at the impressive—and counterintuitive—rate of 4.8 percent. Brynjolfsson attributes this remarkable productivity growth to the investments in ever-improving information technology by firms.[11] Furthermore, it is not simply the size of the IT investment, but the way that the technology is used to affect the organization of work that is important for realizing productivity increases. One dollar spent on IT equipment yields $9 in intangible assets. For example, computerized business processes yield more and better data that in turn can be mined for analysis and to support decision making. An example is online customer support that yields valuable information about customer needs that in turn can lead to insights into the kinds of new products to develop.

Thus, not only does IT have an impact on the economy in terms of the value of information technology goods sold, but it has a multiplicative effect on the efficiency and quality of economic activity. And as Brynjolfsson also argues, the effective use of IT places high demands on the capabilities of the workforce. There is a strong correlation between those firms that are the most productive users of IT and those that place a high value on skilled workers, managers, and professionals, that is, on human capital.[12] Data from the U.S. Department of Labor's Bureau of Labor Statistics consistently rank information technology professions such as software engineer and systems administrator among those for which employment is projected to grow the fastest from 2006 to 2016.[13]

Undoubtedly IT will continue to be a growing contributor to GDP, but it takes time to reap its benefits in terms of products and organizations. Brynjolfsson points out that investment in IT by U.S. firms fell during the period of the recession of the early 2000s; this decline has implications for the nation's ability to sustain productivity growth into the future.

The benefits of IT are not evenly distributed. For example, inequality among workers will increase as some kinds of work are replaced by machines and virtually all occupations demand enhanced information skills. Economic turbulence will grow as industries undergo fundamental

[11]Ibid.

[12]Ibid.

[13]U.S. Department of Labor, Bureau of Labor Statistics, *Occupational Outlook Handbook: Tomorrow's Jobs*, Washington, D.C., available at http://www.bls.gov/oco/oco2003.htm; accessed August 21, 2007.

changes in response to new information technologies. For example, as new entrants such as localized classified-advertisement Web sites, numerous national and local job-search and real estate Web sites, and online auctions have displaced traditional newspaper classified advertising, newspapers have sought new revenue sources, including their own online offerings. Information technology may be the strategic differentiator that allows some firms and industries to survive while others inexorably decline.[14]

IT allows greater efficiency and sparks creative destruction in certain sectors (as, for example, the replacement of classified advertising by craigslist, a set of Web sites containing classified advertisements). Even more important, however, is that IT has created entirely new products and markets that have kept the U.S. economy growing. Much of this growth was achieved through an increase in exports as the impact of IT became felt globally and U.S. companies (in the IT sector in particular) took advantage of new international market opportunities, both in emerging and developed economies around the globe.

Information Technology, Services, and the Post-Scientific Society

Jorgenson, Ho, and Stiroh found that during the latter half of the 20th century, more than 80 percent of U.S. economic growth was driven by input growth—that is, investments in capital and human capital. Growth in total factor productivity (a measure that includes the contribution of purchased inputs—namely, goods and services—as well as capital and labor inputs) accounted for only about 20 percent of U.S. economic growth.[15] However, during the 1995-2000 boom period, labor productivity growth accelerated; even as IT investments slowed after 2000, labor productivity growth continued to increase even more rapidly through 2005.[16] Jorgenson and coauthors traced this acceleration in labor productivity growth to a sharp rise in productivity growth in IT-intensive industries, principally in services, finding that the locus of innovation had shifted from IT-producing industries in manufacturing to IT-using industries in trade and services.[17]

The committee that authored the National Research Council's (NRC's)

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[14]Erik Brynjolfsson, Massachusetts Institute of Technology, "Information Technology and the Economy: Where Are We and Where Do We Go from Here?," workshop presentation to the committee, Boston, Mass., April 19, 2007.

[15]Dale W. Jorgenson, Mun S. Ho, and Kevin J. Stiroh, *Information Technology and the American Growth Resurgence,* MIT Press, Cambridge, Mass., 2005.

[16]Ibid.

[17]Dale W. Jorgenson, Mun S. Ho, Jon D. Samuels, and Kevin J. Stiroh, "Industry Origins of the American Productivity Resurgence," *Economic Systems Research* 19(3):229-252, September 2007.

2007 report *Enhancing Productivity Growth in the Information Age: Measuring and Sustaining the New Economy* found that

> new information technologies have a broad and positive impact on U.S. productivity growth through industries that produce new information technologies and the many more that apply them. New IT applications are also contributing to enhanced workplace productivity as a wide variety of firms adapt to changes in information flows and take advantage of new organizational structures made possible by these innovations. . . . These developments are changing the structure of firms, creating more innovative and more agile enterprises, with positive indirect and long-term implications for productivity growth. . . .[18]

That committee also identified IT as foundational for the structural change to a more services-based economy:

> A structural change most associated with the New Economy today is the transformation of the Internet from a communication [medium] to a platform for service delivery. . . . This has contributed to the remarkable growth of the U.S. service economy, as companies like Google and eBay increasingly exploit information services in new ways. As new business models, enabled by the Web, continue to emerge, they will contribute to sustaining the productivity growth of U.S. economy.[19]

Another interpretation of this "New Economy" structural change is that the country is moving to a "post-scientific" society. Christopher T. Hill describes the United States during the last half of the 20th century as (broadly speaking) a "scientific" society, in which deep understanding of scientific principles was sought as the basis for technological progress. During this period, U.S. leadership in the scientific and technological underpinnings and applications of IT led to U.S. economic leadership in IT and contributed to productivity growth and market development in other sectors as well. But now, he argues, the United States may be well on its way to being a *post*-scientific society, in which market leadership and the creation of wealth depend less on scientific and technological fundamentals and more on integrating these creatively with a knowledge of organizations, business processes, and markets:

> In the post-scientific society, the creation of wealth and jobs based on innovation and new ideas will tend to draw less on the natural sciences and engineering and more on the organizational and social sciences, on the arts, on new business processes, and on meeting consumer needs based on niche production of specialized products and services in which

[18]National Research Council, *Enhancing Productivity Growth in the Information Age: Measuring and Sustaining the New Economy,* The National Academies Press, Washington, D.C., 2007, p. 20 [citations deleted from extract].
[19]Ibid., pp. 22-23 [citation deleted from extract].

> interesting design and appeal to individual tastes matter more than low cost or radical new technologies.
>
> Businesses will not succeed in the post-scientific society by adopting a fast-follower strategy, seeking to emulate the products first brought to market by firms in other countries. Rather, success will arise in part from the disciplined search for useful new knowledge that, regardless of its origins, can be integrated with intimate knowledge of cultures and consumer preferences. Networks of highly creative individuals and collaborating firms will devise and produce complex new systems that meet human needs in unexpectedly new and responsive ways.[20]

Already today, IT products and services rely on sophisticated memory, computing, and communications infrastructures with fundamental science and technology underpinnings—these will always be important. However, the value added and wealth generation are accruing most where there is less competition—at the top, at the user- or customer-facing levels, where a knowledge of customers and business processes is not a commodity. [21]

Thus, the economic landscape is clearly one in which the productivity drivers are all complementary to and/or built on top of IT. Innovation in IT includes foundational work in the underlying technologies as well as innovation in IT-intensive and IT-enabled goods and, increasingly, services.

The Scientific Case: A Fundamental Infrastructure for All Science and Technology

It is generally acknowledged that the third leg of scientific investigation, joining theory and experiment, is computation. For example, computer models, describing the quantum mechanical behavior at the atomic and molecular levels, allow scientists to simulate physical systems in detail, to understand physical phenomena better than is possible by theory or experimentation alone. Computer imaging, such as computed axial tomography (CAT) scans, has become vital in the biosciences and medicine.

Computational science models physical systems by large numbers of equations in many variables. The dynamics of a physical system, such as a chemical reaction, requires the solution of these equations over the time domain with a very high degree of accuracy. The field makes use of numerical algorithms and their analysis to ensure that accurate results

[20]Christopher T. Hill, "The Post-Scientific Society," *Issues in Science and Technology,* Fall 2007, available at http://www.issues.org/24.1/c_hill.html; accessed December 3, 2007.

[21]Ibid.

are achieved as rapidly as possible. Techniques include finite-element methods, fast Fourier transforms, Monte Carlo simulations, multigrid methods, methods for sparse problems, randomized algorithms, deterministic sampling strategies, and average case analysis.

Because the kinds of problems tackled by computational scientists are so large and complex, algorithm designers have learned to exploit parallel computer architectures so that the systems that they wish to study can be modeled in a reasonable amount of time. Computational science problems have traditionally driven the highest performance envelope of computing, from vector supercomputers to very large clusters of computers. As computers become faster, larger and more-complex and fine-grained models are generated for the computers' increased capabilities for prediction and design. At the same time, experimental and computational sciences are generating massive amounts of data, straining the capacities of even the largest supercomputer systems.

The most pressing problems to be solved by computational science are commonly known as Grand Challenges. In 1995, the National Research Council produced a report entitled *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure* (commonly referred to as the Brooks-Sutherland report, after its co-chairs Frederick P. Brooks, Jr., and Ivan E. Sutherland) that defined a new set of scientific and societal Grand Challenges.[22] It identified progress in solving scientific Grand Challenges in such disciplines as cosmology, molecular biology, chemistry, and materials science. In 2005, the NRC report *Getting Up to Speed: The Future of Supercomputing* identified a dozen "compelling applications" for supercomputing. These ranged from military applications (such as stewardship of the nuclear weapons stockpile) to those enabling advances in science and engineering (for example, climate prediction, predicting and mitigating the effects of earthquakes), and transportation (for example, improving vehicle dynamics, fuel consumption, comfort, and safety).[23]

In 2003, the U.S. government's Networking and Information Technology R&D (NITRD) program identified 16 illustrative problems that simultaneously challenge our computational capabilities and would represent significant benefits to society if they could be solved accurately and quickly:

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[22]National Research Council, *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure,* National Academy Press, Washington, D.C., 1995.

[23]National Research Council, *Getting Up to Speed: The Future of Supercomputing,* The National Academies Press, Washington, D.C., 2005, Ch. 4.

- Knowledge environments for science and engineering,
- Clean energy production through improved combustion,
- High-confidence infrastructure control systems,
- Improved patient safety and health quality,
- Informed strategic planning for long-term regional climate change,
- Nanoscale science and technology (explore and exploit the behavior of ensembles of atoms and molecules),
- Predicting pathways and health effects of pollutants,
- Real-time detection, assessment, and response to natural or man-made threats,
- Safer, more secure, more efficient, higher-capacity, multi-modal transportation system,
- Anticipate consequences of universal participation in a digital society,
- Collaborative intelligence (integrating humans with intelligent technologies),
- Generating insights from information at your fingertips,
- Managing knowledge-intensive dynamic systems,
- Rapidly acquiring proficiency in natural languages,
- SimUniverse (learning by exploring), and
- Virtual lifetime tutor for all. [24]

These challenge problems were selected for the way that they support six national priorities, as identified by the science and technology agencies of the U.S. government: leadership in science and technology, national and homeland security, health and environment, economic prosperity, a well-educated populace, and a vibrant civil society. Information technology plays a foundational role in achieving each of these priorities.

The list of illustrative challenges is not expressed directly in terms of trillions of operations per second, petabytes of storage, terabits of network bandwidth, or gigapixels of display. Nevertheless, each depends on enormous advances in computation, storage, communications, and displays for its effective solution. Beyond more powerful computers and networks, NITRD identified the difficult computer technology components—the so-called IT Hard Problems—that require significant advancement in order to construct effective information-technology-based solutions to these societal challenges: new algorithms and capabilities for constructing applications, technologies to support complex heterogeneous systems, more capable hardware technologies, techniques and architectures to achieve high confidence in information technology systems, the architec-

[24]See Networking and Information Technology Research and Development, *Grand Challenges: Science, Engineering, and Societal Advances Requiring Networking and Information Technology Research and Development*, Interagency Working Group on Information Technology Research and Development, available at http://www.nitrd.gov/pubs/200311_grand_challenges.pdf; accessed October 28, 2008.

ture of high-end computing systems, information technology for human augmentation, information management, intelligent systems, methodologies and frameworks for IT system design, techniques to improve IT usability, the development of a highly capable IT workforce, technologies to improve the management of IT, high-performance and ubiquitous network technology and architecture, and more capable software technologies for rapid system design and implementation.

Clearly, information technology is the essential fuel that will propel the knowledge-based society of the 21st century.

RESULTS AND IMPACT OF INFORMATION TECHNOLOGY R&D

Advances in information technology and its applications represent the signal success of U.S. scientific, engineering, business, and governmental communities in the past 50 years.

Information technology has transformed, and continues to transform, all aspects of our lives: commerce, education, employment, health care, manufacturing, government, national security, communications, entertainment, science, and engineering. Information technology also drives the economy—both directly (the IT sector itself) and indirectly (other sectors that are "powered" by advances in IT).[25] To appreciate the magnitude and breadth of these impacts, imagine spending a day without IT. This would be a day without the Internet and all that it enables. A day without diagnostic medical imaging. A day during which automobiles lacked electronic ignition, antilock brakes, and electronic stability control. A day without digital media—without wireless telephones, high-definition televisions, MP3 (MPEG-1 Audio Layer 3) audio, DVD video, computer animation, and videogames. A day during which aircraft could not fly, travelers had to navigate without benefit of the Global Positioning System, weather forecasters had no models, banks and merchants could not transfer funds electronically, factory automation ceased to function, and the U.S. military lacked technological supremacy. It would be, for most people in the United States and the rest of the developed world, a "day the Earth stood still."

Leadership in information technology is vital to our nation. For this reason, it is not surprising that the NRC's Computer Science and Tele-

[25]Analysis suggests that the remarkable growth experienced in the United States between 1995 and 2000 was spurred by an increase in productivity enabled almost completely by factors related to information technology: IT drove the U.S. "productivity revival" during the 1995-2000 period as compared with the 1973-1995 period. See Dale W. Jorgenson, Mun S. Ho, and Kevin Stiroh, "Projecting Productivity Growth: Lessons from the U.S. Growth Resurgence," presentation to the Board of Trustees, Federal Old-Age and Survivors Insurance and Disability Insurance Trust Funds, Washington, D.C., November 7, 2002.

communications Board (CSTB) has frequently been asked to study various aspects of the IT innovation ecosystem. The 1995 report *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure*[26] explored these impacts and originated the subsequently often-reproduced "tire tracks" figure (so called because of its appearance) that illustrated some of the many cases in which fundamental research in information technology, conducted in industry and universities, led to entirely new product categories that became billion-dollar industries 10 to 15 years later. The tire tracks figure also illustrated the complex interplay between industry, universities, and government—the flow of ideas and people—and the interdependencies of research advances in various subfields: there is a complex research ecology at work, in which concurrent advances in multiple subfields are mutually reinforcing, stimulating, and enabling one another.

In 2003, the CSTB report *Innovation in Information Technology*[27] distilled the lessons from eight prior CSTB studies[28] and summarized the nature of innovation in information technology as understood circa 2003 (see Box 2.1). That report's update of the original tire tracks figure is reproduced as Figure 2.1 in this chapter.

Interestingly, during the preparation of the first version of Figure 2.1, in 1994, members of the authoring committee were discouraged because they could not identify current research advances that were likely to lead to new billion-dollar industries. Eight years later, when the second version of the figure was being prepared, more than half a dozen such

[26]National Research Council, *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure,* National Academy Press, Washington, D.C., 1995.

[27]National Research Council, *Innovation in Information Technology,* The National Academies Press, Washington, D.C., 2003.

[28]The eight CSTB studies, arranged here chronologically, are these:

- *Computing the Future: A Broader Agenda for Computer Science and Engineering* (1992);
- *Academic Careers for Experimental Computer Scientists and Engineers* (1994);
- *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure* (1995);
- *More Than Screen Deep*: *Toward Every-Citizen Interfaces to the Nation's Information Infrastructure* (1997);
- *Funding a Revolution: Government Support for Computing Research* (1999);
- *Making IT Better: Expanding Information Technology Research to Meet Society's Needs* (2000);
- *Building a Workforce for the Information Economy* (2001); and
- *Embedded, Everywhere: A Research Agenda for Networked Systems of Embedded Computers* (2001).

These National Research Council reports were published by the National Academy Press (The National Academies Press as of June 2003), Washington, D.C.

BOX 2.1
Important Themes from the Computer Science and Telecommunications Board's Studies of Innovation in Information Technology

A 2003 report of the National Research Council's Computer Science and Telecommunications Board, *Innovation in Information Technology,* distilled lessons about the nature of research in information technology—including the unpredictability of and synergy among research results; the roles of government, industry, and academia; and the social returns from research. The 2003 report summarized these as follows:

- *The results of research*
  —America's international leadership in IT—leadership that is vital to the nation—springs from a deep tradition of research. . . .
  —The unanticipated results of research are often as important as the anticipated results—for example, electronic mail and instant messaging were by-products of research in the 1960s that was aimed at making it possible to share expensive computing resources among multiple simultaneous interactive users. . . .
  —The interaction of research ideas multiplies their impact—for example, concurrent research programs targeted at integrated circuit design, computer graphics, networking, and workstation-based computing strongly reinforced and amplified one another. . . .
- *Research as a partnership*
  —The success of the IT research enterprise reflects a complex partnership among government, industry, and universities. . . .
  —The federal government has had and will continue to have an essential role in sponsoring fundamental research in IT—largely university-based—because it does what industry does not and cannot do. . . . Industrial and governmental investments in research reflect different motivations, resulting in differences in style, focus, and time horizon. . . .
  —Companies have little incentive to invest significantly in activities whose benefits will spread quickly to their rivals. . . . Fundamental research often falls into this category. By contrast, the vast majority of corporate research and development (R&D) addresses product and process development. . . .
  —Government funding for research has leveraged the effective decision making of visionary program managers and program office directors from the research community, empowering them to take risks in designing programs and selecting grantees. . . . Government sponsorship of research especially in universities also helps to develop the IT talent used by industry, universities, and other parts of the economy. . . .
- *The economic payoff of research*
  —Past returns on federal investments in IT research have been extraordinary for both U.S. society and the U.S. economy. . . . The transformative effects of IT grow as innovations build on one another and as user know-how compounds. Priming that pump for tomorrow is today's challenge.
  —When companies create products using the ideas and workforce that result from federally sponsored research, they repay the nation in jobs, tax revenues, productivity increases, and world leadership. . . .

SOURCE: National Research Council, *Innovation in Information Technology,* The National Academies Press, Washington, D.C., 2003, pp. 2-4.

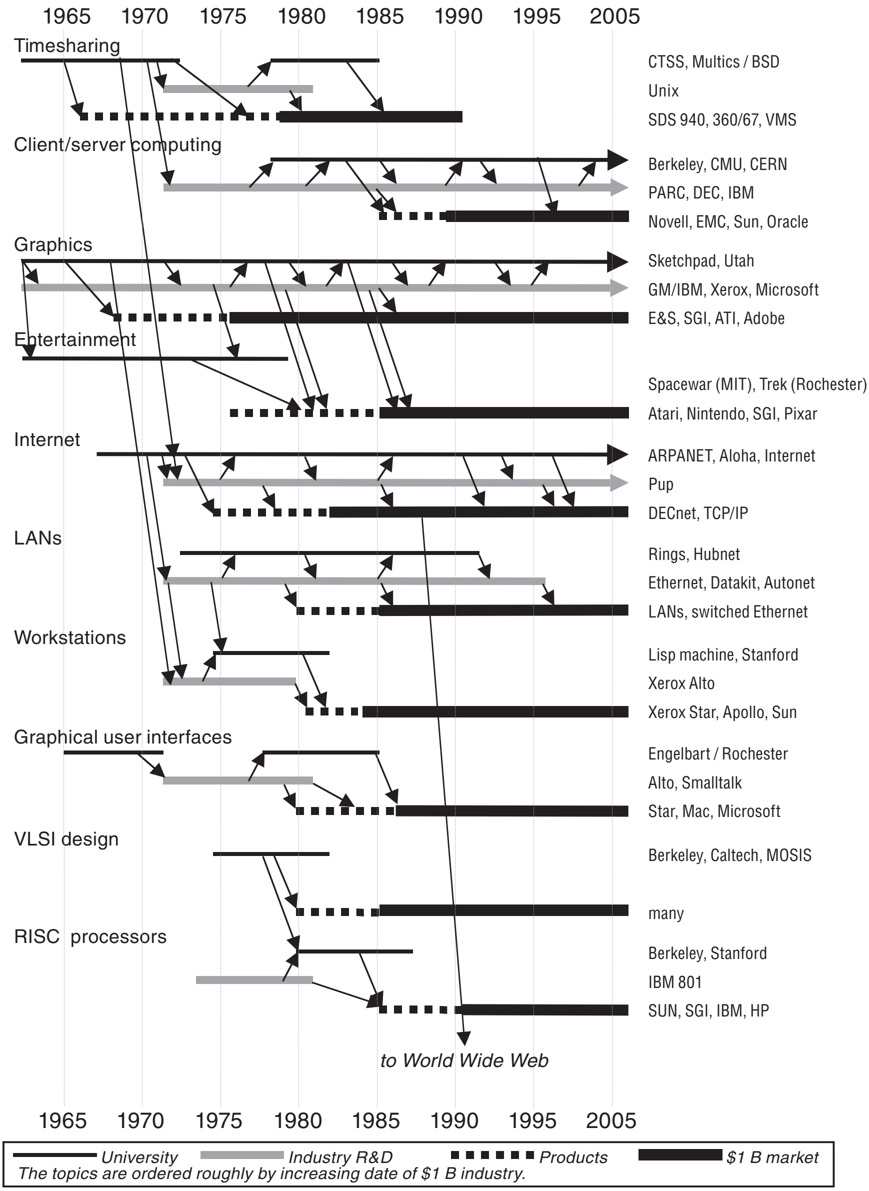
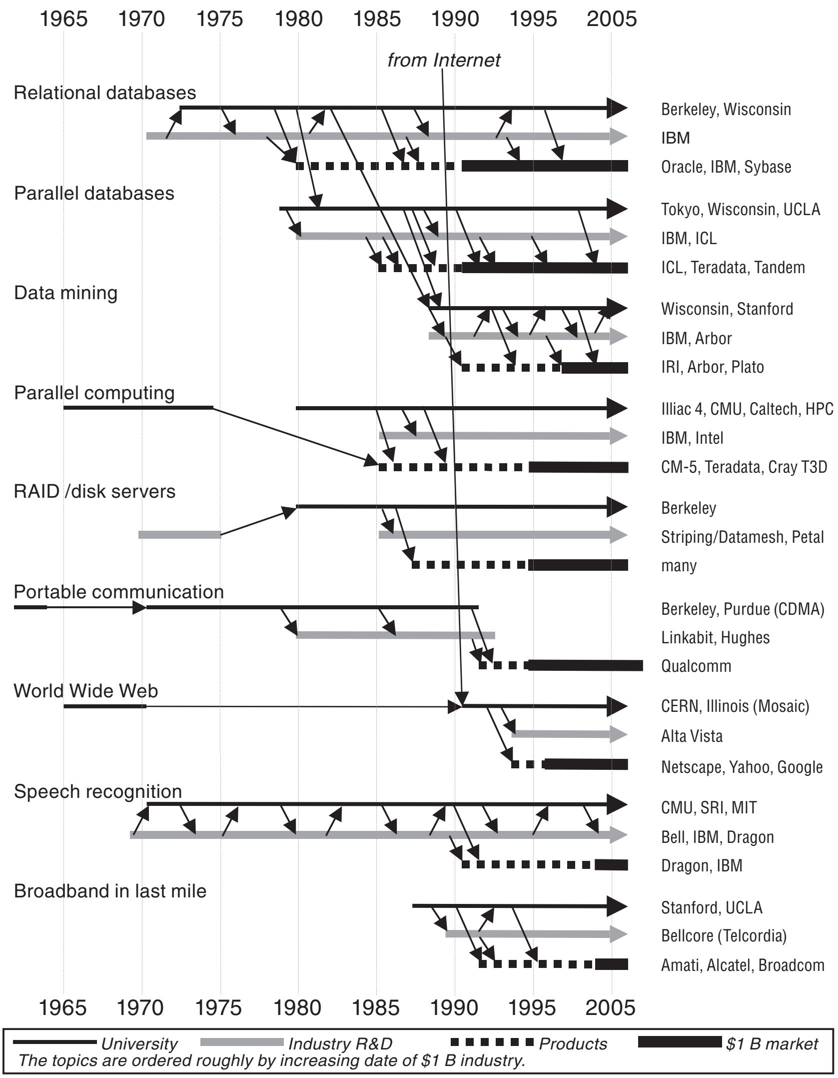


FIGURE 2.1 The updated "tire tracks" diagram originally published in a 1995 report of the National Research Council to provide examples of government-sponsored information technology research and development in the creation of commercial products and industries.



SOURCE: Reprinted from National Research Council, *Innovation in Information Technology*, The National Academies Press, Washington, D.C., 2003. Updated and adapted from figure originally published in National Research Council, *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure*, National Academy Press, Washington, D.C., 1995.

industries had emerged, which demonstrates that predicting the future in a field as dynamic as information technology is incredibly difficult, even for experts.

INFORMATION TECHNOLOGY RESEARCH—THE BOUNDLESS FRONTIER

The advances of information technology over the past 50 years have been truly breathtaking. However, the field remains in its relative infancy, and there is every reason to believe that the best is yet to come—if we take steps to preserve and enhance critical elements of the IT innovation ecosystem.[29] This section highlights just a few examples of the impacts that can be anticipated from advances in information technology during the coming decades.

Improved Auto Safety

In the Defense Advanced Research Projects Agency's (DARPA's) Grand Challenge in 2005, four cars successfully negotiated autonomously a difficult, 103-mile obstacle course in the Mojave Desert. In DARPA's 2007 Urban Challenge, autonomous vehicles performed such maneuvers as merging, passing, negotiating intersections, and parking in a simulated urban environment at the former George Air Force Base in California. These milestones reflect advances in robotics which indicate that it is time to launch a program to create "cars that cannot crash." In the United States alone, automobile accidents cost roughly 40,000 lives and $250 billion each year.[30] It is reasonable to believe that within a decade, tens of thousands of lives, hundreds of thousands of injuries, and tens of billions of dollars could be saved annually, while giving U.S. products a sizable competitive advantage in the $1 trillion worldwide automotive market.

Designing a Next Internet

In 2005, Vinton G. Cerf and Robert E. Kahn received computing's highest prize, the A.M. Turing Award, as well as the National Medal of

[29]See, for example, the slides from Jim Gray's 1998 Turing Lecture, "What Next? A Few Remaining Problems in Information Technology," available at http://research.microsoft.com/~gray/talks/Gray_Turing_FCRC.pdf; accessed August 16, 2007.

[30]National Highway Traffic Safety Administration, "2006 FARS/GES Traffic Safety Facts Annual Report," DOT HS 810 818, available at http://www.nhtsa.gov/portal/nhtsa_static_file_downloader.jsp?file=/staticfiles/DOT/NHTSA/NCSA/Content/TSF/TSF2006FE.pdf; accessed June 19, 2008. In 2006, 42,642 people were killed in highway accidents; the economic cost of motor vehicle crashes in 2000 was $230.6 billion.

Technology and the Presidential Medal of Freedom, for their creation in 1973 of the Transmission Control Protocol (TCP), the language of the Internet. It is remarkable that today's Internet employs the protocols that Cerf and Kahn devised more than 30 years ago (with many significant engineering improvements, of course).

In 1980, there were roughly 200 hosts on the Internet—all of them operated by computer scientists and their friends. In 1990, there were roughly 150,000 Internet hosts. Today, there are about 160 million Internet hostnames, about 64 million active Internet hosts,[31] and an estimated 1 billion Internet users worldwide. The Internet is a victim of its own success. It has reached its limits in terms of scalability, security, robustness, and manageability. Fundamentally new approaches are required in some areas. Creating a "new Internet" that meets the demands of the 21st century is a national priority replete with deep intellectual challenges. The National Science Foundation's Networking Technology and Systems (NeTS) program[32] and its Global Environment for Network Innovations (GENI) experimental infrastructure project were established to work on these and related challenges.[33]

The Personal Memex

In his seminal 1945 paper "As We May Think,"[34] Vannevar Bush described the Memex, a device that would store all information relevant to an individual and which could be searched using spoken commands. Dramatic advances in storage are on the verge of making the Memex feasible in terms of cost and size. Equally dramatic advances in search and retrieval technology, though, are needed to make it feasible functionally. Today's Web search engines represent a remarkable advance in the ability to retrieve information—but even greater advances can be envisioned. For example, today's Web search engines do not really "understand"—they can point to a Web page where an answer to a question might be (if such a Web page exists), but they cannot synthesize an answer to a question. Image and video retrieval works well when the media are explicitly or implicitly tagged, but not so well otherwise. The "contextualization" of retrieval requests similarly has vast room for improvement. A personal

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[31]See February 2008 Web server survey, available at http://news.netcraft.com/archives/web_server_survey.html; accessed February 27, 2008.

[32]See "Networking Technology and Systems (NeTS)," available at http://www.nsf.gov/cise/cns/nets_pgm.jsp; accessed November 20, 2008.

[33]See "GENI Project Office F.A.Q.," available at http://geni.net/faq.html; accessed April 14, 2008.

[34]Vannevar Bush, "As We May Think," *The Atlantic*, July 1945, available at http://www.theatlantic.com/doc/194507/bush; accessed January 6, 2008.

Memex should be able to store and effectively retrieve any digital information ever encountered by its owner, and bring this information to bear on relevant tasks. A Memex for storing and retrieving any digital information encountered within an enterprise might be equally achievable—and at least equally valuable.

Post-Moore's Law Computing

Moore's law describes the exponential increase in inexpensive integrated circuit density that has been enjoyed for more than 30 years. Of course, advances in computing have required more than just a decrease in feature size. The following have also been needed: new design methodologies and tools to handle hundreds of millions of transistors rather than tens of thousands, computer architectures that use these additional transistors to achieve a proportional increase in performance, system architectures that are synergistic with processor capabilities, and system and application software to exploit these new capabilities.

Today the game is changing.[35] It has been possible to continue increasing transistor density. However, concerns about power consumption and heat dissipation, which are of particular importance for mobile and datacenter systems, have forced designers to hold back on increased microprocessor clock speeds. "Multicore" and other architectures that provide significant increases in parallelism are a possible response to this challenge. Revolutionary new approaches to programming will be required in either case. And research into post-silicon computing substrates—such as quantum computing—may open up important new avenues for continued computing performance increases.

Personalized Education

To make educational excellence the norm rather than the exception will help U.S. students reach their full potential. Although information technology is not a panacea for all of the shortfalls associated with the nation's educational system, IT nonetheless offers the potential not only for significantly enhancing learning for all learners, but also for transforming the way that people learn. Coupling educational practice and educational technology with recent advances in the learning sciences—that

[35] These topics are being addressed by a National Research Council study being conducted by the Committee on Sustaining Growth in Computing Performance. See http://sites.nationalacademies.org/cstb/CurrentProjects/CSTB_042221.

is, knowledge of how people learn—can be fruitful.[36] Educational tools including adaptive tutors, massive multiplayer online games, collaborative authoring, learning in context and just-in-time learning, and flexible simulation are needed. IT can contribute to creating a future in which educational excellence is ubiquitous.

Personalized Health Monitoring

The combined trends of Moore's law, microelectromechanical systems sensors, and low-power radios are enabling an explosion of opportunities to create "sensors for everyone." Embedding sensors in everyday devices such as cellular telephones, wristwatches, and household appliances can provide a wealth of important information on individuals' personal activity patterns. As an example, researchers on the subject of obesity want to see day-long and week-long activity patterns so that they can better advise patients on how to alter their behavior. The specifics of where and when people walk, run, use stairs, and so on are important because "lifestyle advice" must be customized to each individual in order to be most effective. In elder care, long-term patterns in the frequency, duration, and mix of an elder's activities can lead to early warning signs of various conditions, both physical and cognitive. Techniques for processing this kind of sensor data range from basic signal processing to sophisticated statistical machine learning. Creating visualization tools and user interfaces that consumers and health care providers can use and with which they can perform what-if analyses is another important direction, coupled with research in psychology on appropriate motivation strategies. Furthermore, IT can provide the security mechanisms and help implement the privacy protections that will be necessary for such monitoring and research programs.[37]

Mastering IT System Complexity

The ever-increasing capabilities of computing systems (including both hardware and software) have managed to keep pace with the ever-increasing aspirations that users have for these systems. However, this remarkable progress has been accompanied by ever-increasing complexity. As a result, today's computer systems are tremendously difficult to design, install, configure, operate, and maintain. The situation is incon-

[36] See, for example, National Research Council, *How People Learn: Brain, Mind, Experience, and School*, Expanded Edition, National Academy Press, Washington, D.C., 2000.

[37] See National Research Council, *Engaging Privacy and Information Technology in a Digital Age,* The National Academies Press, Washington, D.C., 2007.

venient, risky, and expensive—typically, annual outlays for maintenance and operations far exceed total hardware and software costs. Research has finally begun to focus on these issues, and there have been some notable successes: companies such as Akamai Technologies and Google, for example, efficiently operate massive collections of systems that span the globe. These are special situations, though; for the typical home or business desktop system or server facility, the costs of ownership—and the risks—continue to be far too great. A "grand challenge" in computer systems for the next decade is to reduce these costs and risks—to make as much progress on security, privacy, dependability, and ease of use as has been made on increasing computing performance.[38]

Transforming the Developing World

One of the greatest available opportunities for fostering economic growth and security for the United States is to improve the status of the several billion people on the planet currently living in poverty. On the surface it may seem that IT has little role to play in confronting this problem; most of the trappings of IT are far more expensive than can be affordably replicated at this scale. Digging deeper, however, it becomes clear that IT can play a role in designing effective ways to address afflictions such as inadequate health care, lack of clean water, deficient education, and lack of economic opportunity. The design of contextually appropriate information and communication technology to address nations' development issues has recently become a major research focus for a number of institutions. Global projects to develop and deploy low-cost laptops, for example, are intended to address the problem of affordable IT for education and other purposes.

Augmented Cognition

The amount of information with which one is bombarded daily is increasing relentlessly, but a person's ability to absorb, evaluate, and act on that information is not. Information technology is largely responsible for information overload, and information technology must also provide effective tools for coping—for helping people absorb and evaluate information and for calling to their attention at the appropriate time informa-

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[38]See, for example, National Research Council, *Software for Dependable Systems: Sufficient Evidence?* The National Academies Press, Washington, D.C., 2007; and *Toward a Safer and More Secure Cyberspace*, The National Academies Press, Washington, D.C., 2007. An ongoing study by the Committee on Advancing Software-Intensive Systems Producibility, under the auspices of the NRC's Computer Science and Telecommunications Board, is expected to be completed in 2009. See http://sites.nationalacademies.org/cstb/CurrentProjects/CSTB_042212.

tion that requires action on their part. This "augmented cognition" is critical for those who operate in high-stress, high-information environments, but it may be even more important for those who are cognitively impaired—for example, Alzheimer's patients, who with cognitive assistance and monitoring could live fuller, more independent lives.

Driving Advances in All Fields of Science and Engineering

The role of simulation, enabled by advances in high performance computing, in driving advances in all fields of science and engineering is well documented. Today though, we are seeing the emergence of a new form of computational science: one focused on the collection of massive amounts of data from sensors in the world around us and aided by advances in techniques for storing, retrieving, mining, visualizing, and discovering knowledge in those data. Sensors are everywhere—in the oceans, in scientific instruments ranging from telescopes to medical imaging systems, in our civilian infrastructure (buildings, roads, bridges). These sensors generate relentlessly increasing amounts of data. Discovery involves data analysis on a massive scale. Rapid advances in information technology are essential.

SUMMARY

The impacts that can be anticipated from advances in IT during the coming decades as described above are but a few examples of the promise of information technology. Advances in IT have transformed our lives, powered our economy, and changed the conduct of science and engineering. Even so, the field remains in its relative infancy, and greater opportunities lie ahead.

3

The Changing Landscape of the U.S. Information Technology R&D Ecosystem: 1995-2007

This chapter reviews the evolution of the information technology (IT) research and development (R&D) ecosystem in the time period 1995 through 2007. As with any ecosystem in nature, the IT R&D ecosystem responds to external forces to which it has been subjected, in turn influencing those forces by the way that the system evolves. The time from the mid-1990s to the present has been a period of almost unprecedented change, in the global, technical, and industrial contexts.

The chapter is organized in four sections. The first reviews the shocks to the U.S. IT R&D ecosystem in terms of the rise and aftermath of the speculative financial bubble. The second section discusses the emergence of new technology platforms, based on open-source software, collaborative community development, and Web-centric technologies, and the challenges that these present to traditional IT industrial organization. The third section addresses the rapid globalization of the underlying IT industrial sectors, with a particular focus on the cases of the semiconductor, computer, and software industries. It also describes the rise of new regions where IT R&D is performed, both nationally and internationally, focusing particularly on the new IT powerhouses of India, China, and Taiwan. The fourth section describes the role that infrastructure plays in enabling innovation and the importance of enhancing U.S. broadband local-access infrastructure. The chapter concludes with a brief summary.

SHOCKS TO THE U.S. ECOSYSTEM

The period 1995 to 2007 has been a turbulent one for the U.S. economy and the world economy. The early part of the period was characterized by an IT-fueled speculative boom, followed by an economic bust from which the IT sector is just now starting to emerge. This section reviews the shocks to which the IT R&D ecosystem was subjected during this time.

The Rise of "Irrational Exuberance"

The term "irrational exuberance" is credited to former Federal Reserve Board Chairman Alan Greenspan. In a speech given at the American Enterprise Institute in 1996, Greenspan made a general observation about the difficulty of recognizing "unduly escalated asset values." Few seemed concerned about the possibility of irrational exuberance or unduly high asset values as the excitement about the Internet created the dot-com boom. The initial public offering (IPO) of Netscape Communications Corporation in August 1995 symbolizes the beginning of this period. With the benefit of hindsight, those early years can be seen to have fueled a massive expansion and upgrade of the global telecommunications system and powered the adoption of the Internet, but when the bubble of excitement burst in 2000,[1] a powerful jolt was inflicted on the IT R&D ecosystem.[2]

The introduction and adoption of the World Wide Web were predicated on the ubiquity of the personal computer. With intuitive browsers and simple mark-up language, the Web enabled millions of individuals and businesses to create Web sites that could reach hundreds of millions of people and to engage in commerce. Companies formed rapidly, raising venture capital at high valuations to pursue new Web-enabled opportunities. Entrepreneurs and investors were lured into adopting business plans with weak fundamentals and (at least in retrospect) objectives that did not create lasting and tangible customer value. And yet, despite the agony of the bursting bubble, the Internet changed the lives of hundreds of millions of people around the world.

Figure 3.1 shows the rapid growth in venture funding for IT start-ups, particularly in the software and telecommunications sectors, following the creation of the Web in the mid-1990s. (For comparison, biotechnology funding, which did not experience such extreme funding changes, is also shown.) According to data from the *MoneyTree* survey, the number of IT start-up companies receiving venture investments reached a peak of more

[1]For a broad study of the 1995 stock market boom in the context of others and with respect to structural factors contributing to speculative bubbles, see Robert Schiller, *Irrational Exuberance,* Princeton University Press, Princeton, N.J., 2000.

[2]The overall peak in terms of both the total number of venture deals and total amounts raised came in the first quarter of 2000: in that quarter there were 2,129 deals amounting to $28,414 million, according to PricewaterhouseCoopers/Thomson Financial/National Venture Capital Association *MoneyTree Report* historical data, available at https://www.pwcmoneytree.com/MTPublic/ns/nav.jsp?page=historical; accessed August 20, 2007.

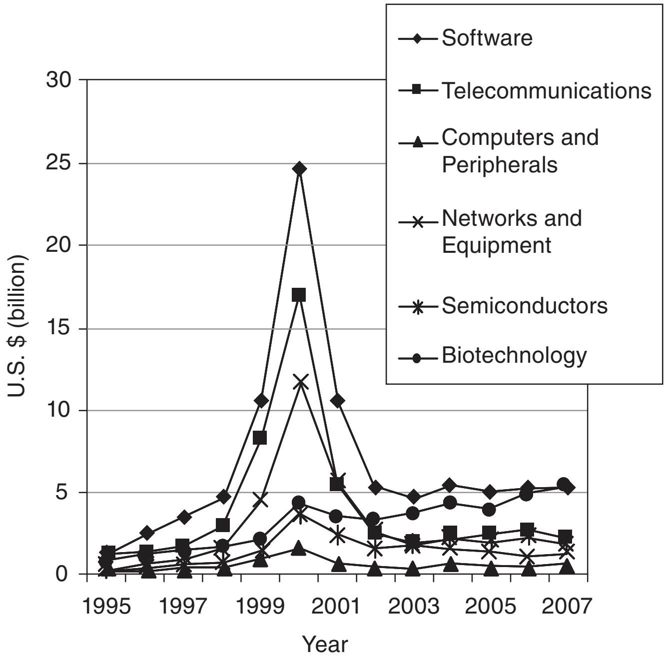

FIGURE 3.1 Total amount of investments by year, 1995 through 2007, in venture funding for IT start-ups in five sectors, compared with that for biotechnology start-ups. The investment bubble in IT start-ups ballooned after 1995 and was deflating by 2001. SOURCE: Data (national aggregate data by industry from 1995 to 2007) from PricewaterhouseCoopers/Thomson Financial/National Venture Capital Association *MoneyTree Report*. Available at https://www.pwcmoneytree.com/MTPublic/ns/nav.jsp?page=notice&iden=B.

than 5,600 in the year 2000, compared with fewer than 1,300 in 1995; the average investment per deal was over $18 million for year 2000 investments, compared with $4.5 million in 1995.[3]

The period 1995 through 2000 was characterized by a number of high-profile success stories along with many large-scale capital deployment mistakes. In retrospect, too many of the IT start-ups that received venture capital funding were ill-conceived, too few of the funded start-ups had solid business fundamentals, and ultimately most squandered their invested capital and went bankrupt.

[3]Data from PricewaterhouseCoopers/Thomson Financial/National Venture Capital Association *MoneyTree Report*, available at https://www.pwcmoneytree.com/MTPublic/ns/nav.jsp?page=historical; accessed November 20, 2008.

The financial woes, and even bankruptcies, of several large telecommunications providers suggest that too many of them attempted to build next-generation data network backbones. This investment occurred even as the somewhat lackluster state of U.S. broadband suggests that too little investment went into the transformation of U.S. narrowband local-access infrastructure into a broadband local-access infrastructure—thus creating a potential impediment to the deployment of cutting-edge applications and services that depend on high data rates. (See the section below entitled "Infrastructure to Enable Multifaceted Innovation.")

At the same time, there are differing perspectives on the net success of investment strategies during this period. Researchers have begun to explore some of the entrepreneurial and investment dynamics of the era. For example, drawing on data contributed to the Business Plan Archive,[4] Goldfarb, Kirsch, and Pfarrer estimate that many less-visible and privately held ventures—accounting for nearly half of dot-com era ventures—survived until 2004.[5] Thus, they characterize the dot-com era as a "legitimate response to a technology shock." However, these authors also recognize that "many *good* opportunities were oversold to investors and the public as *large* opportunities" and that the bursting bubble brought reduced, but more realistic, private and public market valuations.[6]

Subsequent research by Goldfarb, Kirsch, and Miller explored the implications of the pre-2000 "pervasive and persistent belief" in a "Get Big Fast (GBF)" business strategy that was based on the market preemption of competitors and on expected economies of scale associated with network effects. They concluded that belief in the GBF strategy by entrepreneurs, investors, and the public led to overly focused investment in too

[4]The Business Plan Archive (www.businessplanarchive.org) was established in 2002 to preserve business plans and other digital ephemera from the dot-com era technology companies.

[5]Using a sample of new technology ventures drawn from the funding solicitations received by one venture capital fund, Goldfarb, Kirsch, and Pfarrer extrapolated estimates of venture creation during the 1996-2002 period that include transactions not published in the Thomson Financial data. They estimate that 50,000 new ventures were formed to exploit the commercialization of the Internet and that 24,000 of these received some $256 billion from formal and informal investors over the 1996-2002 period. By contrast, according to the authors, Thomson Financial reported only 8,500 transactions but the vast majority ($217 billion) of the investment during this period. See Brent D. Goldfarb, David A. Kirsch, and Michael D. Pfarrer, "Searching for Ghosts: Business Survival, Unmeasured Entrepreneurial Activity and Private Equity Investment in the Dot-Com Era," Robert H. Smith School of Business Working Paper No. RHS-06-027, October 2005, available at http://ssrn.com/abstract=825687; accessed December 1, 2007.

[6]Brent D. Goldfarb, David A. Kirsch, and Michael D. Pfarrer, "Searching for Ghosts: Business Survival, Unmeasured Entrepreneurial Activity and Private Equity Investment in the Dot-Com Era," Robert H. Smith School of Business Working Paper No. RHS-06-027, October 2005, available at http://ssrn.com/abstract=825687; accessed December 1, 2007.

few start-ups and resulted both in too little entry and in both private and public market overcorrections once its limitations were realized.[7]

In retrospect, the GBF strategy had mixed results. It did not work well for a number of firms such as Webvan, Pets.com, or Scient, whose failures and resulting financial losses contributed to a negative public perception of the era.[8] However, the strategy worked well in the long term (i.e., until the present) for a small number of firms such as Amazon, Yahoo!, eBay, and Monster. Indeed, the existence of an environment that led to the successful creation of these leading firms is arguably a unique strength of the U.S. IT R&D ecosystem.

From another perspective, however, the rapid birth and death of IT start-ups and the venture investments during the peak amounted to a valuable form of experimentation—with business models, customer preferences, consumer adoption of the relatively new Internet for entertainment and commerce—that was both faster and perhaps more effective than applied research in a university environment on the same questions might have been. For society as a whole, the hundreds of millions of "written-off" venture dollars went toward market experimentation and toward operationalizing the scientific and engineering advances made possible in part by traditional IT R&D. Nonetheless, going forward, one lesson from this period is that capital misallocation might be avoided through greater focus on how consumers use and value IT (see the section entitled "Infrastructure to Enable Multifaceted Innovation," below).

"Y2K" and the Development of the Indian Software Industry

The year 2000 problem, known as Y2K, or the Millennium Bug, refers to the perceived difficulty of handling 21st century dates in older but still used computing systems. Industry and government voiced concern that mission-critical software that used only two digits to store years would confuse 2000 with 1900 when the calendar wrapped from 1999 to 2000. In the end, after considerable effort to revamp software or introduce operational workarounds, the disruptions caused were minor.

Global efforts to address the Y2K problem provided a major growth impetus for the Indian software industry. Few programmers in the United

[7]Brent D. Goldfarb, David A. Kirsch, and David A. Miller, "Was There Too Little Entry During the Dot Com Era?" *Journal of Financial Economics* 86(1):100-144, 2007, available at www.sciencedirect.com; accessed December 4, 2007.

[8]David Kirsch and Brent Goldfarb, "Small Ideas, Big Ideas, Bad Ideas, Good Ideas: Get Big Fast and Dot Com Venture Creation," Robert H. Smith School of Business Working Paper No. RHS-06-049, November 2006, available at http://ssrn.com/abstract=946446; accessed December 1, 2007.

States were prepared, or even wanted, to deal with fixing the legacy software problems. Firms turned to Indian companies to develop tools to analyze their software for vulnerabilities and to modify their applications. The build-out of global telecommunications services and adoption of the Internet that had recently taken place in India and the rest of Asia helped make it possible to coordinate activities between the United States and overseas. India's Y2K success enticed global IT firms to locate development laboratories and product groups there, where products for global markets are being developed. By 2007, Indian firms had emerged as world-class IT services enterprises.

NASDAQ Bust (2000)

The NASDAQ—National Association of Securities Dealers Automated Quotations—bust came in the aftermath of a soaring stock market of the 1990s. It peaked in March 2000, and the bust began when the valuations of firms with questionable business models could no longer be sustained. The immediate effect was to end the unsustainable expansion plans of many firms, leading to retrenchments and even bankruptcies. A recession ensued, even affecting IT workers. Venture capital investments declined, with start-up companies encouraged to outsource development to reduce costs. The public markets no longer supported technology IPOs, reducing the returns to early-stage investors and increasing investors' aversions.

The general sense of pessimism about the IT sector and a perceived lack of employment appear to have led to the ensuing decline in enrollments in computer science programs. This happened at the same time that the software industry in India and Eastern Europe enjoyed high rates of growth, helping to accelerate the migration of projects to these regions.

In 2007, the markets and the field continued their recovery.[9] Venture capital investment was up, reaching the highest levels since 2001. There had been a number of spectacular recent IPOs, including those of Google (2004), Riverbed Technology (2006), and VMware (2007). The number of technology IPOs on U.S. exchanges was once again increasing,[10] albeit at a sobered pace.[11] As the pace of investment in IT firms increases, access to talent becomes a limiting factor. The demand for students with IT skills

[9]See Kristina Shevory, "In Silicon Valley, Steady But Cautious Growth Returns," *New York Times*, June 27, 2007.

[10]See "Door Is Open to High-Tech Offerings That Meet Thresholds," *New York Times*, June 29, 2007.

[11]As this report went to press in 2008, there were indications of at least a temporary falloff in IPOs, reflecting prevailing economic conditions.

is increasing, but with their numbers reduced, salaries rise and firms look globally for technical talent.[12]

Aftereffects of September 11, 2001

The terrorist attacks of September 11, 2001, profoundly affected the United States, with a redirection of national attention focused on addressing the terrorist threat. Subsequent conflicts in Afghanistan and Iraq led national resources to be redirected to the war effort. There is evidence that some IT research funding has been redirected to national and homeland defense objectives.[13] This type of research is not easily performed in universities owing to campus restrictions on classified research and the presence of large numbers of students, faculty, and other researchers who are foreign nationals. Funding data suggest that the Department of Defense (DOD) has reduced its investment in university research programs.[14]

Furthermore, the post-September 11 environment had other effects. Anecdotal evidence suggests that in the immediate aftermath of September 11, foreign students found it more difficult to enroll in U.S. graduate programs owing to visa difficulties and new background checks at U.S. embassies and consulates abroad.[15] In any case, survey data were collected in early 2004 by the Council of Graduate Schools (CGS) from the 113 graduate schools that enroll nearly half of all international graduate students in the United States. These data indicated an overall decline of

[12]The average salary offer for a college graduate with a computer science major was $53,051 in 2007, up 4.5 percent from the previous year. Only graduates with majors in chemical, electrical, and mechanical engineering had higher average starting salaries. See National Association of Colleges and Employers data reported by Computing Research Association, available at http://www.cra.org/wp/index.php?p=123; accessed February 20, 2008.

[13]See John Markoff, "Pentagon Redirects Its Research Dollars," *New York Times*, April 2, 2005, quoting officials of the Defense Advanced Research Projects Agency (DARPA) as saying that, while the amount of DARPA computer science research funding rose slightly from 2001 to 2004, the portion going to university researchers fell by about 40 percent; available at http://www.nytimes.com/2005/04/02/technology/02darpa.html; accessed April 16, 2008.

[14]For example, the fiscal year 2008 budget request for total DOD basic research (known as 6.1 funding) declined 7.8 percent from the fiscal year 2007 budget, but total DOD university research initiatives declined more, by 14 percent. See http://www.aaas.org/spp/rd/08ptbii4.pdf; accessed October 17, 2007.

[15]See "Science and Security in the Post-9/11 Environment: Foreign Students and Scholars (Updated)," available at http://www.aaas.org/spp/post911/visas/; accessed October 27, 2008. Legislation such as the USA PATRIOT Act of 2001 (Public Law 107-56) and the Enhanced Border Security and Visa Entry Reform Act of 2002 (Public Law 107-173) affected visa procedures.

32 percent in international student applications for the fall of 2004 compared with applications for the fall of 2003. Eighty percent of the schools responding reported decreases in applications for graduate engineering programs; the majority of respondents reported declines in applications from students in the two largest "sending" countries, China (76 percent of respondents reported a decline) and India (58 percent of respondents reported a decline). In the fall of 2004, the CGS reported a 6 percent decline in overall first-time international student enrollment from 2003 to 2004; engineering enrollments dropped 8 percent. This represented the third consecutive year in which the number of first-time international graduate students studying in the United States decreased between 6 percent and 10 percent from the preceding year.[16]

This effect appears to have mitigated by 2007, by which time enrollments were once again increasing. CGS survey data from 172 U.S. universities (including 9 of the 10 with the largest international graduate student enrollment) on international graduate student admissions offers and enrollments for 2006 and 2007 showed that admissions offers were up 14 percent for 2006 compared with those in 2005 and that they were up 7 percent for 2007 compared with those for 2006. First-time enrollment was up 12 percent for 2006 compared with that in 2005 and was up 4 percent for 2007 compared with that in 2006. Admissions and enrollments from China and India showed the greatest increases, with engineering being the field of study showing the largest increases.[17]

Findings for international students overall (undergraduate and graduate) were reported by the Institute for International Education (IIE), which publishes the annual *Open Doors: Report on International Education Exchange* with support from the U.S. Department of State. According to the IIE, the total number of international students enrolled in colleges and universities in the United States increased by 3 percent over that of the previous year to a total of 582,984 in the 2006/2007 academic year; this is the first significant increase since 2001/2002. Engineering students

[16]See Council of Graduate Schools, "Council of Graduate Schools Finds Widespread Declines in International Graduate Student Applications to U.S. Graduate Schools for Fall 2004" and "Council of Graduate Schools Finds Decline in New International Graduate Student Enrollment for the Third Consecutive Year," Washington, D.C., March 2, 2004, and November 4, 2004, respectively. Research reports and summaries from the CGS are available at http://www.cgsnet.org/Default.aspx?tabid=172; accessed December 11, 2007.

[17]See Council of Graduate Schools, "Findings from the 2007 CGS International Graduate Admissions Survey Phase III: Final Offers of Admission and Enrollment," Washington, D.C., November 2007, available at http://www.cgsnet.org/portals/0/pdf/R_intlenrl07_III.pdf; accessed December 11, 2007.

represented about 14 percent of the 2006/2007 international enrollment, up 1.5 percent from the previous year.[18]

However, despite the overall increase in international student enrollment and in engineering enrollment by international students, the IIE data showed a continuing *decrease* in international student enrollments in computer and information sciences. These dropped by about 40 percent from 2003/2004 through 2006/2007. In 2003/2004, about 10 percent of international students (57,739 students) were enrolled in computer and information sciences; by 2006/2007 this had fallen to 5.7 percent (33,437 students).[19] Because computer science departments rely heavily on foreign graduate students, this decrease can have a large impact on computer science degree production.[20]

With respect to graduate education, the Computing Research Association's (CRA's) analysis of National Science Foundation (NSF) data on first-time, full-time graduate student enrollments in computer science showed a large drop in foreign student enrollments, from 6,500 students in 2001 to about 4,300 students in 2003. There was a small decline to about 4,000 students in 2004, then a small rise in 2005 to just over 4,500 students. Throughout this period, the number of foreign graduate students exceeded the number of U.S. graduate students in computer science: U.S. student enrollments rose from about 2,500 in 2001 to about 4,000 in 2003 and then declined to about 3,500 in 2005.[21]

Attracting talented, foreign-born students and retaining them after they graduate are important goals for enabling continued technology entrepreneurship, business formation, and job creation. As noted in Chapter 1, for at least 25 percent of U.S. engineering and technology companies started between 1995 and 2005, at least one key founder

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[18]See Institute for International Education, 2007 data tables and summaries, available at http://opendoors.iienetwork.org/?p=113743; accessed December 11, 2007. See Institute for International Education, *Open Doors 2007: Report on International Education Exchange,* New York, N.Y., 2008.

[19]See the IIE *Open Doors* report statistics by field of study tabulated in Jay Vegso, "Continued Drop in Foreign Total Enrollment in CIS," *CRA Bulletin,* November 12, 2007, available at http://www.cra.org/wp/index.php?p=130; accessed January 2, 2008.

[20]In 2004, over half of doctoral degrees and over 40 percent of master's degrees in the field of computer science were earned by foreign students. Fields that enjoyed growth in foreign student enrollments from 2005/2006 to 2006/2007 included intensive English language (30.0 percent increase), mathematics and statistics (12.3 percent increase), health professions (4.3 percent increase), physical and life sciences (3.4 percent increase), and business and management (2.7 percent increase). See Jay Vegso, "Continued Drop in Foreign Total Enrollment in CIS," *CRA Bulletin,* November 12, 2007, available at http://www.cra.org/wp/index.php?p=130; accessed January 2, 2008.

[21]Computing Research Association, "First-Time, Full-Time Graduate Enrollment in CS by Citizenship," available at http://www.cra.org/wp/index.php?p=120; accessed February 20, 2008.

was born outside the United States. In 2005, these immigrant-founded companies (about 80 percent of which were in the fields of software and innovation and in manufacturing-related services) produced $52 billion in sales and employed 450,000 people.[22] Yet an equally important goal will be to attract a larger share of U.S. citizens to advanced study in the field, as opportunities increase for foreign students to pursue information technology research and development in their own and other parts of the world.

Financial Scandals and Bankruptcies (December 2001)

Enron Corporation was a leading U.S. energy company that went spectacularly bankrupt in late 2001 after claiming revenues of $111 billion in 2000. Its bankruptcy and the subsequent criminal charges brought against company executives, as well as other highly publicized failures such as that of WorldCom, led the U.S. Congress to respond with the Sarbanes-Oxley Act of 2002, informally referred to as SOX.[23] SOX established new standards for boards, management, and accounting firms of U.S. public companies with respect to the visibility of and responsibility for the financial dealings within such companies. In the wake of the passage of SOX, U.S. public companies have faced significant new requirements for implementing and assessing internal controls over financial reporting. Section 404 in particular (pertaining to the certification of the integrity of the financial control structure of a firm) has proven disproportionately costly for young IT companies relative to their limited resources, imposing new costs on venture firms that seek to pursue an IPO.[24]

Various efforts have been advanced to propose modifications to SOX. These include reforms under consideration by the Securities and Exchange Commission (SEC) and other efforts to relax some of the most disproportionate aspects for IT start-ups pursuing an IPO. Whether the SEC reforms or others will go as fast or as far as members of the IT industry hope is uncertain.[25] A secondary concern, more subtle to detect but

[22]Vivek Wadhwa, AnnaLee Saxenian, Ben Rissing, and Gary Gereffi, "America's New Immigrant Entrepreneurs," Duke Science, Innovation, and Technology Paper No. 23, January 4, 2007, available at http://ssrn.com/abstract=990152; accessed December 26, 2007.

[23]The official name of the Sarbanes-Oxley Act of 2002 (Public Law 107-204, 116 Stat. 745) is the Public Company Accounting Reform and Investor Protection Act of 2002.

[24]Section 404 of SOX requires company management and an external auditor to report on the adequacy of the company's internal controls on financial reporting; compliance requires extensive compliance documentation and testing of financial systems and controls. For a summary of a survey on the costs of SOX compliance, see http://fei.mediaroom.com/index.php?s=43&item=204; accessed May 1, 2008.

[25]See Sean Wolfe, "Sarbanes-Oxley Lite," *Red Herring*, January 10, 2007.

with potentially deeper consequences over time, is that over time, boards of directors and the corporate culture that they inspire in these young, small IT companies may shift their primary emphasis on innovation and entrepreneurship to one of regulatory compliance.[26]

Surviving After the Bubble Burst (2001-2004)

Following the bursting of the investment bubble, the eruption of financial scandals, and the spectacular bankruptcies, firms' focus turned both to cost cutting and to regulatory compliance. For fledgling IT start-ups, the most urgent issues involved survival and prospects for going public. For larger firms, cash conservation became far more important. IT budgets gave priority to compliance projects such as fraud detection, internal controls, risk assessment, regulations, and conforming with legislation on corporate governance.[27] Boards became concerned with personal liability and saw a significant increase in their board duties. For many segments of the IT industry, this was the first period of prolonged spending cuts. (By contrast, firms offering compliance systems faced increasing demand.) Spending by telecommunications carriers on equipment in the United States dropped sharply between 2000 and 2003 (from some $52 billion to $20 billion) and has only slowly increased through 2006 (to just over $24 billion).[28] Similarly, growth in data-center equipment such as high-end servers stalled and moved into negative territory. Not all IT segments shrank, and IT spending as a whole grew, albeit at a far reduced pace and according to a substantially altered spending portfolio allocation (for example, companies began to spend more on compliance and control systems to help them meet regulatory requirements, sometimes at the expense of R&D and other longer-term investments).

[26]See Tom Perkins, "The 'Compliance' Board," *Wall Street Journal*, March 2, 2007. A former board member of the Hewlett-Packard Company, Tom Perkins advocated the "guidance board" over the "compliance board" in this op-ed piece.

[27]In addition to SOX, this legislation includes the Bank Secrecy Act/Anti-Money Laundering Laws. The Currency and Foreign Transactions Reporting Act, 31 U.S.C. Sections 5311-5330 and 12 U.S.C. Sections 1818(s), 1829(b), and 1951-1959, also known as the Bank Secrecy Act (BSA), and its implementing regulation, 31 CFR 103, constitute a tool that the U.S. government uses to fight drug trafficking, money laundering, and other crimes. Other laws also provide tools to prevent money laundering. See *Bank Secrecy Act/Anti-Money Laundering: Comptroller's Handbook,* September 2000, available at http://www.occ.treas.gov/handbook/bsa.pdf; accessed October 19, 2007.

[28]"Telecommunications Industry Association 2007 Industry Playbook," p. 4, available at http://www.tiaonline.org/gov_affairs/policyplaybook2007.swf?/policy/policyplaybook2007.swf; accessed March 7, 2008.

The emphasis on cost reduction over growth investments fueled interest in offshoring and outsourcing.[29] For the first time, even young start-up companies in Silicon Valley had to consider these strategies, despite their lack of the infrastructure that larger companies had for managing offshore functions such as R&D.

The Recovery (2005-2007)

The shocks to the IT R&D ecosystem eventually gave way to gradual recovery, beginning in 2005 and continuing through 2007.[30] This recovery has positive attributes. IT budgets are growing globally, consistent with the generally positive economic climate. The enterprise market is no longer the main driver of IT innovation. The consumer market had certainly been important during the bubble period, but during the recovery consumers often became the dominant force, driving IT advances in many segments such as multimedia, social networking, gaming, cellular telephones, personal computers, and even automobiles. Venture capital funding was on the rise through 2007. Yet valuations remain modest, and the concern for cash conservation and sound business models remains strong. Good start-up companies generally reach successful milestones for merger and acquisition (M&A) or IPO.

At the same time, there are important differences between today's environment and the rather unique period of a decade ago. The sources of innovation are more diverse. They include the United States *and* other large markets in Europe and Asia. They include consumers in addition to suppliers and enterprise customers.[31] The importance of consumer markets has continued to grow, especially in new or growing segments such as multimedia, social networking, games, cell phones, personal computers, and even automobiles. Start-up investments by venture capitalists are equally diverse. A majority of the large funds that formerly operated only in Silicon Valley now have offices in Israel, India, and China. Many of the same funds that chose to diversify their investments on the basis of

[29] *Offshoring* is the practice of moving work to developing nations. *Outsourcing* is the practice of purchasing work that was formerly done in-house from an outside vendor.

[30] As this report was being prepared for publication, the effects on venture-funded and other entrepreneurial enterprises from downturns in the housing and credit markets and the economy as a whole were just beginning to be reported. See for example, Matt Richtel and Brad Stone, "Economy Has Become a Drag on Silicon Valley," *New York Times,* April 9, 2008, available at http://www.nytimes.com/2008/04/09/technology/09silicon.html?ref=technology; accessed April 9, 2008.

[31] For a discussion of the trend toward application- and process-oriented innovation initiated by customers, see David Moschella, *Customer-Driven IT,* Harvard Business School Press, Boston, Mass., 2003.

geography are also diversifying across new sectors such as "clean" technology. As a result, while the total amount of venture capital raised and invested is almost identical today to what it was 10 years ago, a materially lower percentage is for U.S.-based IT investments, particularly if one takes into account dollar currency erosion.

Another phenomenon associated with the 2005-2007 recovery was the rapid rise of private equity.[32] Inexpensive debt instruments have made possible large recapitalizations. Even large companies may find this possibility appealing. In the fall of 2006, for example, Freescale Semiconductor agreed to be acquired for approximately $18 billion by a consortium of private equity firms led by the Blackstone Group. The size of this transaction signaled that virtually any IT company is within the reach of private equity interests, if valuation warrants it and sufficient credit is available to finance such large acquisitions. Although merger and acquisition transactions rose dramatically, the pace of technology IPOs has been rather sluggish. These two trends have changed the expectations of IT entrepreneurs. It is unclear yet whether those entrepreneurs choosing to build companies for a short, independent run before acquisition, rather than with a goal of creating independent companies sustainable over the long run, will produce the same kind and quality of innovation as long-run, entrepreneurial companies did in the past. It is also unclear whether the steps taken by private equity investors as they restructure the firms that they acquire will benefit users in the long run and contribute to strengthening or weakening the IT R&D ecosystem.[33]

THE EVOLUTION OF TECHNOLOGY PLATFORMS

The combination of hardware structures, system software, and applications software that together deliver an important foundational set of IT capabilities is often called a *platform*. Important examples today include Web 2.0 capabilities that deliver today's interactive Web sites, the Windows family of operating systems, the Intel x86 instruction set (with implementations also available from Advanced Micro Devices [AMD] and other vendors), and the combination of open-source software (Linux, the Apache Web server, MySQL, and PHP-Perl-Python) used to run dynamic Web sites and commonly known as LAMP, for the four software components that contribute to the platform.

These platforms have been a critical area of IT innovation over the decades. Box 3.1 describes the evolution of major computing platforms up

[32]Dana Cimilluca, "Private Equity Fuels Record Merger Run," *Wall Street Journal*, July 2, 2007.

[33]Ben Worthen, "Is Private Equity Good for Tech Users?" *Wall Street Journal*, June 25, 2007.

to the mid-1990s. The rest of this section describes the major IT platforms of the past decade. Notably, Web services and open-source community development have changed the fundamental nature of software, while wireless network connectivity, mobility and portability, and the emergence of power as a critical resource to manage have significantly affected the prevailing hardware designs.

BOX 3.1
The Evolution of Information Technology Platforms (1960s to Mid-1990s)

- *1960s and 1970s*. Mainframe computers and their software systems dominated. A platform shift from batch to time-sharing occurred, driven by new applications such as online airline reservations, while machine resources were shared across a larger user community. Technology advances made it economical to provide scaled-down "mini-computers" to work groups such as engineering teams for whom dedicated access could be justified.
- *1970s and 1980s*. The microprocessor yielded a shift to personal computers (PCs) and engineering workstations, delivering functionality and performance at a price that could be justified for an individual. The single-user nature of these machines affected the dominant operating systems, such as Disk Operating System (DOS) and UNIX, as well as the kinds of user applications (for example, word processing, spreadsheets, circuit design, and mechanical design). Ethernet advanced the client-server model, in which users' computers communicated to back-end "servers" for storage, mail, and printing services on a local area network (LAN).
- *Mid-1980s and early 1990s*. Multiprocessor systems emerged for high-end transaction processing and fault tolerance. These were often used for the server side of high performance database systems. At the client-machine level, "WIMP" interfaces—Windows, Icons, Menu, Pointing Device—became pervasive.[1] Routers and switches extended LAN technology and enabled the expansion of the National Science Foundation Network (NSFnet). Enterprise software, first in the form of relational database systems and later in the form of software tailored to perform particular enterprise functions and industry sectors, emerged as major IT platform elements. PC software also evolved, with programs for graphical design and page layout.
- *Mid-1990s*. The major platform shift was the emergence of the commercial Internet. This development was driven by the underlying network equipment as well as by new end-user functionality delivered to client-side Web browsers from server-side Web servers, using the protocol architecture of the World Wide Web. New services rapidly emerged for Web directories, Internet search, e-commerce, and auctions.

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[1] See, for example, Thierry Bardini, *Bootstrapping: Douglas Engelbart, Coevolution, and the Origins of Personal Computing,* Stanford University Press, Palo Alto, Calif., 2000.

As platforms evolve, the established IT leaders are presented with both new opportunities and new challenges.[34] Of particular note is that leadership in the definition of new platforms has implications not only for the firms that participate in that definition but for the wider IT sector. IT products and services generally become commoditized over time as multiple firms acquire the know-how to supply similar, competing products; such competition has benefits in terms of lower prices for goods and services. Pressures from lower costs overseas for labor and other essentials thus require that to maintain leadership—or even a strong position—in IT, U.S. firms must constantly focus on achieving high-value innovation as a foundation for developing noncommodity products and services.[35]

Basic research support can play an important role in enabling platform leadership. For example, NSF support for work at the National Center for Supercomputing Applications (NCSA) at the University of Illinois provided the United States with an early lead in Web browser and server technologies, even though the initial Web implementation was at a European research laboratory.

Baseline: Web 1.0 Platform

The year 1995 brought together the World Wide Web (WWW), the Mosaic Web browser, and the commercialized Internet. From this confluence flowed the first generation of Web applications.[36] The so-called Web 1.0 consists of the WWW protocol stack for the exchange of Web pages between servers and browsers, and the first generation of Web sites. Pages are described in Hypertext Markup Language (HTML) and transported between servers and clients by Hypertext Transport Protocol (HTTP). HTTP is constructed on top of the Transmission Control Protocol/Internet Protocol (TCP/IP) protocol stack originally developed for the Advanced Research Projects Agency Network, or Arpanet. Pages are identified by way of a Uniform Resource Locator (URL).

Despite their genesis in university research laboratories, the Web 1.0 services quickly shifted from those for researchers and scientists to those

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[34]For an analysis of approaches to building platform leadership including those used by Google and Qualcomm, see Annabelle Gawer and Michael A. Cusumano, "How Companies Become Platform Leaders," *Sloan Management Review* 49(2):28-35, Winter 2008. See also Timothy Bresnahan and Shane Greenstein, "Technological Competition and the Structure of the Computer Industry," *Journal of Industrial Economics* 47(1):1-40, March 1999.

[35]See National Research Council, *Renewing U.S. Telecommunications Research,* The National Academies Press, Washington, D.C., 2006, p. 58, for a discussion of commoditization and its effects in the telecommunications sector.

[36]See "10 Years That Changed the World," available at http://www.wired.com/wired/archive/13.08/intro.html; accessed October 29, 2008.

BOX 3.2
Google: An Example of Growing from Research to Global Brand, Building on Scalable Infrastructure

In 1998, Google handled 10,000 search queries per day from a “server farm” located in the dormitory room of Larry Page, computer science graduate student at Stanford University. Today, Google has 15,000 employees, diverse products, annual revenues of $15 billion, a market capitalization of more than $150 billion, and is a verb. Google’s story illustrates the critical nature of university research for start-ups and the huge difference that individuals make in the trajectory of a start-up.

Larry Page and his Google cofounder Sergey Brin were research assistants at Stanford contributing to the National Science Foundation’s Digital Library Initiative. Search was a natural component of this effort. Web search was not new. But Page and Brin had a new idea for improving search quality: the PageRank algorithm that weights Web page importance by the number and importance of other Web pages that link to it.

Google was incorporated in late 1998 when Page and Brin received a $100,000 investment from Sun Microsystems cofounder Andy Bechtolsheim. Bechtolsheim had once been a Stanford graduate student as well: he designed the Sun Workstation under the supervision of Professor Forest Baskett, supported by the Defense Advanced Research Projects Agency (DARPA) VLSI Project. (It ran the University of California, Berkeley, UNIX operating system, engineered by Berkeley computer science graduate student and Sun Microsystems cofounder Bill Joy under the supervision of Professors Domenico Ferrari and Bob Fabry, also supported by DARPA.) Page and Brin were introduced to Bechtolsheim by Stanford computer science Professor David Cheriton, who had previously cofounded Granite Networks (high performance networks) and Kealia (high performance servers) with Bechtolsheim. The PageRank patent is held by Stanford and licensed to Google.

focused on consumers. Web “properties” (see below) are the Web sites that are popular among the growing user community in terms of average visits by visitor, number of unique visitors, and other metrics (see Box 3.2 regarding the transition of Google from a government-funded research project to a multibillion-dollar-per-year Web property).

Web Browser, Web Server, and Portals

The historical role of university developers and researchers in creating Web technologies, services, and applications is remarkable. The Mosaic Web browser developed at NCSA was commercialized as Netscape Navigator in late 1994, achieving a memorable initial public offering in August

1995.[37] The browser was freely available for evaluation, although commercial users needed a for-fee license. Navigator pioneered support for dynamically rendered Web pages, providing extensions to HTML and HTTP that provided useful new functionality (albeit sometimes ahead of formally adopted standards).

Navigator's market success triggered a response from Microsoft: Internet Explorer. Starting with the same (publicly available) code base developed at NCSA, Microsoft developed a sequence of versions that ultimately surpassed Navigator in technical sophistication and reliability—especially for Web pages with dynamic content and complicated rendering. Again, the business model was free software for consumers and licenses for commercial use. By 1998, Netscape surrendered in the "browser wars" marketplace competition with Internet Explorer, releasing its code as open source. This in turn gave birth to the Mozilla (later Firefox) browser and its own post-2004 competition with Internet Explorer.

NCSA also developed the early Web server Hyper Text Transfer Protocol Daemon (HTTPd), which Netscape likewise commercialized. Starting with the same code base, a group independently developed the Apache Web server as open source in 1995.[38] A widely used Web applications stack is based on the open-source operating system Linux, the Apache Web server, MySQL (open-source data management), and PHP-Perl-Python (a scripting language for program-driven dynamic Web page behavior), known as LAMP.

Netscape attempted to transition from being a software company to being a "content" company by becoming a *portal*—a collection of Web-based services such as user forums, e-mail, shopping services, news, Web directories, Internet search, messaging, and, more recently, Web logs (blogs) and telephony services (Voice over Internet Protocol). Popular Web sites typically provide a portal front end to back-end Web services.

Directories and Search

With the growth in WWW pages, finding information became a major need. "Jerry's Guide to the World Wide Web," the hierarchical directory

[37] See Audris Mockus, Roy T. Fielding, and James D. Herbsleb, "Two Case Studies of Open Source Software Development: Apache and Mozilla," in *Perspectives on Free and Open Software,* Joseph Feller, Brian Fitzgerald, Scott A. Hissam, and Karim R. Lakhani, eds., MIT Press, Cambridge, Mass., 2005.

[38] For a history of Apache, see Audris Mockus, Roy T. Fielding, and James Herbsleb, "A Case Study of Open Source Software Development: The Apache Server," *Proceedings of the 22nd International Conference on Software Engineering,* Association for Computing Machinery, 2000, pp. 263-272, available at http://opensource.mit.edu/papers/mockusapache.pdf; accessed December 27, 2007.

originally behind Yahoo!, was first compiled in 1994 by two Stanford University graduate students, Jerry Yang and David Filo.

A *Web directory* is a page with organized links to other pages. Editors typically create such directories, or authors can create entries themselves. Alternatively an automatic crawl of the Web can construct a directory. *Web crawlers* follow links within found pages to find subsequently reachable pages. These are analyzed for words and phrases that were used to locate the page. Search engines use a *Web index* to identify pages that match a particular user's search criterion.

Early Web crawlers, circa 1993, included Wanderer (developed at the Massachusetts Institute of Technology) and Aliweb (developed at the European Organization for Nuclear Research), both of which constructed limited indexes. WebCrawler (developed at the University of Washington in 1994) is considered the first to offer full-text search.[39] Infoseek and Lycos (developed at Carnegie Mellon University) soon followed. Infoseek supported more complex Boolean searches. It was acquired by the Walt Disney Company in 1998 and was used by Go.com.[40] Lycos, which started as a Web search site, evolved into Terra Lycos, an advertising-supported Web portal.

The next wave of Web crawlers included AltaVista (from Digital Equipment Corporation [DEC]) and Excite (created by students at Stanford University). AltaVista was notable for the way that it implemented fast Web crawling and used multiprocessor hardware to handle the growing scale of search. Excite combined search services from Magellan and WebCrawler, and was the search back end for Netscape, Apple, and Microsoft. Excite also moved into portal services, ultimately being acquired by the ISP@Home to form Excite@Home in 1999.

The Web searchers Dogpile, Inktomi (developed at the University of California, Berkeley), and Ask Jeeves emerged in 1996. Dogpile was a *metasearcher,* combining the results of other search engines. Inktomi used a cluster-based server architecture to improve search quality while maintaining high throughput. Ask Jeeves (now Ask.com) focused on an easy-to-use natural language system.

Google (developed at Stanford University in 1998) also exploits underlying cluster computing technology to achieve scale in processing. The system's PageRank algorithm ordered matching pages by their importance, defined as a function of how many other pages refer to the page

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[39]WebCrawler was the search engine acquired by America Online (AOL) in 1995, in turn by Excite in 1997, and finally by InfoSpace in the wake of Excite's bankruptcy in 2001.

[40]To illustrate the complex heritage of Web search products, Infoseek's enterprise search product was sold to Inktomi Corporation in 2000, which in turn was sold to Verity in 2002 prior to Inktomi's acquisition by Yahoo!

and their importance in turn. While the search engine Overture pioneered the technology of ad placement and the revenue model of advertising-supported Web search, Google's popularity turned ad placement into a lucrative revenue source. Ad placement is a formidable technology challenge, requiring in response to a search term that large numbers of advertisers bid—in real time—for placing their link on a user's results page. It represents a vibrant research area at the confluence of information technology and economics.

Yahoo! has assembled its current search service from Inktomi and Overture. MSN Search depended on other providers for search, particularly Inktomi until 2004, when it switched to its own service MSN Search. Windows Live Search débuted in 2006.

The Emergence of Web Properties

Beyond search and portals, Web 1.0 led to further categories of Web services. E-commerce sites such as eBay and Amazon.com are the most iconic, but there are many, many more. In September 1995, eBay started as an electronic auction site named AuctionWeb. An eBay innovation is its reputation system: sellers and buyers rate each other at the end of the auction. To simplify the process of paying for auctions, eBay acquired PayPal, a Web service that plays the role of a financial intermediary able to maintain the anonymity of buyers and sellers. eBay collects revenues from a complex fee structure related to the nature of the item listing and the final price of the auction.

Amazon.com was founded in 1994 and launched in July 1995 to sell books online. Amazon.com combines buyer information with collaborative filtering to suggest further products of interest to the buyer. Amazon.com also presents user reviews and allows users to rate the reviewers. Many other firms have also developed a wide array of e-commerce services and capabilities.

Amazon.com is particularly interesting as it also "powers" the electronic stores of other Web sites by providing interfaces to its services infrastructure. Amazon.com Web Services is constructed from underlying services for scalable virtual servers, reliable network storage, message linking across processing and networks, comprehensive Web site traffic data, catalogs and electronic commerce, and historical pricing information.

Evolution: From Web 1.0 to the Web 2.0 Platform

This subsection reviews the rise of Web 2.0, a second generation of Web-based technology, services, and applications that began to emerge in the time frame of the early 2000s.

Defining Web 2.0

Web 2.0 is characterized by community-contributed and community-managed content, existing in many forms: user-contributed postings and comments; user-produced videos, indexed by user-supplied tags and augmented by comments and ratings by other users; social networking, with community formation for communications and sharing information; and photo- and link-sharing services.[41] Publishers' reaching a community that consumes and enhances content is an enabling element. The network is the platform for delivering content to applications that run inside a Web browser. In Web 2.0, the community owns and exercises control over the site information and can use programmable frameworks to make that content dynamic. Users extend the content, labeling it, rating it, and ranking it, thus providing the "social" in social networking. Contrast this with traditional media, with controlled authorship, and proscribed user enhancement of content.

Web 2.0 Platform Elements

The underlying technology for Web 2.0 enables Internet-based applications, accessible through the user interface provided by a Web browser, to customize pages for individual users. For example, Ajax (Asynchronous JavaScript and Extensible Markup Language [XML]) is a Web development framework used to create modern interactive Web applications. JavaScript adds an interpreted programmatic functionality to XML, a content format-specification language. The result is dynamically rendered, content-sensitive Web pages. Other programming frameworks such as Perl, Python, Ruby on Rails, and Adobe Flex provide similar capabilities using different linguistic paradigms and platform building blocks. Each has its adherents and advantages, but the effects are similar: Move your mouse over a page-rendered map to display a floating palette of links to content about that location. The Asynchronous Web browser/Web server protocol extensions enhance responsiveness through background communications that obviate the need to reload an entire Web page when a user action induces a change. Google, for example, provides an Ajax application programming interface (API) to permit individual Web pages to include a search bar. The page provides a context-dependent gateway into the Google back end.

[41]See Tim O'Reilly, "What Is Web 2.0," September 30, 2005, available at http://www.oreillynet.com/pub/a/oreilly/tim/news/2005/09/30/what-is-web-20.html; accessed July 3, 2007. Note that "Web 2.0" is sometimes used to refer to the introduction of greatly increased interactivity into Web sites.

Pervasive Composition in Web 2.0

Web 2.0 applications construct new applications from existing protocols, services, and Web sites. For example, Really Simple Syndication (RSS) is a protocol used to implement content publication by way of "feeds" to distribute news, blogs, podcasts, and other digital media. Reader applications allow users to subscribe to particular feeds, view newly available content, and display selected items. As another example, mashups illustrate the power of composition within Web service architectures: a *mashup* is a kind of Web application that uses the existing Web services frameworks to compose a new Web site from existing sites that support the necessary access APIs.

Case Study: Facebook as a Platform

Facebook, a popular social networking Web site that traces its history to 2004, offers a case study of how modern Web applications exploit pervasive composition to create a new platform for application development that gives rise to a new ecosystem. Facebook's essential structure is the social graph, associating with each user those other users to whom that person is related as a friend or participant in a common group. Applications are constructed around the social graph. For example, when a user changes his or her status (e.g., indicating "I'm in the library now," posting new photos, and so on), the change appears in the news feed of all of the user's friends.

Growing at the rate of 100,000 new users per day, in mid-2007 Facebook opened its internal applications development platform to third parties.[42] It allows developers' applications to access entry points in the Facebook page and to access Facebook-managed information such as user profiles, friends, photos, and event data. When a user clicks in the appropriate area of a Facebook-rendered page, a remote server deployed and managed by the application developer is invoked to process the request, compute a response, and transmit the result back to Facebook. To incentivize developers, Facebook allows them to share in the site's advertising revenues.

Significant Trend: The Rise of Open Source

Community-based development existed before 1995, although the academic and research communities were the most common users of the

[42]See "Facebook Developers Documentation," available at http://wiki.developers.facebook.com/index.php/Main_Page; accessed October 10, 2008.

resulting software. From 1995 on, community development accelerated greatly, and the resulting software became commonly deployed in services and systems accessible by large user communities over the Internet.

What Is Open Source?

Open source makes a program's source code readily available to a developer community, with specific restrictions regarding intellectual property rights. Open-source projects may be overseen by an implementer-in-chief, a small committee of developers and/or editors, or even more democratic mechanisms. The relevant intellectual property regimes cover a wide range, from those that restrict the commercial sale of software incorporating open source to those that allow commercialization. Such software is not necessarily free. However, the business model most commonly used is based on charging for the support, packaging, and customization of the software rather than for the software itself.[43] In the context of Web-based services and applications, open-source community development is the norm. LAMP[44] is an example of an application environment founded on open-source components.

Implications for the Software Industry

Some traditional software firms have responded to the rise of open source by embracing it. As an example, IBM now supports a form of open source for its Web-based products. IBM's Websphere middleware architecture is a set of services for Web-based applications, incorporating open-source components such as Linux, Apache Web server, and Java. In 2005, IBM released Websphere Application Server Community Edition (WAS CE) as open source. WAS CE prepackages commonly needed open-source components, providing a platform within which IBM's other proprietary components could be added. Although the software itself is available free of charge, technical support is by fee.

IBM spearheads Eclipse, a community effort to create an integration environment for software tools for Java and Web services development. Its focus is on enabling the interoperation of tools from a large vendor

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[43]Copyrighted open-source software (and some open-source software that is in the public domain) can be licensed using a variety of mechanisms. See, for example, Andrew M. St. Laurent, *Open Source and Free Software Licensing,* O'Reilly Media, Sebastopol, Calif., 2004; and Lawrence Rosen, *Open Source Licensing: Software Freedom and Intellectual Property Law,* Prentice Hall PTR, Upper Saddle River, N.J., 2004.

[44]See Dale Dougherty, "LAMP: The Open Source Web Platform," January 26, 2001, available at http://www.onlamp.com/pub/a/onlamp/2001/01/25/lamp.html; accessed October 4, 2007.

community. To induce tool vendors to integrate with Eclipse, IBM provides visibility into its APIs and its underlying tool integration services. Open source helps third parties verify that there are no special trapdoors or APIs that give IBM's tools any advantage over their own. In return, IBM creates a highly functional environment for software creation, leveraging third-party tools for Java and its own Web services model, to attract applications developers. This approach is viewed as a critical response to Microsoft's proprietary .NET Framework.[45]

Significant Trend: The Emergence of Mobile and Data-Center Platforms

The major hardware trends of the 1995-2007 period are the following: on the Web access side, the rise of mobile devices; on the Web services side, the concentration of back-end processing into Internet data centers. This subsection reviews some of the dominant hardware trends in both.

Central Processing Units

Intel x86 instruction set processors, with implementations also available from AMD and other vendors, have become dominant. Introduced in the late 1970s and powering the original IBM PC, the Intel x86 has driven the information technology industry to new levels of price and performance. They are now the basis for virtually all PCs, whether server, desktop, laptop, or processor cluster. A number of variations have been introduced, some optimized for high performance (the "extreme" category—suitable for use in high-end servers), others designed for good performance at lower power (the "value" category—driven primarily by the demand of laptops for long battery life), and a third category seeking a compromise between the two (the "mainstream" category—such as for standard desktop PCs). Higher levels of performance have been achieved through higher processor clock rates made possible by shrinking semiconductor process feature sizes and scaled voltages. Through architectural cleverness, instruction-level parallelism makes it possible to issue more than one instruction per clock cycle if the instructions do not require the same machine resources. The challenges of cooling advanced processor chips have precipitated a fundamental shift to achieving higher performance through multicore architectures rather than faster clocks. How best to harness multicore processors to achieve higher levels of performance,

[45]For a more detailed discussion, see Marc Erickson and Angus McIntyre, "What Is Eclipse, and How Do I Use It?" November 1, 2001, available at http://www.ibm.com/developerworks/opensource/library/os-eclipse.html; accessed July 3, 2007.

particularly for desktop rather than server processing, remains a research challenge.

Handheld Devices

Early attempts at creating convenient handheld devices met limited success. The Apple Newton offers one such example. These tended to be proprietary devices, with limited connectivity and programmability and with narrow functionality. The first broadly successful handheld was the Palm Pilot, introduced in 1995. Keys to its success were its shirt-pocket size, long battery life, one-touch PC synchronization, intuitive user interface with personal organizer functionality, simplified writing recognition, instant power on, and a simple programming environment that attracted a developer community to enrich and extend the platform.

Following the first "organizer"-oriented devices, Apple introduced the iPod, which became the most successful consumer-oriented digital media player; Research in Motion, its Blackberry device, initially focused on e-mail; and Palm, its Treo smartphone. Apple's recent introduction of the iPhone is illustrative of the evolution of the handheld device from a specialized gadget to a broad-based mobile computing platform. The new handheld platforms are characterized by the following: modern operating systems supported by a diverse community of application developers; rich wireless connectivity, incorporating multiple radios with transparent roaming to enable ubiquitous network computing; full participation in consumer and business-oriented Web-based services; and being deeply embedded in consumer environments.

Multiple countries contribute to this environment: China produces and consumes more mobile phones than any other country, Korea provides the best and fastest broadband wireless connectivity, Europe and Japan lead the world in using consumer mobile services, while the United States leads in smartphones and business mobile services.

Internet Data-Center Architecture

The Internet data center has emerged as a new platform for providing scaled-up processing, memory, and storage resources to support the network applications used by billions of clients. *Internet data centers* are building-scale computing systems, containing vast numbers of processing clusters and storage servers. Major Web properties and many large enterprises use Internet data centers in one form or another. The ancestor of the data center is the Web hosting facility that came into being in the late 1990s. These facilities provide Web site operators with compute cycles and data storage for rent, on which they can deploy their Web servers and applications. Resources can be shared or dedicated, with trade-offs between performance, security, reliability, and cost. Hosting facilities are purpose-built, with power and cooling sufficient to support a large number of machines within the building.

Most Web properties began by placing their own processing clusters within third parties' facilities. But rapid growth, coupled to a shakeout of hosting facility operators following the bust in 2000, led to a shortage of space at hosting facilities. This led firms into designing their own building-scale computer facilities, integrating processing, storage, internal and external networking, along with integral power and cooling infrastructures. The resulting data centers typically deploy 100,000 to 1 million computers within a single facility.[46]

The total power budget of an Internet data center must consider the demands of the power distribution system itself and the air conditioning systems needed to transfer the heat generated by the equipment as it consumes power. Efficient utilization of data-center resources, considering power as a critical resource to be managed, is critical in data-center design.

Mobile Applications and Communications Platforms

Users demand high performance Internet access from their mobile devices. Access is achieved either by way of packet data over the cellular telephone system or by access over wireless local area networks (WLANs). Third-generation cellular networks are the current state of the art. They are available throughout the United States and the rest of the world. Pre-third-generation data services provided 64 kilobit per second (kbps) circuit-switched data and 384 kbps packet-switched data. This data rate is insufficient for media-rich Web page and application delivery to mobile devices. EDGE—Enhanced Data Rates for GSM (Global System for Mobile communications) Evolution—is an interim method for higher data rates. It is widely available in the United States, achieving up to 236.8 kbps (and a maximum of 473.6 kbps if twice as many slots are used for data encoding). Evolved EDGE is a next-generation technology that uses more advanced encoding methods to increase data rates up to 1 Mbps.[47]

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[46]"Down on the Server Farm," *The Economist*, May 22, 2008, available at http://www.economist.com/displayStory.cfm?source=hptextfeature&story_id=11413148; accessed October 10, 2008.

[47]For more information, see Wikipedia, "Enhanced Data Rates for GSM Evolution," available at http://en.wikipedia.org/wiki/Enhanced_Data_Rates_for_GSM_Evolution; accessed July 31, 2007. See also "GSM/3G Market/Technology Update: EDGE Evolution," Global Mobile Suppliers Association, December 2007, available at http://www.gsacom.com; accessed February 20, 2008.

Recent third-generation deployments include support for High Speed Downlink Packet Access (HSDPA), achieving multimegabit transmissions toward the client. Up to 3.6 Mbps peak downlink data throughput has been achieved in operational networks.[48] Some operators are now deploying High Speed Uplink Packet Access (HSUPA), which will also allow greater uplink speeds, into the multimegabit rate.[49]

The alternative is WLAN technology. The IEEE 802.11 family of standards, also known as Wi-Fi, makes use of license-free spectrum bands. Inexpensive access equipment that is commonly incorporated in laptop computers and other mobile devices placed it in the hands of many users and access points. Wi-Fi can obtain up to 11 Mbps (IEEE 802.11b) or 54 Mbps (IEEE 802.11g) access speeds, but sharing spectrum with other users significantly reduces the effective bandwidth. Wi-Fi is not a replacement for cellular data services; it supports shorter distances between the base station and terminal than that of cellular data services, cannot provide high bandwidth to rapidly moving users, and does not support handoffs across access points. Nevertheless, many inexpensive base stations can be deployed to cover areas dense with pedestrian users, such as city centers and industrial and university campuses. A new generation of IEEE 802.11—IEEE 802.11n—is undergoing the process of standardization. The target performance of the system is up to 248 Mbps, with 74 Mbps typical.[50]

Another standard, WiMAX, refers to IEEE 802.16 and was initially intended as the specification for high-bandwidth, point-to-point wireless access between fixed devices. WiMAX is also intended as a “last mile” technology to be used as an alternative to digital subscriber line (DSL) or cable connectivity to homes and offices. Interest has emerged in mobile WiMAX (IEEE 802.16e) that will provide connectivity to small access devices on the move. Access speeds of up to 70 Mbps and distances of up to tens of miles are possible, but there is a trade-off between distance to the base station and the data rates that can be achieved. User-observed access in the range of 2 Mbps is more likely.[51]

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[48] See Wikipedia, “High-Speed Downlink Packet Access,” available at http://en.wikipedia.org/wiki/HSDPA; accessed July 31, 2007. See also Global Mobile Suppliers Association survey of HSPDA and HSUPA deployments worldwide, available at www.gsacom.com; accessed February 20, 2007.

[49] More information is available at Wikipedia, “List of HSUPA Networks,” available at http://en.wikipedia.org/wiki/List_of_Deployed_HSUPA_networks; accessed July 31, 2007. See also www.gsacom.com; accessed July 31, 2007.

[50] See Wikipedia, “IEEE 802.11,” available at http://en.wikipedia.org/wiki/IEEE_802.11#802.11n; accessed July 31, 2007.

[51] Data available at Wikipedia, “WiMAX,” at http://en.wikipedia.org/wiki/WiMAX; accessed July 31, 2007.

Voice over Internet Protocol

Voice over Internet Protocol, or VoIP (also known as IP telephony) is a method for encoding voice communications using packet-switched rather than the circuit-switched techniques that are used in conventional telephone systems. Audio is sampled, digitized, and encoded into packets, which are then routed on a hop-by-hop basis to the destination, where the samples are converted back into an audio form. End devices are now powerful enough to perform this conversion processing without any specialized hardware. The Session Initiation Protocol (SIP) has been standardized to establish connections between call originators and destinations. Using SIP, Wi-Fi VoIP-enabled handsets can operate like mobile telephones within range of a WLAN. Cellular telephones, already or soon to be equipped with Wi-Fi access, will be able to opportunistically shift between the cellular network and WLANs, on the basis of quality and cost-of-access considerations.

THE EVOLUTION OF INFORMATION TECHNOLOGY INDUSTRY SECTORS

The information technology sector is composed of numerous products and services, perhaps the most significant of which have been semiconductors, computers, and software. This section reviews the historical evolution of these essential sectors of the information technology industry, with a focus on the developments in the 1995-2007 period. Examination of these sectors illuminates the historical sources of U.S. leadership in IT as well as the increasing role that the United States and other nations have come to play in a today's globalized IT industry.

Evolution of the Semiconductor, Computer, and Software Subsectors

Let us look first at the evolution of the industry from the perspective of its three essential subsectors: the semiconductor industry, the computer industry, and the software industry.

The Semiconductor Industry

The transistor was invented at Bell Laboratories in 1947. The technology was widely licensed, and many electronics firms quickly diversified into the industry. These firms were mostly clustered around Boston, New York, and Los Angeles. The industry was research-intensive, with continual product and process advances fueling rapid growth. Particularly in the part of Northern California soon to become "Silicon Valley," employees from some of the original firms formed successful new entrants. The first was Shockley Laboratories, formed by William Shockley, a co-recipient of the Nobel Prize in physics for the transistor. He hired eight talented scientists and engineers who in 1957 left to found Fairchild Semiconductor. Fairchild in turn suffered employee defections to new spin-offs. Many of these became industry leaders, launching the Silicon Valley cluster. Silicon Valley firms accounted for about half the output of the U.S. industry by 1980.[52]

U.S. firms initially dominated the industry. Not only did a U.S. firm invent the transistor, but the U.S. military was the largest consumer of semiconductors and a major funder of semiconductor R&D. Texas Instruments demonstrated the first integrated circuit in 1958; the same year, the U.S. Air Force incorporated semiconductors in designs for the Minuteman missile.[53] Defense and space programs rapidly became major customers. By 1963 the military accounted for nearly half of device sales, financing around 25 percent of semiconductor R&D.[54] Subsequent growth was driven by the computer industry, also based predominantly in the United States.

The first challenge to the semiconductor industry in the United States came from Japan, where the initial inroads were made by firms that pioneered transistor radios and went on to transistorize televisions and other consumer electronics products. The Japanese government negotiated technology licenses and protected domestic producers, later sponsoring industrywide projects to improve production. In the 1970s, Intel and other U.S. firms pioneered memory devices. Japanese firms excelled at their manufacture, enabling them to capture a large share of the expanding market.[55] Later the firms faced competition from established Korean firms that also became leading producers. The latter were aided by their

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[52]Steven Klepper, "Silicon Valley—A Chip Off the Old Detroit Bloc," in *Entrepreneurship, Growth, and Public Policy,* David B. Audretsch and Robert Strom, eds., Cambridge University Press, Cambridge, England, forthcoming. See also Christophe Lecuyer, *Making Silicon Valley: Innovation and the Growth of High Tech, 1930-1970,* MIT Press, Cambridge, Mass., 2006.

[53]Texas Instruments' Jack S. Kilby received the 2000 Nobel Prize in physics for his part in the invention of the integrated circuit. See also Semiconductor Industry Association (SIA), "SIA Interactive Timeline: 1958," available at http://www.sia-online.org/cs/about_sia/history; accessed October 28, 2008.

[54]Richard N. Langlois and W. Edward Steimueller, "The Evolution of Competitive Advantage in the Worldwide Semiconductor Industry," in *Sources of Industrial Leadership,* Richard R. Nelson and David C. Mowery, eds., Cambridge University Press, Cambridge, England, 1999, pp. 26-27. See also Ernst Braun and Stuart MacDonald, *Revolution in Miniature,* Cambridge University Press, Cambridge, England, 1978.

[55]Arthur L. Robinson, "Perilous Times for U.S. Microcircuit Makers," *Science* 208(4444):585, 1980.

recruiting of large numbers of expatriates from U.S. universities and Silicon Valley firms.[56]

Subsequently, U.S. firms recaptured market share in the manufacture of semiconductors, in part owing to favorable exchange rates and growing demand for microprocessors. U.S. firms improved their own manufacturing while outsourcing production to specialist producers, known as foundries. Since the 1960s, U.S. firms had assembled and tested devices in Asia.[57] In the 1980s technological and market developments enabled such Asian firms to become manufacturing specialists,[58] spurring foundries in low-wage countries such as Taiwan. Through government efforts to license process technology and transfer it to sponsored firms, Taiwan developed a vibrant industry that today ranks fourth in the world.[59] Much like Silicon Valley, its industry is composed of numerous spin-offs from incumbent firms and government efforts, concentrated in the Hsinchu Science Park. Its development was also aided by Taiwanese expatriates, many of whom had been educated in the United States and had risen up through the ranks of Silicon Valley semiconductor producers.[60]

The Taiwanese industry enabled the formation of firms specializing in integrated design in the United States—that is, "fabless" firms (i.e., companies that do not operate their own fabrication facilities and therefore can concentrate their R&D resources on design rather than on manufacturing process technologies). Fabless firms coexist with vertically integrated producers and have helped the U.S. industry maintain its prowess. U.S. firms focus on innovative product concept and design, with the manufacturing taking place in Taiwan by firms that focus on advanced chip technology and high-volume processing. The U.S. firms are concentrated in Silicon Valley and other areas with major research universities, reflecting the role that leading university research centers have played in developing new design techniques, software, and engineering talent. As of 2002, 475 fab-

[56]Richard N. Langlois and W. Edward Steimueller, "The Evolution of Competitive Advantage in the Worldwide Semiconductor Industry," in *Sources of Industrial Leadership*, Richard R. Nelson and David C. Mowery, eds., Cambridge University Press, Cambridge, England, 1999, p. 55.

[57]Ernest Braun and Stuart MacDonald, *Revolution in Miniature*, Cambridge University Press, Cambridge, England, 1978, pp. 150-151.

[58]Jeffrey T. Macher and David C. Mowery, "Vertical Specialization and Industry Structure in High Technology Industries," in *Business Strategy over the Industry Life Cycle,* Joel C. Baum and Anita M. McGahan, eds., Elsevier, Amsterdam, 2004, p. 331.

[59]John A. Matthews, "A Silicon Valley of the East: Creating Taiwan's Semiconductor Industry," *California Management Review* 39(4):26-54, Summer 1997; and Hongwu Sam Ouyang, "Agency Problem, Institutions, and Technology Policy: Explaining Taiwan's Semiconductor Industry Development," *Research Policy* 35(9):1314-1328, 2006.

[60]Hongwu Sam Ouyang, "Agency Problem, Institutions, and Technology Policy: Explaining Taiwan's Semiconductor Industry Development," *Research Policy* 35(9):1314-1328, 2006; AnnaLee Saxenian, *The New Argonauts: Regional Advantage in a Global Economy,* Harvard University Press, Cambridge, Mass., 2006.

less firms were located in the United States.[61] The next closest country in number of fabless firms was Canada, with 30 such companies.[62]

Recently the United States has specialized in more research-intensive aspects of semiconductor production, including design and the development of experimental production facilities. Semiconductor Manufacturing Technology (SEMATECH), a nonprofit consortium, was established to pursue advanced R&D in semiconductor manufacturing.[63]

U.S. firms have maintained their global share of patents, as appears to be true of the patenting activities of firms in other countries as well.[64] The leading U.S. firms date to the 1950s and 1960s and have been leading firms for many years; likewise, the leading firms from Japan and Europe have been leaders for many years. In contrast, the newcomers have appeared from South Korea and Taiwan, which now account for 3 of the top 10 firms in the world.[65] Semiconductor applications are becoming more diverse, and customers for the most advanced semiconductors are increasingly located in Asian countries, which may well enable them to move into the more research-intensive segments of the industry, posing greater challenges to the established leaders.[66]

The Computer Industry

As with the semiconductor industry, the computer industry began principally in the United States, with the military providing early impetus

[61]Qualcomm, which has origins in university research, is the first "fabless" company to become one of the top 10 chip suppliers. See Mark LaPedus, "Qualcomm Cracks Top-10 in Chip Rankings," *EE Times,* August 8, 2007, available at http://www.eetimes.com/news/semi/showArticle.jhtml?articleID=201801923; accessed February 27, 2008.

[62]Jeffrey T. Macher, David C. Mowery, and Alberto Di Minin, "Semiconductors," in National Research Council, *Innovation in Global Industries: U.S. Firms Competing in a New World,* Jeffrey T. Macher and David C. Mowery, eds., The National Academies Press, Washington, D.C., 2008.

[63]Between 1987 and 1996, the U.S. government provided funding to SEMATECH to match industry investments. The organization subsequently was renamed International SEMATECH, with half of its current industrial participants now international semiconductor firms. See http://www.sematech.org; accessed October 30, 2008.

[64]Jeffrey T. Macher, David C. Mowery, and Alberto Di Minin, "Semiconductors," in National Research Council, *Innovation in Global Industries: U.S. Firms Competing in a New World,* Jeffrey T. Macher and David C. Mowery, eds., The National Academies Press, Washington, D.C., 2008.

[65]See Wikipedia, "Semiconductor Sales Leaders by Year: Ranking for Year 2006," available at http://en.wikipedia.org/wiki/Worldwide_Top_20_Semiconductor_Sales_Leaders#Ranking_for_year_2006; accessed July 25, 2007.

[66]Jeffrey T. Macher, David C. Mowery, and Alberto Di Minin, "Semiconductors," in National Research Council, *Innovation in Global Industries: U.S. Firms Competing in a New World,* Jeffrey T. Macher and David C. Mowery, eds., The National Academies Press, Washington, D.C., 2008.

as a customer and a supporter of research, much of it done in universities.[67] The market was unclear, and early entrants were composed of office equipment firms, electronics producers, and new entrants. IBM invested heavily in research and marketing to become the early leader. It solidified its position with the System/360, intended for broad use. The only way to compete was with compatible products, such as peripherals and software. This strategy became more feasible after IBM unbundled its software in 1970 under antitrust pressure. The Japanese government orchestrated a policy to produce products compatible with IBM's and then to surpass IBM. A number of competitive computer firms emerged, but to some degree these were hampered by their focus on a target that would soon be undermined. In contrast, European countries unsuccessfully attempted to grow national champions to compete with IBM.[68]

The development of minicomputers and then microcomputers ultimately broke IBM's stronghold in the realm of computers. Minicomputers appealed to sophisticated users who did not need IBM's technical support, enabling new firms to enter the industry successfully. The most prominent was Digital Equipment Corporation, a spin-off of the Massachusetts Institute of Technology's Lincoln Laboratory, itself a product of prior military funding. The development of the microprocessor created further opportunities; the earliest producers were new firms, such as Apple, and electronics producers. The introduction of the PC by IBM fundamentally changed the market. Its modular design, based on Intel's microprocessor and Microsoft's operating system, defined the so-called Wintel standard that has endured. It also allowed the flourishing of independent markets for components, including software, hard disk drives, displays, and other peripherals.

U.S. firms were in the forefront of many of these specialized markets and have continued to maintain their lead in such areas as microprocessors. Simultaneously, the modular design of the PC became driven by a low-technology design and assembly process in which firms primarily integrate innovations developed by high-technology component suppliers.[69] Managing the supply chain thus became more important than being

[67]See, for example, Kenneth Flamm, *Creating the Computer: Government, Industry, and High Technology,* Brookings Institution Press, Washington, D.C., 1988.

[68]Timonthy F. Bresnahan and Franco Malerba, "Industrial Dynamics and the Evolution of Firms' and Nations' Competitive Capabilities in the World Computer Industry," in *Sources of Industrial Leadership,* Richard R. Nelson and David C. Mowery, eds., Cambridge University Press, Cambridge, England, 1999, pp. 79-132.

[69]Jason Dedrick and Kenneth L. Kraemer, "Personal Computing," in National Research Council, *Innovation in Global Industries: U.S. Firms Competing in a New World,* Jeffrey T. Macher and David C. Mowery, eds., The National Academies Press, Washington, D.C., 2008.

a technological innovator.[70] Many of the U.S. PC entrants were new firms, but it was difficult for them to sustain profits. Much of the production of PCs and more recently their design have shifted to lower-cost regions, especially Taiwan, which benefited from the involvement of Taiwanese expatriates. Taiwan now has a number of branded PC and component producers with significant market shares. As of 2005, Taiwanese firms produced 85 percent of laptops sold worldwide. Much of the production of these firms now occurs in China, to take advantage of the lower costs of engineers and labor there. IBM sold its PC business to Lenovo of China. Today China is the world's largest producer of PCs.[71]

U.S. firms still dominate key component industries, such as microprocessors, operating systems, graphics, and hard drives. Asian firms are leaders in displays, memory devices, power supplies, batteries, motherboards, and optical devices. Dell, Hewlett-Packard Company (HP), Apple, and Gateway have a market share of 40 percent, but U.S. firms do little production and even hand off design to others to concentrate on product planning. In this division of labor, component-level R&D, concept design, and production planning are concentrated in the United States and Japan, applied R&D and the development of new platforms in Taiwan, and product development for mature products and nearly all production and related engineering in China. The employment of engineers is stable but not growing in the United States, whereas it is growing rapidly in Taiwan.[72] The growth in PC demand in Asia and the faster adoption of broadband and mobile telephony in some countries outside the United States, particularly Asia, may further accelerate the development of the industry outside the United States.

The Software Industry

Software is provided both by vendors, in the form of products and services, and by users. Until the 1970s, software vendors were largely computer producers—and hardware-producing companies such as IBM, HP, and Sun Microsystems continue to be software producers—but the advent of the PC stimulated the provision of products by software specialists.

[70] G. Fields, *Territories of Profit: Communications, Capitalist Development, and the Innovative Enterprises of G.F. Swift and Dell Computer,* Stanford University Press, Stanford, Calif., 2004.

[71] Jason Dedrick and Kenneth L. Kraemer, "Personal Computing," in National Research Council, *Innovation in Global Industries: U.S. Firms Competing in a New World,* Jeffrey T. Macher and David C. Mowery, eds., The National Academies Press, Washington, D.C., 2008.

[72] Ashish Arora, Chris Forman, and Jiwoong Yoon, "Software," in National Research Council, *Innovation in Global Industries: U.S. Firms Competing in a New World*, Jeffrey T. Macher and David C. Mowery, eds., The National Academies Press, Washington, D.C., 2008.

This subsection focuses on software *producers*, because software services are more difficult to measure, particularly in imports and exports.[73]

The software industry has been dominated by U.S. firms. The computer industry was concentrated in the United States when software first became unbundled from hardware. Further, the government—the military but also the National Science Foundation—has long supported computer science research, largely at universities.[74] Indeed, prior to 1965, virtually anyone who learned to "program" learned to do so as part of the Cold War era Student Achievement Guarantee in Education (SAGE) Program. Consequently, U.S. firms were well positioned to be early providers of software products, ranging from operating systems, to business and consumer applications, to Internet-related software such as browsers and search engines. The economics of the industry—large up-front investments in software development and minimal reproduction costs—have enabled successive generations of U.S. firms to develop entrenched positions in various software products, as exemplified by Microsoft in operating systems.

In Japan, concentrated government efforts have failed to create a successful international industry. In contrast, Israel, Ireland, and India have developed thriving, export-oriented software industries. Each excels in different areas. India has succeeded in software services; Israel has developed niche software products, particularly in security; and Ireland has thrived mainly as a home for U.S. multinationals to localize software products for Europe. Nonetheless, Israel, Ireland, and India share important characteristics. They have an abundant supply of English-speaking, technically skilled workers. Multinationals were either important producers of products—and as such, suppliers of experienced labor and potential founders of domestic firms—or were users of software that helped stimulate domestic firms. Furthermore, each of these countries had significant expatriate technical communities in the United States that played an important role in the formation and management of their domestic firms.[75]

[73]United States Government Accountability Office (U.S. GAO), *Offshoring of Services: An Overview of the Issues*, GAO-06-5, Washington, D.C., November 2005; U.S. GAO, *International Trade: U.S. and India Data on Offshoring Show Significant Differences,* GAO 06-116, Washington, D.C., October 2005; U.S. GAO, *International Trade: Current Government Data Provide Limited Insight into Offshoring of Services,* GAO-04-932, Washington, D.C., September 2004; and Timothy J. Sturgeon, *Services Offshoring Working Group: Final Report,* Industrial Performance Center, Massachusetts Institute of Technology, September 10, 2006.

[74]David C. Mowery and Richard N. Langlois, "Spinning Off and Spinning On: The Federal Government Role in the Development of the U.S. Computer Software Industry," *Research Policy* 25(6):947-966, 1996.

[75]Ashish Arora, Alfonso Gambardella, and Steven Klepper, "Organizational Capabilities and the Rise of the Software Industry in the Emerging Economies: Lessons from the His-

Public policy is credited with having played an important role in Ireland's success.[76] Prompted by a poor economy and extensive emigration in the 1950s, Ireland initiated a policy of luring foreign companies through incentives, particularly to attract manufacturing and service firms involved in international trade. Israel's success is widely viewed as reflecting the broader shift engineered by the government toward R&D-intensive industries, including hardware as well as software.[77] India is the exception: there, government policy was at best not harmful, and other factors such as cost advantages were more beneficial. Furthermore, patent data suggest that U.S. firms have been increasing the number of their inventions in Ireland, Israel, and India.[78] These countries have developed firms that continue to grow and seed new firms, resulting in potentially greater competition for U.S. software firms.

Common Patterns and Future Evolution

U.S. firms were early leaders in semiconductors, computers, and software. The U.S. government, and particularly the U.S. military, played a key role in their launch and early development. Government was the largest initial buyer in each industry for many years. It also funded a substantial amount of research at both companies and universities. Inevitably, government demand declined in importance as each of the industries expanded, although research support in some areas such as software, device physics, and computer architectures has persisted for 20 years or more. Yet the U.S. firms that started when government was the largest customer and the firms that emerged later have both continued to dominate worldwide well after the decline of government support.

The more labor-intensive and less research-intensive activities have moved to lower-wage countries. Often this has been aided by efforts of

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tory of Some U.S. Industries," in *From Underdogs to Tigers: The Rise and Growth of the Software Industry in Brazil, China, India, Ireland, and Israel*, Ashish Arora and Alfonso Gambardella, eds., Oxford University Press, USA, New York, N.Y., 2005, pp. 171-206.

[76]See, for example, Dan Breznitz, *Innovation and the State,* Yale University Press, New Haven, Conn., 2007; and Sean O'Rian, T*he Politics of High Tech Growth: Development in Network States in the Global Economy,* Cambridge University Press, Cambridge, England, 2004.

[77]For analysis of the effects of R&D policies in Israel, see, for example, Manuel Trajtenberg, "R&D Policy in Israel: An Overview and Reassessment," in Maryann P. Feldman and Albert N. Link, eds., *Innovation Policy in the Knowledge-Based Economy,* Kluwer Academic Publishers, Boston, Mass., 2001, pp. 409-454.

[78]The number in Israel increased from about 20 patents in 1995 to about 80 in 2004; the numbers for India and Ireland in 2004 ranged from 10 to 20 and were increasing. See Ashish Arora, Chris Forman, and Jiwoong Yoon, "Software," in National Research Council, *Innovation in Global Industries: U.S. Firms Competing in a New World,* Jeffrey T. Macher and David C. Mowery, eds., The National Academies Press, Washington, D.C., 2008.

the countries' governments to import technology from U.S. firms. The governments in Japan and Israel have been more proactive, financing new technology developments. U.S. expatriates have brought organizational experience from the United States to help establish successful firms in the latecomer countries, reinforcing those governments' efforts. U.S. multinationals have also been instrumental. Many of the latecomer countries have developed impressive firms that have moved into the leadership ranks and are in turn also seeding new domestic entrants.

Inevitably latecomer countries aspire to move into more sophisticated, research-intensive activities. U.S. firms have taken advantage of these new opportunities by increasing not only development but also research in latecomer countries. At the same time, local demand for IT products in the latecomer countries is growing, and these nations are moving into the forefront in some areas as lead users. These developments portend greater competition for U.S. IT firms in the future, while simultaneously presenting new global expansion opportunities.

National Clusters

Firms in certain industries often form in close proximity within a country to create *clusters*. A cluster develops its own dynamics, which allow it to evolve. Clusters enable superior access to specialized labor, suppliers, and information. Clusters often grow up around major research universities, and a strong cluster in turn strengthens nearby institutions like universities, which provide the cluster with trained students and technical knowledge. Cluster firms in the same line of business observe one another and compete fiercely. Complementarities also develop. In the United States, for example, Silicon Valley has not only leading semiconductor firms, but also some of the largest equipment manufacturers and design software firms. Often, a small number of "root firms" are responsible for spinning off a large number of "child firms," thereby forming clusters.[79] Rapidly developing technology creates the opportunities for the creation of new firms to continue. Thus, clusters are important parts of the overall U.S. IT R&D ecosystem.

IT is particularly interesting for the way that it has created entirely new industries and transformed old ones.[80] It is the richness and power

[79]See Steven Klepper, "Employee Startups in High-Tech Industries," *Industrial and Corporate Change* 10(3):639-674, September 2001; and Steven Klepper, "Employee Start-Ups in High Tech Industry," in Stefano Breschi and Franco Malerba, eds., *Clusters, Networks, and Innovation*, Oxford University Press, USA, New York, N.Y., 2006.

[80]For a discussion of this phenomenon in the case of Silicon Valley, see M. Kenney and D. Patton, "The Coevolution of Technologies and Institutions: Silicon Valley as the Iconic High-

of these "tools for thought"[81] that has provided so many opportunities for new firms to form. The United States continues to have two of the world's most sophisticated IT clusters, the San Francisco Bay Area (Silicon Valley) and Boston (Route 128).[82] It should not be surprising that outstanding universities and a strong financial community characterize both regions. There are a number of other, smaller national IT clusters within the United States, including those in San Diego, California; Seattle, Washington; Irvine, California; Austin, Texas; and the Washington, D.C., area. Further, an extensive network of intermediaries has developed to support IT (and other) entrepreneurs.[83]

International Development of Clusters

Since 1995, there has been an international proliferation of IT clusters that have significant R&D underway. They vary in size and with respect to the conditions that motivated their growth. In some of these, such as India (in particular, Bangalore), and China (Beijing and to a lesser degree Shanghai), wage advantages were significant factors. However, in many of these locations, wages were not key factors or, in the case of Scandinavia's wireless technology cluster based around Ericsson and Nokia, were of no significance at all. In the cases of the IT clusters in Israel and Ireland, initially they enjoyed advantageous wages in comparison with wages in the United States and Western Europe, but for these two nations, this is no longer the case.

A number of these clusters are based on narrow specializations. Taiwanese firms have developed strong niches in electronics assembly, particularly for desktop and notebook computers, as well as semiconductor foundries for chip fabrication. Taiwan has parlayed its strengths

Technology Cluster," in P. Braunerhjelm and M. Feldman, eds., *Cluster Genesis: Technology-Based Industrial Development,* Oxford University Press, Oxford, England 2006, pp. 38-60.

[81]Howard Rheingold, *Tools for Thought: The People and Ideas of the Next Computer Revolution,* Simon and Schuster, New York, 1985; and Stephen S. Cohen, John Zysman, and Bradford J. DeLong, "Tools for Thought: What Is New and Important About the 'E-conomy'?" January 1, 2000, available at http://repositories.cdlib.org/brie/BRIEWP138/; accessed July 3, 2007.

[82]A key book on the early development of Silicon Valley is Christophe Lecuyer's *Making Silicon Valley: Innovation and the Growth of High Tech, 1930-1970,* MIT Press, Cambridge, Mass., 2006. For a variety of perspectives on the formation of Silicon Valley, see M. Kenney, ed., *Understanding Silicon Valley: Anatomy of an Entrepreneurial Region,* Stanford University Press, Stanford, Calif., 2000. See also E.M. Rogers and J.K. Larsen, *Silicon Valley Fever,* Basic Books, New York, 1984; and AnnaLee Saxenian, *Regional Advantage: Culture and Competition in Silicon Valley and Route 128,* Harvard University Press, Cambridge, Mass., 1994.

[83]For information on entrepreneurial support networks, see M. Kenney and D. Patton, "Entrepreneurial Geographies: Support Networks in Three High-Tech Industries," *Economic Geography* 81(2):201-228, 2005.

into higher-volume consumer products, such as cellular telephones, personal digital assistants (PDAs), and MPEG-1 Audio Layer 3 (MP3) players, although the actual assembly is increasingly being shifted to China. Despite the gradual increase in Taiwanese semiconductor design firms, the United States still dominates in design.

These smaller nations have found valuable niches, yet because of their size there is little concern that they will dominant the global industry. India and China are different in that they have wages significantly lower than those in the developed nations. In population and gross domestic product (GDP), they dwarf Ireland, Israel, and Scandinavia. Further, given their rapid growth they are increasingly significant in the global economy. Table 3.1 documents the relative size and rate of growth of the developing IT industry in India, Ireland, and Israel. China is not included in Table 3.1 because it has limited software exports at the present time.[84]

India

Understanding India's role in the global IT economy is difficult because of the speed with which it is changing and the fact that even today most of the work is development, not cutting-edge basic research. A decade ago, IT R&D in India was confined to the small operations of a few U.S. pioneers such as HP, Motorola, and Texas Instruments. India did not begin as a performer of development; rather it entered the IT economy by providing programmers and doing routine programming work. Today, the vast majority of Indian software professionals continue to do such routine work. What has changed is that many European and U.S. multinational corporations have established research and development facilities in India. So India, which only 5 short years ago would have hosted very little R&D, is becoming an increasingly significant IT R&D center largely because of the decisions by U.S. IT firms to take advantage of an increasingly rich IT ecosystem.

The significance of the changes in India is worth some attention. India's entry into the global industry dates to 1974, when Burroughs Corporation asked Tata Consultancy Services to supply programmers to install system software for its U.S. client.[85] In the 1980s, a few U.S. firms set up facilities in Bangalore where Indian engineers and programmers

[84] Association for Computing Machinery Job Migration Task Force, *Globalization and Offshoring of Software: A Report of the ACM Job Migration Task Force*, W. Aspray, F. Mayadas, and M. Vardi, eds., Association for Computing Machinery, New York, N.Y., 2006, pp. 120-121.

[85] S. Ramadori, Chief Executive Officer, Tata Consultancy Services, personal interview by Rafiq Dossani, Walter H. Shorenstein Asia-Pacific Research Center, Stanford University, 2002.

TABLE 3.1 Software Exports from India, Ireland, and Israel, Selected Years from 1990 to 2005 (in $ millions, except where otherwise noted)

	India	Ireland	Israel
1990	105	2,132	90
2000	6,200	8,865	2,600
2002	7,500	12,192	3,000
2003	8,600	11,819	3,000
2005	17,100	18,631	3,000
Number employed (2003)	260,000	23,930	15,000
Revenue/employee (2003)	33,076	493,988[a]	273,000
Number employed (2005)	513,000	24,000	NA
Revenue/employee (2005)	33,333	776,000[a]	NA

NOTE: Data for India are from R. Heeks, *India's Software Industry: State Policy, Liberalisation and Industrial Development,* Sage Publications, New Delhi, India, 1996; and Nasscom, *Review of the Indian IT Industry,* New Delhi, India, Nasscom, 2003-2006. Data for Ireland are from http://www.nsd.ie/htm/ssii/stat.htm, downloaded September 26, 2006. Data for Israel are from http://www.iash.org.il/Content/SoftwareInds/SoftwareInds.asp, downloaded August 31, 2003, and http://www.israel21c.org/bin/en.jsp?enDispWho=InThePress&enPage=BlankPage&enDisplay=view&enDispWhat=Zone&enZone=InThePress&Date=08/11/05, downloaded September 26, 2006. Data for Ireland prior to 2003 are in euros (converted at 1 euro = $1.043, the rate on January 5, 2003). From 2003 on, data are converted at 1 euro to $1.26, the rate in January 2004. The most recent figures for Israel are for 2001.

[a]Sands (p. 45) argues that the revenue/employee for Ireland is overstated because of in-country transfers and should be about $160,000. If so, total exports in this table are overstated by a factor of three. See A. Sands, "The Indian Software Industry," in A. Arora and A. Gambardella, eds., *From Underdogs to Tigers: The Rise and Growth of the Software Industry in Brazil, China, India, Ireland, and Israel,* Oxford University Press, New York, N.Y., 2005, pp. 41-71. This finding is seconded by Dan Breznitz, who calculated that sales per employee for Irish-owned software firms hit a high of $104,000 per employee in 1999. See Dan Breznitz, *Innovation and the State,* Yale University Press, New Haven, Conn., 2007. As outlined in the text of this chapter, a number of countries have developed significant IT sectors. Two of them, India and China, are, by virtue of their size, competiveness, and close links to the U.S. IT sector, of the greatest significance for the U.S. IT R&D ecosystem.

SOURCE: Rafiq Dossani and Martin Kenney, "The Implications of Globalization for Software Engineering," in National Academy of Engineering, *The Offshoring of Engineering: Facts, Unknowns, and Potential Implications*, The National Academies Press, Washington, D.C., 2008. Adapted with permission of the National Academy of Engineering, 2008.

developed products for global and domestic markets. Knowledge of the capabilities of Indian programmers and engineers gradually spread, but even in 1990, the Indian IT industry was not well known. By 1995, Indian IT industry growth had quickened, and at that time there were 27,500 Indians in the software services export industry. By 2006, this number had increased to 706,000. India has the second-largest number of software and software services industry workers in the world, following the

United States. The 2007 pace of growth is not slackening, although there are indications of labor shortages by 2010.

After 2000, India's domestic market grew rapidly, from a GDP of $460.2 billion to $805.7 billion in 2005.[86] By early 2007, India was adding 5 million mobile phone users per month (although subscribers pay only $8 per month on average).[87] Similarly, broadband usage in business and among the higher-income groups in India is growing. Even though India is a moderate-sized market, if current growth rates continue, it will be one of the five largest in the world.

There are indications that as respect for their capabilities increases, Indian firms are becoming trusted advisers for Global Fortune 1000 firms. There is some indication that Indian firms are surpassing the U.S. firms on software quality metrics and might be overtaking U.S. providers on quality as well as labor cost advantage.[88] U.S. rivals have expanded their Indian operations. IBM now has approximately 60,000 employees in India and Electronic Data Systems (EDS) approximately 35 percent of its global total. India is likely to be a major recipient of further offshoring.

In software itself, India is also developing capabilities. According to Google's official blog, for example, Google Finance "started as a small project led by a few engineers in Bangalore and later joined by more engineers and finance enthusiasts in Mountain View and New York."[89] All major U.S. software and Internet firms now have large and growing operations in India. Many employ more engineers in India than in any other nation outside the United States.

Semiconductor Design India is also becoming a major semiconductor design center. Indian firms are part of the global value chain for integrated circuit (IC) design, having moved from verification, physical design, and silicon production engineering to higher-value work in architecture and design of analog and digital circuits.[90] Indian firms are now marketing

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[86]World Bank, "Key Development Data and Statistics," 2007, available at http://devdata.worldbank.org/external/CPProfile.asp?PTYPE=CP&CCODE=IND; accessed June 20, 2007.

[87]Ruth David, "Vodafone Wins Stake in India Cell Phone Market," *Forbes,* February 2007, available at http://www.forbes.com/business/2007/02/12/essar-hutch-vodafone-cx_rd_0212bid-update2.html; accessed June 20, 2007.

[88]Leonard Lynn and Harold Salzman, "The 'New' Globalization of Engineering: How the Offshoring of Advanced Engineering Affects Competitiveness and Development," paper presented at the Sloan Industry Studies Annual Meeting, Boston, Mass., 2007.

[89]Google, "Spring Is the Season for Love (and Data)," posted on The Official Google Blog, March 21, 2006, available at http://googleblog.blogspot.com/2006/03/spring-is-season-for-love-and-data.html; accessed June 20, 2007.

[90]Rafiq Dossani and Martin Kenney, "Implications of Globalization for Software Engineering," in National Academy of Engineering, *The Offshoring of Engineering: Facts,*

their expertise to provide end-to-end solutions. They can manage the design handoff to IC producers such as Taiwan Semiconductor Manufacturing Company (TSMC) directly, without involving the end customer.

Many U.S. semiconductor firms now have engineering operations in India,[91] often their largest outside the United States.[92] Members of senior management of these operations often have degrees and experience in the United States.[93] The number of Indian very-large-scale integrated circuit (VLSI) design engineers was 11,300 in 2005[94] and was projected to grow to 33,135 by 2010. For the year 2005, revenues were estimated to be $583 million; they are expected to reach $2 billion by 2010.[95] The leading semiconductor design software firms are also increasing their presence in India, both to service the local market and to support the global market. Although there are currently no commercial fabrication facilities in India, the design functions for many parts of the value chain in semiconductor, design software, and equipment suppliers are beginning to emerge. There is sufficient anecdotal evidence to suggest that India is quite rapidly becoming a force in semiconductor design.

Computer Networking Equipment Networking equipment manufacturing has undergone a severe shakeout since the collapse of the IT bubble. Shifting development to low-cost regions is certainly a consideration. The leading firms all have engineering operations in India. As with semiconductors, India produces a small amount of networking equipment internally or for export. Nevertheless, this situation appears to be changing. For example, Cisco Systems' Globalization Center and chief globalization

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Unknowns, and Potential Implications, The National Academies Press, Washington, D.C., 2008, pp. 49-68.

[91]See Jeffrey T. Macher, David C. Mowery, and Alberto Di Minin, "Semiconductors," in National Research Council, *Innovation in Global Industries: U.S. Firms Competing in a New World,* Jeffrey T. Macher and David C. Mowery, eds., The National Academies Press, Washington, D.C., 2008; and Clair Brown and Greg Linden, "Semiconductor Engineers in a Global Economy," in National Academy of Engineering, *The Offshoring of Engineering: Facts, Unknowns, and Potential Implications,* The National Academies Press, Washington, D.C., 2008, pp. 149-178.

[92]It is important to note that some semiconductor firms have more employees in their manufacturing or semiconductor assembly and test operations in East Asian nations such as China and Malaysia.

[93]Rafiq Dossani and Martin Kenney, "Implications of Globalization for Software Engineering," in National Academy of Engineering, *The Offshoring of Engineering: Facts: Unknowns, and Potential Implications,* The National Academies Press, Washington, D.C., 2008, pp. 49-68.

[94]Indian Semiconductor Association, "Semiconductor Driven Industry in India—A Perspective," February 2006, PowerPoint presentation made available to committee member Martin Kenney by Rajendra Khare, president, Indian Semiconductor Association.

[95]The committee thanks Rajendra Khare, president of the Indian Semiconductor Association, for these data.

officer are now located in India. Cisco plans to double or triple its current number of approximately 2,000 employees in India.[96] Cisco already has more employees in India than it has anywhere else outside the United States. The same is true of Juniper Networks,[97] and even the China-based Huawei Technologies employed about 1,300 engineers in Bangalore in late 2006.[98] The anecdotal evidence suggests that the number of telecommunications equipment engineers in India will continue to grow, although most of this employment will be in multinational corporations (MNCs). It is likely that even with this growth, the number of telecommunications equipment engineers in India will trail that of the United States and China.

IT Start-ups in India The Indian ecosystem for IT start-ups is complicated.[99] The first category is "traditional," India-only start-ups whose headquarters and design operations are in India—for example, the U.S.-venture-funded Tejas Networks. The second category is firms established in the United States but having operations in India. U.S. operations may be limited to a headquarters with finance and marketing functions, with the remaining operations in India; the latter has the majority of the employees and undertakes all product development. Alternatively, there are start-ups that have almost all of their employees in the United States with an engineering facility in India; Tensilica Technologies India is an example of this organization.[100] Finally, there are firms that have the management and core engineering team in the United States, with the rest of the engineering team in India. An example is Telsima, Inc., established in 2004 with international venture funding to develop WiMAX-based broadband

[96]Cisco, "Cisco Provides Update on US $1.1 Billion Investment in India," December 6, 2006, available at http://newsroom.cisco.com/dlls/global/asiapac/news/2006/pr_12-06b.html?CMP=AF17154&vs_f=News@Cisco:+Technology+Innovation+&+Development+News&vs_p=News@Cisco:+Technology+Innovation+&+Development+News&vs_k=1; accessed June 20, 2007.

[97]R. Savitha, "Juniper Networks Office in Chennai by Year-End," *Hindu Business Line*, May 26, 2007, available at http://www.thehindubusinessline.com/2007/03/27/stories/2007032703750400.htm; accessed June 29, 2007.

[98]Ravi Sharma, "Huawei Keeping Fingers Crossed on Simpler Work Visa Norms for Chinese Personnel," *The Hindu*, December 17, 2006, available at http://www.hindu.com/2006/12/17/stories/2006121701920400.htm; accessed June 20, 2007.

[99]Rafiq Dossani and Martin Kenney, "The Evolving Indian Offshore Services Environment: Greater Scale, Scope and Sophistication," Sloan Industry Studies Working Papers, Number WP-2007-34, 2007, available at http://www.industry.sloan.org/industrystudies/workingpapers/index.php; accessed October 25, 2007.

[100]Ashish Dixit, "Tensilica Technologies India: An Update," paper presented at the Globalization of Services—The Second Annual Conference, Stanford, Calif., December 12, 2006, available at http://iis-db.stanford.edu/evnts/4587/Tensilica.pdf; accessed June 20, 2007.

wireless access and software for mobility solutions for media-rich (data-intensive) applications.[101]

Measuring the technical sophistication of these start-ups is difficult, but anecdotal evidence suggests that at least some of them are quite sophisticated. Examples of recent acquisitions of Indian start-ups by U.S. firms[102,103] indicate that these firms are creating value and that more start-ups should be expected.

China

China has become the undisputed global IT equipment-manufacturing leader, which has helped fuel its rapid economic growth. China's success in IT equipment production is different from that of other developing nations in that these are high-technology products.[104] Chinese exports of IT equipment increased from $645 million in 1990 to $81 billion in 2004.[105] Nevertheless, IT manufacturing is mostly a low-margin business. Thus far, with the possible exception of firms such as Huawei and Lenovo, Chinese firms do not compete as global brands; they manufacture for others.[106]

The Chinese government is furthering its domestic industry while also encouraging foreign firms to produce and perform R&D locally. It has steadily increased R&D funding in engineering and the sciences and also encourages the development of its local technology standards in fields such as wireless. Some have interpreted this as "a strategy to dominate the global market for information technology goods."[107] Another interpretation is that the Chinese government and firms seek to decrease their dependence on foreign standards and patents, mostly held by U.S. firms, and for which they must pay royalties. The Chinese government

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[101]Telsima, Inc. 2007. "Corporate Brochure," available at http://www.telsima.com/pic/pdf/download/Corporate_Brochure.pdf; accessed June 20, 2007.

[102]Synopsys, "Synopsys Acquires ArchPro Design Automation," June 18, 2007, available at http://synopsys.mediaroom.com/index.php?s=43&item=468; accessed June 20, 2007.

[103]Computergram International, "Broadcom Acquires Indian Fabless Chip Firm Armedia," July 6, 1999, available at http://www.highbeam.com/doc/1G1-55071676.html; accessed June 20, 2007.

[104]Dani Rodrick, "What's So Special About China's Exports?" CEPR Discussion Paper No. 5484, January 2006, available at http://ssrn.com/abstract=902348; accessed July 2, 2007.

[105]Jason Dedrick and Kenneth L. Kraemer, "Is Production Pulling Knowledge Work to China? A Study of the Notebook PC Industry," *Computer*, July 2006, p. 37, available at http://pcic.merage.uci.edu/papers/2006/dedrick.pdf; accessed June 22, 2007.

[106]Ibid.

[107]David Lague, "China Overtakes U.S. as Supplier of Information Technology Goods," *International Herald Tribune*, December 11, 2005, available at http://www.nytimes.com/2005/12/11/business/worldbusiness/11cnd-hitech.html?ex=1291957200&en=748942b64ba7f2b9&ei=5090&partner=rssuserland&emc=rss; accessed June 22, 2007.

places significant pressure on foreign MNCs wishing to operate in China to establish joint ventures through which the Chinese partner can learn about foreign technologies.

Semiconductors China has become the largest single market in the world for semiconductors.[108] In 2005, it accounted for 24 percent of global semiconductor production and was responsible for 90 percent of consumption growth even as it produced only 7 percent of the worldwide total.[109] As a result, China runs a significant trade imbalance in semiconductors, which is considered a serious issue by Chinese policy makers.

A Chinese fabless semiconductor design industry is now emerging. The firms are small, yet most are enjoying rapid growth. In semiconductor fabrication China is a minor player, although with the facilities already announced or under construction in 2006, its production capacity could approach 10 percent of worldwide wafer production.[110] Much of this foundry capacity competes directly with Taiwan, not with U.S. manufacturers, and little of it will be at the most advanced levels of technologies.[111]

Software and Services The Chinese software services industry is much smaller than its Indian counterpart.[112] According to the Chinese Software Industry Association, there are 300,000 workers employed in more than 6,000 firms; of these workers approximately 160,000 are software professionals, about 25 per firm.[113] According to the Ministry of Commerce, the revenues of the Chinese IT and software services industry increased from $7.17 billion in 2000 to $19.35 billion in 2003. During the same period, software exports increased from $250 million to $2 billion.[114] A

[108]PricewaterhouseCoopers, *China's Impact on the Semiconductor Industry 2006/Update*, 2007, p. 7, available at http://www.pwc.com/extweb/onlineforms.nsf/weblookup/USENGTCENChina'sImpactontheSemiconductorIndustry-2006Update-DownloadForm?opendocument; accessed June 22, 2007.

[109]Ibid., p. 1.

[110]Ibid., p. 24.

[111]Ibid., p. 25.

[112]This subsection, "Software and Services," draws heavily on Chapter 3 in Association for Computing Machinery Job Migration Task Force, *Globalization and Offshoring of Software: A Report of the ACM Job Migration Task Force*, W. Aspray, F. Mayadas, and M.Y. Vardi, eds., Association for Computing Machinery, New York, N.Y., 2006.

[113]T. Tschang and L. Lan Xue, "The Chinese Software Industry," in A. Arora and A. Gambardella, eds., *From Underdogs to Tigers: The Rise and Growth of the Software Industry in Brazil, China, India, Ireland, and Israel,* Oxford University Press, USA, New York, N.Y., 2005, pp. 131-167.

[114]China Software Industry Association, "China Software Export Achieved 7 Times Growth in Five Years," 2005, available at http://www.csia.org.cn/chinese_en/index/; accessed March 2005.

recent report notes that China's total IT services revenues are rising but are barely half of India's $12.7 billion.[115] Growth is driven by internal demand, and exports make up only 10 percent of total annual software service revenues. (For comparison, the global IT services market in 2006 was $671.4 billion.[116])

The Chinese software export industry faces many obstacles. It is fragmented, with few firms capable of undertaking large projects.[117] As China is the world's manufacturer, many of its products contain embedded software. Some portion of this work may be relocated to China.[118] The Chinese firms providing IT services to the West are mostly small. Western firms have also established software subsidiaries in China to support their growing Chinese businesses and to provide offshore services to Asia-Pacific nations, particularly Japan.[119]

IT R&D in China In 2006, the Organisation for Economic Co-operation and Development (OECD) announced that China was the world's second-largest R&D spender.[120] Although accurate figures on R&D spending are difficult to come by, there can be little doubt that R&D is growing rapidly. A number of U.S., European, and particularly Taiwanese electronics firms have established R&D facilities in China. It is likely that most of these facilities focus on adapting products for the local market or on production engineering, but some have global product mandates or are

[115]K.C. Krishnadas, "Fragmented China Software Sector No Match for India, Report Finds," *EE Times,* February 18, 2005, available at http://www.informationweek.com/story/showArticle.jhtml?articleID=60402234&tid=5979; accessed October 4, 2007.

[116]Robert De Souza, Kathryn Hale, Freddie Ng, and Akimasa Nakao, "Dataquest Alert: IT Services Forecast, Worldwide, 2007-2011 (Update)," G00152463, October 9, 2007, available at http://www.gartner.com/DisplayDocument?id=530210; accessed February 27, 2008.

[117]K.C. Krishnadas, "Fragmented China Software Sector No Match for India, Report Finds," *EE Times,* February 18, 2005, available at http://www.informationweek.com/story/showArticle.jhtml?articleID=60402234&tid=5979; accessed October 4, 2007.

[118]C. Brown and G. Linden, "Offshoring in the Semiconductor Industry: A Historical Perspective," in Susan M. Collins and Lael Brainard, eds., *Brookings Trade Forum*, Brookings Institution Press, Washington, D.C., 2005.

[119]"China Becomes Japan's Biggest Software Outsourcing Base," *Xinhua*, April 12, 2007, available at http://news.xinhuanet.com/english/2007-04/12/content_5968762.htm; accessed June 22, 2007.

[120]Organisation for Economic Co-operation and Development, "China Will Become World's Second Highest Investor in R&D by End of 2006, Finds OECD," 2006, available at http://www.oecd.org/document/26/0,2340,en_2649_201185_37770522_1_1_1_1,00.html; accessed June 22, 2007.

doing research for their firms' global operations.[121] The most celebrated of these, the Microsoft Research Asia laboratory in Beijing, employed approximately 300 scientists in 2007.[122] Furthermore, major Chinese firms such as Huawei and Lenovo are investing heavily in R&D. At the current level, China is one of the largest R&D performers in the world. At least in some cases, the R&D is already world-class.

Data Communications Equipment The Chinese data communications equipment industry has grown rapidly, with two globally recognized Chinese firms: Huawei Technologies and ZTE Corporation. Huawei sales reached $11 billion in 2006, with 65 percent from outside China.[123] ZTE's global sales reached $2.8 billion.[124] Huawei's customers include major Western operators, such as British Telecom. Nevertheless, there is no evidence that China is generating large numbers of telecommunications equipment start-ups, despite the fact that it has substantial venture capital resources and a rapidly developing internal market for telecommunications products. In the future, it is possible that entrepreneurs may begin establishing start-ups.

Conclusions Chinese IT R&D will continue its rapid growth, given its past growth, the inherent commercial opportunities, and the importance given to it by the Chinese government. The enormous buildup in IT productive capacity in China will become a magnet for production engineering and higher-level R&D. Given the likely growth of China's domestic market, no major IT firm can afford to ignore the market, and it will be necessary to support that market with some domestic production. Given China's expanding labor pool of low-cost engineers, multinational corporations experiencing pressure on margins are likely to expand their engineering activities there.[125] In terms of R&D, China is rapidly increas-

[121] Xiaohong Quan, "Multinational Corporations' R&D in China: IP Protection and Innovation for the Global Market," PowerPoint presentation, November 29, 2005, available at http://iis-db.stanford.edu/evnts/4317/Xiaohong_(Iris)_Quan_presentation.pdf; accessed June 22, 2007.

[122] Microsoft Research, 2007, available at http://research.microsoft.com/aboutmsr/labs/asia/; accessed June 22, 2007.

[123] Huawei, "Financial Highlights," 2007, available at http://www.huawei.com/corporate_information/financial_highlights.do; accessed June 22, 2007.

[124] ZTE, "Corporate Reports," 2007, available at http://wwwen.zte.com.cn/main/files/2008/04/09/333826174089.pdf; accessed June 22, 2007.

[125] China's current supply of "engineers" who are comparable to engineers in the U.S. workforce is likely smaller than Chinese government data might at first suggest. However, graduation rates are rising, and China is rapidly increasing its production of engineering and technology Ph.D.'s. See V. Wadhwa, G. Gereffi, B. Rissing, and R. Ong, "Where the Engineers Are," *Issues in Science and Technology,* Spring 2007. (But see also Denis Fred Simon,

ing its share of total global R&D. Some Chinese firms are already global competitors in the IT industry, and there are likely to be more.

Taiwan

Taiwan gradually worked its way up the value ladder from producing the simplest parts and assembling consumer electronics products to designing and engineering all but the most sophisticated products. In the process, Taiwanese manufacturers have become among the largest electronics firms in the world. In addition, Taiwan established a world-class semiconductor fabrication industry supporting the U.S. fabless semiconductor industry. Taiwanese firms have become an integral part of global commodity chains developed by U.S. firms.

Facing competition from Japan, U.S. firms sought lower prices by shifting assembly and low-end manufacturing to Taiwan and Korea in the 1960s. U.S. firms and their Japanese competitors established production facilities in Taiwan, sourcing low-technology components from local vendors. The microcomputer provided an opening for Taiwanese firms to supply low-technology parts and components to PC makers. These firms soon evolved into contract assemblers, drawing on a base of smaller component makers. By the early 1990s, Taiwan had become the global center for the production of every component in the PC except for the microprocessor, dynamic random-access memory (DRAM), hard drive, graphics chips, and software. By the late 1990s, Taiwanese firms were assembling not only desktop PCs but notebook computers as well. A U.S. vendor provided the basic specifications for a desktop or notebook PC, and a Taiwanese vendor designed, assembled, and shipped the computer with the vendor's name. Taiwanese firms began to feel margin pressure as local wages increased. They began offshoring production to China. By 2000, every significant Taiwanese electronics firm had a presence in China. Taiwan specialized in the most sophisticated manufacturing, design, marketing, and other headquarters functions. The assemblers have diversified from PCs into other consumer electronics products. They did this as contract manufacturers and not under their own brands, unlike Korea with its Samsung Electronics and LG Electronics global brands.

Taiwan has also become a world leader in contract semiconductor fabrication. Its foundries are enormously capital-intensive facilities, deploying advanced fabrication technologies. The availability of these foundries has enabled U.S. entrepreneurs to establish a significant number of successful specialty IC design firms. Taiwan's own IC design sector

Cong Cao, Ron Hira, and Rick Rashid, "Not Enough U.S. Engineers? (FORUM)," *Issues in Science and Technology*, Summer 2007.)

employed approximately 14,000 chip designers in 2004 and generated $8.6 billion in revenue in 2005.[126] The Taiwanese design industry faces many challenges. Taiwan's wages are nearly double those of China and India. Taiwanese chip designers' capabilities match those of Taiwanese assemblers but lag behind the leading-edge system-level designers, making it difficult for them to get the most lucrative design wins. The movement of the Taiwanese assemblers to China may also relocate business opportunities to lower-cost Chinese designers.

To summarize, Taiwan's position is as a supplier to global firms, primarily from the United States. Although the desktop or laptop PC may have been designed in Taiwan and manufactured in China, most of the added value is captured on the one hand by the U.S. brands that control the distribution channels and on the other by the U.S. firms that provide the high-value components (such as the microprocessor and the software). In fact, using these lower-cost Asian suppliers has kept the U.S. PC industry competitive. Taiwanese firms also provide the critical foundries for the smaller but highly profitable U.S. specialty chip design firms. The Taiwanese IT industry has evolved a mutually beneficial division of labor with its U.S. partners. With the exception of Taiwan's foundries, most of its firms are likely to continue to experience extreme pricing pressure, forcing them to respond by offshoring much of their lower-end work to China.

INFRASTRUCTURE TO ENABLE MULTIFACETED INNOVATION

Information technology plays a pervasive and indispensable role in the United States. As IT becomes almost ubiquitous, Americans use it in increasingly sophisticated ways for work, family life, and entertainment. For example:

- By 2006, almost 70 percent of adult Americans (18 and older) owned a desktop computer, and 30 percent had a laptop.
- In 2001, the Apple iPod was introduced, forever changing the music and entertainment landscape: by 2006, 20 percent of adult Americans had an iPod.
- Over the past decade, cellular telephones and handheld devices have launched a new form of "mobile" communications, connecting people through voice and data applications no matter where they are: in 2006, 73 percent of adult Americans had cell phones, and 11 percent had a handheld device.[127]

[126] Clair Brown and Greg Linden, "Semiconductor Engineers in a Global Economy," in National Academy of Engineering, *The Offshoring of Engineering: Facts, Unknowns, and Potential Implications,* The National Academies Press, Washington, D.C., 2008, pp. 149-178.

[127] Data on the percentage of Americans reporting that they had specific technology are

These networking and device technologies are used for more than entertainment and desktop or laptop computing, however. Applications areas such as transportation, banking and financial services, and health care have been greatly impacted by use of IT. Information technology is now found in dishwashers, cars, lasers, medical equipment, smartcards, and numerous other devices and machines. Critical broadband connectivity connects these endpoints, keeping them working together to create business and consumer value. The network itself continues to evolve, just as do the devices and software that it connects—the infrastructure gets faster, cheaper, and more reliable, and devices are becoming smaller and multimodal.[128]

In the eyes of most Americans, these technologies are not only indispensable to the nation's business operations and their derived productivity, but also facilitate the ongoing learning and creativity of U.S. citizens.

Multifaceted Innovation

Information technology innovation no longer happens only in university or corporate laboratories. Customer-created value is increasingly prominent: IT consumers are leveraging research, innovating, and creating value by combining networking hardware, software, and devices into novel solutions and businesses (see Figure 3.2). In 1995, supplier-created value through technological *product* innovations in information technology predominated. However, this pattern has been changing, as customers are increasingly creating value through IT *application* innovations in industries including health care, professional services, financial services, manufacturing, retail, media and publishing, and education.[129] As a result of the co-evolution of business and IT, the IT R&D ecosystem is becoming increasingly linked with R&D in the wider global economy.

The significance of multifaceted innovation to IT has increased significantly during the study period 1995 to 2007. During this period, IT has permeated almost all aspects of business and society. One consequence of this pervasiveness is that the market-facing, customer-involved aspects of IT are growing very fast. This means, among other things, that "IT jobs" are changing—now often requiring customer-specific, market-specific, and business-specific expertise, not just technology-specific expertise. IT

from Pew Internet and American Life Project Survey, April 2006, available at http://www.pewinternet.org/pdfs/PIP_ICT_Typology.pdf; accessed October 18, 2007. Pew surveyed 4,001 Americans 18 years of age and older by telephone.

[128]Information Technology and Innovation Foundation, *Digital Prosperity: Understanding the Economic Benefits of the Information Technology Revolution,* Washington, D.C., March 13, 2007.

[129]David Moschella, "Aligning R&D with Industry Change," presentation to the committee, Boston, Mass., April 19, 2007.

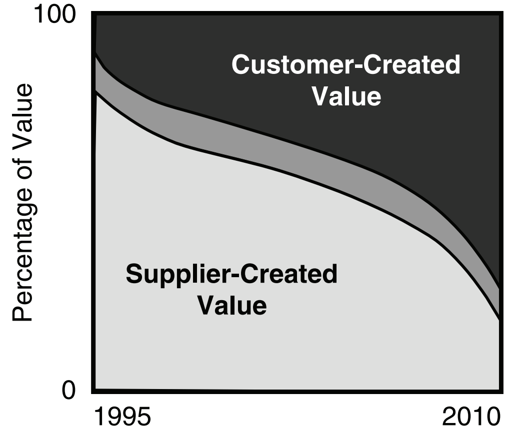

FIGURE 3.2 Shift from supplier-created to customer-created value, 1995-2010.
SOURCE: Adapted from David Moschella, "Aligning R&D with Industry Change," presentation to the committee, Boston, Mass., April 19, 2007.

is enabling new products and services, and innovation in IT also includes innovations in these products and services. The National Research Council expects to embark on a congressionally mandated project looking at education, training, and research dimensions of innovation in IT-enabled services.[130]

Indeed, revenues in the IT sectors are increasingly coming from services (including software maintenance) rather than from product sales. According to Michael Cusumano, software product companies and types of firms experiencing the shift toward services face three kinds of challenges: identifying the best revenue mix (of products and services, bearing in mind that products drive service revenues), creating service offerings that can make a firm's products less commodity-like, and making service

[130] Section 1005 of Public Law 110-69 (the America COMPETES Act of 2007) calls for the Office of Science and Technology Policy, through the National Academies, to conduct a study and to report to Congress on "how the Federal Government should support, through research, education, and training, the emerging management and learning discipline known as service science," which is defined as "curricula, training, and research programs that are designed to teach individuals to apply scientific, engineering, and management disciplines that integrate elements of computer science, operations research, industrial engineering, business strategy, management sciences, and social and legal sciences, in order to encourage innovation in how organizations create value for customers and shareholders that could not be achieved through such disciplines working in isolation."

delivery more efficient (through reuse of software components, standardized process frameworks and training, and automation of services). Thus both suppliers and their customers have ample new opportunities to innovate in underlying technologies, in product- and service-delivery models, in new business models, and in new product and service offerings.[131]

U.S. leadership in many IT-related markets is under competitive pressure. The changing locus of IT innovation, including customers as well as university or corporate laboratories, makes demand leadership by U.S. consumers—that is, having consumers that are among the most technologically sophisticated in the world, with leading-edge product requirements—increasingly important to the U.S. global competitiveness in IT. With multifaceted IT innovation, the rationale is that the most dynamic IT companies will ultimately be in countries with the most demanding IT customers.[132] Thus if a nation's users are not global lead users—requiring and using the most advanced IT functionalities—then in the market segments where their demand lags, that nation's user-driven IT innovation also will lag.[133]

U.S. consumers are not at the leading edge in important market segments such as mobile telephones and wireless services.[134] In part, this has to do with the fact that the wireless infrastructure in this country trails, in coverage and speed, the infrastructure in the European Union, Japan, and now increasingly, China.[135] It is also increasingly evident that U.S. consumers are not the leading adopters of new wireless services such as

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[131]As Michael A. Cusumano discusses, the shift to services on the part of traditional IT-product companies creates new opportunities for innovation, but it also creates new challenges for dedicated IT-services companies. See Michael A. Cusumano, "The Changing Software Business: Moving from Products to Services," *IEEE Computer*, January 2008, pp. 20-27.

[132]For a recent survey of the literature on the adoption and diffusion of IT in businesses, including "co-invention," see Chris Forman and Avi Goldfarb, "Diffusion of Information and Communication Technologies to Businesses," in Terry Hendershott, ed., *Handbook of Economics and Information Systems*, Elsevier, 2006, working paper version available at http://papers.ssrn.com/sol3/papers.cfm?abstract_id=896750#PaperDownload; accessed March 24, 2008.

[133]For development of the lead-user concept, see, for example, Eric von Hippel, "Lead Users: A Source of Novel Product Concepts," *Management Science* 32(7):791-805, 1986; and Glen L. Urban and Eric von Hippel, "Lead User Analyses for the Development of New Industrial Products," *Management Science* 34(5):569-582, 1988.

[134]Recent developments in the U.S. wireless market are signs of significant innovation, including the 3G iPhone from Apple, new competitor products by such vendors as Samsung and LG, and Google's entry into the mobile phone arena with its Android platform.

[135]According to the European Union's (EU's) 12th report on telecommunications markets, mobile penetration stood at 103 percent, and the EU had overtaken Japan with the largest population of 3G subscribers, with 45 million as of the end of 2006; available at http://ec.europa.eu/information_society/newsroom/cf/itemlongdetail.cfm?item_id=3304; accessed August 28, 2007.

ring tones, ringback tones, games, and payment services. The direction of causality is unclear, but infrastructure clearly plays a fundamental role. Both consumer demand and enabling infrastructure are necessary: for example, it is pointless to demand video on a cell phone if the wireless infrastructure cannot support it, or to expect home health care delivery offerings to prosper if broadband penetration is low (see the subsection below entitled "Broadband Speeds and Capabilities" for examples of bandwidths needed to support particular functionalities).

Network Infrastructure and Innovation Leadership

An environment of leading-edge users of technology creates the essential context for technology's next wave and its effective application. In such an environment, all sectors of society, including consumers, businesses, and governments, exploit and make best use of advanced information technology. However, as more leading-edge deployments of IT rely on mobility and a multimedia-capable infrastructure, it appears that the key IT suppliers in these markets will tend to focus their efforts on populations outside the United States because these markets are growing and because the infrastructures are better able to support users of these leading-edge technologies. This focus will, in turn, help those users grow in sophistication and comfort with the technology, surpassing users in the U.S. domestic markets. A situation in which U.S. consumers and users become increasingly less demanding in terms of product features and capabilities is cause for concern, because IT innovation is, increasingly, occurring at the "edge"—through user-driven application innovation.

United States Behind in IT Deployment in Some Domains

While the United States has long led the world as the largest IT market, thereby commanding the attention of the leading global providers of IT products and services, other countries are increasingly taking the lead in deploying IT for certain domains ahead of the United States. According to Morgan Stanley Research, "The large U.S. telecom operators are well behind their European peers in regard to fixed/mobile convergence, due to both structural and system issues."[136] In addition to mobile carrier infrastructure, other areas in which the U.S. failure to deploy IT intelligently is causing our society to fall behind in important ways include broadband infrastructure deployment, health care, and homeland secu-

[136]Mark Shuper, Adnaan Ahmad, Simon Flannery, Nick Delfas, Scott Coleman, Vance Edelson, and Franklin Fu, *Telecommunications 4G: Still the Early Days (WiFi/WiMax in Focus)*, Morgan Stanley Research Telecommunications Report, August 2006.

rity. For example, the Markle Foundation's 2002 report *Protecting America's Freedom in the Information Age* describes the importance of first-rate information collection, analysis, communications, and sharing for purposes of countering threats from terrorism and weapons of mass destruction, as well as pointing out how the U.S. failure to mobilize and deploy IT resources effectively harms response capabilities.[137]

In the past, the U.S. government has played a strong role in establishing U.S. IT demand leadership. From the 1960s through the 1980s, the U.S. government played a fundamental role in the development of numerous fields of information technology—both as a sponsor of broad-based research and as a lead customer in emerging markets.[138] During this period, often through military and space programs, the U.S. government served as a demand leader—a first customer for new commercial products that promised orders large enough to sustain investment in new products and processes.[139] Government has also served as a builder of infrastructure in advance of wider demand, notably for networking in research and education.

However, as commercial markets have outpaced federal procurements, the federal government's role in shaping and sustaining the IT R&D ecosystem has diminished. For example:

- As IT industries have matured and commercial demand for IT has soared, the government has ceased to be the "lead" customer (in terms of

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[137]See Markle Foundation, *Protecting America's Freedom in the Information Age,* New York, N.Y., October 2002, available at http://www.markle.org/downloadable_assets/nstf_full.pdf; see also Markle Foundation, *Creating a Trusted Information Network for Homeland Security,* New York, N.Y., December 2003, at http://www.markle.org/downloadable_assets/nstf_report2_full_report.pdf; both accessed August 28, 2007. See also Jonathan Marino, "DHS Tech Chief Wants Broadband for First Responders," *Government Executive,* March 15, 2007, available at http://www.govexec.com/dailyfed/0307/031507j2.htm; accessed October 18, 2007.

[138]For example, research supported by the Defense Advanced Research Projects Agency's (DARPA's) Information Processing Techniques Office (IPTO) from 1962 through the mid-1980s led to developments including time-sharing, interactive computer graphics, networking, integrated circuit design, and intelligent systems. For a comprehensive history of DARPA's IPTO and its style of "managing for innovation," see Arthur L. Norberg and Judy E. O'Neill, with contributions by Kerry J. Freedman, *Transforming Computer Technology: Information Processing for the Pentagon, 1962-1986,* Johns Hopkins University Press, Baltimore, Md., 1996. See also National Research Council, *Funding a Revolution: Government Support for Computing Research,* National Academy Press, Washington, D.C., 1999.

[139]Federal procurement of integrated circuits for NASA's Apollo spacecraft and for the Minuteman II missile guidance system sparked and sustained early industry investments in manufacturing capacity and encouraged commercial markets for integrated circuits. A notable example of a civilian agency as lead customer is the Census Bureau's purchase of the first Univac computer in 1951. See also National Research Council, *Funding a Revolution: Government Support for Computing Research,* National Academy Press, Washington, D.C., 1999.

cutting-edge needs or dominant purchasing power) for general-purpose hardware or software. The military continues to be a lead customer in certain specific areas (for example, extremely large scale, cyberphysical weapons systems), and in these it faces a struggle to ensure adequate internal and contractor capabilities.[140]

- In some cases, where the government's requirements had been perceived as beyond then-current commercial offerings, the government chose to "make" rather than "buy" needed technologies. Sometimes, the government finds it difficult to—or does not—appreciate when the decision crossover between "make" and "buy" has occurred. As a result, some agencies must now struggle to maintain decades-old and obsolete, but mission-critical, technologies while also attempting to modernize these systems using state-of-the-practice commercial technologies.[141]
- Although the U.S. government was rated a leader in readiness for e-government in 2003,[142] this may not translate into the same kind of lead role that the Defense Advanced Research Projects Agency (DARPA) played in prior decades.[143]
- The U.S. federal government generally does not stand at the forefront in terms of innovative IT use, and federal spending on IT does not dominate the commercial marketplace. Thus the government does not serve as an effective "lead customer" to spur development of new and innovative commercial technologies and products.
- In cooperation with the business school INSEAD, the World Economic Forum produces *The Global Information Technology Report*, which

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[140]This is the subject of an ongoing National Research Council (NRC) study on advancing software-intensive system producibility and of an NRC workshop report: National Research Council, *Software-Intensive Systems and Uncertainty at Scale*, The National Academies Press, Washington, D.C., 2007. For a discussion of the implications of increased Department of Defense reliance on commercial software during a period of increasing globalization in IT industries, see also Defense Science Board, *Report of the Defense Science Board Task Force on Mission Impact of Foreign Influence on DoD Software*, Office of the Undersecretary of Defense for Acquisition, Technology, and Logistics, Washington, D.C., September 2007.

[141]See National Research Council, *The Social Security Administration's E-Government Strategy and Planning for the Future*, The National Academies Press, Washington, D.C., 2007.

[142]In 2003, a United Nations survey found that the United States led the world in "e-government readiness," followed by Sweden, Australia, Denmark, and the United Kingdom. Readiness was measured by a composite index based on an assessment of Web sites, telecommunications infrastructure, and human resource endowment (including literacy). See United Nations, *UN Global E-Government Readiness Report: UN Global E-Government Survey 2003*, available at http://www.unpan.org/egovernment3.asp; accessed July 16, 2007.

[143]"DARPA funding of advanced technologies, particularly in Information Technology (IT), has had enormous impact, although largely on platform technologies that had wide and profound spillovers." See National Research Council, *Innovation Policies for the 21st Century: Report of a Symposium*, The National Academies Press, Washington, D.C., 2007, footnote 2, p. xiv.

ranks 122 countries on the basis of their "networked readiness." This is a metric that the Forum uses to measure the countries' preparation to participate in and benefit from developments in information technology. In the 2006-2007 report, the networked readiness ranking for the United States was seventh place; the United States had been in first place in the 2005-2006 rankings. The drop in the U.S. ranking was attributed to "relative deterioration of the political and regulatory environment."[144] In its 2007-2008 report, however, the World Economic Forum raised the United States' networked readiness ranking to fourth overall, after Denmark, Sweden, and Switzerland. The new report placed particular focus on the role of networked readiness in spurring innovation. The reported U.S. strengths included availability of capital and the quality of U.S. R&D institutions; the reported weaknesses included cost and speed of broadband connectivity.[145]

Comparing Aspects of Broadband in the United States and Abroad

Compared with the more highly regulated environment of past decades, the current telecommunications market environment in the United States has yielded many consumer benefits. However, these benefits have not accrued evenly. By the early years of the 21st century, although broadband was regarded as a national and local imperative, there was substantial geographical variation in the nature of broadband competition, broadband was not available everywhere, and investments

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[144]The World Economic Forum's national Networked Readiness Indicator (NRI) has three components: the environment for IT offered by the country; the readiness of the country's individuals, businesses, and governments; and the usage of IT among these stakeholders. The 10 top-ranked countries were Denmark, Sweden, Singapore, Finland, Switzerland, the Netherlands, the United States, Iceland, the United Kingdom, and Norway. These countries all had NRI scores between 5.71 and 5.42. By comparison, France ranked 23rd, with a score of 4.99, and Mexico ranked 49th, with a score of 3.91. (However, the United States was cited for maintaining its "primacy in innovation, driven by one of the world's best tertiary education systems and its high degree of cooperation with the industry as well as by the extremely efficient market environment.") See World Economic Forum, "Denmark Climbs to the Top in the Rankings of the World Economic Forum's Global Information Technology Report 2006-2007," Press Release, available at http://www.weforum.org/en/media/Latest%20Press%20Releases/gitr_2007_press_release; accessed July 18, 2007.

[145]World Economic Forum, *The Global Information Technology Report 2007-2008,* available at http://www.weforum.org/en/initiatives/gcp/Global%20Information%20Technology%20Report/index.htm; accessed April 9, 2008. Some observers reportedly were skeptical of the improvement in the U.S. ranking owing to their concerns about U.S. broadband capabilities, penetration, adoption, and costs. See John Markoff, "Study Gives High Marks to U.S. Internet," *New York Times*, April 9, 2008, available at http://www.nytimes.com/2008/04/09/technology/09internet.html?ex=1208404800&en=5625fba016b5acbf&ei=5070&emc=eta1; accessed April 9, 2008.

in additional facilities and performance improvements were uncertain.[146] In that environment, although the United States was a world leader in computer usage, it was already lagging in broadband connectivity (especially in the areas of speed and price—see Table 3.2) compared with other countries (albeit those with geographic, population-density, and industrial policy characteristics different from those of the United States).

A number of international rankings show that the United States lags in international comparisons. For example, IDC's "Information Society Index" (ISI) measures the ability of 53 nations to participate in the information revolution. To construct the ISI, IDC includes 15 variables grouped into four types of infrastructure indexes: social, Internet, computer, and telecommunications (telecom) infrastructures. In 2003, the United States ranked first in IDC's computer index, but only 20th in the telecom index, which included the number of broadband households.[147] Another international ranking, by the International Telecommunications Union, based on broadband subscribers per 100 people, put the United States in 20th place in 2006, after a steady decline from 3rd place in 1999.[148]

Table 3.2 presents a snapshot of the United States' uneven international standing in broadband in 2007: according to OECD data, it leads in total number of subscribers, is in the middle of the 10 countries listed in terms of per capita penetration, and is far behind in advertised download speed (at relatively high prices). However, like some of their foreign counterparts, U.S. carriers have continued to deploy combination service offerings and pricing arrangements (for example, bundling television, telephone, and data services in one cable or fiber-optic phone offering), and therefore prices and capabilities are likely to continue to improve in at least some areas of the United States.

The goal of more-ubiquitous, lower-cost, and higher-speed broadband deployment[149] has been the focus of significant analysis and advo-

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[146]National Research Council, *Broadband: Bringing Home the Bits,* National Academy Press, Washington, D.C., 2002; discussion of findings on pp. 13, 18, and 21.

[147]In 2003, the top 10 countries in IDC's composite ISI rankings were Denmark, Sweden, United States, Switzerland, Canada, Netherlands, Finland, Korea, Norway, and the United Kingdom. The IDC's computer index includes PCs per household, IT spending as a fraction of GDP, IT services' contribution to GDP, and software spending; the telecom index includes the number of broadband households, wireless subscribers, and handset shipments. See IDC, "IDC's Information Society Index," available at http://www.idc.com/groups/isi/main.html; accessed July 18, 2007.

[148]J. Windhausen, Jr., *A Blueprint for Big Broadband,* EDUCAUSE White Paper, January 2008, p. 12, citing International Telecommunications Union data, available at http://www.educause.edu/ir/library/pdf/EPO0801.pdf; accessed March 13, 2008.

[149]For technical, regulatory, and policy analyses of broadband, see National Research Council, *Broadband: Bringing Home the Bits,* National Academy Press, Washington, D.C., 2002.

TABLE 3.2 A Snapshot Comparison of Broadband in 10 Countries in 2007

Country	Total Number of Broadband Subscribers (million)	Number of Broadband Subscribers per 100 Inhabitants	Average Advertised Broadband Download Speed (megabits per second)	Average Monthly Cost of Broadband (U.S. $)
United States	66.2	22.1	8.9	53
Japan	27.2	21.3	93.7	34
Germany	17.5	21.2	9.2	NA
Korea	14.4	29.9	43.3	42
United Kingdom	14.4	23.7	10.6	33
France	14.3	22.5	44.2	37
Italy	9.3	15.8	13.1	NA
Canada	8.1	25.0	7.8	51
Spain	7.5	17.0	6.901	NA
Netherlands	5.5	33.5	5.312	39

NOTE: NA, not available.
SOURCE: Based on data of the Organisation for Economic Co-operation and Development presented in J. Windhausen, Jr., *A Blueprint for Big Broadband*, EDUCAUSE White Paper, January 2008, pp. 20-21; 23-24, available at http://www.educause.edu/ir/library/pdf/EPO0801.pdf.

cacy. In January 2002, for example, TechNet, a group of Silicon Valley chief executive officers, proposed that the President and policy makers "make broadband a national priority and set a goal of making an affordable 100-megabits per second broadband connection available to 100 million American homes and small businesses by 2010."[150] A June 2007 report from the Information Technology and Innovation Foundation (ITIF) uses an externalities argument to make its case that government action is needed to advance broadband deployment, because market forces will not be sufficient:

> First, it [broadband] is a not just a consumer technology like the iPod or Blu-Ray player, it is "prosumer" technology that is enabling consumers to also be producers who contribute to economic growth and innovation. Second, it exhibits positive network externalities where the benefits from broadband adoption accrue not just to individual consumers, but to other broadband users and society as a whole. Because of this the

[150]See TechNet, *A National Imperative: Universal Availability of Broadband by 2010*, January 15, 2002, available at http://www.technet.org/resources.dyn/2002-01-15.64.pdf; accessed June 27, 2007.

> social returns from investing in more broadband exceed the private returns of companies and consumers. As a result, market forces alone will not generate the societally optimal level of broadband, at least for the foreseeable future. In markets like this, public policies—in this case a proactive national broadband strategy—are needed to maximize overall societal welfare.[151]

Additionally, based on 2006 OECD data, the ITIF found that the United States had fallen to rank 12th behind countries including Korea, Japan, and Iceland.

A 2007 report of the National Telecommunications and Information Administration (NTIA), *Broadband in America*, describes federal efforts toward the vision of "universal, affordable access" to broadband technology: these include Federal Communications Commission (FCC) efforts to modify regulations in order to provide incentives for network investments by local telephone companies and to stimulate facilities-based investments by other providers, support for cable franchise reforms, and more timely and cost-effective access to rights-of-way on federal land.[152] Using data from various sources, the NTIA reported large increases in various types of high-speed network access (via telephone lines and cable, as well as high-speed wireless) and decreases in prices, over the period from 2001 to 2007.

Significantly, however, the NTIA report notes that "the lack of a single authoritative data set makes it difficult to establish with certainty whether broadband penetration has become ubiquitous, and this Report acknowledges the benefits of better data gathering tools."[153] In part, the piecemeal nature of the U.S. data compared with the data available for some other countries naturally reflects the multiplicity of federal, state, and local policies and regulatory regimes for different types of technologies and providers, as well as the large and growing number of providers (see Table 3.3). Nevertheless, data limitations make it difficult to piece together a complete, current snapshot of broadband in the United States or to evaluate the various claims regarding progress—or lags—in broadband availability. Moreover, the often wide differences between available "broadband" speeds in the United States and foreign counties complicate direct comparisons.

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[151]Robert D. Atkinson, *The Case for a National Broadband Policy*, The Information Technology and Innovation Foundation, Washington, D.C., June 2007.

[152]National Telecommunications and Information Administration, *Networked Nation: Broadband in America*, U.S. Department of Commerce, Washington, D.C., January 2008, pp. i, ii, available at http://www.ntia.doc.gov/reports/2008/NetworkedNationBroadbandinAmerica2007.pdf; accessed March 13, 2008.

[153]Ibid., p. 12.

TABLE 3.3 Number of Providers of High-Speed Lines Nationwide in the United States, 1999-2006, by Technology (over 200 kilobits per second in at least one direction)

	Number of Providers			
Month, Year	ADSL[a]	Cable Modem	All Other[b]	Total[c]
December 1999	28	43	65	105
December 2000	68	39	87	136
December 2001	117	59	122	203
December 2002	178	87	169	299
December 2003	274	110	246	432
December 2004	352	147	312	552
December 2005	820	242	835	1,347
December 2006	862	278	882	1,397

NOTES: According to the National Telecommunications and Information Administration, data through December 2004 include only providers with at least 250 lines per state, which were the only ones required to file; some historical data have been revised.

According to the 2002 report of the National Research Council entitled *Broadband: Bringing Home the Bits* (National Academy Press, Washington, D.C., 2002, p. 63), 200 kilobits per second is not adequate to support a single, TV-quality video stream to each house.

[a]ADSL, or asynchronous digital subscriber line, is carried over copper telephone lines. Because it provides essential infrastructure, broadband constitutes a foundation for leadership elsewhere. Attention here could produce benefits in a number of other areas, including health care (for example, access to broadband facilitates the transfer and analysis of electronic patient records and test results, particularly imaging). Note that the Federal Communications Commission has started a pilot funding program for a nationwide, broadband network dedicated to health care. See "Rural Health Care Pilot Program," available at http://www.fcc.gov/cgb/rural/rhcp.html; accessed October 18, 2007.

[b]"All Other" includes synchronous digital subscriber line (SDSL), traditional wireline, fiber, satellite, fixed and mobile wireless, and power line.

[c]Total is not simply the sum of the first three columns because some providers offer services using multiple technologies.

SOURCE: Data from National Telecommunications and Information Administration, *Networked Nation: Broadband in America,* U.S. Department of Commerce, Washington, D.C., 2008, Table 1, based on data from Federal Communications Commission, *High-Speed Services for Internet Access: Status as of December 31, 2006,* Washington, D.C., October 2007, Table 7.

Unlike the United States, Korea and Japan are small in area, with political institutions that favor a government role in industrial policy. While overall comparisons among countries are difficult, relative rankings in broadband penetration, speeds, and costs are nonetheless relevant because of the linkages between enabling infrastructure, demand leadership, and innovation leadership. For example, although the household penetration (fraction of households that subscribe to a broadband service) of broadband in Korea in 2007 was 90 percent, in the United States it was only 51 percent. The United States also lags in penetration per 100 inhabitants (see Table 3.2). In 2007 the average bandwidth was over 40 Mbps in Korea; it was under 10 Mbps in the United States; the average cost per 1 megabit of capacity was under $1 per month in Korea; it was almost $6 in the United States (see Table 3.2). Korea's high-speed infrastructure is widely credited with enabling its inhabitants to attain demand leadership in content-rich online games.

Japan is pursuing a very aggressive strategy of broadband deployment. It reportedly had the world's fastest broadband service in 2007 (see Table 3.2), a speed (on average, 93.7 Mbps) that enables Japanese consumers to watch full-screen, broadcast-quality television over the Internet. Japan's broadband lead over the United States is attributed in part to better physical infrastructure (newer and better telephone wires and shorter distances between the central office and homes); DSL in Japan is often 5 to 10 times as fast as the services widely offered by U.S. cable providers. However, Japanese industrial policy also plays a role: the Japanese government used subsidies, tax incentives, and regulation to promote high-speed broadband deployment:

- Government subsidies and tax incentives reportedly spurred Nippon Telegraph and Telephone Corp.'s (NTT's) nationwide build-out of fiber-optic lines (offering connection speeds of up to 100 megabits per second) to about 8.8 million Japanese homes. NTT, Japan's largest telephone company, was once government-controlled.
- Government regulation required large telephone companies (NTT, for example) to open up their copper wire networks to small Internet providers at prices that allowed these new broadband companies to charge as little as $22 a month for a DSL connection faster than almost all U.S. broadband services.

These levels of broadband service are enabling the development of a number of valuable new applications, such as low-cost, high-definition teleconferencing for telemedicine and advanced telecommuting.[154]

A fundamental step to being the world leader in information technology use is for the United States to deploy world-class broadband connectivity aggressively over the next decade. The United States currently lags behind other nations such as Japan and Korea in upgrading and deploying national broadband connectivity. Setting, and reaching, a highly ambitious target—such as making 1,000 megabits per second

[154] See Blaine Harden, "Japan's Warp-Speed Ride to Internet Future," *Washington Post*, August 29, 2007, p. A01, available at http://www.washingtonpost.com/wp-dyn/content/article/2007/08/28/AR2007082801990_pf.html; accessed August 29, 2007.

broadband connectivity available to 100 million American homes and small businesses by 2020—would enable the United States to leap well ahead of other countries in this area and to hold that lead.[155]

Governments can use economic incentives and targeted regulations to promote higher-speed connectivity across a common physical infrastructure. By using multiple wavelengths or colors, a single fiber today is able to carry 1 to 10 terabits of data.[156] U.S. terrestrial fiber networks have large amounts of "dark" (unused) fiber, and many fibers already lit could accommodate additional colors.[157] However, a large obstacle remains: the deployment of fiber or the installation of other upgrades to the "last mile" to connect all the endpoints (homes, businesses, government agencies, and other organizations) to the national networks. In the United States, the connectivity landscape is in part a product of historical policy goals (such as universal access for telephony) and the structure of U.S. economic regulation. There is merit in considering models for broadband deployment—for example, models of companies competing in the value-added services market using a common physical infrastructure,[158] or models whereby facilities-based competition is fostered.[159] Value-added services that can benefit from gigabit connectivity include movies on demand, multimedia Web browsing, many-to-many video communications, news groups, and so forth. However, the question remains as to who makes the infrastructure investments and who extracts the value of these services.

In the United States, the complex system of federal, state, and local governance and regulations can present numerous transactional bottlenecks, such as right-of-way restrictions and content franchising (for example, for video), to pursuing such approaches. These may tend to favor the

[155]This target is more ambitious than TechNet's proposal for accelerating broadband deployment and demand, which called for 100 megabit-per-second connectivity by 2010. See "Accelerating Broadband Deployment and Demand," available at http://www.technet.org/issues/broadband/; accessed September 7, 2007. A goal of gigabit connectivity would be useful in helping the United States leapfrog Japan and other nations now moving ahead in broadband deployment.

[156]See "Introducing DWDM [Dense Wavelength Division Multiplexing]," http://www.cisco.com/univercd/cc/td/doc/product/mels/cm1500/dwdm/dwdm_fns.htm; accessed September 7, 2007.

[157]TeleGeography Research, "Global Bandwidth Research Service: Executive Summary," Washington, D.C., 2008, available at http://www.telegeography.com/products/gb/index.php; accessed October 31, 2008.

[158]An inexact analogy would be the federal government paying for an interstate highway system and the private sector creating products (such as cars, gas stations, and motels) that benefit from the use of this infrastructure.

[159]See National Research Council, *Broadband: Bringing Home the Bits*, National Academy Press, Washington, D.C., 2002.

incumbents and slow overall progress toward attaining higher-speed, lower-cost broadband deployment that can support data-rich IT applications and services and enable leading-edge, customer-driven innovation by U.S. consumers.

Broadband Speeds and Capabilities

With respect to broadband, how fast is fast enough? That is, what bandwidth target is desired in order to enable multifaceted innovation? The "answer" is actually a moving target. Consequently, in the 2002 National Research Council report *Broadband: Bringing Home the Bits,* the Committee on Broadband Last Mile Technology did not set bandwidth-specific definitions for what constituted "broadbands," and it deliberately did not set specific bandwidth targets for policy makers. Instead, that committee established a functional definition: "Broadband services should provide sufficient performance—and wide enough penetration of services reaching that performance level—to encourage the development of new applications."[160] Furthermore, that committee recommended a more coherent, consistent broadband policy framework that is service-oriented, rather than being technology-centric.[161]

An important consideration in thinking about broadband leadership and the question of what bandwidth to "target" is the fact that broadband data rates considered adequate a few years ago are no longer sufficient to support new applications and services.[162] Higher-speed services attract more customers because they are more useful for high-data-rate applications (such as video). A higher-speed infrastructure stimulates multifaceted innovation.

In January 2008, the California Broadband Task Force (CBTF) published its final report, *The State of Connectivity: Building Innovation Through Broadband.*[163] The CBTF recommendations included building out "high speed" broadband infrastructure for all Californians, as well as promoting innovative uses of broadband technology. The CBTF adopted a working definition of broadband that includes a basic minimum speed (expected to increase over time) of 512 kbps.[164] Table 3.4, adapted with minor stylistic

[160]Ibid., p. 80.

[161]Ibid., pp. 32-33.

[162]Ibid.; see, especially, Ch. 2 for a discussion of then-current broadband technologies, speeds, and capabilities (as well as economic, regulatory, and policy factors).

[163]California Broadband Task Force, *The State of Connectivity: Building Innovation Through Broadband*, January 2008, available at http://www.calink.ca.gov/taskforcereport/; accessed March 17, 2008.

[164]Ibid., pp. 8, 12.

TABLE 3.4 Bandwidth Ranges Corresponding to Advanced Applications and Services

Bandwidth Range	Applications and Services Enabled
500 kbps–1 Mbps	Voice over IP [Internet Protocol] SMS [short message service] Basic e-mail Web Browsing (simple sites) Streaming Music (caching) Low-Quality Video (highly compressed)
1 Mbps–5 Mbps	Web Browsing (complex sites) E-mail (larger-size attachments) Remote Surveillance IPTV-SD (1-3 channels) [standard definition Internet Protocol television] File Sharing (small/medium) Telecommuting (ordinary) Digital Broadcast Video (1 channel) Streaming Music
5 Mbps–10 Mbps	Telecommuting (converged services) File Sharing (large) IPTV-SD (multiple channels) Switched Digital Video Video on Demand SD Broadcast SD Video Video Streaming (2-3 channels) HD [High-Definition] Video Downloading Low-Definition Telepresence Gaming Medical File Sharing (basic) Remote Diagnosis (basic) Remote Education Building Control and Management
10 Mbps–100 Mbps	Telemedicine Educational Services Broadcast Video SD and Some HD IPTV-HD [high-definition Internet Protocol television] Gaming (complex) Telecommuting (high-quality video) High-Quality Telepresence HD Surveillance Smart/Intelligent Building Control

continued

TABLE 3.4 continued

Bandwidth Range	Applications and Services Enabled
100 Mbps–1 Gbps	HD Telemedicine Multiple Educational Services Broadcast Video Full HD Full IPTV Channel Support Video on Demand HD Gaming (immersion) Remote Server Services for Telecommuting
1 Gbps–10 Gbps	Research Applications Telepresence Using Uncompressed High-Definition Video Streams Live Event Digital Cinema Streaming Telemedicine Remote Control of Scientific/Medical Instruments Interactive Remote Visualization and Virtual Reality Movement of Terabyte Data Sets Remote Supercomputing

SOURCE: Adapted from table entitled "What Is Broadband," p. 12, California Broadband Task Force, *The State of Connectivity: Building Innovation Through Broadband,* January 2008, available at http://www.calink.ca.gov/taskforcereport/; accessed March 17, 2008.

changes from the CBTF report, illustrates the types of applications and services made feasible by increasing bandwidth.

SUMMARY

In this chapter, the intention of the committee has been to illuminate the complex story of the evolution of the U.S. IT R&D ecosystem during the 1995-2007 period. First, it summarized the tumultuous business and technological changes experienced in the IT industry since 1995. The IT R&D ecosystem was affected by business transformations as the Internet was commercialized. In the process, the world experienced the largest venture capital investment bubble in history and an accompanying dramatic stock market bubble. The bubble may not have been entirely negative, because major new firms were created and the ways that people work and play were transformed. However, the collapse of the bubble did lead to a massive reduction in venture capital investing that some believe significantly retarded the commercialization of information technologies. Also, the collapse of the bubble may have discouraged students from entering the computer science and computer engineering fields, possibly leading to longer-term labor shortages.

The committee then turned its attention to the evolution of major platforms (such as Web 2.0, open-source development, new mobile access devices, and services executing within Internet data centers) and to the evolution of the major component sectors of semiconductors, computers, and software. In technological terms, there were two extremely powerful major developments during the period of study: The first of these was the mass popularization of the Internet for purposes of business, uses as tools, and recreational use. The second was the rise of mobile telephony. Information technologies in this time period became ubiquitous. In purely technical terms, IT has permeated nearly every part of daily existence and knitted the world closer together. With this change came a globalization in which, for the first time in history, engineers even in developing nations became more capable of being integrated in the global economy. By discussing India and China—two growing, potential IT industry giants—in particular, the committee places the situation of the U.S. IT R&D ecosystem into a global context. Today, it is no longer possible to understand the health and competitiveness of an isolated U.S. IT R&D ecosystem; it is now necessary to place it in a global context.

Finally, the committee considered the multifaceted nature of IT innovation. IT innovation is no longer mainly supplier-driven. Increasingly, customers are creating value through application innovations. As these new applications and IT-enabled services grow in importance, IT workers will increasingly need more than just technology skills. They will need in-depth business- and market-related knowledge to leverage technology use and differentiate their products and services. For the United States to lead in this new environment, an appropriate network infrastructure is required: ubiquitous, higher-speed, and more-affordable broadband.

With that as background for understanding the current state of the U.S. IT R&D ecosystem, the next chapter argues that the changes since 1995 have resulted in a globalized and fast-changing R&D ecosystem. If the United States does not navigate successfully in this global environment, it will no longer enjoy a position at the center of technological change, one that it has enjoyed for the past decade or more.

4

A Globalized, Dynamic Information Technology R&D Ecosystem

Profound changes have altered the U.S. national information technology (IT) research and development (R&D) ecosystem during the 1995-2007 period that is the focus on this report. The forces of globalization have shaken the foundations of the product, labor, and financial markets of the IT industry. They have created tremendous opportunity, but they also mean that the United States will have to work even harder to remain the global leader in IT R&D. R&D funding models, in both academic and industrial environments, have also evolved. Finally, the nature of the employer-employee relationship has continued to change across most sectors, but perhaps in a deeper way in the IT industry than anywhere else.

THE GLOBALIZATION OF PRODUCT AND LABOR MARKETS

As world markets such as those of India, China, and Eastern Europe open, competition for information technology workers has become global, with many U.S. companies looking the world over for the best talent, in the right place, at the right price. Most U.S.-based technology companies are now global from birth, driving innovation through collaborations with foreign technologists. For example, Figure 4.1 shows the significant increase from 1990 to 2005 in joint patenting by Silicon Valley inventors working with global teams. Figure 4.1 and Box 4.1 illustrate the global nature of IT innovation and sourcing.

Fueling the trend toward global sourcing are significant advances in telecommunications and networking technologies, as well as the evolu-

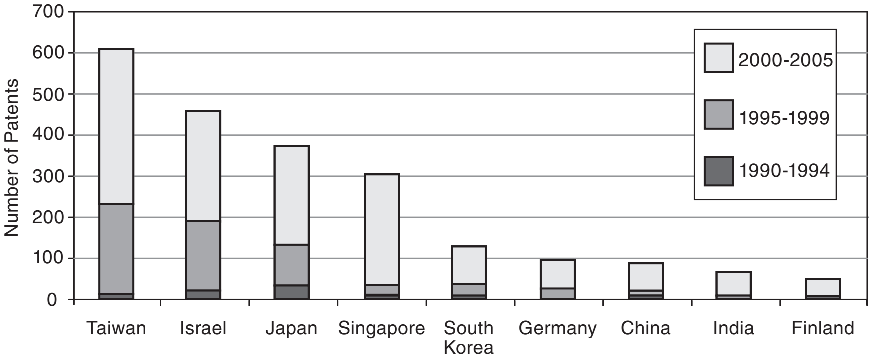

FIGURE 4.1 Foreign co-inventors listed on patents with Silicon Valley inventors, 1990-2005. SOURCE: AnnaLee Saxenian, University of California, Berkeley, presentation to the committee, Mountain View, Calif., February 23, 2007. Based on data analysis conducted by Collaborative Economics, Inc., Palo Alto, Calif., 2007.

tion of work and business processes. One powerful trend is for firms to consider what work they should retain internally and what they should purchase from outside vendors. The decision to purchase from an outside vendor work that was formerly done internally is termed *outsourcing*.

The other powerful trend is to scan the globe to decide where specific work processes should be undertaken. Often, firms are deciding that work can be done more efficiently and effectively in nations outside the United States. Of course, multinational firms have a long history of establishing subsidiaries abroad. What has changed in the past four decades is the increasing movement of work to developing nations. This practice is referred to as *offshoring*. More recently, there has been an upsurge in offshore outsourcing. Finally, this offshoring initially was for the manufacture of goods, but recently it has extended to the production of software and IT services.[1]

The Offshoring of U.S. IT Jobs

According to a recent study by the McKinsey Global Institute, the offshoring of work is more prevalent in the IT sector than it is in any of the other U.S. industry sectors studied. Published in 2005, the report estimated that by 2008, U.S. firms would offshore 18 percent of their demand for high-wage workers in the packaged-software sector and 13 percent

[1]Ron Hira and Anil Hira, *Outsourcing America: The True Cost of Shipping Jobs Overseas and What Can Be Done About It*, AMACOM, New York, N.Y., 2005.

BOX 4.1
iPod and iTunes: Internationalization of Design and Implementation

The Apple iPod is a digital music player with a highly stylized industrial design and an easy-to-use click-wheel user interface. It was not the first media player, but it is certainly the most commercially successful. The first model was announced on October 2001. By April 2007, over 100 million had been sold. As an example of the rapid design cycle of modern consumer products, five generations have been launched in only 6 years: the iPod, iPod mini, iPod shuffle, iPod nano, and video iPod.

The iPod plays audio and video media in standard formats, such as the open standards MP3 (MPEG-1 Audio Layer 3) and Apple proprietary formats.

A key element of Apple's success is the platform which it developed for digital media that encompassed its online store, iTunes. iTunes was introduced in April 2003 to sell individual songs at the price of $0.99 each. iTunes Media is encoded using Apple's AAC format with additional levels of encryption. The representation and its associated digital rights management system make it possible to authorize up to five computers and an unlimited number of iPods to play the files. An unlimited number of audio compact disks can be produced from the digital representation, but at a loss in quality.

The iPod offers an interesting case study in the internationalization of product design and implementation.[1] For the fifth-generation video iPod, among the most costly components are those contributed by companies headquartered in Japan (Toshiba, which supplies the hard drive), Korea (Samsung Electronics, which supplies the flash memory), and the United States (Broadcom Corporation, which supplies the multimedia processor). These components are in turn manufactured around the globe—in China (hard drive), in Taiwan or Singapore (media processor), and in Korea (the memory). The device is assembled by the Taiwanese firm Inventec Corporation in Mainland China. The analysis by Linden, Kraemer, and Dedrick indicates that out of a suggested retail price of $299, the cost of all components of the iPod is $144. Of the $155 price difference, $80 accrues to Apple and $75 to the distributor and retailer. Apple's value is the single largest component and is larger than that associated with the most expensive physical component, Toshiba's hard drive. This value of Apple represents the company's considerable competitive advantage in product conception, design, and marketing. Apple is amply compensated for the innovation that the firm has embedded in the product. The portion captured by U.S. firms—design, distribution, and sales—exceeds the value of its manufactured components. Although to a large extent the iPod is not manufactured in the United States, it is designed and sold here, and U.S. firms do quite well in the bargain.

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[1] See G. Linden, K. Kraemer, and J. Dedrick, "Who Captures Value in a Global Innovation System? The Case of Apple's iPod," Personal Computing Industry Center, University of California, Irvine, June 2007.

in IT services.[2] The McKinsey study used data from the U.S. Department of Labor's Bureau of Labor Statistics, as well as global company-level data, to derive a microeconomic picture of the extent of offshoring that had occurred and was expected to occur. The McKinsey study reported that the theoretical maximum global resourcing for packaged software and IT services represents from 44 to 48 percent of the industry's total employment. However, it is estimated that only 13 to 18 percent would be offshored, owing to a number of barriers ranging from management attitudes, to business process suitability, to lack of sufficient scale, to intellectual property protection.[3]

Another study, by Alan S. Blinder, also uses the Bureau of Labor Statistics data, devising a model that categorizes jobs into two groups—those that can be personally delivered (e.g., medical care, child care, and so forth) and those that can be "impersonally" delivered—that is, the job can be delivered to the end user electronically over long distances with little or no degradation in quality (for example, by call center operators).[4] Blinder's study places all IT jobs in offshorable categories and concludes that the percentage of offshorable IT jobs is roughly twice that estimated by the McKinsey study.[5]

To fully understand the real impact of offshoring in IT, however, one must match up the demand for workers with the supply of workers in the countries to which work is being outsourced. The McKinsey report concludes that although the potential talent pool in low-wage companies is large and growing rapidly, only 17 percent of the potential engineering talent supply is suited for work with international companies.[6] The report explains the reasons for its conclusion, which was based on interviews with 83 human resource managers in multinational companies: the reasons are

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[2]McKinsey Global Institute, *The Emerging Global Labor Market*, June 2005, available at http://www.mckinsey.com/mgi/publications/emerginggloballabormarket/index.asp; accessed August 27, 2007.

[3]As this report was being prepared for publication, a continued weakening of the U.S. currency had increased the cost of goods and services sourced from abroad. Such a trend decreases the benefits of outsourcing and offshoring for U.S. firms.

[4]Alan S. Blinder, *How Many U.S. Jobs Might Be Offshorable?*, Center for Economic Policy Studies [CEPS] Working Paper No. 142, CEPS, Princeton University, March 2007, available at www.princeton.edu/~blinder/papers/07ceps142.pdf.

[5]The notion that all IT jobs can be done remotely from the consumer and/or the core business was questioned by the committee. Many IT jobs are critical to the successful implementation of a business and/or are central to a firm's competitive differentiation. Further, IT R&D also involves work by large teams, who collaborate to create new platforms or services.

[6]Notice that the McKinsey study's conclusion is a point estimate. It is likely, even extremely likely, that nations and workers will try to improve their education and capabilities so that they can participate in the global economy, because in many of these nations this will ensure higher incomes.

dispersion of the labor force, domestic competition for talent, and individual limitations (e.g., inadequate language skills, limited practical skills, lack of cultural fit, inability to work on teams, and lower educational attainment) as well as considerable scarcity of middle-management skills.

This shortage of qualified staff is becoming a headache, according to a recent survey conducted by *The Economist*. According to the 600 executives of multinational companies that were surveyed, the shortage of qualified staff ranked as their biggest concern in China, second in Japan (after cultural differences), and fourth in India (after problems with infrastructure, bureaucracy, and wage inflation). *The Economist* goes on to say:

> Technical skills, particularly in information technology, are lacking in many parts of the region, even India. One of the main concerns is that there are not enough skilled graduates to fill all the jobs being created in a vibrant sector. Nasscom, which represents India's software companies, has estimated that there could be a shortfall of 500,000 IT professionals by 2010. This means companies recruiting at job fairs in India are having to make lucrative offers to capture the most promising students. Even a junior software engineer can expect to take home $45,000/year.[7]

A high turnover rate also helps to drive up wage costs.

The same article in *The Economist* reminds readers how supply and demand in labor markets must equalize through wages, and that the transfer of IT jobs from countries such as the United States to countries such as India and China, while politically and socially alarming, tends to be an overstated and self-regulating phenomenon. According to the McKinsey study, for IT and engineering-based services, if the United States and the United Kingdom continue at their current rate to concentrate their activities in India, China, and the Philippines, the U.S. and U.K. demand for engineers will fully absorb the supply of suitable engineers in India, China, and the Philippines by 2011.[8]

The U.S. Workforce and the Global IT Industry

Information technology professionals play an important role beyond the research and development organizations of technology vendors.

[7]"Capturing Talent," *The Economist*, August 16, 2007, available at http://www.economist.com/business/displaystory.cfm?story_id=9645045; accessed August 27, 2007. See Rafiq Dossani, *India Arriving: How This Economic Powerhouse Is Redefining Global Business*, American Management Association, New York, N.Y., 2007, for a discussion of how institutions of higher education in India are responding to this shortage.

[8]McKinsey Global Institute, *The Emerging Global Labor Market*, June 2005, available at http://www.mckinsey.com/mgi/publications/emerginggloballabormarket/index.asp; accessed August 27, 2007.

Because IT is transforming the foundational business processes of all corporations, IT professionals are increasingly critical to corporations in diverse sectors, such as retailing, hospitality, finance, and pharmaceuticals. Outside corporate walls, IT professionals are also at work in entrepreneurial and small businesses, as well as creating the next wave of software services through technologies such as the Web 2.0 infrastructure. Many are independent consultants.

IT professionals work on a wide variety of challenging technical projects, ranging from research into new scientific frontiers such as high performance computing, speech recognition technology, sensors or radio-frequency identification to new computing platform development and corporate business re-engineering (integrating technology to improve productivity significantly). A recent report from market research firm Forrester Research points to the sophistication of the IT professional job in today's enterprise.[9] According to Forrester, IT professionals can follow a variety of career paths—sourcing, management, innovation, architecture—each of which requires a combination of relationship-management, not just project-management, skills and activities.

Continued Strong Demand for IT Workers

According to data collected by the U.S. Department of Commerce, there are more professional IT workers in the United States today than ever before; "IT professional workers" in this case are defined as computer support specialists; computer programmers; computer systems analysts; computer software engineers; applications, computer, and information systems managers; computer software engineers; systems software, network, and computer systems administrators; all other computer specialists; network systems and data communications analysts; database administrators; computer hardware engineers; computer and information scientists; and computing researchers. In fact, a recent report on globalization and the offshoring of software states:[10]

> According to the U.S. Bureau of Labor Statistics reports, despite a significant increase in offshoring over the past five years, more IT jobs are available today in the US than at the height of the dot.com boom. Moreover, IT jobs are predicted to be among the fastest-growing occupations over the next decade.

[9] Lorie M. Orlov, Samuel Bright, and Lauren Sessions, *Is There a Career Future in Enterprise IT?* Forrester Research, Cambridge, Mass., August 10, 2006.

[10] Association for Computing Machinery Job Migration Task Force, *Globalization and Offshoring of Software: A Report of the ACM Job Migration Task Force,* W. Aspray, F. Mayadas, and M. Vardi, eds., Association for Computing Machinery, New York, N.Y., 2006.

A recent report from the Bureau of Labor Statistics that contains occupational employment projections through 2016 states:

> Computer and mathematical science occupations are projected to add 822,000 jobs—at 24.8 percent, the fastest growth among the eight professional subgroups. The demand for computer-related occupations will increase in almost all industries as organizations continue to adopt and integrate increasingly sophisticated and complex technologies. Growth will not be as rapid as during the previous decade, however, as the software industry begins to mature and as routine work is outsourced overseas. About 291,000—or 35 percent—of all new computer and mathematical science jobs are anticipated to be in the computer systems design and related services industry. The management, scientific, and technical consulting services industry is projected to add another 86,000 computer and mathematical science jobs. This expected 93-percent increase is due to the growing need for consultants to handle issues such as computer network security.[11]

The report also states that among all fields of science and engineering, "computer specialist" is projected to account for 77 percent of all job growth and 66 percent of all available jobs (which includes both growth and positions available due to retirement).

Data from the National Science Foundation (NSF) reinforce the picture of a relatively strong job market for science and engineering graduates, particularly for computer and information science graduates. According to NSF's Scientists and Engineers Statistical Data System, the overall unemployment rate of scientists and engineers in the United States was 2.5 percent in 2006, compared with 3.2 percent in 2003; 2.5 percent is the lowest rate since the early 1990s. For computer/information scientists, the overall unemployment rates were 2.5 percent in 2006 (down from 4.0 percent in 2003).[12] Also, according to a 2006 survey from NSF, the median salary level for computer and information science graduates with bachelor's degrees was $45,000 (the median for all science and engineering fields was $39,000); at the master's level, the median salary was $65,000 (the median for all science and engineering fields was $56,000).[13]

[11]Arlene Dohm and Lynn Shniper, "Occupational Employment Projections to 2016," *Monthly Labor Review,* Bureau of Labor Statistics, Washington, D.C., November 2007, pp. 86-125.

[12]Nirmala Kannankutty, *Unemployment Rate of U.S. Scientists and Engineers Drops to Record Low 2.5% in 2006,* Science Resources Statistics InfoBrief, NSF 08-305, National Science Foundation, Washington, D.C., March 2008. For electrical/computer hardware engineers, overall unemployment rates for 2006 were higher than for computer/information scientists, but still improved: 3.3 percent (down from 5.5 percent in 2003).

[13]Steven Proudfoot, *An Overview of Science, Engineering, and Health Graduates: 2006,* NSF-08-34 (revised), March 2008, available at http://www.nsf.gov/statistics/infbrief/nsf08304/,

Strong Concerns About Sustaining a Strong IT Workforce

Despite the demand, the number of students specifying an intention to major in computing and information sciences has dropped significantly in the past 6 years. For example, according to College Board data for 2006, the number of students indicating on their SAT test a desire to major in computing and information sciences has dropped by almost 50 percent since 2001.[14] Also according to the College Board, in 2006 the SAT mathematics scores (an indicator for success in IT) of those intending to major in computing and information sciences averaged 478, far lower than the mathematics scores for those intending to major in other scientific and mathematical disciplines. These statistics not only point to a sharp decline in the number of students entering the IT educational pipeline,[15] but also raise a concern about the skill sets of those attracted to the discipline.

The problem of declining enrollments in the computing disciplines (as compared with the projected demand) is compounded by the severe lack of participation of underrepresented groups in IT. Although the participation of women, minorities, and people with disabilities in other science, technology, engineering, and mathematics fields is rising overall, their participation is especially low, and even declining, in computing. In 2006, women received 59 percent of all bachelor's degrees, but only 21 percent of computer science degrees.[16] African-American and Hispanic graduates received only 10 percent and 6 percent of 2004 computer science degrees, respectively. Women and minorities are even more severely underrepresented in positions requiring a doctoral degree. Of the 1,189 Ph.D. graduates in computer science or computer engineering in 2005, only 18 percent were women, and only 38 of the total 1,189 (3 percent)

accessed April 9, 2008. See also Jay Vegoso, "Employment and Salaries of Recent CS Graduates," *CRA Bulletin*, March 25, 2008, available at http://www.cra.org/wp/index.php?p=141; accessed April 9, 2008.

[14]College Board, *2006 College Bound Seniors: Total Group Profile Report,* 2006, available at http://www.collegeboard.com/prod_downloads/about/news_info/cbsenior/yr2006/national-report.pdf; accessed February 20, 2007.

[15]Although the following facts are not necessarily a perfect surrogate for high school students' interest in computer science, it is interesting to note that about 12,000 students in the class of 2007 took the Computer Science A Advanced Placement (AP) test; about 4,000 took the more rigorous Computer Science AB test. For comparison, about 14,000 students took the Art History and French tests; almost 50,000 took the Economics Macro test, and about 28,000 took the Economics Micro test. See College Board, *The 4th Annual AP Report to the Nation,* Appendix B, 2008, available at http://professionals.collegeboard.com/profdownload/ap-report-to-the-nation-2008.pdf; accessed April 4, 2008.

[16]National Center for Education Statistics, *Integrated Postsecondary Educational Data System (2005-06),* U.S. Department of Education, Washington, D.C., May 1, 2007.

were members of underrepresented minorities (African-American, Native American, or Hispanic).[17]

The picture is also bleak in the workforce. In 2006, the percentage of women in management, professional, and related occupations was 50.6 percent, whereas the percentage of women in computer and mathematical occupations was only 25.6 percent.[18]

Such low participation has implications beyond the nation's ability to create and sustain a sufficiently large IT workforce. Women and minorities can bring different life experiences and perspectives to innovation, which lead to the design of products and services that benefit a broader range of people. Such perspectives are especially important, considering the changing demographics of the U.S. population[19] as well as the global market for IT products and services. If U.S. companies intend to maintain their competitive advantage both at home and abroad, they must seek the input of a broader segment of the population to achieve innovation. For example, a recent analysis of innovation and diversity with respect to IT patenting revealed that within the United States, mixed-gender invention teams produced the most frequently cited IT patents—with citation rates that were 26 to 42 percent higher than the norm.[20]

How can young people be encouraged to enter computing fields? One essential ingredient is to ensure a strong national IT educational pipeline that prepares and encourages all qualified students regardless of race, gender, or ethnicity to enter the discipline. Without sustained attention and additional measures to attract and retain all qualified students, it will be especially difficult to reverse the negative trends.[21]

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[17]S. Zweben, "Record PhD. Production Continues; Undergraduate Enrollments Turning the Corner," *Computing Research News* 19(3):7-22, 2007.

[18]Bureau of Labor Statistics (BLS), *Current Population Survey: Household Data: Annual Averages: 2007*, BLS, Washington, D.C., Table 11: Employment by detailed occupation, sex, race, and Hispanic ethnicity, p. 212.

[19]Council of Economic Advisors for the President's Initiative on Race, *Changing America: Indicators of Social and Economic Well-Being by Race and Hispanic Origin,* U.S. Government Printing Office, Washington, D.C., September 2007, available at http://www.access.gpo.gov/eop/ca/index.html.

[20]Catherine Ashcraft and Anthony Breitzman, *Who Invents IT? An Analysis of Women's Participation in Information Technology,* National Center for Women and Information Technology, Boulder, Colo., March 2007.

[21]For examples of new measures to improve STEM education and strengthen educational opportunities for students in K-12 (such as ways to retain and reward the most effective teachers), see "Testimony of William H. Gates, Chairman, Microsoft Corporation and Co-Chair, Bill & Melinda Gates Foundation, Before the Committee on Science and Technology, United States House of Representatives, March 12, 2008," available at http://democrats.science.house.gov/Media/File/Commdocs/hearings/2008/Full/12mar/gates_testimony_12mar08.pdf; accessed March 17, 2008.

Concerns About K-12 IT/Computing Education and Talent Generation

Concerns about talent generation are exacerbated by the state of the kindergarten-through-grade-12 (K-12) IT/computing education system in the United States. In its report *The New Educational Imperative: Improving High School Computer Science Education,* the Computer Science Teachers Association (CSTA) correctly assesses the situation as follows:

> Computers have infiltrated all areas of society, and there is now a clear link between technology, innovation, and economic survival. In light of this, one would expect a move within our society to support and standardize computer science education. Yet, no national K–12 computer science curriculum exists. Lack of leadership on high school computer science education at the highest legislative and policy levels has resulted in insufficient funding for classroom instruction, resources, and professional development for computer science teachers. In addition, complex and contradictory teacher certification requirements as well as salaries that cannot possibly compete with industry make it exceedingly difficult to ensure the availability of exemplary computer science teachers. In the face of confusing definitions of computer literacy, information fluency, and the various sub-branches of computer science itself, many schools have lost sight of the fact that computer science is a scientific discipline and not a "technology" that simply supports learning in other curriculum areas. Computer science is not about point and click skills. It is a discipline with a core set of scientific principles that can be applied to solve complex, real-world problems and promote higher-order thinking. In short, knowledge of computer science is now as essential to today's educated student as any of the traditional sciences.[22]

In addition to resources, appropriate information technology fluency objectives for K-12 are needed.[23] Recent research by the CSTA shows the following:

- Only 26 percent of schools require students to take a computer science (CS) course;
- Only 40 percent of schools even offer advanced placement (AP) CS;
- Lack of time in the students' schedules is the greatest impediment to students taking computing courses;

[22]Computer Science Teachers Association (CSTA), *The New Educational Imperative: Improving High School Computer Science Education,* available at http://csta.acm.org/; accessed August 27, 2007.

[23]For an early assessment of fluency issues, see National Research Council, *Being Fluent with Information Technology,* National Academy Press, Washington, D.C., 1999.

- 89 percent of high school computer science teachers say that they experience a sense of isolation and a lack of collegial support in their schools and in their districts;
- Most administrators do not understand that computing is a scientific discipline just like physics and biology;
- There is no consistency in CS teacher certification requirements;
- Computing teachers do not receive the professional development that they need to keep their teaching and technical skills current;
- Administrators, legislators, and congressional committees do not understand the link between supporting K-12 computing education and economic and workplace issues.[24]

Such concerns about the professional IT pipeline and talent pool have arisen as the U.S. share of worldwide bachelor's and doctoral degrees in science and engineering has decreased significantly. The relative decline in the U.S. global position in science and technology overall is also evident in the falling U.S. share of global R&D investment, patents, scientific publications, and researchers (see Table 4.1). If it is to maintain its foundation for competitive strength, the United States faces a long-term need to attract qualified people to science and technology careers.[25]

THE GLOBALIZATION OF VENTURE CAPITAL

Until the late 1980s, for all intents and purposes the United States was the only nation with a vibrant venture capital industry that supported technology-based start-ups.[26] For this reason the United States was in a privileged position. For an entrepreneur seeking to build a global-class IT firm, it was necessary to come to the United States—and many entrepreneurs did. It was in the 1990s that venture capital industries in Taiwan and Israel began growing, with the Taiwanese venture capitalists funding manufacturing firms such as Quanta Computer Incorporated and ASUSTeK Computer; in Silicon Valley they funded start-ups particularly

[24]Computer Science Teachers Association (CSTA) Curriculum Improvement Task Force, *The New Educational Imperative: Improving High School Computer Science Education,* CSTA, Association for Computing Machinery, New York, N.Y., February 2005.

[25]For a business-oriented discussion of the importance of maintaining the STEM pipeline, see, for example, Testimony of William H. Gates, Chairman, Microsoft Corporation and Co-Chair, Bill & Melinda Gates Foundation, Before the Committee on Science and Technology, United States House of Representatives, March 12, 2008, available at http://democrats.science.house.gov/Media/File/Commdocs/hearings/2008/Full/12mar/gates_testimony_12mar08.pdf; accessed March 17, 2008.

[26]The committee thanks Martin Haemmig, Martin Haemmig International, for providing much of the venture capital data used in this section.

TABLE 4.1 Declining Relative U.S. Standing in Worldwide Share of Various Areas of Science and Technology: Share of Global Total (in percent) for Selected Years from 1985 to 2003

Area	1985	1986	1988	2002	2003
Investment in domestic research and development		46			37
New U.S. patents		54			52
Scientific publications			38		30
Scientific researchers	41			29	
Bachelor's degrees in science and engineering	39			29	
New doctorates in science and engineering		52			22

NOTE: Data are only for select years, as provided in source.
SOURCE: Data from Council on Competitiveness, *Competitiveness Index: Where America Stands*, Washington, D.C., 2007, p. 67.

in semiconductor design.[27] The Israeli firms funded by venture capitalists were concentrated in IT (particularly in enterprise software, communications technologies, and security), and many of them immediately opened U.S. offices and later went public on the NASDAQ. For both countries, strong relationships with the United States and U.S. venture capitalists were important for their growth.[28]

Changing Patterns in Global Venture Capital

For at least the past three decades, the U.S. venture capital limited partnerships have been the beneficiaries of inflows of capital from around the world, particularly from European financial institutions. This capital was primarily invested in U.S. technology start-up firms. During that period, the United States was the destination of choice for investment funds, entrepreneurs, and venture capital firms.

[27]For example, for evidence from semiconductor design firms that went public on U.S. markets, see M. Kenney and D. Patton, "The Coevolution of Technologies and Institutions: Silicon Valley as the Iconic High-Technology Cluster," in P. Braunerhjelm and M. Feldman, eds., *Cluster Genesis: Technology-Based Industrial Development,* Oxford University Press, Oxford, England, 2006, pp. 38-60.

[28]Martin Kenney, Martin Haemmig, and W. Richard Goe, "Venture Capital," in *Innovation in Global Industries: U.S Firms Competing in a New World,* Jeffrey T. Macher and David C. Mowery, eds., The National Academies Press, Washington, D.C., 2008. On Israel, see Gil Avnimelech and Morris Teubal, "Venture Capital Start-up Co-evolution and the Emergence and Development of Israel's New High Tech Cluster," *Economics of Innovation and New Technology* 13(1):33-60, 2004.

As late as 1995, there were few globalized venture capital firms, such as Apax Partners, Advent, Sofinnova Ventures, Hambrecht and Quist Capital Management, and Walden International, but most of the elite U.S. IT-oriented venture capital firms invested in international deals rarely and idiosyncratically. During the rise of the dot-com era, start-up firms from Europe, Asia, and Latin America were able to secure funding through European and U.S. markets. This encouraged U.S. venture capitalists to expand their investments abroad. However, it was not until after the collapse of the stock market bubble in 2000 that U.S. venture capital firms decidedly expanded their global reach, with a particular focus on China, Israel, and India. U.S. venture capitalists began building linkages with venture capital firms in other nations and, if and when there was a sufficient deal flow, contextual understanding, and relationships, they developed more permanent foreign operations abroad. According to Ernst & Young, over the period 2005 to 2006, 19 percent of venture capital investing was done across national borders and continents,[29] an increase of 250 percent from 5 years earlier. Another 10 percent of the deals are intra-European or intra-Asian. Thus nearly 30 percent of venture capital is invested across borders.

As Table 4.2 illustrates, North America (predominantly, the United States) clearly remains the most important venture capital location in the world. First, more venture capital is invested there than in the rest of the world combined. Second, it is at the center of the flows of venture capital, with more flowing into and out of North America than to and from any other region. Finally, with the exception of U.S. centricity and the resultant flows into and out of North America, there are only minimal interregional flows of capital. This situation is unlikely to change soon, although that is no reason for complacency: the sophistication of non-U.S.-based venture capitalists and the track record of their funds are beginning to rival those of U.S. venture capitalists and the success of their funds, thereby creating unavoidable competition for both deal flow and limited-partner capital over the long term.

The United States continues to invest more venture capital in IT than do all other regions combined, despite a decline of approximately 8 percent in such U.S. investments from 2003 to 2007. The U.S. investment across all sectors was roughly flat over this period with the exception of communications, which continued to drop, suggesting a powerful hang-

[29]Ernst & Young, *Acceleration: Global Venture Capital Insights Report 2007*, 2007, available at http://www.indiavca.org/upload/library/29_E&Y_Global_VC_Insight_Report_2007.pdf; accessed November 2008.

TABLE 4.2 Interregional Flows of Venture Capital Investment (in millions of U.S. dollars), by Location of Firm and Location of Investment, 2005

Location of Venture Capital Firm (Origin of Investor)	Location and Amount of Investments ($ million)					
	North America	Europe	Israel	Asia	Rest of World	Total
North America	21,914	1,837	158	798	218	24,925
Europe	840	3,486	35	163	59	4,583
Israel	139	30	208	0	0	377
Asia	502	118	4	502	3	1,129
Rest of world	52	42	7	59	231	391
Total	23,447	5,513	412	1,522	511	31,405

SOURCE: Compiled by Martin Haemmig, Martin Haemmig International, www.martinhaemmig.com, from data provided by National Venture Capital Association/Venture Economics, European Venture Capital Association, *Asian Venture Capital Journal,* and Israeli Venture Capital Association.

over effect from the collapse of the dot-com bubble. In Europe and Israel, the decline was greater and spread into nearly every sector.[30]

The greatest recent change in the location of venture capital investing is the emergence of China as a major focus of the investment of venture capital, in particular by foreign firms. In 2006, Chinese firms received $1.9 billion in venture capital investment, making China the second-largest national recipient of venture capital investment.[31] In IT, much of the venture capital investment in China thus far has been in firms that are adapting Western Internet business models for China (for example, gaming, travel sites, job sites, portal, search, and so forth). One area of innovation has been in the mobile applications field. Such investments require relatively little technological innovation but can be very successful, as the Chinese market and online population are already very large and growing

[30]Martin Haemmig, Martin Haemmig International, presentation to the committee, data on cumulative capital invested in IT by region and sector, based on Ernst & Young data, Mountain View, Calif., February 23, 2007.

[31]Ernst & Young, *Acceleration: Global Venture Capital Insights Report 2007*, 2007, available at http://www.indiavca.org/upload/library/29_E&Y_Global_VC_Insight_Report_2007.pdf; accessed November 17, 2008.

very rapidly. Thus far there have been very few impactful R&D-intensive Chinese start-ups funded by venture capitalists,[32] and unlike Japan or Europe, no global IT brand except possibly Lenovo and Huawei has emerged out of China despite its economic prowess. However, there can be little doubt that the technological and scientific level of Chinese R&D is advancing rapidly, and given the size of the market there is the distinct possibility that global-class IT firms could emerge in the next 5 years.

India differs from China in important respects. Indian start-up firms have access to talented engineers and benefit from a sizable local market. However, growth is hampered by a scarcity of management skills and a weak, though improving, business infrastructure. In terms of developing an IT R&D ecosystem in India capable of generating top-quality start-ups, the role of the R&D operations of Silicon Valley firms in India has to be considered. Already, firms such as Adobe Systems, Broadcom Corporation, Cisco Systems, Google, Intel Corporation, Juniper Networks, Oracle, and many more are developing products in India. The results of this hands-on experience will be seasoned product-development specialists. It is almost certain some of these engineers will become entrepreneurs. Despite the scarcity of management skills, indigenous and foreign venture capitalists are already looking for opportunities in India. This is a likely indication that many Indian start-ups will begin to emerge and receive funding over the next several years.

Prior to the late 1990s, the United States benefited from the inflow of capital from other nations. Today the flows of capital are bidirectional. U.S. venture capitalists are globalizing rapidly as IT entrepreneurship becomes more globally dispersed. U.S. venture capitalists are also mobilizing their networks and unique know-how to benefit their portfolio firms regardless of location. As long as the U.S. venture capitalists retain their edge in the soft skills required to build successful start-up companies, they will remain at the center of gravity of the global start-up deal flow and will likely retain their centrality despite this globalization. If, however, portfolio financial returns degrade, if the number of successful initial public offerings (IPOs) fails to recover to historical levels, and if the weight of ecosystem frictions (discussed later in this chapter) proves impossible to overcome, the asset class will weaken, and the globalization of venture capital could cause non-U.S. firms to rise to prominence.

[32]The most R&D-intensive Chinese IT firms are probably Huawei Technologies and ZTE Corporation, neither of which was funded by venture capital. Lenovo is another important Chinese IT firm, which purchased IBM's personal computer division, but Lenovo is not known for cutting-edge IT research or products.

TABLE 4.3 Decline in Percentage of Venture Capital Invested in Information Technology Between 2001 and 2006

Venture Capital Investments	2001 Total Invested Capital ($ billion)	2001 IT Share of Total (percent)	2006 Total Invested Capital ($ billion)	2006 IT Share of Total (percent)
In the United States	36.4	66	25.7	48
In Europe	9.8	60	5.2	51
In Israel	2.2	79	1.4	72
In China	2.9[a]	73	1.9	49

[a]China venture investment for 2001 is skewed by $1 billion investments in each of two companies: Heijan Technology and Semiconductor Manufacturing International Corporation (SMIC).
SOURCE: Martin Haemmig, Martin Haemmig International, "China's and Israel's Role in 'IT' Through Venture Capital," presentation to the committee, Mountain View, Calif., February 23, 2007. Based on data from Ernst & Young and VentureOne, Q1 2007.

Venture Capital Investment in IT

U.S. venture capitalists continue to invest more than those of any other nation in the IT fields: in the first half of 2006 they invested $7.15 billion in IT, with the software and communications segments receiving the most capital. In the first half of 2006, the rest of the world's venture capital investment in IT firms was not even one-third that of the United States.[33] Nevertheless, the percentage of venture capital investment in IT declined from 66 percent of the U.S. total to approximately 55 percent in the first half of 2006. As Table 4.3 indicates, total venture capital investments declined in the United States, Europe, Israel, and China from 2001 to 2006 (after the collapse of the Internet bubble). This global decline was accompanied by a decline in the percentage of total venture capital invested in IT. There was also a slight decrease in the number of IT firms funded, from 3,420 in 2000 to 3,192 in 2007.[34] Venture capital investment in the U.S. IT firms dropped from year 2000, but appears to have stabilized by 2007. From the perspective of this committee, there can be no doubt that with respect to venture capital funding of IT firms, the United States completely dominates other areas of the world. Moreover, with the exception of China and India, the other major locations of venture capital

[33]Martin Haemmig, "China's and India's Role in 'IT' Through Venture Capital," presentation to the committee, Mountain View, Calif., February 23, 2007. Based on data from Ernst & Young and Venture One.

[34]Ibid.

investing suffered similar or even greater declines in IT-related investment between 2001 and 2006.

FRICTIONS IN THE U.S. IT R&D ECOSYSTEM

It appears that a number of inefficiencies have been growing in the U.S. IT R&D ecosystem over the past several years. They do not seem to be concentrated in any single area. Together, they form a pattern of frictions that, over time, could hurt the health and competitiveness of the U.S. ecosystem—particularly given its increasingly global nature. Symptoms of these frictions can be found by examining the data on technology company initial public offerings, technology company mergers and acquisitions (M&As), and overall venture capital activity during the 1995-2006 period.

Although success stories like that of Google (see Box 3.2 in Chapter 3) leave many with the superficial impression that all is well with venture-funded innovation, closer examination suggests that Google is a unique case in scope and magnitude and that the field of play in recent years has lacked depth and breadth. Although reaching an IPO is not a guarantee of long-term future success, IT companies that do not have the opportunity to tap public equity markets will not have the capital required to grow into major industry players and to contribute meaningfully to the creation of high-quality jobs in this country.

In 2006, there were only 40 U.S. technology IPOs; by contrast, in 1995, there were 195.[35] The year 1995 was not yet caught in the distortion of the technology bubble of the late 1990s (the number of technology IPOs peaked during the bubble, at 381 in 1999), and the year 2006 is no longer held back by the post-technology bubble crash. Instead, these numbers represent a meaningful downward trend that has become even more pronounced in 2008[36] and is unlikely to reverse in the near term.

This decline in IPOs is not due to a retrenchment of overall U.S. venture capital activity. The total amount of venture capital invested in the United States in 2006 was reported to be about $26 billion, compared with just over $8 billion in 1995 (see Table 4.4). Similarly, almost twice as

[35]Paul Deninger, Jeffries and Company, presentation to the committee, Boston, Mass., April 19, 2007, citing data from Thompson Financial and Jeffries Broadview IPO Database. The figure excludes telecommunications providers, Internet Protocol service providers, and transactions in which under $15 million were raised.

[36]See, e.g., Ernst & Young, "Global IPO Activity Fallen by More Than Half Since 2007: Lowest Number of Deals over an 11 Month Period Since 1995," Ernst & Young, London, December 9, 2008. Available at http://www.ey.com/global/content.nsf/International/Media_-_Press_Release_-_Global_IPO_activity_fallen_by_more_than_half_since_2007; accessed December 11, 2008.

TABLE 4.4 U.S. Venture Capital, Merger and Acquisition (M&A), and Technology Company Initial Public Offering Activity, 1995-2006

Year	Venture Capital Deals (no.)	Total U.S. Venture Capital Investment ($ billion)	U.S. M&A Transactions: IT, Media, Telecommunications (no.)	U.S. Technology Company Initial Public Offerings (no.)
1995	1,844	8.1	1,461	195
1996	2,573	11.3	1,956	243
1997	3,156	14.9	2.652	155
1998	3,647	21.1	2,847	116
1999	5,507	54.1	3,602	381
2000	7,911	105.2	3,704	264
2001	4,481	40.7	2,403	26
2002	3,091	21.9	2,452	22
2003	2,914	19.8	2,000	22
2004	3,069	22.5	2,294	52
2005	3,127	23.1	2,524	54
2006	3,533	26.3	2,584	40

SOURCES: Venture capital deal data from PricewaterhouseCoopers/National Venture Capital Association *MoneyTree* data, available at https://www.pwcmoneytree.com/MTPublic/ns/nav.jsp?page=notice&iden=B; accessed August 28, 2007. Data on initial public offering and merger and acquisition transactions from Paul Deninger, Jeffries and Company, presentation to the committee, Boston, Mass., April 19, 2007, citing data from Ernst & Young.

many venture capital deals (companies financed) were reported for 2006 as for 1995.[37]

This increase in overall venture activity (amounts invested, numbers of deals) does not correspond to an increase in the number of venture capital firms. To the contrary, the number of firms has decreased. Fueled by the bubble, the number of U.S. venture capital firms making at least one investment in a given year reached 2,206 in the peak year 2000. As is often the case in such situations, the weaker players do not survive and the industry must consolidate: by 2005, this number had dropped to 960.[38]

What accounted for a much lower number of IPOs in 2006 as compared with 1995? Although the IT industry did traverse a rough period

[37]According to PricewaterhouseCoopers/National Venture Capital Association *MoneyTree* data, available at https://www.pwcmoneytree.com/MTPublic/ns/nav.jsp?page=notice&iden=B; accessed August 28, 2007.

[38]Paul Deninger, Jeffries and Company, presentation to the committee citing data from Ernst & Young, Boston, Mass., April 19, 2007.

from 2001 to 2003, IT spending in the United States has bounced back, new technology platforms have emerged and attracted a new generation of IT start-up companies, and IT has become more widely deployed and economically and socially important. One factor in this changing scene has been a shift toward M&As: a greater percentage of young technology companies chose to merge with a larger strategic partner rather than becoming a publicly traded company on a U.S. exchange. As shown in Table 4.4, the number of M&A transactions in the IT, media, and telecommunications sectors rose steadily from 1,461 in 1995 to a peak of 3,704 in 2000, then dropped to an average of about 2,400 transactions annually during the period 2001 to 2006.[39] However, although M&As have become the preferred exit of U.S. IT companies, the number of M&A transactions has not grown in recent years. The juxtaposition of these two trends (a rapid decline in U.S. IT IPOs and a stable, but flat, M&A environment) suggests why the returns to venture funds from their IT investments have sharply declined over the period of this study's scope. With this decline in returns from IT investments, venture investors will naturally rebalance their portfolios, making fewer IT investments in favor of investments in other sectors.

The reasons that may explain the decline in IPOs are multiple and hard to quantify. It is instructive to note that the decline has been a U.S. phenomenon. Even as U.S. public equity markets such as NASDAQ and the New York Stock Exchange (NYSE) have experienced a dearth of IT IPOs in recent years, other markets outside the United States have been more successful and have managed to attract listings from companies that a decade ago would not have considered an IPO in other than a U.S. market. Clearly, the globalization of financial markets and the increased competitiveness of exchanges such as the London Stock Exchange's Alternative Investment Market (AIM) or the Hong Kong exchange have contributed to the weakness described in this section.[40] Another factor may be Chinese government incentives for companies in China to use domestic exchanges for their public offerings. However, these factors do not appear to fully explain the decline.

Over the years, new laws and regulations have been introduced that appear to have had negative and unanticipated side effects on the effectiveness of the U.S. IT R&D ecosystem. Moreover, there are indications that older laws and regulations have not been fully adapted to the chang-

[39]Paul Deninger, Jeffries and Company, presentation to the committee, citing data from Jeffries Broadview Global Mergers 7 Acquisitions database, Boston, Mass., April 19, 2007. M&A transactions dipped to only 2,000 transactions in 2003, and then recovered. There were 2,584 M&A transactions in 2006.

[40]Paul Deninger, Jeffries and Company, presentation to the committee, Boston, Mass., April 19, 2007.

ing realities of a globalized IT environment that is based on new technological platforms and new innovation methods.

As one example, a major source of friction for young IT companies is the current U.S. patent system. Patents are being more actively acquired and vigorously enforced in recent years.[41] Firms are facing dramatically increased hazards of litigation as plaintiffs and even more rapidly increasing hazards as defendants.[42] The increase in litigation cannot be explained by the patenting rate, the level of R&D activity, firm value, or industry composition,[43] leaving changes in patent system implementation (for example, increases in the number of patents being sought and imperfections in patent issuance[44]) as the most likely explanations.

Firms that spend more on R&D are more likely to be sued, and firms that acquire more patents are more likely to sue. The sharp increase in the probability of being sued per R&D dollar spent implies an increase in the "tax" that litigation imposes on innovation. Small firms face much higher marginal enforcement costs and marginal taxes on R&D.

The number of patent lawsuits filed annually in the United States began to rise in the late 1980s and doubled (to almost 1,600 a year) during the 1990s.[45] Simultaneously, the cost to try a patent case in the United States has also increased far more sharply than R&D budgets have. According to a 2001 economic survey conducted by the American Intellectual Property Law Association, the median cost to try a patent case with $1 million to $25 million at risk was almost $1.5 million.[46] By 2003, this amount had increased to $2 million. Moreover, as the amount at risk increases, litigation becomes more expensive. In cases with more than $25 million at risk, the litigation costs were $3 million in 2001 through 2004,

[41]National Research Council, *A Patent System for the 21st Century*, The National Academies Press, Washington, D.C., 2004, p. 19.

[42]According to Bessen and Meurer, the number of patent lawsuits filed annually in the United States doubled during the 1990s, from almost 800 in 1990 to almost 1,600 in 1999; their research also "suggests that patent litigation can affect innovation incentives." James Bessen and Michael Meurer, "The Patent Litigation Explosion," paper presented at American Law and Economics Association Annual Meeting, 2005, p. 1 and Figure 1, available at http://papers.ssrn.com/sol3/Papers.cfm?abstract_id=831685#PaperDownload; accessed March 6, 2008. For litigation hazard findings, see ibid., Table 2.

[43]Ibid., Abstract.

[44]For discussion of patent system implementation and issuance, see, for example, National Research Council, *A Patent System for the 21st Century*, The National Academies Press, Washington, D.C., 2004, Chs. 3 and 4.

[45]James Bessen and Michael Meurer, "The Patent Litigation Explosion," paper presented at the American Law and Economics Association Annual Meeting, 2005. These analyses are based on Derwent data from the United States Patent and Trademark Office.

[46]American Intellectual Property Law Association, *2001 Report of the Economic Survey*, Arlington, Va., 2001.

and $4 million in 2003 through 2005.[47] Most patent litigation never reaches trial but is settled instead.

The phenomenon dubbed by some as the "patent troll" has also been on the rise.[48] Some in the legal profession have argued that entities that acquire ownership of patents with the intention of licensing them, rather than acquiring patents by developing new products, are not in themselves harmful or the root cause of excessive litigation. Instead, they consider poor-quality patents as the root cause.[49] However, in the current patent environment, others do consider these activities to have adverse effects both on the patent system and on innovation.[50] Furthermore, the choice of jurisdiction where a filing is made can dramatically influence the outcome of a patent lawsuit, introducing more risk and volatility into the litigation process for intellectual-property-intensive companies. This can give rise to "forum shopping," where plaintiffs seek a jurisdiction thought to favor plaintiffs. The likelihood of a plaintiff's verdict, for example, is substantially higher in courts in the Eastern District of Texas and in the Central District of California than anywhere else in the country.

These trends suggest that the U.S. IT R&D ecosystem has become far more contentious than it was in the past. In summary, the cost of protecting and defending intellectual property is undergoing rapid inflation. The long-term effects of this phenomenon may be more pernicious:

- The costs of protecting an invention go up. It takes more money to file a patent. It takes longer to be granted a patent. One must file in multiple jurisdictions as markets have become more global.
- It costs more to defend oneself. It is possible for companies that never produce or commercialize a product to extract relatively high

[47]American Intellectual Property Law Association, *2003 Report of the Economic Survey*, Arlington, Va., 2003; and American Intellectual Property Law Association, *2005 Report of the Economic Survey*, Arlington, Va., 2005. For more on direct costs of and potential inefficiencies in the patent system, see National Research Council, *A Patent System for the 21st Century*, The National Academies Press, Washington, D.C., 2004.

[48]The term *patent troll* was reportedly coined in 1981 as a pejorative term to describe companies that game the patent system by snapping up critical bits of technology, then shopping for settlements from companies that might be infringing on the patents. Mike McNamee, ed., "Washington Outlook: A Patent War Is Breaking Out on the Hill," *Business Week*, July 4, 2001, available at http://www.businessweek.com/magazine/content/05_27/c3941058_mz013.htm; accessed September 12, 2007.

[49]See, for example, James F. McDonough, "The Myth of the Patent Troll: An Alternative View of the Function of Patent Dealers in an Idea Economy," *Emory Law Journal* 56:189-228, 2006, available at http://papers.ssrn.com/sol3/papers.cfm?abstract_id=959945; accessed March 6, 2008.

[50]See, for example, David G. Barker, "Troll or No Troll? Policing Patent Usage with an Open Post-Grant Review," *Duke Law and Technology Review*, No. 9, 2005, available at http://www.law.duke.edu/journals/dltr/articles/pdf/2005dltr0009.pdf; accessed March 6, 2008.

license fees from companies that must then add these costs to those of building a market and bringing products to market.

- When damages are awarded, the contribution of the infringed patent can be attributed a disproportionate role.

Taken together, these trends may have a stifling effect on young IT companies, especially those just bringing products to market, that have limited funds and no patent portfolios for use in cross-licensing agreements or as the basis for countersuits. Such companies run a greater risk today of never acquiring sufficient intellectual property protection and mustering enough legal resources to withstand costly and lengthy litigation.

TechNet, a preeminent bipartisan political network of chief executive officers and other senior executives of leading U.S. IT companies, views this matter as a fundamental issue for the IT industry. Key elements of a successful reform of the U.S. patent litigation system might include the following:

- Clear standards for forum selection that curtail the ability of plaintiffs to file infringement actions in jurisdictions most likely to favor plaintiffs;
- Reforms that direct courts to calculate the royalty or damages awards on the basis of a consideration of the proportionate value of the patentee's contribution to the product in question rather than on the full value of the entire product;
- Provisions of current law that have never been interpreted to permit the recovery of worldwide damages in U.S. courts;
- Standards governing awards of multiple damages for willful infringement; and
- Additional reforms, as necessary, to curtail practices that are a drain on innovation.

Another source of friction comes from the unexpected and unanticipated consequences of corporate-governance reform legislation on venture firms pursuing an IPO. The Sarbanes-Oxley Act of 2002 (Public Law 107-204), referred to as SOX, and in particular its Section 404, were passed to improve the quality of corporate governance among U.S. publicly traded companies and to reduce the risks of financial fraud. SOX was created and enacted to a large degree in response to the corporate scandals of such large companies as Enron, WorldCom, and Tyco. (See the discussion of financial scandals as shocks to the IT R&D ecosystem in the Chapter 3 subsection entitled "Financial Scandals and Bankruptcies [December 2001]"). Thus, the intended firm for which SOX was designed was a multi-billion-dollar, multinational corporation listed on

U.S. exchanges. It was not a typical high-growth, sub-$100 million technology company led by creative entrepreneurs and technologists and funded by U.S. venture capitalists. Yet, these smaller companies have been subjected to the same regulations created for the large firms, and the costs of compliance are disproportionately more burdensome.[51]

Young technology companies lack the critical mass required to deploy the administrative staff, processes, and controls mandated by SOX in order to pursue an IPO in the United States. Their lifeblood is technology innovation. They often cannot afford to reallocate a large percentage of their resources away from research and development toward general and administrative costs in order to become compliant and seek a U.S. IPO. Therefore, when crafting corporate-governance legislation and regulations, it is important that policy makers take into consideration unintended consequences on smaller companies.

INDUSTRIAL RESEARCH: SHIFTING PATTERNS OF CORPORATE INFORMATION TECHNOLOGY R&D

The large industrial research laboratories have traditionally been a significant institutional category in the U.S. IT R&D ecosystem.[52] However, by the late 1980s the firms supporting major laboratories, such as AT&T Bell Laboratories, IBM, and Xerox Palo Alto Research Center, came under intensifying pressure to shift their research portfolios toward more applied research and development work. Some other firms, most notably Cisco, have pursued a corporate strategy of "research by acquisition," rather than establishing and maintaining a central research infrastructure (see Box 4.2).[53]

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[51]CRA International, "Sarbanes-Oxley Section 404 Costs and Implementation Issues: Spring 2006 Survey Updates," Washington, D.C., April 17, 2006. The CRA survey was sponsored by four large accounting firms. Self-reported costs for compliance with SOX Section 404 were as follows: smaller companies with market capitalizations of between $75 million and $700 million estimated that implementation costs (including audit fees) amounted to about $1.2 million the first year and $860,000 the second year. For larger companies with market capitalizations over $700 million, the first- and second-year costs were estimated to be about $8.5 million and $4.8 million, respectively. For the smaller companies, SOX Section 404 compliance costs were estimated to be about half of all audit fees the first year and about the same as non-404 audit costs the first year—in other words, SOX Section 404 compliance basically doubled the audit fees.

[52]R. Rosenbloom and W. Spencer, eds., *Engines of Innovation*, Harvard Business School Press, Boston, Mass., 1996.

[53]These changes are part of a more general trend toward what is sometimes called open innovation, whereby ideas flow both from and into corporations: in order to prosper in the face of new markets and competitors, incumbents must transform themselves from "closed" innovation models (with heavy corporate investment in internal R&D) that are no longer sustainable to more open models, without centralized control and where ideas transfer

In the process of shifting toward more applied work, the traditional industry research laboratories underwent a traumatic downsizing. The firms within which they were housed experienced fundamental changes in their business environments owing to increased competition caused by deregulation as well as that from new industry entrants, which in at least some cases were leveraging new IT developments. The business utility of the large central R&D laboratory was called into question. Already in the early 1980s, the first of the major electronics-related laboratories to experience downsizing was RCA's Sarnoff Laboratories—which became too expensive to support as RCA lost its competitive position in the television industry as Japanese and European (i.e., Royal Philips Electronics N.V.) firms and competitors increasingly wrested control of the newest technological developments from RCA.[54] U.S. firms irrevocably lost control of image-display technologies to East Asian companies.[55]

The explanation for the demise of corporate IT R&D laboratories is complex. Ultimately, corporate executives, representing their shareholders, judged that there was insufficient or too delayed return on investment in research. Firms that controlled their industry sector through monopolies or near monopolies often operated the leading laboratories. As these monopolies ended, their ability and commitment to maintain R&D spending waned.[56] Underinvestment yielded to a vicious downward spiral of fewer new technology products to bring to market, further eroding market share and profitability. For example, RCA was the pioneering U.S. television manufacturer, holding most of the basic TV patents. By the mid-1990s its market dominance had collapsed. Yet even as many firms in the IT industry reduced the size of their research laboratories, Microsoft and Intel established and greatly expanded their own industrial research activity.

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out into start-ups and enter by way of acquisition or merger. See Henry Chesbrough, *Open Innovation: The New Imperative for Creating and Profiting from Technology,* Harvard Business School Press, Boston, Mass., 2003.

[54]See, for example, Alfred D. Chandler, Jr., *Inventing the Electronic Century: The Epic Story of the Consumer Electronics and Computer Industries, with a New Preface,* Harvard University Press, Cambridge, Mass., 2005; Margaret Graham, *RCA and the VideoDisc: The Business of Research,* Cambridge University Press, Cambridge, England, 1986; and Michael Porter, *Cases in Competitive Strategy,* Free Press, New York, N.Y., 1983. For a further discussion of the collapse of the U.S. consumer electronics industry, see Martin Kenney and James Curry, *The Globalization of the Television and Personal Computer Industries,* Final Report to the Alfred P. Sloan Foundation, July 26, 1999, available from the authors upon request.

[55]For a discussion of this process, see T. Murtha, S. Lenway, and J. Hart, *Managing New Industry Creation,* Stanford University Press, Stanford, Calif., 2001.

[56]For a discussion of the impacts of the AT&T divestiture on Bell Laboratories and on telecommunications research more broadly, see National Research Council, *Renewing U.S. Telecommunications Research,* The National Academies Press, Washington, D.C., 2006.

BOX 4.2
Acquisition and Development—
A Substitute for Basic Research?

The overwhelming success of U.S. firms that emerged from the venture capital-financed information technology (IT) research and development (R&D) ecosystem in the United States belongs to firms that were not disposed to basic research conducted in central laboratories. For example, Gordon Moore, one of the founders of Fairchild Semiconductor and Intel Corporation, believed that such basic research was unwise, and at Intel a research laboratory was never established.[1] If Intel, which has grown to be one of the largest firms and certainly the richest semiconductor firm in Silicon Valley, did not establish a corporate laboratory, then it is not surprising that other venture capital-financed semiconductor firms also have not established laboratories. The strategic question of whether not having a laboratory to develop new business opportunities places a firm in danger of being outflanked in the rapidly changing IT industries has not yet been satisfactorily answered.

The wisdom in Silicon Valley prior to the 1990s was that purchasing start-ups was futile. Key personnel in the newly acquired firm would leave to establish a competitor, and the acquirer would be left with an empty shell. Cisco Systems demonstrated that it was possible to do acquisitions and, more important, to use the entrepreneurial ecosystem as a substitute for laboratory-derived new technologies.[2] Through a sophisticated, multifaceted monitoring of its environment, Cisco was able to uncover innovations before their widespread adoption and then to purchase a firm that had created such an innovation together with its technology—and, all importantly, to retain a sufficient number of the firm's key personnel. In effect, Cisco is allowing the ecosystem to do its R&D. As the data on the location of Cisco's acquisitions show, the company particularly depends on the entrepreneurial environments such as Silicon Valley to provide its acquisitions. The great majority of the 60 firms acquired by Cisco as of 2007 were located in the San Francisco Bay Area.There are small clusters of Cisco acquisitions in Massachusetts (about 12 firms) and Texas (about 10 firms), but only about 20 firms from the rest of the United States and fewer than 20 from the rest of the world.[3]

These acquisitions came in addition to Cisco's spending approximately 15 percent of its revenue on R&D, much of which is simply to keep existing product lines up to date. Cisco's ability to evolve with the rapidly changing networking marketplace without a dedicated research laboratory, along with the movement from circuit switching to packet switching, combined to overwhelm the incumbent telecommunications equipment providers in the marketplace and sealed the fate of their research laboratories, not only in the United States but in most other nations as well.

Acquisitions have become a routine aspect of Cisco's business model and increasingly of the business model of other major firms in the IT R&D ecosystem. Established firms routinely monitor the environment for promising start-ups. Salient examples are the purchase by Microsoft Corporation of Vermeer Technologies, the producer of an early client-server Web publishing software firm, and of Hotmail,

BOX 4.2 continued

the e-mail start-up, and the purchase by Google of Keyhole for its satellite mapping technologies, and then a variety of other small digital mapping start-ups to improve its map program.

It is interesting to note that Intel has subsequently established a network of more conventional research laboratories and created a collection of small "lablets" close to major universities to capture innovations emerging from that element of the ecosystem.[4] In 2006, Cisco appointed its first vice president of research, Douglas E. Comer, a computer science professor from Purdue University, and established the Cisco Research Center. At this time, the organization appears to play a coordination role rather than that of a research laboratory.[5]

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[1]Gordon E. Moore, "The Accidental Entrepreneur," 2001, available at http://nobelprize.org/nobel_prizes/physics/articles/moore/index.html; accessed June 20, 2007; and Keith Naughton, "Outsourcing: Silicon Valley East," *Newsweek,* March 6, 2006, available at http://www.newsweek.com/id/46807; accessed November 18, 2008.

[2]David Mayer and Martin Kenney, "Economic Action Does Not Take Place in a Vacuum: Understanding Cisco's Acquisition and Development Strategy," *Industry and Innovation* 11(4):299-325, 2004.

[3]Data on Cisco acquisitions compiled by committee member Martin Kenney from information available on Cisco's Web site, www.cisco.com.

[4]See "Intel Research Network of Labs," available at http://techresearch.intel.com/articles/None/1475.htm; accessed August 22, 2007; and "Network of Labs Home," available at http://www.intel-research.net/; accessed March 27, 2008.The U.S. lablets are in Berkeley, California; Pittsburgh, Pennsylvania; and Seattle, Washington.

[5]See "Cisco Research," available at http://www.cisco.com/web/about/ac50/ac207/crc/index1.html; accessed August 22, 2007.

The affordability of research was also affected by the shift from large, technically sophisticated computers to personal computers (PCs) and systems built as commodity boxes with standardized software. Once-well-established computer manufacturers such as Control Data Corporation, Prime Computer, Digital, Tandem Computers, and Compaq Computer Corporation have disappeared from the industry landscape, in part owing to the rise of commodity PCs. High-volume PC makers such as Dell, Acer Incorporated, and Hewlett-Packard Company's personal computer division cannot justify basic research on the very slim profit margins that characterize this industry sector. What has happened in the case of the PC is that R&D has shifted up the supply chain to the component makers, that is, Intel, and to software firms such as Microsoft, Adobe, Intuit, and others. As importantly, if the products of the component makers and software firms are affected by commoditization or a move toward open-source software, this supplier-based R&D could also be threatened.

Among the new generation of Internet firms, the firm perhaps best known for hiring holders of advanced degrees in IT fields is Google, though it does not have a traditional industrial research organization;[57] rather, its researchers are developers who are part of product teams who happen to write technical papers. Yet the size and scale of the systems and applications that they are building place them at the research frontier in many areas. Even here, however, competitive pressures and time to market make it difficult to come up with the sustained investments necessary to tackle truly fundamental research problems.[58]

THE FUNDING AND ORGANIZATION OF INFORMATION TECHNOLOGY R&D

Federal Versus Industrial R&D

The principal reason for the dramatic advances in information technology and the subsequent increase in innovation and productivity is the "extraordinarily productive interplay of federally funded university research, federally and privately funded industrial research, and entrepreneurial companies founded and staffed by people who moved back and forth between universities and industry."[59] This flow of ideas and people, stimulated by investments in research, is a critical element of the IT R&D ecosystem.

Looking across all fields of science and engineering, it can be seen the United States has significantly increased total R&D funding over the past 50 years. Particularly in the past two decades, most of that increase has been in the industrial rather than the federal portion (see Figure 4.2).

However, the vast majority of industry R&D funding is for development, with limited funding devoted to applied research and a relatively small amount for basic research (see Figure 4.3). While not all industrial research is applied research and not all university research is basic

[57]See "About Google Research," available at http://research.google.com/about.html; accessed August 22, 2007.

[58]Historically, the locus of industrial research has tended to be in industries and companies that enjoy high growth and high margins. As these industries and companies mature, unless they find new high-growth/high-margin opportunities, their profit margins decrease and they often cut back on research. In this view, the demise of industrial research is not inevitable; rather, industrial research investment flows from slowing industries and companies to others in emerging, high-growth sectors.

[59]National Research Council, *Funding a Revolution: Government Support for Computing Research,* National Academy Press, Washington, D.C., 1995, p. vii.

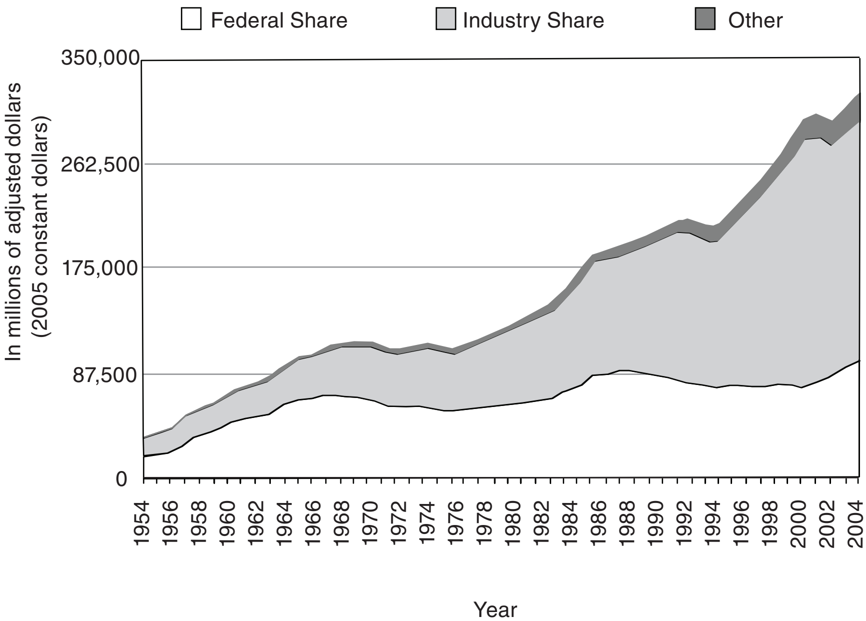

FIGURE 4.2 Total U.S. research and development funding across all fields of science and engineering, 1954-2004, by source. SOURCE: Computing Research Association.

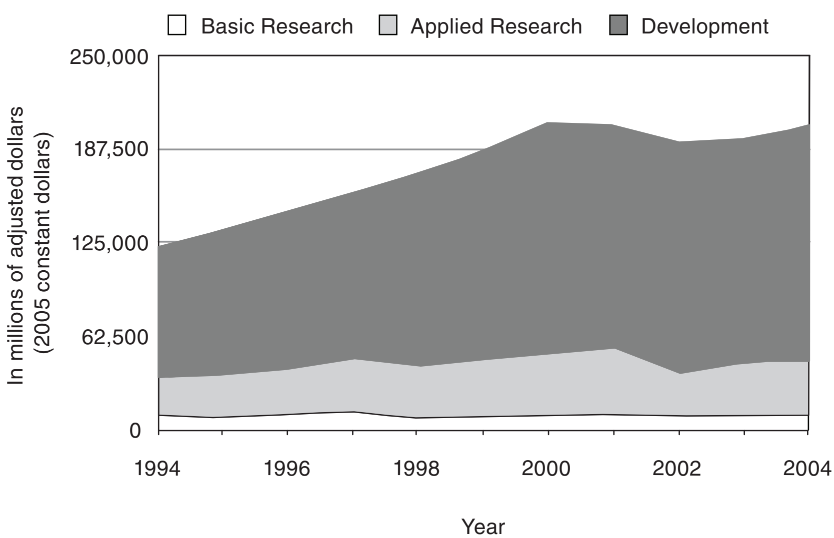

FIGURE 4.3 Industry research and development funding for basic research, applied research, and development, 1994-2004. SOURCE: Computing Research Association.

research, to a large extent this is a valid characterization of activities by these two critical elements of the IT R&D ecosystem. The character of this development-heavy R&D is different from and complementary to federally funded university-based research. The former tends to be focused on product and process development, areas that have more immediate impact on business profitability. However, it is basic research that "puts ideas in the larder" for later use in innovative products.

Getting the fruits of university-based research into the marketplace presents a growing challenge for the people and the institutions involved. The speed and success with which university research results are transferred to industry and commercialized depend critically on universities' choices of technology-transfer mechanisms and incentives and the degree to which entrepreneurship is encouraged within the university community. As Litan, Mitchell, and Reedy have found, the type of technology-transfer organization (TTO) established by a university, as well as the metrics chosen for evaluating the TTO's effectiveness and the incentives offered for entrepreneurial activity by the university community, can foster or impede technology transfer to industry.[60]

One common arrangement is a centralized TTO (which receives all faculty invention disclosures and negotiates all licenses). Although TTOs focus on revenues, licensing, and commercialized inventions, they often have maximization of university revenue (looking for a "big hit") as the central objective, rather than maximization of the numbers of commercialized inventions. Alternative mechanisms and incentive structures are in use, each with its own advantages and disadvantages. These include policies of "free agency," whereby faculty members can choose whether or not to go through the university TTO, as long as they return some portion of their profits to the university; regional alliances among multiple universities; Internet-based "matchmaking" approaches that are built to maximize volume; and "loyalty" models in which universities relinquish all rights in hopes of faculty donating some of their gains back to the university. Litan, Mitchell, and Reedy conclude that it is preferable to move away from the "big hit" model of university technology transfer toward models (including open-source collaborations and non-exclusive licensing) that concentrate on the number of and speed with which university innovations are sent into the marketplace.[61]

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[60]See Robert E. Litan, Lesa Mitchell, and E.J. Reedy, "The University as Innovator: Bumps in the Road," *Issues in Science and Technology*, Summer 2007, available at http://www.issues.org/23.4/litan.html; accessed December 13, 2007.

[61]Ibid.

Federal Funding of Information Technology R&D

Unlike industrial R&D, federal R&D funding consists of a much greater proportion of the investment—and significant increases—in basic research. Note that the main increase in the federal investment in basic and applied research in the past 35 years, and particularly in the most recent decade, has been in the biomedical sciences (see Figure 4.4 for federal agency funding data compiled by the Computing Research Association).

Concerns over the level of federal support for IT R&D are longstanding. In its 1999 report *Information Technology Research: Investing in Our Future*,[62] the President's Information Technology Advisory Committee (PITAC) argued in great detail for a doubling over a period of 5 years of the federal investment in IT R&D, noting that "critical problems are going unsolved, and we are endangering the flow of ideas that has fueled the information economy," and describing the level of investment at that time as "dangerously inadequate."

Comparing the targets for annual increases set in the PITAC report (Table 4.5) and the actual budget levels shown in Figure 4.5 shows that although the federal IT R&D budget initially rose rapidly following publication of the 1999 PITAC report, the lower rate of growth in subsequent years has meant that the budget level 9 years after the release of the PITAC report still has not reached the target set in that report.

This pattern mirrors a broader underinvestment in the physical sciences and engineering highlighted in two recent studies: *Engineering Research and America's Future* (2005) and *Rising Above the Gathering Storm* (2007).[63] *Rising Above the Gathering Storm* had as a major focus the relative lack of investment in engineering and the physical sciences (which include information technology). It is not that investments in the biomedical sciences have been excessive but that investments in engineering and the physical sciences have been too small, placing U.S. technological and economic leadership at risk.

Looked at in isolation rather than in comparison with the rapid growth in funding for the biomedical sciences, the federal investment

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[62]President's Information Technology Advisory Committee (PITAC), in "Executive Summary," *Information Technology Research: Investing in Our Future,* Report to the President, February 24, 1999, available at http://www.nitrd.gov/pitac/report/exec_summary.html; accessed June 27, 2007; see also from the same report: Section V, "Creating an Effective Management Structure for Federal IT R&D," available at http://www.nitrd.gov/pitac/report/section_5.html; accessed June 27, 2007.

[63]National Academy of Engineering, *Engineering Research and America's Future: Meeting the Challenges of a Global Economy,* The National Academies Press, Washington, D.C., 2005. National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* The National Academies Press, Washington, D.C., 2007.

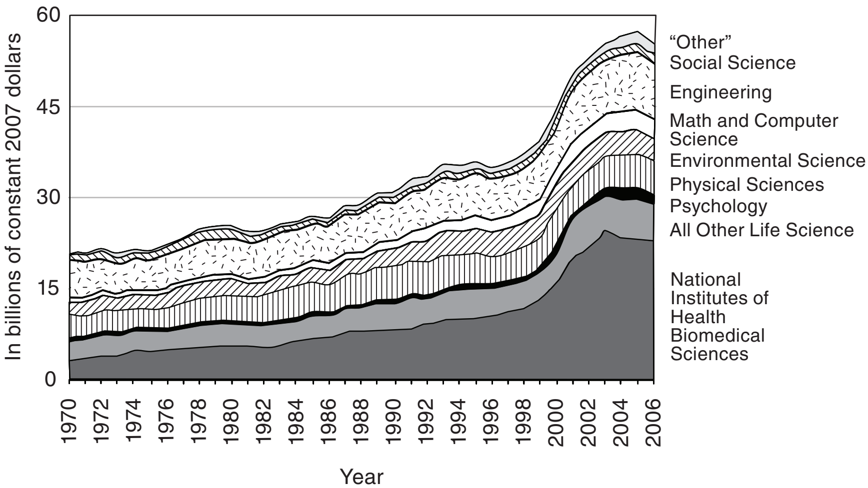

FIGURE 4.4 Federal funding for basic and applied research, by field, 1970-2006.
SOURCE: Computing Research Association.

in IT R&D has also enjoyed a generous increase in the past two decades (see Figure 4.5). However, this increase must be calibrated by several factors, including the enormous and increasing importance of the field, the continued potential for high-impact breakthroughs, and the nation's investment in other fields. As Figure 4.4 clearly shows, not only does the federal investment in IT R&D included in "Math and Computer Science" pale in comparison with the investment in "Biomedical Sciences," but it is smaller than the investment in "All Other Life Science," "Engineering," "Physical Sciences," and "Environmental Science"—exceeding only the investment in "Psychology" and "Social Science"!

TABLE 4.5 Funding Increases for IT R&D Recommended by the President's Information Technology Advisory Committee, FY 2000-FY 2004 ($ millions)

Fiscal Year (FY)	Recommended Increase
FY 2000	472
FY 2001	733
FY 2002	976
FY 2003	1,192
FY 2004	1,370

SOURCE: President's Information Technology Advisory Committee (PITAC), "Executive Summary," in *Information Technology Research: Investing in Our Future,* Report to the President, February 24, 1999, available at http://www.nitrd.gov/pitac/report/exec_summary.html; accessed June 27, 2007.

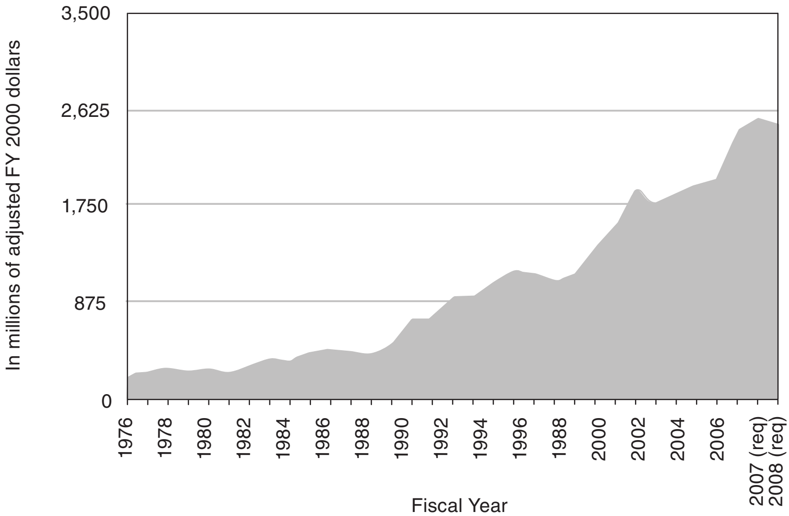

FIGURE 4.5 Federal funding for information technology research and development, fiscal years 1976-2008. NOTE: (req), requested. SOURCE: Computing Research Association.

Indeed, America's public investment in civilian (nonmilitary) R&D in information technology communication lags other economies of interest in absolute dollar terms (see estimates developed by the Institute for Defense Analyses for the President's Council of Advisors on Science and Technology in Table 4.6).

TABLE 4.6 Comparisons of European Union, Japanese, and U.S. Estimated Public Funding of Civilian Information Technology and Communications Research and Development (in billions of dollars, purchasing power parity)

Year	European Union-15	Japan	United States
1999	2.7	1.9	1.2
2000	2.9	2.1	1.3
2001	3.0	2.3	1.6
2002	3.3	2.5	1.5
2003	3.3	2.6	1.7
2004	3.4	2.7	1.9
2005	3.5	2.7	1.8

SOURCE: Institute for Defense Analyses, Science and Technology Policy Institute, briefing to the President's Council of Advisors on Science and Technology, January 9, 2007. Based on data from "Research and Development in Information Science and Technology in Large Industrialised Countries," Commissioned by the Ministère délégué à l'Enseignement supérieur et à la Recherche, Summary Report, April 2006.

According to the Bureau of Economic Analysis (BEA) of the U.S. Department of Commerce, U.S. gross domestic product (GDP) was about $13,247 billion in 2006. Of this, some $521 billion (almost 4 percent) is attributed to what BEA classifies as the "information-communications-technology (ICT) producing industries."[64] Furthermore, this sector—sparked and fueled by IT R&D—experienced double-digit real growth for the third consecutive year in 2006, increasing by 12.5 percent.[65] In 2006, these industries accounted for about 4 percent of the economy but contributed 14.2 percent of real GDP growth.[66] Table 4.7 shows a different measure of the sector's economic contribution: its contribution to real value added (real value added captures the contribution of an industry's labor and capital to real GDP). These contributions, although substantial, reflect only a portion of the overall long-term benefits from IT research investments.

Organization of University Research

Federal funding for university research in information technology has traditionally followed a model of a three-legged stool (see Box 4.3 for a quick view into one university's funding sources and patterns). One leg consisted of modest grants provided by the National Science Foundation[67] and the Defense Science Offices (Office of Naval Research, Army Research Office, and Air Force Office of Scientific Research) to single investigators to work primarily on fundamental research problems. These were either peer-reviewed or evaluated by a panel drawn from technical experts within the government. The grants were sufficient to fund one to two students to work on a research problem.

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[64]According to the BEA, the ICT-producing industries consist of the following: computer and electronic products within durable-goods manufacturing; publishing industries (including software) and information and data processing services within information-producing industries; and computer systems design and related services within professional, scientific, and technical services. See Thomas F. Howells III and Kevin B. Barefoot, "Annual Industry Accounts—Advance Estimates for 2006," *Survey of Current Business*, Table 1, May 2007, Bureau of Economic Analysis, Washington, D.C., available at http://bea.gov/scb/pdf/2007/05%20May/0507_annual_industry_accounts.pdf; accessed August 28, 2007.

[65]See ibid., Table B.

[66]See ibid., Table A.

[67]NSF's Directorate for Computer and Information Science and Engineering (CISE) supports research in three broad areas: computing and communication foundations, computer and network systems, and information and intelligent systems. Other IT-relevant funding sources include the NSF's Office of Cyberinfrastructure and initiatives within the Engineering Directorate.

TABLE 4.7 Percentage Changes in and Real Value Added to U.S. Gross Domestic Product, by Industry Group, 2003-2006

	2003 (%)	2004 (%)	2005 (%)	2006 (%)
U.S. gross domestic product	2.5	3.9	3.2	3.3
Private industries (overall)	2.7	4.2	3.3	3.7
Information-communications-technology (ICT)-producing private industries	7.2	13.7	13.3	12.5

SOURCE: Data from Thomas F. Howells III and Kevin B. Barefoot, "Annual Industry Accounts—Advance Estimates for 2006," *Survey of Current Business,* Table B, May 2007, Bureau of Economic Analysis, Washington, D.C., available at http://bea.gov/scb/pdf/2007/05%20May/0507_annual_industry_accounts.pdf; accessed August 28, 2007.

As a second leg of this model and at the opposite extreme from modest grants to single investigators, the NSF also funded larger-scale, theme-oriented research endeavors through such programs as Engineering Research Centers and Science and Technology Centers. The Department of Defense (DOD) developed the Multidisciplinary University Research Initiative (MURI) Program for similar purposes. These programs were intended to receive support for relatively long periods of time—5 to 10 years, rather than 2 or 3 years for single-investigator grants—and often involved further requirements in terms of industry or institutional matching support. Such centers could encompass the research activities of two dozen faculty members or more, with the result that funding was thinly spread and best used to support work at the intersection of individual investigators' interests. Critical-mass research efforts necessary to achieve breakthroughs were difficult to achieve.

The third leg, uniquely epitomized by Defense Advanced Research Projects Agency (DARPA) support, was critical-mass funding for small teams of faculty and their graduate students: 5 to 6 investigators plus 15 to 20 graduate students. The level of funding was comparable with and sometimes exceeded that of an NSF center, but it was focused on the research activity of a much smaller group. Furthermore, such efforts were not pursued in a vacuum but in the context of a program (see Box 4.4). These efforts consisted of perhaps a dozen similarly sized teams, spanning universities and industry, developing competing technologies but also cooperating on developing a common underlying infrastructure—including, importantly, a research community in an area of strategic need. Examples include the DARPA VLSI Project and the High Performance

BOX 4.3
The Changing Sources of Information Technology R&D Funding

The Computer Science and Artificial Intelligence Laboratory (CSAIL) at the Massachusetts Institute of Technology (MIT) is one of the premier information technology university laboratories in the world. With 93 principal investigators, 471 graduate students, 112 research staff, 46 other staff, and a $45 million per year research expenditure, it is without question a large research enterprise. The laboratory has long enjoyed high levels of research support from the Defense Advanced Research Projects Agency (DARPA).

Table 4.3.1 shows the percentage breakdown of funding sources for the MIT laboratory's activities between 2000 and 2008.[1] The data show a dramatic decrease in the percentage of DARPA funding, matched by a similarly large increase in funding from the National Science Foundation (NSF). By the end of the period, the laboratory's funding base is more balanced than in 2000, with roughly equal portions from nongovernment sources (mostly industry), NSF, and the Department of Defense (DOD). In 2000, DOD provided almost two-thirds of the laboratory's funding.

TABLE 4.3.1 Percentage of Funding for MIT's Computer Science and Artificial Intelligence Laboratory, 2000-2008, by Source

Source	2000 (%)	2001 (%)	2002 (%)	2003 (%)	2004 (%)	2005 (%)	2006 (%)	2007 (%)	2008 (%)
Nongovernment	28.3	33.0	43.2	46.7	39.5	33.1	32.8	32.1	30.8
Government	71.7	67.0	56.8	53.3	60.5	66.9	67.2	67.9	69.2
NSF	7.5	7.9	9.9	15.3	22.9	25.3	26.8	26.7	27.4
DOD Total	62.9	54.2	43.6	33.4	29.7	28.6	24.3	27.8	29.7
DARPA	51.6	47.9	37.9	26.6	25.6	25.6	19.6	23.1	24.2
Other U.S. Government	1.3	4.9	3.3	4.6	7.9	13.0	16.1	13.4	12.1

SOURCE: Rodney Brooks, Massachusetts Institute of Technology, "IT Research Funding: An MIT CSAIL Perspective," presentation to the committee, Boston, Mass., April 19, 2007. Updated and corrected percentages provided to the committee by personal communication from Rodney Brooks, July 15, 2008.

One dimension of the data not made obvious in this table is the increasing level of support from foreign firms for MIT's research. Quanta Computer, a major manufacturer of personal computers based in Taiwan, has entered into a long-term, $20 million research agreement with MIT to investigate what will come "beyond the notebook computer."[2] Nokia, a major manufacturer of telecommunica-

BOX 4.3 continued

tions equipment based in Finland, has established a research laboratory close to MIT to pursue collaborative activities.[3] Clearly, even support for university research is becoming globalized.

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[1]Rodney Brooks, Massachusetts Institute of Technology, "IT Research Funding: An MIT CSAIL Perspective," presentation to the committee, Boston, Mass., April 19, 2007.

[2]See "Quanta Computer, Inc. and the Massachusetts Institute of Technology Announce TParty Project–CSAIL Spotlight," http://www.csail.mit.edu/node/363; accessed December 11, 2008.

[3]See "Nokia and the Massachusetts Institute of Technology Celebrate the Opening of Nokia Research Center Cambridge," April 21, 2006, available at http://press.nokia.com/PR/200604/1046070_5.html; accessed August 24, 2007.

Computing and Communications Program of the late 1980s through the 1990s. This program type of organization was essential in transitioning fundamental research to a size and scale of proof of concept that the rest of the ecosystem could then begin to commercialize.[68]

In 2000, NSF introduced the Information Technology Research (ITR) Program to provide a large-grant funding mechanism. The program did not, however, provide the same sort of programmatic context that DARPA has been able to provide. Thus, the research teams were not organized in a way that enabled them to achieve even better results through the process of competition, cooperation, shared infrastructure, and research community formation. With DARPA's shift away from its traditional support for university-based information technology research in this decade, this third leg of the stool, critical for the field's success in the past, has largely been lost.

In 2007, however, the NSF Directorate for Computer and Information Science and Engineering (CISE) made a small but positive step forward in this regard, with the new Expeditions in Computing Program, which is

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[68]For more on DARPA's early and continuing roles in IT, see "Happy Birthday, Sputnik! (Thanks for the Internet)," *Computerworld*, September 24, 2007, available at http://computerworld.com/action/article.do?command=viewArticleBasic&articleId=9036482&pageNumber=1; accessed October 18, 2007.

BOX 4.4
The Role of the Defense Advanced Research Projects Agency in the Organization of Information Technology R&D

In the early years of the information technology (IT) industry in the United States, the Department of Defense (DOD) played a crucial role, as a supporter of research and as a sophisticated procurer of IT systems. In the 1960s and 1970s, the DOD pulled forward such strategic IT sectors as integrated circuits, computer-aided design software, time-sharing systems, and packet switching networks (i.e., the Advanced Research Projects Agency network, or ARPAnet).

The science offices of the military services—the Office of Naval Research (ONR), the Army Research Office (ARO), and the Air Force Office of Scientific Research (AFOSR)—have a long history of supporting fundamental research related to DOD missions. Further, the DOD maintains its own establishment of research laboratories, to develop specific prototype defense capabilities while also evaluating concepts from the defense contractor community. In terms of organizing research outside the DOD, the major funder of IT research and advanced development has traditionally been DARPA: the Defense Advanced Research Projects Agency (originally "ARPA").[1]

Formed in the late 1950s in the wake of the Soviet launching of *Sputnik* and the American public furor that followed,[2] the agency has acquired an almost magical reputation for establishing ambitious research goals, organizing research communities, and executing programs that expand the technology base to demonstrate new military capabilities. The agency's unofficial charter is to "avoid future technological surprise." Its modus operandi is critical-mass funding to support project teams, organized into cooperative and competitive multiteam programs, under the direction of an empowered program manager (PM) who stands as the mediator between the researchers on the one hand and the DOD customers on the other.[3]

Many within the IT research community point to the late 1980s and early 1990s as the high-water mark of DARPA support for the field. The mid-1980s saw the emergence of DARPA's Strategic Computing Program (SCP) to apply artificial intelligence (AI) techniques to DOD applications in autonomous vehicles, in fleet battle management, and in a pilot's associate. In addition to the demand pull that these stressing applications placed on speech understanding, computer vision, user interfaces, and planning systems, they also put stretch demands on the underlying networked hardware and software systems on which they would execute. That is, these applications' requirements pushed the state of the art in these fields and also required more capabilities in the underlying systems. Therefore, SCP represented a very significant increment in defense funding for IT research.[4]

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[1]For more on DARPA (originally ARPA) management style, see National Research Council, *Funding a Revolution: Government Support for Computing Research,* National Academy Press, Washington, D.C., 1999, pp. 98-105.

[2]Roger D. Launiusk, "Sputnik and the Origins of the Space Age," available at http://history.nasa.gov/sputnik/sputorig.html; accessed March 27, 2008.

[3]See "Strategic Vision," available at http://www.darpa.mil/stratvision.html; accessed January 7, 2009.

[4]Alex Roland and Philip Shiman, *Strategic Computing: DARPA and the Quest for Machine Intelligence, 1983-1993,* MIT Press, Cambridge, Mass., 2002.

BOX 4.4 continued

The High Performance Computing Act of 1991 (Public Law 102-194) was motivated in part by a 1988 report of the National Research Council, *Toward a National Research Network*.[5] Key outcomes of the act were the creation of the federal High Performance Computing and Communications (HPCC) Program[6] and the establishment of a mechanism to coordinate research in communications across the science and technology agencies of the government.[7] Although some agencies saw their funding for HPCC-related research increase owing to the act, much of the work that came under the HPCC rubric was already being carried out by federal agencies.

The multiagency focus combined with the HPCC Program's high visibility and compelling stretch performance goals are credited with motivating a whole generation of researchers to enter the field and contribute to HPCC's success. The size and diversity of the research program grew significantly, encompassing more universities and more firms. A perhaps less well known outcome was that the High Performance Computing Act has fostered collaborative work in which a small number of research administrators within these diverse and often competitive organizations have worked together to rationalize their research and development investments in order to maximize leverage and minimize overlap of effort and to promote and publicize their scientific and technical accomplishments. On the negative side, some have observed that the size of the program attracted the attention of lobbyists, who sought to influence procurements, and of legislators, who sought to earmark funds for projects within their constituencies.

Within the DOD, SCP evolved from an AI program with a modest computing component to a major program in HPCC. The program laid the foundation for today's scalar cluster-based processors and storage systems on which virtually every major Web site depends. By the mid-1990s, DARPA deemphasized its investment in high performance computing, with the technical leadership shifting to the Department of Energy Accelerated Strategic Computing Initiative (ASCI) Program.[8] The ASCI Program focused on developing very large scale parallel

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[5]National Research Council, *Toward a National Research Network*, National Academy Press, Washington, D.C., 1988. This publication is sometimes referred to as the Kleinrock report, after the authoring committee's chair, Leonard Kleinrock.

[6]See, for example, D.B. Nelson, "High Performance Computing and Communications Program," *Proceedings of the 1992 ACM/IEEE Conference on Supercomputing,* Minneapolis, Minn., 1992.

[7]Membership in the program, now known as the Networking and Information Technology Research and Development Program, has expanded over the years. The current members are the Agency for Healthcare Research and Quality, the Defense Advanced Research Projects Agency, the National Nuclear Security Agency, the Office of Science of the Department of Energy, the Environmental Protection Agency, the National Archives and Records Administration, the National Aeronautics and Space Administration, the National Institutes of Health, the National Institute of Standards and Technology, the National Oceanic and Atmospheric Administration, the National Security Agency, the National Science Foundation, and the Offices of the Deputy Under Secretary of Defense (Science and Technology) and Director of Defense Research and Engineering of the Department of Defense.

[8]Department of Energy, Defense Programs, *Accelerated Strategic Computing Initiative (ASCI) Program Plan,* DOE/DP-99-000010592, Washington, D.C., January 2000.

continued

BOX 4.4 continued

machines targeted for the department's nuclear weapons design needs (known as stockpile stewardship). Most of its funding was directed to its contractor-managed weapons laboratories—Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and Sandia National Laboratories—and the machine vendor community. The university HPCC community found it increasingly difficult to receive critical funding to sustain the project teams that had been formed during the earlier stages of HPCC, particularly in areas of computer architecture, parallel software, and internetworking. In 1998 the Next Generation Internet Research Act (Public Law 105-305) was passed, broadening the scope and name of the program to the Networking and Information Technology Research and Development (NITRD) Program. Today, the NITRD Program and the National Coordination Office for NITRD are together the major coordinating umbrella for IT research within the federal government.

Two major characteristics of DARPA-sponsored IT research between the 1960s and 1980s contributed to its success. The first was DARPA's particular style of project-focused research, mentioned above, typically spanning teams of four to five faculty investigators and their students (although teams also included industrial participants), organized into programs in which the teams are driven to cooperate and/or compete through the oversight of the PM. The PM served as a critical intermediary between the researchers and the military customer, placing the research results in the relevant military context while also expressing the military needs in a language that the researchers could understand. The second characteristic was the recognition that it is often just as strategic to build a research community, such as one skilled in developing software for new parallel architectures, as it is to develop the particular technologies that such a community might invent. These characteristics of DARPA successes suggest that simply increasing funding without such a programmatic structure will not yield an ecosystem that is as effective as it was during the past.

intended to provide longer-term research support for teams. The program currently has a total budget of $30 million. Each expedition will be funded at up to $2 million per year for 5 years, and CISE estimates that it will provide three new awards each year.[69]

[69]According to CISE, "The intent is to provide the opportunity to pursue ambitious, fundamental research agendas that promise to define the future of computing and information. In planning Expeditions, investigators are encouraged to come together within or across departments or institutions to combine their creative talents in the identification of compelling, transformative research agendas that promise disruptive innovations in computing and information for many years to come." See "Expeditions in Computing," September 13, 2007, available at http://www.nsf.gov/pubs/2007/nsf07592/nsf07592.txt; accessed October 23, 2007.

CHANGES IN THE RELATIONSHIP BETWEEN EMPLOYEES AND EMPLOYERS

The foundations of the American system of employment were conceptualized under the New Deal and institutionalized in law and by collective bargaining agreements. In return for employees' loyalty and best efforts, employers agreed to fulfill both legally and culturally prescribed obligations: a reasonable expectation of job security and such benefits as health insurance and pension plans. Beginning in the mid-1980s, the cultural contract between worker and employer began to unravel as employment practices and policies shifted toward a laissez-faire philosophy reminiscent of the 19th and early 20th centuries.[70] This context is important when considering the IT workforce issues and patterns of student enrollments discussed previously.

A number of developments contributed to this unraveling. The first was "downsizing" or "rightsizing," euphemisms for what had formerly been known as "layoffs." Until the mid-1980s most layoffs occurred during recessions or when firms found themselves in financial trouble. Layoffs were primarily confined to blue-collar and clerical workers, who often returned to work once the economy improved. In hard times, professionals and managers could assume that they were safe even from temporary layoffs.

During the 1980s, the rules of the game changed. For the first time in history, firms began to shed professional, technical, and managerial workers in large numbers. In fact, by the mid-1990s corporate downsizings were more likely to target managers and professionals than to dismiss other white-collar or blue-collar workers.[71] Moreover, downsizings,

[70]The unraveling of the New Deal employment system has been exetensively documented in Thomas A. Kochan, Harry C. Katz, and Robert B. McKersie, *The Transformation of American Industrial Relations,* Basic Books, New York, N.Y., 1986; Peter Cappelli, Laurie Bassi, Harry Katz, David Knoke, Paul Osterman, and Michael Useem, *Change at Work,* Oxford, New York, N.Y., 1997; Paul Osterman, *Broken Ladders: Managerial Careers in the New Economy,* Oxford University Press, New York, N.Y., 1996; Paul Osterman, *Securing Prosperity: The American Labor Market: How It Has Changed and What to Do About It,* Princeton University Press, Princeton, N.J., 1999; and Paul Osterman, Thomas A. Kochan, M. Locke Richard, and Michael J. Piore, *Working in America: Blueprint for the New Labor Market,* MIT Press, Cambridge, Mass., 2001.

[71]On the nature and extent of downsizing, see Thomas S. Moore, *The Disposable Work Force,* Aldine, New York, N.Y., 1996; American Management Association, *1996 AMA Survey on Downsizing, Job Elimination and Job Creation,* New York, N.Y., 1996; and Harry S. Farber, "The Changing Face of Job Loss in the United States: 1981-1995," pp. 55-142 in *Brookings Papers on Economic Activity: Microeconomics,* The Brookings Institution, Washington, D.C., 1977. On the impact of downsizing on employee perceptions, attitudes, and lives, see Katherine Newman, *Falling from Grace: The Experience of Downward Mobility in the American Middle Class,* Vintage, New York, N.Y., 1989; Charles Heckscher, *White-Collar Blues,* Basic Books, New York, N.Y.,

unlike layoffs of the past, seemed independent of economic cycles. Under pressure from global competition and their stockholders, firms had discovered that streamlining the workforce was necessary to achieve their bottom-line targets and boost their stock prices.[72]

By the late 1990s three practices were augmenting and exacerbating the downsizing: the outsourcing of work to external suppliers, the offshoring of jobs, and the use of contingent labor. Contingent workers are individuals hired, often through staffing agencies, for a limited period of time to perform specific work. Although firms have long employed temporary workers for seasonal and short-term needs, during the late 1980s corporations began to view temporary labor as an extension of the broader strategy of outsourcing. The shift from permanent to contingent employment became particularly widespread in IT centers and among high-technology firms.[73] The Bureau of Labor Statistics reported that, by 1995, 40 percent of all programmers and 29 percent of other IT workers were either contingently employed or worked through outsourcing firms.[74] In Silicon Valley, contractors often comprise between 15 and 30 percent of the labor force.[75]

Data on employment turnover are consistent with the demise of employment security and stable relations between employers and employees. Between 1983 and 2004, average tenure with one's current employer fell by 2.1 years (from 7.3 to 5.2 years) among men between the ages of 35 and 44. Among men between 45 and 54 and between 55 and 65 years of age, the declines were greater: 3.2 years (from 12.8 to 9.6 years) and 5.5 years (from 15.3 to 9.8 years), respectively.[76]

The combination of downsizing, outsourcing, offshoring, and contingent work dramatically altered the tenor of the employment relationship. The first casualty was loyalty. Despite stable levels of job satisfaction and

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1995; Denise Rousseau, *Psychological Contracts in Organizations,* Sage Publications, Thousand Oaks, Calif., 1995; and Denise Rousseau and R.J. Anton, "Fairness and Obligations in Termination Decisions: The Role of Contributions, Promises and Performance," *Journal of Organizational Behavior* 12(4):287-299, 1991.

[72]Wayne F. Cascio, Clifford E. Young, and James R. Morris, "Financial Consequences of Employment-Change Decisions in Major U.S. Corporations," *Academy of Management Journal* 40(5):1175-1189, 1997.

[73]Stephen R. Barley and Gideon Kunda, *Gurus, Hired Guns and Warm Bodies: Itinerant Experts in a Knowledge Economy,* Princeton University Press, Princeton, N.J., 2004.

[74]Angela Clinton, "Flexible Labor: Restructuring the American Workforce," *Monthly Labor Review* 120(8):3-27, 1997.

[75]Chris Benner, *Work in the New Economy: Flexible Labor Markets in Silicon Valley,* Blackwell, Malden, Mass., 2002.

[76]Bureau of Labor Statistics (BLS), *Employee Tenure in 2004,* USDL-04-1829, BLS, Washington, D.C., 2004, available at http://www.bls.gov/news.release/History/tenure_09212004.txt.

a vibrant economy, employees became increasingly distrustful of their employers and less sanguine about their future over the 1990s.[77] Employers, for their part, dropped the pretense of hiring with any expectation of a long-term relationship. Some openly cautioned new hires about the firm's limited commitment to them. Apple's human resource policy, which was reputedly given to each new hire, stated:

> Here's the deal Apple will give you; here's what we want from you. We're going to give you a really neat trip while you're here. We're going to teach you stuff you couldn't learn anywhere else. In return . . . we expect you to work like hell, buy the vision as long as you're here. . . . We're not interested in employing you for a lifetime, but that's not the way we're thinking about this. It's a good opportunity for both of us that this is probably finite.[78]

The second and more important casualty of the altered employment relationship has been the integrity of America's system for insuring the health and welfare of the workforce. During the New Deal the government and industry reached an agreement on how to care for the sick and elderly: Rather than adopting national and universal health care coverage and pension funds, Americans would receive health insurance and pensions through their employers. The employment relationship thus became the cornerstone of America's social safety net, but as the health care costs and pension obligations have risen and as job security has fallen, an increasing number of employers have ceased providing either benefit to workers. Between 1979 and 2004, the percentage of Americans with employer-provided health insurance fell from 69 percent to 56 percent. The rate of decline has been even steeper for Hispanic Americans.[79] While the trends are not specific to the IT industry, not only is it not immune to them, but the fast-changing nature of IT businesses, their rapid globalization, and the need for maximal flexibility of operations has exacerbated these trends in the IT industry.

Trends in pension funds are equally striking.[80] Between 1983 and 2004, the percentage of American workers covered only by a defined-

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[77]National Research Council, *The Changing Nature of Work: Implications for Occupational Analysis*, National Academy Press, Washington, D.C., 1999.

[78]Barbara Ettorre, "The Contingency Workforce Moves Mainstream," *Management Review* 83(2):10-16, 1994, quoting from Apple Computer's written employment contract with every full-time employee.

[79]Lawrence Mishel, Jared Bernstein, and Sylvia Allegretto, *The State of Working America*, An Economic Policy Institute Book, Cornell University Press, Ithaca, N.Y., 2007, Figure 3H.

[80]Data on participation in pension plans are from Alicia H. Munnell and Annika Sunden, "401K Plans Are Still Coming Up Short," in *Issues in Brief*, Center for Retirement Research, Boston College, Boston, Mass., 2006.

benefit plan fell from 62 percent to 20 percent. Conversely, during the same period the percentage of the workforce covered only by a defined-contribution plan grew from 12 percent to 63 percent. As of 2004, one-fifth of working Americans who were eligible to contribute to defined contributions made no contribution whatsoever. Less than 1 percent of workers earning less than $60,000 annually contribute the maximum. Among those earning between $60,000 to $80,000 annually, only 8.3 percent make maximum contributions. In fact, only 58 percent of Americans who make more than $100,000 a year contribute maximally. The situation among technical contractors is at least equally dire, if not more so. Although the well-educated and well-paid high-tech contractors whom Barley and Kunda[81] interviewed were mostly in their 40s and 50s, 45 percent had no retirement account whatsoever. Another 20 percent had only an individual retirement account (IRA). Only 20 percent participated in a 401K or simplified employee pension (SEP) plan.

[81]Stephen R. Barley and Gideon Kunda, *Gurus, Hired Guns and Warm Bodies: Itinerant Experts in a Knowledge Economy,* Princeton University Press, Princeton, N.J., 2004.

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Findings and Recommendations

The U.S. information technology (IT) research and development ecosystem was the envy of the world in 1995, and it remains unquestionably the strongest today. However, this position of leadership is not a birthright. U.S. leadership has been under pressure on several fronts, and leadership cannot be sustained without renewal.[1] In recent years, the rapid globalization of markets, labor pools, and capital flows has helped enable the rise of many strong national competitors. It has created tremendous new opportunities, but globalization also means that the United States will have to work even harder to remain the world leader in IT R&D. Meanwhile, national policies have not always risen to the challenge (such as in IT education and federal funding for research) or have generated unintentional side effects that have reduced the IT R&D ecosystem's effectiveness (for example, as a result of regulations that affect the corporate overhead and competitiveness of innovative IT companies). Thus, the need has never been greater for the nation to recommit itself to providing

[1]These observations are corroborated by a recent report by the RAND Corporation that compares claims of a decline in U.S. global science and technology (S&T) leadership in recent literature with relevant data up to 2006. The RAND report concludes that the United States continues to perform "at or near the top in many measures of S&T leadership, [but that] this leadership must not be taken for granted" and recommends that institutions and incentives integral to the creation and performance of S&T discoveries be sustained and, when necessary, adapted to the changing global economy. See Titus Galama and James Hosek, *U.S. Competitiveness in Science and Technology*, RAND Corporation, Santa Monica, Calif., 2008, p. xxiv, available at http://www.rand.org/pubs/monographs/MG674/; accessed November 20, 2008.

the resources needed to fuel U.S. IT innovation, to mitigate unintended negative consequences from laws and regulations, and to continue to be a nation of lead innovators and users of IT.

The findings and recommendations of the committee presented in the sections below are organized according to four broad objectives. The numbering of the objectives and the related numbering of the findings and recommendations reflect the logical flow of the arguments, not necessarily temporal or other priorities. The objectives are as follows:

- *Objective 1.* Strengthen the effectiveness and impact of federally funded information technology research.
- *Objective 2.* Remain the strongest generator of and magnet for technical talent.
- *Objective 3.* Reduce friction that harms the effectiveness of the U.S. information technology R&D ecosystem, while maintaining other important political and economic objectives.
- *Objective 4.* Ensure that the United States has an infrastructure for communications, computing, applications, and services that can enable U.S. information technology users and innovators to lead the world.

OBJECTIVE 1. STRENGTHEN THE EFFECTIVENESS AND IMPACT OF FEDERALLY FUNDED INFORMATION TECHNOLOGY RESEARCH

Advances in information technology have transformed our lives, powered our economy, and changed the conduct of science and engineering (see Chapter 2). The field of IT is relatively nascent, however, and even greater opportunities lie ahead—provided that IT research is adequately funded. The federal government plays a key role in this regard (see Chapter 4).

The importance of federal investment in scientific research was underscored emphatically in a recent report of the National Academies, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*,[2] which was followed by the administration's American Competitiveness Initiative and passage of the America COMPETES Act of 2007.[3]

A strong case has also been made over the years for investment in IT in particular. A 1995 report of the National Research Council's (NRC's)

[2]National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* The National Academies Press, Washington, D.C., 2007.

[3]The America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science Act (America COMPETES Act) became Public Law 110-69 on August 9, 2007.

Computer Science and Telecommunications Board (CSTB), *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure,* concluded that "federal investment in information technology research has played a key role in the U.S. capability to maintain its international lead in information technology."[4] The "tire tracks" diagram used in that report (and updated in CSTB's 2003 *Innovation in Information Technology*[5]), reproduced as Figure 2.1 in Chapter 2 of this report, compellingly illustrates the critical role that government-funded research, in combination with industry R&D, has played in the establishment of U.S. industries with annual revenues of over $1 billion. Federal investment in fundamental research in information technology has been crucial to the development of the billion-dollar industries that maintain America's leadership in this critical field.[6]

Finding 1.1. A robust program of federally sponsored research and development (R&D) in information technology (IT) is vital to the nation.

Advances in information technology and its applications have played a central role in fueling the success of U.S. scientific, engineering, business, and governmental communities in the past 50 years. Information technology has transformed and continues to transform all aspects of life in the United States: commerce, education, employment, health care, manufacturing, government, national security, communications, entertainment, science, and engineering. Information technology also drives the U.S. economy—both directly (the IT sector itself) and indirectly (other sectors that are "powered" by advances in IT). In short, leadership in information technology is vital to our nation.

A number of reports of the NRC's Computer Science and Telecommunications Board have examined the U.S. IT innovation system. Their

[4]National Research Council, *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure,* National Academy Press, Washington, D.C., 1995, p. 3.

[5]National Research Council, *Innovation in Information Technology,* The National Academies Press, Washington, D.C., 2003.

[6]See National Research Council, *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure,* National Academy Press, Washington, D.C., 1995; and National Research Council, *Innovation in Information Technology,* The National Academies Press, Washington, D.C., 2003. Note that the federal R&D investment is only a fraction of the total R&D investment required to launch a new product, market, or industry, but it provides essential, high-risk seed money. In return, although returns to any individual investment are by no means guaranteed, the tax income to the federal government from billion-dollar industries can vastly exceed the federal research investment.

key findings were recapped in the 2003 report *Innovation in Information Technology,* which contained the following observations:

- America's international leadership in IT—leadership that is vital to the nation—springs from a deep tradition of research. . . .
- The success of the IT research enterprise reflects a complex partnership among government, industry, and universities. . . .
- The federal government has had and will continue to have an essential role in sponsoring fundamental research in IT—largely university-based—because it does what industry does not and cannot do. . . . Industrial and governmental investments in research reflect different motivations, resulting in differences in style, focus, and time horizon. . . .
- Past returns on federal investments in IT research have been extraordinary for both U.S. society and the U.S. economy. . . . Priming that pump for tomorrow is today's challenge.[7]

Finding 1.2. The level of federal investment in fundamental research in information technology continues to be inadequate.

As noted in Chapter 4, the 1999 report of the President's Information Technology Advisory Committee (PITAC), *Information Technology Research: Investing in Our Future,*[8] described the level of federal investment in IT R&D at that time as "dangerously inadequate" and argued for a doubling of that investment over a period of 5 years. Through efforts coordinated by the National Coordination Office for Networking and Information Technology Research and Development (NITRD), the federal government set out to achieve that goal. However, funding by the NITRD participating agencies soon fell short of the annual targets set by PITAC and 9 years later has not reached the recommended doubling of the IT R&D budget.[9]

[7]National Research Council, *Innovation in Information Technology,* The National Academies Press, Washington, D.C., 2003, pp. 2-4.

[8]President's Information Technology Advisory Committee (PITAC), *Information Technology Research: Investing in Our Future,* Report to the President, February 24, 1999, "Executive Summary," available at http://www.nitrd.gov/pitac/report/exec_summary.html, accessed June 27, 2007; see also from the same report: Section V, "Creating an Effective Management Structure for Federal IT R&D," available at http://www.nitrd.gov/pitac/report/section_5.html; accessed June 27, 2007.

[9]As noted in Chapter 4, this pattern mirrors a broader underinvestment in the physical sciences and engineering highlighted in two recent National Academies studies: National Academy of Engineering, *Engineering Research and America's Future: Meeting the Challenges of a Global Economy,* The National Academies Press, Washington, D.C., 2005; and National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* The National Academies Press, Washington, D.C., 2007.

The committee believes that the level of federal investment in information technology research remains inadequate. Indeed, in the 9 years since the PITAC report, the role of IT in all aspects of the life of this nation—from entertainment to commerce to health care to national security—has grown dramatically. At the same time, globalization has expanded dramatically, leading to increasing specialization and pushing the United States to move higher up the value chain, a position that is more R&D-intensive. Short-term competitive pressures on U.S. IT firms have increased dramatically, with the result that few companies are investing in long-term R&D and most high-impact industrial research laboratories are gone.

Recommendation 1.1. As the federal government increases its investment in long-term basic research in the physical sciences, engineering, mathematics, and information sciences, it should carefully assess the level of investment in IT R&D, mindful of the economic return, societal impact, enablement of discovery across science and engineering, and other benefits of additional effort in IT, and should ensure that appropriate advisory mechanisms are in place to guide investment within the IT R&D portfolio.

The committee's analysis of the opportunities in the expanding IT economy, the global competition faced by the United States, and the critical foundation that the federal investment in IT R&D provides for a broad range of economically and socially important IT applications convinced it that the nation's research base is inadequate and that additional investment is needed.

It is difficult to estimate how much should be invested in IT R&D, in part because that estimate must take into account the alternatives for that investment. Looking more broadly at federal R&D investment, the 2007 study *Rising Above the Gathering Storm* made the following recommendation:

> Increase the federal investment in long-term basic research by 10 percent each year over the next seven years through reallocation of existing funds, or, if necessary, through the investment of new funds. Special attention should go to the physical sciences, engineering, mathematics, and information sciences and to Department of Defense (DOD) basic-research funding.[10]

[10]National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* The National Academies Press, Washington, D.C., 2007, pp. 136-137.

A detailed discussion of the rationale and supporting evidence for the recommendation are presented in that report.[11]

Looking at how to establish priorities within the federal research portfolio, the 1993 study *Science, Technology, and the Federal Government: National Goals for a New Era* argued that "the United States should be among the world leaders in all major areas of science" but that some differentiation was necessary: in some fields it was sufficient to be "among the world leaders," but in others "the United States should maintain clear leadership." The 1993 study went on to note criteria that would call for clear leadership in a field:

- The field is demonstrably and tightly coupled to national objectives that can be met only if U.S. research performers are clear leaders. For example, the field of condensed-matter physics drives technological advances in such industrial sectors as microelectronics, advanced materials, and sensors.
- The field so captures the imagination that it is of broad interest to society. An example in astronomy is the recent detection of differences in the cosmic background radiation related to the creation of the universe.
- The field affects other areas of science disproportionately and therefore has a multiplicative effect on other scientific advances, especially those where clear leadership is the objective. For example, molecular biology is critical to advances in health care, biotechnology, agriculture, and industrial processes.[12]

Building on the 1993 study, the 2005 National Academy of Engineering study *Engineering Research and America's Future: Meeting the Challenges of a Global Economy* included the following recommendation:

> The committee strongly recommends that the federal R&D portfolio be rebalanced by increasing funding for research in engineering and physical science to levels sufficient to support the nation's most urgent priorities, such as national defense, homeland security, health care, energy security, and economic competitiveness. Allocations of federal funds should be determined by a strategic analysis to identify areas of research in engineering and science that support these priorities. . . .[13]

The Committee on Assessing the Impacts of Changes in the Infor-

[11]Ibid., Ch. 6, especially pp. 136-143.

[12]National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Science, Technology, and the Federal Government: National Goals for a New Era,* National Academy Press, Washington, D.C., 1993, pp. 18-20.

[13]National Academy of Engineering, *Engineering Research and America's Future: Meeting the Challenges of a Global Economy,* The National Academies Press, Washington, D.C., 2005, p. 4.

mation Technology Research and Development Ecosystem is persuaded that an evaluation of the government's research priorities, which will be required to implement the research investment growth recommended in *Rising Above the Gathering Storm,* will show that the economic return and other benefits of additional effort in IT justify a significant increase in this field. This evaluation merits the attention of first-tier scientists and engineers from academia, industry, and government. The mechanism for capturing and conveying such advice also merits attention.

The High-Performance Computing Act of 1991 (Public Law 102-194) was enacted to "provide for a coordinated Federal program to ensure continued United States leadership in high-performance computing," reflecting information technology's vital role in the economy, national security, and science. Among its provisions is the establishment of a high-performance computing advisory committee to provide an independent assessment of the program, including "whether the research and development undertaken pursuant to the program is helping to maintain the United States leadership in computing technology." That advisory committee was first convened in 1997 and named the President's Information Technology Advisory Committee. Its charter was augmented by the Next Generation Internet Research Act of 1998 (Public Law 105-305).

In 2005, instead of reauthorizing PITAC, the administration decided that the PITAC mission would be assumed by the President's Council of Advisors on Science and Technology (PCAST), which established a 12-member subcommittee to consider networking and IT. Should the executive and/or legislative branches concur that an increased (or retargeted) focus on IT R&D investment is warranted, reconsideration of what federal advisory mechanisms would be most useful may also be warranted. The committee believes that it would be important to include first-tier IT researchers from academia and industry in any future advisory group.

OBJECTIVE 2. REMAIN THE STRONGEST GENERATOR OF AND MAGNET FOR TECHNICAL TALENT

The IT professions are fast-paced, highly creative, and challenging; they often require specialized skills and advanced education. Although strong demand for IT workers is projected in the United States, there is growing concern about the development of IT talent.[14] Despite the

[14]The recent RAND report on U.S. competitiveness identified similar concerns, noting weaknesses in the U.S. kindergarten through grade 12 education system with respect to preparing students in the area of science and technology or attracting sufficient numbers of U.S. students to scientific careers in research or industry. See Titus Galama and James Hosek, *U.S. Competitiveness in Science and Technology,* RAND Corporation, Santa Monica, Calif., 2008, p. xxiii, available at http://www.rand.org/pubs/monographs/MG674/; accessed November 20, 2008.

demand for IT workers, the number of students specifying an intention to major in computing and information sciences has dropped significantly in the past 6 years.[15]

The composition of the IT workforce is also a cause for concern. The participation of women, persons with disabilities, and certain minorities such as African-Americans, Hispanics, and Native Americans is rising overall in other science, technology, engineering, and mathematics fields. In computing, however, the participation of underrepresented groups is especially low, and is even declining.[16]

The trends described above have a direct effect on employers' ability to hire IT professionals—with some IT professional areas, such as senior programmers and systems analysts, being of more concern than others.[17] An excess demand for talent is also felt, perhaps most acutely, in federal agencies such as the Department of Defense that have specialized IT needs and requirements for particular personnel (for example, people who can be granted security clearances).[18]

Finding 2.1. Rebuilding the computing education pipeline at all levels requires overcoming numerous obstacles, which in turn portends significant challenges for the development of future U.S. IT workforce talent.

Concerns about the generation of talent are exacerbated by the poor state of the U.S. IT/computing education system for kindergarten through grade 12 (K-12). In its report *The New Educational Imperative: Improving High School Computer Science Education,* the Computer Science Teachers Association correctly assesses the situation as one in which knowledge of computer science is as essential as knowledge of any of the traditional sci-

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[15]National Center for Women and Information Technology data, as derived from the College Board, *2006 College Bound Seniors: Total Group Profile Report,* 2006, available at http://www.collegeboard.com/prod_downloads/about/news_info/cbsenior/yr2006/national-report.pdf; accessed July 2, 2007.

[16]The National Science Foundation (NSF) Broadening Participation in Computing program intends to increase the number of U.S. citizens and permanent residents receiving postsecondary degrees in computing disciplines, with emphasis on students from communities (women, persons with disabilities, and selected minorities) with "longstanding underrepresentation." Information is available at http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=13510&org=NSF&sel_org=NSF&from=fund; accessed March 27, 2008.

[17]National Center for Women and Information Technology data, as derived from Society for Information Management, *The Information Technology Workforce: Trends and Implications 2005-2008*.

[18]See, for example, the discussions of shortfalls in software expertise in National Research Council, *Summary of a Workshop on Software-Intensive Systems and Uncertainty at Scale,* The National Academies Press, Washington, D.C., 2007.

ences, but in which curriculums, leadership, funding, professional development for teachers, and fluency objectives for students are all deficient (see the discussion in Chapter 4, in the subsection entitled "Concerns About K-12 IT/Computing Education and Talent Generation").[19]

Enrollment is dropping because students, parents, guardians, and school counselors do not understand that computing is a discipline focused on solving real problems, nor that computing is a foundational and broad science. In addition, in most public schools, computing is an elective—students (especially advanced placement and college-bound students) have packed schedules and often do not have the time to take electives. It is likely that the recent emphasis on standardized testing in core areas is also pulling funding and teachers away from computing.

> **Finding 2.2. The participation in IT of women, people with disabilities, and certain minorities, including African-Americans, Hispanics, and Native Americans, is especially low and is declining. This low level of participation will affect the ability of the United States to meet its workforce needs and place it at a competitive disadvantage by not allowing it to capitalize on the innovative thinking of half of its population.**

The National Academies' *Rising Above the Gathering Storm* included the following recommendation:

> Make the United States the most attractive setting in which to study and perform research so that we can develop, recruit, and retain the best and brightest students, scientists, and engineers from within the United States and throughout the world.[20]

The committee supports this general recommendation. It further believes for the following reasons that IT warrants special emphasis within the broad science, technology, engineering, and mathematics (STEM) umbrella as the federal agencies begin to implement the America COMPETES Act of 2007:

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[19]Computer Science Teachers Association, *The New Educational Imperative: Improving High School Computer Science Education,* available at http://csta.acm.org/; accessed August 27, 2007. For an early assessment of fluency issues, see National Research Council, *Being Fluent with Information Technology,* National Academy Press, Washington, D.C., 1999.

[20]National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* The National Academies Press, Washington, D.C., 2007, p. 9.

- Computing is a foundational science to all other STEM disciplines.
- Computing is foundational to recent U.S. productivity gains.
- Computing is increasingly a critical business infrastructure of most major corporations.
- There is a growing demand for IT workers.

Further, as indicated below, the K-16 computing education pipeline is showing signs of significant stress:

- Enrollments in postsecondary 4-year degree programs have been dropping over the past 6 years.
- Unlike most STEM disciplines, computing is an elective in almost all K-12 curriculums, causing students to leave high school with little or no exposure to the discipline; they may have mastered computing literacy (or usage) but not fluency.
- Computing has one of lowest rates of participation by underrepresented groups of any of the STEM disciplines.

Against this backdrop, the committee makes the following recommendation, focusing specifically on information technology:

Recommendation 2.1. To build the skilled workforce that it will need to retain high-value IT industries, the United States should invest more in education and outreach initiatives to nurture and increase its IT talent pool.

The America COMPETES Act of 2007 contains a number of initiatives to create and bolster a diversity of STEM education programs in the United States. This is good news if the initiatives are funded and carried out effectively. However, too often the “T” (technology) component of STEM with respect to IT can be misunderstood as signifying merely teaching students to use computers, or making sure that schools are wired for the 21st century. Agencies implementing this legislation should take special care to ensure that computer science and IT instruction are not overlooked in favor of those disciplines that the broader population better understands.[21]

There has been much debate over how many U.S. IT jobs (and U.S. jobs more generally) can and will be sent offshore. Methodologies for such studies are complex and inconsistent—they use different data sets, differ-

[21]With respect to implementation processes, a useful resource might be the comprehensive look at science education standards found in National Research Council, *National Science Education Standards*, National Academy Press, Washington, D.C., 1996.

ent views of what IT practitioners and researchers do (and hence what can be compartmentalized and offshored), and different time frames. Trying to match projected "offshorable" jobs to suitable labor supply in developing countries is like gazing into a crystal ball. A recent report that focused on the globalization and offshoring of software concluded:

> While offshoring will increase, determining the specifics of this increase [is] difficult given the current quantity, quality, and objectivity of data available. Skepticism is warranted regarding claims about the number of jobs to be offshored and the projected growth of software industries in developing nations.[22]

One thing is clear—the global search for talent in IT is a fact of life, and it is changing the way that firms innovate, the way that firms staff IT development teams, and the overall nature of the U.S. workforce. In fact, viewing the dynamic IT R&D ecosystem as merely one of outflows and inflows may be too limiting.[23] It does not really matter if one subscribes to the view that offshoring will have an evolutionary rather than a revolutionary effect on the United States or the view that offshoring's negative impact in the United States will quickly escalate. The United States cannot be complacent about offshoring or about declining enrollments in IT-related fields.

Finding 2.3. Although some IT professional jobs will be offshored, there are more IT jobs in the United States than at any time during the dot-com boom, even in the face of corporate offshoring trends.

Many have pointed out a recent surge in the number of U.S. computer science doctorates awarded. On closer examination, it becomes clear that this otherwise encouraging phenomenon is almost entirely due to increases in the number of degrees awarded to non-U.S. students.[24] Many

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[22]Association for Computing Machinery Job Migration Task Force, *Globalization and Offshoring of Software: A Report of the ACM Job Migration Task Force,* W. Aspray, F. Mayadas, and M. Vardi eds., Association for Computing Machinery, New York, N.Y., 2006.

[23]AnnaLee Saxenian argues that we should look at this search for talent as "brain circulation" and not "brain drain." She believes that a new type of global talent, which she calls the new "Argonauts," is undermining the old pattern of one-way flows of talent. These "Argonauts" go where they can participate in the best educational or wealth creation opportunities; they are creating a richer and decentralized flow of skill, capital, and technology. See AnnaLee Saxenian, *The New Argonauts: Regional Advantage in a Global Economy,* Harvard University Press, Cambridge, Mass., 2006.

[24]National Science Foundation (NSF) Division of Science Resources Statistics (SRS), "S&E [Science and Engineering] Doctorate Awards: 2005," available at http://www.nsf.gov/statistics/nsf07305/; accessed November 20, 2008.

of these students go on to apply for work visas in the United States or for green cards. Many are turned away because of immigration policies and quotas, despite the fact that the United States has already invested large amounts of money and resources toward their education. In addition, many IT employers have expressed frustration about this state of affairs. Immigrants have been especially significant in high-technology entrepreneurship; for at least one-quarter of the U.S. engineering and technology companies started between 1995 and 2005, mostly in software and innovation/manufacturing-related services ("electronics, computer and hardware design and service companies in addition to engineering services, research and testing"),[25] at least one of the key founders was born outside the United States (see Chapter 1).

Recommendation 2.2. The United States should increase the availability and facilitate the issuance of work and residency visas to foreign students who graduate with advanced IT degrees from U.S. educational institutions.

OBJECTIVE 3. REDUCE FRICTION THAT HARMS THE EFFECTIVENESS OF THE U.S. INFORMATION TECHNOLOGY R&D ECOSYSTEM

An emerging pattern of inefficiencies in the U.S. IT R&D ecosystem could, over time, hurt the health and competitiveness of the U.S. ecosystem. Symptoms of frictions can be found by examining the data on technology company initial public offerings (IPOs), technology company mergers and acquisitions (M&As), and overall venture capital activity during the 1995-2007 period. There has been a meaningful decline in the numbers of technology IPOs in the United States and a trend toward M&As as the preferred exit strategy for start-up firms (see in Chapter 4 the section entitled "Frictions in the U.S. IT R&D Ecosystem"). While M&As have become the preferred exit of U.S. IT companies, the M&A environment for IT companies has been stable, but flat. As a consequence of fewer IPOs and a shift toward M&A exits, the returns to venture capital funds from their IT investments have declined sharply over the period examined in this study.

Finding 3.1. Fewer young, innovative IT companies are gaining access to U.S. public equity markets.

[25] Vivek Wadhwa, AnnaLee Saxenian, Ben Rissing, and Gary Gereffi, "America's New Immigrant Entrepreneurs: Part 1," Duke Science, Innovation, and Technology Paper No. 23, January 4, 2007, p. 19, available at http://ssrn.com/abstract=990152; accessed December 26, 2007.

The reasons that may explain this decline in technology IPOs and in returns from IT venture investments are multiple and hard to quantify. Nevertheless, the committee believes that they are, at least in part, symptoms of an added friction in the U.S. IT R&D ecosystem. There is no way to interpret in a favorable light the sharp decline in the number of IT companies reaching the IPO milestone. Although reaching an IPO is not a guarantee of long-term future success, IT companies that do not have the opportunity to tap public equity markets will not have the capital required to grow into major industry players and to contribute meaningfully to the creation of high-quality jobs in the United States.

Over the years, new laws and regulations have been introduced that appear to have had negative, unanticipated, and unwanted side effects on the effectiveness of the U.S. IT R&D ecosystem. Moreover, there are indications that older laws and regulations have not been fully adapted to the changing realities of a globalized IT environment that is based on new technological platforms and new innovation methods.

As one example, a major source of friction for young IT companies is the current U.S. patent system. Patents have been more actively acquired and vigorously enforced in recent years.[26] Firms are facing dramatically increased hazards of litigation as plaintiffs and even more rapidly increasing hazards as defendants (see Chapter 4).[27] The sharply increased probability of being sued implies an increase in the "tax" per R&D dollar that litigation imposes on innovation. Small firms face much higher marginal enforcement costs and marginal taxes on R&D.

As the U.S. IT R&D ecosystem has become far more contentious, the cost of protecting and defending intellectual property is undergoing rapid inflation. The long-term effects of this phenomenon may be more pernicious, in terms of the costs of protecting an invention, the costs of defending against an infringement claim, and the size of damages awarded, relative to the contribution of an infringed patent.

Taken together, these trends may have a stifling effect on young IT companies, especially those just bringing products to market, that have limited funds and no patent portfolios for use in cross-licensing agreements or as the basis for countersuits. These companies run a greater

[26]National Research Council, *A Patent System for the 21st Century*, The National Academies Press, Washington, D.C., 2004, p. 19.

[27]According to Bessen and Meurer, the number of patent lawsuits filed annually in the United States doubled during the 1990s, from almost 800 in 1990 to almost 1,600 in 1999; their research also "suggests that patent litigation can affect innovation incentives." James Bessen and Michael Meurer, "The Patent Litigation Explosion," paper presented at the American Law and Economics Association Annual Meeting, 2005, p. 1, available at http://papers.ssrn.com/sol13/Papers.cfm?abstract_id=831685#PaperDownload; accessed March 6, 2008. For litigation hazard findings, see ibid., Table 2.

risk today of never acquiring sufficient intellectual property protection and mustering enough legal resources to withstand costly and lengthy litigation.

Key elements of a successful reform of the U.S. patent litigation system might include the following:

- Clear standards for forum selection that curtail the ability of plaintiffs to file infringement actions in "plaintiff-friendly" jurisdictions;
- Reforms that direct courts to calculate the awards of royalties or damages on the basis of the proportionate value of the patentee's contribution to the product in question rather than on the full value of the entire product;
- Provisions of current law that have never been interpreted to permit the recovery of worldwide damages in U.S. courts;
- Standards governing awards of multiple damages for willfulness; and
- Additional reforms, as necessary, to curtail practices that are a drain on innovation.

Another source of friction is that corporate-governance reform legislation has had unexpected consequences for start-up firms. Historically, initial public offerings have been one of the important exits for venture firms. The Sarbanes-Oxley Act of 2002 (Public Law 107-204), called SOX, and in particular its Section 404, were passed in response to corporate scandals at several large companies, in order to improve the quality of corporate governance among U.S. publicly traded companies and to reduce the risks of financial fraud. However, the type of firm for which SOX was designed was a multi-billion-dollar, multinational corporation listed on U.S. exchanges—not a sub-$100 million technology company seeking to grow rapidly. Yet under SOX, these smaller firms are subject to the same regulations created for the large firms, and the costs of compliance are disproportionate. As a result, it is harder for new, small firms to grow into new major industry players by tapping public equity markets.

Recommendation 3.1. Congress and federal agencies such as the Securities and Exchange Commission and the Patent and Trademark Office should consider the impact of both current and proposed policies and regulations on the IT ecosystem—and especially on young, innovative IT businesses—and consider measures to mitigate these where appropriate.

OBJECTIVE 4. ENSURE THAT THE UNITED STATES HAS AN INFRASTRUCTURE THAT CAN ENABLE U.S. INFORMATION TECHNOLOGY USERS AND INNOVATORS TO LEAD THE WORLD

IT innovation no longer happens only in university or corporate laboratories. Customer-created value is increasingly prominent: IT consumers are leveraging research, innovating, and creating value by combining networking hardware, software, and devices into novel solutions and businesses (see Chapter 3). In the mid-1990s, supplier-created value through technological *product* innovations in information technology predominated. However, this pattern has been changing, as customers are increasingly creating value through IT *application* innovations in industries including health care, professional services, financial services, manufacturing, retail, media and publishing, and education.[28] Similarly, an explosion of Web- and Internet-delivered content and services, many of which feature user-generated content, has led to increasing end-user-driven innovation.

Finding 4.1. The most dynamic IT sector is likely to be in the country with the most demanding IT customers and consumers.

An environment of leading-edge users of technology creates the essential context for technology's next wave and its effective application. In such an environment, all sectors of society, including consumers, businesses, and governments, exploit and make the best use of advanced information technology. However, if a nation's IT users are not global lead users—requiring and using the most advanced IT functionalities—then in the areas where demand lags, that nation's user-driven IT innovation will also lag.

Access to broadband, which provides the high-speed communications links in the "last mile" to connect homes and organizations to the Internet, is one especially important ingredient. The current telecommunications market environment in the United States has yielded many consumer benefits compared with the more highly regulated environment of past decades. However, despite broadband being frequently cited as a national and local imperative, the nation continues to strive for affordable, ubiquitous, and high-performance broadband. Notably, there is significant geographical variation in the availability of broadband service and the degree of market competition. Moreover, although there have been

[28] David Moschella, Leading Edge Forum, "Aligning R&D with Industry Change," presentation to the committee, Boston, Mass., April 19, 2007.

promising recent developments, such as announcements of large fiber-to-the-home deployments by AT&T and Verizon, an enhanced-performance standard for cable modem service (Data Over Cable Service Interface Specifications 3.0), and deployment of increasingly capable wireless services, the extent to which such enhanced facilities and other performance improvements will be deployed nationwide is uncertain.[29] In contrast, many other nations have been carrying out successful national programs to deploy high-speed, low-cost broadband. As a result, although the United States had an early lead in broadband deployment and remains a world leader in computer usage, it finds itself today lagging a number of other nations—notably Japan and Korea—in broadband connectivity.

Finding 4.2. In terms of nationwide availability, use, and speed of broadband, the United States—the inventor of broadband technology—has been losing ground compared with other nations.

A fundamental step toward being the world leader in information technology use is for the United States to deploy world-class broadband connectivity aggressively over the next decade. A number of groups have cited the availability of broadband as an important goal. For example, in January 2002, TechNet, a group of Silicon Valley chief executive officers, proposed that the President and policy makers "make broadband a national priority and set a goal of making an affordable 100-megabits per second broadband connection available to 100 million American homes and small businesses by 2010."[30]

More recently, in January 2008, the California Broadband Task Force (CBTF) recommended the building out of "high speed" broadband infrastructure for all Californians and the promotion of innovative uses of broadband technology. The CBTF's working definition of broadband includes a basic minimum speed, expected to increase over time, of 512 kbps.[31]

In the United States, a complex system of federal, state, and local governance and regulations can present numerous bottlenecks to pursuing ubiquitous, higher-speed, more-affordable broadband.

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[29]National Research Council, *Broadband: Bringing Home the Bits,* National Academy Press, Washington, D.C., 2002; discussion of findings on pp. 13, 18, and 21.

[30]See TechNet, *A National Imperative: Universal Availability of Broadband by 2010,* January 15, 2002, available at http://www.technet.org/resources.dyn/2002-01-15.64.pdf; accessed June 27, 2007.

[31]California Broadband Task Force, *The State of Connectivity: Building Innovation Through Broadband*, January 2008, available at http://www.calink.ca.gov/taskforcereport/; accessed March 17, 2008.

Recommendation 4.1. The United States should establish an ambitious target for regaining and holding a decisive lead in the broad deployment of affordable gigabit broadband services. Federal and state regulators should explore models and approaches that reduce regulatory and jurisdictional bottlenecks and should increase incentives for investment in these services.

Setting—and reaching—a highly ambitious target such as the one proposed by TechNet would enable the United States to leap well ahead and hold that lead.[32] However, this committee has chosen to follow the lead of the Committee on Broadband Last Mile Technology, which in its 2002 NRC report *Broadband: Bringing Home the Bits*, deliberately chose not to establish specific bandwidth targets for policy makers (see in Chapter 3 the subsection entitled "Broadband Speeds and Capabilities"). What constitutes "fast enough" has been and will continue to be a moving target. An effective policy regime would ensure that the capabilities of what is available at an affordable price would continue to improve in performance commensurate with application needs and would provide sufficient "headroom" to provide an opportunity for additional innovation.

Historically, the U.S. government has played a strong role (as an R&D funder and as a lead customer) in establishing U.S. IT demand leadership. Although its total share of the IT market is much smaller than it once was, the U.S. government nonetheless can play an important role as demand leader in the increasingly competitive, global IT markets of today—and tomorrow. This implies a role of broadly fostering research and commercial innovation and also, where appropriate, sponsoring R&D to help meet particular government demands. The federal government has a natural leadership role in certain sectors, such as defense and homeland security (especially in the area of cyberphysical systems), in which federal agencies' requirements are particular to their missions and commercial analogues are scarce.[33]

Recommendation 4.2. Government (federal, state, and local) should foster commercial innovation and itself make strategic investments

[32]This bandwidth target is more ambitious than TechNet's proposal for accelerating broadband deployment and demand, which called for 100-megabit-per-second connectivity by 2010; available at http://www.technet.org/issues/broadband/; accessed September 7, 2007. A goal of gigabit connectivity would be useful in helping the United States leapfrog Japan and other nations now moving ahead in broadband deployment.

[33]For analyses of specific areas where government R&D leadership in software is needed to ensure timely innovation to meet defense needs, see National Research Council, *Preliminary Observations on DoD Software Research Needs and Priorities: A Letter Report*, The National Academies Press, Washington, D.C., 2008.

in IT R&D and deployment so that the United States can retain a global lead position in areas where it has particular mission requirements.

CONCLUSION

The globalization of the world's economy is a fact that cannot be ignored. The global IT R&D landscape now is quite different from what it was in 1995. To thrive in this new environment, the United States should play to its strengths, notably its continued leadership in conceptualizing the idea-intensive new concepts, products, and services that the rest of the world desires. This is the area in which the greatest increments of value added are captured.

Toward this end, it is necessary for the United States to have the best-funded and most-creative research institutions; to develop and attract the best technical and entrepreneurial talent among its own people as well as from around the world; to make its economy the world's most attractive for forming new ventures and growing small, innovative firms; and to create the environment to ensure the deployment of the most advanced technology infrastructure, applications, and services here in the United States for the benefit of our people, institutions, and firms.

The committee trusts that this report will be useful to policy makers and the public in helping the nation achieve these goals and in fostering a vibrant and thriving U.S. IT R&D ecosystem for many decades to come.

Appendixes

A

Biosketches of Committee Members and Staff

COMMITTEE MEMBERS

Eric Benhamou, *Co-Chair*, is chair and chief executive officer (CEO) of Benhamou Global Ventures, LLC. Benhamou Global Ventures, started in 2003, invests and plays an active role in innovative high-tech firms throughout the world. Mr. Benhamou is also the chairman of the board of directors of 3Com Corporation and Palm, Inc. He is an adjunct professor of Entrepreneurship and Family Enterprise at INSEAD. He served as CEO of Palm, Inc., from October 2001 until October 2003. Mr. Benhamou served as CEO of 3Com Corporation from September 1990 until December 31, 2000. Mr. Benhamou's professional and personal accomplishments center on the creation and intelligent deployment of information technology toward improving the performance of businesses and nonprofit organizations and the quality of life of individuals around the world. In 1981, Mr. Benhamou cofounded Bridge Communications, an early networking pioneer, and was vice president of engineering until the merger with 3Com in 1987. Before joining Bridge Communications, he worked 4 years at Zilog, Inc., serving as project manager, software engineering manager, and design engineer. In 2003, Mr. Benhamou was appointed to the Joint High Level Advisory Panel of the U.S.- Israel Science and Technology Commission by U.S. Commerce Secretary Donald Evans. In 1997, President Clinton appointed Mr. Benhamou to the President's Information Technology Advisory Committee, which advises the president on research and development focal points of federal programs to maintain

U.S. leadership in advanced computing and communications technologies and their applications. In 1998, Mr. Benhamou was recognized by former Israeli Prime Minister Benjamin Netanyahu with the Foreign Investor Jubilee Award. That same year, Mr. Benhamou received the Ellis Island Medal of Honor, which pays homage to the immigrant experience, as well as to individual achievements of U.S. citizens from various ethnic backgrounds. In 1998, he became a fellow of the International Engineering Consortium. He is a graduate of the American Leadership Forum, which seeks to revitalize leadership within communities across the nation. In 1997, Mr. Benhamou received the Medaille Nessim Habif from Ecole Nationale Supérieure d'Arts et Métiers, Paris. In 1992, he received the President's Environment and Conservation Challenge Award, the United States' highest environmental award. Mr. Benhamou currently serves as chairman of the board of Cypress Semiconductor, as lead director of RealNetworks, Inc., and Voltaire, and as a member of the board of directors of Silicon Valley Bancshares. He serves on the board of directors of privately held companies, Contextream, Finjan, and Purewave Networks. He served on the board of the New America Foundation, a Washington, D.C.-based think tank until December 2007. Mr. Benhamou serves on the executive committee of TechNet. He was a member of the Computer Science and Telecommunications Board (CSTB) and is a member of the Markle Task Force on Information Security. In addition, he serves on the boards of the INSEAD School of Business, the Stanford University School of Engineering, and Ben Gurion University of the Negev. He is the chairman of the Israel Venture Network, a venture philanthropy organization for a stronger Israeli society. Mr. Benhamou holds honorary doctoral degrees from Ben Gurion University of the Negev, Widener University, Western Governors University, and the University of South Carolina. He has a Master of Science degree from Stanford University's School of Engineering and a Diplôme d'Ingénieur from Ecole Nationale Supérieure d'Arts et Métiers, Paris.

Randy H. Katz, *Co-Chair,* (NAE), is the United Microelectronics Corporation Distinguished Professor, Electrical Engineering and Computer Science Department, University of California, Berkeley. He joined the Berkeley faculty in 1983, where since 1996 he has been the United Microelectronics Corporation Distinguished Professor in Electrical Engineering and Computer Science. He is a fellow of the Association for Computing Machinery (ACM) and the IEEE, and a member of the National Academy of Engineering and the American Academy of Arts and Sciences. He has published more than 250 refereed technical papers, book chapters, and books. His textbook, *Contemporary Logic Design,* has sold more than 85,000 copies and has been used at more than 200 colleges and universities. A second edition, cowritten with Gaetano Borriello, was published in 2005. He has supervised 43 M.S. theses and 33 Ph.D. dissertations (including one ACM Dissertation Award winner and eight women), and leads a research team of more than 10 graduate students, technical staff, and academic visitors. Recognitions of Dr. Katz's work include 13 best-paper awards (including one "test of time" paper award and one selected for a 50-year retrospective on IEEE Communications publications), three best-presentation awards, the Outstanding Alumni Award of the Computer Science Division, the Computing Research Association's (CRA's) Outstanding Service Award, the Berkeley Distinguished Teaching Award, the Air Force Exceptional Civilian Service Decoration, the IEEE Reynolds Johnson Information Storage Award, the American Society for Engineering Education's Frederic E. Terman Award, and the ACM Karl V. Karlstrom Outstanding Educator Award. In the late 1980s, with colleagues at the University of California, Berkeley, Dr. Katz developed Redundant Arrays of Inexpensive Disks (RAID), a $15 billion per year industry sector. While on leave for government service in 1993-1994, he established whitehouse.gov and connected the White House to the Internet. His current research interests are reliable, adaptive distributed systems supported by new services deployed inside the network. His prior research interests have included database management, very large scale integrated circuit (VLSI) computer-aided design (CAD), high performance multiprocessor (Snoop cache coherency protocols) and storage (RAID) architectures, transport (Snoop TCP) and mobility protocols spanning heterogeneous wireless networks, and converged data and telephony network and service architectures. Dr. Katz received his undergraduate degree from Cornell University and his M.S. and Ph.D. degrees from the University of California, Berkeley. In May 2007 he received a Doctor of Philosopy (Honoris Causa) from the University of Helsinki.

Stephen R. Barley is the Charles M. Pigott Professor of Management Science and Engineering; the co-director of the Center for Work, Technology and Organization at Stanford University's School of Engineering; and the co-director of the Stanford/General Motors Collaborative Research Laboratory. He holds a Ph.D. in organization studies from the Massachusetts Institute of Technology. Prior to coming to Stanford in 1994, Dr. Barley served for 10 years on the faculty of the School of Industrial and Labor Relations at Cornell University. He was editor of the *Administrative Science Quarterly* from 1993 to 1997 and the founding editor of the *Stanford Social Innovation Review* from 2002 to 2004. He has served on the editorial boards of the Academy of Management journal, *The Journal of Management Studies and Organization Science.* Dr. Barley has been the recipient of the Academy of Management's New Concept Award. He was a member of the Board of Senior Scholars of the National Center for the Educational Quality of the Workforce and co-chaired the National Research Council committee on the changing occupational structure in the United States that produced the report *The Changing Nature of Work* in 1999. Dr. Barley has written extensively on the impact of new technologies on work, the organization of technical work, and organizational culture. He edited a volume on technical work, entitled *Between Craft and Science: Technical Work in the United States,* published in 1997 by Cornell University Press. In collaboration with Gideon Kunda of Tel Aviv University, Dr. Barley recently published a book on contingent work among engineers and software developers, entitled *Gurus, Hired Guns and Warm Bodies: Itinerant Experts in the Knowledge Economy,* with Princeton University Press. Dr. Barley teaches courses on the management of R&D, the organizational implications of technological change, organizational behavior, social network analysis, and ethnographic field methods. He has served as a consultant to organizations in a variety of industries including publishing, banking, computers, electronics, and aerospace.

Andrew B. Hargadon is an associate professor of technology management and director of technology management programs at the Graduate School of Management at the University of California, Davis. Prior to his academic appointment, he worked as a product designer at IDEO and Apple Computer and taught in the Product Design program at Stanford University. Dr. Hargadon's research focuses on the effective management of innovation, and he has written extensively on knowledge and technology brokering, the role of learning and knowledge management in innovation, and the strategic role of design in managing technology transitions. His research has been used to develop or guide new innovation programs in organizations as diverse as the Canadian Health Services, Silicon Valley start-ups, Hewlett-Packard, and the U.S. Navy. Dr. Hargadon has published numerous articles and chapters in leading scholarly and applied publications, including *Harvard Business Review, Administrative Science Quarterly, Organization Science, California Management Review,* and *Research in Organizational Behavior.* He serves on the editorial board of *Administrative Science Quarterly, Organization Science, Organization Studies,* and the *Academy of Management Review.* He teaches corporate executive programs and gives lectures on the creativity, design, and management of innovation. He received his Ph.D. from the Management Science and Engineering Department in Stanford University's School of Engineering, where he was named Boeing Fellow and Sloan Foundation Future Professor of Manufacturing. He received his B.S. and M.S. in Stanford University's Product Design Program in the Mechanical Engineering Department.

Martin Kenney is a professor in the Department of Human and Community Development at the University of California, Davis, and senior project director, Berkeley Roundtable on the International Economy, University of California, Berkeley. He has authored or edited five books and more than 100 articles on the development of high-technology clusters, the growth of venture capital, and university-related entrepreneurship in the United States, China, and Europe. Dr. Kenney's current work concentrates on three areas. His research on services offshoring to India has helped him develop both an important perspective on the issue and a range of contacts and knowledge throughout the Indian outsourcing industry. In another area, Dr. Kenney has been studying the venture capital industry since 1988. More recently, his work in this area has focused on the globalization of venture capital. Finally, Dr. Kenney has advised numerous corporations, universities, governments, and financial institutions on a range of issues, including university/industry relationships, economic development, and venture capital. He has keynoted for a major U.S. law firm on offshore outsourcing and participated in World Bank East Asian studies on high-technology clusters and venture capital. He has built a comprehensive database of initial public offerings (IPOs) in the years 1996-2004, from which he is mining a number of novel correlations. He received his Ph.D. in development sociology in 1984 from Cornell University and his B.A. in 1974 and M.A. in 1976, both in sociology, from San Diego State University.

Steven Klepper is Arthur Arton Hamerschlag Professor of Economics and Social Science at the Department of Social and Decision Sciences in the College of Humanities and Social Sciences at Carnegie Mellon University. He is also on the faculty of the Tepper School of Business and is an affiliate of the H. John Heinz III School of Public Policy and Management at Carnegie Mellon. His fields of specialization include the evolution of industry and the determinants of technological change, statistical procedures to cope with measurement error, and tax compliance. He is an associate editor of *Management Science* and is on the editorial boards of *Economics of Innovation and New Technology* and *Empirica.* He is a research associate in the Centre for Research on Innovation and Competition, the University of Manchester, and has served on the National Science Foundation's Economics Advisory Panel. His books and articles focus on innovation, economic development, economic evolution, and technological change as a factor in the growth and decline of industry. His publications include "Firm Survival and the Evolution of Oligopoly," *Rand Journal of Economics* (2002); "Entry, Exit, Growth, and Innovation over the Product Life Cycle," *American Economic Review* (1996); with W. Cohen, "A Reprise of Size and

R&D," *Economic Journal* (1996); with W. Cohen, "Firm Size and the Nature of Innovation Within Industries," *Review of Economics and Statistics* (1996). He received his Ph.D. in economics from Cornell University in 1975.

Edward D. Lazowska (NAE) holds the Bill and Melinda Gates Chair in Computer Science and Engineering at the University of Washington. His research and teaching concern the design, implementation, and analysis of high performance computing and communication systems. Dr. Lazowska is a member of the National Academy of Engineering and a fellow of the American Academy of Arts and Sciences. He chaired the Computing Research Association board of directors from 1997 to 2001, the National Science Foundation's Computer and Information Science and Engineering Advisory Committee from 1998 to 1999, the Defense Advanced Research Projects Agency's Information Science and Technology Study Group from 2004 to 2006, and the President's Information Technology Advisory Committee from 2003 to 2005. He served for 6 years on the National Research Council's (NRC's) Computer Science and Telecommunications Board (CSTB), and has served on a number of NRC study committees, including the Committee on Improving Learning with Information Technology, the Committee on Science and Technology for Countering Terrorism—Panel on Information Technology, the Committee on Research Horizons on Networking, and the Committee to Review the Multi-Agency HPCC Program. He contributed extensively to the CSTB summary report *Innovation in Information Technology.* Dr. Lazowska received his A.B. from Brown University in 1972 and his Ph.D. from the University of Toronto in 1977, when he joined the University of Washington faculty.

Lenny Mendonca is a director (senior partner) in the San Francisco office of McKinsey & Company, Inc., the world's leading global management consulting firm, where he leads the firm's knowledge development. Mr. Mendonca is on the Shareholders' Council of McKinsey (its board of directors), oversees the firm's communications (including the *McKinsey Quarterly*), and is chair of the McKinsey Global Institute. He has helped dozens of corporate, government, and nonprofit clients solve their most difficult management challenges. Mr. Mendonca is the chairman of the Bay Area Council, on the board of directors of the Economic Institute of the Bay Area and the Bay Area Science and Innovation Consortium. He is on the board of the New America Foundation, Common Cause, a trustee for the Committee for Economic Development, and on the Advisory Council for the Stanford Graduate School of Business. He serves on the board of ChildrenNow, DonorsChoose, and the California Business for Educational Excellence Foundation, and is a member of the Alliance for the San Francisco Unified School District. Mr. Mendonca has led several

McKinsey research efforts. He has written and spoken extensively on globalization, corporate social responsibility, economic development, regulation, education, energy policy, health care, financial services, and corporate strategy. He received his M.B.A. and certificate in public management from the Stanford Graduate School of Business. He holds an A.B., magna cum laude, in economics from Harvard College. Mr. Mendonca is the founder and owner of the Half Moon Bay Brewing Company.

David C. Nagel is the former president and CEO of PalmSource, Inc. Before going to PalmSource, Dr. Nagel held leadership positions as chief technology officer (CTO), AT&T; president, AT&T Labs; and CTO, Concert (a joint venture of AT&T and British Telecommunications Group). Dr. Nagel also was senior vice president, Apple Computer; and chief of NASA Human Factors Research, NASA Ames Research Center. He has also served on national and international advisory committees, including the President's Information Technology Advisory Committee and the Federal Communications Commission's Technology Advisory Council (1999). Dr. Nagel also is a member of the boards of directors of Tessera Technologies, Inc., and Leapfrog Technologies, Inc. He also serves as chairman of Arcsoft, a private developer of software for mobile imaging, and as lead independent director of Epocrates, Inc., a private company and leading provider of medical information systems for mobile devices and the World Wide Web. He has a Ph.D. in psychology (perception and mathematical) and an M.S. and B.S. in engineering, all from the University of California, Los Angeles. He is on the board of trustees of the International Computer Science Institute and an emeritus director of the board of the Tech Museum of Innovation, San Jose, California.

Arati Prabhakar joined U.S. Venture Partners (USVP) in 2001 after 15 years of working with world-class engineers and scientists across many fields to brew new technologies. As a general partner at USVP, her primary focus is fabless semiconductor and semiconductor manufacturing opportunities. She serves on the boards of directors of Arradiance, Kilopass, Kleer, Leadis Technology (NASDAQ: LDIS), Lightspeed Logic, Pivotal Technologies, and SiBeam. Dr. Prabhakar was a program manager and then director of the Microelectronics Technology Office at the Defense Advanced Research Projects Agency (DARPA) from 1986 to 1993. At DARPA, she supported R&D in company and university laboratories in semiconductor manufacturing, imaging, optoelectronics, and nanoelectronics. In 1993, President Clinton appointed her director of the National Institute of Standards and Technology, where she led the 3,000-person staff until 1997. Dr. Prabhakar then joined Raychem Corporation as senior vice president and chief technology officer. She was subsequently vice president and then president of Interval Research Corporation. Dr. Prabhakar received her B.S. in electrical engineering from Texas Tech University in 1979. She received an M.S. in electrical engineering in 1980 and a Ph.D. in applied physics in 1984 from the California Institute of Technology (Caltech). She began her career as a Congressional Fellow at the Office of Technology Assessment in 1984 to 1986. Dr. Prabhakar has been honored as a distinguished alumna of Texas Tech and of Caltech, and she has been awarded an honorary doctorate from the Rensselaer Polytechnic Institute. She is a fellow of the IEEE and serves on advisory boards for Stanford University, the University of California, Berkeley, and the University of California, Santa Barbara.

Raj Reddy (NAE) is the Mozah Bint Nasser University Professor of Computer Science and Robotics in the School of Computer Science at Carnegie Mellon University. He began his academic career as an assistant professor at Stanford University in 1966. He has been a member of the Carnegie Mellon faculty since 1969. He served as the founding director of the Robotics Institute from 1979 to 1991 and as the dean of the School of Computer Science from 1991 to 1999. Dr. Reddy's research interests include the study of human-computer interaction and artificial intelligence. His current research interests include the Million Book Digital Library Project, a multifunction information appliance that can be used by the uneducated, the Fiber to the Village Project, Mobile Autonomous Robots, and Learning by Doing. He is a member of the National Academy of Engineering and the American Academy of Arts and Sciences. He was president of the American Association for Artificial Intelligence from 1987 to 1989. Dr. Reddy was awarded the Legion of Honor by President Mitterand of France in 1984. He was awarded the ACM Turing Award in 1994, the Okawa Prize in 2004, the Honda Prize in 2005, and the Vannevar Bush Award in 2006. He served as co-chair of the President's Information Technology Advisory Committee from 1999 to 2001 under Presidents Clinton and Bush. Dr. Reddy received a B.E. degree from the Guindy Engineering College of the University of Madras, India, in 1958 and an M.Tech degree from the University of New South Wales, Australia, in 1960. He received a Ph.D. degree in computer science from Stanford University in 1966.

Lucinda Sanders is a cofounder of the National Center for Women and Information Technology and currently is executive in residence, Alliance for Technology, Learning and Society (ATLAS) with the University of Colorado. Ms. Sanders developed many years of industry and executive experience in the communications software business, with a broad knowledge base including customer relationship management (CRM) e-business solutions, call-center technologies, and multimedia communications. From May 1999 to August 2001, she was vice president, Avaya Inc., CRM Solutions R&D and CTO. From August 1996 to May 1999 she served as CTO for Lucent Technologies Customer Care Solutions and from January 1995 to August 1996 she served as department head for Lucent Bell Labs R&D. Ms. Sanders has received numerous awards such as the Distinguished Engineering Alumni Award, Silicon Valley Tribute to Women in Industry, Partner of Choice, Trail Blazer, Touch Award, and Bell Labs President's Silver Award. She also received the most prestigious Bell Labs award (the Fellow Award), which recognized her for technical excellence in software architectures, participation on teams creating first-to-market solutions for enterprise private branch exchange (PBX) systems, multimedia communication systems (including Voice over IP), and call centers. She has a M.S. in computer science from the University of Colorado and a B.S. in computer science from Louisiana State University and holds six patents.

CSTB STAFF

Joan D. Winston was a program officer for the Computer Science and Telecommunications Board (CSTB) of the National Research Council from March 2006 through May 2008. She also worked on CSTB studies that produced *Preliminary Observations on DoD Software Research Needs and Priorities: A Letter Report* (2008), *Social Security Administration Electronic Service Provision: A Strategic Assessment* (2007), and *Summary of a Workshop on Software-Intensive Systems and Uncertainty at Scale* (2007). She was a consultant to CSTB in 2005-2006. Before joining CSTB, she was an assistant director (information technology team) at the Government Accountability Office. From 1998 to 2001, she was principal associate at Steve Walker and Associates, LLC, which managed early-stage venture funds focusing on information technology. From 1995 to 1998, she was director of policy analysis for Trusted Information Systems, Inc. From 1986 to 1995, she held various analytical and project direction positions at the congressional Office of Technology Assessment (OTA) and was recognized as an OTA senior associate in 1993. Before OTA, she worked briefly for the Congressional Research Service of the Library of Congress. Ms. Winston started her career as an engineer at the Charles Stark Draper Laboratory, Inc., in Cambridge, Massachusetts. She has an S.B. in physics and an S.M. in technology and policy, both from the Massachusetts Institute of Technology.

Jon Eisenberg is director of the Computer Science and Telecommunications Board of the National Research Council. He has also been study director for a diverse body of work, including a series of studies exploring Internet and broadband policy and networking and communications technologies. In 1995-1997 he was a Science, Engineering, and Diplomacy Fellow of the American Association for the Advancement of Science at the U.S. Agency for International Development, where he worked on technology transfer and information and telecommunications policy issues. Dr. Eisenberg received his Ph.D. in physics from the University of Washington in 1996 and B.S. in physics with honors from the University of Massachusetts at Amherst in 1988.

Kristen R. Batch was an associate program officer for the Computer Science and Telecommunications Board of the National Research Council from 2002 to 2008, where she was also involved with projects focusing on the interoperability of voter registration databases and the policy and ethical implications of offensive information warfare and studies that resulted in the following publications: *Toward a Safer and More Secure Cyberspace* (2007), *Engaging Privacy and Information Technology in a Digital Age* (2007), *Asking the Right Questions About Electronic Voting* (2005), *Signposts in Cyberspace: The Domain Name System and Internet Navigation* (2005), *A Review of the FBI's Trilogy Information Technology Modernization Program* (2004), and *The Internet Under Crisis Conditions: Learning from September 11* (2002). While pursuing an M.A. in international communications from American University, she interned at the National Telecommunications and Information Administration in the Office of International Affairs and at the Center for Strategic and International Studies in the Technology and Public Policy Program. She received a B.A. from Carnegie Mellon University in literary and cultural studies and Spanish, and received two travel grants to conduct independent research in Spain.

Margaret Marsh Huynh, senior program assistant, was with CSTB from January 1999 to November 2007. She supported a number of projects, including Whither Biometrics, Wireless Technology Prospects and Policy, Advancing Software-Intensive Systems Producibility, and Assessing the Impacts of Changes in the Information Technology Research and Development Ecosystem. She also worked on the projects that produced the reports *Signposts in the Cyberspace: The Domain Name Systems and Internet Navigation* (2005), *Getting Up to Speed: The Future of Supercomputing* (2004), *Beyond Productivity: Information Technology, Innovation, and Creativity* (2003), *IT Roadmap to a Geospatial Future* (2002), *Building a Workforce for the Information Economy* (2001), and *The Digital Dilemma: Intellectual Property in the Information Age* (2000). Ms. Huynh also assisted with the National Telecommunications and Information Administration workshop on improving spectrum management through economic and other incentives (2006), the Government Accountability Office/NRC forum on information resource management and the Paperwork Reduction Act (2005), as well as the workshops on IT issues for the behavioral and social sciences. Prior to coming to the NRC, Ms. Huynh worked as a meeting assistant at Management for Meetings, April to August 1998, and as a meeting assistant at the American Society for Civil Engineers from September 1996 to April 1998. Ms. Huynh has a B.A. (1990) in liberal studies with minors in sociology and psychology from Salisbury University, Salisbury, Maryland.

Morgan R. Motto, program associate, has been with CSTB since December 2007 supporting several projects, including the Wireless Technology Prospects and Policy, Improving Processes and Policies of Information Technology in the Department of Defense, Future of Libraries and Museums, and the State Voter Registration Databases. Previously, she worked with the Board on Environmental Studies and Toxicology (BEST) on the Human Biomonitoring for Environmental Toxicants, Sediment Dredging at Superfund Megasites, Applications of Toxicogenomic Technologies to Predictive Toxicology and Risk Assessment, Evaluating the Efficiency of Research and Development Programs at the Environmental Protection Agency, Review of the NIOSH Respiratory Disease Research Program, Review of the Federal Strategy to Address Environmental, Health, and Safety Research Needs for Engineered Nanoscale Materials, and Improving Risk Analysis Approaches Used by the U.S. EPA. Prior to coming to the NRC, Ms. Motto worked as project manager for international affairs and technology at the U.S. Pan Asian American Chamber of Commerce. She earned a B.A. in International Affairs and East Asian Studies from the Elliott School of International Affairs at the George Washington University.

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Workshop Agendas

PERSPECTIVES ON THE INFORMATION TECHNOLOGY R&D ECOSYSTEM

NOVEMBER 2, 2006
WASHINGTON, D.C.

10:45-11:00 a.m.	Welcome to the Open Session and Workshop Overview of Computer Science and Telecommunications Board (CSTB) and Study (Goals, Timing) *Eric Benhamou and Randy H. Katz, Committee and Workshop Co-Chairs*
11:00 a.m.-12:00 noon	Perspectives from Study Sponsor and Charge to the Committee *Peter Freeman, National Science Foundation*
12:00 noon-12:30 p.m.	Working Lunch
12:30-2:30 p.m.	Panel One: Perspectives on the IT R&D Ecosystem from Federal Agencies Making IT R&D Investments

Discussion Topics:
- What are your agency's investment philosophy, strategy, and interests for IT research?
- From your perspective, what is the state of the IT R&D ecosystem? Has this changed or do you see it changing?
- What aspects of the ecosystem do you think are working well, and where are you looking to make improvements?
- What do you think could be done to maintain or improve the health and vitality of the ecosystem? Who can do this? Who should do this?
- What studies and data, including funding data, do you think the committee should take into account (please provide these or provide links).

Panelists:
Simon Szykman, National Coordination Office for Networking and Information Technology R&D
Deborah Crawford, National Science Foundation
Anthony Tether, Defense Advanced Research Projects Agency
André van Tilborg, Office of the Deputy Under Secretary of Defense, Science and Technology
Daniel Hitchcock, Department of Energy
Michael Marron, National Institutes of Health

Q&A with panelists

2:30-2:45 p.m.	Break
2:45-4:15 p.m.	Panel Two: Perspectives on the IT R&D Ecosystem from Academic and Business Communities

Discussion Topics:
- From your perspective, what is the state of the IT R&D ecosystem? Has this changed or do you see it changing?
- What aspects of the ecosystem do you think are working well, and where would you look to make improvements?

- What do you think could be done to maintain or improve the health and vitality of the ecosystem? Who can do this? Who should do this?
- What studies and data do you think the committee should take into account (please provide or provide links).

Panelists:
William Aspray, Association for Computing Machinery
Andrew Bernat, Computing Research Association
Andrea Hoffman, TechNet
Charles Wessner, Board on Science, Technology, and Economic Policy, National Research Council

Q&A with panelists

4:15-5:45 p.m. Panel Three: Perspectives on the Potomac-Area IT Start-up Environment

Discussion Topics:

- From your perspective, what is the regional climate like for IT start-ups? How has this changed? Where do you see it going?
- What is the provenance of most of the successful start-ups in this region?
- What are the key advantages for start-ups in this area? The key hindrances?
- What is your perspective on funding prospects and viability of IT-centered start-ups based on technology transferred from university research? Based on technology developed in government-industry partnerships? Spun out of national laboratories and Federally Funded Research and Development Centers (FFRDCs)?
- What could be done to improve funding and viability of IT-centered start-ups? Who should do this? Who can do this?
- What studies and data do you think the committee should take into account (please provide or provide links)?

	Panelists: *John May, New Vantage Group* *Jonathan Silver, Core Capital Partners* *Raymar Dizon, Maryland Department of Business and Economic Development*
	Q&A with panelists
5:45 p.m.	Closing Remarks by Committee and Public *Eric Benhamou and Randy H. Katz, Co-Chairs*
6:15-7:00 p.m.	Adjournment and Public Reception

INFORMATION TECHNOLOGY R&D ECOSYSTEM WORKSHOP—SILICON VALLEY

FEBRUARY 23, 2007
MOUNTAIN VIEW, CALIFORNIA

9:00-9:15 a.m.	Welcome to the Open Session and Workshop *Eric Benhamou and Randy H. Katz, Committee and Workshop Co-Chairs*
9:15-10:45 a.m.	Panel I: Perspectives on China's and India's Roles in the IT R&D Ecosystem *Session Organizer: Martin Kenney, University of California, Davis*
	Panelists: *Vinod Dham, NewPath Ventures LLC* *Dixon Doll, DCM-Doll Capital Management* *Martin Haemmig, Consultant* *Lenny Mendonca, McKinsey & Company*
	Q&A with panelists
10:45-11:00 a.m.	Break
11:00 a.m.-12:30 p.m.	Panel II: Perspectives from Long-Time Observers of the Ecosystem *Session Organizer: Randy H. Katz, University of California, Berkeley; Committee and Workshop Co-Chair*

	Panelists: *John Markoff,* New York Times, *and Visiting Lecturer, Stanford University* *Geoffrey Moore, TGC Advisors* *Kara Swisher,* Wall Street Journal *Hal Varian, University of California, Berkeley*
	Q&A with panelists
12:30-1:30 p.m.	Working Lunch Remarks and Discussion *John Toole, Executive Director and CEO, Computer History Museum*
1:30-3:00 p.m.	Panel III: Perspectives from Serial Entrepreneurs and Angel Investors *Session Organizer: Arati Prabhakar, U.S. Venture Partners*
	Panelists: *Ron Conway, Angel Investors* *Judy Estrin, Packet Design* *Andreas von Bechtolsheim, Sun Microsystems*
	Q&A with panelists
3:00-3:30 p.m.	Break
3:30-5:00 p.m.	Panel IV: A Cross-Industry, Global View of the Ecosystem *Session Organizer: Steven Klepper, Carnegie Mellon University*
	Panelists: *Timothy Bresnahan, Stanford University* *Rafiq Dossani, Stanford University* *David Mowery, University of California, Berkeley (participating by conference phone)* *AnnaLee Saxenian, University of California, Berkeley (participating by conference phone)*
	Q&A with panelists

5:00-5:30 p.m.	Banking Business Models for Working with Innovative Companies *Kenneth Wilcox, Silicon Valley Bank and SVB Financial Group*
5:30 p.m.	Closing Remarks for Workshop
6:00 p.m.	Working Dinner
7:30 p.m.	Discussion with Carver Mead, Foveon, Inc. *The public is welcome.*

INFORMATION TECHNOLOGY R&D ECOSYSTEM WORKSHOP—BOSTON

APRIL 19, 2007
BOSTON, MASSACHUSETTS

8:00 a.m.	Welcome to the Open Session and Workshop *Eric Benhamou and Randy H. Katz, Committee and Workshop Co-Chairs*
8:00-8:30 a.m.	European Venture Perspectives on the IT R&D Ecosystem *Paul Deninger, Jeffries Broadview* Q&A
8:30-10:00 a.m.	Policy Dimensions of the IT R&D Ecosystem *Session Moderator: Eric Benhamou, Benhamou Global Ventures, LLC; Committee and Workshop Co-Chair* Panelists: *Erik Brynjolfsson, Massachusetts Institute of Technology* *Bob Litan, Kauffman Foundation (participating by conference phone)* *Bob Kimball, RealNetworks, Inc. (participating by conference phone)* Q&A with panelists
10:00-10:30 a.m.	Break

10:30 a.m.-12:00 p.m.	State of University–Industry Relationships in the IT R&D Ecosystem *Session Moderator: Raj Reddy, Carnegie Mellon University* Panelists: *Katharine Ku, Stanford University* *Scott Shane, Case Western Reserve University (participating by conference phone)* *Rodney Brooks, Massachusetts Institute of Technology* *Kenneth Morse, Massachusetts Institute of Technology* Q&A with panelists
12:00 p.m.-1:00 p.m.	Working Lunch, with Speaker *Irving Wladawsky-Berger, IBM*
1:00-1:15 p.m.	Break
1:15-2:30 p.m.	International Dimensions of the IT R&D Ecosystem *Session Moderator: Eric Benhamou, Benhamou Global Ventures, LLC; Committee and Workshop Co-Chair* Panelists: *Orna Berry, Gemini Israel Funds and Israel Venture Association* *David Wei, Lenovo (participating by conference phone)* *David Moschella, Leading Edge Forum* Q&A with panelists
2:30-3:00 p.m.	Break
3:00-4:30 p.m.	Emerging IT Platforms—from Sensors to Internet Data Centers, from Open Source to Web 2.0 *Session Moderator: Randy H. Katz, University of California, Berkeley; Committee and Workshop Co-Chair*

	Panelists: *Jamey Hicks, Nokia Research Center, Cambridge* *Jeffrey Jaffe, Novell, Inc.* *Luiz Andre Barroso, Google, Inc. (participating by conference phone)* *Siobhan O'Mahoney, Harvard Business School*
	Q&A with panelists
4:30-5:00 p.m.	Break
5:00-6:30 p.m.	Workforce and Social Issues *Session Moderators: Stephen Barley, Stanford University; and Lucy Sanders, National Center for Women and Information Technology*
	Panelists: *Phillip J. Bond, Information Technology Association of America* *Daryl Chubin, American Association for the Advancement of Science* *David Finegold, Rutgers, The State University of New Jersey* *John Sargent, Department of Commerce*
	Q&A with panelists
6:30 p.m.	Adjournment
6:30-8:30 p.m.	Dinner
7:15 p.m.	Speaker: *Robert M. Metcalfe, Polaris Venture Partners*