Renewing U.S. Telecommunications Research

Robert W. Lucky and Jon Eisenberg, Editors,
Committee on Telecommunications Research and Development, National Research Council

ISBN: 0-309-66396-2, 96 pages, 8 1/2 x 11, (2006)

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Committee on Telecommunications Research and Development

Computer Science and Telecommunications Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

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This study was supported by the National Science Foundation under award number CNS 0238609. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the agency that provided support for the project.

International Standard Book Number 0-309-10265-0

This report is available in PDF format from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

Printed in the United States of America

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[1] Fred Chang resigned from the committee in October 2005 when he became director of research at the National Security Agency.

Preface

The Committee on Telecommunications Research and Development was convened by the National Research Council's Computer Science and Telecommunications Board to conduct an assessment of U.S. telecommunications research and development (R&D). Sponsored by the National Science Foundation, the study examines changes in the level of research support, research focus, and research time horizon in industry; discusses the importance of support for telecommunications research within universities; and addresses implications of the current research landscape for the health of the U.S. telecommunications sector, as well as the U.S. economy and society. The report comes at a time of increasing attention to the health of U.S. R&D across many sectors. Although some of the issues raised mirror those seen in other sectors, there are also marked differences with respect to research in telecommunications, some owing to the support for R&D historically provided through the Bell System.

The committee's findings and recommendations are provided in Chapter 5. Chapters 1 through 4 provide related supporting evidence and discussion.

Robert W. Lucky, *Chair*
Committee on Telecommunications Research and Development

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:

William J. Brinkman, Princeton University,
David D. Clark, Massachusetts Institute of Technology,
Stephen Dukes, Imaginary Universes, LLC,
Judith Estrin, Packet Design,
James Flanagan, Rutgers University,
David Goodman, Polytechnic University,
Butler W. Lampson, Microsoft Corporation,
Frederick Leonberger, EOvation Technologies, LLC, and
Andrew J. Viterbi, Viterbi Group, LLC.

Although the reviewers listed above 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 Elsa Garmire of Dartmouth College's Thayer School of Engineering. Appointed by the National Research Council, she 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

Executive Summary

The modern telecommunications infrastructure—made possible by research performed over the last several decades—is an essential element of the U.S. economy and society. But the U.S. position as a leader in telecommunications technology is now at risk because of the recent decline in domestic support for long-term, fundamental telecommunications research. To help understand this challenge, the National Science Foundation (NSF) asked the National Research Council to assess the current state of telecommunications research in the United States. This report provides an examination of telecommunications research support, focus, and time horizon in industry and academia and discusses the implications for the health of the sector. Finally, it presents recommendations for enhancing U.S. telecommunications research efforts.

FINDINGS

Telecommunications has expanded greatly over the past few decades from primarily landline telephone service to the use of fiber optic, cable, and wireless connections offering a wide range of voice, image, video, and data services. Yet it is not a mature industry, and major innovation and change—driven by research—can be expected for many years to come.

Without an expanded investment in research, however, the nation's position as a leader is at risk. Strong competition is emerging from Asian and European countries that are making substantial investments in telecommunications R&D.

For many telecommunications products and services that are now commodities, the United States is at a competitive disadvantage compared with countries where the cost of doing business is lower. Continued U.S. strength in telecommunications, therefore, will require a focus on high-value innovation that is made possible only by a greater emphasis on research. Expansion of telecommunications research is also necessary to attract, train, and retain research talent.

Telecommunications research has yielded major benefits such as the Internet, radio frequency wireless communications, optical networks, and voice over Internet Protocol. Promising opportunities for future research include enhanced Internet architectures, more trustworthy networks, and adaptive and cognitive wireless networks.

Nevertheless, research support has fallen off in recent years. Prior to the restructuring of the telecommunications industry in 1984, the Bell System's research labs played a dominant role in long-term, fundamental telecommunications research for the United States. Post-restructuring, industrial support for such research has declined, become more short-term in scope, and become less stable. A diverse array of competing telecommunications firms—telephone, cable, Internet, and wireless—emerged, leaving most research to equipment vendors, which increasingly focused on short-term goals. Telecommunications research is increasingly being done at universities rather than by industry, and outside rather than inside the United States. In addition, the diversity of players in today's telecommunications industry makes it difficult to design and deploy major, end-to-end innovations.

Federal funding of long-term research has not increased to cover the decline in industry support. No systematic efforts, such as took place for the semiconductor industry with SEMATECH, have emerged. Because the benefits of much telecommunications research cannot be appropriated by individual firms, therefore, public funding of such research appears necessary.

The NSF and the Defense Advanced Research Projects Agency (DARPA) have been the two primary sources of federal telecommunications R&D support. NSF, long a supporter of telecommunications R&D spanning a range of topics, has recently been increasing its attention to telecommunications R&D, with an emerging emphasis on new approaches to networking. DARPA, which funded a number of important telecommunications advances in the past (including elements of the Internet itself), has been shifting its emphasis toward more immediate military needs and giving less attention to long-term telecommunications research.

RECOMMENDATIONS

A strong, effective telecommunications R&D program for the United States will require a greater role for government-sponsored and university research, and more funding of long-term research by industry. The committee recommends that the federal government establish a new research organization—the Advanced Telecommunications Research Activity (ATRA)—to stimulate and coordinate research across industry, academia, and government. ATRA would be a hybrid of activities of the sort historically associated with DARPA (which through the ARPANET program managed a research portfolio, developed a vision, and convened industry and academia to build what would become the Internet) and SEMATECH (which brought the semiconductor industry together, initially with some federal support to complement industry dollars, to fund joint research, development, and roadmapping activities). There are a number of options for where within the federal government such a program could fit, each with its own set of tradeoffs (see Chapter 4). For example, ATRA's proposed mission would align with that of existing agencies within the Department of Commerce, and NSF has developed mechanisms for joint academic-industry engineering research, albeit more focused and on a smaller scale.

The committee also recommends that all segments of the U.S. telecommunications industry increase their support for fundamental research, possibly taking advantage of the avenue provided by participation in joint, cooperative research activities organized by ATRA. Indeed, industry should provide a significant fraction of total R&D funding for ATRA, which would support researchers from academia and industry and provide industry with a way to pool funds, spread risk, and share beneficial results.

ATRA's mission would be to (1) identify, coordinate, and fund U.S. telecommunications R&D; (2) foster major architectural advances; and (3) strengthen the U.S. telecommunications research capability. Key suggested steps for implementing ATRA are (1) establishment of mechanisms for carrying out project-based research; (2) establishment of advisory committees with high-level industry participation; (3) exploration of the need for R&D centers; and (4) establishment of a forum for key parties to discuss critical technology development issues.

Effective expansion of federal support of telecommunications research through ATRA will require participation from both service providers and equipment vendors to help identify the most critical research needs together with complementary industry investments in research. ATRA can play an important role in facilitating mechanisms to enable service providers to pool research support.

Even with ATRA, NSF and DARPA will remain important contributors to U.S. telecommunications research efforts. The committee recommends that NSF and DARPA assess their investments in basic telecommunications research and consider increasing both their emphasis on and their level of investment in such research. Both should establish criteria for determining the appropriate level of telecommunications research funding. NSF should continue to strengthen its support for telecommunications research and should consider programs for attracting and developing young research talent. To stay at the forefront, DARPA should continue support of telecommunications research for military applications, even if there is the chance of commercial development of those technologies. In formulating its research programs, DARPA should also consider the telecommunications capabilities of potential adversaries and the risk of dependence on foreign suppliers for key technologies.

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The Importance of Telecommunications and Telecommunications Research

How important is telecommunications as an industry, and how important is telecommunications research to the overall health of that industry? Underlying these questions are several others. How important is telecommunications to the U.S. economy and society? To what extent are U.S. consumers likely to benefit directly from telecommunications research in terms of new products and services that enhance their lives or improve their effectiveness or productivity? How much scope for innovation is there left in telecommunications, or has telecommunications matured to the point that it is merely a commodity service or technology?

The core findings of this study—which are supported throughout this report—are that the telecommunications industry remains of crucial importance to the United States as a society, that a strong telecommunications research capability continues to be essential to the health and competitiveness of this U.S. industry internationally, and that the health of this industry strongly affects the U.S. economy in many ways.

TELECOMMUNICATIONS—AN EVOLVING DEFINITION

Before the emergence of the Internet and other data networks, telecommunications had a clear meaning: the telephone (and earlier the telegraph) was an application of technology that allowed people to communicate at a distance by voice (and earlier by encoded electronic signals), and telephone service was provided by the public switched telephone network (PSTN). Much of the U.S. network was owned and operated by American Telephone & Telegraph (AT&T); the rest consisted of smaller independent companies, including some served by GTE.

Then in the 1960s, facsimile and data services were overlaid on the PSTN, adding the ability to communicate documents and data at a distance—applications still considered telecommunications because they enabled new kinds of communication at a distance that were also carried over the PSTN. More recently, of course, communication at a distance has expanded to include data transport, video conferencing, e-mail, instant messaging, Web browsing, and various forms of distributed collaboration, enabled by transmission media that have also expanded (from traditional copper wires) to include microwave, terrestrial wireless, satellite, hybrid fiber/coaxial cable, and broadband fiber transport.

Today consumers think of telecommunications in terms of both products and services. Starting with the Carterphone decision by the Federal Communications Commission in 1968,[1] it has become permissible and increasingly common for consumers to buy telecommunications applications or equipment as products as well as services. For example, a customer-owned and customer-installed WiFi local area network may be the first access link supporting a voice over Internet Protocol (VoIP) service, and a consumer may purchase a VoIP software package and install it on his or her personally owned and operated personal computer that connects to the Internet via an Internet service provider.

The technologies used for telecommunications have changed greatly over the last 50 years. Empowered by research into semiconductors and digital electronics in the telecommunications industry, analog representations of voice, images, and video have been supplanted by digital representations. The biggest consequence has been that all types of media can be represented in the same basic form (i.e., as a stream of bits) and therefore handled uniformly within a common infrastructure (most commonly as Internet Protocol, or IP, data streams). Subsequently, circuit switching was supplemented by, and will likely ultimately be supplanted by, packet switching. For example, telephony is now routinely carried at various places in the network by the Internet (using VoIP) and cable networks. Just as the PSTN is within the scope of telecommunications, so also is an Internet or cable TV network carrying a direct substitute telephony application.

Perhaps the most fundamental change, both in terms of technology and its implications for industry structure, has occurred in the architecture of telecommunications networks. Architecture in this context refers to the functional description of the general structure of the system as a whole and how the different parts of the system relate to each other. Previously the PSTN, cable, and data networks coexisted as separately owned and operated networks carrying different types of communications, although they often shared a common technology base (such as point-to-point digital communications) and some facilities (e.g., high-speed digital pipes shared by different networks).

How are the new networks different? First, they are integrated, meaning that all media—be they voice, audio, video, or data—are increasingly communicated over a single common network. This integration offers economies of scope and scale in both capital expenditures and operational costs, and also allows different media to be mixed within common applications. As a result, both technology suppliers and service providers are increasingly in the business of providing telecommunications in all media simultaneously rather than specializing in a particular type such as voice, video, or data.

Second, the networks are built in layers, from the physical layer, which is concerned with the mechanical, electrical and optical, and functional and procedural means for managing network connections to the data, network, and transport layers, which are concerned with transferring data, routing data across networks between addresses, and ensuring end-to-end

[1] See 13 F.C.C.2d 420 (1968).

connections and reliability of data transfer to the application layer, which is concerned with providing a particular functionality using the network and with the interface to the user.[2]

Both technology (equipment and software) suppliers and service providers tend to specialize in one or two of these layers, each of which seeks to serve all applications and all media. As a consequence, creating a new application may require the participation and cooperation of a set of complementary layered capabilities. This structure results in a horizontal industry structure, quite distinct from the vertically integrated industry structure of the Bell System era.

All these changes suggest a new definition of telecommunications: *Telecommunications is the suite of technologies, devices, equipment, facilities, networks, and applications that support communication at a distance*.

The range of telecommunications applications is broad and includes telephony and video conferencing, facsimile, broadcast and interactive television, instant messaging, e-mail, distributed collaboration, a host of Web- and Internet-based communication, and data transmission.[3] Of course many if not most software applications communicate across the network in some fashion, even if it is for almost incidental purposes such as connecting to a license server or downloading updates. Deciding what is and is not telecommunications is always a judgment call. Applications of information technology range from those involving almost no communication at all (word processing) to simple voice communications (telephony in its purest and simplest form), with many gradations in between.

As supported by the horizontally homogeneous layered infrastructure, applications of various sorts increasingly incorporate telecommunications as only one capability among many. For example telephony, as it evolves into the Internet world, is beginning to offer a host of new data-based features and integrates other elements of collaboration (e.g., visual material or tools for collaborative authoring). Another important trend is machine-to-machine communication at a distance, and so it cannot be assumed that telecommunications applications exclusively involve people.

THE TELECOMMUNICATIONS INDUSTRY

Like telecommunications itself, the telecommunications industry is broader than it was in the past. It encompasses multiple service providers, including telephone companies, cable system operators, Internet service providers, wireless carriers, and satellite operators. The industry today includes software-based applications with a communications emphasis and intermediate layers of software incorporated into end-to-end communication services. It also includes suppliers of telecommunications equipment and software products sold directly to consumers and also to service providers, as well as the telecommunications service providers

[2]The descriptions of layers were adapted from the Open Systems Interconnect Reference Model (ISO 7498-1), which provides a useful tool for conceptualizing network layers—see <http://standards.iso.org/ittf/PubliclyAvailableStandards/s020269_ISO_IEC_7498-1_1994(E).zip>.

[3]The term "telecommunications" takes on a particular significance with respect to the Telecommunications Act of 1996 and implementing regulations. The broad definition adopted here is intended solely to capture the scope of relevant research, not to make any statement about what technologies and services should or should not be considered telecommunications for regulatory purposes.

themselves. It includes companies selling components or intellectual property predominately of a communication flavor, including integrated circuit chip sets for cell phones and cable and digital subscriber line (DSL) modems.

No longer a vertically integrated business, the telecommunications industry is enabled by a complex value chain that includes vendors, service providers, and users. The telecommunications value chain begins with building blocks such as semiconductor chips and software. These components are, in turn, incorporated into equipment and facilities that are purchased by service providers and users. The service providers then, in turn, build networks in order to sell telecommunications services to end users. The end users include individuals subscribing to services like telephony (landline and cellular) and broadband Internet access, companies and organizations that contract for internal communications networks, and companies and organizations that operate their own networks. Some major end-user organizations also bypass service providers and buy, provision, and operate their own equipment and software, like a corporate local area network (LAN) or a U.S. military battlefield information system. Software suppliers participate at multiple points in the value chain, selling directly not only to equipment vendors but also to service providers (e.g., operational support systems) and to end users (e.g., various PC-based applications for communications using the Internet).

An implication of defining telecommunications broadly is that every layer involved in communication at a distance becomes, at least partially, part of the telecommunications industry. The broad range and large number of companies that contribute to the telecommunications industry are evident in the following list of examples:

- *Networking service providers* across the Internet and the PSTN, wireless carriers, and cable operators. Examples include AT&T, Comcast, Verizon, and DirecTV.
- *Communications equipment suppliers* that are the primary suppliers to service providers. Examples include Cisco, Lucent, and Motorola.
- *Networking equipment suppliers* selling products to end-user organizations and individuals. Examples include Cisco's Linksys division and Hewlett-Packard (local area networking products).
- *Semiconductor manufacturers*, especially those supplying system-on-a-chip solutions for the telecommunications industry. Examples include Texas Instruments, Qualcomm, Broadcom, and STMicroelectronics.
- *Suppliers of operating systems that include a networking stack.* Microsoft is an example.
- *Software suppliers*, especially those selling infrastructure and applications incorporating or based on real-time media. Examples include IBM, RealNetworks (streaming media), and BEA (application servers).
- *Utility or on-demand service providers* selling real-time communications-oriented applications. Examples include AOL and Microsoft (instant messaging) and WebEx (online meetings).
- *Consumer electronics suppliers* with communications-oriented customer-premises equipment and handheld appliances. Examples include Motorola and Nokia (cell phones), Research in Motion (handheld e-mail appliances), Polycom (videoconferencing terminals), Microsoft and Sony (networked video games), and Panasonic (televisions).

What is striking about this list is how broad and inclusive it is. Even though many of these firms do not specialize solely in telecommunications, it is now quite common for firms in the larger domain of information technology to offer telecommunications products or to incorporate telecommunications capability into an increasing share of their products.

THE IMPORTANCE OF TELECOMMUNICATIONS

Telecommunications and Society

The societal importance of telecommunications is well accepted and broadly understood, reflected in its near-ubiquitous penetration and use. Noted below are some of the key areas of impact:

- *Telecommunications provides a technological foundation for societal communications*. Communication plays a central role in the fundamental operations of a society—from business to government to families. In fact, communication among people is the essence of what distinguishes an organization, community, or society from a collection of individuals. Communication—from Web browsing to cell phone calling to instant messaging—has become increasingly integrated into how we work, play, and live.
- *Telecommunications enables participation and development*. Telecommunications plays an increasingly vital role in enabling the participation and development of people in communities and nations disadvantaged by geography, whether in rural areas in the United States or in developing nations in the global society and economy.
- *Telecommunications provides vital infrastructure for national security*. From natural disaster recovery, to homeland security, to communication of vital intelligence, to continued military superiority, telecommunications plays a pivotal role. When the issue is countering an adversary, it is essential not only to preserve telecommunications capability, but also to have a superior capability. There are potential risks associated with a reliance on overseas sources for innovation, technologies, applications, and services.

It is difficult to predict the future impact of telecommunications technologies, services, and applications that have not yet been invented. For example, in the early days of research and development into the Internet in the late 1960s, who could have foreseen the full impact of the Internet's widespread use today?

Telecommunications and the U.S. Economy

The telecommunications industry is a major direct contributor to U.S. economic activity. The U.S. Census Bureau estimates that just over 3 percent of the U.S. gross domestic income (GDI) in 2003 was from communications services (2.6 percent) and communications hardware (0.4 percent)—categories that are narrower than the broad definition of telecommunications offered above. At 3 percent, telecommunications thus represented more than a third of the total fraction of GDI spent on information technology (IT; 7.9 percent of GDI) in 2003. In fact, the fraction attributable to telecommunications is probably larger relative to that of IT than these figures suggest, given that much of the GDI from IT hardware (particularly semiconductors) could apply to any of several industries (computing, telecommunications, media, and electronics, for example). If one assumes IT to be the sum of computers (calculating), computers (wholesale), computers (retail), and software and services, the total GDI for IT is

$440 billion, compared to the total for telecommunications (communications hardware plus communications services) of $335 billion, making telecommunications' contribution to GDI just under 80 percent of IT's contribution to GDI.[4]

The telecommunications-related industries are also a major employer—communications services employed 1 million U.S. workers in 2002, representing 1.1 percent of the total private workforce, and communications equipment companies employed nearly 250,000 people.[5] Moreover, telecommunications is a high-tech sector, with many highly skilled employees.

Telecommunications is a growth business. Although markedly reduced investment in some parts of the sector (following the bubble years of the late 1990s) may have given an impression of low growth in the long run, a longer-term view taking into account the need for humans and machines to communicate suggests that telecommunications will continue to grow apace, as evidenced by the ongoing expansion of wireless and broadband access services throughout the world.

Telecommunications is also a key enabler of productivity across the U.S. economy and society.[6] Not only is telecommunications an industry in itself, but it also benefits nearly every other industry. In the 1990s the U.S. GDP grew rapidly, and the U.S. economy was among the strongest in the world. It is widely believed that the Internet economy played a significant role in this success.

Today, however, new wireless applications, low-cost manufacturing innovations, and handset design are some of the areas in which the Asian countries are outinvesting the United States in R&D and are seeing resulting bottom-line impacts to their economies. For the United States to compete in the global marketplace—across industries—it needs the productivity that comes from enhancements in telecommunications. If the telecommunications infrastructure in the United States were to fall significantly behind that of the rest of the world, the global competitiveness of all other U.S. industries would be affected. Conversely, the growth in U.S. productivity has been based in part on a telecommunications infrastructure that is the most advanced in the world.

U.S. leadership in telecommunications did not come by accident—success at the physical, network, and applications levels was made possible by the U.S. investment in decades of research and the concomitant development of U.S. research leadership in communications-related areas. Telecommunications has been and likely will continue to be an important foundation for innovative new industries arising in the United States that use telecommunications as a primary technological enabler and foundation. Recent examples of innovative new businesses leveraging telecommunications include Yahoo!, Amazon, eBay, and Google. Telecom-

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[4]GDI estimates for 2003 from U.S. Census Bureau, *Statistical Abstract of the United States: 2004–2005* (124th Edition), Washington, D.C., Table 1116, p. 715, 2004, available online at <http://www.census.gov/prod/2004pubs/04statab/infocomm.pdf>.

[5]Data for 2002 from U.S. Census Bureau, *Statistical Abstract of the United States: 2004–2005* (124th Edition), Washington, D.C., Table 1117, p. 715, 2004, available online at <http://www.census.gov/prod/2004pubs/04statab/infocomm.pdf>.

[6]For more on the relationship between information and communications technologies and economic productivity, see, for example, Dale W. Jorgenson and Kevin J. Stiroh, "Raising the Speed Limit: U.S. Economic Growth in the Information Age," *Brookings Papers on Economic Activity, 2000–1*, pp. 125-235, 2000; and Erik Brynjolfsson and Lorin M. Hitt, "Beyond Computation: Information Technology, Organizational Transformation and Business Performance," *Journal of Economic Perspectives*, 14(4):45, Fall 2000.

munications is also specifically a key enabler for other industries in which the United States has important competitive advantages and a positive balance of trade, such as financial services and entertainment (e.g., movies and music).

Finally, telecommunications is an important component of the broader IT industry, which is sometimes viewed as having three technology legs:[7] processing (to transform or change information), storage (to allow communication of information from one time to another), and communications (to transmit information from one place to another). The boundaries between these areas are not very distinct, but this decomposition helps illustrate the breadth of IT and the role that telecommunications plays. Increasingly IT systems must incorporate all three elements to different degrees,[8] and it is increasingly common for companies in any sector of IT to offer products with a communications component, and often with a communications emphasis. The IT industry's overall strength depends on strength across communications, processing, and storage as well as strength in all layers of technology—from the physical layer (including communications hardware, microprocessors, and magnetic and optical storage), to the software infrastructure layers (operating systems and Web services), to software applications.

Telecommunications and Global Competitiveness

In this era of globalization, many companies are multinational, with operations—including R&D—conducted across the globe. For example, IBM, HP, Qualcomm, and Microsoft all have research facilities in other countries, and many European and Asian companies have research laboratories in the United States. Increasing numbers of businesses compete globally. Every company and every industry must assess the segments and niches in which it operates to remain globally competitive.

Both Asian and European nations are continuing to pursue strategies that exploit perceived U.S. weakness in telecommunications and telecommunications research as a way of improving their competitiveness in telecommunications, as well as in information technology more broadly. Leapfrogging the United States in telecommunications has, in the opinion of the committee, been an explicit and stated strategy for a number of Asian (in broadband and wireless) and European (in wireless) nations for the past decade, with notable success. These efforts have aimed to stimulate the rapid penetration of physical-layer technologies for residential access (broadband access, especially in Asia) and wireless and mobile access (cellular networks, especially in Europe).

THE IMPORTANCE OF CONTINUING INVESTMENT IN TELECOMMUNICATIONS RESEARCH: SUMMARY COMMENTS

Telecommunications research is best understood as a seed that germinates, developing into lasting value for the U.S. economy. Figure 1.1 depicts the research ecosystem and the

[7]D. Messerschmitt, "Convergence of Computing and Telecommunications: What Are the Implications Today?" *Proceedings of the IEEE*, 84(8):1167-1186, 1996.

[8]Computer Science and Telecommunications Board, National Research Council, *Making IT Better: Expanding Information Technology Research to Meet Society's Needs*, National Academy Press, Washington, D.C., 2000.

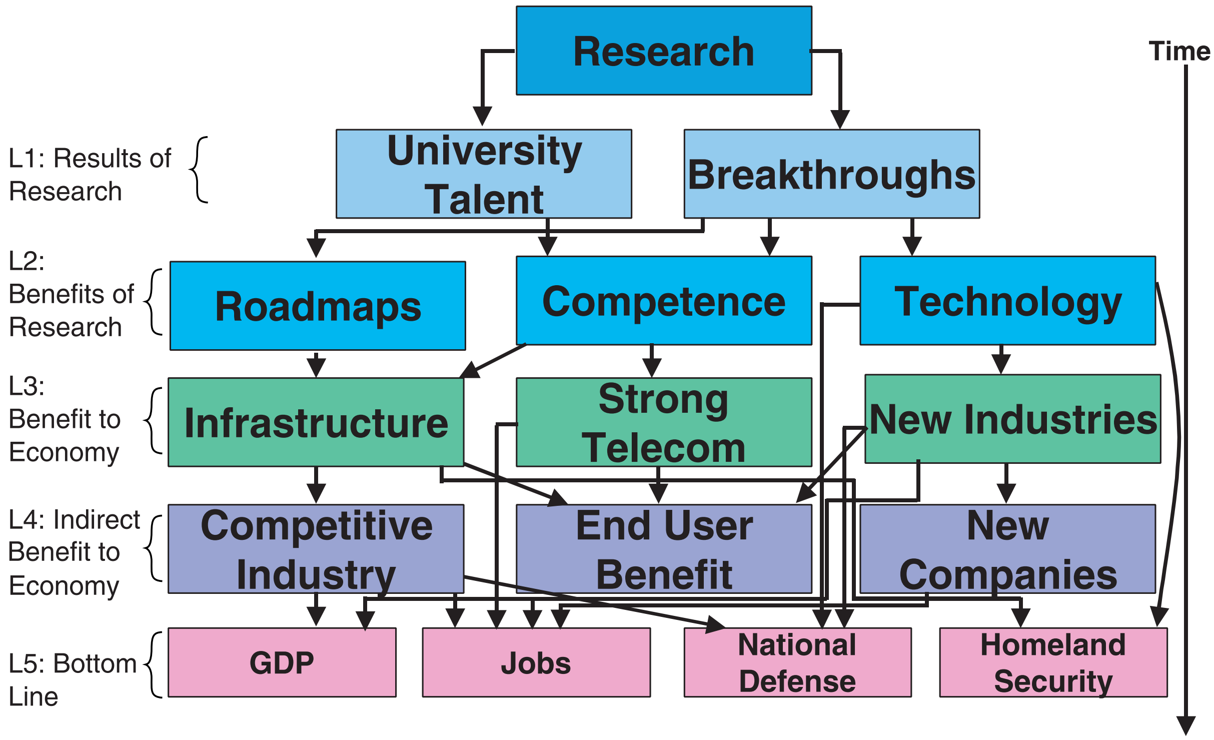

FIGURE 1.1 Impact of telecommunications research.

benefits it enables, many of which are built up recursively over time as a result of interactions among the various levels. The picture is, to be sure, simplified—the interactions between the different elements are more complex than can be reasonably characterized by the diagram—but Figure 1.1 does provide a realistic view of the impacts of research.

Shown at the top of Figure 1.1 is the research enabled by available funding. Level 1 shows the *direct results*: Researchers conduct exploratory studies, achieving technical *breakthroughs* and developing their expertise and their basic understanding of the areas studied. *Talent* is thus nurtured that will be expressed in the future in industry and academia. None of these results of research can be characterized as end benefits. Rather, the development of talent and the achievement of breakthroughs build a capability for later revolutionary advances.

At Level 2 the benefits of research begin to become evident. Researchers collaborate, and individual insights and results begin to fit together. The university talent generated in Level 1 develops competence—not simply low-level job skills that can be easily transported anywhere, but rather the next-generation expertise needed to ensure a skilled U.S. telecommunications workforce. The United States has access to this skilled workforce first and can thus benefit directly from the talent and knowledge base generated in Level 1 that are fundamental to continuing technological advances and being able to perform in the best future jobs.

Also at Level 2 comes the maturing of fundamental breakthroughs and their transition to usable, deployable technology for next-generation telecommunication systems and the development of roadmaps to help guide research investments.

The major benefits to the economy obtained at Level 3 are the coalescence of Level 1 and 2 elements. Skilled workers, a competence to understand the new technology, the availability of the technology, and shared goals are the ingredients required to create a healthy telecommunications industry and, more broadly, a capable telecommunications infrastructure.

Interestingly, not all of the research performed affects telecommunications alone. Because telecommunications touches multiple industries, the technology base it provides also often enables the creation of entirely new industries. The success of the iPod and other portable digital music players, for example, rests in part on earlier telecommunications-inspired work on how to compress audio for efficient transmission over limited-bandwidth channels.

At Level 4, an indirect benefit of research is a telecommunications infrastructure that provides advantages to all industries that use telecommunications. There are also end-user or consumer benefits that accrue to having an outstanding infrastructure, such as enhanced education, entertainment, and personal convenience. Finally, new companies also emerge from these new industries.

Level 5 aggregates the key benefits of research in broad areas of national concern. Concerning economic impact, the strong telecommunications industry, new spin-off industries, and more competitive industries (across the board) result in a higher GDP for the country, as well as job creation. Technological leadership and economic strength also help ensure strong leadership and capability in national defense and homeland security.

The full benefits of the process depicted in Figure 1.1 develop over an extended period of time, with a long-term buildup over several years between the seed investments in research and realization of the ultimate bottom-line benefits. Each step takes time: from innovation to mass deployment and impact. Investments by both government and industry in research by academia and industry lead to both short- and long-term contributions.

Over the years, CSTB studies have documented this phenomenon across multiple areas of information technology and telecommunications research. In particular, its 1995 report *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure*[9] and a 2003 update[10] illustrate how long-term investments in research across academia and industry have led to the creation of many new, important U.S. industry segments with revenues that came to exceed $1 billion.

In closing, it is worth noting the perils of losing leadership in telecommunications. Because of the time lag, the nation may continue to exhibit leadership at Levels 4 and 5 (and possibly Level 3) even as it is failing to renew capability at Levels 1 and 2. Since Levels 3 through 5 are most visible to policy makers and the public, there is a potential to perceive the situation as less dire than it really is. If Levels 1 and 2 are left to atrophy, serious problems will occur at Levels 3 through 5. If that happens, then recovery will take a long time—or even prove impossible.

[9] Computer Science and Telecommunications Board, 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.

[10] Computer Science and Telecommunications Board, National Research Council, *Innovation in Information Technology*, The National Academies Press, Washington, D.C., 2003.

2

The Evolution of the U.S. Telecommunications Industry and Effects on Research

The structure of the U.S. telecommunications industry has changed dramatically over recent decades, with consequences for research. Major changes over the past several decades have included the breakup of the Bell System, especially the 1984 divestiture, the 1995 creation of Lucent Technologies, and the advent of long-haul competitors such as MCI and Sprint; the transformation of cable system operators into telecommunications providers as they adopted the hybrid fiber/coaxial cable digital architecture, which supports digital, high-capacity, two-way communications; the development and mainstream adoption of the Internet, including the rise of a whole new class of industry players (e.g., Cisco, Microsoft, Google, and so on); and the creation and growth of a competitive wireless services market resulting in broad penetration of cellular voice and data services.

These changes have yielded many benefits, including a much broader array of telecommunications services, a more diversified and competitive market, and an environment in which new innovations move more quickly to the marketplace. But they have also led to decreased industry support for long-term telecommunications research and a general shift in research focus from the long term to the short term. As has been observed by many others, there has been an overall downturn in many areas of U.S. industry research.[1] Along similar lines, a report released earlier this year by the National Academies concluded that the nation's commitment to basic research in science and engineering needs to be sustained and strengthened.[2]

The full impact of these trends on long-term telecommunications research is probably not yet evident, as the industry continues to exploit fundamental knowledge gained over the past

[1]This phenomenon is not new. See, for example, Rosenbloom et al., *Engines of Innovation*, Harvard Business School Press, Cambridge, Mass., 1996.

[2]See National Academy of Sciences, National Academy of Engineering, and Institute of Medicine of the National Academies, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, prepublication, The National Academies Press, Washington, D.C., 2006, available online at <http://www.nap.edu/catalog/11463.html>.

several decades. The concern is that without substantial renewed investment in fundamental, long-term telecommunications research, the United States will eventually consume its own intellectual "seed corn" and thus run out of new ideas within the next decade or perhaps even sooner. Chapter 3 examines further some of the implications of curtailed research investment.

BELL SYSTEM RESEARCH AND CONSEQUENCES OF THE BELL SYSTEM'S BREAKUP

For roughly a century, the U.S. telecommunications infrastructure was largely defined by the Bell System, a telephony monopoly regulated under a series of consent decrees that gave it the right to operate, maintain, and expand the U.S. telephone system. The chief research and development arm of the Bell System, Bell Laboratories, was created in 1925, following demonstration in 1915 of the feasibility of coast-to-coast long-distance service and realization of the importance of a viable research and development laboratory to effective deployment. Successful nationwide implementation of long-distance service required, for example, a device with sufficient gain to offset the signal losses in the 3000-mile stretch of the U.S. transcontinental cable. The development of the vacuum tube amplifier for use in telephone circuits, which started in the 1910s, took many years of fundamental research and required extremely close cooperation between the research community that had originally invented the vacuum tube technology and the development community that introduced the vacuum tube amplifier into the telephone network.

Bell Laboratories relied heavily on managers who understood the benefits to the company (and society) of fundamental research and were able to provide a work environment that fostered world-class research in virtually every aspect of telecommunications technology. Stable funding for research was provided via a tax levied on the service revenues of most of the Bell operating companies, an approach approved by state regulators. The revenue from the services tax was more than sufficient to fund unfettered investigations over almost 6 decades into almost every aspect of telecommunications, from basic materials (and the associated physics and chemistry) to large-scale computing and networking platforms and systems. Over time, Bell Laboratories' support for basic science and engineering led to major advances in telephony spanning terminals, switching, transmission, services, and operations. Out of the Bell System research program also came many world-famous innovations, including the transistor, information theory, the laser, the solar cell, communications satellites, and fiber-optic communications. Perhaps the most notable benefit of the research was the creation of the semiconductor industry as a result of the mandatory public licensing of Bell's patent for the transistor. In addition, research in basic science at Bell Labs was recognized by six Nobel prizes for strides in quantum mechanics, solid-state physics, and radio astronomy.

A number of other companies were also involved at the time in developing new telecommunications technologies and equipment. The work of companies like GTE Automatic Electric, TRW Vidar, and Northern Telecom, along with Bell's own Western Electric, pushed telephony forward through advances in handset design and digital switching, for example.

Bell Labs also served as an important nucleus for the broader telecommunications research community: in the predivestiture era, university researchers and telecommunications research leaders from around the world commonly spent summers or sabbaticals at Bell Labs, where they could conduct exploratory research that could not have been undertaken elsewhere.

Despite its many successes, there were many criticisms of the predivestiture regulated monopoly (and this report is certainly not calling for a return to the Bell System structure). For instance, until government actions forced a change, the Bell System prohibited the attachment of third-party equipment on customer premises, which many viewed as stifling innovation. Monopoly status also meant that there were few pressures on the Bell System for rapid innovation in its services, and a number of innovative technologies developed by Bell Labs either were not adopted or were adopted very slowly.

Divestiture and Its Effects

The Bell System ended in 1983. Divestiture resulted in the separation of the local Bell System operating companies (which provided local telephone service to large regions of the United States) from the long-distance parts of the network (known as long-lines communications) and ended the license fee arrangement through which the regional operating companies supported Bell Labs. At the time of the separation, Western Electric (the equipment manufacturing part of the Bell System) was assigned to the part of the company that would be called AT&T), along with most of the research and development resources of Bell Labs. The regional Bell operating companies (RBOCs), the providers of local phone service, formed an R&D consortium called Bellcore (Bell Communications Research, later renamed Telcordia Technologies) and agreed to fund Bellcore to do the majority of the R&D needed to support them—at least for an initial period on the order of 5 to 7 years. Subsequently the RBOCs sold Bellcore to SAIC, causing the new lab to seek support outside the RBOCs and subsequently make radical changes in the scope and direction of its research program.

As a result of divestiture, the fundamental split in the Bell System propelled AT&T (and its R&D arm Bell Labs) into a competitive landscape for the first time, with aggressive competitors such as MCI and Sprint seeking to compete for long-distance services—for both residential and business customers. Thus although a tax on telecommunications revenue remained as a source for funding R&D at Bell Labs, the prospects for increased competition, lower telecommunications prices, and decreasing telecommunications revenues for AT&T, as well as the regulatory pressures to lose market share to new competitors, led to the beginning of the reduction in the long-term, unfettered, fundamental research done at Bell Labs. Additionally, divestiture marked the beginning of a process of transforming the telecommunications industry in the United States from a vertically organized structure (where one body, the Bell System, had control over every aspect of the telecommunications process, from components, to boards, to systems, to services, to operations) to a horizontally organized structure (where multiple competitors existed at every level of the hierarchy and where no single entity had full responsibility for the network architecture, end-to-end network operations, or long-term fundamental research that would enable the creation of an evolutionary path into the future).

Subsequent Splits and Spin-offs and Research Cutbacks

The second stage of the breakup of the Bell System occurred at the end of 1995 when the existing AT&T (which had acquired the computer services company NCR several years earlier) made the decision to divest both the computer operations part of the business (selling it back to NCR) and the equipment manufacturing part of the business (with the creation of Lucent Technologies) in order to compete more actively in the areas of wireless and cable services. As part of this trivestiture a large percentage of the resources of Bell Labs (as well as the rights to use of the Bell Labs name) went to Lucent Technologies for research and development in support of the creation of new products. About one-fourth of the research component of Bell Labs (along with significant development resources) joined AT&T and formed AT&T Labs, with the goal of conducting research and development that would be most appropriate to a services company that was venturing into the areas of wireless and broadband communication services.

Former Bell System entities continued to evolve. Over time Lucent Technologies spun off the component manufacturing part of the company as Agere Labs and the enterprise business systems part of the company as Avaya Labs. Telcordia was acquired by SAIC and later purchased by two private equity firms. AT&T spun off the wireless services part of the business (as AT&T Wireless, subsequently acquired by Cingular in 2004) and sold the cable services part to Comcast Communications. SBC and AT&T then merged in early 2005 under the AT&T name. Early 2006 saw a proposed acquisition by AT&T of Bell South.

It initially appeared as though research might continue to grow and prosper within the former Bell family laboratories—Lucent Bell Labs, Bellcore research, the new AT&T Labs, Agere Labs, and Avaya Labs—as well as within new telecommunications firms. Indeed, figures gathered by Michael Noll showed that the number of former Bell family company researchers grew from about 1000 in 1960 to 1200 in 1981 to about 1920 in 1997, but then fell off to 1570 in 2001. Data reported by Noll on research and development expenditures by the Bell family companies showed significant growth from 1981 ($3.2 billion) to 2001 ($6 billion).[3]

One of the Bell System offshoots, Lucent, continued to make a significant commitment to research, albeit one that decreased in total dollar terms as Lucent shrank. It has continued to fund Bell Laboratories at a rate of roughly 1 percent of revenue, further supplemented by some support from government research and development contracts. That allocation of 1 percent, which might be viewed as a best practice for a large equipment vendor, funds a mix of research in basic sciences, exploration of disruptive technologies, and more incremental work for meeting current customer needs.

THE EMERGENCE OF NEW TELECOMMUNICATIONS PLAYERS

Cable

The cable industry began in the 1940s and 1950s as a way to get television signals into remote areas. Antennas were placed in advantageous locations (e.g., the top of a mountain) and the signals were distributed along coaxial cable lines to local homes. As cable systems grew in size and number, and in the types of signals or services they provided, a full-fledged, wide-reaching industry began to take shape. According to the National Cable and Telecommunications Association (NCTA), by 1962 there were already nearly 800 cable systems with almost 900,000 subscribers in the United States.[4]

[3] A. Michael Noll, "Telecommunication Basic Research: An Uncertain Future for the Bell Legacy," *Prometheus*, 21(2):184-185, June 2003.

[4] National Cable and Telecommunications Association, "History of Cable Television," 2005, available online at <http://www.ncta.com/Docs/pagecontent.cfm?pageID=96>.

A good deal of organized, focused research and development work has enabled the evolution of cable as a telecommunications industry. In the late 1980s a group of cable company executives formed CableLabs, a nonprofit consortium of cable system operators, to pursue new cable telecommunications technologies, improve the business capabilities of cable operators, and help cable companies develop and take advantage of new technologies. For example, CableLabs was involved in the development and specification of cable modem technology (work initially funded by MCNS Holdings—composed of TCI, Time Warner Cable, Cox, and Comcast), eventually administering the specifications and performing certification and qualification of products. In addition, the early 1990s saw CableLabs involved in developing fiber-optic trunking and work to develop fiber-optic regional rings to link individual municipal cable systems. This work drew on earlier, more fundamental telecommunications research, such as work on fiber-optic communications, that had been developed at such places as Bell Labs. CableLabs work cuts across the layers from device and equipment standards through applications.

CableLabs—while not doing fundamental research itself—continues to play other important roles for the cable industry, such as helping to facilitate specification development, providing testing facilities to ensure quality equipment, and generally serving as a clearinghouse for information on current and prospective technological advances. More recently, CableLabs has been involved in the development of high-definition television systems, VoIP packet networking, interoperable interface specifications for real-time multimedia, and standards to create a common platform for interactive services.[5,6]

The Internet

In the early 1960s, the vision for a research program aimed at networking computers took shape at the Defense Department's Advanced Research Projects Agency (ARPA, later DARPA). As early as 1965, ARPA was sponsoring research into cooperative time-sharing computers and packet switching. Plans for the ARPANET began to take shape in 1966, and in 1968 DARPA awarded a key contract to Bolt Beranek and Newman Inc. (BBN) to produce a key component in implementing the network, interface message processors (or IMPs). A year later, the first nodes in the ARPANET became active, allowing research in host-to-host protocols and how best to utilize network resources. By 1971, the ARPANET included 15 nodes, and work was underway on e-mail. As noted in an earlier CSTB report, however, the ARPANET was not DARPA's only networking research activity—the organization also supported related research on terrestrial and satellite packet radio networks.[7]

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[5]The committee received a briefing from CableLabs' David Reed at a meeting in Washington, D.C., on Nov. 3, 2003. For more information about CableLabs and its history, see Cable Television Laboratories Inc., "A Decade of Innovation: The History of CableLabs 1988-1998," 1998, available online at <http://www.cablelabs.com/about/overview/History.html>.

[6]More general information regarding the development of the cable industry is available from the following two resources: Congressional Research Service, "Cable Television: Background and Overview of Rates and Other Issues for Congress" (RS21775), 2004, available online at <http://www.opencrs.com/rpts/RS21775_20040405.pdf>; and FCC, "Evolution of Cable Television," 2000, available online at <http://www.fcc. gov/mb/facts/csgen.html>.

[7]Computer Science and Telecommunications Board, National Research Council, *Funding a Revolution: Government Support for Computing Research*, National Academy Press, Washington, D.C., 1999, available online at <http://newton.nap.edu/html/far/>, p. 174.

Other key DARPA-funded work concerned the protocols used for communicating over the network. As work progressed on the ARPANET, it became clear that a replacement for the original Network Control Protocol would be needed to address the vision of an open architecture enabling a network of networks, a concept that called for a different approach to disseminating information, ensuring interoperability, and dealing with errors and transmission quality. The early 1980s saw the adoption of Transmission Control Protocol/Internet Protocol (TCP/IP) as a Defense Department standard, and the cutover of the ARPANET to the new protocol. DARPA not only funded and managed a research portfolio; it also facilitated the development of a vision and served as a convener for industry and academia, notably through the Internet Engineering Task Force.

The Internet's development continued with the spin-off of MILNET to support DOD operations and new mission-focused computer networks developed by the Department of Energy, NASA, and NSF, together with broader networks such as USENET and BITNET. In 1986, NSF launched its NSFNet program, an effort to link (among other things) a number of U.S. academic supercomputing centers.[8] NSFNet was envisioned as a general high-speed network that could link many other academic or research networks (including the ARPANET) using the research results and operational experience obtained from ARPANET. The NSFNet proved very successful. Its upgrade to handle growing demand and other subsequent changes opened the door for the participation of the private sector in the network.[9]

The mid to late 1980s saw continuing DARPA-supported research and development in areas such as routers and their protocols. Meanwhile, the speed of the NSFNet's backbone saw great improvement, and the Domain Name System, a critical component facilitating Internet growth and reliability, was introduced. NSF support was also critical to the development of the first widely used graphical Web browser, Mosaic, which was developed in 1993 by a researcher at the National Center for Supercomputing Applications.

The Internet was highly successful in meeting the original vision of enabling computers to communicate across diverse networks and in the face of heterogeneous underlying communications technologies.[10] Its success—measured in terms of commercial investment, wide use, and large installed base—is also widely understood to have made innovation in the Internet much harder over time. (Innovation in the Internet's architecture proper should be distinguished from innovative uses of the network, which have flourished as a direct consequence of the Internet's flexible, general-purpose design.) CSTB's *Looking Over the Fence at Networks: A Neighbor's View of Networking Research*[11] characterized this problem in terms of three types of potential ossification: intellectual (pressures to be compatible with the current Internet risk stifling innovative ideas), infrastructural (an inability to affect what is deployed in commercial

[8]For more detailed information on NSFNet, see National Science Foundation, "The Launch of NSFNet," [undated], available online at <http://www.nsf.gov/about/history/nsf0050/internet/launch.htm>.

[9]For more background on Internet commercialization, see Brian Kahin, ed., "Commercialization of the Internet: Summary Report" (RFC 1192), 1990, available online at <http://www.ietf.org/rfc/rfc1192.txt>.

[10]Additional information about the Internet's early years and development is available from the following resources: Leiner et al., "A Brief History of the Internet," 2003, available online at <http://www.isoc.org/internet/history/brief.shtml>; and Robert H. Zakon, "Hobbes' Internet Timeline (v8.1)," 2005, available online at <http://www.zakon.org/robert/internet/timeline/>.

[11]Computer Science and Telecommunications Board, National Research Council, *Looking Over the Fence at Networks: A Neighbor's View of Networking Research*, National Academy Press, Washington, D.C., 2001, available online at <http://books.nap.edu/html/looking_over_the_fence/report.pdf>.

networks makes it hard for researchers to experiment with new capabilities), and system (problems tend to be addressed with short-term fixes that are easier to deploy than with solutions that would be more desirable in the long run).

Concerns of these sorts—together with an appreciation that the Internet's design, though highly successful, has a number of shortcomings—have served as the inspiration for new networking research initiatives, such as the National LambdaRail initiative and new research programs at the National Science Foundation.

Cellular and Wireless

In the early 1970s, following years of resistance to the idea, the Federal Communications Commission (FCC) began setting aside a range of radio frequencies for radio telephony. Near the end of that decade, a trial of cellular phone technology had been conducted in Chicago, and the world's first commercial cellular phone service was introduced in Tokyo, Japan.

By the early 1980s, the FCC was issuing wireless telephony licenses and setting up metropolitan and rural jurisdictions (so-called metropolitan statistical areas and rural service areas), and, by the middle of the decade, first-generation wireless systems were being deployed in the United States. These systems were based on analog cellular technology using the advanced mobile phone system (or AMPS) technology that had been developed by Bell Labs. Cellular technology was being deployed in other countries, as well, although the technology and standards adopted internationally were very different from those used in the United States. Thus began one of today's most vibrant and competitive industries—competition among wireless providers in today's market is fierce, and new products and services emerge almost on a daily basis now.

Growing consumer demand and the need to make better use of available spectrum resources fueled the development of a second generation of wireless technologies (also commonly referred to as 2G technologies). This second generation marked the transition to a fully digital technology, providing enhanced quality and enabling better use of spectrum resources. While the European wireless industry settled on global system for mobile communications (GSM) for its 2G standard, two major wireless standards emerged in the United States: time division multiple access (TDMA), a technology standard adopted by the Telecommunications Industry Association in 1989; and code division multiple access (CDMA), a newer, competing technology developed and championed by Qualcomm. 2G technology included many improvements over first-generation technology; for example, 2G included such advanced digital features as compression, network control techniques, bandwidth conservation measures, and full support for voice mail.

The next generation of wireless technology (so-called 3G technology) promises to add even greater speed, capacity, and services—indeed, one recent report describes 3G as "bringing Internet capabilities to wireless mobile phones."[12] Along the way to 3G, there has also been a good deal of work on 2.5G technologies (e.g., CDMA2000, 1xRTT, and GPRS) to help bridge the fairly large gap between 2G and 3G, as well as to build out the networks and infrastructure required by the newer technologies.

[12] Linda K. Moore, Congressional Research Service, *Wireless Technology and Spectrum Demand: Advanced Wireless Services* (RS20993), 2006, available online at <http://opencrs.cdt.org/document/RS20993/>.

IMPACTS OF THE CHANGING LANDSCAPE ON INVESTMENT IN RESEARCH

Increased Competition and the Pressure on Research Investment

One result of the divestiture of the Bell System, subsequent splits and spin-offs, and the entry of new types of telecommunications services providers was a much more competitive telecommunications industry. The cost—and retail price—of long-distance calls fell rapidly between 1984 (the initial divestiture) and 2004 (when carriers began offering voice over IP service broadly to consumers). Wireless telephony grew rapidly, reaching nearly 208 million accounts in the United States by the end of 2005.[13] Broadband access to the Internet became widely available. Cable system operators started introducing their own local telephone services over their new digital, two-way infrastructure. Business data service prices fell steadily as well.

A consequence of increased competition at every level of the telecommunications value chain was that the industry players found themselves operating with tighter margins and lower revenues.

The 1996 Telecommunications Act and subsequent FCC decisions led to a further evolution of the regulatory environment. The impact of these developments on innovation and R&D—and on the industry more broadly—has been the subject of much debate. Some caution, for example, that such policies as unbundling and the use of total element long-run incremental costs in the regulation of incumbent local exchange carriers had the effect of dampening investment by the local exchange carriers because competitors could appropriate some of the investment made by the carriers. Others cite significant benefits of these policies to the consumer (reduced prices) and the market (lower barriers to market entry).

From about 1990 to 2000, the period of high growth in the telecommunications industry meant that there were sufficient revenues to attract many new entrants into the telecommunications market, each of which invested heavily in creating new network facilities. This time period also saw venture capital play a more prominent role in the telecommunications industry (Box 2.1). Capital expenditures by these new carriers provided significant revenue streams to equipment vendors, and it appeared that research in telecommunications was continuing at a pace comparable to that of the Bell System prior to divestiture. But once this large build-out had been completed, and as the Internet bubble popped, investment declined significantly.

Reductions with the Bursting of the Internet Bubble

When the so-called Internet bubble burst at the end of the 20th century, much of the telecommunications industry was faced with a glut of infrastructure investments as the demand for these facilities slowed, leading to wholesale failures of major companies throughout the industry. During the boom years, companies had accumulated debt on the order of several trillion dollars across all players in the industry and suddenly had to service the debt with rapidly decreasing revenues. A result was wide-scale layoffs of workers, failures of several major telecommunications players, and drastic reductions in capital spending by carriers,

[13] CTIA, *Wireless Quick Facts*, April 2006, available online at <http://files.ctia.org/pdf/Wireless_Quick_Facts_April_06.pdf>.

BOX 2.1 The Role of Venture Capital in Innovation and Research

Although it is sometimes argued that the venture capital invested in industry is supplanting traditional mechanisms for achieving innovation, venture capital represents development funding, not research funding. Leading-edge developers that have a profit requirement will quickly curtail their research directions in favor of achieving corporate financial goals. Moreover, the surge in funding that peaked in 2000 has fallen off almost as quickly as it appeared. Total telecommunications venture funding peaked at nearly $5 billion in the second quarter of 2000 before dropping back down to roughly $560 million per quarter just 2 years later—a level that has remained fairly constant into 2006.[1]

Despite venture capital's important role in the U.S. innovation system and its many contributions to U.S. leadership in high technology, including telecommunications, its role is not to supply the basic and applied R&D that has fueled many of the major telecommunications advances mentioned in this report and elsewhere. Instead, it seeks to fund specific product innovation that can deliver short-term returns. Venture capital funds typically have a lifetime of 5 to 7 years, and investors seek significant commercial returns in that time frame. In contrast, major telecommunication advances can require longer-term efforts often continuing for a decade or more and requiring risk-taking, broad-based, interdisciplinary, multifaceted support—such as that historically provided by the Bell System or provided today when federal agencies fund long-term academic research. Over the long term, the venture capital model itself depends heavily on being able to select promising areas for investment from a stream of results from long-term research.

[1]According to data available from PriceWaterhouseCoopers. See <http://www.pwcmoneytree.com/exhibits/NationalAggregateData95Q1-06Q1_FINAL.xls>.

along with associated significant reductions in the funding for existing research programs at places like Lucent Bell Labs, AT&T Labs–Research, Telcordia, and other major telecommunications players.

Shifts from the High-Margin Public Telephone Network to New, Lower-Margin Services as a Source of Revenue

Another major change in the telecommunications industry has been a major shift from basic, high-margin, wireline telephony services provided by the public switched telephone network (PSTN) to wireless and broadband services that both complement and compete with the traditional services and are associated with lower margins.[14] As a result, revenue is shifting

[14]TIA's 2004 Telecommunications Market Review and Forecast (Telecommunications Industry Association, Arlington, Va., 2004) observes that (p. 33) "[t]he local exchange market is declining for the first time since the Great Depression. Consumers are beginning to cancel wireline services and rely on wireless, while DSL [digital subscriber line] and cable modem services are eliminating the need for second lines for Internet connectivity. Increased use of email and other messaging is cutting into call volumes." It goes on to say (p. 45) that "landline toll service, like the local services market, is facing a long-term decline in overall usage."

from the local exchange carriers (e.g., Verizon, SBC (now called AT&T), and Bell South) and interexchange carriers (e.g., AT&T, MCI, and Sprint) to wireless and broadband access service providers (e.g., Comcast, Time-Warner, AOL, Cingular, Verizon Wireless, T-Mobile, and Sprint PCS). Unfortunately almost none of the wireless or broadband service providers have been funding long-term research, nor are there indications at present that any will undertake to do so in the foreseeable future.

Increased Emphasis on Vendors' Role in Supporting Research

All of the participants in the telecommunications value chain could, in principle, invest in research, but the nature of those investments would likely differ because of varying motivations and incentives. Traditionally, investments in research by end users (the demand side)[15] seeking to improve the technologies available from providers and vendors (the supply side) have been the primary source of fundamental and long-time-horizon results that are much more likely to enter the public domain, making them available to all and increasing their impact. Open access to such results is particularly important for telecommunications, given that the value of a communications network grows with the number of its users, with more widely adopted and standardized technologies bringing greater benefits to all users.

As a result of the structural changes in the telecommunications industry, the source of funds for investing in research has shifted from the demand side—telephone customers who paid for Bell System research via a tax on telephony usage—to the vendors of equipment, software, and chips, although the U.S. military (through DARPA, the Army, the Navy, and the Air Force) continues to be a major source of investment in telecommunications research. Currently, end-user organizations and commercial intermediaries are investing very little in research (an exception is AT&T, which has maintained a vestige of Bell Labs but has cut that back substantially, due to dramatic reductions in traditional telecommunications revenues over the past 3 years, from a support level of close to $140 million in 2001 to a support level of below $60 million in 2004).

Today, for commercial technologies, most of the investment is made by supply-side equipment vendors and semiconductor and software companies. Service providers and equipment vendors primarily support research leading to near-term incremental additions to their own products and services, and are likely to keep the results of their short-term research programs proprietary in the interest of gaining competitive advantage.

Although demand-side entities are generally more likely to direct their research investments toward more fundamental and long-time-horizon opportunities, a major economic impediment to doing so is so-called free-riding. Since the goal of a demand-side entity is typically not to gain proprietary advantage, but to make innovative solutions available through the totality of its suppliers, demand-side investments in research usually benefit everybody, that is, all suppliers and other demand-side entities. Thus, companies or entities failing to invest in research can still benefit from the investments of others, and there is a temptation to gain a free ride on those investments—and a disincentive to invest in results that become largely a public good.

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[15] For more perspective on user-centered innovation, see Eric Von Hippel, *Democratizing Innovation*, MIT Press, Cambridge, Mass., 2005, available online at <http://web.mit.edu/evhippel/www/democ.htm>.

The problem of free-riding is not new. Predivestiture, non-Bell telephone companies like MCI and Worldcom—but with the notable exception of GTE—invested little in research. Other areas of telecommunications such as cable television, which was able to exploit optical transmission technologies for its new hybrid fiber-coaxial cable deployments in the 1990s, similarly depended on and benefited from new technologies arising from Bell Labs and from government-sponsored research. Today this trend has been accentuated as the fragments of the divested Bell System have greatly curtailed or eliminated research investments, especially those targeted at advancing the general telecommunications technologies available through their suppliers.

Another increasingly used mechanism or trend involves larger companies acquiring smaller innovative start-ups (perhaps in lieu of funding or otherwise supporting in-house research and development work) to stimulate their own growth and innovation. While this trend does seem more oriented toward short-term goals, it underscores the importance of early support or funding for the often high-risk research and development that contribute to the creation of these smaller spin-off companies.

Moving responsibility for research to suppliers increases the volatility of funding. The capital expenditures of service providers are dependent on the rate of change of their revenues, which can fluctuate rapidly, often owing to cyclical technology changes. For example, recent years have seen a sharp downturn in traditional wireline telephony revenues and purchases of new equipment by carriers. Sustaining a high-quality research organization requires stable funding, and volatility and uncertainty can have significant consequences. For example, in recent years, a number of prominent researchers have moved from industry research laboratories to universities as they seek a more stable environment in which to conduct their research.

The Decreasing Time Horizon of Research

The decline in attention to long-term research is quite evident when looking at the history of Bell Labs, the institution that for decades was most closely associated with long-term telecommunications research. Long-term research supported advances in areas such as switching, transmission, and services, and shorter-term research was aimed at operating and improving existing technologies and systems. Although most of the system building and systems engineering and integration were done by developers and system architects, researchers were traditionally heavily involved in the process since they were the ones who had created the fundamental technology on which the new systems were based.

It has become clear that even as the number of researchers was growing in the late 1990s, the former Bell family research enterprise was undergoing significant changes. Because internal corporate management decisions about research and development are proprietary and detailed historical data were not maintained, quantifying this shift is very difficult. However, testimony to the committee and comments received from a number of researchers clearly indicate a qualitative shift in the time horizon for research. Long-term, fundamental research aimed at breakthroughs has declined in favor of shorter-term, incremental and evolutionary projects whose purpose is to enable improvements in existing products and services. This evolutionary work is aimed at generating returns within a couple of years to a couple of months and not at addressing the needs of the telecommunications industry as a whole in future decades. Insiders and outsiders have observed in comments to the committee that the

TABLE 2.1 Sources of Papers Presented at the 2005 International Conference on Communications and the 2005 IEEE Global Telecommunications Conference (Globecom)

Source	Number of Papers	Percentage
U.S. universities	470	34.8
U.S. industry	50	3.7
Asia	332	24.6
Europe	278	20.6
Other (majority from Canada)	222	16.4
TOTAL	1,352	100

focus of 80 to 90 percent of research at the Bell family labs is now concentrated on short-term innovation rather than long-term fundamental research. Although a closer alignment of the interests of research laboratories and companies benefits U.S. industry, the often associated reduction in fundamental, long-term research hurts the telecommunications industry in the long run.

Decline in Industry Participation in Publishing Research

Additional evidence for the decline in research spending and the shift from longer- to shorter-term research in the U.S. telecommunications industry is seen in the number of technical papers authored by industry researchers. At two recent major international conferences held annually in the field of communications (which represent at least part of the telecommunications landscape), there was a dramatic decrease in the number of conference papers authored by industry researchers. Table 2.1 lists the sources of the 1352 papers presented at the 2005 International Conference on Communications (ICC) and the 2005 IEEE Global Telecommunications Conference (Globecom). Only a handful of U.S. industry research labs were represented by more than one paper at the two conferences (see Table 2.2).

Although it could be the case that U.S. telecommunications companies have decided to restrict presentations of work by their researchers (and developers) at such conferences, the committee considers it much more likely that the statistics on publication by author affiliation shown in Tables 2.1 and 2.2 do reflect a dramatic decline in industry efforts in long-term research.[16]

A decline in publication by industry authors is also suggested by the decreasing fraction of industry-researcher-authored papers in the *IEEE Transactions on Communications* (Figure 2.1),

[16]A reviewer of this report in draft form noted another possible factor—that companies increasingly "document" their research through patents and participation in standards-setting activities rather than publications.

TABLE 2.2 Number of Papers Presented by U.S. Industry Research Laboratories (for companies with more than one paper) at the 2005 International Conference on Communications and the 2005 IEEE Global Telecommunications Conference (Globecom)

U.S. Industrial Research Laboratory	Number of Papers
Qualcomm	9
Lucent	6
Telcordia	4
IBM	4
Marvell Semiconductor	3
Mitsubishi Research U.S.	3
Motorola	2
Conextant	2

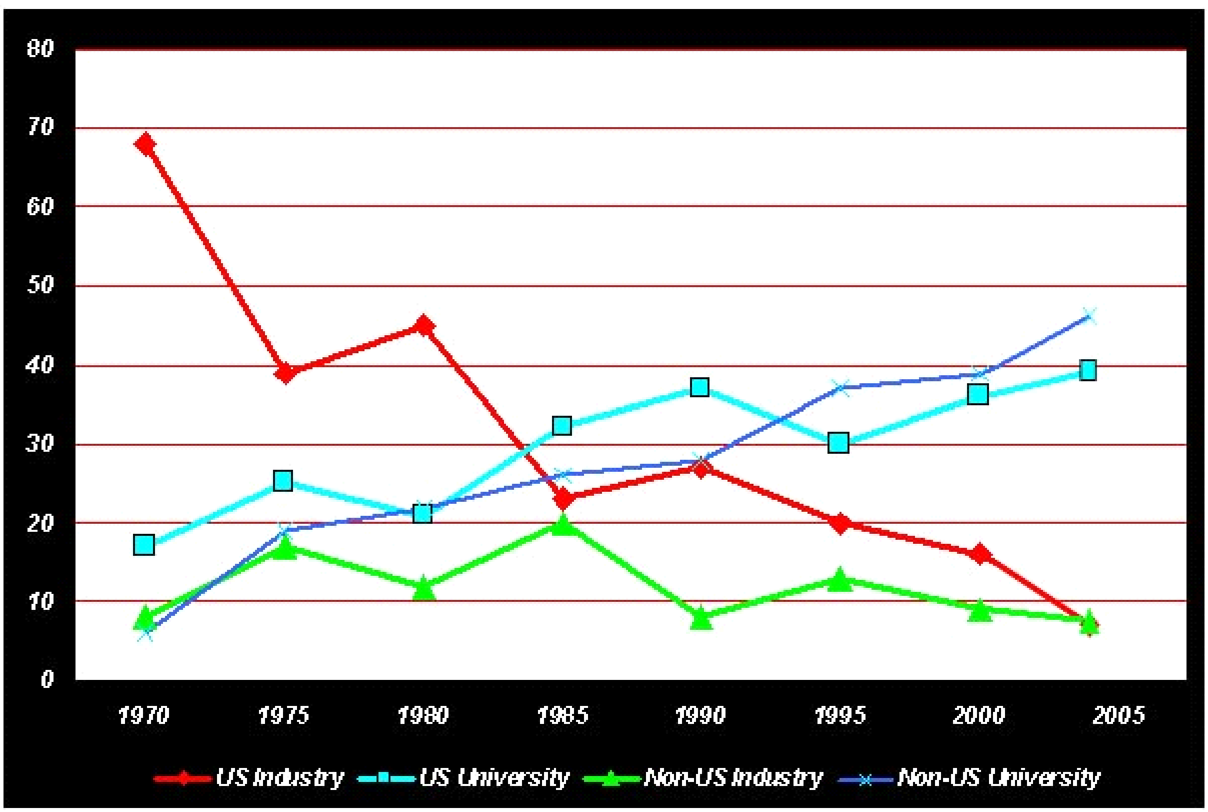

FIGURE 2.1 Percent authorship of papers in the *IEEE Transactions on Communications*, 1970 to 2005.

arguably the most prestigious journal in the communications area. In 1970 approximately 70 percent of the papers in the transactions were authored by industry; in 2003 that percentage had fallen by an order of magnitude to about 7 percent. The reduced contributions from industry have been partially offset by an increase in the number of academic papers—both from U.S. and foreign universities.

U.S. Participation in Publishing Research

It can also be seen that publications from universities outside the United States are greater in number than publications from universities within the United States—albeit by a small amount. In addition, the level of publication from industry outside the United States is now roughly the same as the level from U.S. industry.

Within U.S. universities, there are multiple indications that much U.S. academic research in telecommunications is being carried out by foreign national graduate students. In the papers published in Globecom 2005, 459 of the 675 authors from U.S. universities (68 percent) have apparently Asian surnames. This observation is consistent with data showing that roughly 60 percent of the Ph.D.s in engineering and 50 percent of the Ph.D.s in computer science awarded in the United States are being awarded to non-U.S. citizens.[17]

GOVERNMENT SUPPORT FOR TELECOMMUNICATIONS RESEARCH

Overall Investment

Government support for telecommunications research has been small compared with support for other areas of IT, arguably because of the spending on research by the Bell System (until divestiture) and by its progeny. Precise figures are, unfortunately, difficult to come by. Perhaps because telecommunications has not been considered a strategic area for investment, telecommunications research activities do not fall neatly into programs labeled as "telecommunications" nor is telecommunications research funding across the U.S. government tracked as a separate category by NSF's Division of Science Resources Statistics.

However, a top-down indication of the level of investment can be obtained from *Networking and Information Technology Research and Development: Supplement to the President's Budget for FY2006*,[18] a report of the National Coordination Office for Networking and Information Technology Research and Development. It describes the networking and information technology research spending by its 11 participating agencies—NSF, NIH, DOE (Office of Science), NASA, DARPA, the National Security Agency, the Agency for Healthcare Research and Quality,

[17]Based on data compiled by the Computing Research Association; see <http://www.cra.org/info/education/us/phd.citizenship.html>.

[18]Subcommittee on Networking and Information Technology Research and Development, Committee on Technology, National Science and Technology Council, *Networking and Information Technology Research and Development: Supplement to the President's Budget for FY2006*, National Coordination Office for Networking and Information Technology Research and Development, Arlington, Va., February 2005, available online at <http://www.nitrd.gov/pubs/2006supplement/>.

NIST, NOAA, EPA, and DOE/National Nuclear Security Agency—that provide the bulk of federal research in these areas. The report divides federal research spending into seven categories—high-end computing infrastructure and applications, high-end computing R&D, human computer interaction and information management, large-scale networking (LSN), software design and productivity, high-confidence software and systems, and social, economic, and workforce). The total research spending across these agencies and areas for FY 2006 is $2.1 billion, whereas for LSN—the area likely to contain the most telecommunications-related research—it is $328 million, or 16 percent of the total.

The numbers are not definitive: there might, for example, be some physical sciences work that supports telecommunications, and (similarly uncounted) physical sciences work that supports IT as well. Also, not all of the LSN budget supports networking research per se. For example, the biggest contributor to support for LSN is NIH, at least some of which appears to be for networks for health sciences research rather than for networking research itself. Considering funding for all agencies except for NIH funding, the FY 2006 spending on LSN is $230 million out of $1.7 billion, or 14 percent. Also, the second largest supporter of LSN research is NSF ($95 million); some of NSF's LSN budget also supports research infrastructure rather than networking research, making the percentage for research itself even lower.

National Science Foundation

There are elements of programs in NSF's Computer and Information Science and Engineering (CISE) and Engineering (ENG) directorates that address aspects of telecommunications research. The CISE directorate has, for example, long been an important supporter of networking research (as noted in "The Internet," the section above on the development of the early Internet). Over the years the ENG directorate has made investments in various areas including wireless and optical communications, and it has established several engineering research centers related to telecommunications. In the view of the committee, however, these efforts as a whole have not represented a major programmatic emphasis by NSF on telecommunications nor reflected a comprehensive, coordinated research strategy in telecommunications.

Today, as outlined above, telecommunications programs in total see only a modest level of funding. In addition, testimony provided to the committee indicated that overall proposal acceptance rates for most NSF programs related to telecommunications (in the CISE and ENG directorates) have been 10 percent or less for the past several years.[19]

In 2004, NSF announced a new $40 million per year program called Network Technology and Systems (NeTS), which represents a significant new investment in telecommunications research and education projects and will focus on the following four areas: programmable wireless networks, networking of sensor systems, networking broadly defined, and future Internet design.[20] The program has latitude for interdisciplinary work that could also involve physical devices and could suggest a wide range of research topics in the control, deployment,

[19]In his May 2004 testimony to this committee, Guru Parulkar of NSF indicated that proposal acceptance rates "in the single digits" were typical for CISE networking research programs.

[20]For more information on NeTS and its four focus areas, see <http://www.nsf.gov/pubs/2006/nsf06516/nsf06516.htm>.

and management of future networks. However, although the NeTS program is a welcome source of additional support and programmatic emphasis on telecommunications research, its relatively modest size is likely to have little overall impact on low proposal acceptance rates.

In 2005, NSF announced the Global Environment for Networking Investigations (GENI) initiative, a program still in the planning stage that will focus on new concepts for networking and distributed system architectures and on experimental facilities to investigate them at large scale. Envisioned as encompassing a broad community effort that engages other agencies and countries, as well as corporate entities, the GENI initiative will emphasize the creation of new networking and distributed system architectures that, for example:

- Build in security and robustness;
- Enable the vision of pervasive computing and bridge the gap between the physical and virtual worlds by including mobile, wireless, and sensor networks;
- Enable control and management of other critical infrastructures;
- Include ease of operation and usability; and
- Enable new classes of societal-level services and applications.[21]

Defense Advanced Research Projects Agency Support

Long a source of support for research on large-scale problems, DARPA has led in computer networking (via the ARPANET and its derivatives) and in the creation of the Internet (via its support of TCP/IP protocols and related computer networking services such as e-mail, ftp, gopher, and others) and remains committed today to advances in telecommunications-focused research. In the early 1990s, DARPA was involved in the research on and adoption of asynchronous transfer mode (ATM) technology, as well as research into packet technologies for voice and video. Along with nearly 40 other organizations, DARPA also completed work on the Gigabit Testbed Initiative, an effort by a host of universities, telecommunication carriers, industry, national laboratories, and computer companies to create a number of very-high-speed network testbeds and explore their use for scientific research and other applications.[22] In the late 1990s, DARPA also funded the All Optical Networking Consortium, which was formed by the cooperation of Bell Laboratories, Digital Equipment Corporation, and the Massachusetts Institute of Technology to examine the unique properties of fiber optics for advanced broadband networking. DARPA has also been a long-standing, significant funder of wireless research.

Currently, telecommunications research programs in support of battlefield communications continue to be a focus of DARPA's work. Examples include the Information Processing Technology Office's (IPTO's) Situation Aware Protocols in Edge Network Technologies (SAPIENT) program,[23] and the Advanced Technology Office's (ATO's) Information Theory

[21]National Science Foundation, Directorate for Computer and Information Science and Engineering, *The GENI Initiative*, 2005, available online at <http://www.nsf.gov/cise/geni/>.

[22]The final results of this initiative were captured in the following report: Corporation for National Research Initiatives, *The Gigabit Testbed Initiative: Final Report*, 1996, available online at <http://www.cnri.reston.va.us/gigafr/>.

[23]More information about IPTO's work can be found online at <http://www.darpa.mil/ipto/>.

for Mobile Ad-Hoc Networks, Mobile Network MIMO, Rescue Transponder, Networking in Extreme Environments, and NeXt-Generation Communications programs.[24]

DARPA has had a long and illustrious history of funding high-risk, high-reward projects, many of which have changed the face of military systems, computing environments, networking, other military technologies, and ultimately technologies in private industry.[25]

Other Federally Funded Telecommunications Research

The previous sections highlight several of the more prominent federal funding programs related to telecommunications. But there have been many other important areas of investment over the years. Within DOD itself, the service laboratories (Office of Naval Research, Air Force Office of Scientific Research, and the Army Research Office) as well as other military R&D centers (such as MIT Lincoln Laboratory, Rome Air Development Center, Army Satellite R&D at Ft. Monmouth, and so on) have made significant investments in a wide array of telecommunications technologies. Another mission-driven investment was made by NASA in support of satellite and space missions. Finally, programs at the National Telecommunications and Information Administration's Boulder laboratory have helped advance the field of wireless propagation.

HISTORICAL CHALLENGES TO DOING MORE TELECOMMUNICATIONS RESEARCH IN ACADEMIA

An indirect consequence of the traditionally high levels of funding for research by the Bell System and by its progeny has been modest attention to telecommunications in academia compared to many other areas of information and communications technology. Since almost every aspect of telecommunications was provided by monopoly carriers (both in the United States and abroad), it was difficult to create viable telecommunications courses in academia and to attract professors who were knowledgeable about the changing telecommunications environment.

More recently, corporate investment in academic work has been quite modest and confined largely to a few successful consortium research programs that have attracted industry support and have also, in some cases, been funded by state initiatives. Several state programs, notably in California and Georgia,[26] support academic telecommunications research and interactions with industry.

Another challenge in teaching telecommunications or carrying out a relevant research program in universities is that the facilities and resources at academic institutions are not adequate to address the architectural and operational issues of large-scale telecommunications networks. Since there has never been any pressure or financial incentive to create the resources

[24] Likewise, more information about ATO's work can be found online at <http://www.darpa.mil/ato/>.

[25] For a history describing the transition of DARPA research into the military, other government organizations, and private industry, see DARPA, "Technology Transition," [undated], available online at <http://www.darpa.mil/body/pdf/transition.pdf>.

[26] For more information on these programs, see <http://www.calit2.net> and <http://www.gcatt.org>, respectively.

and infrastructure for such research (since these have traditionally and historically been the domain of the monopoly carriers), most university researchers have opted instead to focus on core technologies like semiconductors, computing, signal processing, and communication theory, where meaningful research can be done at a much smaller scale with fewer resources, and where both industry and government have been more willing to provide the support needed to create long-range academic programs.

INTERNATIONAL SUPPORT FOR TELECOMMUNICATIONS RESEARCH AND DEVELOPMENT

In the course of its work the committee developed a keen sense of the increasing competition from international telecommunications industries (in terms of both technology and price). However, it is very difficult to collect comprehensive information on international R&D investment related to telecommunications or to assess how such investments affect a given industry. Still, there is ample evidence that a number of other nations place considerable emphasis on R&D in this sector. Three member countries of the Organisation for Economic Co-operation and Development, for example, have legal or regulatory mandates for such research:[27]

- Japan's NTT law requires NTT to conduct research relating to telecommunications technologies and makes NTT (including the regional companies NTT East and NTT West) responsible for promoting and disseminating the results of telecommunications research.
- Korea's telecommunications basic law allows the Ministry for Information and Communications (MIC) to recommend that service providers contribute a percentage of total annual revenues to telecommunications research. R&D investments by carriers may be internal or external; external contributions are made to an MIC-administered fund that is then distributed to Korean research institutes.
- In 2003, France's telecommunications regulations required France Telecom to spend 4 percent of its unconsolidated revenues on research and development.

In addition, several nations and regions conduct major research programs with significant government investment. It is, of course, difficult to compare research programs in detail because of differences in program structure, definitions of telecommunications, and so forth. However, several examples of investments made outside the United States provide a compelling illustration of the high priority being placed on telecommunications R&D outside the United States. Major initiatives include the following:

- The European Union Sixth Framework Programme includes nearly $300 million in funding for telecommunications research under the Information Society Technologies program: €138 million for mobile and wireless systems and "platforms beyond 3G," €65 million for "broadband for all," €63 million for "networked audiovisual systems and home platforms," and €18 million for research networking testbeds.[28]

[27] OECD, *OECD Communications Outlook 2005*, OECD Publishing, Paris, 2005, p. 75.
[28] Budgets for 2004-2005 annual calls for proposals; see <http://www.cordis.lu/ist/activities/activities.htm>.

- Japan's National Institute of Information and Communications Technology has an almost entirely government-funded budget of over $500 million that supports nearly 500 employees, 60 percent of whom are researchers.[29] Another government-supported institution, the Research Institute of Telecommunications and Economics, carries out economics and policy research related to telecommunications.

Another development is that some U.S. academic telecommunications researchers have turned to foreign corporations for funding and have, according to information available to members of the committee, received funding from companies such as Toshiba (Japan), Huawei (China), and Samsung (Korea)—which have become formidable competitors of U.S. firms. To gain such support, academic institutions have sometimes been asked to surrender ownership or agree to co-ownership of intellectual property stemming from the research.

Finally, beyond research programs, many nations have signaled their commitment to telecommunications as a critical societal and economic element. In particular, China has fostered a strong and growing telecommunications industry. Briefers to the committee and reviewers of this report noted the increasing technical sophistication and competitiveness in pricing of Chinese equipment vendors.[30] Countries such as Japan (e-Japan), Korea (e-Korea Vision 2006), and Taiwan (e-Taiwan) have launched national programs that aim to broadly promote the deployment, adoption, and use of information and telecommunications technologies. They feature a variety of elements ranging from research funding to policy reforms to incentives for broadband deployment to national standards and standards-development processes that (if only indirectly) aim to strengthen domestic industries.

[29] See <http://www.nict.go.jp/overview/> or overview pamphlet at <http://www.nict.go.jp/overview/news/pdf-box/NICT-e.pdf>.

[30] A 2004 *Business Week* article profiled one such prominent Chinese company, Huawei, noting that the company was spending 10 percent of its revenues on R&D. See Bruce Einhorn, "Huawei: More Than a Local Hero," *BusinessWeek Online*, 2004, available online at <http://www.businessweek.com/magazine/content/04_41/b3903454.htm>. Also, for more insight into Chinese competitiveness and its implications for U.S. entrepreneurs, see Reed Hundt, *In China's Shadow: The Crisis of American Entrepreneurship*, Yale University Press, New Haven, Conn., 2006.

3

The Case for Renewed Investment in Telecommunications Research

Discussing the importance of ongoing improvements in telecommunications and the key ingredients in sustaining a healthy telecommunications ecosystem, this chapter considers why research and leadership in telecommunications matter.

WHY RESEARCH MATTERS

The Role of Research Advances in Creating Modern Telecommunications

Research over the past several decades has led to advances ranging from incremental improvements to real breakthroughs (so-called disruptive changes[1]). Major advances have occurred, for example, in the underlying "physical layer" communications technologies for wireless, optical fiber, and wireline transmission. These include:

- *Local area networking technology, notably Ethernet and successively faster generations of Ethernet standards*, which have made it possible to connect many millions of computers both within organizations and to the wider world through the Internet;
- *Radio-frequency communications* technologies for cellular systems and wireless local area networks, which have enabled modern mobile voice and data communications and have fueled the growth of the entire mobile phone industry;
- *Optical networks*, which have revolutionized communications by providing extraordinary amounts of communications bandwidth over very long distances at very low unit cost,

[1]Disruptive technological change often presents significant challenges to incumbents who are using existing technologies, but it also leads to dramatically better capabilities for users and to the spawning of entire new industries.

and whose tremendous communications capacity has enabled significant transformations of the public switched telephone network, cable systems, and the Internet; and

- *Broadband local access communication*, enabled by technological innovations such as digital subscriber line and cable modems, which has made high-speed Internet access widely available to homes and small businesses.

Disruptive technological change has occurred at the protocol and network levels as well. Two notable examples include:

- *The Internet*—the realization of a revolutionary communications paradigm—which introduced a new, highly flexible network architecture and protocols, and ultimately enabled myriad new applications and services; and
- *Packetization of voice and video, such as voice over Internet Protocol (VoIP)*, which provides voice communications with greater flexibility and efficiency and has opened up opportunities for application innovation beyond the boundaries of the public switched network.

At the level of applications, the Internet in turn has provided a unique laboratory for the creation of innovative applications—e-mail, instant messaging, collaboration, World Wide Web (WWW) browsers and servers, electronic auctions, and business to business (B2B) and business to consumer (B2C) electronic commerce—that have changed consumer behavior and business interaction. Audio and video have expanded as well, from traditional cable broadcast networks to digital cable systems to switched video on the Internet, file sharing, and pay-per-view.

Traditional telephony has also been transformed over time. Out-of-band signaling protocols for the public switched telephone network, such as the current global standard Common Channel Signaling System No. 7 (SS7), have made possible the modern worldwide public telephone network by supporting such features as worldwide direct dialing, wireless roaming, local number portability, and toll-free calling. Telephony has also branched out into new application areas: voice over packet, wireless telephony, and integrated voice/data applications are industry-shaping developments.

Developments in optical communications provide a good illustration of how multiple threads of research in electronics, photonics, signal processing, and coding theory have all contributed to the remarkable growth in optical transport capacity. These developments were driven first by the advantage of displacing the copper transport plant with optical fiber (early 1980s); the emergence of pervasive global connectedness (1980s and 1990s); widespread Internet use (starting in the mid-1990s); and broadband data and video access (starting circa 2000). High-speed electronic and optical devices have kept a steady pace with this demand to enable the growth in optical capacity with gigabits-per-second (Gbps) silicon and GaAs circuits appearing in 1985, leading to today's commercial InP circuits working in 40-Gbps optical channels. Recent laboratory results have shown that 100-Gbps electronic circuits are possible. The first reports between 1986 and 1988 of erbium-doped amplifiers led to wavelength-division multiplexing (WDM), which made it practical to carry multiple optical channels on a single fiber. Today more than 100 channels can be carried in a single fiber, with aggregate capacity exceeding 6 terabits per second. After the introduction of WDM, new optical fiber types that balance between chromatic dispersion and optical nonlinearities were introduced in the early 1990s, successfully extending the capacity and range of optical transport systems.

Complementing the fiber evolution has been the evolution in signal modulation formats, resulting in more compact signal spectra and more robust channels. Finally, new coding methods, in particular forward-error correction schemes, have greatly increased the design margins possible for optical transport and have figured significantly in the enhancement of capacity and range over the past 5 or 6 years. Further technological advances in all-optical signal regeneration, modulation formats, and channel filtering are expected to continue to enable improvements in fiber-optic communications.

The Potential for Research Spin-offs

It is also worth reflecting on the many notable spin-offs of past telecommunications research. Examples include:

- *Transistors*, which spawned the entire semiconductor and computer industry, and an enormous range of applications in communications, computing, media, and entertainment;
- *Lasers*, which have seen widespread application in medicine (surgery), consumer electronics (CD and DVD players), manufacturing, and even toys and games;
- *Karmarkar's algorithm for linear programming*, which solved a long-standing problem in computer science and is an example of the kind of widely applicable solutions to mathematical problems that arise in telecommunications;
- *UNIX*, created as a result of work aimed at constructing a simple operating system that facilitated the construction of widely reusable software tools; the telecommunication industry's requirements for high performance helped push forefront research in simple yet powerful software systems, and today, various flavors of UNIX are the dominant open standard in operating systems;
- *Reduced instruction set computing*, the first prototype system for which (the 801 Minicomputer at IBM Research) had as its application objective a telephone switching system;
- *Satellite communications* and the entertainment industry spawned by Telstar, which today are much broader in scope than the point-to-point communications Telstar was built for and were made possible by the initial investment in a single application;
- *Coding and information theory*, developed for data compression and error-correction, which has also found application in diverse areas such as cryptography, probability theory, biology, and investment theory.

Of course, that such spin-offs occurred reflects in no small part the significant investment in long-term research that was made in the Bell system era. These and other spin-offs also demonstrate that making major advances in telecommunications requires the solution of technical problems across the spectrum from theory to device physics to software, yielding results that can have broad utility.

Research for National Defense and Homeland Security

Research in commercial and defense applications of telecommunications has contributed significantly to U.S. military strength. Captured in the phrase "network-centric warfare," the central and growing importance of communications systems to national defense and homeland security makes these key areas that rely on having a strong U.S. research and skill base.

The intensity of the communications demands that can arise in defense applications is evident in the concept of the future battlefield as being totally dependent on communications: from the fiber-optic cores of military networks to the satellite systems that provide long-reach communications to the tactical radios carried by soldiers on the battlefield. Some of these requirements are fulfilled via commercial off-the-shelf (COTS) products. Use of COTS products is often highly desirable as a means of reducing the cost of infrastructure, yet such products bring concerns as well (see the discussion below in the section "Leadership for National Defense and Homeland Security"). For example, military requirements can exceed what COTS products alone can deliver, perhaps because the demands (e.g., the need for multilevel security) are higher or the application environment is different, because of the presence of an adversary, for instance.

In addition to emphasizing the impact of U.S. communications research on C4I (i.e., command, control, communications, computers, and intelligence[2]), it is also important to briefly note the relevance to C4I of the engineering disciplines. Much of the basic mathematics that underlies telecommunications engineering is also relevant to command and control systems. Almost any computing device depends heavily on communications technology, both internally to communicate between subelements of the computer and externally to communicate with other devices. And the field of intelligence is replete with examples of reliance on telecommunications. Hence, telecommunications research is significant for and integral to the capability and capacity of many aspects of the overall defense system.

A strong U.S. telecommunications research capability is also important for several indirect reasons related to defense and homeland security:

- *Skill base of engineering talent: education and training*. To solve the specialized communications issues in C4I requires that the United States have the best telecommunications engineers in the world, which in turn requires that a vibrant commercial industry be maintained. Otherwise, the best engineers will migrate to countries that have protected or low-cost businesses, and ultimately U.S. security will be put at risk.
- *Delivery capability of government suppliers*. Because meeting military requirements depends on fundamental understanding of very-high-speed optical networks, satellite communications, and support of mobility in the battlefield, it is not sufficient to have a cadre of educated and trained individuals. Corporate environments must also be available in which such individuals are trained to work together in teams on system-level designs, and to take an interdisciplinary approach.
- *Interconnectedness of defense systems*. As more defense- and homeland security-related systems are interconnected, the pressure will increase on the United States to develop new technologies here at home, because relying on foreign suppliers for critical network components like firewalls and communications software might open the door to serious compromises of security and availability across a wide range of defense capabilities.
- *Military superiority.* In a military context, the goal is superiority over the adversary, which requires having the best research and engineering capability in the world.

[2]For more information about C4I, see Computer Science and Telecommunications Board, National Research Council, *Realizing the Potential of C4I: Fundamental Challenges*, National Academy Press, Washington, D.C., 1999, available online at <http://fermat.nap.edu/html/C4I/>.

Potential Impacts of Future Research

Telecommunications continues to be a dynamic sector in which significant innovation is possible provided proper research investments are made. Some examples of potential payoffs from telecommunications research include the following:

- A significantly enhanced Internet architecture that goes beyond incremental improvements to the existing network architecture to provide enhancements such as greater trustworthiness in the network core and customer networks, improved addressing and routing, and end-to-end quality of service provisioning;[3]
- New network architectures that take advantage of ever-greater storage densities, processing speeds, and communications bandwidths;
- More trustworthy telecommunications networks better able to address such challenges as maintaining the security of the voice network even in the face of a rising frequency, sophistication, and severity of attacks and the complexities and interdependencies that come with the convergence of voice and data networks;
- Ubiquitous, higher-performance, more-affordable broadband access that enables richer, more interactive applications, including applications in such important areas as health care and education;
- Telepresence and telecollaboration environments that reproduce a local space at a distance and enable spatially separated individuals or teams to work more readily in concert;
- Public safety networks that offer higher mobility, better adaptation to harsh and changing conditions, and increased resiliency to damage;
- Adaptive/cognitive wireless networks that enable higher-performance communications, make more efficient use of radio spectrum, and complement or supplant today's chiefly wired networks;
- Location-based wireless networks that provide information and services tailored to the local environment;
- Self-organizing sensor networks that have large numbers of nodes, are energy efficient, and have self-organizing capabilities, which would enable ubiquitous, cheap monitoring of the environment and weather, sensing of biological or chemical agents, and monitoring of facilities; and
- New semiconductor devices that enable higher performance and new forms of communications and computing.

The section that follows discusses several broad research areas in more detail.

Some Important Areas of Emphasis for Future Telecommunications Research

Defining Future Architectures in an Era with More Diffuse Responsibility for End-to-End Issues

Major innovation in telecommunications has always depended on the industry's ability to make major architectural shifts. Telecommunications networks are large, complex systems

[3] For a recent overview, see David Talbot, "The Internet Is Broken," *Technology Review*, 108(11):62-69, December 2005-January 2006, available online at <http://www.technologyreview.com/infotech/wtr_16051,258,p1.html>.

whose reliability, security, and evolvability are dependent on the development of coherent and well-conceived architectural concepts. Historical examples within the public telephone network of such major architectural shifts include direct-distance dialing, digital transmission and switching, and the incorporation of cellular telephony into the public telephone network. The Internet is another example of a major architectural advance, one made possible by a multiyear research effort funded by the federal government for the first couple of decades (largely on behalf of military and internal research applications).

Will future advances of this magnitude be more difficult to achieve in today's environment, particularly in the United States? The situation now is more dynamic than in the Bell System days, involving more competition and more opportunities for creative new ideas. Today, however, multiple vendors' products are used to configure U.S. telecommunications infrastructure and deliver services, and multiple service providers (and thus even more vendors) are involved in delivering services that cross provider boundaries. As a result of the industry's shift to a horizontal structure and its fragmentation into a large number of firms, neither vendors nor service providers are prepared to take responsibility for end-to-end systems design.

No single vendor can now drive architectural change in the same way that AT&T was able to do in the past. Telecommunications vendors are able to make incremental improvements within existing frameworks, but major advances in system architecture or services may be more difficult, and innovation in services and applications may become constrained by continued reliance on obsolete network architectures. Also, what solutions are developed and deployed may be unnecessarily complex, fragile, and vulnerable because of too little investment in architectural work.

Cable television's recent architectural transformation shows how an industry can create a new entity (in this case, CableLabs) to help drive change at least within a particular sector of the telecommunications industry. Cable systems were transformed from one-way, broadcast-only systems into two-way, multilayer systems that migrated fiber much further into the infrastructure while retaining coaxial cable as the final link to the customer. This new architecture positioned the cable industry to deliver video, voice, and data services. The nonprofit CableLabs consortium (described in greater detail in Chapter 2) was established to address end-to-end issues for the cable industry through activities to identify and develop new technologies, write specifications, certify products, and disseminate information to the cable industry. Its activities are supported by subscription and testing fees paid by its members. CableLabs helped foster the introduction of digital transmission and the hybrid fiber coaxial cable architecture found in modern cable systems and developed a series of specifications for cable modems known as the Data Over Cable System Interface Specification.

Infrastructure Enhancement

Physical connectivity is the foundation for telecommunications networks. Imagine that the United States had never deployed copper wires and coaxial cable to connect its homes and businesses and now wanted to design the best possible telecommunications infrastructure. There is little doubt about the best design choice—optical fiber for high bandwidth complemented by wireless for mobility and flexibility. Optical communications would give everyone the greatest possible amount of bandwidth, would be useful for essentially all applications that have been imagined, and would be future proof—it is known how to continually get more and more bandwidth out of each fiber. The cost of installing the fiber would be no greater than the cost of a new installation of any other medium.

Today U.S. telecommunications infrastructure has little fiber to the premises, although fiber makes up most long-haul and metropolitan area networks. Realizing the goal of fiber everywhere involves a number of problems requiring research. For example, while the cost of optical components is not a significant problem in core networks because the cost is spread across many users, the components represent a nontrivial expense for local access networks, which serve only one user or a handful of users. How can the cost of optical components be reduced sufficiently to make fiber to the home affordable? What architectural approaches offer the best mix of affordability, performance, and evolvability? What are the future applications that will drive the need for increasing bandwidth?[4]

Metropolitan area networks are currently receiving much commercial attention. With today's abundance of fiber in the core, and with access networks creating larger demands, an important focus of research is to develop architectures that effectively handle ever-greater volumes of optical transmission in metropolitan areas. Core networks themselves will require advances, and as more capability is introduced into the access networks, the need will grow to continue to improve the bandwidth-times-distance product, as will demands to increase the performance of national networks.

Wireless networks provide an even more fertile area for exploration. Access to higher bandwidth, which has spurred growing use of the wired Internet and is now becoming available to wireless LAN users (via WiFi and WiMAX) and fully mobile users (via 3G technology), is basic to the creation of the so-called mobile Internet. There are many opportunities for further progress. At the physical level fundamental data rate limits for most environments are still very far from being achieved, and there are practical impediments, such as topography and the costs of certain components such as filters, to enhanced performance. Further development of multiple input, multiple output (MIMO) antenna technology, for example, offers opportunities to drive even greater capacity of wireless networks.

Infrastructure Trustworthiness

Although an area of great, growing, and shared concern is the trustworthiness (i.e., security and reliability) of U.S. telecommunications, related research does not seem to be keeping pace with these concerns.[5]

The voice network was designed, engineered, and refined to continue to operate in all but the most severe disasters and has generally performed well as a result. Over the past century, it has evolved from a largely mechanical system into a sophisticated electronic switching network with a signaling network overlay and a rich set of vertical services provided by

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[4]An earlier CSTB committee examined many of these and other related issues. See, for example, Chapter 4 in Computer Science and Telecommunications Board, National Research Council, *Broadband: Bringing Home the Bits*, National Academy Press, Washington, D.C., 2002, available online at <http://fermat.nap.edu/html/broadband/>.

[5]See, for example, Computer Science and Telecommunications Board (CSTB), National Research Council (NRC), *Critical Information Infrastructure Protection and the Law*, The National Academies Press, Washington, D.C., 2003, p. 66; and CSTB, NRC, *Trust in Cyberspace,* National Academy Press, Washington, D.C., 1999.

attached processors and databases. This evolution was clearly necessary to support the ubiquity of interconnections, increases in call volume, and provision of new services. The resulting network has proven generally reliable and secure. But like all networks, it is potentially vulnerable to electronic attack.[6]

Data networks, and the Internet in particular, evolved in a very different way. The Internet began as an open collaboration among trusted peers. The protocols were developed to optimize interconnection, simplicity, and access—characteristics that have proven to be some of the Internet's greatest strengths, adding to its reliability and scalability. But while redundancy and distribution were contemplated, security and quality of service were not prominent concerns early on. Despite the demonstrated advantages of the current architecture, every device connected to the Internet can become a source of or a target for malicious activity. And such malicious activity has flourished, most publicly in the form of hackers/crackers, viruses, worms, Trojan horses, or denial-of-service attacks. Today both the network and every networked device requires some form of protection, but the protection is neither uniform nor universal.

Trustworthiness issues also arise at the intersection of the public telephone network and the Internet. Initially, voice and data network interaction was limited to common transport systems and the use of the voice network to carry data between dial-up modems. Today, digital subscriber line (DSL) services carry data over the same lines that formerly carried only voice conversations. The volume of data traffic now surpasses the volume for voice traffic, a development that forces consideration of the eventual migration of voice traffic to the data network. In fact, this migration has begun—albeit more slowly than initially projected—with voice over IP (VoIP), IP Centrex, and softswitch technology. Over time voice traffic will increasingly be carried by packet transport and routing. In the interim, interworking between the traditional public switched telephone network and the data networks must be provided. Convergence of the voice and data networks, although compelling in features and potential cost savings, also requires research into the reliability and security of existing voice services and the overall converged network.

In addition to convergence, new technologies are also enabling new network capabilities and services that will in turn pose new challenges to trustworthiness. Dense wavelength-division multiplexing (DWDM), optical switching, a migration of Ethernet into metropolitan networks, virtual private networking, multiprotocol label switching (MPLS), video, unified messaging, and various forms of wireless data all require intelligent network components or devices. Devices and services for personal computing, mobile Internet use, and a plethora of other applications that will leverage these emerging capabilities will also bring more complexity into the core and edges of the network—and thus new challenges to ensuring security and reliability.

Public data networks have been built and the number of network providers—including 30 major Internet backbone providers and thousands of Internet service providers—has increased at an unprecedented rate. As a result of all these rapid changes, public networks now have many more interfaces to competing networks and therefore many more points of vulner-

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[6]Reflecting the network's national importance, additional measures (e.g., planning, coordination, and information sharing via creation of entities such as the National Security Telecommunications Advisory Committee and the National Coordinating Center for Telecommunications) have been taken to help avert attacks and remediate their consequences.

ability. The number of new network equipment manufacturers has grown as well. In an environment of fierce competition, manufacturers tend to concentrate on improving raw performance and introducing complex features, sometimes at the expense of building in capability for survivability and security or performing robust testing and quality assurance before products enter the network. In addition, today's business and regulatory environment does not necessarily provide sufficient incentives for building in redundancy and security commensurate with societal needs. Clearly, the need to focus research efforts on such critical issues as the reliability and security of the telecommunications infrastructure is now more important than ever.

WHY LEADERSHIP MATTERS

Leadership is especially important in light of such issues as competing effectively in today's global marketplace; ensuring U.S. national defense and homeland security; maintaining a telecommunications infrastructure supportive of sustained innovation in telecommunications, which in turn enables innovations in many other industrial sectors; and maintaining the capacity to create new industries.

Historically, the United States has been able to translate a number of key research advances into leadership positions in telecommunications, as illustrated by the following examples:

- CDMA technology, which was originally invented and championed by U.S. firms, has now been accepted as the worldwide standard for third-generation (3G) mobile networks;
- DSL technology, cable modems, and hybrid fiber coaxial cable technology, all U.S.-invented, are used to deliver broadband services throughout the world.
- The Internet and its TCP/IP protocols, pioneered in the United States with DARPA funding, have come to dominate data networking.

The majority of the research and innovation that drove the development of related new businesses was done in the United States, positioning U.S. industries to have first-mover advantage. Not only has the United States been the leader in the core telecommunications technologies and information technology more generally (including processing, storage, communications, and software), but the new businesses and applications built around these technologies are also core areas of U.S. leadership. Ownership of intellectual property is also a benefit that often accrues to the country that can lead in innovation, with broad worldwide patents granted to those companies and universities creating fundamental new advances. This patent position also benefits these organizations economically.

Advantage often—but not always—goes to the home country. On the supply side, it has been beneficial for U.S. trade and commerce that U.S. innovators and first-movers have been able to export their products and solutions to other countries. With the United States in the lead for Internet innovation, for example, U.S. companies such as Cisco and Wellfleet Communications had a natural market to address, created the initial products, and positioned themselves well for the future. Other companies such as RSA and Qualcomm developed and patented key technologies and created strong businesses based on that intellectual property. Companies such as AOL and Yahoo! were naturally positioned to succeed in markets for new services, and new applications markets were developed by companies like Amazon and eBay.

These examples illustrate notable instances of research breakthroughs having enabled a technology capability that has, in turn, led to U.S. intellectual leadership in that area. There are, to be sure, counter-examples. For technologies like television, high-definition television (more recently), and mobile phone hardware, for example, much of the early work or breakthroughs occurred in the United States, but much of the commercial advantage and manufacturing success has been reaped elsewhere (e.g., Japan, China, Scandinavia, and so on).

Although the WWW was created in Europe, the focus quickly shifted to the United States, where a crucial WWW tool, the graphical browser, was developed—another example of the power of strong research leadership and of the importance of the Internet research and development ecosystem in the United States, which went on to play a leading role in further innovations such as graphical Web browsers, e-business, and Internet search. The lesson is that future technology leadership will likely follow the paradigm of advantage to the home innovator.

The Global Telecommunications Market

Many firms today operate and compete on a global scale, and various forces are at work to increase the competitiveness of other nations in high-tech sectors such as telecommunications. Among the many contributing factors are increased investment by other countries in their own domestic research and training, other forms of government investment in and support for domestic industries, growing domestic markets, and lower labor costs. In the large economies of the Pacific Rim, for example, considerable investment is being made in developing the workforce. Since open standards define much of the telecommunications system, foreign suppliers have an opportunity to bring to market the same products that U.S. competitors offer, but much more cheaply due to lower prevailing wages, less need to invest in basic research, and often a return on their investment guaranteed by home country purchase policies.

Although almost all telecommunications markets are now global, the degree of openness and true competitiveness varies. The United States has an open market, with virtually no pressures to buy from local manufacturers. Although the U.S. model is most likely to provide the lowest cost and most innovative services to consumers, it does lead to a situation in which U.S. manufacturers do not have a leg up in their home market and are also substantially handicapped in foreign markets.

The typical response to such competitive pressures would be to invest in research that leads to new products that other manufacturers lack, as a way of reestablishishing preeminence. However, there are several obstacles to following this path in telecommunications. Today's horizontal industry structure makes many kinds of investment by an individual firm speculative. In addition, in telecommunications there is a general expectation for compatibility with prevailing standards, which makes it difficult for a firm to position itself many years ahead of its competitors. Research advances that lead to major innovative breakthroughs, new architectural approaches, and the like are thus especially valuable in responding to global competition.

Leadership for National Defense and Homeland Security

Two areas where U.S. interest in ensuring telecommunications leadership is clear are national defense and homeland security. Historically, U.S. technical leadership in commercial communications has extended to the military space, and at the same time a host of fundamental telecommunications technologies were developed to meet military needs. Examples of such DARPA-funded telecommunications advances are the Internet (from ARPANET), optical networking (from MONET), and ad hoc wireless networks.

In theory, the United States could deploy state-of-the-art networks using foreign-origin technology and supporting research. In practice, however, research, development, and deployment of the most advanced technologies tend to go hand-in-hand.

Without a continuing focus on telecommunications R&D, the United States will increasingly be forced to purchase technology and services from foreign sources. Several risks are evident: (1) U.S. dependence on foreign sources to meet critical defense needs; (2) loss of exclusive or early access to state-of-the-art communications technology; (3) loss of know-how to employ state-of-the-art technology; (4) opportunities for other nations to introduce security holes into equipment and networks; and (5) loss of technical capability for cyberdefense, such as cybersecurity, network assurance, and cryptography. Network trustworthiness is an especially important subject for public investment, given that it is a public good[7] in which individual firms tend to underinvest.

In a future conflict, an overseas telecommunications equipment supplier to the U.S. military could become an adversary, making a reliable supply of COTS products less likely. Another substantial concern with foreign COTS products involves vulnerabilities that might be designed into highly complex and sensitive communications systems that could be used or compromised later or in a time of war. The situation is far more complicated when it comes to specialized devices. Clearly, for the U.S. military to have an edge against an adversary requires systems that are better than what is available as COTS products.

Protection of critical infrastructure—which includes telecommunications networks—is an important element of homeland security. Today, U.S. telecommunications companies, in addition to providing voice and data communication services to customers via public and private networks, are also responsible for providing a large fraction of the telecommunications infrastructure used by government and the military. The requirement for greater sophistication in the protection of critical infrastructure is an immense and growing concern. The challenges include:

- Maintaining the security of today's voice network;
- Maintaining and improving network robustness in the face of the technical and operational convergence of the voice and data networks, an expanded number of competing network operators, the increasing size and importance of the Internet, the burgeoning rise in use of voice over IP applications, and widespread deployment of "always-on" broadband access technologies;
- Addressing a rising frequency, sophistication, and severity of cyber-attacks;
- Maintaining greater awareness of possible risks associated with using foreign-produced communications infrastructure or COTS products (as mentioned above); and
- Recognizing that the commercial market is motivated more by the quest for performance and features than by understanding of the need to ensure security and reliability.

[7]This general issue is discussed in more detail in an earlier CSTB report. See Computer Science and Telecommunications Board, National Research Council, *Computers at Risk: Safe Computing in the Information Age*, National Academy Press, Washington, D.C., 1991, p. 17, available online at <http://www.nap.edu/catalog/1581.html>.

Ensuring a Critical Mass of Talented Researchers

The early 21st century is a time of major change with respect to telecommunications—as legacy networks are being phased out and new networks are being phased in, and as pressures from overseas competition mount. Now more than ever, research will play a critical role in determining the future health of the entire U.S. telecommunications ecosystem. In the past, research support has contributed to the production of many talented technical leaders, and one essential component of any strong research system is the cohort of talented researchers involved. A healthy level of research support is vital for developing this talent pool and for maintaining and enhancing expertise in telecommunications.

Talent development in telecommunications generally is heavily supported by research funds as graduate students assist seasoned professors in research efforts. Inadequate research funding at this stage can complicate the ability of universities to attract or develop graduate students and their professors. Graduates have historically taken positions as postdoctoral researchers, often at major industrial research laboratories. At this stage, too, there is a need for research funding.

During the 1970s, 1980s, and 1990s, many new, talented Ph.D.s left major universities with detailed knowledge of a specific discipline and began work for industrial research laboratories, where they refined their skills, studied applications of forward-looking ideas, constructed prototypes, published papers, attended conferences, met the other experts in the area, and generally progressed toward being leaders in their field.

Assessment of the true impact of this model is very difficult to measure, but there is little doubt that it has been large. For example, many major telecommunications firms have histories that can be traced to individuals who worked at Bell Laboratories, Bellcore, BNR, IBM Research, Xerox PARC, Motorola, and others. Although the committee is unaware of systematically collected data on this point, anecdotal evidence suggests that the number of telecommunications industry leaders developed in this way is quite large.

With fewer research opportunities available in industry today, it is more difficult for new graduates to find opportunities to mature as researchers. The implications of this trend for sustaining a healthy pool of talent and expertise are significant. In today's start-up companies, former students are almost immediately thrust into product development. The opportunity for a period of exploration and intellectual growth is thus diminished and, as a result, young Ph.D.s may develop less insight into a technological area (while arguably gaining a better vision of the whole development process and increasing their chances of turning almost any decent strategy, technological or otherwise, into profitability).

Several universities have over the years introduced interdisciplinary programs in telecommunications that focus more on telecommunications as an industry rather than just basic communications technology (e.g., basic communications courses and research in modulation, coding, protocols, signal processing, and queuing theory) and also address attendant financial, structural, legal, regulatory, and technological issues. Those programs usually span such disciplines as electrical engineering, computer science, business administration, public policy, and law.[8] They generally offer master's or other professional degrees rather than doctoral

[8]The International Telecommunications Education and Research Association, which seeks to advance telecommunications science through excellence in research and education, has a dozen institutional members located at universities and colleges across the United States. See <http://www.itera.org/membership.htm>.

degrees and, in the experience of the committee, infrequently serve as a pathway into a career in telecommunications *research*.

As noted in other sections of this report, discussion of telecommunications issues must now be framed within the current context of global competition among numerous multinational organizations—and this is certainly the case with respect to producing and retaining talented researchers. As the developing world's educational institutions grow stronger, there is an increased capacity for leading-edge research and development work abroad. This growing educational capacity combined with improving worldwide telecommunications capabilities and lower wages in developing countries creates pressure for U.S. and other firms to move more of their research and development and other high-skill jobs outside the United States. In addition, as academic and industry research opportunities in the United States begin to lag those in other countries, foreign students who are studying in the United States will be more likely to return to their home countries and participate in the creation of telecommunication networks and services of the future there rather than in the United States.

The solution is for the United States to continue to innovate and ensure adequate research support and research opportunities, especially for younger researchers. Leadership in research and education is crucial for the maintenance of a technically literate workforce capable of filling all of the positions across the telecommunications ecosystem—including reliable software developers, application writers, engineers, systems engineers, researchers, teachers, and so on. If U.S. research remains at the forefront, U.S. students will be exposed to the next generation of technologies earlier than the rest of the world. However, the necessary leadership and an adequate level of talent for telecommunications research can be sustained only if a healthy U.S. university research system exists. Renewed investment and resulting opportunities will make it possible to attract, train, and retain the research talent required for the United States to maintain a strong position in telecommunications.

4

Mechanisms and Best Practices for Renewing Telecommunications Research

BEST PRACTICES FOR LONG-TERM RESEARCH INVESTMENTS

Several factors are cited by former Bell Laboratories researchers as having contributed to that lab's success with fundamental research. The context for telecommunications research has changed significantly since that time, but these fundamental lessons nonetheless have application today:

- *Stable research funding.* The concept of no major growth in boom times and no major cutbacks in bad times for the industry translated to consistent support for fundamental research. The result was a stability of funding and of growth that allowed long-term goals to be pursued.
- *Research that was limited only by ideas, rather than by resources*. This ideal was achieved by enabling highly talented individuals to pursue ideas until either success was achieved or it became obvious that the ideas would not work.
- *Research that was problem-driven*. Research was managed in the Bell System in accord with a clear and consistent mission informed by constant exposure to real technology (and business) problems and close coupling to the Bell operating companies. People working in fundamental research were made aware of the most pressing technical problems requiring revolutionary solutions. Such close coupling between research and operations enabled the transfer of new technology to practice.
- *Support for interdisciplinary research*. At Bell Laboratories, researchers spanned a broad range of disciplines from physics to economics and thus were able to tackle the cross-disciplinary problems that often arise in designing, deploying, and operating telecommunications systems.

It is, of course, extremely unlikely that this full set of conditions can be replicated in an industry research laboratory today. However, they can be seen as characteristics of the ideal academic environment for telecommunications research that can be factored into the design and management of both government- and industry-supported research programs.

THE IMPORTANCE OF COLLABORATION ACROSS ACADEMIA AND INDUSTRY

Researchers outside industry can be disadvantaged for some types of research by a lack of specifically necessary information or access to facilities that are crucial to a quality and relevant outcome. An example is a researcher leveraging network traffic statistics to define a superior protocol (what are realistic traffic models?), or a researcher defining superior mechanisms to manage network recovery from disaster (what are realistic assumptions about the scope of damage to the network?). In fact, as research becomes more immediately relevant it inevitably becomes more dependent on "inside" information and facilities. It is thus essential that industry seek to inform the research sponsors and performers as to their more critical long-term issues and opportunities that are amenable to research. Concerns about intellectual property in such collaboration can be addressed by having faculty researchers sign nondisclosure agreements that let them work with and understand the industrial context in depth but that also protect a company's intellectual property unless permission is granted by the company.[1]

Researchers themselves are also motivated to make an impact, and in most cases welcome and appreciate visibility into what the ultimate customers of the research—both industry and end users—see as their greatest need. Armed with that understanding, they can pursue their own ideas, some with more near-term and direct application and others more radical and speculative. This is not to imply that industry should define and direct both the research projects and the approaches that are pursued. Nor does it imply that all telecommunications-related research should tackle issues defined by industry. Researchers are more enthusiastic and ultimately more effective if they pursue their own ideas, and industry itself often fails to encourage or even recognize radical new innovations.

THE IMPORTANCE OF VISION

Past U.S. leadership in telecommunications has benefited from the creation and pursuit of a well-defined vision for managing investments. However, in today's telecommunications environment, which includes a broad array of service providers and equipment vendors, such a clearly defined and broad vision is much more difficult to achieve.

In the predivestiture Bell System, the development of a vision and associated roadmapping activities for the telephone system were carried out largely by AT&T (together with a small number of overseas telephone companies that were also vertically integrated monopoly providers). AT&T and its peers were successful in developing and realizing a series of major new visions—such as direct long-distance dialing, electronic switching, digital transmission and switching, and out-of-band signaling and intelligent network services (which separated service logic from switching equipment).

[1] There are also other ideas emerging regarding new means for collaboration; see, for example, Raymond E. Miles, Grant Miles, and Charles C. Snow, *Collaborative Entrepreneurship: How Communities of Networked Firms Use Continuous Innovation to Create Economic Wealth*, Stanford University Press, Stanford, Calif., 2005.

Significant vision-setting and associated design work have also been carried out in particular sectors of the telecommunications industry. The cable industry developed a new architecture—hybrid fiber coaxial cable—that allowed delivery of digital, two-way services over its networks. The wireless industry is now well into the deployment of a third generation of cellular services (which exist in several different flavors), each of which has supported greater capacity in terms of users and bandwidth per user, and has involved broad thinking about desired capabilities and the technological advances required to achieve them. Such efforts are generally considered to have been successful within the confines of individual industry sectors, but they have not addressed major architectural issues across these sectors.

Although individual segments of the industry have successfully pursued the rollout of new services, such as second-generation cellular or hybrid fiber coaxial cable television, the United States today does not have processes or forums for defining or implementing broader (cross-sector) visions or for establishing how much and what types of research are needed.

The situation stands in contrast to that in some other regions of the world where institutions and processes are in place to define and implement telecommunications visions (see the section "International Support for Telecommunications Research and Development" in Chapter 2). There are, to be sure, strong arguments on both sides of the debate over the benefits of planned and structured technological programs versus unstructured ones in which many individual firms can attempt to develop their ideas. Nonetheless, it is worth exploring further the role that vision-setting activities could play in fostering future telecommunications advances.

VISION FOR THE 21st CENTURY

A major shift occurred in telecommunications toward the end of the 20th century. A growing realization emerged that the PSTN was not an efficient and cost-effective way of moving large amounts of data over a network. The basic insight was that packet-based networks could statistically multiplex data (including real-time voice and video) over a best-effort data network and still achieve high performance, universal connectivity, and reliable data transport. The Internet, which is really just an interconnection of hundreds of thousands of such packet networks, has proved this idea on a wide scale and has become the model for telecommunications in the 21st century. This breakthrough arose in an environment in which DARPA leadership, vision setting, and funding allowed research, development, and early deployment and operation to be performed by a diverse yet small and tightly knit community in an environment relatively free of commercial concerns.

The promise of the Internet is the ability to bring unlimited bandwidth and computational power to every home, office, and even to individuals who are highly mobile, thereby enabling people to remain in constant contact with other people and with information of virtually any form. Hence one formulation of a big-vision problem for the 21st century would be something like "Universal Broadband Connectivity—Anywhere, Anytime." But who will espouse this (or an appropriate alternative) vision, who will champion it through the regulatory and standardization bodies, who will invest in the necessary array of technologies, and who will work through the details associated with designing, implementing, and deploying products and services? In contrast to some other regions of the world (most notably Korea and Japan in Asia and various European nations), neither U.S. industry nor the U.S. government has a clearly defined, forward-looking vision for telecommunications, and more importantly, no process in place to define and implement such a vision. The consequence of this lack of vision is that the necessary complementary investments that should be made by the semiconductor houses, the equipment vendors, and the service providers—all in support of a vision held in common—may not be made because of the risk of investing in areas that are not supported across the telecommunications industry.

The most successful visions will originate not only from new technological capabilities, but also from commercial and societal need. Execution of a vision requires not only the design and implementation of technology but also coordinated activities by regulators and government and industries such as those that finance the ventures. Thus it is important that not only industry, but also the brightest minds in academia and government and regulatory agencies be active participants. Also, although a U.S. vision would focus on the future of U.S. telecommunications applications and supporting infrastructure and services, the global range of both networks and technology supply chains means that coordination with global vision-setting efforts is essential.

Without a clear vision in place, the risk is that the U.S. telecommunications industry will take a "wait and see" approach and make as few risky investments as possible until a de facto vision is defined externally, either in the global telecommunications community by the few countries that take leadership roles, or by the international standards bodies (which in the absence of other leadership provide the de facto roadmaps for the introduction of new technology). Either path could have negative long-term effects on the U.S. economy if leadership in telecommunications moves to Asia and Europe and the United States has to play the role of a fast follower—a role to which we are generally unaccustomed.

ROADMAPS

The path through which new technologies are introduced varies considerably across different industries. Sometimes, an innovation can be made based on a small, local, granular investment. But more often, an advance requires complementary work to be done in a variety of areas by a variety of actors.

In the semiconductor industry, for example, the effort to bring ever-faster processors to market requires an entire industry to move together. Fabricators must make enormous investments in new manufacturing facilities, tooling companies must move to a next generation of fabrication processes, and microprocessor manufacturers must be convinced that a more powerful system will sufficiently expand the market to justify the investment.

Roadmapping is a process to address these complementarities. The semiconductor industry, for example, is guided by two fundamental elements. First, there is the semiconductor industry's International Technology Roadmap for Semiconductors (ITRS),[2] a mechanism that allows all players to move to the next generation of technologies and practices smoothly and simultaneously.[3] The ITRS identifies the short- and long-term technological challenges and needs facing the semiconductor industry. It is sponsored by the U.S.-based Semiconductor

[2]See <http://public.itrs.net/>.

[3]For another overview of the semiconductor roadmap, see Bill Spencer, Linda Wilson, and Robert Doering, "The Semiconductor Technology Roadmap," *Future Fab Intl.*, 18, January 2005, available online at <http://www.future-fab.com/documents.asp?d_ID=3004>.

Industry Association (SIA), the European Semiconductor Industry Association, the Japan Electronics and Information Technology Industries Association, the Korean Semiconductor Industry Association, and the Taiwan Semiconductor Industry Association. In addition, SEMATECH (described in more detail below) acts as the global communication center for the ITRS, and the ITRS team at SEMATECH coordinates events in the U.S. region. Second, the industry benefits from the insight provided by more than 20 years' experience with the successful introduction of new technologies and products—insight that assures manufacturers that each expansion in capability will result in an expansion of market.

An industry roadmap is, in essence, a strategic plan for an entire industry, undertaken as a precompetitive industry collaborative activity, that informs the need for specific research directions, identifies necessary complementary investments across the horizontal industry that spans semiconductors to applications and content, and identifies related policy issues. It recognizes that the industry is characterized not only by competition of like companies (like service providers in the same geographical region), but also by non-competitive complements (like semiconductor manufacturing equipment and fabrication facilities, or telecommunications transmission facilities and the applications making use of them) where some level of precompetitive coordination can greatly reduce investment risks for all participants without interfering with competition or negating its benefits. A good roadmap is not overly prescriptive, however, and only does what is necessary to ensure success of the industry as a whole and no more, and leaving as much as possible to market choice.

Roadmaps are already used in segments of the telecommunications industry. For example, the Optoelectronics Industry Development Association produces a roadmap covering optical components and, to some extent, optical communication systems. Also, various segments of the industry and individual firms have carried out efforts to define and develop new architectures, including the cable industry (which has deployed hybrid fiber coaxial cable and which is pursuing voice over IP) and both the cable and telephone companies (which are pursuing a variety of strategies for deploying fiber to the home and the "triple play" of video, Internet, and phone services).

Broader roadmapping activities for telecommunications would be somewhat different from those for the semiconductor industry—the issues are more complex and involve more interdependencies. There are a large number of potential actors. Delivering a new set of services on a new telecommunications infrastructure may require the cooperation of many component providers, system vendors, application developers, and service providers. The service providers themselves—including incumbent local exchange carriers, competitive local exchange carriers, cable multiple system operators, cellular carriers, and wireless service providers—cover a wide range of interests, regulatory status, and geographical coverage. Moreover, with telecommunications spanning all layers from physical infrastructure to applications and content, investment decisions may involve content providers in addition to service providers. However, the basic idea is still relevant that processes and forums get people thinking about the longer term, and in a more coordinated way.

Roadmapping should not be mistaken for a definitive path that a technology or industry must follow. A roadmap certainly does identify certain technologies and applications that are important or even necessary for growth of an industry as a whole, and it identifies the complementary investments (and staging of those investments) necessary for industry progress. However, a roadmap often incorporates alternative scenarios that might ultimately be successful, and does not try to pick which might finally be accepted. Roadmaps often explicitly attempt to leave as much freedom as possible for individual companies to differentiate themselves at the competitive stage—only doing what is necessary to ensure success of the industry as a whole and no more, and leaving as much as possible to the discretion of market choices.

Roadmapping requires broad participation and sustained, significant investment. Undertaking an industry-wide roadmap is likely to be a costly and time-consuming task if it is done well and has broad support and participation. Roadmaps are also living documents that must be updated as circumstances change.

The environment for telecommunications investment is also shaped by legislative and regulatory decisions. The overall framework for the telecommunications industry as a partly regulated industry has long been the subject of specific legislation. Implementation of this legislation is carried out through ongoing regulatory proceedings. Both factors contribute to the uncertainty surrounding new, long-term infrastructure investments.

Another piece of the roadmapping puzzle is the set of standards organizations. Equipment vendors move directly from the standards organization to implement the ideas into products, often even concurrently with the standards negotiations. Here U.S. companies have been leaders recently in setting the standards in some organizations such as the Internet Engineering Task Force. Standards are also developed through organizations such as the Institute of Electrical and Electronics Engineers and the International Telecommunication Union. Today there are new standards organizations (e.g., Chinese efforts to establish unique versions of CDMA; 4G standards coming out of Japan) in which the United States has not been playing as strong a role.

A more vertical structure to the telecommunications industry, greater government involvement, or a history of collaboration have made roadmapping a more central part of telecommunications programs outside the United States, accompanying the broader involvement of governments in directing technical developments and infrastructure deployment. Policies in Korea have long emphasized the deployment of broadband infrastructure. In the European Union, collaboration that begins at the research level through the framework programs establishes an early set of partnerships among countries, service providers, manufacturers, and other participants in the value chain. In Europe, these efforts have extended much further—to later standardization of the actual new architectures, as was the case with the GSM wireless system.

In contrast, the United States tends to rely heavily on market forces and has a philosophy that lack of central control spurs innovation—and these arguments certainly carry considerable weight. Yet, it may well be possible to make use of roadmapping without unduly inhibiting innovation, nor does roadmapping necessarily imply the heavy hand of government. Certainly the semiconductor industry is widely viewed as having benefited from following that path.

Roadmapping and Research

There are several ways in which roadmaps can help focus and enhance the impacts of research.

First, roadmaps can add predictability to infrastructure deployments. An invention in one part of a value chain has impact only if an industry consensus across many different types of companies motivates each to do its share. The absence of any roadmap makes this consequence doubtful. The result: no motivation to invest in research.

Second, roadmaps can enhance the impact of short- to medium-term research. A component maker might create a much better device, but unless the vendor incorporates the new device in its products, the service provider uses it to improve service, and the customer likes the feature, there is no guarantee that it will be used.

Third, roadmaps can help enable disruptive system-level research. Disruptive change in technology often requires upsetting the role that each company plays in a value chain. To successfully develop such architectures requires an interdisciplinary approach, namely diverse participants that bring different perspectives to the table. To get system-level insights frequently requires cross-company cooperation, which is difficult.

An interesting example is the DARPA-funded MONET program of the mid-1990s. In this cross-company and university consortium, the teams used the opportunity to invent much of the advanced optical technology that had an impact on the industry in the late 1990s. Here the U.S. government played an important convening role, aside from providing the funding.

Although opinions vary as to the ultimate effectiveness of the program, the European Union Sixth Framework Programme for telecommunications research provides an example of how research and roadmapping interrelate. The structure of the research projects anticipates the ultimate creation of an infrastructure. Each program involves a variety of players, including component manufacturers, system vendors, software firms, universities, and service providers. As a result, companies can better evaluate the impact of their technology, and several players in the industry can plan new beneficial roadmaps together.

Advantages and Disadvantages of Telecommunications Roadmapping

To summarize, roadmapping processes could help the telecommunications industry address several critical issues:

- *Ensuring complementary progress in the underlying core technologies.* Such a roadmap, which would address physical-layer communications, computing, and storage technologies, has striking similarities to the semiconductor industry's roadmap.
- *Enhancing intermodal and end-to-end interoperability*. Issues include architecture and functional interoperability across vendors, equipment types, and geographic regions.
- *Identifying and exploring complementary elements required for realizing a vision.* For example, interactive broadband multimedia applications depend on complementary investments by distinct industry segments including applications (software industry), compelling content (the video game, music, and movie industries), the network and access to broadband connectivity (the telecommunications service provider industry), and customer premises equipment (computer and consumer electronics industry).
- *Identifying knowledge gaps.* Obvious gaps include technology or manufacturing processes. Other knowledge gaps include economic viability (e.g., building ubiquitous broadband access facilities) and the viability of the market opportunity (e.g., how much customers would be willing to pay).
- *Identifying complementary policy, legal, and regulatory considerations.* Roadmapping can also be used to identify needed changes in the legal or policy framework (e.g., telecommunications policy or intellectual property rights) and needed regulatory initiatives and their viability (e.g., policies relating to spectrum use or broadband deployment).

On the other hand, roadmapping is not a panacea and brings with it a number of tradeoffs and possible limitations. For example, the roadmapping process could hinder the adoption of new, disruptive technologies (e.g., incumbents may be unwilling to try radical innovations). It also should be recognized that there is quite a leap from agreement on an element of a roadmap to a commitment to purchase a product.

MECHANISMS FOR INDUSTRY, GOVERNMENT, AND UNIVERSITY COLLABORATION ON R&D FUNDING

A variety of interesting models for mobilizing research and development support have developed to answer particular R&D needs. CableLabs, described in Chapter 2, provides an example of a telecommunications sector organizing itself to address the focused needs of a particular set of stakeholders.

Experiences from the electric power and semiconductor industries provide additional examples of how industry or industry in combination with the federal government can come together to address critical research needs:

- *Electric Power Research Institute.* In 1971, U.S. public and private utilities created an organization to conduct electricity-related R&D. Under pressure from Congress (which had signaled in hearings that it might call on a federal agency to play this role), the Electric Power Research Institute (EPRI) began work in 1973 as a private, nonprofit organization to provide clear, credible scientific and technical research. Today, EPRI's members represent over 90 percent of the U.S. electricity research community, and the organization maintains a member-driven annual budget of around $272 million. The majority of EPRI's members are investor owned, but the organization's membership also includes international organizations, and it classifies roughly 7 percent of its members as "federal/state" (e.g., the Tennessee Valley Authority, California Energy Commission, and so on).
- *Semiconductor Research Corporation.* The Semiconductor Research Corporation (SRC) was created in 1981 with the help of the Semiconductor Industry Association (SIA) to stimulate cooperative research into semiconductor technology by industry and U.S. universities. SRC was funded by member companies through fees based on their semiconductor sales and other factors. Early 1982 saw the newly incorporated SRC lining up a number of industry and university partners, and by 1983 SRC could count as members nearly 30 universities and such industry heavyweights as, among others, AMD, DEC, Honeywell, Intel, IBM, Motorola, GE, Harris Corp., and HP. SRC's 1983 budget was approximately $11 million—primarily industry funding—and since it was established SRC has funded more than $500 million in long-term semiconductor research. SRC has also established partner relationships with other institutions such as NSF and SEMATECH.
- *SEMATECH.* In 1987, 14 U.S. semiconductor companies joined forces to create a nonprofit research and development organization called SEMATECH to improve domestic semiconductor manufacturing. A year later, Congress—worried about the increasing U.S. dependence on foreign suppliers for semiconductor technology—appropriated $100 million per year for 5 years to match SEMATECH's industrial funding. The federal funding for SEMATECH was channeled through DARPA because semiconductor manufacturing was seen as vital to the nation's defense technology base. DARPA continued its investment in SEMATECH beyond the original deadline, but in 1995 SEMATECH announced that it would wean itself from

public assistance and seek an end to matching federal funding after 1996 as a result of the renewed health of the U.S. industry. A critical element of SEMATECH's program over the years has been the development and refinement of a technology roadmap for the semiconductor industry. Reflecting the value of its work, SEMATECH has since grown and expanded to include significant international participation.[4]

The National Science Foundation has also established programs for collaborative engineering research among academia and industry. Chief among these is the Engineering Research Centers program[5] that was established in 1985 to support cross-disciplinary, systems-oriented research between academia and industry, education and outreach, and technology transfer. The engineering research centers (ERCs) have supported research on a range of subjects from bioengineering to earthquake engineering to microelectronic systems and information technology. Fiscal year 2004 total annual funding from all sources provided directly to each ERC ranged from $3.1 million to $11.3 million, with NSF's contribution ranging from $2.5 million to $4.0 million per year.[6]

NSF also administers the Industry University Cooperative Research Centers program,[7] which aims to use limited NSF investments to stimulate industry-academic research partnerships with the bulk of the support coming from industry center members. Focus areas for centers in this program include advanced electronics, advanced manufacturing, civil infrastructure systems, information and communications, and system design and simulation, among others. In the past, some work coming out of this program has been very telecommunications specific. For example, in 1997 a professor at a communications-related center founded a company to design a new switch capable of applying his algorithms for maximizing quality of service. After 3 years of work, this company was acquired for nearly half a billion dollars.[8]

ESTABLISHING AN ADVANCED TELECOMMUNICATIONS RESEARCH ACTIVITY

The committee believes that a hybrid approach is best suited to the challenges facing the telecommunications industry. Such a hybrid, dubbed the Advanced Telecommunications Research Activity (ATRA) in this report, would (1) draw in part on the strengths of the DARPA model in enabling creative, often risk-taking research under the direction of a lean, agile, and independent cadre of program managers that would include researchers from both industry and academia; (2) draw on the strengths of the industry-driven models represented by SEMATECH, SRC, and EPRI to ensure significant industry participation and buy-in; and (3) reflect the collaborative, multidisciplinary research model in the NSF Engineering Research Centers program. Most research would be performed externally at universities and other research institutions; in-house research might be appropriate in specific areas.

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[4] A more detailed history of SEMATECH is available in Computer Science and Telecommunications Board, National Research Council, *Funding a Revolution: Government Support for Computing Research*, National Academy Press, Washington, D.C., 1999, available online at <http://newton.nap.edu/html/far/>, p. 129.

[5] See <http://www.erc-assoc.org/> for complete information.

[6] As reported at <http://www.erc-assoc.org/factsheets/overview.html>.

[7] See <http://www.nsf.gov/eng/iucrc/>.

[8] As reported at <http://www.nsf.gov/eng/iucrc/directory/overview.jsp>.

Industry funding would represent a significant fraction of total funding, and industry researchers would be deeply involved in research activities. Further, to ensure that ATRA is responsive to industry needs, one or more advisory committees would be established with representatives from equipment suppliers and service providers. Additional advisory committees might be established to address individual major technology areas (e.g., optical and wireless communications or network security) or the interplay between technology and regulatory developments.

The new research organization's multifaceted mission would include the following:

- *Identifying, coordinating, and funding telecommunications research for the nation.* The focus would be critical telecommunications research in which the nation is currently underinvesting, including (1) long-time-horizon speculative research that seeks to explore transformative new ideas; (2) precompetitive research that seeks to turn both incremental and transformative ideas into practice, suitable for others to exploit commercially; (3) long-term and precompetitive research on network trustworthiness, when commercial incentives are insufficient to motivate research to make the nation's critical infrastructure more robust; and (4) interdisciplinary research at the intersection of technology, economics, and policy, including work that studies the technical, economic, and sociological issues underlying regulatory decisions.
- *Fostering the conception, development, and implementation of major architectural advances.* Major advances in telecommunications capability—such as direct long-distance dialing, hybrid fiber coaxial cable systems, or the Internet—have all required the conception, development, and deployment of novel network architectures. Similar advances in the future depend on carrying out sustained research and development activities.
- *Strengthening the nation's telecommunications research capacity* by building up research groups, centers, and other institutions with sufficient scale and breadth of expertise to tackle real-world problems and by strengthening connections between the industrial and academic communities and among the telecommunications, semiconductor, and computer segments of the IT industry. To provide major experimental facilities useful to but beyond the capabilities of individual university research groups or firms, an infrastructure for fabrication, prototyping, and testing would be supported as needed. To facilitate research and development on large-scale problems, such as end-to-end interoperability testing or network security and reliability, major facilities for experimentation would be supported as needed.

Options for Locating the New Telecommunications Research Activity in the Federal Government

ATRA could be established simply by supplementing the mission of NSF or DARPA, but it might be preferable to create it as a standalone activity. NSF is largely focused on enabling fundamental breakthroughs and stimulating a wide diversity of activities rather than addressing problems with an explicitly industry focus, although its Engineering Research Centers program is a possible model. DARPA today focuses more on military applications and appears unlikely to sponsor a major activity aimed at challenges and opportunities of a predominantly commercial nature.

Another possible home for such an activity is the Department of Commerce, which already conducts research and standards activities through the National Institute of Standards and Technology (NIST) and which supports some telecommunications research through the National Telecommunications and Information Administration's (NTIA's) research and engineering branch, the Institute for Telecommunications Sciences, which is noted, for example, for its work on radio propagation. NIST has a long track record of working with industry on problems of interest to industry and a long tradition of research on IT and telecommunications problems. NTIA's mission centers around telecommunications, and it has a research program, albeit much smaller and narrower than the activities recommended here.

TOWARD INCREASED INDUSTRY SUPPORT FOR TELECOMMUNICATIONS RESEARCH

Research that seeks fundamental breakthroughs in communications services and applications or seeks to define new service architectures and transition strategies may not necessarily benefit any one company exclusively, but companies that have made more strategic or rapid research investments stand to benefit as new capabilities are developed and deployed in the industry. The committee believes that the U.S. telecommunications industry should certainly increase its support for more fundamental, cooperative, breakthrough research—although the committee also understands that the issues involved in doing so are complex. For example, a primary obstacle to overcome is "free-riding" (a concept described in more detail in Chapter 2), whereby any one company can benefit from the freely available results of research even while failing to contribute to it. A solution might be the use of mechanisms for sharing resources and responsibility for research across the industry, as an alternative to conducting proprietary research within each carrier. Another way to encourage service provider participation is for government to provide matching funds or other incentives such as R&D tax credits.

One avenue for increasing industry support for fundamental research would be participation in joint, cooperative research activities organized by ATRA and funded jointly by industry and government whereby industry could pool funds, spread risk, and share beneficial results through cooperative efforts between industry and academia. Another option is cooperative resource sharing. An example is a shared-responsibility research program conducted not long ago by the regional Bell operating companies through Bellcore, which they owned jointly. However, as the companies began to compete with one another, they divested Bellcore. In contrast, the proposed ATRA would not be subject to the same pressures because it would be led by the federal government rather than a board made up of competing firms.

An organization such as Bellcore can provide a forum for research and development work that spans multiple service providers and addresses issues offering little potential for companies to distinguish themselves individually and thus little incentive to invest; for certain activities, significant savings from centralization and economies of scale and scope; and opportunities for conducting end-to-end interoperability testing across equipment manufactured by different vendors that otherwise would entail an investment in equipment too expensive for individual research groups.

Examples from other industries of creative cooperation show that, provided care is taken in the type of research conducted (e.g., keeping the time horizons long and focusing on major architectural advances), the outcomes can be mutually beneficial to the industry as a whole while not harming the chance to compete vigorously in current or nearer-term business opportunities. Examples of simultaneous cooperation and competition ("co-opetition") can be found in such diverse organizations as SRC, SEMATECH,[9] and EPRI and in standards development groups organized by the Internet Engineering Task Force, the Institute of Electrical and Electronics Engineers, and the Telecommunications Industry Association.

[9]William J. Spencer and Peter Grindley, "SEMATECH After Five Years: High-Technology Consortia and U.S. Competitiveness," *California Management Review*, 35(4):9-32, Summer 1993.

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Findings and Recommendations

Providing a capability for overcoming barriers of distance and time, telecommunications is an essential element of the infrastructure for operation of the U.S. economy and society. Many U.S. companies—indeed whole new industries—have benefited from and even developed as a result of U.S. strength in telecommunications. Notably, the modern Internet and Internet-based businesses ranging from Cisco to Yahoo! would not have been possible without past telecommunications research leading to such advances as high-speed optical communications and packet-switched networks.

Today, however, the position of the United States as a leading producer of telecommunications technology, basic knowledge, and necessary human talent (a critical component—as described in Chapter 3) is at risk. The risk is magnified by the long period of time—as much as a decade or even longer—that it can take to translate a fundamental discovery or big new idea into a commercial product or service or to educate and train a new researcher.

The committee's findings below outline challenges to the telecommunications sector's continuing capacity for innovation. The recommendations that follow identify actions that the U.S. telecommunications industry, research community, and government should take together to strengthen the nation's telecommunications research institutions and programs.

FINDINGS

Finding 1. The scope of telecommunications technology and of the industry itself has grown dramatically over the past few decades, driven primarily by the success of the Internet and its applications, by the digitization of all types of media and forms of communication, and by the rising importance of communications as a key enabling technology.

The telecommunications industry, which once consisted mainly of the telephone companies and their equipment vendors, has expanded greatly. It now includes a broad set of service providers, including telephone companies, cable operators, Internet service providers, and wireless carriers, as well as equipment vendors offering fiber-optic, cable, and wireless connections. Telecommunications comprises all the hardware and software for the telecommunications infrastructure and the applications that run over that infrastructure. It involves communication of information in a wide array of media including voice, images, animation, video, documents, and data.

Finding 2. Without a renewed and sustained investment in telecommunications research, the United States risks losing global leadership in telecommunications and related industries, with significant consequences for the U.S. economy and society.

Should the United States be concerned if leadership in telecommunications moves offshore, as has occurred for many other entire industries? The recent fast pace of innovation, the array of new ideas to be pursued, and the substantial investment in telecommunications by other nations are all indications that telecommunications remains a high-value sector in which rapid innovation and fundamental change will continue well into the future. Far from a mature industry, telecommunications is thus one in which the United States should strive for continuing leadership. The importance of maintaining U.S. leadership is underscored by telecommunications' critical contribution to U.S. leadership in information technology in general, its important contribution to improving productivity in nearly all industries, and its role in national security and homeland defense.

Finding 2.1. The United States faces strong and growing competitive pressures from nations that are making significant investments in telecommunications R&D.

Nations such as China, Japan, Korea, and member states of the European Union have identified telecommunications as a strategic area for economic development and have launched a variety of initiatives to enhance academic, industry, and joint industry-academic research in accord with vigorously promulgated national visions. Equipment vendors in a number of countries (such as China) now compete strongly with U.S. firms and have been very successful in emerging markets. Some nations' active support for their domestic industries has extended beyond investment in research to include measures for protection of domestic telecommunications industries, thus placing further stress on the U.S. telecommunications industry.

Finding 2.2. The health of the U.S. telecommunications sector depends on maintaining leadership in innovation.

Telecommunications products and services generally become commoditized over time as multiple firms acquire the know-how to supply similar, competing products, and such competition has benefits in terms of lower prices for goods and services. To maintain leadership—or even a strong position—in telecommunications in the face of pressures from lower costs overseas for labor and other essentials thus requires that U.S. firms constantly focus on achieving high-value innovation as a foundation for developing non-commodity products and services. Research leadership in telecommunications by U.S. academic research institutions and government and industry labs has historically given the nation an advantage in terms of access to new technologies and the highest-caliber engineering talent.

Notable benefits have accrued to the United States as a result of its leadership in defining the Internet's design, for example. However—by virtue of its very success—the existing Internet architecture has become difficult to change. Despite many potential avenues for significant improvements in areas ranging from security to real-time audio and video transmission, research and development has become largely incremental in nature. Moreover, the current architecture is largely commoditized, and firms from other nations will become increasingly able to deliver competitive products and services. Research aimed at defining future architectures promises particular benefits because U.S. firms will be positioned to offer new kinds of services and not just incremental improvements to existing ones.

Finding 2.3. Without renewed investment and resulting opportunities to do research, it will be very difficult to attract, train, and retain the research talent required for the United States to maintain a strong position in telecommunications.

Sustaining a base of researchers and research institutions is critical to the long-term health of a research discipline. Without adequate research funding, it will be hard to attract new students to the field, retain foreign students in the United States, provide critically needed support for postdoctoral researchers, or attract and develop new faculty and industrial researchers.

Finding 2.4. U.S. critical infrastructure, national defense, and homeland security, which depend on having uninterrupted access to leading-edge telecommunications technology, are potentially threatened by the loss of a domestic telecommunications industry.

Without a continuing focus on telecommunications R&D, the United States will increasingly be forced to purchase telecommunications technology and services from foreign sources. Risks include (1) U.S. dependence on foreign sources of technology to meet critical defense needs; (2) loss of exclusive or early access to state-of-the-art communications technology; (3) loss of know-how to employ state-of-the-art technology; (4) opportunities for other nations to introduce security holes into equipment and networks; and (5) loss of technical capability for cyberdefense in such areas as cybersecurity, network assurance, and cryptography.

Finding 3. Investment in telecommunications research yields major direct and indirect benefits.

Finding 3.1. U.S. telecommunications research has yielded tremendous direct and indirect returns.

Notable payoffs from U.S. investment in telecommunications research and related areas in recent decades include the following:

- *The Internet*, which realized a new communications paradigm, introduced a new, highly flexible network architecture and protocols, and ultimately enabled myriad new applications and services;
- *Radio-frequency communications* technologies for cellular systems and wireless local area networks, which have enabled modern mobile voice and data communications;
- *Optical networks*, which have revolutionized communications by providing extraordinary communications bandwidths at very low unit cost; and
- *Voice over IP (VoIP),* which provides voice communications with enhanced flexibility and efficiency and has provided opportunities for innovation in applications beyond those provided by the public switched network.

Additional examples are provided in Chapter 3.

Finding 3.2. There are many promising avenues for telecommunications research, and renewed U.S. investment would yield major dividends, as indicated by the following possible results:

- An enhanced Internet architecture that goes beyond incremental improvements to deliver capabilities such as greater trustworthiness in the network core and in customer networks, improved addressing and routing, and end-to-end quality-of-service provisioning;[1]
- More trustworthy networks that can better cope with the rising frequency, sophistication, and severity of attacks and the complexities and interdependencies associated with the convergence of voice and data networks;
- Telepresence and telecollaboration environments that reproduce at a distance a local space with the fidelity needed to allow people to work in concert;
- Public safety networks that offer greater mobility, interoperability, adaptability to harsh and changing conditions, and increased resiliency to damage; and
- Adaptive and cognitive wireless networks that enable higher-performance communications and more efficient use of radio spectrum, allowing them to provide capabilities that rival and complement those associated with wired networks.

Additional examples are provided in Chapter 3. As in the past, the biggest payoffs may well come from unanticipated breakthroughs achieved in the course of pursuing such challenging problems.

Finding 3.3. Telecommunications research carried out on behalf of the telecommunications industry can have a powerful payoff for all members of the industry.

Because the value of a network grows with the number of its users, network operators will seek to make their networks interoperable with those of other operators. Interoperation requires some degree of common technology, which means that many network innovations cannot be appropriated by a single player.

Finding 4. Over the past two decades, U.S. telecommunications research has been adversely affected by the level of research investment and the decreasing time horizon of research.

The erosion of telecommunications research in industry mirrors, to a certain extent, broad cutbacks in U.S. industry R&D in general. The impact has been significant, underscoring the historical importance of industry research and mirroring the rapidity of the telecommunications sector's restructuring following divestiture in 1984. The problems were obscured during the time of the Internet bubble, which saw a surge of telecommunications-related investment, but became quite apparent when the bubble's bursting led to a dramatic decrease in telecommunications research investments in 2001 and beyond.

Finding 4.1. Historically, the Bell System played a leading role in long-term, fundamental telecommunications research in the United States.

The Bell System maintained a large research program and talent pool and ensured a flow of ideas and innovation across disciplines and among the research, business, and operational divisions of AT&T. It supported an infrastructure that nurtured successive advances in the

[1] For a recent overview, see David Talbot, "The Internet Is Broken," *Technology Review*, 108(11):62-69, December 2005-January 2006, available online at <http://www.technologyreview.com/infotech/wtr_16051,258,p1.html>.

development chain from device fabrication to systems design to implementation and operation. It also provided a nucleus for the telecommunications research community. Because of the Bell System's historical ability to conduct so much research in-house, however, the federal government did not emphasize support for academic research in telecommunications or otherwise encourage academia to address problems important to the telecommunications industry. University researchers themselves tended to concentrate on research areas more amenable to work by individual investigators or small research groups, such as semiconductors, communications theory, and signal processing, leaving to industry research related to the design and operation of large-scale communications networks. Notable exceptions, such as computer networking research supported by the Defense Advanced Research Projects Agency (DARPA) and NSF (which led to the Internet), illustrate the enormous potential payoff from government-supported and university-based research on new architectural ideas.

Finding 4.2. In the wake of divestiture in 1984 and industry restructuring that followed, industry support for telecommunications research has declined and has also become less stable and more incremental and short-term in outlook.

The U.S. telecommunications industry's transformation reflects both the series of breakups of the Bell System (divestiture and subsequent reorganization and spin-offs) and the entry of new, non-vertically-integrated telecommunications firms such as cable system operators, Internet service providers, and wireless carriers.[2] At the same time, new, often Internet-focused companies have also introduced products and services that help account for the broadening scope of telecommunications referred to in Finding 1.

Some had hoped that the former Bell constituents (Lucent Bell Labs, Bellcore, and AT&T Research) could sustain a high level of long-term, fundamental research investments, but this proved impossible given the profound changes occurring in the industry. The telephone companies, facing growing competition, all but eliminated long-term, fundamental research programs, leaving responsibility for technological innovation to their equipment vendors. New telecommunications operators in cable, wireless, and digital subscriber line (DSL) services, lacking dominance and a high-margin foundation, generally adopted the same approach. The cable industry launched its own cooperative research and development activity, CableLabs, which focuses on such matters as standards development and conformance testing and does not support a broad, long-term research program.

An important drawback of the vendor-based research paradigm is that it is much more susceptible to economic cycles than is carrier-based research support, because vendor revenues are linked to the rate of carrier capital expenditure, which has tended to fluctuate and then fell sharply in recent years, rather than to subscriber fees, which tend to be more stable.

It is notoriously difficult to compile definitive data on support for industry research and development, but the situation described in testimony to the committee is clear—industry support for telecommunications research has decreased (as measured in dollars, numbers of researchers, and publications), and the work that is funded now has become increasingly

[2]Recently, there have been several mergers between what were historically local exchange carriers and interexchange carriers, leading to greater vertical integration—but not integration between service providers and equipment vendors.

short-term in focus—evolutionary rather than revolutionary—at a time when global competitors of the United States have placed a priority on long-term research in this area. Anecdotal reports indicate that basic research scientists in industry are being shifted to development work and that publication by industry researchers in telecommunications journals has decreased.

Finding 4.3. In many critical technology areas, industry can look to the federal government to help support fundamental long-term research. Despite the decline in funding for research following the restructuring of the Bell System, however, the federal government did not assume this traditional funding role for telecommunications, thus contributing to the current gap in support for long-term telecommunications research.

With industry having played such a large role in U.S. telecommunications research before divestiture in 1984, the federal government's research investment in telecommunications was understandably small compared with its investment in other areas of information technology or in other industrial sectors. Long-term concerns similar to those now faced in the telecommunications sector prompted the establishment of research organizations for the semiconductor and power industries, with the implicit or explicit participation of government. Indeed, the current situation in telecommunications is somewhat analogous to the crisis faced by the U.S. semiconductor industry in the 1980s, when international competition and decreased R&D funding threatened that industry's long-term viability. In response, the Semiconductor Research Corporation and SEMATECH were formed. Their work is widely credited with having played an important role in the recovery, renewed leadership, and long-term viability of the U.S. semiconductor industry (more information on SEMATECH and related efforts can be found in Chapter 2). Notably, there have been no parallel systematic efforts—either government- or industry-led—for telecommunications.

Finding 5. In today's telecommunications landscape, major architectural innovation is difficult to achieve.

The greater difficulty today in achieving architectural innovation involves several factors. Multiple visions are now being pursued by various segments of the telecommunications industry, and although an increased diversity of players provides more fertile ground for new ideas, it also makes widespread deployment of good ideas more difficult. Moreover, no single entity is able to appropriate the results of long-term, fundamental research or to comprehensively address the engineering and standardization issues associated with end-to-end solutions that must span multiple service providers and multiple sectors of the industry. The research that can be conducted by a single vendor or sector is less well positioned to tackle end-to-end issues, and the need to coordinate decisions among a multitude of players greatly complicates achieving major new architectural advances. As a result, vendors tend to favor incremental improvements to today's networks over more fundamental and high-risk research that seeks major advances in new or enhanced end-to-end applications and services and the architectural innovation that supports them.

Finding 6. The roles of NSF (the largest overall federal sponsor of information and communications technology research) and DARPA (a traditionally important sponsor of telecommunications research) have been evolving, with implications for telecommunications research.

Finding 6.1. Long a supporter of networking research and network deployment, NSF is moving toward a more strategic emphasis on telecommunications research.

Although NSF's Computer and Information Science and Engineering (CISE) directorate has long supported a networking research program, its Engineering (ENG) directorate supports research in such areas as wireless communications, and several of its engineering research centers have addressed telecommunications, these efforts have not reflected a comprehensive, coordinated research strategy. Modest funding for telecommunications programs has also been accompanied by a reportedly small and shrinking proposal acceptance rate.

The creation in 2004 of CISE's Network Technology and Systems (NeTS) program, however, represents an increased emphasis on telecommunications research at NSF. The new program spans a wide range of research topics in the control, deployment, and management of future networks and provides a framework for interdisciplinary work. Still in development as of this writing, the new Global Environment for Networking Investigations (GENI)—aimed at the exploration of new architectural ideas in experimental facilities that allow investigation at large scale—would represent a major initiative in this area.

Finding 6.2. DARPA's support for telecommunications research is now focused more on meeting specialized military needs than on stimulating broader technology advances of use for both commercial and military purposes.

DARPA-sponsored research has led to many significant telecommunications advances in such areas as packet-switched networking, development of ARPANET and the Internet, optical communications, and ad hoc radio networks, as well as to the establishment of successful U.S. telecommunications companies that are now global leaders, including Broadcom, Rambus, and Aetheros. In addition, DARPA has historically played an important role in promulgating visions that stimulated commercial development and adoption of new technologies, as well as in building communities of researchers. In recent years, the focus of DARPA research has shifted toward more immediate or specialized military needs. Putting aside the debate about the extent to which the military's research portfolio should concentrate on the short term versus the long term, a consequence is the loss of an important source of support for longer-term telecommunications research.

RECOMMENDATIONS

The recommendations below lay out steps that the United States should take to develop and sustain a multifaceted, reinvigorated telecommunications research program. The recommendations envision a greater role for government-sponsored and university research in telecommunications than has been evident in the past and also envision additional investment by industry in more work of a fundamentally high-risk character with more attention to overall architectural issues. The recommendations are all aimed at so-called precompetitive activities; when the time arrives for development, implementation, and deployment, it will be up to equipment and software suppliers to create and manufacture the products and to service providers to deploy the necessary facilities and services.

Determining how much funding to provide for such a telecommunications research initiative involves, of course, a complex set of budgetary tradeoffs among research programs and between research and non-research activities. The committee does not make a recommendation for a specific funding level but notes that funding should be consistent with the vital role played by telecommunications in the U.S. economy and society and with the direct contributions made by the U.S. telecommunications industry to the nation's economy and security. Funding should also be consistent with telecommunications' role as a critical element of information technology (some 16 percent of the total federal networking and information technology research and development budget today goes to telecommunications; see Chapter 2). Finally, the investment should be large enough to support a critical mass of researchers and research; one estimate can be drawn from the predivestiture Bell Labs, whose budget of over $500 million (in today's dollars) for basic research was sized to provide the breadth and depth to comprehensively address telecommunications research issues.

Recommendation 1. The federal government should establish a new research organization—the Advanced Telecommunications Research Activity—to rejuvenate fundamental and applied telecommunications research in the United States and to stimulate and coordinate activities across industry, academia, and government that can translate research results into deployments of significant new telecommunications capabilities.

In light of the findings presented above, the committee believes that a new national research organization, which it dubs the Advanced Telecommunications Research Activity (ATRA), should be established by the federal government. This recommendation is inspired in large part by the enormous leaps in telecommunications technology historically attributable to DARPA and Bell Labs and the success of broad industry consortia such as SEMATECH.

Recommendation 1 and Recommendation 2 below both contemplate significant federal support for telecommunications research. However, their full effects will come only with the participation of both service providers and equipment vendors. ATRA would provide (1) a forum for convening federal research sponsors, academic researchers, and industry to identify research that is relevant to industry's most critical needs and (2) a mechanism for the telecommunications industry to pool funds to conduct precompetitive research. Government matching funds would provide an additional incentive for industry participation.

In terms of structure, the committee considered the pros and cons of different models (described in Chapter 4) and decided that a hybrid approach is best suited to the challenges facing the telecommunications industry. The committee envisions ATRA as a hybrid of activities of the sort historically associated with DARPA (which through the ARPANET program managed a research portfolio, developed a vision, and convened industry and academia) and SEMATECH (which brought a struggling high-tech sector together, initially with some federal support to complement industry dollars, to fund joint research, development, and roadmapping activities). ATRA would be staffed by program managers who would include researchers from both academia and industry. Industry funding would represent a significant fraction of total ATRA funding, and industry as well as academic researchers would be deeply involved in research activities.

There are a number of options for where within the federal government such a program could fit, each with its own set of tradeoffs (see Chapter 4). The committee does not make a specific recommendation for locating such a program but notes that ATRA's proposed mission would align with that of existing agencies within the Department of Commerce and that NSF has developed mechanisms for joint academic-industry engineering research, albeit more focused and on a smaller scale.

ATRA's multifaceted mission would include the following (see Chapter 4 for more discussion of the items below):

• *Identifying, coordinating, and funding telecommunications research for the nation.* ATRA's focus would be on critical telecommunications research in which the nation is currently underinvesting.

• *Fostering the conception, development, and implementation of major architectural advances.* ATRA would place a priority on research that aims to make possible major architectural advances that result in the development of dramatically new telecommunications capabilities (such as the Internet was when it was developed) rather than incremental improvements to existing capabilities.

• *Strengthening the nation's telecommunications research capacity* by building up research groups, centers, and institutions with sufficient scale and breadth of expertise to tackle real-world problems and by strengthening connections between the industry and academic communities and among the telecommunications, semiconductor, and computer segments of the IT industry. To provide major experimental facilities useful to but beyond the capabilities of individual university research groups or firms, ATRA would consider establishing and supporting an experimental infrastructure for such activities as fabrication, prototyping, and testing.

Roadmapping (see Chapter 4) would be a useful tool for (1) establishing research priorities, (2) identifying complementary investments and actions required to realize major advances, and (3) examining the interplay between technical, business, and policy considerations. ATRA could serve as both a neutral convener and a partial source of funding for such activities, perhaps learning from the role played by SEMATECH with respect to the International Technology Roadmap for Semiconductors (ITRS)—see Chapter 4 for a discussion of both SEMATECH and ITRS.

Long-term investments are required to realize the sorts of innovation contemplated in connection with ATRA. It would likely take at least 5 years to develop a major advance (such as a superior replacement architecture for the Internet) and several more years to see that design reflected in products and services in the market. But history shows that a well-conceived research program yields numerous payoffs, including shorter-term advances and unforeseen long-term benefits.

The following are suggestions for specific steps to be considered in implementing the committee's first recommendation.

1. Establish mechanisms for carrying out project-based research involving academia and industry and build up a core technical staff to manage research projects and coordinate activities. Mechanisms such as broad agency announcements would allow ATRA to solicit promising ideas from academia and industry. These ideas would be used to jump-start a research program, help establish a critical mass of researchers, and garner sufficient industry matching funding to allow the establishment of research centers that can attract significant industry participation—organizations along the lines of the NSF-supported engineering research centers that are described in Chapter 4.

ATRA would provide leadership by setting overall goals and objectives but should foster a diversity of ideas and a robust competition in ideas among rival research groups. Universities should receive a significant portion of funding to conduct unfettered research while educating future generations of U.S. researchers. However, ATRA should also address industry interests by providing support for industry to collaborate with universities. By allocating funding to both universities and corporations, ATRA would help achieve the critical goal of connecting the key components for future success.

2. Establish advisory committees that include significant, high-level industry participation. Advisory committees with representatives from equipment suppliers and service providers would help ensure that ATRA is responsive to industry needs. The participation of high-level executives is critical to both ensuring ATRA's relevance and sustaining industry buy-in and support for ATRA activities. This requirement suggests the wisdom of creating an executive council that includes chief executives of equipment and software suppliers and service providers along with representatives from federal agencies concerned with telecommunications and telecommunications research (e.g., DARPA, the National Institute of Standards and Technology (NIST), the National Telecommunications and Information Administration (NTIA), NSF, and the Federal Communications Commission). Additional advisory committees might be established to address individual major technology areas (e.g., optical and wireless communications or network security) or the interplay between technology and regulatory developments.

3. Explore future needs for R&D centers and shared facilities to complement distributed, project-based research. There are a number of research problems whose investigation might ultimately require centers or shared facilities. For example, characterizing and improving the security and reliability of a large-scale communications network, especially when it comprises multiple interconnected service providers that use diverse technologies, requires a much broader perspective than can be brought by any individual or group of individuals. Centers may also be a way to more efficiently provide certain experimental facilities—such as for fabrication, prototyping, and testing. For example, research that depends on fabrication of integrated circuits or other devices may require access to facilities that are beyond the reach of a university-based research group. Finally, centers provide a nucleus for academic-industry collaboration and for interdisciplinary research.

There are several plausible options for establishing R&D centers: establishing university-based centers in which industry participates, extending the mission and size of a government laboratory such as those at NIST, or establishing a federally funded research and development center for telecommunications research. Selecting the appropriate types and mix of institutions would be an important task for ATRA and would depend on industry interests and institutional capabilities. Research priorities that emerge from vision-setting and roadmapping activities would also help inform the design of such centers.

4. Establish a forum in which lawmakers, regulators, research funding agencies, and industry can share knowledge about technological developments, visions and roadmaps, and policy and regulation. To maximize the leverage of establishing ATRA and increasing industry participation in R&D, it is essential that lawmakers and regulators understand the impact of legislation and rulemaking on the R&D enterprise, and that both they and researchers consider and reflect in their thinking the interplay between the policy environment, business opportunities, and technological directions.

Recommendation 2. The National Science Foundation and DARPA should assess their investment in basic telecommunications research and consider increasing both their emphasis on and their level of investment in such research.

Even with the creation of ATRA, both NSF and DARPA will retain important roles in strengthening U.S. telecommunication research. Both have successful research management cultures that complement each other and the activities envisioned for ATRA. In particular, both have been very effective at identifying, building up, and supporting research communities in areas of national interest.

As a starting point and as a periodic activity, both NSF and DARPA should look across their programs to determine how much funding is actually being directed to telecommunications research and should then develop criteria for establishing the appropriate level of funding going forward. Relevant criteria include (1) the size of the telecommunications research community and the number of highly rated proposals that can be funded, (2) the size of the telecommunications industry's R&D budget, and (3) provision of support for telecommunications research within the broader IT research budget in proportion to the size of the telecommunications segment compared with the size of the IT industry as a whole.

Recommendation 2.1. The National Science Foundation should continue to strengthen its support for telecommunications research.

NSF has significant strengths in supporting basic research, training researchers, and building research communities that can play an important role in strengthening the U.S. research base in telecommunications. CISE's growing commitment to supporting research in this area is evident, and the committee encourages NSF to sustain such attention.

In addition, and reflecting the greater emphasis being placed in this program area, NSF should also consider establishing programs aimed specifically at attracting and developing young research talent in telecommunications. Options would include supporting graduate and postdoctoral fellowships in telecommunications or establishing a young-investigator program that would provide start-up support for promising research talent, targeted at telecommunications.

Finally, existing mechanisms such as the CISE Advisory Committee or new ones, such as formal or informal consultations with the director of the proposed ATRA, should be used to keep abreast of new ideas, major challenges, and promising research directions emerging from academia and industry.

Recommendation 2.2. DARPA should continue to invest in telecommunications research for military applications even if there is some chance that the commercial sector will develop such technologies.

In light of the importance of maintaining a cutting-edge telecommunications capability in a network-centric military, DARPA should periodically reexamine its investments in telecommunications. Factors to consider include (1) the telecommunications capabilities attainable by potential U.S. adversaries by virtue of the burgeoning commercial telecommunications sector overseas and (2) the risks associated with having to rely on components and systems that are increasingly being developed overseas. DARPA's role would be complementary to that of NSF and the proposed ATRA. Compared to NSF, for example, DARPA has a culture of focused programs with more active management and significant industry participation.

Recommendation 3. All segments of the U.S. telecommunications industry should increase their support for additional fundamental research. One avenue would be through participation in joint, cooperative research activities organized by the proposed ATRA.

As described above, the emphasis of industry research in recent years has shifted toward short-term product opportunities within the context of existing overall network architectures and away from the more fundamental and high-risk opportunities and major advances in cross-cutting end-to-end applications and services and supporting architectures that are essential to the long-term health of the U.S. telecommunications sector. Both equipment vendors and service providers (including providers of wireline telephony, wireless, broadband, Internet, satellite, and cable) should consider identifying and using mechanisms through which they could provide more support for fundamental research. ATRA, proposed in Recommendation 1, is intended to provide a way for the telecommunications industry to pool funds, spread risk, and share beneficial results through cooperative efforts between industry and academia that are jointly funded by industry and government.

Appendixes

Appendix A

Biographies of Committee Members and Staff

Robert W. Lucky, *Chair*, retired in 2003 as corporate vice president of Applied Research at Telcordia Technologies, which he joined in 1992. He began his telecommunications career at AT&T Bell Laboratories in Holmdel, N.J., where he was initially involved in studying ways of sending digital information over telephone lines. The best-known outcome of this work was his invention of the adaptive equalizer—a technique for correcting distortion in telephone signals that is used in all high-speed data transmission today. The textbook on data communications that he co-authored became the most-cited reference in the communications field over the period of a decade. At Bell Labs he moved through a number of levels to become executive director of the Communications Sciences Research Division in 1982, where he was responsible for research on the methods and technologies for future communication systems. He has been active in professional activities and has served as president of the Communications Society of the IEEE (Institute of Electrical and Electronics Engineers), and as vice president and executive vice president of the parent IEEE. He has been editor of several technical journals, including the *Proceedings of the IEEE*, and since 1982 he has written the bimonthly "Reflections" column of personalized observations about the engineering profession in *Spectrum* magazine. In 1993 these "Reflections" columns were collected in the IEEE Press book *Lucky Strikes . . . Again*. He is a fellow of the IEEE and a member of the National Academy of Engineering. He is also a consulting editor for a series of books on communications through Plenum Press. He has been on the advisory boards or committees of many universities and government organizations and was chair of the Scientific Advisory Board of the United States Air Force from 1986 to 1989. He was the 1987 recipient of the prestigious Marconi Prize for his contributions to data communications, and he has been awarded honorary doctorates from Purdue University and the New Jersey Institute of Technology. He has also been awarded the Edison Medal of the IEEE and the Exceptional Civilian Contributions Medal of the U.S. Air Force. Lucky is a frequent speaker before both scientific and general audiences. He has been an invited lecturer at about 100 different universities and has been a guest on a number of network television shows, including Bill Moyers' "A World of Ideas," where he discussed the impacts of future technological advances. He is the author of the popular book *Silicon Dreams*, a semi-technical and philosophical discussion of the ways in which both humans and computers deal with information. A native of Pittsburgh, he attended Purdue University, where he received a bachelor of science degree in electrical engineering in 1957 and master of science and doctoral degrees in 1959 and 1961.

James D. Adams is a professor of economics at Rensselaer Polytechnic Institute. In addition he is a research associate of the National Bureau of Economic Research in Cambridge, Massachusetts. Prior to joining Rensselaer he was a professor of economics at the University of Florida. He has also held visiting appointments at the U.S. Bureau of Labor Statistics, the U.S. Bureau of the Census, and the George J. Stigler Center for the Study of the Economy and the State at the University of Chicago. He received a B.A. in economics from the University of New Mexico in 1967 and a Ph.D. in economics from the University of Chicago in 1976. Adams has published numerous articles on the economics of technical change, with an emphasis on the causes and consequences of industrial and academic research and development, as well as numerous articles in the fields of labor and public economics. His current research focuses on the limits of the firm in research and development, the measurement of scientific influence, the identification of alternative channels of knowledge externalities in the economy, the structure and meaning of scientific teams and collaborations, the speed of diffusion of scientific research, the interaction between investment in industrial research and development and investment in physical capital, and the determinants of research and teaching productivity in academia.

John M. Cioffi is a professor of electrical engineering at Stanford University. He worked at Bell Laboratories from 1978 to 1984 and at International Business Machines Research from 1984 to 1986. Cioffi founded Amati Com. Corp. in 1991 (purchased by TI in 1997) and was officer/director from 1991 to 1997. He currently is on the board of directors of ASSIA (chair), Teranetics, ClariPhy, and Vector Inc. and is on the advisory boards of Portview Ventures, Wavion, MySource, and Amicus. Cioffi's specific interests are in the area of high-performance digital transmission. His various awards include Marconi fellow (2006); holder of Hitachi America Professorship in Electrical Engineering at Stanford (2002); member, National Academy of Engineering (2001); IEEE Kobayashi Medal (2001); IEEE Millennium Medal (2000); IEEE fellow (1996); IEEE J.J. Thomson Medal (2000); University of Illinois Outstanding Alumnus (1999); IEEE *Communications Magazine* best paper (1991); ANSI T1 Outstanding Achievement Award (1995); NSF Presidential Investigator (1987-1992); and ISSLS Outstanding Paper award (2004). Cioffi has published over 250 papers and holds over 80 patents. He has a B.S.E.E. degree from the University of Illinois and a Ph.D.E.E. from Stanford University.

Richard A. DeMillo is the John P. Imlay Dean and Distinguished Professor of Computing at the Georgia Institute of Technology. He is also a member of the board of directors for RSA Security. He returned to academia after a career as an executive in industry and government. He was chief technology officer for Hewlett-Packard, where he had worldwide responsibility for technology and technology strategy. Prior to joining HP, he was in charge of Information and Computer Sciences Research at Telcordia Technologies (formerly Bellcore) in Morristown, New Jersey, where he oversaw the development of many Internet and Web-based innovations. He has also directed the Computer and Computation Research Division of the National Science Foundation. Before joining industry during the Internet boom, he held several academic positions. He was professor of computer sciences and director of the Software Engineering Research Center at Purdue University. He also held major faculty positions at Georgia Tech, where he was the founding director of the Software Research Center, and had a visiting professorship at the University of Padua in Padua, Italy. As dean of the College of Computing he is the chief academic officer for one of the largest programs at Georgia Tech. He is deeply immersed in the problem of creating a high-tech workforce that will be competitive in the new "flat world" created by the convergence of enabling technology and geopolitical forces. The author of over 100 articles, books, and patents, DeMillo has conducted research that spans computer science and includes innovation in computer networking, computer security, software engineering, and mathematics. His present research interests are focused on information security. He is developing hardware-based architectures for trusted computing platforms and investigating methods for securing wireless communication services. He is a fellow of the American Association for the Advancement of Science and the Association for Computing Machinery (ACM).

Reed Hundt served as chair of the Federal Communications Commission (FCC) from 1993 to 1997. Prior to heading the FCC, he was a partner in the Washington, D.C., office of Latham & Watkins. Mr. Hundt currently serves on the board of directors of Intel, Pronto Networks, Tropos Networks, Polyserve, Entrisphere, and Access Spectrum, and he is an advisor to the Blackstone Group and to McKinsey & Company. He is a member of the advisory committee at the Yale School of Management and co-chair of the Forum on Communications and Society at the Aspen Institute. Mr. Hundt is the author of *You Say You Want a Revolution: A Story of Information Age Politics* (Yale University Press, 2000) and *In China's Shadow: The Crisis of American Entrepreneurship* (Yale University Press, 2006). He graduated magna cum laude from Yale College (1969) with exceptional distinction in history. He is also a graduate of Yale Law School (1974) and is a member of the District of Columbia, Maryland, and California bars.

Jeffrey M. Jaffe is executive vice president and chief technical officer of Novell. He is responsible for Novell's technology direction, as well as leading Novell's product business units. Jaffe serves as a member of Novell's Worldwide Management Committee. After receiving a Ph.D. in computer science from MIT in 1979, Jaffe joined IBM's Thomas J. Watson Research Center. During his tenure at IBM, he held a wide variety of technical and management positions, including vice president, Systems and Software Research, corporate vice president of technology, and general manager of IBM's SecureWay business unit, where he was responsible for IBM's security, directory, and networking software business. Jaffe most recently served as president of Bell Labs Research and Advanced Technologies, where he established new facilities in Ireland and India, and he served as chair of the board of the New Jersey Nanotechnology Consortium. Jaffe was also appointed by President Bill Clinton to serve on the Advisory Committee for the Presidential Commission for Critical Infrastructure Protection. He has also chaired the Chief Technology Officer group of the Computer Systems Policy Project and has served on the National Research Council's Computer Science and Telecommunications Board. He is a fellow of ACM and the IEEE. Jaffe holds a B.S. in mathematics and an M.S. in electrical engineering in addition to his doctorate from the Massachusetts Institute of Technology.

Edward Kozel has been the managing member of Open Range Ventures, a venture capital firm, since January 2000. Until 2002 he was a member of the board of directors of Cisco Systems, Inc., where he worked for 11 years in a variety of roles, including chief technology officer and senior vice president of business development. During his tenure at Cisco, he founded the business development group, which, under his direction, was responsible for more than 22 technology acquisitions and 25 minority investments. Kozel is an industry innovator who previously worked at Boeing, McDonnell Douglas, and SRI International, where he participated in the early design and development of the Internetwork Protocol (IP) model and TCP/IP, packet radio networks, and highly distributed information systems. In addition to Yahoo!, Kozel serves on the boards of Reuters PLC and Symbol Technologies. He graduated from the University of California, Davis with a degree in electrical engineering.

Rajiv Laroia is the chief technology officer (CTO) of Qualcomm Flarion Technologies. He was the founder and CTO of Flarion Technologies, a company that specialized in wireless broadband technology. Flarion was acquired by Qualcomm in January 2006. Prior to launching Flarion, Dr. Laroia was with Lucent Technologies' Bell Laboratories' Mathematical Sciences Research Center. In 1997, he became head of Bell Labs' Digital Communications Research Department in the Wireless Research Center, where he and his team started to develop a flash-OFDM technology-based wireless data system. His years at Bell Labs have generated numerous publications and patents with total patent licensing revenue in excess of $25 million. He received his Ph.D. and M.S. degrees from the University of Maryland, College Park in 1992 and 1989 and a B.Tech. degree in 1985 from the Indian Institute of Technology, Delhi—all in electrical engineering. He is an expert in CDMA, TDMA, and other cellular multiple-access technologies and is intimately familiar with current and next-generation wireless standards.

David Messerschmitt is Roger A. Strauch Professor Emeritus of Electrical Engineering and Computer Sciences at the University of California, Berkeley. His current research interests fall at the overlap between technology, business, and economics. More specifically, he considers how technology should be different than it is currently in order to meet the needs of end users and end-user organizations and to be more successful in the marketplace. Messerschmitt holds several patents and has authored several books on networked applications. He is a member of the Advisory Committee of NSF's Division of Computer Science and Engineering, the NSF Blue Ribbon Panel on Cyberinfrastructure, and the National Academy of Engineering. He served on the Computer Science and Telecommunications Board. He is also an IEEE and International Engineering Consortium fellow. He received his M.S. (1968) and Ph.D. (1971) in computer information and control engineering from the University of Michigan, Ann Arbor.

Eli M. Noam has been a professor of economics and finance at the Columbia Business School since 1976. He served for 3 years as a commissioner for public services of New York state; was director of the Columbia Institute for Tele-Information, a university-based research center focusing on strategy, management, and policy issues in telecommunications, computing, and electronic mass media; and was chair of the M.B.A. concentration in media management and of the Virtual Institute of Information. He has also taught at Columbia Law School, Princeton University's Economics Department and Woodrow Wilson School, and the University of St. Gallen, and he is active in the development of electronic distance education. An author or editor of 24 books and over 300 articles in economics journals, law reviews, and interdisciplinary journals, he is a former member of the President's Information Technology Advisory Committee (PITAC). Noam was also a member of the boards or advisory boards for the federal government's FTS-2000 telecommunications network, the IRS's computer system reorganization, the National Computer Systems Laboratory, the National Commission on the Status of Women in Computing, the Intek Corporation, and Jones International University, the first accredited e-university. He served on the National Research Council study committee that produced *Broadband: Bringing Home the Bits* (2002). He is a fellow of the World Economic Forum, a member of the Council on Foreign Relations, a commercially rated pilot, and an active search and rescue mission pilot with the Civil Air Patrol (1st Lt.). He received the degrees of A.B. (Phi Beta Kappa), M.A., Ph.D. (economics), and J.D. from Harvard University.

Daniel Pike is chief technology officer of GCI Cable and Entertainment. He entered the cable industry in 1973 (LVO/United) and recently served as CTO of Classic Communications (2000-2003). Prior to that he was senior vice president of science and technology for Prime Cable and its related entities (1977-2000). He has served on the board of directors of CableLabs since its inception, received the NCTA Vanguard Award for Science and Technology in 1991 and the Texas Telecommunications 2000 Johnny Mankin Award, was elected to the SCTE Hall of Fame, is a former director of COM21 (a cable modem manufacturer), and advises other technology-related organizations. He is a fellow of the Institute of Electrical and Electronics Engineers and the Society of Cable Telecommunications Engineers, is a member of the Society of Motion Pictures and Television Engineers, and speaks frequently and publishes on broadband and telecommunications issues. He served on the Computer Science and Telecommunications Board. Pike earned bachelor of science and master of science degrees from Oklahoma State University.

Lawrence Rabiner is the associate director, Center for Advanced Information Processing at Rutgers University. He retired as the vice president of research at AT&T Laboratories in 2002 after a career at AT&T that spanned almost 40 years in Research. He has co-authored four major books in the signal-processing field: *Theory and Application of Digital Signal Processing* (1975), *Digital Processing of Speech Signals* (1978), *Multirate Digital Signal Processing* (1983), and *Fundamentals of Speech Recognition* (1993). He has written or co-authored over 300 articles, including many on speech recognition and speech synthesis, and has been the recipient of 25 patents. He is a fellow of the IEEE (1976) and the Acoustical Society of America, served as editor of the ASSP *Transactions*, and is a former member of the *Proceedings of the IEEE* editorial board. He has also been active in the Signal Processing Society and its predecessors, acting as its vice president (1973) and president (1974-1975). He is a member of the National Academy of Sciences and the National Academy of Engineering. Rabiner received his B.S. and M.S. degrees in electrical engineering simultaneously in 1964, and his Ph.D. in 1967, all from MIT. His Ph.D. thesis and some of his early work at Bell Laboratories were in the field of speech synthesis, and since 1967 he has worked on a range of topics in the areas of digital signal processing and machine recognition of speech, including digital filter design, implementation of digital systems, spectrum analysis systems, pattern recognition clustering methods, and the hidden Markov model method.

Theodore S. Rappaport is the William and Bettye Nowlin Professor in Engineering at the University of Texas and is director of the Wireless Networking and Communications Group

(WNCG) at the university's Austin campus, a center he founded in 2002. From 1988 to 2002, he was on the electrical and computer engineering faculty of Virginia Tech, where he founded the Mobile & Portable Radio Research Group (MPRG), one of the world's first university research and teaching centers dedicated to the wireless communications field. In 1989, he founded TSR Technologies Inc., a cellular radio/PCS software radio manufacturer that was sold in 1993. In 1995, he founded Wireless Valley Communications Inc., a pioneering creator of site-specific radio propagation software for network design and management. Wireless Valley was acquired by Motorola Inc. in 2005. Rappaport received the Marconi Young Scientist Award in 1990, an NSF Presidential Faculty Fellowship in 1992, the Sarnoff Citation from the Radio Club of America in 2000, the Fredrick S. Terman Outstanding Electrical Engineering Faculty Award from the American Society of Engineering Education in 2002, and the Stuart F. Meyer Award from the IEEE Vehicular Technology Society in 2005. Rappaport has over 100 U.S. or international patents issued or pending and has authored, co-authored, and co-edited 18 books in the wireless field. In 1999, his work on site-specific propagation received the IEEE Communications Society Stephen O. Rice Prize Paper Award. He serves on the editorial boards of several academic and technical journals, is a fellow of the IEEE, and is active in the IEEE Communications and Vehicular Technology societies. He has consulted for over 25 multinational corporations and has served the International Telecommunication Union as a consultant for emerging nations. He received B.S., M.S., and Ph.D. degrees in electrical engineering from Purdue University in 1982, 1984, and 1987, respectively.

William J. Spencer advises the Washington Advisory Group on corporate R&D strategy, technology management, and corporate-academic partnerships. Dr. Spencer is Chairman Emeritus of International SEMATECH, a research and development consortium of international corporations involved in semiconductor manufacturing. He served as CEO and president of SEMATECH from 1990 to 1997, during which time the U.S. semiconductor industry regained its global market position and SEMATECH evolved from a government industry cooperative to an international R&D activity. Prior to 1990, Dr. Spencer managed worldwide research and technology for Xerox Corporation as group vice president and senior technical officer at Xerox's headquarters in Stamford, Connecticut, and as vice president and manager of the Xerox Palo Alto Research Center. He was director of microelectronics and then director of weapon systems development at Sandia National Laboratories from 1973 to 1981. He began his career at Bell Telephone Laboratories in 1959. Dr. Spencer is a research professor of medicine at the University of New Mexico as a result of work he did at Sandia National Laboratories on the first implantable electronic drug delivery systems. As a member of the National Academy of Engineering, he has contributed to several National Research Council studies on high-technology industries; technology strategies for the future; and international cooperation and competitiveness. He is vice chair of the National Research Council's Board on Science, Technology, and Economic Policy. Spencer received his Ph.D. and M.S. degrees from Kansas State University, and an A.B. from William Jewell College in Missouri.

David Teece is Mitsubishi Bank Professor of International Business and Finance at the Haas School of Business, University of California, Berkeley. He is director of Berkeley's Institute of Management, Innovation and Organization (IMIO). He has been at Haas since 1982. He previously served as assistant professor of business economics at Stanford University. His research interests include the competitive performance of firms in the global marketplace, innovation and the organization of industry, and technology policy, telecommunications policy, antitrust policy, and energy policy at the national and international levels. He holds M.A. and Ph.D. degrees in economics from the University of Pennsylvania, and B.A. and M.Comm. degrees from the University of Canterbury.

Hemant Thapar is chair and CEO of Link-A-Media Devices, a fabless semiconductor company specializing in the development of system-on-chip connectivity solutions for storage media. After receiving his Ph.D. degree from Purdue University in 1979, Thapar held various technical and management positions in advanced technology development at Bell Telephone Laboratories, Holmdel (1979-1984) and at IBM Corporation, San Jose (1984-1994). He co-founded DataPath Systems Inc. in 1994 and was its CEO until July 2000 when it merged with LSI Logic Corporation, where he was a senior vice-president until 2004. He has also served on the faculty of Santa Clara University since 1984 where he regularly teaches graduate-level courses in digital communications and signal processing. He is also on the advisory committee of Ambala College of Engineering and Applied Research, a newly formed engineering school in India. Thapar's interests are in the areas of communication signal processing, system engineering, and VLSI development. He has authored many publications and patents in the areas of data communications, networking, and data storage. He is co-recipient of three best-paper awards for his work on high-speed data transmission and high-density data storage. Thapar has served as guest editor of two issues of the *IEEE Journal on Selected Areas in Communications* devoted to signal processing and coding for data storage. Thapar is a fellow of the IEEE.

Jack K. Wolf is the Stephen O. Rice Professor of Magnetics in the Electrical and Computer Engineering Department at the University of California, San Diego. Prior to joining UCSD, Wolf held full-time faculty appointments at New York University, the Polytechnic Institute of Brooklyn, and the University of Massachusetts at Amherst. His research interests are signal processing for recording, information theory, coding theory, and communications. His industrial experience includes working at RCA Laboratories, Bell Laboratories, and Qualcomm Inc. At Qualcomm Inc. he was concerned with the design and development of wireless communication systems. He was a Guggenheim fellow and a former president of the IEEE Information Theory Group. He received the 2001 Claude E. Shannon Award from the IEEE Information Theory Society and the 1998 Koji Kobayashi Computer and Communications Award from the IEEE. In 1975 he received the IEEE Information Theory Group Prize Paper Award for the paper "Noiseless Coding for Correlated Information Sources," which he co-authored with David Slepian. He is editor of the book series "Information Technology: Transmission Processing and Storage" published by Kluwer Academic/Plenum Publications. He is a member of the National Academy of Engineering. He received his B.S.E.E. degree from the University of Pennsylvania and M.S.E., M.A., and Ph.D. degrees from Princeton University.

Staff

Jon Eisenberg is director of the Computer Science and Telecommunications Board of the National Research Council. At CSTB, he has been the study director for a diverse body of work, including a series of studies exploring Internet and broadband policy and networking and communications technologies. Current studies include an examination of emerging wireless technologies and spectrum policy and a study of how to use information technologies to enhance disaster management. In 1995-1997 he was a AAAS Science, Engineering, and Diplomacy Fellow at the U.S. Agency for International Development, where he worked on environmental management, technology transfer, and information and telecommunications policy issues. He received his Ph.D. in physics from the University of Washington in 1996 and a B.S. in physics with honors from the University of Massachusetts at Amherst in 1988.

David Padgham rejoined CSTB as an associate program officer in the spring of 2006 following nearly 2 years as a policy analyst in the Association for Computing Machinery's (ACM's) Washington, D.C., Office of Public Policy, where he worked closely with that organization's public policy committee, USACM. Previously, he spent nearly 6 years with CSTB, working on—among other things—the studies that produced *Trust in Cyberspace*, *Funding a Revolution*, *Broadband: Bringing Home the Bits*, *LC21: A Digital Strategy for the Library of Congress*, and *The Internet's Coming of Age*. Currently, he is focused on the CSTB projects related to telecommunications R&D, software dependability, and privacy in the information age. He holds a master's degree in library and information science (2001) from the Catholic University of America in Washington, D.C., and a bachelor of arts degree (1996) in English from Warren Wilson College in Asheville, N.C.

Cynthia A. Patterson (study director through June 2004) was a study director and program officer with the Computer Science and Telecommunications Board. She worked on a diverse set of CSTB projects, including a project on critical information infrastructure protection and the law, a study on the future of supercomputing, and a study on telecommunications research and development. She was also involved with the congressionally mandated study on Internet searching and the Domain Name System. Prior to joining CSTB, Patterson completed an M.Sc. from the Sam Nunn School of International Affairs at the Georgia Institute of Technology. Her graduate work was supported by the Department of Defense and SAIC. She was also employed by IBM as an IT consultant for both federal government and private industry clients; her work included application development, database administration, network administration, and project management. She received a B.Sc. in computer science from the University of Missouri-Rolla.

Jennifer M. Bishop, program associate, has been with the Computer Science and Telecommunications Board since 2001. She is currently involved in studies on policy consequences and legal/ethical implications of offensive information warfare and assessing the information technology research and development ecosystem. She also maintains CSTB's contact database, handles updates to the CSTB Web site, coordinates the layout and design of *Update*, the CSTB newsletter, and designs book covers and promotional materials. Prior to her move to Washington, Bishop worked for the city of Ithaca, New York, coordinating the Police Department's transition to a new SQL-based time accrual and scheduling application. Her other work experience includes designing customized hospitality industry performance reports for RealTime Hotel Reports, LLC, maintaining the police records database for the city of Ithaca, and freelance publication design. She is a visual artist working in oil and mixed media. She holds a B.F.A. from Cornell University.

Phil Hilliard (research associate through June 2004) was a research associate on the professional staff of the Computer Science and Telecommunications Board who worked on projects focusing on telecommunications research, supercomputing, and dependable systems. Before joining the National Academies, he worked at BellSouth in Atlanta, Georgia, as a competitive intelligence analyst and at NCR as a technical writer and trainer. He earned an M.B.A. from Georgia State University (2000) in Atlanta and a B.S. in computer and information technology from Georgia Institute of Technology (1986) in Atlanta. He is currently working on a master's of library and information science in Florida State University's online program.

Appendix B

List of Individuals Who Made Presentations to the Committee

Although the briefers listed below provided much useful information of various kinds to the committee, they were not asked to endorse this study's conclusions or recommendations, nor did they see the final draft of this report before its release.

APRIL 28-29, 2003
WASHINGTON, D.C.

Robert Leheny, Defense Advanced Research Projects Agency
Mari Maeda, National Science Foundation
Ed Thomas, Federal Communications Commission

JULY 17-18, 2003
NEWPORT BEACH, CALIFORNIA

Henry Samueli, Broadcom
Don Shaver, Texas Instruments
Raj Yavatkar, Intel

NOVEMBER 3-4, 2003
WASHINGTON, D.C.

Hassan Ahmed, Sonus Networks
Fred Baker, Cisco Systems
James McGroddy, IBM (retired)

Note: Affiliations shown were curent at the time the briefings were given.

Craig Partridge, BBN
John Pinkston, University of Maryland, Baltimore County
Krish Prabhu, Morgenthaler
David Reed, CableLabs
William Semancik, National Security Agency

FEBRUARY 12-13, 2004
SAN FRANCISCO, CALIFORNIA

Richard Newton, University of California, Berkeley

MAY 3-4, 2004
WASHINGTON, D.C.

Sandy Fraser, Fraser Research
Steve Papermaster, President's Science and Technology Advisory Committee
Guru Parulkar, National Science Foundation

What Is CSTB?

As a part of the National Research Council, the Computer Science and Telecommunications Board (CSTB) was established in 1986 to provide independent advice to the federal government on technical and public policy issues relating to computing and communications. Composed of leaders from industry and academia, CSTB conducts studies of critical national issues and makes recommendations to government, industry, and academia. CSTB also provides a neutral meeting ground for consideration of complex issues where resolution and action may be premature. It convenes discussions that bring together principals from the public and private sectors, ensuring consideration of key perspectives. The majority of CSTB's work is requested by federal agencies and Congress, consistent with its National Academies' context.

A pioneer in framing and analyzing Internet policy issues, CSTB is unique in its comprehensive scope and its effective, interdisciplinary appraisal of technical, economic, social, and policy issues. Beginning with early work in computer and communications security, cyber-assurance and information systems trustworthiness have been cross-cutting themes in CSTB's work. CSTB has produced several reports that have become classics in the field, and it continues to address these topics as they grow in importance.

To do its work, CSTB draws on some of the best minds in the country and from around the world, inviting experts to participate in its projects as a public service. Studies are conducted by balanced committees without direct financial interests in the topics they are addressing. Those committees meet, confer electronically, and build analyses through their deliberations. Additional expertise is tapped in a rigorous process of review and critique, further enhancing the quality of CSTB reports. By engaging groups of principals, CSTB obtains the facts and insights critical to assessing key issues.

The mission of CSTB is to

- Respond to requests from the government, nonprofit organizations, and private industry for advice on computer and telecommunications issues and from the government for advice on computer and telecommunications systems planning, utilization, and modernization.
- Monitor and promote the health of the fields of computer science and telecommunications, with attention to issues of human resources, information infrastructure, and societal impacts.
- Initiate and conduct studies involving computer science, technology, and telecommunications as critical resources.
- Foster interaction among the disciplines underlying computing and telecommunications technologies and other fields, at large and within the National Academies.

CSTB projects address a diverse range of topics affected by the evolution of information technology. For further information about CSTB reports and active projects, see <http://cstb.org>.