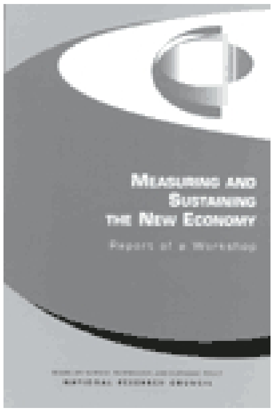

Measuring and Sustaining the New Economy: Report of a Workshop

Dale W. Jorgenson and Charles W. Wessner, Editors, Board on Science, Technology, and Economic Policy, National Research Council

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Preface

The decade of the 1990s witnessed rapid technological change in communications, computing, and information management. This phenomenon coincided with the sustained expansion of the U.S. economy through much of the 1990s.[1] Along with other structural and policy explanations this technological change is a key element in the strong growth in labor productivity, especially after 1995. The term "New Economy" captures the role that these new technologies are thought to play in contributing to the non-inflationary growth and high employment that characterized this period.

Although the New Economy is, itself, a macro phenomenon, its underlying dynamics appear to combine elements of technological innovation, structural change, and public policy.

- Technological innovation—more accurately, the rapid rate of technological innovation in information technology (including computers, software, and telecommunications) and the rapid growth of the Internet—are seen by some as underpinning the productivity gains that characterize the New Economy. These productivity gains derive from greater efficiencies in the production of computers from expanded use of information technologies.[2]

[1]See Jorgenson, Dale and Kevin Stiroh. 2000. "Raising the Speed Limit: U.S. Economic Growth in the Information Age" *Brookings Papers on Economic Activity*; 0(1), pp. 125-211. This paper is reproduced in this volume.

[2]See, for example, Stephen Oliner and Daniel Sichel. 2000. "The Resurgence of Growth in the late 1990's: Is Information Technology the Story?" *Journal of Economic Perspectives* 14(4) Fall. Oliner and Sichel estimate that improvements in the computer industry's own productive processes account for about a quarter of the overall productivity increase. They also note that the use of information technology by all sorts of companies accounts for nearly half the rise in productivity.

Many therefore believe that the New Economy is closely linked to the unprecedented rate of technological innovation characteristic of information technology industries.[3]

- Structural changes arise from a reconfiguration of knowledge networks and business patterns made possible by innovations in information technology. Phenomena, such as business-to-business e-commerce and Internet retailing, are altering how firms and individuals interact, enabling greater efficiency in purchases, production processes, and inventory management.[4] These structural changes are still emerging as the use and applications of the Internet continue to evolve.
- Public policy plays a major role at several levels. This includes the government's role in fostering rules of interaction within the Internet[5] and its discretion in setting and enforcing the rules by which technology firms, among others, compete.[6] More familiarly, public policy concerns particular fiscal and regulatory choices that can affect the rate and focus of investments in sectors such as telecommunications. The government also plays a critical role within the innovation system.[7] It provides national research capacities,[8] incentives to promote education and training in critical disciplines, and funds most of the nation's basic research.[9] The government also plays a major role in stimulating innovation, most

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[3]See Alan Greenspan's remarks before the White House Conference on the New Economy, Washington, D.C., April 5, 2000. <www.federalreserve.gov/BOARDDOCS/SPEECHES/2000/20000405.HTM>. For a historical perspective, see the Proceedings below. Ken Flamm compares the economic impact of semiconductors today with the impact of railroads in the nineteenth century.

[4]See, for example, Brookes Martin and Zaki Wahhaj. 2000. "The Shocking Economic Impact of B2B," *Global Economic Paper*, 37, Goldman Sachs, February 3.

[5]Dr. Vint Cerf notes, in the Proceedings, that the ability of individuals to interact in potentially useful ways within the infrastructure of the still expanding Internet rests on its basic rule architecture: "The reason it can function is that all the networks use the same set of protocols. An important point is these networks are run by different administrations, which must collaborate both technically and economically on a global scale." Also in the Proceedings, see the presentation by Dr. Shane Greenstein on the evolution of the Internet from academic and government-related applications to the commercial world.

[6]The relevance of competition policy to the New Economy is manifested by the intensity of interest in the antitrust case, *United States versus Microsoft*, and associated policy issues.

[7]See Richard Nelson, ed. 1993. *National Innovation Systems*, New York: Oxford University Press.

[8]The STEP Board has underway a major review of the role and operation of government-industry partnerships for the development of new technologies. Major recent publications include National Research Council, Charles W. Wessner, ed. 2001. *The Advanced Technology Program—Assessing Outcomes*, Washington, D.C.: National Academy Press, and National Research Council. 2000. *SBIR—An Assessment of the Department of Defense Fast Track Initiative,* Washington D.C.: National Academy Press.

[9]National Research Council. 2001. *Trends in Federal Support of Research in Graduate Education,* Washington, D.C.: National Academy Press.

Box A: The New Economy Enigma

"How can it be that the recent surge in investment in computers, and the great efforts most companies are making to get the most out of the Internet and other new technologies, are failing to have a marked effect, or indeed any cyclically adjusted effect, on America's service and non-durable manufacturing industries? One possibility is that the output of these industries is not being properly measured. Measuring the output of service industries is notoriously difficult; so is measuring the inputs of the high-tech capital that many such industries use intensively. Maybe investment and production of final goods and services have both been understated. If so, the performance of the American economy would be much better than the figures seem to suggest, and perhaps even as good as most people appear to think."

The Economist, "Performing Miracles," June 15, 2000

broadly through the patent system.[10] Government procurement and awards also encourage the development of new technologies to fulfill national missions in defense, health, and the environment.[11] Collectively, these public policies play a central role in the development of the New Economy.

Sustaining this New Economy will require public policy to remain relevant to the rapid technological and structural changes that characterize it. Data on the New Economy is a key input in the policy-making process. Yet, current statistics do not fully capture changes in productivity and growth brought about by recent applications of information technologies.[12]

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[10]In addition to government-funded research, intellectual property protection plays an essential role in the continued development of the biotechnology industry. See Wesley M. Cohen and John Walsh, "Public Research, Patents and Implications for Industrial R&D in the Drug, Biotechnology, Semiconductor and Computer Industries" in *Government-Industry Partnerships in Biotechnology and Information Technologies: New Needs and New Opportunities*, Washington, D.C.: National Academy Press, forthcoming.

[11]For example, government support played a critical role in the early development of computers. See Flamm. 1988. *Creating the Computer*, Washington, D.C.: The Brookings Institution. For an overview of government-industry collaboration, see the introduction to the recent report on the Advanced Technology Program, National Research Council, *The Advanced Technology Program: Assessing Outcomes*. Charles W. Wessner, ed. 2001. Washington, D.C.: National Academy Press.

[12]See the presentation in this volume by the then Under Secretary of Economic Affairs at the U.S. Commerce Department, Robert Shapiro, and then Deputy Under Secretary for Economic Affairs, Lee Price.

While recent studies confirm soaring labor productivity in the computer manufacturing industry and in the durable goods manufacturing industry, the surge in investments and use of new information technologies is not captured in the statistics on the American service and non-durable manufacturing industries.[13] Measurement problems continue to hamper our understanding of the impact of advances and cost reductions in areas such as telecommunications.

THE ROLE OF THE STEP BOARD

Since 1991 the National Research Council's Board on Science, Technology, and Economic Policy (STEP) has undertaken a program of activities to improve policymakers' understanding of the interconnections between science, technology, and economic policy and their importance to the American economy and its international competitive position. The Board's interest in the New Economy and its underpinnings derive directly from its mandate. The STEP Board's activities have corresponded with an increased recognition by policymakers of the importance of technology to economic growth.[14]

WORKSHOP AND DISCUSSIONS

The impetus for this workshop follows from a recognition by members of the STEP Board that economic issues related to the phenomenon referred to as the New Economy are distinguished by important questions on one hand and a surprising lack of data on the other. As with other STEP Board initiatives, this study is intended to bring together the needed expertise to illuminate a complex and important area of policy research.

To this end, on October 6, 2000, the STEP Board convened a workshop on Measuring and Sustaining the New Economy. The workshop included presentations and remarks from leading academics and innovators in the information technology sector (Appendix B lists these individuals). The "Proceedings" chapter of this volume contains summaries of their presentations and discussions. Given the quality and the number of presentations, summarizing the workshop proceedings has been a challenge. We have made every effort to capture the main points made during the presentations and the ensuing discussions. We apologize for any inadvertent errors or omissions in our summary of the proceedings.

[13]See Jorgenson and Stiroh, *op. cit*. Also see: Robert Gordon. 2000. "Does the New Economy Measure up to the Great Inventions of the Past?" *Journal of Economic Perspectives* 14(4), Fall.

[14]See Paul Romer. 1990. "Endogenous Technological Change," *Journal of Political Economy,* 98(5): 71-102. See also: Gene Grossman and Elhannan Helpman. 1993. *Innovation and Growth in the Global Economy*, Cambridge, MA: MIT Press.

ACKNOWLEDGEMENTS

There is considerable interest in the policy community in a better understanding of the technological drivers and appropriate regulatory framework for the New Economy, as well as in a better grasp of its operation. This interest is reflected in the support on the part of agencies that have played a role in the creation and development of the New Economy. We are grateful for the participation and the contributions of the National Aeronautics and Space Administration, the Department of Energy, the National Institute of Standards and Technology, and Sandia National Laboratories.

Several members of the STEP staff deserve recognition for their contributions to the preparation of this report. We are once again indebted to Alan Anderson for his preparation of the meeting summary and his contribution to the introduction. We wish to thank Sujai Shivakumar, who recently joined the STEP team, for his many contributions to the report. We are also indebted to David E. Dierksheide and McAlister Clabaugh, who have once again played an instrumental role both in preparing the conference and, with Christopher Hayter, helped prepare this report for publication.

NRC REVIEW

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 NRC'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: Dr. Martin N. Baily, Institute for International Economics; Dr. Kenneth Flamm; Lyndon B. Johnson School of Public Affairs, University of Texas; Dr. Barbara M. Fraumeni, Bureau of Economic Analysis; Dr. Robin Gaster, North Atlantic Research, Inc.; and Dr. Daryl Hatano, Semiconductor Industry Association.

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

STRUCTURE

This report has three parts: an Introduction which summarizes the proceedings and issues associated with the New Economy, followed by the Proceedings themselves, and supplemented by a recent research paper. This report represents the first step of a major research effort by the Board on Science, Technology, and Economic Policy designed to advance our understanding of the factors shaping the New Economy, the metrics necessary to better understand it, and the policies best suited to sustaining the greater productivity and prosperity that it promises.

Dale W. Jorgenson Charles W. Wessner

I

EXECUTIVE SUMMARY

Executive Summary

Throughout the 1970s and 1980s, Americans and American businesses regularly invested in ever more powerful and cheaper computers. In doing so, they assumed that advances in information technology would yield higher productivity and lead to better business decisions. These expected benefits did not materialize—at least in ways that were readily measured. This phenomenon was called the "computer paradox," after Robert Solow's remark in 1987 that "we see the computer age everywhere except in the productivity statistics."

By the mid-1990s, however, new data began to reveal an acceleration of growth accompanying a transformation of economic activity. This shift in the rate of growth coincided with a sudden, substantial, and rapid decline in the prices of semiconductors and computers. After 1995 it appears there was a point of inflection; price declines abruptly accelerated from 15 to 28 percent annually. In the same period, investments in computers exploded. The contribution to growth attributed to computers rose more than five-fold to 0.46 percent per year in the late 1990s. Software and communications equipment contributed an additional 0.30 percent per year for 1995 to 1998. Preliminary estimates through 1999 suggest further increases for all three categories.

This period also coincides with the widespread adoption of the Internet, the emergence of the "dot-com" e-companies, a surge in venture capital investment and, in some quarters, predictions that the concept of business cycles no longer applied. The symposium reviewed in this volume does not focus on the transitory phenomena once identified with the New Economy. Indeed, the decline of the dot-com companies and the re-emergence of the business cycle were already apparent when the symposium was convened.

The New Economy referred to here addresses changes in the U.S. economy as it capitalizes on new technologies, new opportunities and—in particular—on national investments in computing, information, and communication technologies. Use of this term reflects a growing conviction among economists that substantial change is underway in the U.S. economy—a change driven by continued gains in productivity in large part due to the production and deployment of information technology.[1] From 1973 to 1995 U.S. productivity growth was at the rate of 1.4 percent a year. Between 1996 and 2000, however, labor productivity grew at an annual rate of 2.5 percent a year.

Although a macroeconomic phenomenon, the processes underlying the New Economy appear to combine elements of technological innovation, structural change, and public policy.

- The rapid rate of technological innovation in information technology—most evident in the observance of Moore's Law—seems to underpin the New Economy's productivity gains.
- Structural changes have arisen from a reconfiguration of knowledge networks and new patterns of business activity made possible by innovations in information technology. Business-to-business e-commerce and Internet retailing, among other new methods, enable firms and individuals to communicate, manage inventory, handle production processes, and make purchases more efficiently.
- Public policy can sustain the New Economy in important ways. Government policies such as those on taxation, regulation, and intellectual property protection provide the underpinnings for economic growth. Public procurement and cooperative activities, such as cost-shared partnerships and general support for education and scientific and engineering research, directly affect processes of innovation, often decisively. Rules of the game, including antitrust and other regulations that set the bounds of competition, form an additional element of the broader public policy framework.

THE CHALLENGE OF MEASUREMENT

Change is often slow to become apparent in ways that can be readily measured, especially when it occurs in ways not previously measured. For example, recent measures reflect soaring labor productivity growth in the computer manufacturing industry. Productivity growth has also been generally higher for indus-

[1]Not all economists, however, are ready to proclaim a technologically driven New Economy, if only because they have been unable to discern a measurable economy-wide benefit from the substantial investments that U.S. business has made in these new technologies. See, notably, R. Gordon. 2000. "Does the New Economy Measure up to the Great Inventions of the Past?" *Journal of Economic Perspectives* 14(4) Fall.

tries that manufacture durable goods. Similar changes are less apparent outside these sectors although many, including the service sector, have invested heavily in information technologies.[2] Measurement problems at present preclude a clear resolution to this puzzle. Understanding the New Economy phenomenon through better data is key to the task of developing policies that sustain it.

SUSTAINING THE NEW ECONOMY

Innovations, particularly in information technologies, are believed to be fueling this boost in productivity.[3] In addition to the analysis presented here by Jorgenson and Stiroh,[4] recent studies by Oliner and Sichel[5] show that rapid adoptions of information technologies, made possible by a concomitant fall in price, have been an essential factor propelling U.S. productivity gains. Maintaining this pace, in turn, depends on maintaining the rate of technological innovation in the information technology sector. Sustaining the New Economy over the longer run thus may depend to a considerable extent on continued technological innovations and the supporting policies needed to preserve the pace of technological advance envisaged in Moore's Law.

EXPANDING THE NEW ECONOMY

Developments in the semiconductor industry have enabled a swift decline in the price of information technologies. This, in turn, has provided economic incentives for firms to substitute information-technology-based equipment for other forms of capital and labor services. This injection of new capital is understood to underpin the rise in productivity.[6] Widening use of the Internet has also

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[2]Robert Gordon, *op. cit*., notes, for example, that since service industries stand in the middle of the supply chain, their contributions are finally embodied in the final goods sold to consumers. If so, they would be measured as a part of the Gross Domestic Product. Others, such as Brynjolfsson and Hitt argue that the benefits of new information technologies rarely show up in official macroeconomic data since these do not pick up changes in product quality, time savings, convenience, etc. See, Erik Brynjolfsson and Lorin M. Hitt. 2000. "Beyond Computation: Information Technology, Organizational Transformation and Business Performance," *Journal of Economic Perspectives* 4(4), pp. 23-48, Fall.

[3]Innovations in biotechnology, such as genomic-based drug development, and in energy supply, such as solid-state lighting and fuel-cell technologies, promise to add further to the high-tech base of the New Economy.

[4]See Dale W. Jorgenson and Kevin J. Stiroh, "Raising the Speed Limit: U.S. Economic Growth in the Information Age," in this volume.

[5]Stephen Oliner and Daniel Sichel. 2000. "The Resurgence of Growth in the Late 1990s: Is Information Technology the Story?" *Journal of Economic Perspectives* 14(4) Fall.

[6]See Dale Jorgenson, "Information Technology and the U.S. Economy." Presidential Address to the American Economic Association, New Orleans, LA, January 6, 2001.

created significant potential for increasing productivity.[7] Expanding and deepening the adoption of information technologies across the economy is also seen as an essential component to sustaining the productivity growth characteristics of the New Economy.

To address these issues the Board on Science, Technology, and Economic Policy convened a symposium on "Measuring and Sustaining the New Economy" on October 6, 2000. As the STEP Board's Vice-Chair, Bill Spencer noted, the symposium was convened out of both a sense of opportunity and a sense of uncertainty. While sustaining the New Economy is crucial for sustaining U.S. prosperity, a lack of data leaves unresolved many related policy questions. The symposium brought together a group of national experts to examine where additional information and research is needed on growth in the Information Age. The participants focused their deliberations on defining and measuring the New Economy, examining its technological drivers, and expanding applications of advanced technologies across the economy.

[7]See Robert E. Litan and Alice M. Rivlin. 2000. "The Economy and the Internet: What Lies Ahead?" Internet Policy Institute: <http://www.internetpolicy.org/briefing/litan_rivlin.html>, November.

II

INTRODUCTION

Introduction

The term "New Economy" has been used extensively in recent years. It describes the dynamic of the U.S. economy as it capitalizes on new technologies, new opportunities, and in particular on national investments in computing, information, and communication technologies—or collectively, information technology. Use of the term New Economy also reflects the growing conviction that substantial change has occurred in the structure of the U.S. economy and that this change may be permanent.[1] This change, it is thought, hinges on dynamic increases in productivity and the correlating impact of investments in the information technology sector.[2]

[1]See Organisation for Economic Co-operation and Development. 2000. "Is There a New Economy? A First Report on the OECD Growth Project," June, p. 17. See also, M. N. Baily and R. Z. Lawrence. "Do We Have an e-conomy?" NBER Working Paper 8243, April 23, 2001, at http://www.nber.org/papers/w8243.

[2]This is especially so for the computer hardware sector and perhaps for the Internet sector as well, although there is insufficient empirical evidence on the degree to which the Internet may be responsible. For a discussion of the impact of the Internet on economic growth see "A Thinker's Guide," *The Economist*, March 30, 2000. For a broad study of investment in technology capital and its use in various sectors, see McKinsey Global Institute. 2001. *U.S. Productivity Growth 1995-2000, Understanding the Contribution of Information Technology Relative to Other Factors.* Washington, D.C.: McKinsey & Co. October.

THE ECONOMIC IMPACT OF THE SEPTEMBER ATTACKS

The tragic events of September 11, 2001 delineate a new period of economic uncertainty in the United States.[3] As noted at the time of the conference (see below), the recent downturn in the economy comes on the heels of earlier warning signals—including the burst of the dot-com bubble—indicating that the economic boom of the 1990s was slowing. Prospects for the global economy also appear to have deteriorated, with fading growth prospects for America's main economic partners.[4] The economic costs inflicted by the attacks are known to be substantial, but their full scope and the appropriate policy response are still unclear. These developments have led some to question whether the optimism of the "New Economy" was not merely a fad.

The premise of this report is that the New Economy is not a fad but, rather, a long-term productivity shift of major significance. In the context of this analysis, the New Economy does not refer to the boom economy of the mid to late 1990s. The introduction of advanced productivity-enhancing technologies, the key feature of the New Economy, obviously does not eliminate the business cycle. Instead, as this report emphasizes, the New Economy refers to particular technological and structural changes that positively impact productivity and growth. These positive developments need to be understood better if they are to be nurtured by appropriate policies. To do so, issues of measurement must be addressed on a systematic basis by the responsible agencies. Measuring and sustaining the investments that underpin the recent growth characteristic of the New Economy thus take on an added imperative in the normal downturns of the business cycle. The aggravation of the cyclical downturn caused by the shock of the September attacks makes this effort all the more timely and pressing.

At the time of this workshop in October 2000, the strength and durability of U.S. economic performance continued to surprise forecasters, although the clouds on the horizon were apparent even then. Indeed, the value of many of the "dot-com" companies, which to some characterized the New Economy, had fallen steeply by then. This sharp drop in value and resurgence of more traditional business models created uncertainties about a new era of growth. Economic developments since the workshop have, of course, accentuated these concerns, emphasizing the policy relevance of the issues identified in this report.

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[3]See "The Business-Cycle Peak of March 2001," National Bureau of Economic Research, November 26, 2001, at http://www.nber.org/cycles/november2001/. While dating the beginning of the recession as March 2001, the NBER Business Cycle Dating Committee noted that "the [September] attacks clearly deepened the contraction and may have been an important factor in turning the episode into a recession." The Committee also found "continuing fast growth in productivity" after March 2001, noting that this and the "sharp declines in the prices of imports especially oil raised purchasing power while employment was falling."

[4]See "GDP Forecasts," *The Economist*, November 22, 2001. This article reports on recent estimates by the OECD that the industrial world is experiencing the first economic contraction for 20 years.

Box A: Key Questions About the New Economy

As they look for ways to describe this New Economy, economists have raised, among others, the following questions[5]

- Has the economy growth rate trend been raised, and could it go even higher?
- Has the lowest unemployment rate consistent with stable inflation (or NAIRU—the Non-Accelerating Inflation Rate of Unemployment) been reduced? If so,
  — How much further might it fall?
  — How long can the economy expand without the emergence of inflation?
  — How long can productivity increases and global competition keep wage pressures in check?
- Have the primary sources of growth changed with the emergence of information technology?
  — Will "Moore's Law"[6] continue to contribute to productivity growth?
  — Will the synergies between Moore's Law and Metcalfe's Law[7] generate spillovers that fuel growth in other sectors?

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[5]See for example, K. Stiroh. 1999. "Is There a New Economy?" *Challenge,* July/Aug, Vol. 42, No. 4, 1999, pp. 82-101.

[6]See Gordon E. Moore. 1965. "Cramming More Components onto Integrated Circuits," *Electronics* 38(8) April 19. Here, Dr. Moore notes that "[t]he complexity for minimum component costs has increased at a rate of roughly a factor of two per year. Certainly over the short term, this rate can be expected to continue, if not to increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain nearly constant for at least 10 years. That means by 1975, the number of components per integrated circuit for minimum cost will be 65,000." See also, Gordon E. Moore, "The Continuing Silicon Technology Evolution Inside the PC Platform," *Intel Developer Update*, Issue 2, October 15, 1997, where he notes that he "first observed the 'doubling of transistor density on a manufactured die every year' in 1965, just four years after the first planar integrated circuit was discovered. The press called this 'Moore's Law' and the name has stuck. To be honest, I did not expect this law to still be true some 30 years later, but I am now confident that it will be true for another 20 years."

[7]Metcalfe's Law poses that the value of communication networks and Internet applications rises as more people are connected.

A CALL FOR MORE INFORMATION

The recent decline in economic activity and the perceived over-investment in some sectors (e.g., telecommunication networks) only underscore the need expressed by the workshop participants for more and better information. The participants affirmed that policy makers need better ways to measure the contribution of software and telecommunications and more information about the contributions of the Internet to the economy. We also need a better understanding of how long the information technology sector can maintain its exceptional pace of growth, based substantially on the progress foreseen by Moore's Law.

Many economists have been reluctant to proclaim a technologically driven New Economy if only because they have been unable to discern a measurable economy-wide benefit of the substantial investments by U.S. business in new technologies. Throughout the 1970s and 1980s Americans and American businesses regularly invested in ever more powerful and cheaper computers. They assumed that advances in information technology—by making more information available faster and cheaper—would yield higher productivity and lead to better business decisions. The expected benefits did not materialize—at least in ways that were readily measured. Even in the first half of the 1990s productivity remained at historically low rates, as it had since 1973. This phenomenon is often called "the computer paradox," after Robert Solow's casual but often repeated remark in 1987: "We see the computer age everywhere except in the productivity statistics."[8]

A Point of Inflection

By the mid-1990s, however, it became clear that something was changing at a fundamental level. While growth rates did not return to those of the "golden age" of the U.S. economy in the 1960s, new data began to reveal an acceleration of growth accompanying a transformation of economic activity. This shift in the rate of growth had coincided with a sudden, substantial, and rapid decline in the prices of semiconductors and computers; the price decline abruptly accelerated from 15 to 28 percent annually after 1995.[9] In response, investment in computers exploded. Computers' contribution to growth rose more than five-fold, to 0.46 percent per year in the late 1990s. Software and communications equipment contributed an additional 0.30 percent per year for 1995-1998. Preliminary estimates through 1999 reveal further increases for all three categories.[10]

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[8]R. Solow. 1987. "We'd Better Watch Out." *New York Times Book Review*, July 12. The implications of the Solow Productivity Paradox have since been actively discussed. For example, see J. E. Triplett. 1999. "The Solow Productivity Paradox: What Do Computers Do to Productivity?" *Canadian Journal of Economics* 32 (2) April, pp. 309-34.

[9]Jorgenson and Stiroh, *op. cit.*, p. 2.

[10]*Ibid.*

With these data in hand, the paper proposed by Jorgenson and Stiroh documents the case for "raising the speed limit"—that is, for revising upward the intermediate-term projections of growth for the U.S. economy. After a 20-year slowdown dating from the early 1970s the average labor productivity had grown by 2.4 percent per year during the period 1995-1998. This exceeded the rate for 1990-1995 by a full percentage point.[11]

Economic Impact of the Internet

Along with the rise in productivity grew the expectation that new information technologies would improve business practices, generate spillovers to other industries, and raise productivity throughout the economy. Some economists anticipated that Internet use, in particular, would contribute to the following:

- **Reduce the cost of transactions** necessary to the production and distribution of goods and services;
- **Enhance the efficiency of management,** especially by enabling firms to manage their supply chains more effectively and communicate more easily both within the firm and with customers and partners;
- **Increase competition,** making prices more transparent, and broadening markets for both buyers and sellers;
- **Increase consumer choice,** convenience, and satisfaction in a variety of ways.[12]

The prospect of savings made possible by applying information technology has resulted in some tantalizing estimates. One such calculation suggests that perhaps $20 billion a year could be saved by digitizing medical insurance claims, with speed and convenience improved in the bargain. Annual economy-wide cost savings, once fully realized, were estimated to grow to $200 billion annually, with consumers rather than businesses the primary beneficiaries.[13]

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[11]Jorgenson and Stiroh, *op. cit.* Also see: Oliner, S. and Sichel, K. 2000. "The Resurgence of Growth in the Late 1990s: Is Information Technology the Story?" *Journal of Economic Perspectives* 14(4) Fall.

[12]Robert E. Litan and Alice M. Rivlin summarized these results at a recent conference held in Washington, D.C. See "The Economy and the Internet: What Lies Ahead?" Internet Policy Institute, November 2000, found at <http://www.internetpolicy.org>. The conference was sponsored jointly by the Internet Policy Institute, the Brookings Institution, the Berkeley Roundtable for the International Economy, the Department of Commerce, and the Organization for Economic Cooperation and Development.

[13]Litan and Rivlin, *op. cit.* (pages unnumbered).

Box B: Total Factor Productivity

Total Factor Productivity (TFP) measures the efficiency with which both the labor and capital factor resources are used to produce output. In other words, higher TFP reflects a smarter and better use of the labor and capital resources available for a given level of output. It is defined as:

$$TFP = Output / (Capital + Labor)$$

This definition, by itself, is simple and uncontroversial, and national accountants have a high-resolution picture of productivity in such traditional sectors in the economy as manufacturing. Here, measures of output and factor inputs are largely well-established.

The question of how to measure the relevant outputs and inputs in the new and fast changing sectors that underpin the New Economy is, however, much less clear and is one of the central themes of this report. The sections below—relating to the challenge of quantification and problems of measurement—highlight the observations of participants in the workshop and underscore the need for the resources necessary to improve government statistical capabilities.

Gains in Total Factor Productivity

To date, the recorded gains in total factor productivity (Box B) have been attributed in substantial measure to the information-technology-producing industries—that is, those that produce computers, semiconductors, and associated products. The evidence is equally clear, however, that these gains have not spilled over to computer-using industries and services, such as finance, insurance, and real estate.[14] Robert Gordon, a critic of many New Economy assumptions, finds that there is "no productivity growth in the 99 percent of the economy located outside the sector which manufactures computer hardware."[15]

[14] Jorgenson and Stiroh, *op. cit.*, p. 3.

[15] Robert Gordon. 1999. "Has the 'New Economy' Rendered the Productivity Slowdown Obsolete?" Manuscript. Northwestern University. June 12. Also, by the same author, "Does the New Economy Measure up to the Great Inventions of the Past? *op cit*.

Box C: Productivity Growth and the Internet

"We have a tantalizing fact—that productivity accelerated at just about the time the Internet burst on the scene. Whether or not the Internet was the cause of the speedup in productivity growth will be a matter for economic historians to sort out some years from now."

Alan S. Blinder, "The Internet and the New Economy"

The Challenge of Quantification

As participants in this workshop agreed, we still cannot quantify the economic impact of the Internet, which came into wide public use in the same year (1995) as Jorgenson and Stiroh's point of inflection. As Alan Blinder writes, this is partly because many Internet-related activities do not appear in official statistics.[16] For example, Internet retailing may offer benefits to consumers, such as easier comparison-shopping, removal of travel costs, and 24-hour availability, but such gains are not counted in the Gross Domestic Product. While the Internet may offer the greatest productivity benefits in the sphere of business-to-business commerce—where vast virtual marketplaces may reduce the costs of supply—the corporate systems and partnerships that may realize these benefits are only now being put in place (Box C).

If Blinder and others are correct, high-speed computers may have been waiting on the connectivity of the Internet to use their power to boost productivity on a national scale.[17] If this is true, we must wait some years more before the productivity statistics capture this change. Meanwhile, the rapid pace of change in this "new" or "emerging" economy provides a smorgasbord of emerging synergies, new economic opportunities, and new statistics to consider and new needs for better measures, as we attempt to determine the emerging outline and prospects of the New Economy.

The Problem of Measurement

Participants in the workshop noted that the contribution of information technologies to the economy is difficult to capture accurately. These problems are

[16]Alan S. Blinder. 2000. "The Internet and the New Economy," Internet Policy Institute, first published January; <http://www.internetpolicy.org>.

[17]For a fuller development of this theme, see Stephen S. Cohen, J. Bradford DeLong, and John Zysman. 2000. "Tools for Thought: What Is New and Important About the 'E-conomy'?" BRIE Working Paper 138 (Berkeley: Berkeley Roundtable on the International Economy).

made more acute given the fast-changing nature of information technology and the complex and often invisible roles it plays in economic processes.

Asymmetries in Data

It was noted that current statistical methods are suited better to pick up some forms of information over others. Illustrating the challenges facing the federal statistical system, Dr. Bresnehan of Stanford University noted the discrepancy between measures of *output* in the information technology sector (which he noted are adequate) and measures of output where information technology is used as an *input* in other sectors (which are not).[18] Dr. Greenstein of Northwestern University added that conventional measures of GDP provide good data on established channels by which goods and services are distributed, but fail to capture such information about goods and services when there are concurrent changes in the distribution methods.[19] Illustrating the implications of asymmetries in data availability, Dr. Price of the Department of Commerce observed that data on the value of packaged software (which is more easily measured both in terms of nominal value and price) may not be as important to productivity as other forms of software whose value is more difficult to capture—resulting in under-valuation.[20] He stressed the need to further refine statistical methods to better quantify the value of information technology.

Difficulties in Measuring Value

Several workshop participants emphasized the problems in *valuing* information technologies. Dr. Flamm of the University of Texas observed that it is difficult to calculate the percentage of improvement in computers that come from semiconductors since the answer depends on the worth of semiconductors in the value of computers.[21] Dr. Brynjolfsson of the Massachusetts Institute of Technology further noted some hazards in equating price with value for computers, particularly given that consumers are often not price-sensitive, valuing instead service, brand loyalty, and perceived quality.[22] Further to the issue of value, Dr. Mowery of the University of California at Berkley noted that it is difficult, from the point of view of statistics, to see the contributions of the semiconductor industry since it is hard to measure the output of "user" industries. He added that the economy outside the computer industry has become "a bit of a black planet" in terms of understanding quality improvements in their products.[23]

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[18]See remarks by Dr. Bresnahan in the Proceedings section of this report.
[19]See remarks by Dr. Greenstein in the Proceedings section of this report.
[20]See remarks by Dr. Price in the Proceedings section of this report.
[21]See remarks by Dr. Flamm in the Proceedings section of this report.
[22]See remarks by Dr. Brynjolfsson in the Proceedings section of this report.
[23]See remarks by Dr. Mowery in the Proceedings section of this report.

Box D:
Challenges for Accurate Measurement of the New Economy

The workshop, which drew together economists with an appreciation of technology and technologists with an appreciation of economics, identified key challenges regarding the measurement of the New Economy. Among the core themes that run through the report are

- the need for better measurement of the output of the service sectors,
- the impact of technology on user sectors,
- the contribution of the semiconductor industry,
- the emergence of the communications industry,
- changes in distribution methods,
- organizational capital and other intangibles,
- assessing the value of business information systems, and
- difficulties when investments are reported as expenses in source data.

As Dr. Lee Price of the Department of Commerce observed, "From the vantage point of an economist, one of the largest challenges is accurately measuring what is happening in the New Economy."

The Technology Adoption Curve

The impact of new technologies on the sustainability of the New Economy rests crucially on how information technologies are integrated and adopted throughout the economy. Workshop participants, both implicitly and explicitly, referred to an S-shaped technology adoption curve for new technologies. Some argued that we are near the bottom of the curve and about to take off; others suggested that we are in the middle and thus enjoying rapid productivity gains from the widespread adoption of information technologies; still others indicated that marginal productivity gains from information technologies might be waning, signifying that we are already near the top of the technology adoption curve.

Workshop participants noted that a major constraint in sustaining the New Economy might not be the rate of innovation itself, but rather the rate of technology absorption. Sid Abrams of AT Kearney noted that business organizations often face challenges in reengineering themselves to take better advantage of the technologies available. While the cutting edge of technology may advance, their potential to advance business productivity may depend on the extent that executives are aware of the possibilities and/or uncertain of the effects of adopting new technologies in their organizations. Indeed, as Ralph Gomery of the Alfred P. Sloan Foundation concluded, the ability to *absorb* rapid advances in technology and the cost of re-doing the business organization to take advantage of these advances are, in many cases, more significant for sustaining productivity-led growth than the rate or *propulsion of* technological advance. In essence, the question is not merely one of more technology, but rather one of how businesses can integrate productivity-enhancing changes induced by technology they already have or find available.

SUMMARY OF THE WORKSHOP

This section summarizes the presentations and comments of the participants. The Proceedings section reports these in more detail.

In opening remarks, Bill Spencer observed that the workshop was being convened out of a sense of both uncertainty and opportunity. The STEP Board had agreed to instigate this study, in part, from feeling that many issues related to recent economic growth, the impact of information technologies, and the Internet were distinguished by many questions on one hand and a surprising lack of data on the other. This gap is particularly evident in productivity growth derived from new technologies and their collective impact on the economy. The Internet exemplifies both the potential and the uncertainty of major features of this new economy.

A Revolution to Rival the Industrial Revolution?

Dr. Vint Cerf opened his remarks with the bold opinion that the "consequences of this information revolution will be as great or greater than the effects of the industrial revolution." He then qualified this assertion by noting that the Internet is in its early years and no one can yet predict which ideas for the Internet will prove most useful as we move through the current period of experimentation. He emphasized that the growth of Internet use, while extremely fast, is distributed unevenly. Its continued growth faces a variety of challenges involving technological challenges (e.g., carrying new modalities, smoothing two-way service, finding enough addresses for everyone), as well as economic and political challenges (e.g., such as who should own, regulate, and tax digitized information). He predicted additional ubiquitous devices, more daily uses, and more convenience as we learn to apply the emerging capabilities of the Internet. In response to a question from Dr. Wessner, Dr. Cerf suggested that the most likely showstoppers in Internet growth will not be technical but political, as traditional sources of tax revenue and authority are eroded by technical progress.

Panel I: Defining and Measuring the New Economy

Robert Shapiro of the U.S. Department of Commerce noted that the U.S. economy seems to have entered a high-performance period in the 1990s that looks different from others.[24] He acknowledged that his department faces many difficulties in "measuring" the New Economy. The U.S. economy, he observed, has matured, yet productivity gains have accelerated, real GDP growth has quickened, real hourly wages have risen, business investment has continued to rise (most of it for information technology) while inflation has remained moderate. Beneath the higher productivity and growth figures, he identified three conditions:

1. Capital deepening—the acceleration in the growth of capital stock.
2. Disinflation, which has held back price pressures for more than a decade.
3. Innovation, particularly in technology that drives productivity.

Other contributing features, he noted, were network effects (where the value of an innovation increases the more it is used), cascading innovation (new information technology brings deeper changes in the way a firm operates), and networks that match manufacturers with their suppliers. The discussion following his talk made clear the continuing need for and challenge in providing statistical techniques that capture these new features of the economy.

The Point of Inflection

Dr. Jorgenson addressed the economic acceleration in the 1990s with a more specific focus on the period around 1995. At that point, the ongoing decline in computer prices reached a point of inflection and suddenly doubled. In searching for the causes of this point of inflection, Dr. Jorgenson noted that he found that total factor productivity was rising in some industries, including information technology but not in all. The sustainability of this increased rate of growth, he concluded, depends on the persistence of high rates of technological progress and is subject to considerable uncertainty because of incomplete information about prices of software, telecommunications equipment, and other important sectors.[25]

Dr. Cerf commented that software costs have risen in the telecommunications industry and wondered whether this could limit future productivity. Dr. Brynjolfsson said that although software productivity had not been measured

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[24]At the time of this workshop, Robert Shapiro was serving as Under Secretary of Commerce for Economic Affairs.

[25]See the paper by Dale W. Jorgenson and Kevin J. Stiroh, "Raising the Speed Limit: U.S. Economic Growth in the Information Age" in this volume. See also Dale W. Jorgenson, "Information Technology and the U.S. Economy," Presidential Address to the American Economic Association, New Orleans, Louisiana, January 6, 2001.

as accurately as hardware productivity, it was still growing impressively—on the order of 10 to 15 percent. He felt that this improvement was not yet reflected in official statistics.

Dr. Raduchel commented that software production was a hardware-intensive process, so that economies in hardware tend to reduce software costs and raise productivity. Dr. Raduchel also summarized his experiences in re-engineering companies, emphasizing that the portion spent on information technology is only 5 to 10 percent; the rest is spent on training, testing, data collection, and other human activities that by current accounting standards, are recorded as General and Administrative expenses (G&A) rather than as investments in productivity.[26] Dr. Jorgenson concluded the discussion by reiterating the need for a better understanding of software productivity and suggesting that the recent inclusion of software in Department of Commerce statistics was a sign of progress.

Panel II: Drivers of the New Economy

Dr. Gomory opened the panel by emphasizing the difficulty of predictions, and urged some humility in the present exercise—a sentiment that was echoed by other participants. While hardware predictions are difficult, software predictions are more so, and most elusive of all are predictions about the social consequences of technological transformations.

Dr. Gomory then introduced Dr. Spencer, who began his presentation with the "modest proposal" that the nation's recent surge of economic growth may be entirely due to semiconductors. While inviting critiques of that serious hypothesis, he said he would also address the impact of semiconductors on other information technology components and raise some questions about what might happen if the growth in that technology slows. He noted that the rapid growth of the industry was driven partly by lower costs (especially for microprocessors, magnetic memory, and DRAMs) and the higher productivity described by Dr. Jorgenson. This higher productivity, he said, comes at a time when most engineers see the approach of physical limits on further improvements in minimum feature size, transistor density, oxide layering, and other critical features of semiconductors.

Dr. Jorgenson asked whether advances in non-semiconductor technologies might stave off the time when the semiconductor industry hits a physical "wall" of limits. Citing such examples as fiber optics and ways of writing software more efficiently, Dr. Spencer agreed that the future of IT would depend not only on semiconductor productivity, but also in jumps in other complementary technolo-

[26]For a discussion of "Organizational Informatics," see Rob Kling and Roberta Lamb, "IT and Organizational Change in Digital Economies: A Sociotechnical Approach," in Brynjolfsson and Kahin, eds., *Understanding the Digital Economy,* p. 296. They write: "Thirty years of systematic, empirically grounded research on IT and organizational change suggests that many organizations have trouble changing their practices and structures to take advantage of IT."

gies. Dr. Raduchel added that the most interesting challenges would likely involve finding more effective uses for already developed technologies. "Innovations have no value," he said, "unless consumers see that value and use it."

Unchanged Productivity in R&D

David Mowery of the University of California, Berkeley, turned to the "economics of the New Economy," trying to see how advances in information technology have propelled new process and design techniques. He found that instead of using computer simulations and other new techniques, the process side of information technology was relatively old-fashioned, relying on incremental change. Into this gap has leapt a range of specialized firms that design, develop, and market process technologies, as well as supply and equipment technologies. These firms increasingly specialize in individual pieces of "real estate" on wafers and chips, trading techniques among themselves on the Internet. More generally, he said, there is still no evidence that information technology has raised the "productivity" of R&D or of knowledge production. To gain a better grasp of the importance of semiconductors to the larger economy, we need better measures of quality improvement in automobiles, consumer electronics, and communications, major end-users of semiconductors.

During the discussion period, Dr. Mowery commented again on the vertically specialized firms that are entering the semiconductor industry to focus on development at the leading edge of commercial technology. He questioned whether such highly focused "upstream" research could be maintained unless it is supported by more basic research—a concern seconded by Dr. Gomory.

Five Trends of Microprocessors and Computers

In his presentation Alan Ganek of IBM posited five major trends, drawn from recent innovations in information technologies. The first is a continuing ability to overcome apparent physical limits in information technology. Improvements in processors from innovations in materials and designs are not the whole story, noted Mr. Ganek. He pointed also to circuit design, logic design, and packaging techniques as well as to improvements in memory storage and fiber optic technology as key factors propelling progress in information technology.

The second trend brought to light was the growing pervasiveness of computing devices that will interconnect computing everywhere and change the way people interact with other people and objects in the digital world. While the personal computer will remain important, he noted that pervasive devices, such as data-capable cell phones and personal digital assistants, will become the dominant means of information access.

The third trend is a utility-like model for value delivery to businesses based on an intelligent infrastructure. Here the network becomes a repository of intelligence across a broad spectrum of applications, such as caching, security, multicasting, and network management, so that the application does not know what the device looks like.

The fourth trend relates to the formation of e-marketplaces and virtual enterprises. Of all the software being written, noted Mr. Ganek, the most important relates to such enterprise processes as business-to-consumer and business-to-business activities. He observed that the building blocks of electronic commerce are already emerging to support these processes.

Mr. Ganek's fifth prediction was that electronic businesses of the future will be dynamic, adaptive, and continually optimized. They will facilitate powerful business analytics and knowledge management. Computers will no longer be seen as tools of automation but will be an integrated part of strategic decision making.

He closed by emphasizing that the pharmaceutical industry is about to enter a dramatically new phase through the introduction of "deep computing" for rational drug design, genomic data usage, personalized medicine, protein engineering, and molecular assemblies.

During the discussion period Dr. Myers of Xerox asked about the possibility of thinking machines—a goal of NASA, for example, in developing semi-autonomous, self-learning spacecraft. Mr. Ganek replied that many people are working toward this goal, but so far their systems are not holistic in the sense of being able to do actual learning and they have not been able to simulate the ability of neural networks.

Something Very Significant

Kenneth Flamm of the University of Texas at Austin continued the discussion of computers and microprocessors by looking at trends from an economist's viewpoint. He began by addressing what Dr. Jorgenson described as a point of inflection; when the steady trend in computer price declines seem to have accelerated abruptly around 1995. Dr. Flamm said that after years of seeing only a steady decline, he too had come to the view that an acceleration—of a magnitude even greater than described in official figures—had occurred. He had calculated a quality-adjusted price performance of 60 to 68 percent per year for microprocessors, which he called extraordinary. He concluded saying that something "very significant for the economy" had happened and that it was likely to have a lasting, positive effect.

Panel III: Communications and Software: A Globally Distributed System

Robert Borchers of the National Science Foundation, the moderator of this session, said that several studies had made positive linkages between basic research in information technology and the economy. As a result, the National

Science Foundation now funds basic information technology research in universities on many of the questions being raised in this workshop.

The first speaker, Alfred Aho of Lucent Technologies, talked about the impact of basic research, and particularly communications research, on the information-based economy. He sketched a world of communications systems that will not simply be automated versions of existing systems. These, he said, will be replaced by radically new styles of services that effectively turn the world into a global distributive system that will include data, computation, and communication. These services will depend heavily on improved software productivity and reliability, where considerable effort is now focused.

Daniel Ling of Microsoft observed that while progress has been made in software productivity, there remain worrisome needs that merit much more research. He described various advances in communications, including the advent of "post-Internet" software adapted primarily for wireless devices; the potential for data accessibility "anytime, anywhere"; the digital convergence of sound, video, and other media; and the evolution of software from a purchased commodity to an online service tailored to specific needs.

Panel IV: Applications and Policy Issues

As moderator, Dr. Raduchel of AOL Time Warner opened the session. Acknowledging the difficulty of defining the new economy, he suggested that one of its central features was likely to be the wide availability of information, made possible first by the copier and now by e-mail. He illustrated the power of democratized information with several anecdotes and urged the workshop participants to continue to focus on this task of definition.

Shane Greenstein of Northwestern University continued the discussion of communications by examining ways to sustain innovation in communications markets and identifying policy issues that deserve attention. He highlighted several issues facing communications markets. These include:

- the difficulties of adapting the essentially free environment of the Internet to a commercial environment;
- the regulatory complexities of bringing the Internet the last mile into users' homes and offices;
- the best ways to narrow the digital divide between Internet users and non-users; and
- the difficulties in deciding whether commercial and security "gateways" that restrict Internet access are acceptable.

Turning from policy to applications, Eric Brynjolfsson of the Massachusetts Institute of Technology reiterated previous comments about the risk of making predictions and suggested that e-business is not exempt from this risk. In marketing, for example, he observed that one early prediction was that the Internet would bring fierce price competition and eliminate brand loyalty. In a study of online booksellers, however, Dr. Brynjolfsson and colleagues found that there were three other variables in addition to price, the most important being whether the buyer had visited that Web site before. More generally, consumers appear to perceive more differences between products than that which economists might impute to them. These distinctions are made in gauging customer service, product selection, and the convenience and timeliness of the product or service offered. In addition, he amplified Dr. Raduchel's point that e-business is only fractionally concerned with actual technology, and most of its activity concerned implementation, organization, and co-inventions that bring valuable new abilities. He suggested that businesses need significant changes in accounting to reflect the true value of corporate assets.

Elliot Maxwell of the U.S. Department of Commerce turned from economic issues of e-business to consider a series of policy questions:

- How will the issue of taxing e-commerce be resolved?
- Who will control and apportion the electromagnetic spectrum?
- Will the infrastructure, on which e-commerce rides, be robust enough?
- Who will control the domain name system and open it to competition?
- Can the privacy of Internet users be assured?
- How can national laws be applied to an international Internet?
- Can intellectual property be preserved on an open Internet?

"I think what we are striving to do in the government," said Mr. Maxwell, "is to find ways to work together with the private sector, non-governmental organizations, consumers, and businesses." If we work together, he concluded, we might find solutions that allow and encourage the growth of e-commerce instead of stifling it.

Tim Bresnahan of Stanford University returned to the theme discussed by Dr. Brynjolfsson: value creation from the use of information technology. We do not yet have the tools, he said, to measure the value of business information systems, which are "among the most valuable human artifacts." This problem is amplified by the difficulty of changing business systems and the high organizational costs of such changes. In noting recent changes that had enhanced value, he conjectured that the advent of the Web browser might have had more impact than commonly supposed—and could even explain at least part of the point of inflection noted by Dr. Jorgenson. This single innovation had solved a "best of both worlds" problem in permitting applications that are as easy to use as personal computers but have the power of large systems.

Continuing to address the theme of value, Sid Abrams of AT Kearney said that he works with senior executives and major companies to help them navigate and take advantage of dramatic changes in the business world. Many of his clients are daunted by the challenge of new technologies and unsure about their eventual benefit. To assuage their anxieties and justify the substantial investments, e-business techniques would have to bring companies closer to their customers and more tightly integrate them with other businesses in ways that improved effectiveness and profits.

Panel V: Roundtable Discussion

Dr. Jorgenson moderated the discussion and opened by requesting suggestions on how to structure further discussion of the complex and central topic of the New Economy. Dr. Raduchel responded that two central issues deserved further discussion: measurement and sustainability. There is much uncertainty about how to measure the parameters of the New Economy, he said. Much of the available data is not reported in useful forms and is not helpful in understanding trends. Dr. Price agreed, saying that one of his largest challenges in the Department of Commerce is to measure accurately what is happening in the New Economy. Many economists believe that some features of growth have changed, he said, but without better measurements he cannot verify these changes, isolate their causes, or predict whether they will continue.

Dr. Brynjolfsson underscored the need to measure the "dark matter" other speakers had referred to. He said that some of it might be difficult or even impossible to measure but not all of it. The good news, he said, is that the Internet itself is producing new, large data sources, such as those he demonstrated in his talk.

Dr. Raduchel also suggested that the United States needs to move toward a more tightly coupled Internet (that is, one like telephony in which one or a few agents were able to rationalize regulatory conditions).

Absorption and Cost

Dr. Gomory agreed with earlier speakers that the rate of technology advances was "not the name of the game" today but rather the ability to absorb it and the cost of re-doing the business organization to take advantage of it. The question is not one of how businesses can acquire more technology but one of how they can integrate changes induced by technology they already have.

As an additional point, he said that changes are relatively easy to make in the business world, where the desire to be successful and profitable is a powerful driver. He suggested that one of the great-unrealized possibilities for the New Economy is to find useful drivers for areas such as education and government where business motivations do not apply.

Key Role of Technical Standards

Dr. Jorgenson asked for a technologist's view of these questions, and Mr. Ganek suggested that the issue of technical standards, especially for wireless devices, was crucial in sustaining the economy. Without standards and better access technologies, the United States could find itself at a competitive disadvantage. Dr. Aho agreed that if wireless becomes the dominant mode of accessing the information infrastructure, the intellectual leadership driving the Internet may move offshore. Dr. Flamm said that one explanation for the United States' slow progress in wireless is national economic forces. That is, unlike Europe and Japan, the United States has a fixed-rate access model for local landlines, meaning that telephone service—and Internet connections—are essentially free.

Dr. Aho raised two other points. One was the need to ensure the reliability of the Internet infrastructure, which, like the highway system needs to be refurbished periodically and will never be completed. The second point was that the Internet came out of a government research program. Yet there has been little discussion about what roles the government should—and should not—play in facilitating the transition to new ways of doing business and arbitrating issues such as taxation that set the parameters for that business.

Dr. Mowery agreed that measurement should have a high priority and suggested that a panel of the National Academies could be an appropriate body to articulate the characteristics and effects of needed investments in e-commerce applications. He said that many studies have demonstrated that 80 percent of the investments are non-technological investments but that this conclusion cannot be repeated frequently enough.

Jeffrey Macher of Georgetown University echoed Dr. Mowery's comments on measurement and suggested a study of learning curves. He referred to the day's discussion of semiconductors and its learning curve for density, optics, transmission capacity, magnetic storage, and other features. He suggested an attempt to determine whether shifts of the learning curve are caused by new science, new technology, or some government policy and whether features of each industry, such as market structure, industry standards, and government policy, are influenced by changes in productivity.

Dr. Ling of Microsoft advocated more work on the issue of sustaining the economy and whether adverse conditions of intellectual property, privacy, and taxation could become major obstacles to economic growth by starting to fragment the market.

Margaret Polski of AT Kearney brought up the need for additional research on Internet technologies and the lag time between original research and implementation. Dr. Spencer agreed and emphasized that we are living off the results of research done 25 and 30 years ago.

In closing remarks, Dr. Wessner noted a disjunction between the predictions of continued technological progress and the difficulties faced by CEOs in capitalizing on new technologies. If CEOs do not find new applications useful and manageable, he asked, would they continue to invest in information technology at the same level? He also underlined the importance of Mr. Maxwell's series of questions about taxation and other potential policy roadblocks to the development of economies, noting that to achieve the enormous promise of these technologies, public policy will have to evolve in many significant ways.

Dr. Spencer closed the symposium by thanking the participants for their contributions in both technology and economics and reiterated the importance of better understanding the concept of the New Economy and of devising better ways to measure its activities.

Dale W. Jorgenson   Charles W. Wessner

III

PROCEEDINGS

Introduction

Bill Spencer
International SEMATECH

Bill Spencer, Vice Chairman of the National Research Council's Board on Science, Technology, and Economic Policy (STEP), introduced himself and welcomed participants to the meeting on measuring and sustaining this "New Economy." He said that his interest in the topic began more than a year ago when a course on the topic was initiated by a group of students at the University of California, Berkeley. Surprised at the degree of the group's interest, he subsequently agreed to co-teach a course with Dr. Kenneth Flamm, one of the workshop participants, on "The Technology and Economics of the Internet."

Dr. Spencer said that, while he had learned a great deal about economics from his colleagues, he felt economic issues related to the Internet were distinguished by many questions and a "surprising" lack of data, particularly on productivity growth in some technologies. He subsequently learned that Dr. Dale Jorgenson, another workshop participant and STEP Board Chairman, had studied the topic. Further discussions between the two evolved into the current workshop.

Dr. Spencer said that the format of this STEP meeting, like others that have introduced broad, complex topics, was designed to bring together a small group of experts to examine an area where information and research may be needed and to consider additional workshops on more specific topics. He invited the participants to help locate and develop the subtopics that might shed the most light on questions of economic growth in the information age.

He also thanked several groups for helping to make this symposium possible, including Sandia National Laboratories, the National Institute of Standards and Technology, NASA (for a major grant to the STEP Board), and the staff of the National Research Council. He then introduced the first speaker, Vint Cerf.

Welcome to the New Economy

Vint Cerf
WorldCom

Dr. Cerf, widely regarded as one of the fathers of the Internet, said that he planned to offer a sense of where the Internet is now and where it's going, and to raise several policy issues, including the nature of the economics of the Internet. As a point of departure, Dr. Cerf said that the following features distinguish the Internet:

- It is the largest network of networks in the world.
- It uses TCP/IP protocols and packet switching.
- It runs on any communications substrate.

Dr. Cerf began by suggesting a parallel between the generation of electric power and its distribution over copper wires and the generation and distribution of information and computation via the Internet. It is well known that electric motors run 24 hours a day doing chores, many of which are invisible, such as powering the compressors of household refrigerators. We each are likely to depend on tens to hundreds of these motors, often without being aware of them, as part of our modern infrastructure. The Internet and computers linked to it will be of similar importance so that each of us would depend on hundreds or thousands of pieces of software that run in the background, doing invisible jobs for us. Unlike electric motors, which tap into the power of huge generators on the electrical grid, computers tap into information drawn from anywhere on the network. The consequences of this information revolution would be as great or greater than the effects of the industrial revolution.

A Brief History of the Internet

Dr. Cerf reminded the audience that the Internet is in fact hundreds of thousands of connected networks. The reason it can function is that all the networks use the same set of protocols. An important point is that these networks are run by different administrations, which must collaborate both technically and economically on a global scale.

This system was also designed to run on any communications substrate. Dr. Cert said that when he and Robert Kahn first started collaborating, they wanted to make sure that the Internet and Internet packets would run on top of any future communications technologies that might develop. Thus, they chose the simplest format they could imagine—underlying technologies that only had to deliver digital signals from point A to point B with some probability of arrival greater than zero. The goal of designing the Internet protocol to run on everything, he said, was so important that they had a T-shirt made that read “IP on everything.” This objective has remained essentially intact for 25 years. Now, however, as a consequence of creating this communications substructure of Internet protocol, people are beginning to use it for other applications that sit on *top* of the underlying infrastructure.

The Future of the Internet is Uncertain

Dr. Cerf said that the Internet was still in the middle of its “gold rush” period, which has several implications. The first is that this gold rush will probably resemble others in that the people who make money during a gold rush are not the people looking for gold but the people selling picks and shovels to the miners. This is what the telecommunications companies have been doing—selling the electronic equivalent of picks and shovels to people who are looking for gold on the Internet. The second is that no one knows exactly where or how much gold will be found. There are many business models and many new ideas for businesses on the network as we move through a period of great experimentation.

Growth is Rapid but Early

Dr. Cerf noted that the period of rapid Internet growth began in 1988, when the number of computers on the network began to double each year. Between 1997 and 2000, the number of dot-com domains alone grew from 1.3 million registrations to 15 million. In the same period, the number of hosts almost quintupled. The number of countries accessible on the Internet rose to 218. A few weeks before the workshop the last of Africa’s 54 countries came online. By approximate count, the number of users has grown by more than a factor of six in the three-year period.

In comparison, there are nearly a billion telephone terminations around the world, representing a much larger network. Of those billion terminations, about 300 million are cell phones and 700 million are wire-line. The rate of growth of cell phones in some countries exceeds 50 percent per year, whereas wire-lines tend to increase at about 5 to 10 percent per year. Internet use, however, has grown from 80 to 100 percent per year since 1988, outstripping even the spectacular growth of cell phones.

Patterns of Internet Use

Internet Users are Distributed Unevenly

To illustrate the broad geographic distribution of Internet use, he presented statistics from an Irish company called NUA (Figure 1).[1] As recently as three years ago, most Internet users were in North America; today fewer than half are in North America. Users in Europe have doubled in the last year, as have users along the Asian-Pacific rim. However, the population along the Asian-Pacific rim exceeds 2 billion if one includes China, India, Indonesia, Malaysia, and Japan. Of these 2 billion, only 75 million are Internet users.

Even within those broad areas, Internet penetration is geographically uneven. In Japan for example, Internet access through a mobile telephone network has grown quickly, adding approximately 16 million users in the last year and a half, from a population of 120 million. In Latin America, the number of users has almost tripled in the last year, from about 5.8 million to over 13 million. In Africa the number has doubled from about 1.3 million to about 2.7 million. Most users in Africa, however, live in South Africa, Egypt, Tunisia, and Morocco. Users in the Middle East have doubled in the last year. Most of those users are in Israel, but a significant fraction is now appearing in the surrounding Arab countries.

Internet Growth is Extremely Fast

Dr. Cerf projected that by the end of this decade the number of Internet users would approach 3 billion—about half the world's population—if growth rates continue as they have in recent years (Figure 2). He cited his own projection made a year ago of 900 million devices on the Internet by 2006, and compared that with an estimate by the cell phone industry of more than 1.5 billion devices by 2004. When he combined his own estimates with those of the cellular phone industry and others they pointed to almost 2.5 billion devices on the network in just six years. "That should scare some people," because the current IP version 4 address space includes only 4.2 billion end points and that number is never

[1] See <http://www.nua.com/surveys/how_many_online/index.html>.

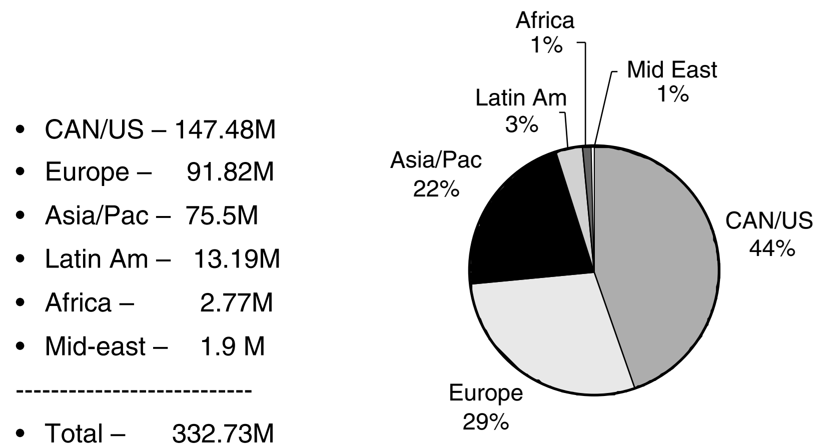

FIGURE 1 Internet Users by Region, July 2000.
SOURCE: www.nua.ie

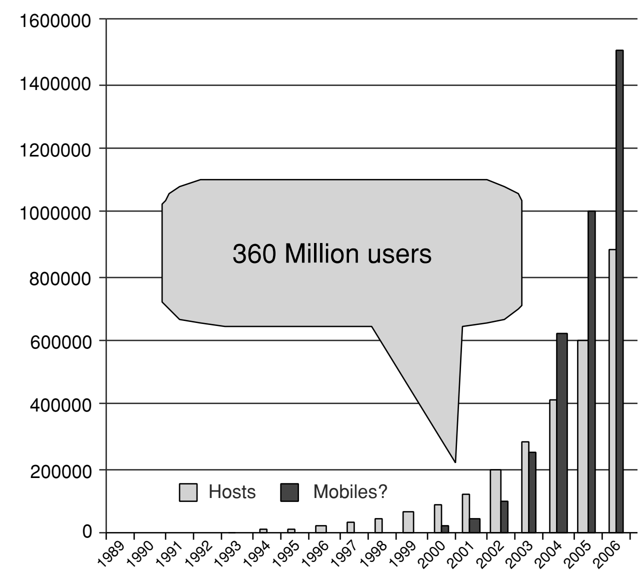

FIGURE 2 Global Internet Hosts (in thousands), 1989–2006.
SOURCE: Dr. Vint Cerf, based on www.nw.com, June 2000 + LM Ericsson

achieved because the address space is allocated hierarchically like the telephone system. He estimated an efficiency of no more than 60 percent in the address space allocation, which would provide room for only 2.4 billion devices by 2006.

New Challenges and Future Trends

The Challenge of Carrying New Modalities

Another factor to take into account is that the Internet is now being asked by its users to carry new modalities, such as video, telephony, and radio. Dr. Cerf recalled experimenting with voice over the Internet as early as 1975, when the backbone of the Internet carried only 50 kilobits of data per second—about the speed of a dial-up modem today. Those early experiments did manage to carry voice signals by compressing them, but the sound quality was poor. Carrying sound on the Web is common now—especially one-way sound—and carrying radio is possible, requiring only 15 to 20 kilobits per second in the lower-quality ranges; however, because the packets do not flow smoothly and uniformly, they must be buffered. As a result, sound reception is affected by small delays. Given a sufficient number of buffered packets, sound quality is good, however.

High-quality video reception of 30 frames per second on a full screen requires a capacity of about 400 kilobits per second, which is not available on a dial-up line using a modem. The limit of a typical display on a dial-up line is about a 2-inch display, delivering six or seven frames per second. For high-quality video on the Internet, subscribers will require dedicated access via digital subscriber loops, cable modem, or alternatives to cable-like multi-channel, multipoint distribution systems (MMDS). Dr. Cerf said that he now operates a network for a commercial company that delivers five megabits per second per channel to business customers who have 45-megabit-per-second access to the Internet.

Added Challenges of Two-Way Service

Dr. Cerf noted that telephony, which is a two-way interactive service, brings several challenges that are not present in one-way video or radio transmission. In telephone the delay between two parties must be as low as possible. Conversations carried over a double satellite hop are degraded by delays of at least one second of round-trip time. Internet telephony could suffer similar delays if the packets are queued, stored, and forwarded in the current fashion. A one-second delay is enough to degrade a conversation, because one party must wait for a response from the other. Squeezing delay out of the Internet requires a change in some of the packet priorities so that one packet can be placed at the front of the queue of packets. In addition, both the backbone of the Internet and the access links at the edge of the Internet must be faster in terms of transmission data rate. Progress on the backbone does seem imminent. The underlying capacity of the optical fiber Internet is typically at least 10 gigabits per second, with a terabit[2] per second predicted for the first quarter of 2001. Most of the delay in Internet telephony today is attributable to the relatively low edge data rate, especially on a dial-up link.

More Internet-Enabled Devices

Dr. Cerf said he is convinced that there would be a very large number of devices on the Internet because people are able to build hardware that is compatible with Internet protocols. In 1999, two students at the University of Massachusetts built a two-chip Web server that did so at very little expense. According to Moore's Law, the cost, size, weight, space, and power of hardware will drop steadily so that eventually "it becomes possible to Internet enable just about any technology." He showed a picture of an Internet-enabled refrigerator with a LCD display and access to the Internet built nearly two years ago by Electrolux in Sweden. The refrigerator augments the traditional household mags-and-paper communication system with an ability to send and receive e-mail and go out on the Internet.

He also showed a picture of an Internet-enabled picture frame that, when connected to a predetermined Web site, downloads 10 pictures, and displays them one at a time without the need to learn Windows or any other software or to log manually onto the Internet. He suggested that more and more devices that have narrow functions and that are Internet-enabled would be developed.

He then showed a slide of a product built by Jaguar International of Japan—an Internet-enabled sewing machine. It allows the sewer to download fonts and logos into the sewing machine and sew those fonts and logos into the fabric, all at consumer prices.

Other kinds of Internet-enabled devices include Web TV, Palm Pilots, and Nokia 9000s, which are three-way cell phones—a cell phone, a pager, and an e-mail station. Dr. Cerf displayed on his belt an Internet-enabled two-way pager that is able to send and receive e-mail. It has a small liquid crystal display like the Nokia 9000 and a tiny keyboard. He said that the device is so easy to use that his staff sometimes sends e-mail back and forth across a conference table during meetings.

He then returned to the example of the refrigerator and its potential for additional devices, including a barcode scanner that would indicate the contents of the refrigerator. The scanner might not read how much milk is actually in the container, but it would remember that the milk entered the refrigerator three weeks ago and would send an e-mail reminder that fresh milk is needed. If the refrigera-

[2]A terabit, or one trillion bits, is equivalent to the text of 300 sets of the *Encyclopedia Britannica* (Alfred Aho, Lucent Technologies).

tor were online, it might search the Internet for recipes for its contents and signal that it contained sufficient ingredients for, say, chicken cacciatore. Alternatively, if you were shopping, you might receive an e-mail from the refrigerator reminding you to pick up the marinara sauce. A final example, seen in Japan, was an Internet-enabled bathroom scale. This scale sends your weight to your family doctor each time you step on the scale. This information could then become a part of your medical record.

A Trend Toward Wireless Devices

Dr. Cerf reiterated that many devices would be used on the Internet, a lot of them wireless. Cell phones are developing rapidly. While traditional GSM phones in Europe only deliver about 9.6 kilobits per second—adequate for e-mail but not enough for surfing the Internet—the GPRS, or general packet radio service, will transmit data at 100 or 128 kilobits per second. Third-generation cell phones are expected to have a burst rate of two megabits per second, a substantial improvement over 9.6 kilobits. He reported seeing in Geneva last October some Internet-enabled cameras with radio links, able to take a digital picture and transmit it to a Web site. Parents could take a picture of the kids going off to school and the picture could appear on Grandma and Grandpa's Internet-enabled picture frame five minutes later.

Many radio-based systems are beginning to carry Internet traffic. Digital broadcast satellites can do multicasting; the local multipoint distribution service (LMDS), and the MMDS alternatives to cable can carry hundreds of megabits per second. Ricochet is a 128-kilobit-per-second mobile link to the Internet, a service of Metricom. Wireless local area networks, or LANs, can transmit information at 11 megabits per second for more than 1,000 feet. Dr. Cerf reported using them both at work and at home. A wireless LAN card in his computer receives an Internet address from the local server and allows him to work anywhere in the house or office. Bluetooth is a new radio technology that enables low-power radio linkage of multiple devices just a few feet apart. A desktop, a laptop, a printer, and other input-output devices can all be linked without wires.

While online devices are attractive, they all require an Internet address to send or receive an Internet packet at any moment. This increases the demand for Internet address space leading, in Dr. Cerf's opinion, to the need for a new version of Internet protocol from version 4.0 to version 6.0. Version 5.0 was an experiment that was discarded about 15 years ago. Version 6.0 has 128-bit address space, which means a total of 10^{38} addresses.

Economic and Political Dimensions of the Internet

From an economic point of view, Dr. Cerf said, an estimated $6.8 trillion worth of activity takes place on the Internet or by electronic means (Table 1). The

TABLE 1 Global e-Commerce in 2004

North America	$3.5 Trillion (U.S. $3.2T)
Western Europe	$1.5 Trillion
Asia/Pacific	$1.6 Trillion
Latin America	$0.082 Trillion
Rest of the World	$0.069 Trillion
Total	$6.79 Trillion (20% of the global economy)

SOURCE: <http://www.forrester.com/ER/Marketing/1,1503,212,FF.html> and <http://www.worldbank.org/poverty/wdrpoverty/report/index.htm>

estimated global economy will amount to approximately $32 to $35 trillion worldwide by 2004, which means that roughly 20 percent of the world's economy may be Internet-focused in four years. For the sake of economic stability, therefore, it is essential to have a highly robust and reliable Internet.

Other Internet issues are part of any discussion of the New Economy. These include policy-related issues that will be brought into sharp relief as the Internet expands globally. For example, the Internet is not sensitive to international borders. It flows about the world without awareness of national boundaries or any of the laws that apply within those boundaries. One border-related issue that has aroused debate over the last several years is the issue of whether cryptography can be exported. The United States was quite restrictive in its policies at first. That approach has changed an important step toward ensuring the high-quality cryptography needed to ensure the security, authenticity, and privacy of electronic transactions on the network.

Who Owns Digitized Information?

Trademark, copyright, intellectual property, and patents are all-important issues on the Internet because it is so easy to move information around in digital form. The legal actions against such Internet firms as Napster arise from the concern of music companies that copyrighted material is being improperly copied or transmitted through the network. Internet service providers are not equipped to monitor the transmissions that go through their networks because of the high volume and the partial, packet-sized view of the material that flies past at speeds of a terabit a second. Even if a provider could see the contents of a packet that began, for example, "Call me Ishmael," and could identify those words as the beginning of *Moby Dick*, the provider would still not know if it is copyrighted material or whether the sender was authorized to send it to the receiver. Such problems, he suggested, must be addressed at a higher level.

Who Should Regulate the Internet?

Other issues have to do with the regulation of telecommunications. Until now, regulatory frameworks for television, radio, and telephony have been distinct. They will soon have to collaborate or merge in some awkward fashion because all forms of communication can be carried over a single medium. This suggests that regulation should no longer be based on the service being provided but on whether the medium that carries the service is a monopoly. For example, cable would be considered a monopoly if only one party is allowed to use it. In the case of the twisted-pair telephone system, if only one party were allowed to use the line it would have a monopoly on the medium. As a result, society might be tempted to regulate the medium without necessarily regulating the service that is on top of it. It might not be necessary to regulate telephony, video, or radio services because the regulatory challenge lies at the core of the transmission system.

Who Should Tax the Internet?

An especially contentious issue is taxation and whether local, state, and national governments should be permitted to tax business transactions on the Internet. Dr. Cerf suggested that Internet transactions should be taxed to the extent that they mirror commercial transactions of the "real world." Otherwise there is disparity between companies that sell books in the physical world and those that sell the same thing in the Internet world. If 20 percent of the world's economy does depend on the Internet any time soon, and that portion of the economy is not taxed, the money to run governments will have to come from other forms of taxation, presumably from income and property taxes. This debate has yet to be resolved.[3]

The Internet in Outer Space

As a final issue—and one that will have an impact on the economics of the Internet—he predicted that over the next 20 years the Internet would expand into outer space. "And this is not a pipe dream," he said. "This is real engineering activity." He described working at the Jet Propulsion Laboratory for two years with a team that is designing an interplanetary Internet protocol. The design is essentially complete, he said, and the first prototypes have been implemented.

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[3]For a discussion of the debate over taxing Internet commerce, see Hal R. Varian, "Taxation of Electronic Commerce," Internet Policy Institute, April 2000 at <http://www.internetpolicy.org/briefing/4_00_story.html>. Professor Varian points out that, because online commerce is global, its tax treatment will also be global and must deal with countries that employ value-added taxes as well as those that use state sales taxes. Within the U.S., he writes, "The current system of state taxes is overly complex and poorly designed. No matter what one thinks will happen with online purchases it stands in need of serious reform."

The team will insert an Internet protocol on a satellite to be launched at the end of 2000 around the Earth; another is scheduled for a lunar landing a year later and a third protocol system is scheduled to be used in 2003 on two rovers that will explore Mars.[4]

The larger objective is to "create an Internet backbone in space." Each successive mission will carry a portion of that backbone and, to the extent that those assets have lifetimes beyond the mission itself, each mission will increase the size of that backbone toward the eventual goal of a major interplanetary backbone that will support the exploration of the solar system in the near term and, in the longer term, experiments in the commercialization of space. If launch costs can be pared down to about $500/kilogram, certain kinds of businesses could justify using near-Earth orbits. If that happens, the existence of a backbone architecture that can support commercial uses in space may become essential the same way that the Internet is becoming an important infrastructure for commerce on Earth.

Dr. Cerf ended by commenting on the rapid pace of advances surrounding the Internet and the complexity of issues to be resolved as more and more of the world's population comes online.

DISCUSSION

Potential Show-Stoppers

Dr. Spencer invited questions on Dr. Cerf's talk. Dr. Wessner began by asking what might be the show-stopper in this otherwise rosy scenario of Internet evolution. Dr. Cerf replied that technological disaster, such as lack of transmission capacity, was a possibility. However, this seemed unlikely because recent tests indicated that capacity is growing rapidly. Today the network runs 10-gigabit-per-second fiber optic lines with a capacity of 40 gigabits per second. Engineers had demonstrated a near-term capacity potential of a trillion bits per second a few months earlier, and more recently a test of seven trillion bits per second was announced. "So I don't think that fiber will be a show-stopper."

Dr. Cerf noted that developing routers that are fast enough to transmit packets of data to the Internet, he said, present a more complex challenge and a potential bottleneck. So far, he said, the router vendors have been able to develop higher capacity switching systems each time they are needed.

The Need for a Legal Framework

A more serious show-stopper could be the continued lack of a legal framework to support electronic commerce on the Internet. The treatment of content

[4]The November 15, 2000, launch took place on schedule, but the satellite lost its radio link to the ground a few days into the mission.

must be consistent and simple to avoid great disparities "at the edges" and between countries. Dr. Cerf cited the example of a looming court case in France against the giant Internet company Yahoo. A user had posted content on a Web site that included Nazi memorabilia, and it is illegal under French law to post such content in public. Dr. Cerf was scheduled to be an expert witness in the case, and one issue he had been asked to resolve is whether an access provider might be expected to detect that Internet material might reach a citizen of a certain country. His answer would have to be no, because a provider does not know for certain from addressing data where the packets are going. He warned that policy decisions made by different countries could create sufficient disparities to jeopardize global commerce.

Network Reliability

Dr. Myers of Xerox Corporation returned to the issue of network reliability, recalling the electrical blackout more than three decades ago when most of the power grid of the Northeast shut down. He asked who would be responsible if the Internet analog of a blackout or brownout were to block companies from doing business by halting the flow of information.

Dr. Cerf answered that the Internet service providers have the responsibility of providing a reliable infrastructure, but that the issues of interconnecting segments of the Internet have not been resolved and that the business models for interconnection between Internet service providers are not fully formed. By one model, the company that connects to an existing company pays for the connection. This does not resolve who pays when two parties connect to each other. Yet another model says that two companies of about the same size that exchange the same amount of traffic will not charge each other for the connection between them. Until the economics of such connections are settled there may be some difficulty in developing fully robust systems.

Where Should Regulation and Taxation Occur?

Dr. Aho returned to the subject of regulation to ask whether regulation would most appropriately occur at the source, in the transition, or at the point of reception.

Dr. Cerf answered that the point of regulation would probably depend on what is being regulated. Content, he said, is more easily regulated at the source. Content regulation is complex when it threatens to become censorship. For content that is widely agreed to be illegal, such as child pornography, regulation at the source seems sensible.

On the other hand, applying taxation to the Internet can be much more complex. One would have to determine where the transaction takes place and the parties involved in the transaction. Are the parties located in the host computer that contained the information, or where your personal computer happens to be? Dr. Cerf suggested that geophysical location might become less and less important. For example, an online purchase might be made from anywhere in the world, so that the transaction might more reasonably be said to occur at the billing address of the credit card holder. For a cable system, a more appropriate regulation point might be the address of the subscriber—the delivery point. Such ambiguities must be resolved for Internet commerce to thrive.

Dr. Brynjolfsson concluded the discussion by pointing out the very large projected size of e-business. He said that the projections of $3.5 trillion a year in the United States and about $6.7 trillion worldwide are realistic and that such projections have been revised upward each year. He cautioned that care must be taken when comparing business-to-business volume with national or global GDP because the same good and its components may be sold at many Web sites, but would be counted only once in GDP. In principle, while the projections for future business-to-business volume may be reasonably realistic, they need to be considered in context, and are not directly comparable.

Panel I

Defining and Measuring the New Economy

INTRODUCTION

Robert Shapiro
U.S. Department of Commerce

Dr. Shapiro began by saying that defining and measuring the New Economy is one of the most important questions facing economic policy today. He said that the topic holds special interest for him and for his office, the Economics and Statistics Administration of the Department of Commerce, which oversees two of the nation's three major statistical agencies, notably the Bureau of the Census and the Bureau of Economic Analysis.

He said that the challenge of measuring the New Economy has proven to be a difficult one: "It really is a process of calibrating and recalibrating our understanding of new technologies and new measures in order to slowly construct a picture that makes sense to us and corresponds to the parameters of statistics."

A Critical Question for U.S. Policy

The other part of his department's job is to advise the Secretary of Commerce and the administration on issues of economic policy: whether the performance of the economy since 1995 is a temporary phenomenon, for example, or something more structural and long term. This is obviously a critical question for policy because the growth and productivity gains associated with the New Economy, if sustained, would not only improve the lives of all Americans, but it would also provide the resources to tackle almost any policy task in the next decade, from strengthening Social Security and cutting taxes to extending health coverage. An important indicator of the permanence of the economic conditions of recent years will be whether the economy's extraordinary performance continues in the next business cycle. Another is whether other advanced countries can replicate our higher growth and productivity, since a truly New Economy can hardly be confined to a single country.

Defining the New Economy

Defining the New Economy by Results

Dr. Shapiro noted that it seemed beyond doubt that the U.S. economy entered a period of high performance in the 1990s and that this cycle looks quite different from others in recent memory. As previous expansions of the postwar period aged, productivity and output growth slowed, inflation rose, real wages stagnated, and profits declined. The current expansion has matured and lasted longer than any of its predecessors, and yet productivity gains have accelerated from an average rate of 1.4 percent a year in the early 1990s to 2.9 percent since 1995. Real GDP growth has quickened. It has averaged about 4 percent in years seven and eight of this expansion, as compared to 1.1 percent or less in those years of the long expansions of the 1960s and 1980s. Real hourly compensation has grown after a long period of relative stagnation. The just announced income numbers for 1999 show a record of five consecutive years of income gains for average households. At the same time, profits have continued to grow generally. Moreover, strong output and profits have fueled very vigorous growth in real business investment, producing a record seven straight years of double-digit gains in investment and equipment, most of it for information technology hardware and software. Finally, inflation continued to fall through most of this period and even now, after several years of full employment, remains moderate.

Defining the New Economy by Conditions

The New Economy could be defined by these results. We could also define it, he said, by its conditions. Behind higher productivity and growth, for example, lie at least three key developments:

1. Capital deepening—the acceleration in the growth of capital stock.
2. Disinflationary forces that have held back price pressures for more than a decade, including more intense competition associated with deregulation and expanding world trade, shifts to tight fiscal policies at home and abroad, and the falling prices of information technology itself.
3. The power of innovation.

Information Technology and Productivity

New Combinations

Today, economies grow not by increasing capital or labor but by finding new ways to combine them that are more productive. Because the dominant forms of innovation for the last 20 years have come from information technology, many analysts point to information technology in defining the New Economy. Certainly, a critical factor in the recent performance of the United States has been the convergence of enormous increases in computing power and data storage with similar increases in the speed and carrying capacity of data communications systems, along with the growing power of new software. These advances have produced sharp, steady declines in the prices of computer and communications equipment that have driven both sustained business investment and a surge in Internet activity.

In fact, it is the particular character of information technology innovation that may best define what is new about the New Economy. Many of these technologies have qualities that seem to make a real economic difference. Most obviously, they provide a new way of managing a resource common to every aspect of economic life. That is, information technology represents a general-purpose innovation that is being applied to every sector and aspect of the economic process.

Network Effects

Dr. Shapiro noted that another difference is the network effects that characterize many information technology markets. That is, the more the technology is deployed, the greater its value. If you buy a Saab, the car is worth the same to you whether there are 5,000 other Saabs on the road or 100,000. When you buy

Box A:
Taking Full Advantage of Information Technology

"A growing body of firm-level evidence . . . shows that simply installing advanced information technology, by itself, has little effect. Firms that buy information technology equipment do not raise their productivity unless they also rethink and change their organizations to take full advantage of information technology's capacities. So organizational innovation may be as important as the technology itself."

Robert Shapiro, U.S. Department of Commerce, 1998-2001

Windows or a new graphics program, its value may increase as more people buy it, because that increases your ability to communicate and interact. In a certain sense, network effects can bring increasing rates of return; as innovation spreads, its productivity benefits can increase not just arithmetically but quadratically.

Cascading Innovation

Finally, as industries apply information technology to their businesses, economists see evidence of what might be called cascading innovation. Productivity gains come not just from faster processing of information but also from changes in the way a firm operates and from additional technological advances made possible by the information technology. Moreover, as information technology spreads and its potential is more widely recognized, it generates demand for even faster processing—that is, another round of information technology innovation, which in turn creates the potential for more innovation both organizationally and in the products and services the re-organized and information-technology-enabled firm can create. This demand forms the economic basis for Moore's Law, under which the computing capacity of chips doubles every 18 months. Moreover, these enormous and regular increases in chip power provided the technological basis for the Internet, which in turn now generates more rounds of cascading innovation in how businesses operate and what they produce.

The Network Model

Recognizing again that the important factor is not so much the information technology investment but what businesses and workers do with it, we could approach this question of the New Economy from the point of view of the firm. Here one can see the shape of what some call the network model of digital economy firms. The key tasks for these firms are to form a network of special goods and services, enter a network that ultimately will produce or support a final product, or provide the goods and services that support the network itself.

A simple example is the "big three" automakers' project to move their supply chains to the Web, shifting online hundreds of billions of dollars a year in orders from tens of thousands of suppliers. Perhaps a better example of a network model is the Cisco Corporation, which outsources virtually all of its production so it can focus on product design and innovation. Last year Cisco received 78 percent of its orders and handled 80 percent of its customer service issues on the Internet.

Substituting Information Technology Capital for Labor

Information technology and the network model for the firm may drive other New Economy changes in how we work. Looking into questions of job creation, Economics and Statistics Administration researchers ranked U.S. industries according to their degree of information technology intensity, that is, the ratio of information technology equipment per worker. They then divided the list into two groups. One included the most information-technology-intensive industries measured by the ratio of information technology equipment per worker, which produced about 50 percent of all income in the nonfarm business sector. The second encompassed the relatively less information-technology-intensive industries that produced the other 50 percent of total income. They found that most of the employment growth in the last decade occurred in the less information-technology-intensive industries. The more information-technology-intensive half of the economy accounted for only 12 percent of the growth in employment between 1987 and 1998. This may suggest that one of the features of the New Economy is that it substitutes information technology capital for labor in noninformation technology industries, even as it generates jobs in the information technology sector itself at high rates.

Nevertheless, within the high-growth information technology sector itself, the Department of Commerce expects employment in the information technology industry to grow 40 percent over the next 8 to 10 years. It also expects the number of workers in core information technology fields, today roughly 2.4 million computer scientists, engineers, systems analysts, and programmers, to nearly double.

A Need for More Compelling Evidence

Regardless of how this New Economy is defined and measured, he said, not everyone agrees there is anything very new about it. Dr. Shapiro cited Robert Gordon of Northwestern University as one who argues that the increases in productivity have come almost entirely in the 12 percent of the economy that produces durable goods and that information technology has not been very productive elsewhere in the economy. These conclusions have been challenged by economists at the Commerce Department, the Federal Reserve, and others (including the next symposium speaker, Dale Jorgenson). Still, no one knows for certain until the nation has completed this business cycle and until more compelling evidence is developed.[5]

Dr. Shapiro concluded by saying that a skeptic could maintain that the verdict is still out, and that the skeptic could be right. “But in all frankness,” he said, “we don’t think so.”

[5]For more discussion of the views of Professor Gordon and others, see the special section on “The New Economy” in *The Economist,* September 23, 2000, pp. 5-40.

DISCUSSION

Difficulties in Measuring the Effects of Information Technology

A brief discussion period followed, during which Dr. Bresnahan suggested that the Department of Commerce's framework might offer two challenges to the federal statistical system. One is a wide discrepancy between the department's greatly improved measures of output in the information technology sector itself and the less effective way it measures the improvement of output when information technology is used in other sectors. The second is that the network model constituted a serious challenge to traditional ways of measuring firm establishment and might require new concepts for capturing the locus of economic activity in the network world.

Dr. Shapiro responded to the first question by saying that the difficulty in measuring the effects of information technology in the major service sector reflects a problem in statistical technique. The Commerce Department has made significant progress in financial services and banking, in which the productivity numbers have been revised. Such progress, however, is difficult to sustain without resources: The budget for the Bureau of Economic Analysis had been cut for every one of the last seven years, so that by 2000 the economy was 25 percent larger and the bureau's real budget to measure the economy was 12 percent smaller.

Self-Service "Operators"

Dr. Cerf commented that gathering good economic data is important to making good economic decisions and added an anecdote about productivity in the telephone system. Years ago when a person wanted to make a phone call, an operator had to place it. With direct-distance dialing, everyone became their own operator. Given that self-service is similarly becoming an important component in what happens on the Internet, bringing an important impact to the cost of operations, he inquired as to whether economic statistics can take self-service into account.

The Need for New Measures

Dr. Shapiro answered that the department is currently trying to do this, beginning with the first "e-tail" statistics and proceeding next year with the first annual business-to-business measures.

He mentioned a larger conceptual problem, which is to adapt the structural logic of the statistics to large changes in the economy. That is, how can they develop measures that capture new activities and still be able to compare what is happening today with what has happened in previous years. This is particularly difficult when changes in a firm or in the nature of work alter the way the Bureau of Labor Statistics (BLS) needs to measure unemployment and employment. The

BLS is trying, for example, to find an appropriate way to measure the contribution of stock options to national income. He said that the best answers to such challenges would probably be known only in retrospect.

Dr. Price, also of the Department of Commerce, agreed that one of an economist's greatest challenges for the last 30 years has been to develop new measures for economic activity. For example, traditional means of measuring GDP focus on market activity. Today, many activities captured by market activity, such as child care, elderly care, sick care, and food preparation, used to be done by families. Yet economists call the economy larger when these functions are transferred to "market activity." At the same time, the department used to record services such as gasoline pumping, which have now moved out of the market. However, because the traditional concept is market activity, economists still take such work into account in looking at welfare over time.

Dr. Price said that similar problems would probably emerge in the future. The amount of self-service education and health care will probably increase, for example, and the Bureau of Labor Statistics has no effective way to measure it. In health care, people are doing more self-education before going to a doctor, which changes the output of health care centers.

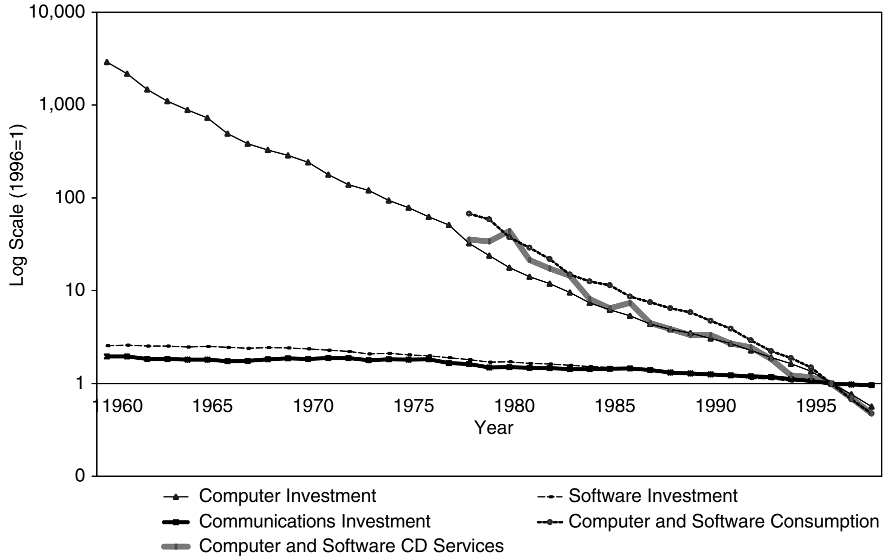
RAISING THE SPEED LIMIT: U.S. ECONOMIC GROWTH IN THE INFORMATION AGE

Dale Jorgenson
Harvard University

Professor Jorgenson said he would discuss the "relatively narrow issue" of how to integrate the picture of technology painted by Vint Cerf with the macro picture of the economy described by Robert Shapiro. He added that this task is central to the mission of the Board on Science, Technology, and Economic Policy—a mission for which the National Research Council is positioned to be "ahead rather than behind the rest of the economics profession in this important arena." The current workshop presents an unusual opportunity because its participants include some of the technologists and economists leading the nation's effort to understand this complex issue.

Dr. Jorgenson began with recent projections from the Congressional Budget Office. These projections indicated that the economic forecasting community had missed the mark in its projections as recently as three years earlier in predicting an unending deficit. What has happened since, he said, is causing a sea change in thinking about the economic role of technology (Figure 3).[6]

[6]Dr. Jorgenson's remarks at the workshop were based partly on a paper with the above title, prepared last spring with Kevin J. Stiroh of the Federal Reserve Bank of New York and published as *Brookings Papers on Economic Activity 1*:2000. This paper is reproduced in this volume.



Notes: All price indexes are relative to the output price index.
CD refers to Consumer Durables.

FIGURE 3 Relative Prices of Information Technology Outputs, 1960–1998.

A Sudden Point of Inflection in Prices

The first challenge in understanding this change is to integrate economic and technological information, starting with an examination of prices. Dr. Jorgenson affirmed Dr. Cerf's insight that, "once you commit something to hardware, Moore's Law kicks in" and showed how quickly the prices of information technology—in terms of computers and computing investments—have declined at a rate basically determined by Moore's Law. Translated to the portion of computer technology that can be associated with Moore's Law, this decline would be about 15 percent a year. In 1995, however, the decline in computer prices suddenly doubled in a dramatic "point of inflection" that has only recently been identified.

The Dark Planet

Some of this change could be attributed to improved semiconductor technology, but this abrupt shift seems to be part of a larger trend that reflects important gaps in our information. One of these gaps is an absence of data about communications equipment. Another gap is the role of software, the "dark planet" in our information system. In fact, software investment was not even part of our eco-

Box B:
A Fundamental Economic Change

"The continued strength and vitality of the U.S. economy continues to astonish economic forecasters. A consensus is now emerging that something fundamental has changed, with 'new economy' proponents pointing to information technology as the causal factor behind the strong performance of the U.S. economy. In this view, technology is profoundly altering the nature of business, leading to permanently higher productivity growth throughout the economy. Skeptics argue that the recent success reflects a series of favorable, but temporary, shocks. . . ."[7]

Dale Jorgenson, Harvard University and Kevin Stiroh,
Federal Reserve Bank of New York

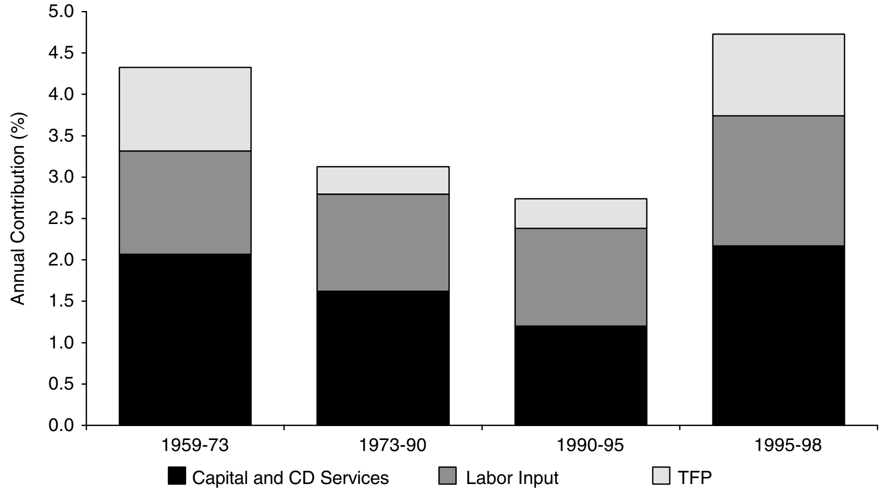
nomic information system until a year or so ago. As a result, we have an incomplete picture of the New Economy. This point of inflection has attracted considerable attention and emphasized the need for more complete data.

The Initial Skepticism of Economists

Most economists have held the opinion that information technology is important to the economy but no more important than other components. That is, computer chips are no more important than potato chips. In fact, if the food industry were placed on the same dollar-output chart with all components of information technology, it would dwarf the output of the entire information economy.

To counter that skepticism Dr. Jorgenson compared the growth rate of information technology with the growth of the rest of the economy. The nominal shares of output for computers have been fairly stationary, but prices have declined by about 40 percent a year. That means that the real value of computer output is going up at precisely the same 40 percent rate. Moreover, if one rates the nominal share by the growth rate of output information technology becomes far more important. In fact, it accounts for about 20 percent of the economic growth that has taken place in the "new era" since 1995, the point of inflection he identified in the price statistics (Figure 4).

[7] *Ibid*, p. 1.



Notes: An input's contribution is the average share-weighted, annual growth rate.
TFP defined in Equation (2) in text.
CD refers to Consumer Durables.
TFP refers to Total Factor Productivity.

FIGURE 4 Sources of U.S. economic growth, 1959–1998.

Information Technology in the New Economy

Dr. Jorgenson then traced the history of information technology growth since 1959. Through the slow-down of the 1980s and then the real slowdown of 1990 the New Economy appeared to hold nothing new. "It had been there all along but it was building momentum." The sudden point of inflection came in 1995 when the New Economy took hold and began to change economic thinking.

New Features

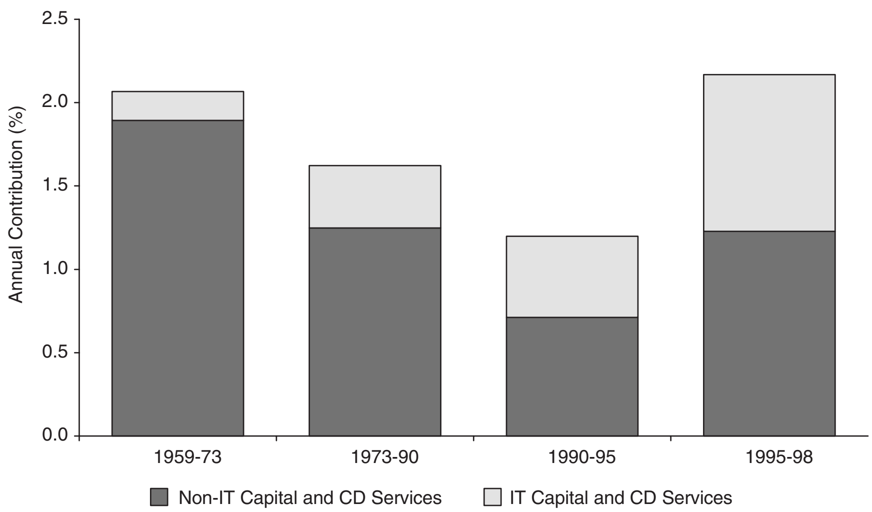
Several new features have emerged. First, in assessing the impact of information technology, one must include not only computers but also communications equipment and software. Another new feature is that the consumer portion of information technology has become quite important since the advent of the personal computer.

The Role of Information Technology in Building Production Capacity

Moving to the role of information technology in building the production capacity of the economy, he noted that information technology behavior was very distinctive, as already emphasized in the data on prices. No other component of the economy shows price declines that approach the rate of information technology. That is the primary reason why the New Economy is indeed new. Information technology has become faster, better, and cheaper—attributes that have formed the mantra of the New Economy.

Some Consequences of Faster, Better, Cheaper

This faster-better-cheaper behavior means that weights applied to information technology investments must be different from weights applied to other investments. First, investments have to pay for the cost of capital, which is about 5 percent. Second, they have to pay for the decline in prices, which represents foregone investment opportunity. The rate of decline was about 15 percent before the point of inflection in 1995 and rose to about 30 percent after it. The rate is a huge amount relative to the rest of the economy where investment prices tend to trend upward rather than downward. Third, investors have to pay for depreciation, because information technology turns over every three or four years, costing another 30 percent. In all, every dollar of investment produces essentially a dollar of cost annually just to maintain its productive capacity and measure its contribution to the input (Figure 5).



Notes: An input's contribution is the average share-weighted, annual growth rate.
CD refers to Consumer Durables.

FIGURE 5 Input contribution of information technology, 1959–1998.

Next, Dr. Jorgenson showed the same process from the input side. This is the share of capital as an input, which is approximately 10 percent. When one takes into account the fact that information technology is growing at rates that reflect the drop in prices and the rise in output, the result is the contribution of capital to the U.S. economy. In this picture, information technology contributes almost half the total. He noted that “it’s an extremely important phenomenon and it’s one with which economics must contend.” It is surprising that economists have taken so long to understand this because there is nothing new about the New Economy’s underlying features, which have been developing for years. An examination of information technology growth before 1995 would have produced a picture that was the same in its essential features.

Features of Recent Economic Growth

He then turned to another dimension of change, which is the substantial recent growth of the economy. The basic explanation for this growth is that components of information technology have been substituted for other inputs. These investments were going into sectors that are using information technology and they are displacing workers. We are deepening the capital that is part of the workers’ productive capacity, in regard not only to computers but also to software, communications equipment, and other technology.

Reminding his audience that prices of computers have been declining approximately 30 percent a year, he showed a graph that demonstrated that the growth is not limited to computers but also includes communications equipment and software. Does that mean that the substitution of cheaper computers for workers also obtains for software? He said that the answer is probably “yes.” However, this answer is not supported by statistics, which lack sufficient information about prices for software and telecommunications equipment. “But, I think it’s pretty obvious that that’s going on,” he said, “and that is an important gap in our story.”

He then showed a depiction of the sources of U.S. economic growth—capital, labor, and productivity—and cautioned care in the use of productivity. Productivity is often used in the sense of labor productivity, as in the industries that use information technology, and labor productivity is rising rapidly. However, total factor productivity, which is the output per unit for all inputs, including capital as well as labor, is not going up in those industries. That is why this growth in total factor productivity is highly, though not exclusively, concentrated in information technology.

Rapid but Transient Job Growth

Beginning in 1993, the United States experienced one of the most dramatic declines in unemployment in American history, leading to the extraordinary creation of 22 million jobs. This is not unique in historical experience, but it is a very large figure. According to business forecasters, this growth will not persist, because the growth rate of the labor force will be roughly the same as the growth rate of the working age population, which is now about half the growth rate that has obtained since 1993.

The growth story is also transient in the following sense. The level of output will remain high because of the investment opportunities in information technology. However, in the long run, the growth of investments is closely associated with the growth of output. In the absence of another point of inflection—a further acceleration in the decline in information technology prices—output growth will lead to a permanently higher level. The new growth will last only long enough to reach this new higher level and will not affect the long-term growth of the economy.

Rising Total Factor Productivity[8] *in Information Technology*

This leads to the following question: How much of total factor productivity growth in information technology—which could lead to a permanent increase in our economic growth rate—is due to identifiable changes in technology?

Dr. Jorgenson translated the change in prices into increased productivity growth. When this is done, we see an increase in productivity due to information technology from about 2.4 percent to about 4.2 percent between 1990–1995 and 1995–1998. This means there is an increase in total factor productivity due to information technology that is about the equivalent of 0.2 percent per year. This turns out to be a very large number, because the total factor productivity growth from the period 1990–1995 was only 3.7 percent. As a result, this increase in the rate of decline of information technology prices has enormously expanded the opportunities for future growth of the U.S. economy. If that persists, as Dr. Jorgenson predicted, it will continue to raise the economic growth rate for the next decade or so.

Uncertainty About the Future

However, an additional factor represents a large gap in economic understanding. This is the moderate increase in productivity growth in the rest of the economy about which, "frankly we don't know a great deal about it." If we fill in the gaps in the statistical system by imputing the rates of decrease in computer prices to telecommunications equipment and software, then it turns out that all

[8]Total Factor Productivity (TFP) measures the efficiency and effectiveness with which both labor and capital resources are used to produce output. In other words, TFP means making smarter and better use of the labor and capital resources available. A simplified way of expressing TFP is TFP = Output/(Capital + labor).

the productivity growth in the period 1995–1998, which represents a permanent increase in the growth rate of the economy is due to information technology. This demonstrates the wide range of uncertainty about the future of the U.S. economy with which forecasters have to contend.

Dr. Jorgenson explained the contributions of different industries to total factor productivity growth. While electronics and electronic equipment were among the leaders, he noted that the biggest contributor turned out to be trade sector, followed by agriculture and communications. Thus, "this is not only an information technology story and this represents the challenge to the Board on Science, Technology, and Economic Policy and to all of us here, which is to try to fill in some of the gaps and understand the changes that are taking place."

Summary

Dr. Jorgenson offered the following summary of his thesis: As recently as 1997 economists were convinced of the validity of the so-called Solow paradox—we see computers everywhere but in the productivity statistics. That has now changed dramatically. A consensus has emerged that the information technology revolution is clearly visible in productivity statistics. The visibility of this revolution has been building gradually for a long time, but something sudden and dramatic happened in 1995, when an accelerated decline in computer prices, pushed by the decline in semiconductor prices that preceded it, made obvious the contribution of information technology to productivity statistics.

Dr. Jorgenson closed by returning to what actually happened in 1995—a change in the product cycle of the semiconductor industry from three years to two years. In addition, new technologies began to emerge, such as wavelength division multiplexing, that represent rates of change that exceed Moore's Law and have yet to be captured in our statistical system. He suggested that a better understanding of the sustainability of the growth resurgence and the uncertainties that face policy makers should be regarded as a high national priority.

DISCUSSION

Concern About Software Productivity

Dr. Cerf noted that in the telecommunications business the cost of hardware as a fraction of total investment is dropping. That has not helped a great deal because the price of software has risen dramatically in absolute terms and also as a fraction of total investment. He said that productivity in software might turn out to be key for the future productivity of a good fraction of the economy, but he is concerned because of the industry's limited success in producing large quantities of highly reliable software. Software productivity might have risen by a factor of only three since 1950, seriously lagging hardware advances. As hardware costs continue to fall, he speculated that cost becomes less important, while software becomes critical. He posed the question of whether the problem of software productivity and reliability will seriously interfere with the future productivity of the New Economy.

Professor Jorgenson invited an answer from Eric Brynjolfsson, whom he characterized as "probably the world's leading expert on this." Dr. Brynjolfsson said that he had tried to measure some of the productivity improvements, described in a paper with Chris Kemerer, because software productivity had not been measured nearly as accurately as hardware productivity.[9] They found that software productivity has not improved as fast as hardware, but it had still grown impressively—on the order of 10 to 15 percent—compared to the rest of the economy. Their study concerned only packaged software, which has more economies of scale than custom software. The improvements in custom software have been slower, although there has been a steady movement from custom software toward packaged software. He concluded that there is a great deal of unmeasured productivity improvement in software production, but that this is beginning to appear in statistics of the Bureau of Economic Analysis.

The True Costs of Re-engineering a Company

Bill Raduchel commented that because software production is a hardware-intensive process, falling costs of hardware will tend to reduce software costs and raise productivity. This observation was based on his experience of 10 years as a CIO, his role in re-engineering a company three times, and his consulting experience on about 50 other projects. The last re-engineering project cost $175 million, of which information technology expenditures were less than $10 million. The other $165 million appeared over three years as General and Administrative (G&A) expenses for testing, release, data conversion, training, and other activities. He said that productivity would actually decline in some cases because implementation costs show up in the statistics. Once implementation is complete, gross margins and productivity suddenly jump. The changes in business practices actually drive productivity, and these changes are set functions inside the company. Only 5 to 10 percent of the expense of any re-engineering project goes for IT; the other 90 to 95 percent is spent for training and testing and data collection, all of which by accounting rules is booked as G&A. If one looks only at company statistics, one sees an increase in G&A—overhead—rather than an investment to increase productivity.[10]

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[9]Erik Brynjolfsson and Chris Kemerer. 1996. "Network Externalities in Microcomputer Software: An Econometric Analysis of the Spreadsheet Market," in *Management Science*, December.

[10]For a discussion of re-engineering, see B. J. Bashein, M. L. Markus, and P. Riley. 1994. "Business Process Reengineering: Preconditions for Success and How to Prevent Failures," *Information*

More Concerns About Software

Dr. Aho added that the issue of software is an extremely important one, and that software productivity has always been a matter of concern to software engineers. He also raised several questions: How much software is required to run the global economy? At what rate is it growing? Are there any measures of the volume of software? He raised a related issue: Once software is added to a system, it is difficult to remove it. He expressed concern that in many cases, the software people in a company are younger than the systems they are maintaining. This can create handicaps in trying to upgrade such systems.

Dr. Jorgenson commented that both the preceding observations were germane in describing what we know about software investment. He said that such figures are not available for other countries in comparable form and they exclude the phenomenon described by Dr. Raduchel. We have made some progress in our knowledge about software especially since 1999, the year when the Department of Commerce began to track it. The most significant gap in our knowledge, however, is how to use these numbers to calculate productivity. He ended the session by expressing the hope that the current workshop would shed some light on precisely this issue.

Systems Management (Spring). The authors write that re-engineering "...was enthusiastically advanced by the popular business press and was tried by a substantial number of major business firms, despite high costs and a failure rate of 75 percent."

Panel 2

Drivers of the New Economy

INTRODUCTION

Moderator: Ralph Gomory
Alfred P. Sloan Foundation

Ralph Gomory opened the panel by emphasizing the difficulty of prediction. Substantial bodies of experts, he reminded the group, "have at best a mixed record of predicting what matters." He raised the examples of the collapse of the Soviet Union and the emergence of the Internet, great events that were "invisible in prospect and dominant if you look backward." Such examples, "should give us some feeling of modesty about what is being attempted today."

The Difficulty of Predicting New Hardware

Noting that prediction is not uniformly bad, Dr. Gomory described Moore's Law as an excellent example of prediction that works. Behind this law is a rather orderly process of the reduction of dimensions—in this case, for semiconductors. The predictions flowing from Moore's Law have been very good. However, not all technical prediction is that easy and or even possible. He recalled the era when it was believed electronic devices would soon replace disk drives, which are mechanical devices. At the time, given the technology of disk drives, this was a credible projection. As recently as 15 years ago the heads of disk drives were flying over the surface at a clearance of about 1 micron. Because the surface is seldom perfectly flat, the heads often touched it. Few people believed it was possible to lower the heads any further. That technical prediction was harder to do correctly. Eventually people got the technology right and stopped predicting that semiconductors would displace disk drives. We now know that the progress of disk drives has been at least as rapid as that of semiconductors and in fact they deserve to be given far more credit for their contribution to the present data storage revolution.

The Greater Difficulty of Predicting Software Innovations

Even more difficult to predict, Dr. Gomory suggested, is the progress of software. He recalled a recent conversation about how the inability to produce software might be a stumbling block to progress. He had heard those sentiments as long ago as the 1960s, when IBM launched the little remembered Future Systems project, or FS. IBM labored for three years because it had come to the same conclusion: that hardware costs would drop and the only route to continued profits would be to generate software more cheaply. The result was FS, a system aimed at making programming easier and more profitable. Future Systems never saw the light of day and cost IBM much of its leadership in technology during the three years it struggled to bring it out.

Discontinuous Change

What happened to software productivity was that companies discovered "huge levers of productivity in switching from custom to packaged software." The lesson, he said, is that there are ways around many seeming roadblocks in technology, but they are hard to predict. While arguing that "the record of prediction is awful on the things that really matter," there are nonetheless a few notable successes. In this context it is especially important to be modest in predicting the social consequences of technological transformations. He doubted that one could predict when the cumulative effect of technological change would suddenly manifest itself. He used the analogy of a bathtub that fills gradually until the accumulated water produces a point of overflow. This point represents a discontinuous change that does not depend on opening the faucet wider. He compared certain elements of technology that can be predicted, such as the software productivity of a programmer, and certain elements of technology that are harder to predict, such as the effects of new standards. He cited the Internet as the most stunning example of this effect, where agreement on a common protocol enabled the system as a whole to function effectively and to have an enormous impact on society. Such a confluence is almost impossible to predict. Even when we think we understand a phenomenon we might not be able to apply our understanding to the next phenomenon.

Dr. Gomory closed by reminding his audience of the complexity of the task they were attempting. He urged caution and suggested an effort to segregate what is predictable from what is not, and to be aware of the nonlinear effects that can upset even the most informed predictions.

SEMICONDUCTORS: THE ARRIVAL OF THE NEW ECONOMY

Bill Spencer
International SEMATECH

Dr. Spencer began with the "modest proposal" that the nation's recent surge of economic growth was due principally to semiconductors. He invited his audience to critique that serious hypothesis and point out any errors in reasoning. He also said he would address the impact of semiconductors on other major components of information technology hardware and software. Finally, he said he would raise some questions about what might happen if the growth in technology slows.

Rapid Growth of the Industry

Dr. Spencer began by illustrating the rapid growth of the semiconductor industry from 1975 to 1995, a period when worldwide sales rose from about $4.4 billion to a peak of about $141 billion. In 1996 there was a significant drop in sales. He said he would be talking about projections out to the year 2015, which is the end of the roadmap created for the semiconductor industry.

He described a major change that had occurred in the semiconductor business over the last few decades. When he first worked in the industry, in the early 1960s, the ingots grown by his company were cut into wafers 30 millimeters in diameter; today's commercial wafers have grown to 300 millimeters in diameter. Early semiconductor manufacturers polished the wafers and then processed them on vacuum equipment they bought and adapted themselves. Today the semiconductor equipment business alone is about a $50 billion business and the materials business is worth a little less than half of that. Much of the new technology for semiconductors in the future is going to come from those same equipment and materials suppliers. New techniques of exposing and etching finer lines or designing more transistors on a circuit will come from suppliers and not from the semiconductor industry itself.

Lower Costs and Higher Productivity

The primary reason for the growth in the industry is the drop in cost and simultaneous rise in productivity that Dr. Jorgenson discussed. He said that the growth in productivity had increased steadily by 25 or 30 percent per year since the early 1960s—and cited the saying around Silicon Valley that "every integrated circuit ultimately costs $5—except for those that cost less."

The most important factor in productivity growth has been reduction in feature size, made possible by lithography equipment that can produce ever-finer lines. Size reduction has accounted for nearly half of productivity growth. Yield improvement, too, has contributed a sizeable fraction, growing at 4 to 5 percent annually for a long time. Yields on integrated circuits are now above 90 percent, however, and these are achieved six to nine months after opening a new factory. Therefore, yield improvement will not be able to contribute much more to productivity growth. Wafer size will improve further, he said. Wafer diameter has risen by a factor of 10 in the last 30 years. Engineers in Japan are experimenting with 450-mm wafers, "which is the size of a large pizza." It is a challenge to hold 1-micron uniformity on a wafer that large. The rest of the productivity gains result from other equipment changes and better processes.

Costs of DRAMs

The interesting questions, said Dr. Spencer, are what will happen if that productivity growth begins to taper off and what can be done to perpetuate the growth. He showed a graph, used by the Dell Company, of cumulative DRAM production versus cost—DRAM prices per bit—in real dollars (Figure 6). It

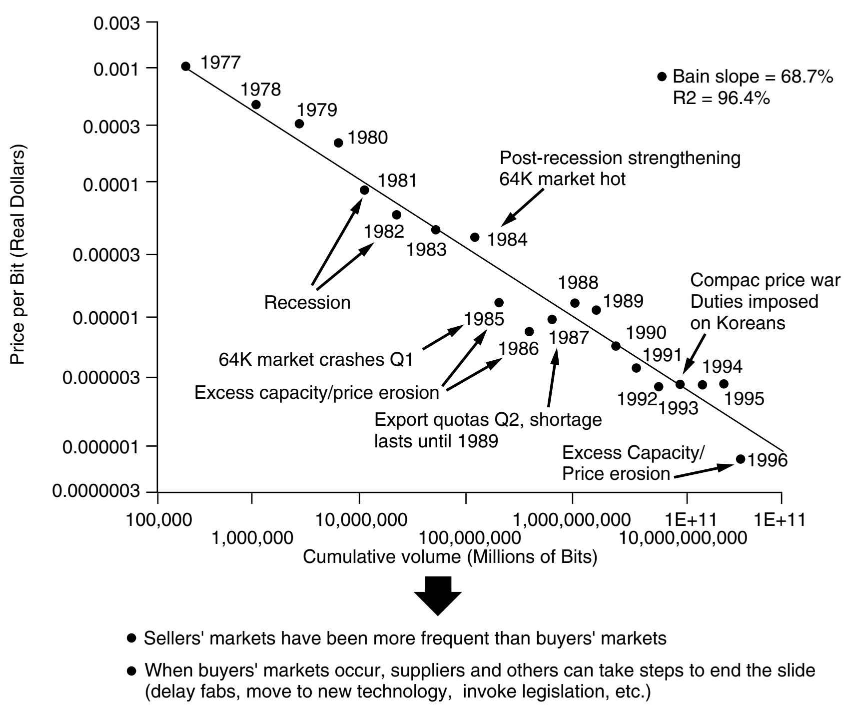

FIGURE 6 DRAM Price Per Bit.

showed that DRAM prices declined steadily from 1977 to 1992, with a flattening from 1992 to 1995. During these four years of flat prices, semiconductor sales in dollars approximately tripled, he said, and people in the memory business were making handsome profits. Then the industry entered a period of overcapacity; prices dropped precipitously between 1995 and 1996, and total sales fell about 10 percent. Dr. Spencer also attributed some of this drop to legal and international trade policies that handicapped the industry.

Costs of Microprocessors and Memory

A similar phenomenon can be seen in microprocessors, he said. A curve adapted from the semiconductor roadmap showed a drop in price per million instructions per second (MIPS) between 1980 and 1995 of 24 percent per year. The 1997 NTR Roadmap "Affordable Cost" Model predicted that for each DRAM generation of three years, cost would continue to drop steadily by half. Also illustrated was a pronounced decline in price of each new processor from the time of introduction to maturity.

A similar curve can be used to illustrate the dropping price of magnetic memories, said Dr. Spencer. In fact, the price per megabyte of magnetic memory on hard disk drives has dropped by 50 percent a year, a higher rate than semiconductors, while hard-drive density has increased at 60 percent a year.[11] He said that in his opinion the drop in magnetic memory prices is largely a function of price pressure from semiconductor memory. These gains in productivity have also pushed down the prices of LCDs, keyboards, batteries, and other personal computer components. The progress in these technologies is remarkable at a time when military procurement is a minor factor and the automobile industry is growing only slowly.

A Roadmap for Semiconductors

Dr. Spencer then traced the history of the roadmap for semiconductors. The first such roadmap was designed by the National Advisory Committee on Semiconductors (NACS). This group of distinguished business and university representatives assembled by President Reagan formulated a national policy on semiconductors in the mid-1980s. At that time the U.S. semiconductor business was at its nadir and many people predicted that the industry would follow the U.S. television and consumer electronics businesses into near extinction.

NACS organized Microtech 2000, and one of their boldest proposals was to leap one whole level of technology to move directly to 1-gigabit memories by the year 2000. The semiconductor industry disliked that idea. Instead, noted Dr. Spencer,

[11]These figures for rigid disk drives are from Bill Frank, *Insight,* 1997.

we have reached 1-gigabit memory today—not by jumping a generation but by speeding up the generations. The first roadmap of the semiconductor industry was done in 1992, mostly by a group from SEMATECH that was chaired by Bill Howard, then at Motorola. A second roadmap was created in 1994.

The Acceleration of Moore's Law

When the roadmap began in 1992, a technology generation had, since the 1960s, been three years in length. In 1992 the minimum feature size of a device was 500 nanometers. In 1995 the minimum was 350 nm and the roadmap predicted that it would drop to 250 in 1998. Instead, after the roadmap was created, the size dropped to 250 nm in two years instead of the customary three years. The roadmap then accelerated in 1997 and again in 1999 when 180-nanometer technology began. Thus, in a decade the industry moved from doubling the number of transistors in a given area every 18 months to doubling it every 12 months. It had raised, in effect, the pace of Moore's Law even faster. The international roadmap predicts that this pace will continue to the year 2003 and then perhaps return to its previous three-year pace (Figure 7).

The Question of Physical Limits for Semiconductors

The plan for International SEMATECH, whose members represent 50-60 percent of the semiconductor business worldwide, is to try to stay on the two-year cycle. That goal, said Dr. Spencer, raises two interesting questions. One, are we

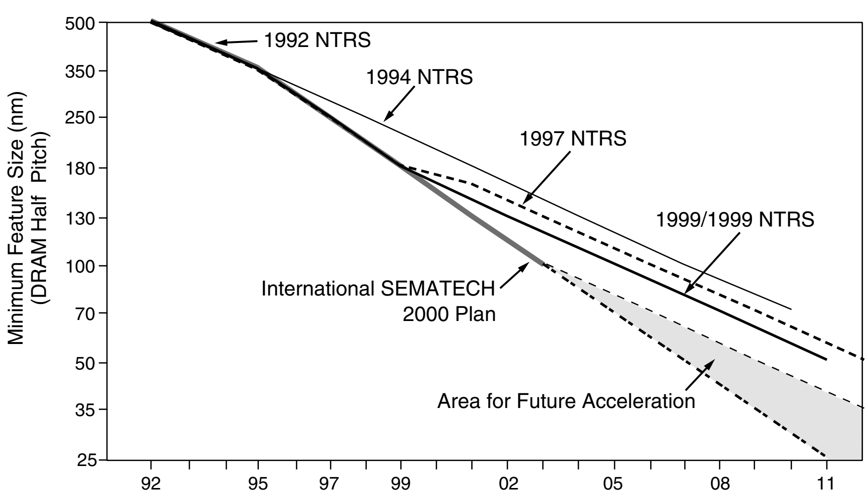

FIGURE 7 Semiconductor Roadmap Acceleration.

accelerating improvements in technology at about the same time we approach a wall of physical limits? Oxide layers on semiconductors are now only about 4 or 5 atoms in thickness, which means that atomic flatness is required over the width of the gate or the yields begin to drop. Other dielectrics may make further progress possible.

Another problem has to do with lithography, where empiricism has won out. An equation that relates resolution in lithography to the wavelength and numerical aperture of the optics has an empirical constant. Nobody knows what makes up that empirical constant, but engineers have been able to change it by a factor of two from 1995 to the present. Lithography has gained additional capability to make finer lines by using the same wavelength, something thought impossible previously, so there are still tricks that can make the hardware more efficient. No one knows how many more such tricks can be found. In addition, the software challenge of designing a billion transistors on a chip constitutes another kind of wall. Without new technology it seems only a matter of a few years before these engineering walls form an impassable barrier.

Dr. Spencer raised the question of why the semiconductor industry had decided on a two-year cycle instead of a three-year cycle. The answer to this question is not obvious other than a sense that a group of companies had discussed the matter and decided it was possible and therefore desirable. This change has put great pressure on equipment suppliers, who must now produce a new generation of equipment every two years instead of every three years.

The Rapid Market Penetration of Computers and Internet Access

Dr. Spencer showed a graph that compared the growth rates of homes in the United States that had access to electricity, television, telephones, cars, and radio with the growth rates of homes that had access to computers and the Internet (Figure 8). Both computers and the Internet are growing at approximately the same rapid rate as radio during the 1920s and 1930s and television during the 1950s and 1960s. He noted that only telephone and automobile growth slowed (temporarily) during the Great Depression of the 1930s, while electricity and radio continued to grow during those years. Television, radio, and electricity all peaked at over 99 percent of penetration. For the Internet about 55 percent of U.S. homes will be connected by 2005.

He closed his talk by revisiting—but declining to answer—the thorny question of when we will reach physical limits that begin to restrain semiconductor growth. Silicon CMOS, the dominant semiconductor technology today, should support traditional productivity growth in the industry for the next five to ten years. The factors slowing productivity growth are as likely to be economic (e.g., cost of manufacturing) as reaching the physical limits of transistors in silicon. There are emerging technologies, such as quantum computing, that may extend the life of digital processing and storage.

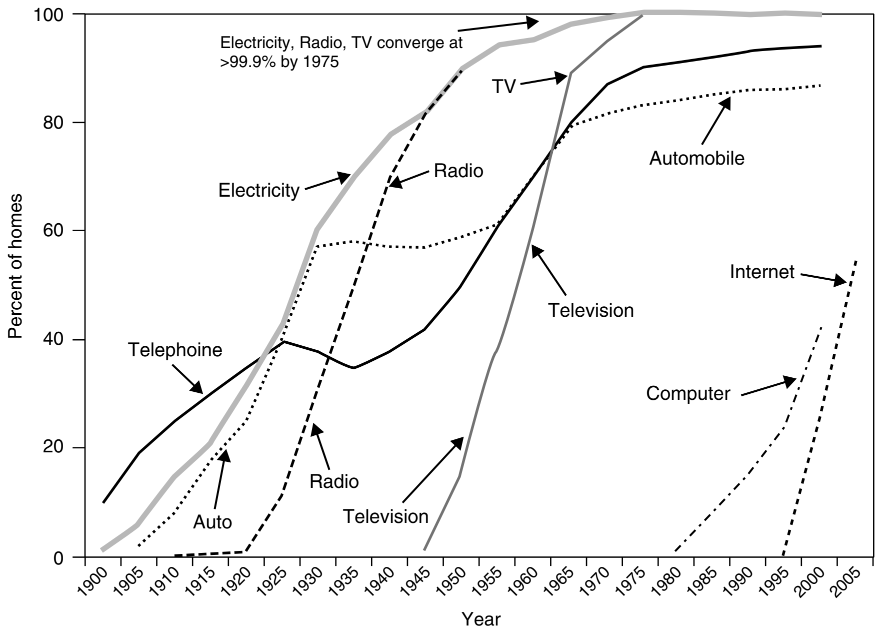

FIGURE 8 Penetration of New Technologies in U.S. Homes, 1900-2005.

DISCUSSION

A History of Forward Leaps in Technology

Dr. Jorgenson asked Dr. Spencer whether he thought the risks to the semiconductor industry are greater "on the downside or the upside." He cited Dr. Spencer's statement that some technologies are progressing more rapidly than semiconductors. One example is the communications technology of wave division multiplexing, which by doubling every six months, is propelling the growth of the Internet. He asked whether prospects could be even better than the most optimistic view of the Semiconductor 2000 plan.

Dr. Spencer replied that there are always times when technology makes tremendous leaps forward. This happened in semiconductors with the advent of CMOS technology. The industry had believed for a long time that it could not build MOS devices, and when this was discovered to be possible, it enabled many techniques that could not be done with bipolar technology. He said that fiber optics was another example. He also mentioned software productivity: that increased computing power and low-cost memory allowed new, efficient ways to write software. He compared this with the first Alto microcomputer built at the Xerox Palo Alto Research Center in the late 1970s. This feat required a great deal of microcoding, which is virtually obsolete today. Microcoding was the only way to operate the Alto, because systems then lacked sufficient processor speed and physical space for memory.

He also suggested that fiber optic technology might provide a powerful growth boost to communication technology, as long as it is possible to move from electronic to optical switching. The same might happen in computers, thanks to the RISC-based architecture that has increased the number of operations that can be done per cycle of clock speed. Thus, the future of information technology would depend not only on semiconductor productivity but also on major jumps in other technologies.

The Challenge of Finding Real Value in Technology

Bill Raduchel observed that the most interesting problem over the next decade rests not so much in creating new technology but in figuring out how to do something useful with it. New technologies are growing faster than consumers can absorb them. Virtually anything is possible, he said, and if it isn't possible now, "give me one year or two years or three years of these growth rates and it will be." The challenge is to find real value in all the new technology. It is useful to change outmoded business practices and to clean up software systems. The understanding at Sun Microsystems is that innovations have no value unless consumers see that value and use it. The upside may not be in the raw bits but in finding an application for the new technology. He mentioned having talked with people who spend large amounts of money for cellular licenses without having a plan for how to use them. He termed this development "scary"—a willingness to invest in expensive technologies without any ideas for using them.

Jon Baron asked whether the cost of semiconductors is becoming a larger or smaller share of computer costs. Dr. Spencer answered that a semiconductor's share of the cost of a personal computer is about 40 percent today versus about half that a decade ago.

A Leap in Internet Access

Lee Price commented on a recent survey by the Commerce Department on home Internet access.[12] He said that (although he did not have precise figures) the trend in access was climbing steeply. For home ownership of computers he

[12]U.S. Department of Commerce. 2000. *Falling Through the Net: Toward Digital Inclusion*. Washington, D.C.: Economics and Statistics Administration and National Telecommunications and Information Administration.

cited different trends for two different periods. For the period 1984–1992 the rising curve in computer ownership was beginning to flatten. Then for the most recent three years, from 1997 to 2000, home computer buying rose again as more people used the computers to access the Internet. He also said that people who use computers at work are more likely to use them at home.

The Role of Semiconductors in Driving Growth

David Morgenthaler commented on the degree to which semiconductors have driven recent economic growth, citing a regional study he helped to fund. The question is what were the economic drivers of 100 to 130 years ago when northeastern Ohio was the Silicon Valley of the country? Early indications are that a combination of petroleum and the internal combustion engine were the drivers that made the region a center of innovation for the country. He suggested that the semiconductor is probably the counterpart today. Dr. Gomory agreed, with the caveat that other advances were probably playing a role as well, such as the ability to price a color printer at less than $100. He then introduced the next speaker, David Mowery.

SEMICONDUCTORS: ECONOMICS OF THE NEW ECONOMY

David Mowery
University of California, Berkeley

Dr. Mowery addressed the economic issues raised by Dr. Spencer's remarks by discussing how and where the gains in productivity that have resulted from the application of computing and information technology in the semiconductor industry have been realized. He noted that much of the progress in the performance of computers and related information technology products reflects progress in semiconductor components. Conversely, significant advances in manufacturing and design performance within the semiconductor industry are associated with the application of computing and information technology.

The "Copy Exactly" Process Technology

In recent research with colleagues at the University of California, Berkeley, and Georgetown University, Dr. Mowery and his group[13] found that innovation in semiconductor manufacturing processes, particularly the development and introduction of new process technology in this industry, retains a strong element of

[13]His collaborators included Dave Hodges, Rob Leachman, and Jeff Macher, under the auspices of the Berkeley Competitive Semiconductor Manufacturing Project.

trial and error. It relies to a remarkably small extent on simulations or reliable, robust, predictive models.

A good example of this approach to process innovation is the so-called "copy exactly" philosophy that the Intel Corporation relies on in transferring process technologies among manufacturing plants. This approach to managing the development and transfer of process technologies concedes that in the absence of a complete understanding of the process technology it is necessary to copy the entire system—the length of pipes, the placement of equipment—exactly, rather than in a way that is based on engineering or scientific knowledge. This is a remarkable example of pre-scientific problem solving and trial-and-error experimentation in this industry. At the same time, however, semiconductor manufacturing process technology and manufacturing performance have benefited enormously from the application of computing technology to manufacturing process control, data capture, and analysis.

In some respects the process technology side of the semiconductor industry resembles that of the chemicals industry in the 1940s and 1950s. During this period in the chemicals industry, process technologies frequently were developed and initially applied in small pilot plants, and subsequently scaled up and applied in commercial-scale plants. This approach to process development was time consuming and tied up expensive facilities for long periods while people worked on incremental improvements in process technologies. The application of computers to the design and simulation of chemical reactions and the use of minicomputers to monitor plant operations have changed the development and management of manufacturing processes in the chemicals industry. The lack of a complete scientific understanding of semiconductor manufacturing processes is likely to constrain the scope for increased application of computer technologies to process simulation and manufacturing management. With advances in understanding, however, such expanded applications could have a transformative effect on industry structure and performance.

New Specialty Firms in Design

Computer-aided tools have been widely applied to the design of semiconductor devices, yet design remains a constraining factor in technical progress. Innovation in this industry has been a horse race between design and manufacturing technologies, and design has been the key constraining factor. This is revealed to some extent in the successive formulations of Moore's Law. Initially the doubling in transistor density on semiconductor devices took only one year; subsequently the time required for such an advance was extended to a year and a half. These revisions have been driven by constraints in design rather than in manufacturing.

This design bottleneck has had interesting implications for the evolution of the industry's structure. Integrated firms that combine design and manufacturing now face increased competition from specialists in design and manufacturing. The semiconductor industry is undergoing structural change and some vertical disintegration with the entry of a large number of specialized design and marketing firms—called fabless semiconductor firms. Specialized manufacturers, the so-called "foundries," now play a more important role in the semiconductor industry. In addition, semiconductor equipment firms are now more important as developers of new process technologies than simply as suppliers of new equipment. All of this progressive vertical specialization is facilitated by advances in Web-based and other information and communication technologies.

New Models That Rely on Vertical Specialization

What are the implications of specialized entry and the focus of these specialized performers for the long-term productivity of the industry? Research by the University of California, Berkeley, team suggests that the specialized manufacturers of chips adopt a more incremental approach to management of the introduction of new process technologies. Process technologies are being upgraded more frequently and continuously within these foundries, which develop capability in the frequent introduction of process technologies. The pace of these applications may influence the extent to which they create bottlenecks and these bottlenecks may influence the evolution of the industry structure.

The future of this industry will include numerous experiments in new business models that rely on vertical specialization. Design firms increasingly are specializing in individual pieces of real estate on wafers and chips. There is a growing trade among these design firms in design components, or IP blocks, facilitated by the Internet. An interesting question is whether such trends in the semiconductor industry will be replicated elsewhere in the New Economy.

Does New Knowledge Affect Process Development?

One characteristic of the New Economy is its reliance on the application of new knowledge to economic life. How are information and communications technology affecting the processes and perhaps the productivity of knowledge production itself? For example, how has the infusion of information and communications technology affected the trial-and-error processes that historically have governed process development and introduction in the semiconductor industry? Will this industry's future development follow a path that resembles that of chemical manufacturing during the 1970s and 1980s? Other scholars have argued, with limited evidence, that general-purpose technologies, such as information technology, should raise the productivity of R&D or of knowledge production. This or future workshops might cast some light on this issue through case studies and discussions.

The Contribution of Semiconductors to Other Sectors

Finally, some evidence on the effects of technical progress in semiconductors on the larger economy may be available from an examination of trends in markets for semiconductors. Slightly less than half the end-user markets for semiconductors currently are in the computing industry. The other leading users are automobiles, consumer electronics, and communications. Because measures of quality improvement in the output of these sectors are almost entirely lacking, it is difficult to assess the contributions of semiconductors to these and other sectors of the U.S. economy. Without better measures of quality improvements in the output of various sectors it will be difficult to trace the contributions of the semiconductor industry or other industries that produce critical inputs to the New Economy. This is not a trivial task, given the diverse array of outputs in an industry like consumer electronics.

DISCUSSION

The Importance of Better Data for Other Technologies

Dr. Jorgenson disagreed that there is a gap in our knowledge about the change in the price of semiconductors. He said that thanks to the work of people at the Department of Commerce, the Federal Reserve Board, and other places we know a good deal about semiconductor prices. In addition, there is a long tradition of measuring computer prices. For telecommunications he noted that, as Dr. Flamm pointed out more than 10 years ago, we have made little progress. However, we do know that semiconductors directly affect those technologies that behave in ways similar to computer prices but whose rates of improvement are not captured in routine statistics. These technologies carry increasing importance and measurement efforts should receive top priority.

A second priority should be to learn more about software. Dr. Jorgenson noted competing views in this respect. Some people think that software is basically something that is a hand industry that changes little; others, including Drs. Spencer and Raduchel, argue that it has changed and that it is affected by the progress of semiconductors because of the impact of computers in the production of software. We, however, do not know much about this effect and it is important to learn more. Dr. Jorgenson placed lower priority on understanding processes that are less closely related to the progress of semiconductors.

David Mowery replied that he had not addressed the organization of the innovation process, but he did stress innovation in the form of entry by different kinds of firms—non-integrated firms in manufacturing, the fabless firms, and the extension upstream of equipment firms into process development.

The Importance of Flexible Organizations

Shane Greenstein offered an historical note, observing that several decades ago Silicon Valley was known for more than just innovations in an engineering sense; it was also known for its inventiveness in the creative organizational design and for its generation of knowledge in these new organizational forms. These had not been seen before and were quite dynamic. People moved across organizational boundaries and took knowledge with them. That was one of the factors that made this industry so dynamic. He said that this might be an important source of bottlenecks and an important place to look for the creation of value and new organizational forms.

Dr. Mowery agreed with Dr. Greenstein that the new approaches to organizing and managing R&D in many of these pioneering firms are important. He suggested, however, that such structures might be even more difficult to understand and quantify than the other factors he had discussed.

Measuring the Activity of "User" Industries

Dr. Mowery also addressed Dr. Jorgenson's point about semiconductor knowledge gaps, saying that unless we can measure the output of the "user" industries more effectively it is hard to see the contributions of the semiconductor industry. He suggested starting with the communications and consumer electronics industries, given their complexity. He added that the rest of the economy—outside the computer industry—has become "a bit of a dark planet" in terms of understanding quality improvements in their products.

The Complex Interactions of Technology and Society

Dr. Gomory said he would exercise his privilege as moderator to say he agreed with those remarks. He said that it was overly simplistic to try to describe the progress of the semiconductor industry solely in terms of whether finer lines could be etched onto semiconductors. He said that it would be equally wrong to focus on the flying height of disks. This is not a one-parameter phenomenon, he said; much more is going on.

He praised the remarks of Dr. Mowery, saying that even scientific fads had to be reproduced exactly to understand what is happening and how long the pipeline is. We understand some things, he said, that are in narrow areas, but we are also groping and are having to do things empirically.

Alluding to Adam Smith, Dr. Gomory raised the example of the pin factory, where gains arise from specialization. When an industry grows, specialization becomes possible. In the early days of software there was just one undifferentiated bundle that retrieved files. Today the part that used to retrieve files has become the whole database software industry. He compared an industry to the surface of a balloon; as it is blown up, what was a speck on the surface becomes large and now contains many features of specialization and efficiency. The interactions of technology and society are highly complex and around each small bit of truth that we understand is a huge dark area that we do not understand. He urged the group to be aware of these dark areas and not to base their understanding on a few narrow parameters.

The Value of Sharing Knowledge

Dr. Spencer added two comments. The first was that the day when somebody could leave a semiconductor company with some knowledge and take it to another company had probably passed. He said that the last serious case he had heard was at Intel, when—as someone humorously put it—vulture capitalists lured away some of the people who were making static memory, causing Intel to go after them. He said that one of the biggest surprises to those who began to work at SEMATECH fifteen years ago was that "everybody knew everything" and there were no secrets.

His second comment was that the rapid early growth of the semiconductor and integrated circuit industries was possible because there were no patents. Use of the patent for the semiconductor and the transistor was provided to everyone for a modest fee due to the Bell System's consent decree with the U.S. government. This precedent, he added, may be an important lesson for the biotechnology industry. The same was true for the integrated circuit; a patent case between Texas Instruments and Fairchild Semiconductor resulted in this technology not being patented.

The Need for More Basic Research

Dr. Mowery added that the vertically specialized firms that are entering the semiconductor industry are focusing largely on development work at the commercial, leading edge of technology. He questioned whether this sort of highly focused, upstream research could be maintained without better integration with more basic research. Dr. Gomory seconded this concern and expressed the hope that the workshop would further explore this and related issues, such as the powerful role of venture capitalists in enabling many developments in technology.

MICROPROCESSORS AND COMPUTERS: FIVE TRENDS

Alan Ganek
IBM

Mr. Ganek focused his talk on five trends that help to describe the present state of information technology and affect all its components.

An Optimistic View on Overcoming Limits

The first trend is the straightforward observation that progress in information technology continues at an ever increasing pace. This might seem obvious, he said, but most technology areas have rapidly improved and then reached a point of maturity and growth levels off. Even for microprocessors and computers we are near that point of maturity, although its exact position is unknown.

Indeed, there is some doubt in the semiconductor industry that its pace of growth can continue. Historically, about 50 percent of its improvements have been made through better yield per wafer, finer lithography, and other scaling techniques that reduce size and produce better electrical behavior. He showed evidence, however, that the pace of lithography improvements in the past few years has been faster than ever before.

He then turned to the transistor and a representation of the gate dielectric mentioned by Dr. Spencer. He noted that the transistor is now only about a dozen atomic diameters thick, and it is not clear how to reduce that thickness further than one-half of its current dimension. "So there are real fundamental atomic limits you approach," he said. "That may make you wonder, why am I so optimistic?" He answered his own question by suggesting that improvements will come from other directions, supplementing the lithography and other aspects of scaling he had mentioned. "Physicists are famous for telling us what they cannot do and then coming back and doing something about it."

Factors That Improve Performance

He illustrated his point with a chart where every figure represented a factor that improves performance at the same feature size (Figure 9). The challenge is that such improvements are one-time effects that must be followed by something else. Nonetheless, materials science has provided many such effects, such as introducing copper to interconnect the substrates of the chip; dielectrics that improve performance through the wires; and silicon on insulator that improves the circuitry within it. Silicon germanium is an alternative technology that does not replace CMOS but it does allow you to build mixed-signal processors at very high frequencies that can handle digital and analog circuitry together. He showed the relevance of this technology to Dr. Cerf's comment that the communications industry's urgent need is to make the translations from huge fiber backbones to routers and other components that can convert optical to electrical signals.

He then offered another illustration of how speed can be increased despite the physical challenges. He showed a picture of a friend holding the first experimental gigahertz processor on a wafer. Just three years ago a gigahertz was three times the speed of any commercially available processor and yet it was produced on a 300-megahertz processor line. This was done not by semiconductor power but by redesigning the data flows to triple the performance of the processor. The

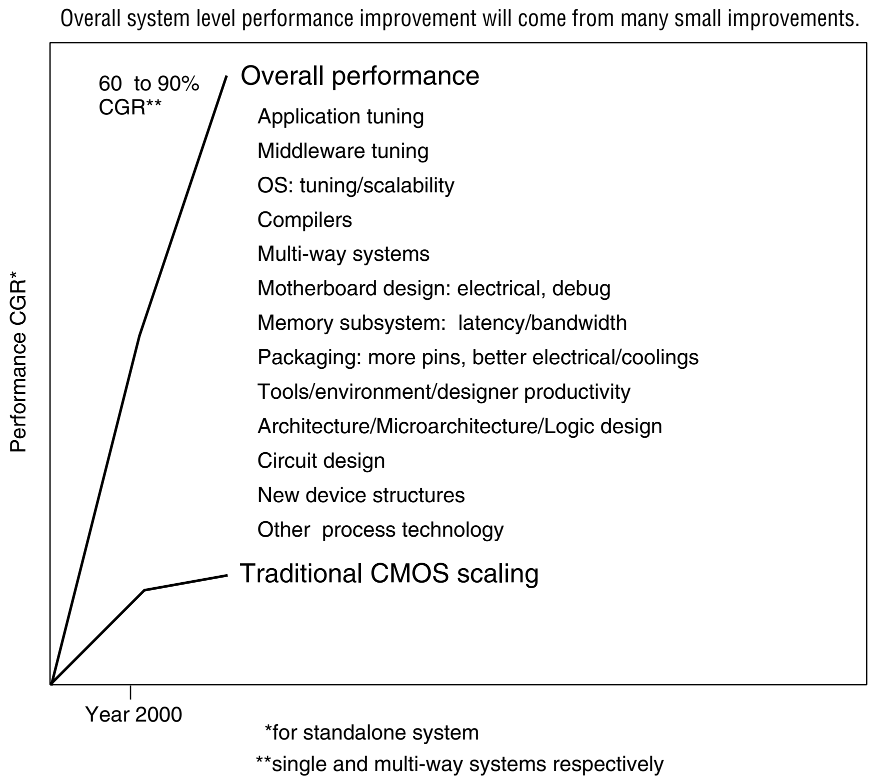

FIGURE 9 System-level Performance Improvement.

increased speed, therefore, was purely a design attribute, similar to those mentioned earlier by Dr. Morgenthaler. His point was that many factors could maintain the growth of computing power.

The Processor is "Not the Whole Game"

After showing a growth line of conventional bulk CMOS as evidence that growth was starting to level off, he said he was optimistic that engineers would keep finding ways to push it forward. He could not say whether it would continue as an exponential curve or something less, but he expressed confidence in continued price performance. He stressed that from a systems perspective, processor performance alone "is not the whole game." IBM estimates that of the compound growth rate in systems performance, about 20 percent has been due to traditional

CMOS scaling. In uniprocessor systems about 60 percent of the compound growth rate has come from a stack of other factors, and for multiway systems 90 percent of the growth has come from other factors.

These factors include other process technology, circuit design, logic design, tools, environment, and packaging techniques. He said that packaging as an art had fallen out of vogue at IBM but is now being reestablished because of the leverage it provides. In addition to these factors is the whole software stack, including compilers, middleware, and—probably the single best biggest lever in actual deployment—application tuning. A poorly tuned application, he said, imposed a sheer waste of processor speed. Mr. Ganek said he saw tremendous opportunities to continue the progress in ways that complement the basic CMOS drivers.

Continuing Progress in Supercomputers

He then discussed growth in the speed of supercomputers, which are inherently parallel machines, and offered a forecast of an 84 percent compounded growth rate in terms of teraflops, or trillion floating point operations per second. This rate would be even higher if one began with the Deep Blue chess-playing machine; great speed is possible in special-purpose machines. Deep Blue's technology is now used in a Department of Energy 12-teraflop machine for simulating nuclear events. IBM is now collaborating with the Japanese to build a machine that simulates molecular dynamics: a very narrow-focus machine that has the potential of yielding 100 teraflops within the next year or two. The Blue Gene protein-folding system IBM is building will have 1 million processors, each of which has 1-gigahertz speed. That may not sound fast but each chip will have 32 processors as well as integrated communications and memory functions—"a completely radically different architectural design that will get a tremendous amount of performance."

Mr. Ganek mentioned the inexact but interesting scale by which Ray Kurzweil has compared microprocessors with living organisms: The Deep Blue machine was probably at the capacity of a lizard and the IBM ASCI white machine is about at the level of a mouse. Humans would fall into the 20- or 30-petaflop range—a range that one would expect general-purpose supercomputers to handle by about 2015. If this scale has any validity, "that means we're going to go through the equivalent of 400 million years of evolution over the next 15 years."

The Growth of Memory

Mr. Ganek reemphasized that performance involves more than processors. Storage is especially important and has moved more rapidly than semiconductors for the past decade in terms of price performance. The compounded annual growth rate of storage capacity has increased from 60 percent in the beginning of the decade to 100 percent at present. Now, many desktop computers have disks with storage densities of 20 gigabits per square inch. Mr. Ganek said that when he first learned the term "superparamagnetic limit," he was taught that that limit was 8 gigabits per square inch, and that limit has already been exceeded by a factor of 2.5. Scientists now believe that 100 gigabyte-per-square-inch density is achievable with magnetic technology, and they believe that alternative technologies may perform even better.

He showed an illustration of a 340-megabyte disk drive in a form factor only slightly larger than a quarter now available at a gigabyte and said that in three or four years this will be available at 5 or 6 gigabytes. In general, the ability to have cheap storage everywhere is going to continue. Then he showed how this translates into price performance, "which is why we're going to be using so-called electromechanical devices like storage instead of just memory for a long time to come." He predicted that in 2005 the cost of storage would be only about a third of a cent per megabyte. Given the time required to erase data, it will be less expensive to keep them than to delete them.

A New Window for Fiber Optics

He commented on fiber optics and the worry of many people about the maturity of erbium-doped fiber amplifiers. Recently, wavelength division multiplexing has opened a new window for growth. He did warn that progress is never a continuous curve, and that backbone bandwidth is determined largely by the capacity of the fiber that is deployed. "It is a step function and the backbone you have is only good as what is laid." He said that the good news, based on conversations with industry experts, is that backbone capacity is growing at a tremendous rate around the country and that in two or three years it may reach the neighborhood of 10 to 20 petabits. He added that it was not apparent that the quantity or quality of content was developing at nearly that rate. "Last mile" access technologies such as cable, xDSL, and cellular, which connect local networks to the backbone, limit the full use of backbone bandwidth.

The Pervasiveness of Computing Devices

In introducing the second trend, Mr. Ganek then touched on a subject raised by Dr. Cerf, the growing pervasiveness of computing devices, which will interconnect computation everywhere and change the interaction of people and objects in the digital world. Pervasive devices will become the dominant means of information access. The personal computer will continue to drive a healthy business but it will be dwarfed by the growth of data-capable cell phones, which will pass the installed personal computer base in 2002, and the additional growth of personal digital assistants (PDAs), smart cards, smart cars, smart pagers, and appliances. He then showed a Watchpad being developed at IBM that has 500 megahertz of processing capability, a new display technology with high resolution, a phone directory, IrDA communication channels, calendar, pager, and other features. He called it "elegant, always on you, always on, easy to use, and hard to lose." In four or five years people will have 5 or 6 gigahertz of capability on their wrists with a convenient and flexible user interface. Its touch-screen interface is superior to the small pointing stylus that is so easily lost.

Mr. Ganek predicted more mixed modes of technology, including voice recognition which will display results in more useful ways. Today in some applications one can ask for airline information, for example, but it is difficult to remember it all. If the verbal request can be answered with a screen display, the information can be kept for subsequent interactions with other systems. The application of such technology is not limited to traditional business functions and personal data acquisition. These devices might be thought of as clients that do the job of finding information.

Such devices can also become servers. He showed a device that helps patients with Parkinson's disease. With sensors in the brain connected by wires in the skin to a pacemaker-like unit at the heart, the device senses an oncoming tremor and generates an impulse to stimulate the brain and avert the tremor. Pacemakers—of which there were "until recently, more in the world than Palm Pilots"—can also broadcast information about vital signs. This means that people can be walking Web servers that provide critical medical information. Such devices are not just retrievers of information; they are continuous sources of real-time information.

The Potential of Software Through 'Intelligent Networks'

A third trend is a utility-like model for value delivery based on an intelligent infrastructure. Mr. Ganek compared it to the motor analogy that Dr. Cerf introduced. Looking back to 1990 and earlier, people assumed that clients would access an enterprise through an application server on a network, one client at a time. Now, in addition to individual enterprises there are new providers that offer a range of services. The clients are network clients of an intelligent network and the enterprise they are associated with is only one of many sources of information. The network becomes a repository of intelligence across a broad spectrum of applications, such as caching, security, multicasting, network management, and transcoding, so that the application does not need to know what the device looks like.

This direction relates to the earlier discussion of software development and productivity. Individuals writing lines of code have made good progress but not at the exponential rates of lithography, for example. Such deployments are the next step beyond the packages mentioned earlier, where software for electronic utilities has an economy of scale. The software is provided through the network and people accessing those utilities need to make fewer in-house changes. Small businesses might need only a browser to access the software. For larger concerns the system is more complex, but the service is still outsourced and the software is developed with a larger economy of scale.

The Formation of E-Marketplaces and Virtual Enterprises

The fourth trend also concerns software for business. He said that when he started writing software, he had a notion of subroutines that had to do with such low-level functions as figuring out the sine curve or sorting. Today, writing software has moved to much higher-level components that are becoming synonymous with business objects. Of all the software being written the most important relates to enterprise processes: business-to-consumer processes, business-to-business processes. Moreover, electronic commerce building blocks are emerging to support these enterprise processes.

E-marketplaces are being formed that may mediate up to 50 percent of business-to-business commerce by 2004. The marketplaces will be able to bring many buyers and many sellers together and add such functions as dynamic pricing, frictionless markets, and value-added service. It is too early to know exactly how this will happen, Mr. Ganek said, but the e-marketplace is already a tremendous force in determining how people deploy technology for business, which has a direct bearing on the economy. People have moved from using the Internet like a shopping catalog to a many-to-one procurement tool. Now they are matching many suppliers with many buyers and getting commerce done in a much less expensive way. Instead of days, weeks, and months business transactions will take hours and minutes.

The final step of development will be virtual enterprises, which will play an important role in the evolution of collaborative commerce. There are many questions about how virtual enterprises will work: will they form their relationships dynamically using discovery technology to find out who else is out there? What can they deliver? How can a business be constructed electronically by connecting these different pieces? Industry consortia are working together to find the answers.

The Electronic Business of the Future

The fifth trend is that the electronic business of the future is going to be dynamic, adaptive, continually optimized, and dependent on powerful business analytics and knowledge management. Those who started using information technology in businesses years ago saw it largely as a tool for automation—doing manual tasks faster and cheaper. Information technology is now the arena where companies compete with one another. It is no longer simply a plus-side attribute; it is a frontier for creating new strategy and revenue generation.

He offered the high-end example of insurance risk management. How companies in this business manage their risks and invest is critical to whether they succeed. The more risk factors a company can analyze at one time the more valuable the analysis. Risk computations turn out to be very complex, however. A typical supercomputer in 1995 running at perhaps 1 gigaflop would take about 100 hours to solve a problem involving three risk factors. This solution would be helpful but too slow for the pace of business. In 1999 the same company might have a 25-gigaflop computer that is reasonably affordable and could do the same analysis in two to three hours. This still does not include all the desired parameters, but the company could look at the problem several times a day and start to make some judicious choices that contribute to a competitive edge.

In 2002, when the same company might expect to have a teraflop machine, it could run the same problem in minutes. This speed could begin to change how the company functions and what actions it takes in the stock market in real time. Such computing ability will move into virtually every business. As an example, he cited IBM's ability to do supply-chain analyses that assess trade offs between inventory and time to market. Such analyses save the company an estimated amount in the hundreds of millions of dollars a year in the personal computer business. Because it is so hard to make a profit in the personal computer business that computing ability probably allows that company to stay in the business.

The Promise of Deep Computing

He closed with the example of what more efficient computing is beginning to do for the pharmaceutical industry. The cost of producing new chemical entities has more than quadrupled since 1990, while the number of new entities has remained essentially flat. The number of new drugs being produced by deep computing, however, is beginning to rise, and this number is estimated to triple by the year 2010. These deep computing processes include rational drug design, genomic data usage, personalized medicine, protein engineering, and molecular assemblies. This projection is speculative, he emphasized, but it shows the extent to which a major industry is counting on radically new uses of information technology.

DISCUSSION

The Wish for Self-Learning Machines

Dr. Myers passed along a wish list from Dan Goldin, administrator of the National Aeronautics and Space Administration, who hopes to develop spacecraft that can cope with unexpected conditions by making autonomous decisions. Remote decision making would eliminate the long time delay involved in communicating with Earth for instructions. True decision making, however, would require computers that are, to some extent, self-actuating, self-learning, and self-programming. This, in turn, may imply a new form of computing architecture.

Mr. Ganek responded that a number of challenges lie ahead in designing such thinking machines. He mentioned the exercise in computer science known as the Turing test, in which a human interacts with a computer behind a curtain. If the responses of the computer are so accurate that the human cannot tell it is a machine, the machine passes the Turing test. At present, software engineers lack the ability to program such a machine, even if it had a 30-petaflop speed. Some machines can do self-learning on a small scale, such as using natural language technology to categorize e-mails. In a bank, for example, a system might be able to route e-mail to the loan department, the mortgage department, or investments. When it makes mistakes it is self-learning in the sense that it will improve the algorithms. Many people are working on system management to deploy computer systems and make them more adaptable. So far these systems are not holistic in the sense of being able to do actual learning across the spectrum of all aspects of managing complex systems. Very serious investment is being applied in this area.

Dr. Wessner asked whether the pharmaceutical companies are working actively on deep computing to produce new products. Mr. Ganek replied affirmatively, noting that “there is a frenzy in this area, trying to understand how to take advantage of these technologies,” especially with the new genomic data becoming available. He pointed out that some of the most promising techniques have nothing to do with hardware but with finding better patterns of discovery algorithms that can reduce algorithmic complexity and speed up problem solving.

MICROPROCESSORS AND COMPUTERS: THE PHENOMENON OF PRICE DECLINES

Kenneth Flamm
University of Texas at Austin

Dr. Flamm prefaced his remarks by saying that he was an economist who has been looking at the field of microprocessors and computers for about 15 years. He has seen, until recently, a picture of relative continuity rather than dramatic shifts. He confessed, however, that he has now begun to lean toward Dr. Jorgenson’s view that there was a point of inflection around 1995.

Some Problems with Models and Weighting

He began with: Let me tell you what I thought I knew until recently. He said he had a good picture of the rate of price performance improvement in semiconductors and computers over time, through both his own studies and the literature on rates of price performance in computers and semiconductors. He suggested two difficulties. The first is that typically the numbers used in national income accounts are too low. For example, the computer price deflators in current use are those of the Bureau of Labor Statistics (BLS), not the Bureau of Economic Analysis (BEA). The BLS uses a methodology of hedonic adjustments to matched models, which have at times underestimated the true rate of price performance improvement in computers.[14]

Dr. Flamm's second point was that some people have done credible studies suggesting that if one tries to calculate the percentage of the improvement in computers that comes from semiconductors, the answer depends on the weight of semiconductors in the value of computers. The problem is that national income accounts for the United States do not have good information for this weighting. According to Dr. Flamm, if the semiconductor content in computers is 15 to 20 percent, then about half the technological improvement in computers has come from semiconductors. If the content is as high as 40 percent, then virtually all the improvement is coming from semiconductors. This, he reminded his audience, has to be amended by the fact that computer numbers are probably too low, so other factors beyond semiconductors must play a role. It is a "giant mess" if you look only at the traditional numbers.

Dramatic and Surprising Price Declines

Dr. Flamm added a note from his personal experience in working on litigation questions. An interesting aspect of litigation work, he said, is the occasional access to proprietary data, which may be more detailed and more accurate than publicly available data. The public data show price performance improvements in personal computers in the range of 30 to 35 percent for the early 1990s. That is an uptick from a historical rate, which has been closer to 20 percent since the 1950s. Recently, however, unpublished hedonic studies of price performance indexes for personal computers have shown annual rates in the 40-45 percent range. He said he could not make public the proprietary data underlying these statements, but remarked that credible hedonic studies have shown these really dramatic and surprising price declines in personal computers after adjusting for other factors (Figures 10 and 11).

Where, he asked, is this large and surprising number coming from? He returned to Moore's Law, and suggested there might be an economic corollary. This extension of Moore's Law might argue that the industry is able to produce four times as many devices every three years per square centimeter of area. If one adds the assumption that wafer-processing costs remain roughly constant, the result is a minus 37 percent per year compound annual growth rate in the cost of the device.

[14]Hedonic pricing is a technique used to adjust the raw dollar figure of a price to account for the fact that the priced object changes in values that are not reflected in the price (e.g., computers are constantly improving in power and quality while selling for the same or similar prices).

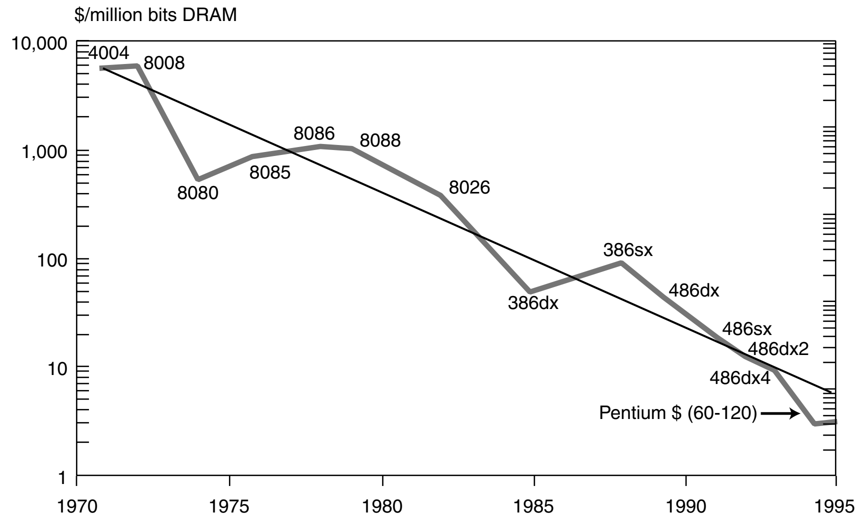

FIGURE 10 Cost of 1 Million Instructions per Second.

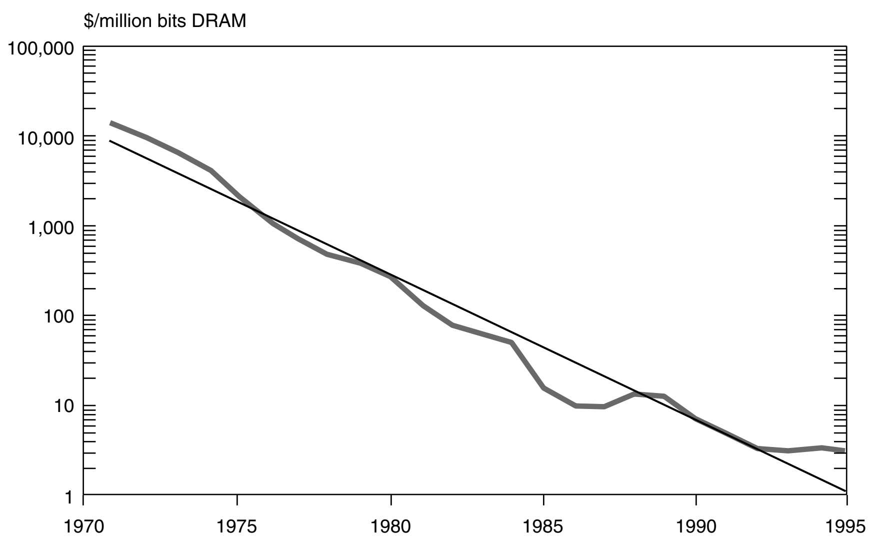

FIGURE 11 Cost of 1 Million Bits of DRAM.

Analysis of DRAM Price Performance

He went on to say that instead of being four times as many devices every three years, recent acceleration in the pace of semiconductor innovation may mean there are as many as four times as many devices every two years. The annual cost decline would then be 50 percent instead of 37 percent. He asked his audience to remember that number and then expressed some doubts about it. He said that the most manufacturing-intensive product he could think of is the DRAM, which is basically a commodity product, a regular feature reproduced over and over on a single chip. If there is any place where a pure manufacturing cost improvement will appear, he said, it is in DRAM prices. Has there been a shift in DRAMs from a 37 percent decline in costs to a 50 percent decline? He said that any such decline is hard to detect, especially in light of the difficulty of separating cyclical downturns in this highly cyclical industry from sector trends over time.

He then turned to a comparison of DRAM and microprocessor costs. The typical microprocessor diagram shows a simplistic measure of cost per MIPS per microprocessor cost and a typical DRAM diagram shows the change over time of cost per million bits of DRAM. For simple averages, the two diagrams gave trend rates for data from 1971 to 1995, showing about 29 percent per year per dollar per MIPS and about 38 percent per year per dollar for DRAM—almost exactly what this economic corollary to Moore's Law would predict.

Sharp Declines in Microprocessor Prices Around 1995

He then offered a more sophisticated view of these trends, adjusting for quality, which showed a slowing rate of price performance improvement from the decade 1975–1985 to the decade 1985–1994.[15] However, when this improvement is averaged over the period, trying to separate the secular trend from the cyclical ups and downs, both microprocessors and DRAMs are "pretty much right on the money" at about 32 percent. What about more recent changes, he asked? He said that he recently found a rich data set on Intel and AMD microprocessor prices, and he developed an estimated hedonic price index for microprocessors over the period on a monthly basis, from about January 1996 to relatively recently, and compared this with the Producer Price Index (PPI) (Figure 12). The PPI changed little until mid-1997, and the index is now roughly synchronized with the previous numbers. When he looked at the rates of change, however, for the four-year period, he found declines in quality-adjusted price performance of 60 to 68 percent. The PPI, while somewhat lower, was in the same range. He called this "an extraordinary noticeable increase in the rate of decline of microprocessor prices—substantially higher than any numbers I have seen for anything

[15]See K. Flamm. 1997. "More for Less: The Economic Impact of Semiconductors," Semiconductor Industry Association Report, December.

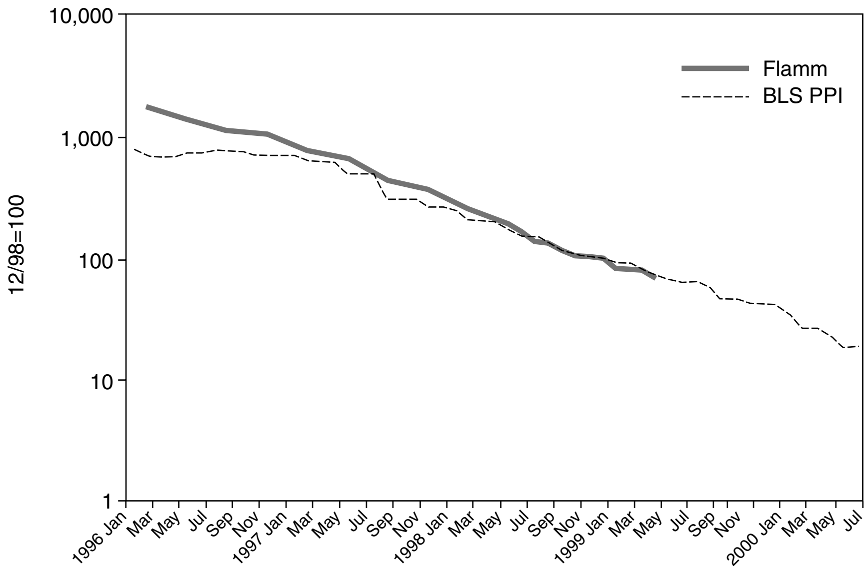

FIGURE 12 Microprocessor Price Indexes.

like DRAMs." A re-examination of the most recent data for DRAMs revealed that they, too, declined at similar rates in the late 1990s.

Possible Causes of the Decline

In speculating about the causes, he looked at the rates of decline in personal computer prices and compared them to estimated rates of decline in microprocessors (controlling for innovations such as the location of level-two caches on the same module as processors, higher bus speeds, and higher clock rates) (Table 2). Following a period of deceleration in the rate of price performance in the 1980s, he saw what appeared to be an acceleration around 1995. He now agrees with Dr. Jorgenson on the grounds that although no single obvious causes are apparent, this collection of data points leads to the conclusion that there has been a marked acceleration in the rate of price performance improvement in the last five years, "unbelievable though it may seem."

Dr. Flamm returned to semiconductors to ask about their impact on the U.S. economy. First, he pointed out that the raw numbers were pretty impressive. Semiconductors were now the largest manufacturing industry in the United States in terms of value added. Measured by value added (i.e., contribution to U.S. GDP), he said, semiconductors were number one in the list of Standard Industrial Classification codes. Second, he said, the percentage of U.S. GDP coming out of this

TABLE 2 Quality-Adjusted Microprocessor Prices Computer Annualized Rates of Decline

Period	Flamm (percent)	BLS PPI (percent)
2/96 to 2/98	–62.3	–46.0
2/98 to 2/99	–69.0	–56.8
2/98 to 4/99	–67.9	–58.6
4/99 to 7/00		–66.8

one four-digit industry was approaching 1 percent and much of this increase has been recent. The latter data points have an element of estimation and were "just a calculation of semiconductor nominal value added as a percentage of GDP," but he suggested it could be added "as another data point in our 'something happened in the 1990s' story."

The Large Impact of Information Technology on GDP

Dr. Flamm's last point was that there has been a major change in the relationship between the semiconductor and computer industries. It is obvious to people who follow the industry that more of what used to be done in the computer industry is now being done in the semiconductor industry. Historically, the computer industry has been the major customer for the semiconductor industry. Among several little noticed changes, however, is the emergence of the communications industry as a much larger consumer of semiconductors. He said there is little data to describe this relationship.

In addition, he noted a rise in the R&D intensity of semiconductors and a fall in the R&D intensity of computers. "That is not rocket science," the major retailers, such as Dell and Compaq, are doing little R&D on personal computers (he noted IBM as an exception). To a large extent, Intel and its competitors are doing the R&D for the personal computer industry. If one totals the value added in computers and semiconductors and asks how that total is distributed between the two industries, again there is obviously a sharp uptick in the early to mid-1990s.

"How do we evaluate the impact of this change on the economy?" he asked. The usual custom for economists is to calculate how much producers gain and how much consumers gain and derive a total number.[16] The mathematics shows, he said, that one year's technological improvement at the old historical rate

[16]He noted that most of the gains in pricing are passed on to consumers. This, he said, differs from industries in which a monopolist chooses to claim the results of technological improvements as profit. In this competitive industry most of the gains have been competed away in the form of price declines.

amounted to about 0.16 percent of GDP and that one year's improvement is realized for the rest of calendar time. That is, it lowers costs forever, so that next year's improvement is added to it. If this were compounded for 20 years, the technological improvement would amount to about 5 percent of GDP; if it were compounded over 30 years (which would require a lot of brave assumptions), the improvement would equal about 20 percent of GDP—an enormous figure.

An Important Message from the Railroads

Dr. Flamm then compared the economic role of the semiconductor with that of the nineteenth-century railroads, which have been studied extensively by economic historians as examples of technological change. Those studies show that there were two waves of railroad building in the United States: one from 1830-1860 and a second from 1860-1890. At the end of the first period the total benefit to consumers in lowered transportation costs was about 4 percent of GDP. At the end of the second period, after 60 years of railroad building, the benefit to consumers exceeded 10 percent of GDP (GNP then).

In contrasting the benefit of railroads with that of semiconductors it is important to recognize the role of the government, which has a very price-inelastic demand for semiconductors. Depending on how government purchases are treated, the estimated benefit to consumers from semiconductor improvement is somewhere between two and four times the benefit from railroads.

He concluded by saying that something very significant for the economy has happened, and that another insight from the case of the railroads may also apply to the case of information technology. That is, economic historians have looked at railroads not only in the United States but also in other countries, and they have concluded that the impact of railroad building in Brazil or Mexico or Serbia as a percentage of GNP was considerably higher than in the United States. The reason is that before the railroads were built in other countries there was virtually no competing transportation infrastructure. In the United States railroads had to compete with a well-developed system of canals and macadam roads and turnpikes. Therefore, in Mexico or Brazil the benefit over 60 years might have been 20 to 40 percent instead of 10 percent of GDP.

The present digital economy is an obvious analog to the transportation economy of the nineteenth century. Those countries with well-developed infrastructures of information technology and computing experienced a large benefit from the recent decline in technology costs. Countries lacking a basic information technology infrastructure are likely to gain even larger relative benefits from cost declines in information technologies. If the analogy with railroads is sound, he concluded, other countries may look forward to very large benefits in the near future, especially in the developing world.

Panel 3

Communications and Software

INTRODUCTION

Moderator: Robert Borchers
National Science Foundation

Dr. Borchers mentioned that a number of studies by the National Academies in the last few years, notably the Brooks and Sutherland report,[17] had made a credible linkage between fundamental research in information technology and the economy. The study's famous "tire tracks" diagram[18] demonstrated a causal linkage between fundamental university-based research and significant segments of the economy. The President's Information Technology Advisory Committee, commonly called PITAC, translated that theme[19] into both public policy and the budget. They succeeded in allocating funding to an information technology research program to support fundamental research in universities. The goal of the program is to drive economic growth in information technology.

So far, said Dr. Borchers, the program has been successful. Last year it received several hundred million dollars in new money for information technology research and this year the amount may be larger. PITAC chose half a dozen topics,

[17]F.P. Brooks and I. E. Sutherland. 1995. *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure*. Washington, D.C.: National Academy Press.

[18]See Brooks and Sutherland, *op. cit*. p. 2, Figure E51 which illustrates that government-sponsored computing research stimulates the creation of innovative ideas and industries.

[19]See PITAC—Report to President, *Information Technology Research: Investing in Our Future,* at <http://www.ccic.gov/ac/report/>.

including software, scalable information infrastructure, scalable public key infrastructure, software engineering, the human workforce, and human-computer interactions. He added that accessibility is an important focus these days in high-performance computing, his own field. He then introduced the first of the two speakers for the session.

COMMUNICATIONS

Alfred Aho
Lucent Technologies

Dr. Aho said he would talk about the impact of basic research and particularly communications research on the information-based economy. He said that basic research in computer and information science and engineering has been the font of the information technology economy that we are now moving into.

Toward Network-Hosted Services

He warned against predictions in this fast-moving field: Just ten years ago the World Wide Web did not exist, and no one could have predicted the degree of connectivity that exists today. Already we see a phenomenal penetration of computers and information, but what these figures will look like 10 years hence is anyone's guess. He did make one guess—that more people will use applications and services hosted on the network and more will use network services in the conduct of business. Small and medium-size businesses will adopt network-hosted applications to compete with large businesses. Large businesses, in turn, will focus on core competencies and refocus their information technology staffs on strategic issues.

He spoke of several examples of the rapid growth of communications services:

- 5 million e-mail messages will be sent in the next hour;
- 35 million voice-mail messages will be delivered in the next hour;
- 37 million people will log onto the Internet today and choose from among a billion Web pages;
- Internet traffic will double in the next 100 days.

Other advantages of the network-hosted economy are that it reduces capital and operations expenses, allows businesses to become global, permits virtual enterprises and institutions, improves trust in network security, allows for storage and applications anywhere in the network, and improves network performance.

The Need for Talented People

One factor that may limit how fast information-hosted technology will evolve is the availability of talented people. Almost every information industry has a huge shortage of talented people who are needed to create next-generation systems. In many classical telephone companies, those who run the systems have an average education of high school plus one year of community college. Companies are introducing into this global information infrastructure some of the most sophisticated technology ever created and asking people with little background to take care of the systems. The switching speed of a human neuron is unlikely to change in the next 20 years, "and this has consequences in almost all layers of the protocol stack with regard to how the information age is going to evolve."

First is the limit to how much new technology and techniques people can absorb. The human challenges of dealing with technology will be significant in terms of its penetration and use. The challenges in software engineering will be equally daunting. Dr. Aho said that he began a course he taught by asking the students to estimate the total number of lines of software required to support the world's telecommunications infrastructure. The students' answers began with a few thousand and ranged upward to perhaps a million. In fact, Lucent's most advanced switch has somewhere between 10 and 15 million lines of code; Windows NT has about 35 million lines of code. Few people, he said, pay attention to how hard it is to evolve the huge software systems that support the new kinds of applications.

Web-Based Provisioning

The Emergence of Application Service Providers

Moving up to the application layer of the protocol stack, Dr. Aho said, we see the emergence of new classes of Application Service Providers (ASPs) that provide services unimaginable just five years ago. Some 500 new entrants have emerged in just a few years. Some of them are joining to form economic "ecosystems," in which they partner with other ASPs to provide suites of services tailored to certain segments of the industry. He cited an estimated growth rate of the ASP market of over 90 percent to $2 billion by 2003. This joining, done largely from economic necessity, produces another layer of complexity and potential difficulties in how business will be conducted.

Bandwidth Trading and Customer Care

In addition to new kinds of service providers and services, Web-based provisioning of transport services will enable bandwidth trading that will function like a NASDAQ market. One can imagine any kind of service available on the network and create a market or exchange in which economic forces decide what is bought and sold for what price.

Another new development, particularly for businesses, is modes of customer care heretofore unimagined. Enterprises can use Web call centers to take care of their customers with sophisticated software agents. These centers will integrate Internet and telephone access, provide functionality to multiple enterprises, provide fully functional remote agencies (through disaggregated "soft switches") with dynamic load balancing across agents, and maintain "blended agent pools" for voice, Web, and outbound calls and back-office workflow tasks. Caching and intelligent redirection will reduce traffic congestion and increase speed for Web access.

New Systems and Drivers

He added that the way we educate ourselves, entertain ourselves, and deliver education and health services in the future will not simply be automated versions of existing systems. These will be replaced by radically new styles of offering services that we can only imagine today. Companies will put new kinds of services into the network to do this, effectively turning the world into a global distributive system that will include data, computation, communication—essentially all the things imagined for semiconductors and the construction of personal computers.

This new network-hosted economy is being enabled, in turn, by new technology drivers as systems of the 1990s evolve into systems of 2000+. For example, we have moved from semiconductor to microprocessor; now will come systems on a chip. We have moved from analog to digital; now will come cells and packets on optical fiber. We have moved from narrow bandwidth to the information highway; now will come flexible multiservice broadband to endpoints (Table 3).

Rapid Evolution of Optical Systems

Referring to previous discussions of Moore's Law, he said that some other areas of technology were moving even more rapidly in some other areas. Optical transmission capacity, for example, is doubling every year, revolutionizing network architectures and economics. Some optical systems are going into terabit and even the petabit range. Engineers at Lucent have been able to put hundreds of gigabits on a single wavelength; in most recent experiments they have put over 1,000 wavelengths on a single fiber. Given hundreds of gigabits on a wavelength and hundreds to thousands of wavelengths, by the middle of this decade systems will deliver petabits per second.

With all this information the challenge would be to use it with our limited neural-processing capacity, and to find the information we want. To do this Lucent engineers have made glass more transparent by removing a water bubble in the

TABLE 3 Technology Shifts are the Enablers of the Network-hosted Economy

1990s		2000+
• Semiconductor to mircoprocessor	→	Systems on a chip
• Analog to digital	→	Cells packets on optical
• Narrow bandwidth to information highway	→	"Flexible" multi-service broadband to endpoints
• Expensive bandwidth with complex architectures	→	Almost free bandwidth and simple architectures
• Dumb access devices to information applicance	→	Network-enriched, heterogeneous appliances with natural language interfaces
• Preprogrammed service logic	→	Downloadable Applets, "Servelets"
• Proprietary to open systems	→	Open, but reliable, secure systems
• Dumb to intelligent networks connecting places	→	From connecting places to connecting people and data anytime, anywhere
• Internet: research tool to e-commerce	→	Cooperating Network of Networks

fiber optic cables. This allows them to amplify broad ranges of wavelengths. They have also reduced the cost of devices that put information on and off these fibers and applied new chirp pulse lasers that allow the selection of separate wavelengths, each one of which can be separately modulated as a single system. Another interesting phenomenon is the use of microelectrical systems to switch wavelengths. Lucent has just introduced a product called the lambda router, which works by creating on a wafer an array of hundreds of tiny pop-up mirrors mounted on a two-gimbal system. A beam of light comes in from an optical fiber and the mirror is adjusted to reflect it off another mirror and send it to the exit fiber. This type of switching is much cheaper and more power-efficient than traditional electronic switching, so the manufacturer can visualize giving corporations and ultimately consumers their own wavelength on which to communicate with others.

Challenges for Routers and Software

An interesting question, said Dr. Aho, is what type of protocol stack will be put on this wavelength. In other words, what lies between the information technology and the lambda router in this world of the future? He reiterated that electronic routers may not be able to cope with the speed of optical transmission in the future.

A similarly complex question is what kind of software infrastructure will enable these new applications on the network. He said that one goal is to make available to the community at large application programming interfaces on the network on top of which one can create new network-hosted solutions. In the past, communications systems have tended to keep a closed environment in which only the service provider could control the network services. The Internet, by contrast, will bring a growth of new services and new applications at the endpoints because of the open protocol center.

For the immediate future, Dr. Aho foresees the creation of devices like soft switches that give third-party service providers the ability to construct services and control certain resources on the network. This must be done in a way that prevents a third-party service provider from destroying the network for other providers and users, which leads to an important question: Because these new services will be created by software, how will reliable software be produced for this new world? Dr. Aho cited two interesting papers written in the 1940s: one by John von Neumann, who said we can get more reliable hardware out of unreliable components by using redundancy, and one by Claude Shannon, who showed how to create more reliable communication over a noisy channel by using air detecting and correcting codes. Today redundancy and air detecting and correcting codes are used routinely in practice, but the world awaits a paper on how to get more reliable software out of unreliable programmers. Dr. Aho suggested that such a paper would be worth a Turing Award.[20]

A Focus on Software Productivity and Reliability

He reported that considerable effort is now focused on software productivity and reliability. In software feature verification, he said, there is a Moore-like curve. In the last two decades, algorithmic improvements have allowed programmers to verify automatically that software has certain properties. A unit that extracts from a C program a finite-state model allows modeling of the desired properties for the code, using a form of linear temporal logic. A property might be that when a user picks up a phone he should get a dial tone. This can be expressed as a temporal logic formula. The system takes the negation of this when one picks up the phone and never gets a dial tone. Model checking can then determine a violation of that property: Is it possible for the system to be in a state where picking up the phone never brings a dial tone.

[20]Von Neumann, Shannon, and Turing were pioneers in artificial intelligence. John von Neumann designed the basic computer architecture still used today, in which the memory stores instructions as well as data, and instructions are executed serially. He described this in a 1945 paper. Claude Shannon showed that calculations could be performed much faster using electromagnetic relays than they could using mechanical calculators. He applied Boolean algebra. Electromechanical relays were used in the world's first operational computer, Robinson, in 1940. Robinson was used by the English to decode messages from Enigma, the German enciphering machine. Alan Turing conceived of a universal Turing machine that could mimic the operation of any other computing machine. However, as did Godel, he also recognized that there exist certain kinds of calculations that no machine could perform. Even recognizing this limit on computers, Turing still did not doubt that computers could be made to think. The Association for Computing Machinery presents the Turing Award, in honor of Alan Turing, annually to individuals who have made significant technical contributions. See <http://www.acm.org>.

This, said Dr. Aho, is a simplistic example, but over the past 20 years engineers have made Moore-like improvements in software feature verification. A problem that used to take seven days now can be done in seven seconds. Lucent applied this technology to a recent product—the telephony features that were verified using this system—and took the specification for these services, extracted from them properties that were written in linear temporal logic, and then in a matter of minutes verified that the code satisfied the properties of this kind of specification. A goal is to extend this technology to software more broadly because the ability to produce reliable software on a global scale will be essential to a robust economy.

As businesses come to depend on the interoperable infrastructure, such questions will become crucial to a sustainable economy. In general we will need an open, global network infrastructure that will be able to host these services. The Internet must become much more user friendly in terms of its interface devices.

He mentioned a visit to the Georgia Institute of Technology for the inauguration of a broadband institute, where he talked with a professor who was designing shirts embedded with computers that could monitor human vital signs. One such design was inspired by a mother who had lost her first child to SIDS and wanted to prevent a second tragedy. The professor made a baby-size shirt with monitoring equipment and a wireless link. Other applications might include monitors for extreme athletes who are trying to push the envelope of what humans can do or systems to help take care of elderly parents so they can live at home longer.

He reserved judgment as to whether there will ever be a network experience as natural as a face-to-face conversation and concluded with a proposed test of such an experience: Would you want to propose to your significant other over the network or in person? “That,” he concluded, “is my test for the future.”

SOFTWARE: THE CHALLENGE TO GETTING THERE

Daniel T. Ling
Microsoft

Dr. Ling said he would talk about the supporting technologies that are helping the software industry, some exciting new applications driving the software industry, and some of the difficulties in writing software.

In terms of supporting technologies, he said that several participants had discussed the good news at the center of the network, but that toward the edges the situation is not quite as rosy. Within a building, for example, wireless LANs and Bluetooth have a high bandwidth, but wireless wide-area applications such as cellular satellite do not have high performance. For residences there is some penetration by ADSL and cable modem, but he said that, for example, ASDL is not available at his own house.

Dr. Ling mentioned the concerns about the network effects of Metcalfe’s

Law[21] and an even stronger network effect related to the number of communities that can be formed in a network with n participants. He suggested that this effect might be between n^2 and 2^n. Referring to magnetic storage, he said that Michael Lesk, now at the National Science Foundation, has studied these effects,[22] as have Hal Varian and Peter Lyman at Berkeley,[23] and attempted to calculate how much information is produced in a year. They arrived at a number of 2 exabytes[24] per year. At a few dollars per gigabyte, the expense of storing all the information produced a year online in magnetic storage would be only a few billion dollars. He said that considering Dr. Aho's imminent transmission rate of petabits per second, this amount of data could be transmitted quickly as well, which he found quite amazing.

Dr. Ling then raised the topic of microelectromechanical systems (MEMs), saying that MEMs receive the benefit of all the semiconductor technology and will transform the information technology industry. He described the MEMs-based optical switch and MEMs-based displays made by Texas Instruments and other companies. The main idea behind MEMs is to be able to make inexpensive sensors and actuators, including displays, to bring computing into a closer tie with the real world. He cited special MEM devices that could measure structural changes in buildings after an earthquake, describing which sections have been damaged and which have not, and MEM devices for the body, mentioned by Dr. Aho. He said that MEM technology has the potential to bring dramatic change to information technology.

Batteries Do Not Obey Moore's Law

Dr. Ling turned to technologies that are not increasing exponentially, especially batteries. Many optimistic scenarios are based on the availability of many mobile or isolated devices, all of which require batteries. The amount of power density that can be packed into a battery has not risen fast and for lithium ion batteries will soon approach a theoretical maximum power density of 5652 kJ/l. Portable applications, such as radios, need a certain minimum amount of power. Display applications need a minimum amount of light to be visible to the human eye. Audible signals need a certain volume of sound. In other words some requirements for power do not scale.

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[21]Metcalfe's Law states that the usefulness, or utility, of a network equals the square of the number of users. Robert Metcalfe founded 3Com Corporation and designed the Ethernet protocol for computer networks.

[22]See <http://www.lesk.com/mlesk/ksg97/ksg.html>.

[23]See <http://www.sims.berkeley.edu/research/projects/how-much-info/index.html>.

[24]In the sequence gigabyte, terabyte, petabyte, and exabyte, an exabyte is 10^{18} bytes.

The Need for More Research on Writing Software

A second worrisome category of technology is writing software. Productivity has improved, partly through increased computing power, which brings more tools and makes the programmer more productive. Higher-level, object-oriented languages also make a difference, as do improved programming environments. Especially helpful in making programmers more productive are large, reusable components that include tremendous functionality and can be used repeatedly. An example is an operating system. In the past, operating systems were able to support disks and printers, but today they provide a number of services that programmers do not have to deal with, such as the windowing system, the graphical user interface, the TCP/IP (Web) protocol, and the HTTP (browser) protocol. Operating systems increase productivity, as do databases and Web servers, and these increases are experienced indefinitely.

Clearly, however, this area also calls for research. Dr. Ling recalled the PITAC report[25] and the more recent NRC report,[26] both of which mentioned the importance of software, in particular, the difficulty of making the very large-scale distributed systems that are fundamental to the advances envisioned today for IT. These systems are enormously complex and will require multiple cooperating firms to build. They also have to be secure, reliable, and able to enforce privacy. Once these functions go onto the Web they must be able to resist attacks and probing by hackers, which is an enormous challenge.

Some Pre- and Post-Internet Software

Dr. Ling said that just for fun he had listed a half dozen drivers of software and divided them into pre-Internet and post-Internet categories. In the pre-Internet category are computation and simulation, which were primary motivations behind the invention of computers. Such uses have transformed science in many ways, some of which can be seen in bioinformatics, genomics, molecular biology, and astronomy. He cited the Sloan Foundation's funding of the Sloan Digital Sky Survey, which has spurred significant discoveries by comparing astronomical data from different points in time. Environmental science, engineering, and design have been transformed by computing. CAD models were used to design the Boeing 777, demonstrate the aircraft to customers, and simulate repair scenarios.

Other pre-Internet drivers include back- and front-office automation. Herman Hollerith, one of the pioneers of IBM, first used computing largely to do the census and moved from there to payroll, billing, and other basic applications. These came to include databases, which are still a hot area, now often called data

[25]President's Information Technology Advisory Committee. 1999. *Report to the President: Information Technology Research: Investing in Our Future*. Washington, D.C., February.

[26]National Research Council. 2000. *Making IT Better: Expanding Information Technology Research to Meet Society's Needs*. Washington, D.C.: National Academy Press.

warehouses. These data warehouses allow a firm to analyze all transactions, to separate products that are selling from those that are not, and to decide what to buy and what to recommend. Enterprise resource-planning software allows firms to do their payroll, personnel, and other routine processes within the company in a single system. It includes customer relationship management and supply chain management. Finally, personal productivity software got its start with the personal computers as the classical spreadsheet. Word processing applications went on to functions such as diagramming, personal financing, and mapping software. More recently the pre-Internet technologies have moved to the "PIN" area of personal informational management, e-mail, calendars, and contacts.

Data Anytime, Anywhere

As we move to the post-Internet drivers of software, we see a dramatic change in that people begin to expect their data anytime, anywhere through a variety of wireless devices. The World Wide Web started with physicists who wanted to share information, so that browsers were designed to weed and find information. This was exciting for two reasons. The first was that it provided worldwide access to information and allowed people to share data with no gatekeepers. This alone was a remarkable change from the old days of closed, proprietary, vertical systems, such as Lexus and Nexus. This has developed into a push for large digital libraries and e-books that can be carried anywhere.

Another big transition has been the integration of other pieces of technology into the Internet function, such as GPS, to produce a new range of services. For example, agriculture—a very basic, old industry—has combined GPS with information technology to change tremendously. Knowing what seeds, fertilizers, and pesticides they have put into small plots of land, farmers can now track the yields of each plot by satellite.

Then came the first version of e-commerce, where customers go to Web sites such as Amazon, eBay, and Priceline to engage in some transaction. The auction site eBay is interesting because auctions are an ancient market mechanism that has suddenly become practical on a large scale because of the Internet. Priceline raises the question of whether the fixed price is passé.

The Digital Convergence of Media

Another step ahead is the digital convergence of media. The initial version of this has been streaming sound and video that comes over the Internet. The personal video recorder has the possibility of transforming the broadcast TV industry. The concept of prime time loses importance when you can record, program, and view it at your convenience. The differential values of those slots of time become uncertain. The Internet has also allowed companies, such as Amazon.com, to learn a great deal about the behavior of their customers, which was very difficult in traditional retailing.

The Napster case shows that distributed, anonymous, peer-to-peer systems have arrived, whether we like them or not. Dr. Ling cited Napster as an interesting example, because it used centralized directory services, which created an entity that could be sued. Other distributors are not centralized and there is no one to sue. We must take this into account, he said, when we think of commerce in the next generation. The systems are here—anonymous, encrypted, completely decentralized.

Software as a Service

Version 2 of e-commerce, he said, will feature machine-to-machine commerce and less human-to-Web-site commerce. He cited a prediction[27] that online retailers will become less integrated as their individual functions—customer contact, warehousing, billing, and shipping—are sliced off. New firms will be constructed from these slices that will operate by machines talking to machines. Customers will go to a service they trust that will recommend the products and they will go to another service to pick up the products. They may even fill the shopping cart from companies throughout the Web. New marketplaces will form with new market mechanisms such as compilatory auctions. New ways of measuring and maintaining a reputation will evolve.

Dr. Ling concluded by pointing out that software is changing from a commodity to a service. He said that researchers are concerned about their ability to quantify the amount of money going into software if people were to rent software that is tailored to their needs rather than buying shrink-wrapped boxes of software designed to broad standards. "Software as a service," he concluded, "is definitely the trend."

The Potential for Collaboration

Finally, Dr. Ling addressed the area of communications and collaboration, a "big, new application for computing" that started with e-mail and is moving on to AOL's instant messaging and presence. There is enormous interest in additional conferencing and collaboration tools to allow remote collaborators to join as virtual work groups. Many firms are designing annotation functions to allow for "living documents" created by widely dispersed people who are able to make comments, ask questions, or post annotations. These annotations can all be searched and classified to distinguish private annotations, for example, from public questions from the audience or exam questions or answers to questions. All such tools have the ability to transform our educational process.

[27]S. Jurvetson. 1999. "From the Ground Floor," *Red Herring*, <http://www.redherring.com/mag/issue72/news-groundfl.html>, November 1.

Panel 4

Applications and Policy Issues

INTRODUCTION

Moderator: Bill Raduchel
AOL Time Warner

The Power of Democratized Information

Dr. Raduchel opened the session by groping for a definition of the New Economy: "Do we have something here?" he asked. "Is it different? How do we sustain it? How do we share it?" He recalled an economics professor who asked his class to name the most important technology for sustaining the industrial revolution in Britain. The professor's answer was a distillery to make gin—because millions of people could not have undergone the enormous personal dislocations of the industrial revolution, from agrarian to urban life, without the comfort of gin.

He saw a parallel in the dislocations of the New Economy, especially for those who are not fortunate enough to live at the frontier of technological development. He mentioned that when he was working at Xerox, they measured the number of times that documents were copied at the point where they were first copied. The results were surprising; what was being copied was not usually an original but "a copy of a copy of a copy of a copy." In other words the copier began to spread and democratize information in a way the Internet is doing even more effectively today.

Remarking on the importance of changing practices, he told a story dating from the Gulf War.[28] It described how General Pagonis ran what many people called the most successful military logistics operation in history. When the general arrived in the theater of war he introduced a new rule: any person in his chain of logistics command could send a message on a three-by-five card to any other person in the chain of command, without fear of retribution, and this message would have to be answered in 24 hours. Thus, he allowed the lowliest private to send a note to the highest general, and he enforced this rule. The vast majority of notes concerned routine matters. Nevertheless, a tiny fraction carried messages that were of critical importance (General, the tires we're getting don't match the trucks we have. Is that a problem?), and these averted huge potential problems. Dr. Raduchel said, "Those of you who live in big corporations with lots of Generation-X employees will understand that this is a description of e-mail."

Weak Signals, Diverse Sources

He closed with a story he heard at the Santa Fe Institute about beehives and ant colonies as organisms. A researcher said that for the colonies to survive the key issue was their ability to combine weak signals from diverse sources in ways that drive innovation. He conjectured that e-mail, in allowing weak signals from diverse sources to reach a person with decision-making ability, might drive innovation in a similar ways. He concluded that the free flow of information is a powerful driver of "whatever this new economy is," and that one goal of the symposium today was to help focus on such issues.

COMMUNICATIONS

Shane Greenstein
Northwestern University

Dr. Greenstein focused on ways to sustain innovation in communications markets and on emerging policy issues that deserve attention in the United States. He defined an emerging issue as an issue for which clear analysis could lead to better decisions, in comparison to "just muddling through as usual." As a representative of academia, he would bring a slightly different viewpoint to some of these issues.

Some Bottlenecks to Progress

Within communications he focused on the Internet, beginning with three factors "that are going to be bottlenecks to progress in the next five years." The first

[28]W. G. Pagonis and J. L. Cruikshank. 1993. *Moving Mountains: Lessons in Leadership and Logistics from the Gulf War*. Boston: Harvard Business School Press.

is that there are alternative modes for developing new infrastructure in communications, and these modes are treated asymmetrically by present legal structures. Second, the costs and benefits of restructuring communications industries are difficult to observe; therefore, revised policies for these industries will be difficult to formulate. Third, some core and long-established principles for the regulation of communication activities are being upended by current changes in technology, which raises new regulatory challenges.

He approached these three themes by looking backward five years and forward to the next five. In the last five years, we have gone through a period that has almost no precedent. Researchers have shown that the Internet emerged from a two-decade incubation period as a government-managed technology program and became a refined and malleable commercial operation whose features are relatively advanced.

Bringing the Internet into the Commercial World

The early Internet had some peculiar features. It was optimized to a noncommercial environment, with end applications generally assumed to be independent of transport mode. It also presumed a lack of gateways, which is now being questioned. The Internet accommodated the needs of the Academy as well as a number of other organizations that had helped to set its standards.

When this technology—in other words, TCP/IP-based applications—was thrown into a commercial environment, it forced an extensive retrofit of the existing communications infrastructure. The experience was not unlike the displacement of the telegraph by telephony, when two independent communications structures arose independently. The Internet retrofit was straightforward because it was expedient to link dial-up modems with the existing public telephone switch network. This fostered rapid entry of customers and a huge demonstration effect. People quickly saw how easy it was to use and wanted to join. It also stimulated unprecedented and almost spontaneous growth of the communications infrastructure. The growth of the Internet represents a massively decentralized, unorchestrated investment activity. There is no precedent in communications for such a pervasive application of a relatively refined technology, although there is precedent in other realms of electronics.

Addressing the Last-Mile Problem

The business aspect of this new technology, however, was not refined, which resulted from its incubation in academic and government environments. That, said Dr. Greenstein, presents three problems. The first is the last-mile problem: how to wire or otherwise connect individual users and businesses from their homes or offices to the nearest Internet backbone. The earliest and still the most common way to do this is by dial-up Internet access through the telephone system. The United States fell into this mode largely because of a set of regulations, almost unique among nations, that use flat-rate pricing structures for local telephone services. The effect of these regulations, written long before the Internet was conceived, is to make Internet dialing cheap and expedient.

It is not obvious that dial-up service is the preferred route to the Internet, especially for the next generation of broadband communication. Indeed, there are now three competitors offering to help users span that last mile—telephone companies' own services, Internet service providers using the telephone network, and cable companies that were formed with only television in mind; wireless access is coming as well. The problem with this particular competition is that all three modes are controlled by different regulatory regimes, for different reasons, and none was designed to cope with Internet issues.

Underlying this issue is this country's ideal of promoting technology-neutral policies, and the current regulatory combination does not seem to support this. The ideal last-mile policy would begin by letting markets decide among a variety of alternatives, especially when there are large technological complexities. There is unintended favoritism, however, in current regulations. For example, common carrier regulation in telephony requires companies to provide service in high-cost areas. Internet service providers have an enhanced service exemption, and cable companies must comply with rules about content and distribution mix. In addition, all three regimes are regulated in different ways across the country. These variations in regulation make a huge difference in whether a given Internet business model can succeed, he said. This issue will arise many times in the years to come, as it did in the open-access debate over AOL's acquisition of Time Warner.

The Effect of New Regulations on Business Models

Another looming difficulty is the likelihood of disruptions when information-intensive activities are restructured. Some 70 percent of home Internet use is now "free" or supported by advertising, which has had a large impact on media companies. If this unusual condition is changed by new regulations, it will affect many business models. He said that the benefits and costs of dislocation are difficult to measure, and this lack of data can lead to bad policy. For example, GDP easily misses changes in distribution methods. It gives good data on established channels but poor data on new channels. Price changes may be missed and quantities wrong. People are participating in new kinds of economic exchange that are not measured or that are valued in wrong ways. An increase in welfare can appear as a decline in GDP.

Intermediaries can provide valuable services in a time of transition between new possibilities and what the technical frontier allows. These are environments we do not measure well. For example, how do we measure the economic value of a customized technology to the invention of a new business model? Nor do we measure well the value of adapting something to a unique situation. This could represent a bottleneck.

Legal and Regulatory Principles

Dr. Greenstein turned next to emerging challenges to basic legal and regulatory principles behind communications industries in the United States, beginning with three trends. First, a tradition inherited from common carrier regulation is that of a " bright line" between content and distribution. One reason for this line is that it reduces the danger of bottlenecks in information delivery. The thinking is that competitive delivery information across multiple modes lessens worries about joint ownership issues like this. We worry about that because there are now bottlenecks in delivery as well as asymmetries in the cost of different modes of delivery.

Second, there is no agreement yet about how best to deliver and retrieve information to and from the household or business. Therefore, open-access rules are going to be reviewed continuously—the basic principles that affect the returns on investment in any kind of last-mile activity. Businesses are reluctant to invest in an environment without regulatory commitment.

Third, regulatory bodies at the national and state levels are accustomed to issues flowing to them at a certain rate. The present environment is bringing issues to them at a much faster rate and with greater frequency than they have ever seen, and they are not equipped to handle them. The amount of expertise necessary to make intelligent decisions is high, and this in turn, raises new questions about appropriate discretion in governance at the agency level. Many dimensions of the next generation of communications infrastructure will be influenced by local regulatory decisions in various states.

Will the Commercial Markets Serve Everyone?

Dr. Greenstein turned to another assumption that will be challenged: that the communications infrastructure will continue to be virtually ubiquitous. An established principle in this country is that governments first allow the commercial markets to function freely and then they promote services for those who are underserved. For the next five years, however, what will the commercial markets do with the Internet if they are left alone? Who will not be served? Dr. Greenstein said that he had examined these questions, and a lesson of the last five years is that commercial dial-up Internet access serves about 90 percent of the population without any help. This means that low-density areas can be targeted quite easily, with the help of some subsidies.

It is much harder to predict whether the digital divide will widen over the next five years. The quality of access varies among different groups and different geographic regions, and ease of access differs with training, education, and income level. It is not clear how the commercial markets will offer or restrict access. The Internet system inherited from the academic environment presumed a lack of gateways and a transparent system without excludability. The ideal entrepreneurial system, however, must be able to exclude people so that it can charge fees for entry and earn a profit.[29]

The Issue of Internet Gateways

Indeed, Dr. Greenstein said, the next generation of communications networks has many gateways. Some are necessary security firewalls, some virtual private network tunnels. Nevertheless, their effect is to exclude people from the network. For uses like point-to-point communications people are uncomfortable when somebody has the financial right to exclude somebody else. The debate over instant messaging at AOL suggests a larger debate to come. He returned to the example of Napster as a possible example of a profitable business model: a company that uses centralized directory services to facilitate point-to-point communication. As such, a larger company would probably buy Napster immediately. What should the regulatory and standard-making bodies do about all this? What will be the difference between a public and a private infrastructure?

Dr. Greenstein summarized his talk with three points:

1. There are alternative modes for developing new infrastructure and they are presently treated asymmetrically.
2. We are seeing the restructuring of information-intensive activities and we have little understanding of where they are going.
3. Some core principles behind the regulation of communication activities are being upended and these will be debated over the next decade.

ECONOMIC ISSUES OF E-BUSINESS

Erik Brynjolfsson
MIT/Sloan School of Management

Dr. Brynjolfsson began by noting previous comments about the risk of making predictions and suggested that e-business is not exempt from this risk. He

[29]For a discussion of issues pertaining to the ‘digital divide,’ see D. L. Hoffman and T. P. Novak’s chapter, “The Growing Digital Divide: Implications for an Open Research Agenda,” in Brynjolfsson and Kahin, eds. 2000. *Understanding the Digital Economy: Data, Tool, and Research*. Cambridge, Mass.: MIT Press. They write: “. . .although the decentralized nature of the Internet means that it can easily expand in terms of the number of people who can access it, an individual’s access may be constrained by his or her particular economic situation.” (p. 246). While the digital divide remains real, current trends of increased access by minorities are encouraging.

said that if economists have a modestly good record in predicting technological changes, this is not the case for predictions about organizational and business model impacts.

There are parts of the economy we can measure fairly well but there are also dark areas that we do not understand. He admitted that some of the keys to the New Economy lie hidden in those dark areas, including ways to evaluate new business models and organizational structures. He talked about two parts of that dark area: how technology and the Internet are changing markets and how they are changing firms and organizations. All of these entities—markets, firms, networks, and network organizations—can be thought of as information processors. Researchers including Hayek, Roy Radner, and others[30] have modeled them as such and suggested that they will be significantly affected by the dramatic changes in information processing described earlier in the symposium.

An Investigation of Internet Buying Behavior

Dr. Brynjolfsson started with a discussion of predictions about e-business, including the prediction that the Internet, by lowering search costs and facilitating comparisons among products, would lead to fierce price competition, dwindling product differentiation, and vanishing brand loyalty.[31] He cited the rise of price search engines and comparison intermediaries. He demonstrated one of them that can check several dozen Internet bookstores and seek out the best price for a given book and rank them by price in just a few seconds. He found a typical spread among these search engines of about $10 for a given book, which is fairly significant. There is also information about shipping time, shipping charges, and other criteria, but they largely de-emphasize the company itself so that the main feature the shopper sees is the price.

Dr. Brynjolfsson and his colleagues decided to take advantage of the data gathered by these search companies to try to understand how consumers were actually using the Internet to shop. They knew that every book is the same—down to the last comma—no matter who is selling it, so they hoped to detect the motivations for purchasing from a particular seller. They were able quickly to gather over a million price offers from company logs for a period of 69 days. They wanted to see whether a consumer would simply buy from the cheapest source or whether other factors would matter.[32]

[30] President's Information Technology Advisory Committee. 2000. *Report to the President on Resolving the Digital Divide: Information, Access, and Opportunity*. Washington, D.C., February.

[31] See OECD, "Electronic Commerce: Prices and Consumer Issues for Three Products: Books, Compact Disks, and Software," DSTI/ICCP/IE(98)4/Final for an empirical investigation into the effects of Internet competition.

[32] See E. Brynjolfsson and B. Kahin, eds. 2000. *Understanding the Digital Economy: Data, Tools, and Research.* Cambridge, MA: MIT Press.

Price Is Not the Most Important Factor

They were surprised to find that there were four important variables, not just one. Total price was quite significant, as was shipping time and advertising. However, the most important factor was whether the person had previously visited that site before. This can be tracked on the Internet by "cookies," which are signals left on the hard drive to speed the downloading of a site already visited. The site owners can also tell when you have returned to their site—by far the most important factor in making a purchase. This reveals that even though a book is as close to a commodity as one might expect to get on the Internet, price was not everything. In fact, fewer than half the buyers chose the lowest-priced entries on the tables. Moreover, this is among the set of consumers who chose to go to a price intermediary in the first place, so one would assume they are more price sensitive than the average consumer. Instead, service, branding, customer loyalty, and the quality of the experience all made a big difference.

In a second exercise, Dr. Brynjolfsson conjectured that these results would be more likely to hold as they start testing more heterogeneous products and products with more levels of unobserved service quality. For instance, they looked at the subset of consumers who wanted their screen sorted on the basis of delivery times instead of price. Indeed, delivery time was more important and price was less important, but other features were also more important, such as various measures of branding and other ways of guessing at the unobserved quality of the vendor, such as shipping time, which is harder to guarantee than price.

Third, they were able to begin to quantify the value of customer loyalty. They could see that a customer who has shopped there is more likely to come back again, even when they have access to shopping intermediaries. As a result, this market has been altered substantially by access to shopping intermediaries and over the next year or less many more sophisticated intermediaries will populate not just business-to-consumer markets but even more of the business-to-business markets.

The Internet Is Not the Great Equalizer

In this case the expected "law of one price" did not hold. There is much more to a product than its price, even for a commodity item. Researchers have to be careful when making measurements, because they might not capture everything, whether for purchase of a personal computer or service. In fact, consumers apparently perceive much more differentiation between products than economists might impute to them, such as customer service, product selection, convenience, and timeliness. These considerations should be acknowledged even if they cannot always be measured.

Dr. Brynjolfsson said that managers say they are putting a lot of their information technology effort into addressing things that economists and statisticians

Box C: Beyond the Law of One Price

"The expected law of one price did not hold. There is much more to a product than its price, even for a commodity item. Researchers have to be careful when making measurements, because they might not capture everything, whether for purchase of a personal computer or service. In fact, consumers apparently perceive much more differentiation between products than economists might impute to them, such as customer service, product selection, convenience and timeliness. These considerations should be acknowledged even if they cannot always be measured."

Erik Brynjolfsson

do not yet measure, such as quality, customer service, flexibility, and speed. For example, Amazon got six times as many click-throughs as one would predict if one took only price into account.

The good news is that clickstream data brings a tremendous amount of new information that can be analyzed to predict consumer behavior. He compared this technique with experimental methodology of 5 to 10 years ago. He imagined that he had found 50 undergraduates, paid them a dollar, asked them that if they had $10 to spend, would they buy the book from the red store or the blue store. This would not only be very difficult to do, but it would not be nearly as accurate as real consumers looking at a million and a half real price offers.

E-Business Is Not Just About Technology

Dr. Brynjolfsson turned to the topics of production and organization, stressing the point that e-business is not just about technology. He described a joint project with Merrill-Lynch, a sponsor of the Center for E-Business at MIT, to study online versus traditional brokerages. A traditional brokerage has a physical retail front office where customers interact directly with brokers. An Internet brokerage has a Web site where customers interact with Web servers and e-mail-based communication. To gain some indication of how that technology affects the brokerage, an online broker might buy the technology using traditional assumptions about its cost and what the hedonic price improvement is. This would be missing the forest for the trees, said Dr. Brynjolfsson, to limit oneself to such assumptions. In fact, the differences between a traditional and online brokerage are both more complex and more significant.

The Importance of Co-invention

E-business, he said, includes a tremendous amount of what Dr. Bresnahan referred to earlier as co-invention,[33] the process by which technology brings opportunities to invent new business models and new organizational structures.[34] Internet entrepreneurs and managers spend a great deal of time calculating what the compensation structure should be, who should be the target for the market, and what the revenue streams are going to be. That is why the entrepreneurs earn so much money: Those with successful Internet business models have learned that the technology is important only as a catalyst in this e-business revolution. This conclusion, said Dr. Brynjolfsson, is seen time and time again in every industry. The success of Amazon.com provides a good example. Simply adding e-mail services to a traditional bookstore would not bring even a small fraction of the personalization, customization, book recommendation, and the other parts of the business model that Amazon invented.

Measurement of Intangible Assets Is Difficult

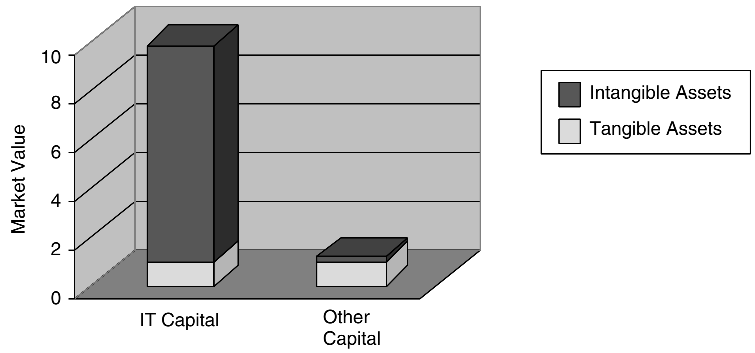
He said that he does not yet have good data on how to measure the value of such e-business context, but his group has studied traditional information technology and has found a striking difference between the intangible investments associated with information technology versus traditional capital investments (Figure 13). Investors value $1 of information technology capital at about $10 of traditional capital but not because information technology is that much more valuable. The reason for the difference is that whenever somebody spends $1 in information technology they have to spend another $9 or $10 on implementation, organization, and other co-invention costs.[35]

Investors apparently understand that additional costs are really investments, even though accountants write the costs off in the current year as an expense. In reality this investment creates assets—some new business process or customer base—and these assets bring new abilities. This is one reason for the success of Wal-Mart, he said; its managers have developed a well-understood and valuable set of business processes that are difficult to copy. Such knowledge is somewhat "sticky" and particular to the organization that develops it. Its value is also diffi-

[33] See Dr. Bresnahan's presentation in this panel (p. 115).

[34] Shane Greenstein writes about the frameworks and data for understanding how commercial processes translate Internet technologies into economic value. See his chapter in E. Brynjolfsson and B. Kahin, eds., *Understanding the Digital Economy: Data, Tools, and Research, op. cit*., p. 173. He writes: "General-purpose technologies like the ones that drive the Internet do not diffuse immediately without change. Often the critical factor influencing adoption are 'co-inventive' activities—inventions that adapt the technology to specific unique users."

[35] Bill Raduchel used virtually the same figures in his presentation. This point is also addressed in this panel by Sid Abrams in his presentation on the transition from old business to e-business. .



Each dollar of IT capital is correlated with about $10 of Stock Market Value

=> $9 of intangible assets per $1 of visible IT assets

FIGURE 13 Tangible and Intangible Assets.
SOURCE: Brynjohlsson and Yang, "Intangible Costs and Benefits of Computer Investments: Evidence from the Financial Markets."

cult to measure, even though enormously important to the success of modern businesses.

The Value of Organizational Capital

He showed a final chart summarizing an attempt to measure the computer capital of a series of firms and come up with an organizational capital metric. Dr. Brynjolfsson's group sent a survey to about 500 human resource managers and asked them how they organized production. They distilled the results into a single dimension of organizational capital. They found that organizational capital and computer capital were correlated with each other, but most strikingly, investors rewarded firms that ranked high in both computer capital and organizational capital. Dr. Brynjolfsson judged that it must be fairly difficult to bring these two into high equilibrium, or else the returns would be beaten down.

He summarized by saying that the Internet is transforming the way markets function and that the successful Web businesses of today are just the first wave of this transformation. Secondly, the Internet is transforming firms themselves. He repeated the finding that technology is just the tip of the iceberg in that transformation. It is a very important tip—arguably the catalyst that enables it all—but it is not where most of the time, effort, and investment go. Most of the investment goes into the intangible costs that change the way firms organize themselves.

New Types of Capital and New Measurement Techniques

This suggests that businesses need a significant change in accounting that reflects the true value of corporate assets. For much of the twentieth century the physical elements of land and labor dominated accounting values. Today we must acknowledge the value of new types of capital and develop tools to measure them if we are going to understand the role of electronic business in the New Economy.

E-BUSINESS POLICY ISSUES

Elliot Maxwell
U.S. Department of Commerce

Mr. Maxwell discussed policy issues that are being raised by e-business, with special attention to the dislocations it causes and the effort to make e-business policies that reflect societal values. The rapidity of change brought about by e-business has drawn attention to these needs, especially since policy evolves more slowly than technology, and much more slowly than business itself, which has strong incentives ("let's call them fear and greed") that inspire rapid development.

The Debate over Internet Policy

Internet policies began as a set of debates between two widely separated positions. One was the libertarian notion that if you just leave Silicon Valley alone, everything will be all right. At the other extreme were some people in government who said we understand this best and we can make sure it does not have negative impacts on our society or our economy. He suggested that both viewpoints are wrong. He suggested that the question could be recast as follows: How can we find new ways of thinking about policy that will let e-business develop locally and globally in ways consistent with the values of our society?

The first major issue, Mr. Maxwell said, was to construct an essentially legal framework for e-business. The concept of electronic commerce must be accompanied by a concept of electronic contracts and contract law in the United States. This is a state-based activity, and every state has laws requiring a physical contract and a physical signature. The question became how to have a contractual environment for electronic commerce, including authentication. What does it mean to have a signature in cyberspace?

So the first national engagement in policy making for electronic commerce ran up against a whole set of inhibitions. One of them was whether to have a national framework or to stay at the state level. There was a Republican Congress essentially committed to devolution of power to the states, and they were besieged by people from the world of e-commerce who said we could not have different rules in every state and argued for a resolution at the national level.

The Difficult Issue of Taxing Internet Commerce

With issues of taxation there is again tension between the cyberworld and the world of states and localities, some of which rely on sales and use taxes for up to 50 percent of their revenues. The Supreme Court has ruled that the traditional remote sellers, such as the major catalog companies, are not required to collect taxes for states in which they do not have a significant physical presence.

This situation virtually mirrors that of the Internet. How will the sales and use tax tensions be resolved? Is there a technical means of collecting taxes that does not place a great burden on the merchant? How can Internet companies satisfy the 6,000+ distinct localities that have jurisdiction to impose different kinds and rates of taxes? In New York State, for example, there is a different tax level for "big marshmallows" than for "small marshmallows."

Nor is the tax problem confined to the United States. The European Union (EU) works on a value-added-tax (VAT) system, and it has proposed to levy VAT taxes on digitally delivered goods from outside the EU. Their argument is that when a German firm sells digitally delivered goods to the Netherlands, it has to pay the VAT; if a firm sells the same goods to the Netherlands from Utah, it pays no VAT and receives a competitive advantage.

Interoperability Among Systems of Different Jurisdictions

Instances of discrimination are common in the physical world; for example, books and newspapers have different tax rates. However, a broader tension is how to find a process that looks at these questions in a global context and at least allows, in the telephone metaphor, "interoperability" among different systems. It does not seem likely, he said, that different jurisdictions will ever have the same policies. Each has different legal systems, different histories, and different customs.

Digital signature laws present a troubling precedent: Utah has a different rule from Michigan, which has a different rule from New York, which has a different rule from California. How can we do electronic contracts? Tariffs raise the same questions. Imagine trying to define an Internet consumer space: I have a company in California, I have a server in France, I sell a digitally delivered good to someone ordering from Hungary who wants to take delivery in Bangalore—and then it doesn't work. Who makes the rules about that transaction? Who interprets the rules and enforces them? Countries have never had to examine such questions. There are many "choice of laws" and "conflict of laws" precedents, but they usually concern admiralty cases involving large physical ships.

He cited the example of restrictions at the state level on sales of automobiles over the Web. Local auto dealers argue to state governments that they are customers and constituents of the state and it would be unfair to let them fall prey to larger national companies. There are now state rules that prohibit national companies from selling automobiles or financing auto purchases over the Internet. If all politics is local, he asked, how will we have national markets—both for business-to-consumer companies and business-to-business companies? National markets will be difficult without agreements on jurisdictions and mechanisms to resolve disputes.

Standards for Infrastructure and Spectrum

A second set of questions, Mr. Maxwell said, concerns the infrastructure itself. Among these, the first question is whether the infrastructure on which e-commerce rides will be robust enough. The answer depends in part on telecommunications policy and how it evolves. Will there be open access? Will the same rules apply for transmission of high-speed data to telephone companies, to cable, and especially to wireless? He noted that in the wireless world there is essentially one Internet service provider (ISP) serving one wireless provider. In the case of Japan, DoKoMo made NTT the largest ISP in the country when it brought 12 million customers onto its wireless Web. There is a question of how to ensure competition at every layer of the stack.

The second question is how governments will set policy on the control of the electromagnetic spectrum. New technologies can only develop quickly if spectrum is available, and many people believe that countries must agree to use the same portions of the spectrum around the world—something that has not happened with respect to the United States, Europe, and Japan. Issues of standards must also be resolved, but spectrum is a far more difficult situation. Various portions are already occupied—in many cases, by the U.S. government in general and by its Department of Defense in particular. To decide how to use that spectrum for the "highest and best" functions will be a difficult challenge for governments and may largely determine how quickly we move to a wireless Web environment. There is a very strong need to ensure that standards facilitate rather than inhibit competition.

Technical Management Issues

We have to resolve a set of policy questions that determine technical management of the Internet. For example, we have to learn to resolve disputes in the domain-name system. How this system is opened to more competition will have an important effect on branding, trademarking, and decision making in a global context. The United States has been able to move a good deal of decision making into a group called ICANN,[36] that is now holding elections. Organization of ICANN has been delayed longer than anticipated because setting up elections in

[36]For more information on the Internet Corporation for Names and Numbers, see <http://www.icann.com>.

cyberspace is difficult to conceptualize and implement. As a result, said Mr. Maxwell, we still confront "a bucket of legal framework issues, a bucket of infrastructure issues, and a third bucket that might be called the trust bucket." In other words, only with the assurance of a legal framework and a robust infrastructure will people be willing to use the Web for business transactions at increasing rates.

The Need to Resolve Privacy Issues

Obviously one of those issues is privacy, and privacy is more than just the protection of personal information. It tends to include related issues such as credit card security and authentication: Is the person with whom I am transacting business really who I think the person is? Is this communication secure? Will the transaction be resolved? Unless we can find satisfactory mechanisms for protecting privacy and enhancing trust, said Mr. Maxwell, e-business will not grow as fast as we wish.

He referred to the earlier discussion of pervasive computing and called attention to the privacy implications of people wearing medical sensors in their shirts. The privacy implications of distributed computing are very different from those of centralized communications. The government will not be organizing or controlling this new world and individuals will face the issue of reliability before they decide to commit critical functions to this environment. Such questions will affect the development of both the Internet technology and electronic markets.

The flip side of the privacy issue is the question of anonymity and encryption of communications to provide anonymity. The policy implications of anonymity are very large. Humans have never had the kind of opportunity for anonymous speech that is now available on the Internet. How do we respond, Mr. Maxwell asked, when people can do things anonymously that are unattractive to society? What should the policy framework be for thinking about questions of anonymity?

Threats to Internet Openness

A related question concerns the enforcement of national laws on an international Internet. The first law applied in the United States to content on the Web was against obscenity and pornography. The first content law in China was applied against sedition. France wanted laws to preserve the French language. Germany worried about Nazi paraphernalia. Every country has an impulse to protect its citizenry from certain content. These impulses could potentially balkanize the content of the Web and reduce dramatically the notion of openness—the ability of any individual to reach any other individual or source of information.

Openness and Innovation

On the business side, no one knows how the rule-making process and the jurisdictional claims of parties will affect this traditional openness and the development of commerce. The question of intellectual property protection has come to the forefront without resolution. Rules about copying are going to shape how businesses evolve. The technological capabilities here are both sword and shield.

He closed by reiterating several major points about innovation and openness. He suggested that innovation on the Internet depends both on the openness of the Internet and on the ability to exchange information freely. Openness itself can be seen in the kinds of devices, the modes of transport underlying the Internet, the freedom to connect to anybody else, and the ability to explore any content. Threats to openness constitute potential threats to innovation: You cannot communicate with certain parties, you do not have jurisdiction here, and you cannot enter these walled gardens of content.

"I think what we are striving to do in the government," Mr. Maxwell concluded, "is to find ways to work together with the private sector, non-governmental organizations, consumers, and businesses. If we work together, we may find interoperative situations that allow and encourage this kind of growth instead of stifling it."

INVESTMENTS IN INFORMATION TECHNOLOGY APPLICATIONS

Tim Bresnahan
Stanford University

Dr. Bresnahan returned to the theme discussed by Dr. Brynjolfsson—value creation using information technology. He began with business information systems, which "are among the most valuable human artifacts," but "we don't measure their value very well." We know a great deal about business systems within companies or at their boundaries, which include such systems as accounts payable, accounts receivable, and automated teller machines, the ancestors of e-business. He said that we do not know a great deal about how they create value and about how much they cost, although that might now be changing.

As business information systems take advantage of the Internet they cut across the boundaries of countries, businesses, and individual households in radically different ways. One business information system that has changed is human resource management. He told of returning to Stanford after a year away and finding himself able to re-establish his benefits package from home, by himself. Working on the Internet, he could select among participating health insurance companies and then select the desired features of that company. One of the ways business information systems create value is by offering new kinds of service opportunities for employees and, more typically, for customers.

The Dark Area

The value of these opportunities, however, is difficult to measure. We have had more success at measuring how much business information systems cost. In the United States, general-purpose software represents about 10 percent of the cost of business information systems to the corporate sector. For custom software the cost of invention is about 20 percent. The remaining 70 percent is the "dark area" that Dr. Brynjolfsson mentioned earlier. He said that this unknown portion could be measured in various ways—by its value to successful companies, perhaps, or by examining the demand curve for large changes in hardware and software. He said that it ranged in size from 5 to 10 times the other expenditures in business systems cost.

A new information system might be installed, for example, to permit customers to check their bank balances at home. In addition to the hardware, however, people would be needed to answer the phone and enter information into a computer. Jobs and management tasks would have to be changed through extensive planning, retraining, and testing. These functions would take up roughly 70 percent of the invention costs of the system.

Potential Bottlenecks

A major concern is to reduce the impact of bottlenecks that may jeopardize the business operation. Dr. Raduchel suggested earlier that 90 to 95 percent of the costs of a major re-engineering project were spent on training, testing, data conversion, and other expenses outside the categories of hardware and software. The business invention more than the technical invention is typically the bottleneck for creating new value. These processes are difficult to measure in cost or time, partly because they do not appear in the accounts of the inventing firm. Dr. Brynjolfsson estimated that a firm might need 5 to 10 years after initial adoption of the new technology to create value. This general rule applies to all upgrades in technology. It applied to new technical capability that came with the invention of the platform mainframe computer in 1964 as much as it applies to the capabilities that came with commercialization of the Internet in 1995.

Why It is Difficult and Expensive to Change Business Systems

The first reason it is expensive to change business systems is that it is conceptually more difficult. Typically it is more difficult to understand how to change people's jobs, how organizations work, and to understand what customers might like than to understand hardware and systems software. The latter is cumulative and can be understood by young people in a deep way as they gain scientific or engineering knowledge. The business side of business information system invention draws on things we do not understand in an organized way—the psychology, invention, and organization of work and the creation of value for the end user. What does a customer want from a bank? No one knows.

The second reason business systems are expensive to change is that they do not lend themselves to economies of scale. These economies are very effective for hardware, software, network, and platform technologies, with enormous reuse across thousands of firms or millions of end users. Business information systems, however, need fitting and adapting to the idiosyncrasies of individual companies.

The Effect on Markets and Supply Chains

In the future, markets and supply chains, rather than individual companies, will be automated. He said that he would be very pleasantly surprised if the economies of scale in the future equal those of the past. The markets will be different, not just in what is being bought and sold but also in the informational connection between buyers and sellers. Issues of reputations, belief, and trust will be paramount. He mentioned the fraud detection systems that the credit card industry has had to implement, such as those that track three gasoline purchases in the same day and other peculiar transaction patterns. Markets require time to build up such information-processing devices, and he predicted that such business inventions would create bottlenecks in the future. In addition, no one knows with precision the economic value of these systems, or what business information systems that cut across the boundaries of organizations can do.

One encouraging sign is that markets are flexible enough to experiment with different models. He cited the recent shift in the view that market automation would be done by a new form of organization: the dot-com company. That view was discouraged earlier this year but not because markets are not going to be automated. Instead, there was a broad shift toward the opinion that product and service firms, not new dot-coms, are going to perform that automation. He said that kind of experimentation—trying one model of organization, abandoning it cheaply, and going on another one—is in the end healthy for the markets.

Automating White-Collar Sales Functions

Dr. Bresnahan said, “There will be a lot of value here, depending on how you count it.” Between a quarter and a third of employment in the United States is held by people in white-collar bureaucracies who participate in buying or selling. This fraction includes not just sales people but many jobs that expedite, track, and fulfill transactions of all kinds. Much of this work is not creative or rewarding, and most of it can be automated, given the right systems. The present system is inherently wasteful and represents considerable money that is available for extending the business information systems across the boundaries of firms.

The Importance of the Browser

Referring to the earlier discussion of a possible point of inflection in 1995, he asked what had changed in the last five years. If there was indeed an increase in the pace of technical progress in hardware, could that have caused the upturn in productivity on the Internet? He thought this extraordinarily unlikely. There is too great a natural lag time between the application of new technology and realization of new value.

There were, however, important technical changes for business systems in 1995, notably the application of the Web browser. This permits the development of new applications. In particular, it solves what he and Dr. Greenstein have called the best of both worlds problem. That is, a browser permits the design of applications that are as easy to use as a personal computer but have the power of large systems. It allowed for the creation of a new class of applications for which the end user does not have to be technically trained. The application can be used only occasionally, and it can be distributed more broadly.

Standard-Space Networking

A second important development has been standard-space networking, which changes the environment for the development of business information systems. This is complementary to further advances in hardware, involving improved architectures and the openness and ubiquity that accompany cheaper hardware and permit the creation of more applications. A third change is a large increase in the volume of transactions and devices.

Policy Must Be Pro-Innovation

Turning to policy, he suggested strongly that infrastructure policy must be pro-innovation and, to the extent possible, supportive of change. It may be that intellectual property policy is now so protective of individual inventors as to be too protective and even anti-innovative. In addition, existing dominant firms should not be allowed to prevent innovation by blocking the entrance of new firms.

The last issue Dr. Bresnahan addressed was the tremendous increase in investment in business information systems, by which he meant primarily anything that is platforming, and an equally large increase in investment in application software. Are we sure, he asked, that macro-economic conditions played no role in those increases? The commonest explanation is that a technological boom set off a macro-economic boom, but it is difficult to determine which of those causes was primary. He closed by reminding his audience that the source of policy that may be most important for information technology industries is none other than the Federal Reserve in Washington.

OLD BUSINESS TO E-BUSINESS: THE CHANGE DYNAMIC

Sid Abrams
AT Kearney

Mr. Abrams began by reflecting on how much our concept of communication has changed over the last several years. Communication used to be restricted to verbal exchanges with people who were in the same time and space. As we began to disperse geographically we went to the Pony Express to carry letters and then to the modern post office. This still did not bridge the space separation. Then the telephone and the telegraph began to overcome the space issue but not the time issue. To talk with somebody in France we still had to coordinate because of the six-hour time difference. The Internet takes away both time and space issues, and wireless applications will do so even more.

Tangible Benefits of E-Business Are Not Clear

He suggested that the biggest challenge for companies as they shift to new forms of technology is that we all still need to eat, we need to put gas in our cars, we need drugs to take care of ourselves, we need airplanes to fly in. Thus, while e-business and the Internet and new technology are often exciting and fun, they are also very complex. For senior business executives who mostly believe in the benefits of technology and e-business and are investing pretty heavily in them, the tangible and quantifiable benefits as defined by the business world are still unknown.

Mr. Abrams said that he was coming from a different perspective than many of the speakers. He is part of an organization that works with senior executives and major companies to help them navigate, implement, and take advantage of the changing business world. He said he would like to describe some of the challenges companies are facing and what technology can do to help them cope with change.

The Second Wave of Internet Innovation

Mr. Abrams described life today, from corporate boardrooms to global exchanges, as a whirlwind of electronic activity that is first experienced by many people in buying books online—the business-to-consumer aspect of Internet commerce. Venture capital firms have created new firms, and new firms have created new Internet portals. His opinion is that the current or second wave of Internet innovation will be more difficult and complex, partly because it will focus on the restructuring of organizations as well as their entire value chains (Table 4).

Over the last five years his company has conducted semi-annual surveys of senior and chief executive officers from companies around the world. These sur-

TABLE 4 Redefining Economic Organizations: Applications of IT.

- Reduces cost and time in the supply chain
- Provides greater market coverage with primarily incremental operational cost increases
- Alters traditional scale economies, barriers to entry, and buyer/seller power
- Provides an effective way to add value
- Creates the basis for cooperative relationships with customers and suppliers
- Generates new organizational structures and governance models

veys show that while senior executives are aware of the growing role of technology, the real challenge for management is to find technology that is tightly integrated with business strategy and operation. The survey also showed that while 97 percent of these executives are convinced that technology will continue to have a very significant role, just over 70 percent believe that their primary focus will be designing and carrying out an e-business strategy. We see that e-business is driving a lot of restructuring, yet industries are participating at different rates and at different stages of evolution.

Different Rates of Participation in E-Business

High-tech and computer electronics industries were the first to think about e-business, in large part because they helped create the environment and the technology that allows it to happen. The sectors that provide consumer goods and products will participate and reap real benefits much later. They have to learn how to adapt their brick-and-mortar environment where food is produced and grown, and they also have major concerns around channel disintermediation. The auto industry has begun its transformation, but its ability to restructure the supply chain across the supplier base and to push themselves out into the dealer network meets a whole host of challenges around quality assurance, supply, reliability of suppliers, and trust issues around domination of certain categories.

Within industries, early adopters tend to be very large organizations—companies that have offices in more than 11 different countries and sales greater than $10 billion. It is in such companies that senior directors have been able to create a vision of technology's role in helping them change their industry. Around the globe the effects of the Internet are not yet ubiquitous. In the United States the survey shows that 78 percent of executives say technology is now beginning to change the way they do business. In Central and South America, by contrast, fewer than 28 percent of senior executives view technology as having an impact. This is because it is difficult to find skilled people, there is little common understanding of the meaning of a competitive business base, and it is difficult to raise capital for technology investments. He said that many large offshore companies and countries in Western Europe have operations in Central and South America and the Far East, but they are reluctant to invest there because they cannot be confident of earning a near-term profit.

Mr. Abrams reports that a concern for profits is driving much corporate behavior, although some companies have reacted differently. Some have tried to create a better environment for their employees by offering easy access to computers and the Internet.

Uncertain Results from E-Marketplaces

In general, senior executives are racing to create electronic marketplaces. The electronics industry alone has 17 to 20 electronic marketplaces for the exchange of goods and materials between buyers and sellers. The consumer goods industry has at least three dominant ones, and the automakers are creating them as well. The challenge for all of these industries is to define new business models. Companies are investing anywhere from $15 million to more than $200 million to start these exchanges; it costs upward of $100 million for the first year of operation. No one yet knows where the benefits will come from. Part of the challenge chief executive officers have to face is that doing procurement over the Internet is easier than creating a digital supply chain with your suppliers, as well as doing collaborative planning, forecasting, and replenishment with your other partners. “What they scratch their heads over,” he said, “is this question: If it’s so hard to get benefits from procurement, how do I get it from the rest of these things?”

Knowing When to Invest in E-Business

Mr. Abrams emphasized his own belief in the power of technology, but said he had to put himself in the shoes of his clients, who face several challenges. One is “how to learn what I don’t know.” Several years ago companies made a major shift from legacy systems to the enterprise resource environment (ERE). Senior executives spent significant sums of money on these systems, and in 1996 more than two-thirds of them were satisfied with the rate of progress. In 1998, 57 percent were satisfied, and this year 10 percent were satisfied. The CEOs had had to tell their boards that all the anticipated benefits did not materialize. While these leaders now recognize some of the shortcomings of ERE and some of the problems it didn’t solve, they are still unsure about the wisdom of investing millions of dollars to participate in the electronic marketplace.

A second challenge reported by Mr. Abrams is the increased complexity and rapid change of business-related technology, including both hardware and software. He recalled buying his first cell phone in the early 1990s, when it cost $800 and was the size of a box of tissues. The question for businesses is compounded: When will the latest great thing for one’s business be outdated, and how can a large current expense be justified?

TABLE 5 Challenges to Implementing IT Applications in Existing Firms.

• E-Business models radically shift how value is created and where it is generated in the value network, often creating channel conflicts
• The nature and magnitude of change is difficult to estimate, which makes it difficult to plan and manage
• Business processes must be re-engineered and integrated
• Multiple infrastructures must be maintained and existing business must be protected until transformation is completed
• Resources are inadequate for large-scale, rapid change
• Individuals resist e-business models

The Pain of Re-engineering

A third challenge, mentioned briefly above, is the complex impact of a new system on many aspects of an organization. Senior executives of any company, from 10 people to 120,000 people or more, confront the same issues: What do I do with all the people who work here, how do I ensure that this company participates, and how do I deal with the political, emotional, and social ramifications of a transformation whose features I can't imagine? How do we develop our people to be successful? What is the right organization model? How do I take my traditional old-economy company and give it the entrepreneurial spirit of a dot-com without destroying our business and causing a bloodbath in the boardroom?

Still, Phenomenal Potential for E-Business

Despite all these challenges the potential for e-business is phenomenal. The Meta Group projects that by 2003 more than 40 percent of the Global 2000 companies will have adopted an enterprise view; they will all be participating in e-business to some degree and the more advanced will be following an enterprise architecture approach—linkage between strategy, business process, and technology. How can this be done? One vision is that companies will be closer to consumers. For consumers to participate in an e-business world, technology needs to be powerful enough to operate virtually in real time and it needs to be as pervasive as the telephone is today. Applications must be truly meaningful and useful. Standards must be clear to ensure ease-of-use compatibility.

On the business-to-business side, organizations must adjust as value chains become more tightly integrated. On the business-to-consumer side, people will need the skills to use the Internet productively. In countries with extensive Internet use companies will need to understand a new set of labor issues between employees and employers.

Clearly, the price of technology will continue to fall even as technology becomes more powerful and useful. If productivity gains are to continue, senior executives must learn a new language and culture as they struggle to guide their companies through this transformation and benefit from it. From a policy point of view, the government needs to promote both basic and applied research that will help organizations adapt to this challenging new world.

Panel 5

Roundtable Discussion

Moderator: Dale Jorgenson
Harvard University

Dr. Jorgenson encouraged round table participants to think about the charter for the Board on Science, Technology, and Economic Policy and to suggest questions to pursue in greater detail on the relationship between the New Economy and technology.

MEASUREMENT AND SUSTAINABILITY

Dr. Raduchel proposed that two issues deserved further discussion: measurement and sustainability. First, he suggested that there is much uncertainty about how to measure the parameters of the New Economy. He said that much of the available data were not reported in useful forms and they were not helpful in understanding trends. For example, when expenses that are investments in new business processes are listed as G&A, the distortion confuses both investors and policy makers. He suggested that some of the major questions raised during the symposium could be answered if the historical record contained appropriate accounting procedures.

He also worried about moving from a loosely coupled Internet to a tightly coupled Internet, the latter being rare but desirable. As an example of a tightly coupled system he cited telephony, for which AT&T once set effective standards for the world. Because of its dominant market share, AT&T was also able to influence regulation in a way that is not seen on the Internet. He suggested that a tightly coupled Internet might not be achievable without the proper institutional framework. He proposed that countries that develop more tightly coupled relationships would have competitive advantages over countries that do not. Establishing effective standards for a more tightly coupled environment requires some understanding of who the referee is, and one cannot have tight standards without a referee. In closing, he returned to the issue of measurement and how investments in business processes are reported in the accounts of companies. There must be a better understanding of where money is going even if it is clarified only in footnotes.

CLARIFYING THE MEASUREMENT ISSUE

A questioner asked whether Dr. Raduchel's point was that some functions are not measured while others are improperly measured. Dr. Raduchel said that creating a new enterprise resource environment system, for example, is accounted for as increases in overhead spending, which is required by the Financial Accounting Standards Board (FASB), and shows up as G&A expenses. In corporate reports $100 million spent on parties for company employees looks the same as $100 million spent inventing new business processes to make the company more efficient. He described this as a major issue in trying to understand how much money a company spends on such projects and what the outcome is. In current reporting there is no way to tell whether a project fails or succeeds. Yet there are very different approaches in ways a company is required to capitalize and write it off if it did not succeed. Companies would not like the revised approach because they would not want to report the failure. Dr. Raduchel said that the technology is the initial driver to create new processes, but design of the new processes matters even more than the driver. Unless we have the right accounting it is difficult to measure productivity and to answer some of the questions posed today.

Lawrence Slifman of the Federal Reserve Board supported Dr. Raduchel's encouragement of the FASB to look closely at capitalizing rather than expensing a variety of information-technology-related, but not physical, investments made by firms. He suggested that the National Academies should play a role in highlighting the importance of this point, perhaps with representatives of the FASB.

HOW CAN BUSINESSES ABSORB THE CHANGE INDUCED BY TECHNOLOGY?

Dr. Gomory of the Sloan Foundation agreed that the rate of technology advances was "not the name of the game" today. Whether technology continues to progress at the same rate or faster is not as important as the ability to absorb it and the cost of re-doing the business organization to take advantage of it.

He pointed out that to a considerable extent nobody knows how a business works. It's a little bit like a human being; we see them running around and standing and talking without knowing how they digest anything. Yet we don't sit around thinking how we digest; we just digest. To a large extent business functions that way.

You might also say that no one knows how to make a disk file, he continued. Making a disk file takes a huge organization. Somebody has to know how to heat the building and to clean the air, and these are all separate people. The interaction of all these abilities in the end produces a disk file. Much of that knowledge is not written down, so when managers start re-doing a business they must deal with many customs and ways of doing things that were never articulated and unexpected problems arise. There is plenty of technology and the transformations that lie ahead will not occur without it. The question is not how can businesses acquire more technology but how can they absorb the change induced by the technology they already have?

EDUCATION AND GOVERNMENT LAG BEHIND ELECTRONICALLY

He added an additional point: Most of these changes are possible because they occur in the business world, where the desire to be successful and profitable is a powerful driver. However, there are worlds where that driver does not apply, including education and government. The ability to give courses online has been with us for at least seven years, but the educational world is reacting slowly. There is no internal driver, he said; schools are dragged reluctantly toward this new possibility. In regard to the second world, he suggested that people have not thought much about the possibility of changing the interaction of people and government. If a street is not well swept, do we really try to call the department of sanitation of the local government? Most people do not bother because they know it is too difficult and time consuming to interact with government. He maintained there are tremendous possibilities of online interaction between people and their local government on concrete issues that are untouched. At present there is no driver to encourage this, just as there is no driver for online education. He concluded by suggesting that one of the great unrealized possibilities for the New Economy is to find useful drivers for areas where normal business motivations do not apply.

EARLY STEPS IN MEASURING THE NEW ECONOMY

Dr. Price of the U.S. Department of Commerce praised the format of the symposium, which drew together economists with an appreciation of technology and technologists with an appreciation of economics. This brings the opportunity to raise some truly important issues. From his vantage point as an economist, one of his largest challenges is accurately measuring what is happening in the New Economy. He said that a growing number of U.S. economists believe some fea-

Box D: The Challenge of Measurement

Dr. Lee Price of the Department of Commerce, praised the format of the symposium, which drew together economists with an appreciation of technology and technologists with an appreciation of economics. This, he said, brings the opportunity to raise some truly important issues. From his vantage point as an economist, one of the largest challenges is accurately measuring what is happening in the New Economy.

tures of growth have changed, but he needs much better measurements to be able to predict whether it is sustainable and what is causing it.

To illustrate the challenge of gathering accurate data, he used the example of how much business spends on software. The Bureau of Economic Analysis (BEA) reported that in 1987 the nominal business investment in software totaled about $28 billion. Last October the agency reported that this figure had grown to $149 billion in 1999, 12 years later. Since then, he said, they had received new data, and last summer they revised that figure upward to $180 billion. The BEA said that it was better to be reasonably accurate than to be precisely wrong and report a figure of zero. Just the notion of having software counted could change the way people viewed the size of information technology and the investment in it. He said that it is important to make these measurements even if they are not precise.

THE ECONOMIC EFFECT OF THE INTERNET

Dr. Price said that he is often asked about the economic effect of the Internet, and that his usual response is that he doesn't know, because it is so difficult to separate Internet effects from other effects. The department measures information technology, he said, but the workshop participants had agreed that technology accounts for only a part of the total economic effect. He noted that he would like to measure the change in productivity since 1995, whether it is labor productivity or total factory productivity. However, his department cannot yet quantify the rate of change of new technology. He said he could not yet supply researchers with the specific contributions of individual components of information technology, such as semiconductors, storage, or browsers.

He made the point that technology policy did not seem to be a partisan issue. When the administration changed from Republican to Democrat in 1993, better technology was put into various offices. When the U.S. House of Representatives changed from Democrat to Republican in 1995, better technologies to access the

Internet were installed. He said that the trend to support new technology seems to hold true around the country, as management upgrades technology to the level of its familiarity.

SUGGESTIONS FOR FURTHER DISCUSSION

Dr. Price proposed several issues for further discussion by symposium participants. One is how to quantify the output of information-technology-producing industries. Another is how to calculate the value of software to businesses, especially the two-thirds of the business investment in software that is not packaged. Packaged software is more easily measured, both in terms of nominal value and price but may not be as important to productivity. He said the department has made advances in measuring real output of semiconductors, computers, and telecommunication equipment, but has had less success in measuring the output of information-technology-intensive activities, such as business services, education, and financial services. He expressed some doubt about properly measuring this output because it is basically a function of activities at the margins, as currently measured.

Dr. Price mentioned another important challenge of the new technology on the economy and on the ability to measure its activity—and this is the blurring line between distinct businesses and how they are defined. He said that the department's knowledge about the economy derives from sample companies in defined industries. The department tries to categorize the entire economy in this way, industry by industry. If the boundaries of industries and the boundaries of companies operating in those industries are blurred, the sampling becomes less accurate. Dr. Price invited the assistance of the participants in helping with these definitions.

At the same time, the department can help businesses by using opportunities that arise from new technology, such as the ability to collect more data faster. They are giving businesses the opportunity to contribute for the first time to a major monthly online series on durable goods orders, inventories, and shipments. Only a small number of companies have enrolled, and the statistics will improve if the number of companies grows. Information technology can help the department analyze what does come in more effectively, especially when they get terabits of monthly data on prices or shipments rather than the kilobits they now receive.

IS IT DESIRABLE TO DISPLACE SALES WORKERS?

In response to a question, Dr. Price said he agreed with Dr. Bresnahan that a quarter to a third of workers are involved in exchanging goods and automating purchasing and selling functions, and that automating these functions represents a large opportunity for productivity. "You don't get productivity going up without labor being displaced somewhere," he said, "and that's clearly a place where it gets displaced." He suggested that the policy implications of that displacement are probably positive. Thirty years ago there was resistance to technological change on the grounds that people might be displaced and unable to find other jobs. In many cases, however, those people have sufficient skills to find jobs elsewhere.

A TECHNOLOGIST'S PLEA FOR STANDARDS

Dr. Jorgenson asked for a technologist's view of these questions, and Mr. Ganek suggested that the issue of technical standards was crucial in sustaining the economy. He suggested that Internet growth has soared because of the advancement of very simple standards, none of which individually was a technical revolution. The convergence of HTML, HTTP, and TCP/IP created an infrastructure that "allowed interesting things to happen." Looking ahead, certain infrastructure issues in the United States are worrisome, especially in regard to the wireless infrastructure. He said that the projects at the leading edge of wireless mobile technology are being done in places like Helsinki, Tokyo, and Tel Aviv. "The United States has standards that don't allow convergence," he said, "and we need standards that drive better access." The United States has abundant wireless companies but they utilize a variety of incompatible standards. He said we should be looking for some proactive way to adopt common standards to simplify and thereby extend our infrastructure. He agreed with Dr. Greenstein that access technology as a whole needs to be on the same solid footing as the backbone technologies, or the country could find itself at a competitive disadvantage.

Dr. Raduchel concurred that wireless is highly important, and observed that the United States is five years behind Europe and Japan.

THE RISING IMPORTANCE OF WIRELESS

Dr. Aho of Lucent Technologies reinforced the opinion that the United States hasn't paid enough attention to wireless standards. He raised an additional aspect of the wireless issue: There are at least an order of magnitude more cell phones in the world than personal computers, and personal digital assistant numbers are relatively small but growing rapidly. If wireless access becomes the dominant mode of accessing the information infrastructure, the intellectual leadership driving the Internet may move offshore. This is a major concern if we want to keep this country competitive in this arena.

RELIABILITY AND THE ROLE OF GOVERNMENT

Dr. Aho raised two other points. One was the need to ensure the reliability of the Internet infrastructure. Like the nation's highway system, the information technology infrastructure will have to be refurbished periodically, and it will never be completed. Therefore, deciding when to upgrade the infrastructure becomes an important question. It will become more difficult as the embedded user base rises. The nation must adopt policies that allow technological rejuvenation of the infrastructure, like continuing education for the people who maintain it and use it; "lifelong education is going to be a watchword for the information age." The second point, little discussed at the workshop, was that the Internet came out of a government research program. As the nation moves into a world of e-commerce, it needs to consider what roles the government should play in facilitating the transition to new ways of doing business and arbitrating issues such as taxation that set the parameters for that business. In addition, there are sound arguments for keeping the government out of certain areas.

A CONSOLIDATION OF DOT-COMS

Mr. Morgenthaler emphasized the changes that are going to occur as this New Economy evolves. He called attention to the dot-com-financing crisis currently underway, which he predicted would get worse. He suggested that weakness in business-to-consumer and business-to-business could be equally bad. Perhaps this is part of a normal capitalistic evolution of consolidation and weeding out of most of the suppliers. He reminded his audience that a century ago the country had 2,000 automobile companies. He predicted that many new Internet companies would also wash away but noted that the symposium had not discussed what would emerge from this tumultuous stage.

Dr. Spencer suggested that to some degree the current dot-com turmoil was a function of financing behavior. He said that two types of venture capitalists had supported the dot-com companies: those that caught the wave early and "unloaded their holdings on bigger fools" and those that mistrusted the business model of the dot-coms from the beginning and focused their attention on the Internet infrastructure. He agreed that many people would be hurt during the period unless the business models were sounder than they appeared.

A VIEW ON THE U.S. POSITION ON WIRELESS

Dr. Flamm of the University of Texas at Austin returned to the topic of wireless devices. He said that the United States' slower progress in wireless is the flipside of a lead in broadband technology that is fundamentally driven by economic forces. That is, the U.S. fixed-rate access model for local landlines means that phone service—and Internet connections—are essentially free. In Europe and Japan, landlines are metered. There was no economic incentive to use wireless links for Internet access or routine telephony in the United States, where the marginal cost of such usage is essentially free. At the margins such use is not free in Europe, so wireless has less of an economic hurdle to jump. He said this economic explanation was not entirely popular, however. Some in the technical community prefer to view this as a failure in U.S. policy, rather than a natural and perhaps inevitable consequence of economic forces.

A PLEA FOR "DO NO HARM" REGULATION

Alan Wolff of Dewey Ballantine offered the news that seven states have adopted or are considering legislation to ban the reading of X-ray results outside the state. This is a response to an X-ray machine developed by General Electric that puts out a digital signal that can be read anywhere. This kind of limitation, he warned, would slow the expected growth of e-commerce. He called on industry and government to jointly plan a "do no harm" regulatory approach to forestall such proscriptions of commerce.

A CALL FOR MORE IMAGINATIVE MEASUREMENT

Dr. Brynjolfsson of MIT underscored the need to measure the dark matter that Ralph Gomory and other speakers referred to. He said that some of it might be difficult or even impossible to measure, but not all of it. The good news is that the Internet itself is producing new, large data sources, such as those he demonstrated in his talk, which may provide avenues for understanding the dark matter. He encouraged participants not to restrict themselves to measuring only activities for which good data are already available.

He also remarked on economists' difficulty in reaching a level of precision that would allow distinction between successful and unsuccessful projects. He noted that Dr. Jorgenson did pathbreaking work on human capital without waiting for accounting data to appear. He suggested that if economists could find useful things to say about the value of human capital, they might be able to use the same model to describe the value of organizational capital.

Dr. Mowery agreed that measurement should have a high priority and repeated a question that arose during his talk: How does new technology influence R&D processes? He referred to the prediction that information technology promises dramatic improvement in drug discovery for the pharmaceutical industry. "What does the realization of this potential require within the industry?" he asked. Finally, he suggested that a panel of the National Academies could be an appropriate body to articulate the characteristics and effects of e-commerce applications. Those effects would be seen in industry structure, intermediation, disintermediation, employment issues, and other areas. He said many studies have demonstrated that 80 percent of the investments needed to realize the returns from these technologies are non-technological investments. This conclusion, he stressed, "cannot be repeated frequently enough, because it is not widely appreciated. I think an Academy panel could do a very effective job of making that case."

Jeffrey Macher of Georgetown University echoed Dr. Mowery's comments on measurement and commented on how often speakers referred to learning curves. He referred to the earlier discussion of semiconductors and the learning curve for density, optics, transmission capacity, magnetic storage, and other features. He suggested a closer look at movement along the learning curve to see whether shifts of the learning curve are caused by new science, new technology, or some government policy. It would be interesting to measure performance and productivity and to try to attribute features of each industry to changes in productivity, such as market structure, industry standards, and government policy.

POOR POLICIES COULD BECOME OBSTACLES

Dr. Ling of Microsoft addressed the issue of sustaining the economy and suggested looking more closely into some of the points the economists brought up, such as intellectual property, privacy, and taxation. These were important because they could become major obstacles to economic growth if they start to fragment the market.

Margaret Polski of AT Kearney brought up the need for additional research on Internet technologies and the lag time between original research and implementation. Dr. Spencer agreed that we are living off the results of research done 25 and 30 years ago.

FINAL REMARKS

Dr. Wessner of the National Research Council raised several points, "not as summaries but to test the group's reaction." First he noted a disjunction between the predictions of continued technological progress and the difficulties faced by CEOs in capitalizing on new technologies. If CEOs do not find new applications useful, he asked, would they continue to make these information technology investments at the same level? Ideally there is some alignment between the trajectory of R&D investments and their usefulness in business applications.

He emphasized a point raised earlier by Dr. Spencer by asking if we were making the right investments in lithography and whether those investments would continue to push this curve upward. He wondered if the investments were being made at the necessary level in the United States.

Finally, he underlined the importance of Mr. Maxwell's series of questions about taxation and other policy roadblocks and their potential effects on commerce. He also called attention to Mr. Maxwell's discussion of the international dimensions of the Internet and the type of applications envisioned. He noted the skill of the European community in positioning itself on questions of standards, as it has done in subscribing to GSM standards for wireless devices, and noted the importance of these questions for U.S. policy. He said that this country sometimes seems to have a tradition of not turning to the government until "the hole is very deep," particularly with regard to international issues affecting high-tech sectors. He closed by calling attention to the disconnect between such international roadblocks and the great potential offered by new technologies.

CLOSING THANKS

Dr. Spencer closed the symposium by thanking the participants for their contributions. He said that he had personally found the meeting highly informative in both the areas of technology and economics. He reiterated the importance of better understanding the concept of the New Economy and of devising improved ways to measure its activities. "It is an important topic," he concluded, "and I look forward to additional workshops where we can explore in greater depth some of the major themes we discussed today."

IV

APPENDICES

Appendix A

Raising the Speed Limit: U.S. Economic Growth in the Information Age

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May 1, 2000

ABSTRACT

This paper examines the underpinnings of the successful performance of the U.S. economy in the late 1990s. Relative to the early 1990s, output growth has accelerated by nearly two percentage points. We attribute this to rapid capital accumulation, a surge in hours worked, and faster growth of total factor productivity. The acceleration of productivity growth, driven by information technology, is the most remarkable feature of the U.S. growth resurgence. We consider the implications of these developments for the future growth of the U.S. economy. (JEL Codes: O3, O4)

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INTRODUCTION

The continued strength and vitality of the U.S. economy continues to astonish economic forecasters.[1] A consensus is now emerging that something fundamental has changed with "new economy" proponents pointing to information technology as the causal factor behind the strong performance of the U.S. economy. In this view, technology is profoundly altering the nature of business, leading to permanently higher productivity growth throughout the economy. Skeptics argue that the recent success reflects a series of favorable, but temporary, shocks. This argument is buttressed by the view that the U.S. economy behaves rather differently than envisioned by new economy advocates.[2]

While productivity growth, capital accumulation, and the impact of technology were topics once reserved for academic debates, the recent success of the U.S. economy has moved them into popular discussion. The purpose of this paper is to employ well-tested and familiar methods to analyze important new information made available by the recent benchmark revision of the U.S. National Income and Product Accounts (NIPA). We document the case for raising the speed limit—for upward revision of intermediate-term projections of future growth to reflect the latest data and trends.

The late 1990s have been exceptional in comparison with the growth experience of the U.S. economy over the past quarter century. While growth rates in the 1990s have not yet returned to those of the golden age of the U.S. economy in the l960s, the data nonetheless clearly reveal a remarkable transformation of economic activity. Rapid declines in the prices of computers and semi-conductors are well known and carefully documented, and evidence is accumulating that similar declines are taking place in the prices of software and communications equipment. Unfortunately, the empirical record is seriously incomplete, so much remains to be done before definitive quantitative assessments can be made about the complete role of these high-tech assets.

Despite the limitations of the available data, the mechanisms underlying the structural transformation of the U.S. economy are readily apparent. As an illustration, consider the increasing role that computer hardware plays as a source of economic growth.[3] For the period 1959 to 1973, computer inputs contributed less

[1]Labor productivity growth for the business sector averaged 2.7% for 1995-99, the four fastest annual growth rates in the 1990s, except for a temporary jump of 4.3% in 1992 as the economy exited recession (BLS (2000)).

[2]Stiroh (1999) critiques alternative new economy views, Triplett (1999) examines data issues in the new economy debate, and Gordon (1999b) provides an often-cited rebuttal of the new economy thesis.

[3]Our work on computers builds on the path-breaking research of Oliner and Sichel (1994, 2000) and Sichel (1997, 1999), and our own earlier results, reported in Jorgenson and Stiroh (1995, 1999, 2000) and Stiroh (1998a). Other valuable work on computers includes Haimowitz (1998), Kiley (1999), and Whelan (1999). Gordon (1999a) provides an historical perspective on the sources of U.S. economic growth and Brynjolfsson and Yang (1996) review the micro evidence on computers and productivity.

than one-tenth of one percent to U.S. economic growth. Since 1973, however, the price of computers has fallen at historically unprecedented rates and firms and households have followed a basic principle of economics—they have substituted towards relatively cheaper inputs. Since 1995 the price decline for computers has accelerated, reaching nearly 28% per year from 1995 to 1998. In response, investment in computers has exploded and the growth contribution of computers increased more than five-fold to 0.46 percentage points per year in the late 1990s.[4] Software and communications equipment, two other information technology assets, contributed an additional 0.30 percentage points per year for 1995-98. Preliminary estimates through 1999 reveal further increases in these contributions for all three high-tech assets.

Next, consider the acceleration of average labor productivity (ALP) growth in the 1990s. After a 20-year slowdown dating from the early 1970s, ALP grew 2.4% per year for 1995-98, more than a percentage point faster than during 1990-95.[5] A detailed decomposition shows that capital deepening, the direct consequence of price-induced substitution and rapid investment, added 0.49 percentage points to ALP growth. Faster total factor productivity (TFP) growth contributed an additional 0.63 percentage points, largely reflecting technical change in the production of computers and the resulting acceleration in the price decline of computers. Slowing labor quality growth retarded ALP growth by 0.12 percentage points, relative to the early 1990s, a result of exhaustion of the pool of available workers.

Focusing more specifically on TFP growth, this was an anemic 0.34% per year for 1973-95, but accelerated to 0.99% for 1995-98. After more than twenty years of sluggish TFP growth, four of the last five years have seen growth rates near 1%. It could be argued this represents a new paradigm. According to this view, the diffusion of information technology improves business practices, generates spillovers, and raises productivity throughout the economy. If this trend is sustainable, it could revive the optimistic expectations of the 1960s and overcome the pessimism of *The Age of Diminished Expectations*, the title of Krugman's (1990) influential book.

A closer look at the data, however, shows that gains in TFP growth can be traced in substantial part to information technology industries, which produce computers, semi-conductors, and other high-tech gear. The evidence is equally clear that computer-using industries like finance, insurance, and real estate (FIRE) and services have continued to lag in productivity growth. Reconciliation of mas-

[4]See Baily and Gordon (1988), Stiroh (1998a), Jorgenson and Stiroh (1999) and Department of Commerce (1999) for earlier discussions of relative price changes and input substitution in the high-tech areas.

[5]BLS (2000) estimates for the business sector show a similar increase from 1.6% for 1990-95 to 2.6% for 1995-98. See CEA (2000, pg. 35) for a comparison of productivity growth at various points in the economic expansions of the 1960s, 1980s, and 1990s.

sive high-tech investment and relatively slow productivity growth in service industries remains an important task for proponents of the new economy position.[6]

What does this imply for the future? The sustainability of growth in labor productivity is the key issue for future growth projections. For some purposes, the distinctions among capital accumulation and growth in labor quality and TFP may not matter, so long as ALP growth can be expected to continue. It is sustainable labor productivity gains, after all, that ultimately drive long-run growth and raise living standards.

In this respect, the recent experience provides grounds for caution, since much depends on productivity gains in high-tech industries. Ongoing technological gains in these industries have been a direct source of improvement in TFP growth, as well as an indirect source of more rapid capital deepening. Sustainability of growth, therefore, hinges critically on the pace of technological progress in these industries. As measured by relative price changes, progress has accelerated recently, as computer prices fell 28% per year for 1995-98 compared to 15% in 1990-95. There is no guarantee, of course, of continued productivity gains and price declines of this magnitude. Nonetheless, as long as high-tech industries maintain the ability to innovate and improve their productivity at rates comparable even to their long-term averages, relative prices will fall and the virtuous circle of an investment-led expansion will continue.[7]

Finally, we argue that rewards from new technology accrue to the direct participants; first, to the innovating industries producing high-tech assets and, second, to the industries that restructure to implement the latest information technology. There is no evidence of spillovers from production of information technology to the industries that use this technology. Indeed, many of the industries that use information technology most intensively, like FIRE and services, show high rates of substitution of information technology for other inputs and relatively low rates of productivity growth. In part, this may reflect problems in measuring the output from these industries, but the empirical record provides little support for the "new economy" picture of spillovers cascading from information technology producers onto users of this technology.[8]

The paper is organized as follows. Section II describes our methodology for quantifying the sources of U.S. economic growth. We present results for the period 1959-1998, and focus on the "new economy" era of the late 1990s. Section

[6]See Gullickson and Harper (1999), Jorgenson and Stiroh (2000), and Section IV, below, for industry-level analysis.

[7]There is no consensus, however, that technical progress in computer and semi-conductor production is slowing. According to Fisher (2000), chip processing speed continues to increase rapidly. Moreover, the product cycle is accelerating as new processors are brought to market more quickly.

[8]See Dean (1999) and Gullickson and Harper (1999) for the BLS perspective on measurement error; Triplett and Bosworth (2000) provide an overview of measuring output in the service industries.

III explores the implications of the recent experience for future growth, comparing our results to recent estimates produced by the Congressional Budget Office, the Council of Economic Advisors, and the Office of Management and Budget. Section IV moves beyond the aggregate data and quantifies the productivity growth at the industry level. Using methodology introduced by Domar (1961), we consider the impact of information technology on aggregate productivity. Section V concludes.

II. THE RECENT U.S. GROWTH EXPERIENCE

The U.S. economy has undergone a remarkable transformation in recent years with growth in output, labor productivity, and total factor productivity all accelerating since the mid-1990s. This growth resurgence has led to a widening debate about sources of economic growth and changes in the structure of the economy. "New economy" proponents trace the changes to developments in information technology, especially the rapid commercialization of the Internet, that are fundamentally changing economic activity. "Old economy" advocates focus on lackluster performance during the first half of the 1990s, the increase in labor force participation and rapid decline in unemployment since 1993, and the recent investment boom.

Our objective is to quantify the sources of the recent surge in U.S. economic growth, using new information made available by the benchmark revision of the U.S. National Income and Product Accounts (NIPA) released in October 1999, BEA (1999). We then consider the implications of our results for intermediate-term projections of U.S. economic growth. We give special attention to the rapid escalation in growth rates in the official projections, such as those by the Congressional Budget Office (CBO) and the Council of Economic Advisers (CEA). The CBO projections are particularly suitable for our purposes, since they are widely disseminated, well documented, and represent "best practice." We do not focus on the issue of inflation and do not comment on potential implications for monetary policy.

(a) Sources of Economic Growth

Our methodology is based on the production possibility frontier introduced by Jorgenson (1966) and employed by Jorgenson and Griliches (1967). This captures substitutions among outputs of investment and consumption goods, as well inputs of capital and labor. We identify *information technology* (IT) with investments in computers, software, and communications equipment, as well as consumption of computer and software as outputs. The service flows from these assets are also inputs. The aggregate production function employed by Solow (1957, 1960) and, more recently by Greenwood, Hercowitz, and Krusell (1997), is an alternative to our model. In this approach a single output is expressed as a function of capital and labor inputs. This implicitly assumes, however, that investments in information technology are perfect substitutes for other outputs, so that relative prices do not change.

Our methodology is essential in order to capture two important facts about which there is general agreement. The first is that prices of computers have declined drastically relative to the prices of other investment goods. The second is that this rate of decline has recently accelerated. In addition, estimates of investment in software, now available in the NIPA, are comparable to investment in hardware. The new data show that the price of software has fallen relative to the prices of other investment goods, but more slowly than price of hardware. We examine the estimates of software investment in some detail in order to assess the role of software in recent economic growth. Finally, we consider investment in communications equipment, which shares many of the technological features of computer hardware.

i) Production Possibility Frontier

Aggregate output Y_t consists of investment goods I_t and consumption goods C_t. These outputs are produced from aggregate input X_t, consisting of capital services K_t and labor services L_t. We represent productivity as a "Hicks-neutral" augmentation A_t of aggregate input:[9]

$$(1) \quad Y(I_t, C_t) = A_t \cdot X(K_t, L_t).$$

The outputs of investment and consumption goods and the inputs of capital and labor services are themselves aggregates, each with many sub-components.

Under the assumptions of competitive product and factor markets, and constant returns to scale, growth accounting gives the share-weighted growth of outputs as the sum of the share-weighted growth of inputs and growth in *total factor productivity* (TFP):

$$(2) \quad \bar{w}_{I,t}\Delta \ln I_t + \bar{w}_{c,t}\Delta \ln C_t = \bar{v}_{K,t}\Delta \ln K_t + \bar{v}_{L,t}\Delta \ln L_t + \Delta \ln A_t,$$

where $\bar{w}_{I,t}$ is investment's average share of nominal output, $\bar{w}_{C,t}$ is consumption's average share of nominal output, $\bar{v}_{K,t}$ is capital's average share of nominal income, $\bar{v}_{K,t}$ is labor's average share of nominal income, $\bar{w}_{I,t} + \bar{w}_{C,t} = \bar{v}_{K,t} + \bar{v}_{L,t} = 1$, and Δ refers to a first difference. Note that we reserve the term *total factor productivity* for the augmentation factor in Equation (1).

[9] It would be a straightforward change to make technology labor-augmenting or "Harrod-neutral," so that the production possibility frontier could be written: $Y(I, C) = X(K,AL)$. Also, there is no need to assume that inputs and outputs are separable, but this simplifies our notation.

Equation (2) enables us to identify the contributions of outputs as well as inputs to economic growth. For example, we can quantify the contributions of different investments, such as computers, software, and communications equipment, to the growth of output by decomposing the growth of investment among its sub-components. Similarly, we can quantify the contributions of different types of consumption, such as services from computers and software, by decomposing the growth of consumption. As shown in Jorgenson and Stiroh (1999), both computer investment and consumption of IT have made important contributions to U.S. economic growth in the 1990s. We also consider the output contributions of software and communications equipment as distinct high-tech assets. Similarly, we decompose the contribution of capital input to isolate the impact of computers, software, and communications equipment on input growth.

Rearranging Equation (2) enables us to present results in terms of growth in *average labor productivity* (ALP), defined as $y_t = Y_t/H_t$, where Y_t is output, defined as an aggregate of consumption and investment goods, and $k_t = K_t/H_t$ is the ratio of capital services to hours worked H_t:

$$(3) \quad \Delta \ln y_t = \bar{v}_{K,t} \Delta \ln k_t + \bar{v}_{L,t} (\Delta \ln L_t - \Delta \ln H_t) + \Delta \ln A_t .$$

This gives the familiar allocation of ALP growth among three factors. The first is *capital deepening*, the growth in capital services per hour. Capital deepening makes workers more productive by providing more capital for each hour of work and raises the growth of ALP in proportion to the share of capital. The second term is the improvement in *labor quality*, defined as the difference between growth rates of labor input and hours worked. Reflecting the rising proportion of hours supplied by workers with higher marginal products, labor quality improvement raises ALP growth in proportion to labor's share. The third factor is *total factor productivity* (TFP) growth, which increases ALP growth on a point-for-point basis.

ii) Computers, software, and communications equipment

We now consider the impact of investment in computers, software, and communications equipment on economic growth. For this purpose we must carefully distinguish the *use* of information technology and the *production* of information technology.[10] For example, computers themselves are an output from one industry (the computer-producing industry, Commercial and Industrial Machinery),

[10]Baily and Gordon (1988), Griliches (1992), Stiroh (1998a), Jorgenson and Stiroh (1999), Whelan (1999), and Oliner and Sichel (2000) discuss the impact of investment in computers from these two perspectives.

and computing services are inputs into other industries (computer-using industries like Trade, FIRE, and Services).

Massive increases in computing power, like those experienced by the U.S. economy, therefore reflect two effects on growth. First, as the production of computers improves and becomes more efficient, more computing power is being produced from the same inputs. This raises overall productivity in the computer-producing industry and contributes to TFP growth for the economy as a whole. Labor productivity also grows at both the industry and aggregate levels.[11]

Second, the rapid accumulation of computers leads to input growth of computing power in computer-using industries. Since labor is working with more and better computer equipment, this investment increases labor productivity. If the contributions to output are captured by the effect of capital deepening, aggregate TFP growth is unaffected. As Baily and Gordon (1988) remark, "there is no shift in the user firm's production function (pg. 378)," and thus no gain in TFP. Increasing deployment of computers increases TFP only if there are spillovers from the production of computers to production in the computer-using industries, or if there are measurement problems associated with the new inputs.

We conclude that rapid growth in computing power affects aggregate output through both TFP growth and capital deepening. Progress in the technology of computer production contributes to growth in TFP and ALP at the aggregate level. The accumulation of computing power in computer-using industries reflects the substitution of computers for other inputs and leads to growth in ALP. In the absence of spillovers this growth does not contribute to growth in TFP.

The remainder of this section provides empirical estimates of the variables in Equations (1) through (3). We then employ Equations (2) and (3) to quantify the sources of growth of output and ALP for 1959-1998 and various sub-periods.

(b) Output

Our output data are based on the most recent benchmark revision of the NIPA.[12] Real output Y_t is measured in chained 1996 dollars, and $P_{Y,t}$ is the corresponding implicit deflator. Our output concept is similar, but not identical, to one used in the Bureau of Labor Statistics (BLS) productivity program. Like BLS, we exclude the government sector, but unlike BLS we include imputations for the service flow from consumers' durables (CD) and owner-occupied housing. These

[11]Triplett (1996) points out that much of decline of computer prices reflects falling semi-conductor prices. If all inputs are correctly measured for quality change, therefore, much of the TFP gains in computer production are rightly pushed back to TFP gains in semi-conductor production since semi-conductors are a major intermediate input in the production of computers. See Flamm (1993) for early estimates on semi-conductor prices. We address this further in Section IV.

[12]See Appendix A for details on our source data and methodology for output estimates.

imputations are necessary to preserve comparability between durables and housing and also enable us to capture the important impact of information technology on households.

Our estimate of current dollar, private output in 1998 is $8,013B, including imputations of $740B that primarily reflect services of consumers' durables.[13] Real output growth was 3.63% for the full period, compared to 3.36% for the official GDP series. This difference reflects both our imputations and our exclusion of the government sectors in the NIPA data. Appendix Table A-1 presents the current dollar value and corresponding price index of total output and the IT assets—investment in computers I_c, investment in software I_s, investment in communications equipment I_m, consumption of computers and software C_c, and the imputed service flow from consumers' computers and software, D_c.

The most striking feature of these data is the enormous price decline for computer investment, 18% per year from 1960 to 1995 (Chart 1). Since 1995 this decline has accelerated to 27.6% per year. By contrast the relative price of software has been flat for much of the period and only began to fall in the late 1980s. The price of communications equipment behaves similarly to the software price, while consumption of computers and software shows declines similar to computer investment. The top panel of Table 1 summarizes the growth rates of prices and quantities for major output categories for 1990-95 and for 1995-98.

In terms of current dollar output, investment in software is the largest IT asset, followed by investment in computers and communications equipment (Chart 2). While business investments in computers, software, and communications equipment are by far the largest categories, households have spent more than $20B per year on computers and software since 1995, generating a service flow of comparable magnitude.

(c) Capital Stock and Capital Services

This section describes our capital estimates for the U.S. economy from 1959 to 1998.[14] We begin with investment data from the Bureau of Economic Analysis, estimate capital stocks using the perpetual inventory method, and aggregate capital stocks using rental prices as weights. This approach, originated by Jorgenson and Griliches (1967), is based on the identification of rental prices with marginal products of different types of capital. Our estimates of these prices incorporate differences in asset prices, service lives and depreciation rates, and the tax treatment of capital incomes.[15]

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[13]Current dollar NIPA GDP in 1998 was $8,759.9B. Our estimate of $8,013B differs due to total imputations ($740B), exclusion of general government and government enterprise sectors ($972B and $128B, respectively), and exclusion of certain retail taxes ($376B).

[14]See Appendix B for details on theory, source data, and methodology for capital estimates.

We refer to the difference between growth in capital services and capital stock as the growth in *capital quality* $q_{K,t}$; this represents substitution towards assets with higher marginal products.[16] For example, the shift toward IT increases the quality of capital, since computers, software, and communications equipment are assets with relatively high marginal products. Capital stock estimates, like those originally employed by Solow (1957), fail to account for this increase in quality.

We employ a broad definition of capital, including tangible assets such as equipment and structures, as well as consumers' durables, land, and inventories. We estimate a service flow from the installed stock of consumers' durables, which enters our measures of both output and input. It is essential to include this service flow, since a steadily rising proportion is associated with investments in IT by the household sector. In order to capture the impact of information technology on U.S. economic growth, investments by business and household sectors as well as the services of the resulting capital stocks must be included.

Our estimate of capital stock is $26T in 1997, substantially larger than the $17.3T in fixed private capital estimated by BEA (1998b). This difference reflects our inclusion of consumer's durables, inventories, and land. Our estimates of capital stock for comparable categories of assets are quite similar to those of BEA. Our estimate of fixed private capital in 1997, for example, is $16.8T, almost the same as that of BEA. Similarly, our estimate of the stock of consumers' durables is $2.9T, while BEA's estimate is $2.5T. The remaining discrepancies reflect our inclusion of land and inventories. Appendix Table B-1 list the component assets and 1998 investment and stock values; Table B-2 presents the value of capital stock from 1959 to 1998, as well as asset price indices for total capital and IT assets.

The stocks of IT business assets (computers, software, and communications equipment), as well as consumers' purchases of computers and software, have grown dramatically in recent years, but remain relatively small. In 1998, combined IT assets accounted for only 3.4% of tangible capital, and 4.6% of reproducible, private assets.

We now move to estimates of capital services flows, where capital stocks of individual assets are aggregated using rental prices as weights. Appendix Table

[15] Jorgenson (1996) provides a recent discussion of our model of capital as a factor of production. BLS (1983) describes the version of this model employed in the official productivity statistics. Hulten (2000) provides a review of the specific features of this methodology for measuring capital input and the link to economic theory.

[16] More precisely, growth in capital quality is defined as the difference between the growth in capital services and the growth in the average of the current and lagged stock. Appendix B provides details. We use a geometric depreciation rate for all reproducible assets, so that our estimates are not identical to the wealth estimates published by BEA (1998b).

B-3 presents the current dollar service flows and corresponding price indexes for 1959-98, and the second panel of Table 1 summarizes the growth rates for prices and quantities of inputs for 1990-95 and 1995-98.

There is a clear acceleration of growth of aggregate capital services from 2.8% per year for 1990-95 to 4.8% for 1995-98. This is largely due to rapid growth in services from IT equipment and software, and reverses the trend toward slower capital growth through 1995. While information technology assets are only 11.2% of the total, the service shares of these assets are much greater than the corresponding asset shares. In 1998 capital services are only 12.4% of capital stocks for tangible assets as a whole, but services are 40.0% of stocks for information technology. This reflects the rapid price declines and high depreciation rates that enter into the rental prices for information technology.

Chart 3 highlights the rapid increase in the importance of IT assets, reflecting the accelerating pace of relative price declines. In the 1990s, the service price for computer hardware fell 14.2% per year, compared to an increase of 2.2% for non-information technology capital. As a direct consequence of this relative price change, computer services grew 24.1%, compared to only 3.6% for the services of non-IT capital in the 1990s. The current dollar share of services from computer hardware increased steadily and reached nearly 3.5% of all capital services in 1998 (Chart 3).[17]

The rapid accumulation of software, however, appears to have different origins. The price of software investment has declined much more slowly, –1.7% per year for software versus –19.5% for computer hardware for 1990 to 1998. These differences in investment prices lead to a much slower decline in service prices for software and computers, –1.6% versus –14.2%. Nonetheless, firms have been accumulating software quite rapidly, with real capital services growing 13.3% per year in the 1990s. While lower than the 24.1% growth in computers, software growth is much more rapid than growth in other forms of tangible capital. Complementarity between software and computers is one possible explanation. Firms respond to the decline in relative computer prices by accumulating computers and investing in complementary inputs like software to put the computers into operation.[18]

A competing explanation is that the official price indexes used to deflate software investment omit a large part of true quality improvements. This would lead to a substantial overstatement of price inflation and a corresponding understatement of real investment, capital services, and economic growth. According

[17]Tevlin and Whelan (1999) provide empirical support for this explanation, reporting that computer investment is particularly sensitive to the cost of capital, so that the rapid drop in service prices can be expected to lead to large investment response.

[18]An econometric model of the responsiveness of different types of capital services to own- and cross-price effects could be used to test for complementarity, but this is beyond the scope of the paper.

to Moulton, Parker, and Seskin (1999) and Parker and Grimm (2000), only prices for prepackaged software are calculated from constant-quality price deflators based on hedonic methods. Prices for business own-account software are based on input-cost indexes, which implicitly assume no change in the productivity of computer programmers. Custom software prices are a weighted average of prepackaged software and own-account software, with an arbitrary 75% weight for business own-account software prices. Thus, the price deflators for nearly two-thirds of recent software investment are estimated under the maintained assumption of no gain in productivity.[19] If the quality of own-account and custom software is improving at a pace even remotely close to packaged software, this implies a large understatement in investment in software.

Although the price decline for communications equipment during the 1990s is comparable to that of software, as officially measured in the NIPA, investment has grown at a rate that is more in line with prices. However, there are also possible measurement biases in the pricing of communications equipment. The technology of switching equipment, for example, is similar to that of computers; investment in this category is deflated by a constant-quality price index developed by BEA. Conventional price deflators are employed for transmission gear, such as fiber-optic cables, which also appear to be declining rapidly in price. This could lead to an underestimate of the rate of growth in communications equipment investment, capital stock, and capital services, as well as an overestimate of the rate of inflation.[20] We return to this issue at the end of Section II.

(d) Measuring Labor Services

This section describes our estimates of labor input for the U.S. economy from 1959 to 1998. We begin with individual data from the Census of Population for 1970, 1980, and 1990, as well as the annual Current Population Surveys. We estimate constant quality indexes for labor input and its price to account for heterogeneity of the workforce across sex, employment class, age, and education levels. This follows the approach of Jorgenson, Gollop and Fraumeni (1987), whose estimates have been revised and updated by Ho and Jorgenson (1999).[21]

The distinction between labor input and labor hours is analogous to the distinction between capital services and capital stock. Growth in labor input reflects the increase in labor hours, as well as changes in the composition of hours worked as firms substitute among heterogeneous types of labor. We define the growth in

[19]According to Parker and Grimm (2000), total software investment of \$123.4B includes \$35.7B in prepackaged software, \$42.3B in custom software, and \$45.4B in own-account software in 1998. Applying the weighting conventions employed by BEA, this implies \$46.3B=\$35.7B+0.25*\$42.3B, or 38% of the total software investment, is deflated with explicit quality adjustments.

[20]Grimm (1997) presents hedonic estimates for digital telephone switches and reports average price declines of more than 10% per year from 1985 to 1996.

[21]Appendix C provides details on the source data and methodology.

labor quality as the difference between the growth in labor input and hours worked. Labor quality reflects the substitution of workers with high marginal products for those with low marginal products, while the growth in hours employed by Solow (1957) and others does not capture this substitution. Appendix Table C-1 presents our estimates of labor input, hours worked, and labor quality.

Our estimates show a value of labor expenditures of $4,546B in 1998, roughly 57% of the value of output. This share accurately includes private output and our imputations for capital services. If we exclude these imputations, labor's share rises to 62%, in line with conventional estimates. As shown in Table 1, the growth of the index of labor input L_t appropriate for our model of production in Equation (1) accelerated to 2.8% for 1995-98, from 2.0% for 1990-95. This is primarily due to the growth of hours worked, which rose from 1.4% for 1990-95 to 2.4% for 1995-98, as labor force participation increased and unemployment rates plummeted.[22]

The growth of labor quality decelerated in the late 1990s, from 0.65% for 1990-95 to 0.43% for 1995-98. This slowdown captures well-known underlying demographic trends in the composition of the work force, as well as exhaustion of the pool of available workers as unemployment rates have steadily declined. Projections of future economic growth that omit labor quality, like those of CBO discussed in Section III, implicitly incorporate changes in labor quality into measured TFP growth. This reduces the reliability of projections of future economic growth. Fortunately, this is easily remedied by extrapolating demographic changes in the work force in order to reflect foreseeable changes in composition by characteristics of workers such as age, sex, and educational attainment.

(e) Quantifying the Sources of Growth

Table 2 presents results of our growth accounting decomposition based on an extension of Equation (2) for the period 1959 to 1998 and various sub-periods, as well as preliminary estimates through 1999. As in Jorgenson and Stiroh (1999), we decompose economic growth by both output and input categories in order to quantify the contribution of information technology (IT) to investment and consumption outputs, as well as capital and consumers' durable inputs. We extend our previous treatment of the outputs and inputs of computers by identifying software and communications equipment as distinct IT assets.

To quantify the sources of IT-related growth more explicitly, we employ an extended production possibility frontier:

[22]By comparison, BLS (2000) reports growth in business hours of 1.2% for 1990-95 and 2.3% for 1995-98. The slight discrepancies reflect our methods for estimating hours worked by the self-employed, as well as minor differences in the scope of our output measure.

$$(4) \quad Y(Y_n, C_c, I_c, I_s, I_m, D_c) = A \cdot X(K_n, K_c, K_s, K_m, D_n, D_c, L)$$

where outputs include computer and software consumption C_c, computer investment I_c, software investment I_s, telecommunications investment I_m, the services of consumers' computers and software D_c, and other outputs Y_n, Inputs include the capital services of computers K_c, software K_s, telecommunications equipment K_m, and other capital assets K_n, services of consumers' computers and software D_c and other durables D_n, and labor input L.[23] As in Equation (1), total factor productivity is denoted by A and represents the ability to produce more output from the same inputs. Time subscripts have been dropped for convenience.

The corresponding extended growth accounting equation is:

$$(5) \quad \begin{aligned} &\overline{w}_{Yn}\Delta\ln Y_n + \overline{w}_{Cc}\Delta\ln C_c + \overline{w}_{Ic}\Delta\ln I_c + \overline{w}_{Is}\Delta\ln I_s + \overline{w}_{\mathrm{Im}}\Delta\ln I_m + \\ &\overline{w}_{Dc}\Delta\ln D_c = \overline{v}_{Kn}\Delta\ln K_n + \overline{v}_{Kc}\Delta\ln K_c + \overline{v}_{Ks}\Delta\ln K_s + \overline{v}_{Km}\Delta\ln K_m \\ &+ \overline{v}_{Dn}\Delta\ln D_n + \overline{v}_{Dc}\Delta\ln D_c + \overline{v}_L\Delta\ln L + \Delta\ln A \end{aligned}$$

where $\overline{w}$ and $\overline{v}$ denote average shares in nominal income for the subscripted variable $\overline{w}_{Yn} + \overline{w}_{Cc} + \overline{w}_{Ic} + \overline{w}_{Is} + \overline{w}_{\mathrm{Im}} + \overline{w}_{Dc} = \overline{v}_{Kn} + \overline{v}_{Kc} + \overline{v}_{Ks} + \overline{v}_{Km} + \overline{v}_{Dn} + \overline{v}_{Dc} + \overline{v}_L = 1$, and we refer to a share-weighted growth rate as the *contribution* of an input or output.

i) Output Growth

We first consider the sources of output growth for the entire period 1959 to 1998. Broadly defined capital services make the largest growth contribution of 1.8 percentage point (1.3 percentage points from business capital and 0.5 from consumers' durable assets), labor services contribute 1.2 percentage points, and TFP growth is responsible for only 0.6 percentage points. Input growth is the source of nearly 80 percent of U.S. growth over the past 40 years, while TFP has accounted for approximately one-fifth. Chart 4 highlights this result by showing the relatively small growth contribution of the TFP residual in each sub-period.

More than three-quarters of the contribution of broadly defined capital reflects the accumulation of capital stock, while increased labor hours account for slightly less than three-quarters of labor's contribution. The quality of both capital and labor have made important contributions, 0.45 percentage points and 0.32 percentage points per year, respectively. Accounting for substitution among het-

[23]Note we have broken broadly defined capital into tangible capital services, K, and consumers' durable services, D.

erogeneous capital and labor inputs is therefore an important part of quantifying the sources of economic growth.

A look at the U.S. economy before and after 1973 reveals some familiar features of the historical record. After strong output and TFP growth in the 1960s and early 1970s, the U.S. economy slowed markedly through 1990, with output growth falling from 4.3% to 3.1% and TFP growth falling almost two-thirds of a percentage point from 1.0% to 0.3%. Growth in capital inputs also slowed, falling from 5.0% for 1959-73 to 3.8% for 1973-90, which contributed to sluggish ALP growth, 2.9% for 1959-73 to 1.4% for 1973-90.

We now focus on the 1990s and highlight recent changes.[24] Relative to the early 1990s, output growth has increased by nearly two percentage points for 1995-98. The contribution of capital jumped by 1.0 percentage point, the contribution of labor rose by 0.4 percentage points, and TFP growth accelerated by 0.6 percentage point. ALP growth rose 1.0 percentage point. The rising contributions of capital and labor encompass several well-known trends in the late 1990s. Growth in hours worked accelerated as labor markets tightened, unemployment fell to a 30-year low, and labor force participation rates increased.[25] The contribution of capital reflects the investment boom of the late 1990s as businesses poured resources into plant and equipment, especially computers, software, and communications equipment.

The acceleration in TFP growth is perhaps the most remarkable feature of the data. After averaging only 0.34% per year from 1973 to 1995, the acceleration of TFP to 0.99% suggests massive improvements in technology and increases in the efficiency of production. While the resurgence in TFP growth in the 1990s has yet to surpass periods of the 1960s and early 1970s, more rapid TFP growth is critical for sustained growth at higher rates.

Charts 5 and 6 highlight the rising contributions of information technology (IT) outputs to U.S. economic growth. Chart 5 shows the breakdown between IT and non-IT outputs for the sub-periods from 1959 to 1998, while Chart 6 decomposes the contribution of IT outputs into the five components we identified above. Although the role of IT has steadily increased, Chart 5 shows that the recent investment and consumption surge nearly doubled the output contribution of IT for 1995-98 relative to 1990-95. Chart 6 shows that computer investment is the largest single IT contributor in the late 1990s, and that consumption of computers and software is becoming increasingly important as a source of output growth.

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[24]Table 2 also presents preliminary results for the more recent period 1995-99, where the 1999 numbers are based on the estimation procedure described in Appendix E, rather than the detailed model described above. The results for 1995-98 and 1995-99 are quite similar; we focus our discussion on the period 1995-98.

[25]See Katz and Krueger (1999) for explanations for the strong performance of the U.S. labor market, including demographic shifts toward a more mature labor force, a rise in the prison age population, improved efficiency in labor markets, and the “weak backbone hypothesis” of worker restraint.

Charts 7 and 8 present a similar decomposition of the role of IT as a production input, where the contribution is rising even more dramatically. Chart 7 shows that the capital and consumers' durable contribution from IT increased rapidly in the late 1990s, and now accounts for more than two-fifths of the total growth contribution from broadly defined capital. Chart 8 shows that computer hardware is also the single largest IT contributor on the input side, which reflects the growing share and rapid growth rates of the late 1990s.

The contribution of computers, software, and communications equipment presents adifferent picture from Jorgenson and Stiroh (1999) for both data and methodological reasons. First, the BEA benchmark revision has classified software as an investment good. While software is growing more slowly than computers, the substantial nominal share of software services has raised the contribution of information technology. Second, we have added communications equipment, also a slower growing component of capital services, with similar effects. Third, we now incorporate asset-specific revaluation terms in all rental price estimates. Since the acquisition prices of computers are steadily falling, asset-specific revaluation terms have raised the estimated service price and increased the share of computer services. Finally, we have modified our timing convention and now assume that capital services from individual assets are proportional to the average of the current and lagged stock. For assets with relatively short service lives like IT, this is a more reasonable assumption than in our earlier work, which assumed that it took a full year for new investment to become productive.[26]

This large increase in the growth contribution of computers and software is consistent with recent estimates by Oliner and Sichel (2000), although their estimate of contribution is somewhat larger. They report that computer hardware and software contributed 0.93 percentage points to growth for 1996-99, while communications contributed another 0.15. The discrepancy primarily reflects our broader output concept, which lowers the input share of these high-tech assets, and also minor differences in tax parameters and stock estimates. Whelan (1999) also reports a larger growth contribution of 0.82 percentage points from computer hardware for 1996-98. The discrepancy also reflects our broader output concept. In addition, Whelan (1999) introduces a new methodology to account for retirement and support costs that generates a considerably larger capital stock and raises the input share and the growth contribution from computer capital.

Despite differences in methodology and data sources among studies, a consensus is building that computers are having a substantial impact on economic growth.[27] What is driving the increase in the contributions of computers, software, and communications equipment? As we argued in Jorgenson and Stiroh

[26]We are indebted to Dan Sichel for very helpful discussions of this timing convention.

[27]Oliner and Sichel (2000) provide a detailed comparison of the results across several studies of computers and economic growth.

(1999), price changes lead to substitution toward capital services with lower relative prices. Firms and consumers are responding to relative price changes.

Table 1 shows the acquisition price of computer investment fell nearly 28% per year, the price of software fell 2.2%, and the price of communications equipment fell 1.7% during the period 1995-98, while other output prices rose 2.0%. In response to these price changes, firms accumulated computers, software, and communications equipment more rapidly than other forms of capital. Investment other than information technology actually declined as a proportion of private domestic product. The story of household substitution toward computers and software is similar. These substitutions suggest that gains of the computer revolution accrue to firms and households that are adept at restructuring activities to respond to these relative price changes.

ii) Average Labor Productivity Growth

To provide a different perspective on the sources of economic growth we can focus on ALP growth. By simple arithmetic, output growth equals the sum of hours growth and growth in labor productivity.[28] Table 3 shows the output breakdown between growth in hours and ALP for the same periods as in Table 2. For the entire period 1959-1998, ALP growth was the predominant determinant of output growth, increasing just over 2% per year for 1959-98, while hours increased about 1.6% per year. We then examine the changing importance of the factors determining ALP growth. As shown in Equation (3), ALP growth depends on a capital deepening effect, a labor quality effect, and a TFP effect.

Chart 9 plots the importance of each factor, revealing the well-known productivity slowdown of the 1970s and 1980s, and highlighting the acceleration of labor productivity growth in the late 1990s. The slowdown through 1990 reflects less capital deepening, declining labor quality growth, and decelerating growth in TFP. The growth of ALP slipped further during the early 1990s with the serious slump in capital deepening only partly offset by a revival in the growth of labor quality and an up-tick in TFP growth. Slow growth in hours combined with slow ALP growth during 1990-95 to produce a further slide in the growth of output. This stands out from previous cyclical recoveries during the postwar period, when output growth accelerated during the recovery, powered by more rapid hours and ALP growth.

For the most recent period of 1995-98, strong output growth reflects growth in labor hours and ALP almost equally. Comparing 1990-95 to 1995-98, output growth accelerated by nearly 2 percentage points due to a 1 percentage point increase in hours worked, and a 1.0 percentage point increase in ALP growth.[29]

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[28]See Krugman (1997) and Blinder (1997) for a discussion of the usefulness of this relationship.

Chart 9 shows the acceleration in ALP growth is due to rapid capital deepening from the investment boom, as well as faster TFP growth. Capital deepening contributed 0.49 percentage points to the acceleration in ALP growth, while acceleration in TFP growth added 0.63 percentage points. Growth in labor quality slowed somewhat as growth in hours accelerated. This reflects the falling unemployment rate and tightening of labor markets as more workers with relatively low marginal products were drawn into the workforce. Oliner and Sichel (2000) also show a decline in the growth contribution of labor quality in the late 1990s, from 0.44 for 1991-95 to 0.31 for 1996-99.

Our decomposition also throws some light on the hypothesis advanced by Gordon (1999b), who argues the vast majority of recent ALP gains are due to the production of IT, particularly computers, rather than the use of IT. As we have already pointed out, more efficient IT-production generates aggregate TFP growth as more computing power is produced from the same inputs, while IT-use affects ALP growth via capital deepening. In recent years, acceleration of TFP growth is a slightly more important factor in the acceleration of ALP growth than capital deepening. Efficiency gains in computer production are an important part of aggregate TFP growth, as Gordon's results on ALP suggest. We return to this issue in grater detail below.

iii) Total Factor Productivity Growth

Finally, we consider the remarkable performance of U.S. TFP growth in recent years. After maintaining an average rate of 0.33% for the period 1973-90, TFP growth rose to 0.36% for 1990-95 and then vaulted to 0.99% per year for 1995-98. This jump is a major source of growth in output and ALP for the U.S. economy (Charts 4 and 9). While TFP growth for the 1990s has yet to attain the peaks of some periods in the golden age of the 1960s and early 1970s, the recent acceleration suggests that the U.S. economy may be recuperating form the anemic productivity growth of the past two decades. Of course, caution is warranted until more historical experience is available.

As early as Domar (1961), economists have utilized a multi-industry model of the economy to trace aggregate productivity growth to its sources at the level of individual industries. Jorgenson, Gollop, and Fraumeni (1987) and Jorgenson (1990) have employed this model to identify the industry-level sources of growth. More recently, Gullickson and Harper (1999) and Jorgenson and Stiroh (2000) have used the model for similar purposes. We postpone more detailed consideration of the sources of TFP growth until we have examined the impact of alternative price deflators on our growth decomposition.

[29]BLS (2000) shows similar trends for the business sector with hours growth increasing from 1.2% for 1990-95 to 2.3% for 1995-98, while ALP increased from 1.58% to 2.63%.

(f) Alternative Growth Accounting Estimates

Tables 1 through 3 and Charts 1 through 9 report our primary results using the official data published in the NIPA. As we have already noted, however, there is reason to believe that the rates of inflation in official price indices for certain high-tech assets, notably software and telecommunications equipment, may be overstated. Moulton, Parker, and Seskin (1999) and Parker and Grimm (2000), for example, report that only the pre-packaged portion of software investment is deflated with a constant-quality deflator. Own-account software is deflated with an input cost index and custom software is deflated with a weighted average of the prepackaged and own-account deflator. Similarly, BEA reports that in the communications equipment category, only telephone switching equipment is deflated with a constant-quality, hedonic deflator.

This subsection incorporates alternative price series for software and communications equipment and examines the impact on the estimates of U.S. economic growth and its sources. Table 4 presents growth accounting results under three different scenarios. The Base Case repeats the estimates from Table 2, which are based on official NIPA price data. Two additional cases, Moderate Price Decline and Rapid Price Decline, incorporate price series for software and communications equipment that show faster price declines and correspondingly more rapid real investment growth.[30]

The Moderate Price Decline case assumes that prepackaged software prices are appropriate for all types of private software investment, including custom and business own-account software. Since the index for prepackaged software is based on explicit quality adjustments, it falls much faster than the prices of custom and own-account software, –10.1% vs. 0.4% and 4.1% respectively, for the full period 1959-98 according to Parker and Grimm (2000). For communications equipment, the data are more limited and we assume prices fell 10.7% per year throughout the entire period. This estimate is the average annual "smoothed" decline for digital switching equipment for 1985-96 reported by Grimm (1997). While this series may not be appropriate for all types of communications equipment, it exploits the best available information.

The Rapid Price Decline case assumes that software prices fell 16% per year for 1959-98, the rate of quality-adjusted price decline reported by Brynjolfsson and Kemerer (1996) for microcomputer spreadsheets for 1987-92. This is a slightly faster decline than the –15% for 1986-91 estimated by Gandal (1994), and considerably faster than the 3% annual decline for word processors, spread-

[30]The notion that official price deflators for investment goods omit substantial quality improvements is hardly novel. The magisterial work of Gordon (1990) successfully quantified the overstatements of rates of inflation for the prices of a wide array of investment goods, covering all producers' durable equipment in the NIPA.

sheets, and databases for 1987-93 reported by Oliner and Sichel (1994). For communications equipment, we used estimates from the most recent period from Grimm (1997), who reports a decline of 17.9% per year for 1992-96.

While this exercise necessarily involves some arbitrary choices, the estimates incorporate the limited data now available and provide a valuable perspective on the crucial importance of accounting for quality change in the prices of investment goods. Comparisons among the three cases are also useful in suggesting the range of uncertainty currently confronting analysts of U.S. economic growth.

Before discussing the empirical results, it is worthwhile to emphasize that more rapid price decline for information technology has two direct effects on the sources of growth, and one indirect effect. The alternative investment deflators raise real output growth by reallocating nominal growth away from prices and towards quantities. This also increases the growth rate of capital stock, since there are larger investment quantities in each year. More rapid price declines also give greater weight to capital services from information technology.

The counter-balancing effects of increased output and increased input growth lead to an indirect effect on measured TFP growth. Depending on the relative shares of high-tech assets in investment and capital services, the TFP residual will increase if the output effect dominates or decrease if the effect on capital services dominates.[31] Following Solow (1957, 1960), Greenwood, Hercowitz, and Krusell (1997) omit the output effect and attribute the input effect to "investment-specific" (embodied) technical change. This must be carefully distinguished from the effects of industry-level productivity growth on TFP growth, discussed in Section IV.

Table 4 reports growth accounting results from these three scenarios—Base Case, Moderate Price Decline, and Rapid Price Decline. The results are not surprising; the more rapid the price decline for software and communications, the faster the rate of growth of output and capital services. Relative to the Base Case, output growth increases by 0.16 percentage points per year for 1995-98 in the Moderate Price Decline case and by 0.34 percentage points in the Rapid Price Decline case. Capital input growth shows slightly larger increases across the three cases. Clearly, constant-quality price indexes for information technology are essential for further progress in understanding the growth impact of high-tech investment.

The acceleration in output and input growth reflects the increased contributions from IT, and determines the effect on the TFP residual. In particular, the output contribution from software for 1995-98 increases from 0.21 percentage points in the Base Case to 0.29 percentage points under Moderate Price Decline to 0.40 percentage points with Rapid Price Decline. Similarly, the capital services contribution for software increases from 0.19 to 0.29 to 0.45 percentage points.

[31]This point was originally made by Jorgenson (1966); Hulten (2000) provides a recent review.

The contribution of communications equipment shows similar changes. Residual TFP growth falls slightly during the 1990s, as the input effect outweighs the output effect, due to the large capital services shares of IT.

This exercise illustrates the sensitivity of the sources of growth to alternative price indexes for information technology. We do not propose to argue the two alternative cases are more nearly correct than the Base Case with the official prices from NIPA. Given the paucity of quality-adjusted price data on high-tech equipment, we simply do not know. Rather, we have tried to highlight the importance of correctly measuring prices and quantities to understand the dynamic forces driving U.S. economic growth. As high-tech assets continue to proliferate through the economy and other investment goods become increasingly dependent on electronic components, these measurement issues will become increasingly important. While the task that lies ahead of us will be onerous, the creation of quality-adjusted price indexes for all high-tech assets deserves top priority.

(g) Decomposition of TFP Growth

We next consider the role of high-tech industries as a source of TFP growth. As discussed above, production of high-tech investment goods has made important contributions to aggregate growth. CEA (2000), for example, allocates 0.39 percentage points of aggregate TFP growth to the computer production, while Oliner and Sichel (2000) allocate 0.47 percentage points to the production of computers and computer-related semi-conductor production for the period 1995-99.[32]

We employ a methodology based on the price "dual" approach to measurement of productivity at the industry level. Anticipating our complete industry analysis in Section IV, below, it is worthwhile to spell out the decomposition of TFP growth by industry. Using the Domar approach to aggregation, industry-level productivity growth is weighted by the ratio of the gross output of each industry to aggregate value-added to estimate the industry contribution to aggregate TFP growth. In the dual approach, the rate of productivity growth is measured as the decline in the price of output, plus a weighted average of the growth rates of input prices.

In the case of computer production, this expression is dominated by two terms; namely, the price of computers and the price of semi-conductors, a primary intermediate inputs into the computer-producing industry. If semi-conductor industry output is used only as an intermediate good to produce computers, then its contribution to computer industry productivity growth, weighted by computer industry output, precisely cancels its independent contribution to aggregate

[32]Gordon (1999a), Stiroh (1998), and Whelan (1999) have also provided estimates.

TFP growth.[33] This independent contribution from the semi-conductor industry, based on the complete Domar weighting scheme, is the value of semi-conductor output divided by aggregate value added, multiplied by the rate of price decline in semi-conductors.

We report details of our TFP decomposition for the three alternative cases described above for 1990-95 and 1995-98 in Table 5, and summarize the IT vs. non-IT comparison in Chart 10. In our Base Case, using official NIPA data, we estimate the production of information technology accounts for 0.44 percentage points for 1995-98, compared to 0.25 percentage points for 1990-95. This reflects the accelerating relative price changes due to radical shortening of the product cycle for semi-conductors.[34]

As we have already suggested, the estimates of price declines for high-tech investments in our Base Case calculations may be conservative; in fact, these estimates may be *very* conservative. Consider the Moderate Price Decline Case, which reflects only part of the data we would require for constant-quality estimates of the information technology price declines. This boosts the contribution of information technology to TFP growth to 0.64 percentage points, an increase of 0.20 percentage points for 1995-98. Proceeding to what may appear to be the outer limit of plausibility, but still consistent with the available evidence, we can consider the case of Rapid Price Decline. The contribution of information technology to TFP growth is now a robust 0.86 percentage points, accounting for all of TFP growth for 1995-98.

As a final observation from the TFP decomposition, we note that the TFP acceleration in the late 1990s does not appear to be entirely located within IT-producing industries. While the actual growth rates vary considerably across our three alternative cases, non-IT TFP growth increased markedly in each case when the early 1990s are compared to the late 1990s. This runs counter to the conclusion of Gordon (1999b), who reports the entire acceleration of labor productivity growth in the late 1990s reflects gains in IT-production. This divergence likely reflects Gordon's detrending procedure which attributes a sizable portion of recent productivity growth to cyclical factors, as well as his focus on labor productivity and our focus on TFP growth.

This acceleration of non-IT TFP growth could also be interpreted as evidence of a "new economy." If these productivity gains do indeed reflect spillovers

[33]This calculation shows that the simplified model of Oliner and Sichel (2000) is a special case of the complete Domar weighting scheme used in Section IV.

[34]Relative price changes in the Base Case are taken from the investment prices in Table 5. Output shares are estimated based on final demand sales available from the BEA website for computers and from Parker and Grimm (2000) for software. Investment in communications equipment is from the NIPA, and we estimate other final demand components for communications equipment using ratios relative to final demand for computers. This is an approximation necessitated by the lack of complete data of sales to final demand by detailed commodity.

from IT into non-IT industries, this would provide some missing evidence for the new economy side. Alternatively, however, this could reflect technological progress in non-IT industries that is entirely independent of the IT revolution. Differentiation between these two hypotheses is impossible at the aggregate level, and requires detailed industry data for the most recent period 1995-98. Without this data, identification problems prevent us from drawing firm conclusions about the sources and implications of the acceleration of TFP in non-IT industries.

III. SETTING THE SPEED LIMIT

We now consider the sustainability of recent U.S. growth trends over longer time horizons. Rapid output growth is highly desirable, of course, but cannot continue indefinitely if fueled by a falling unemployment rate and higher labor force participation. Output growth driven by continuing TFP improvements, on the other hand, is more likely to persist. The sustainability of growth has clear implications for government policies. Since economic growth affects tax revenues, potential government expenditures, and the long-term viability of programs like Social Security and Medicare, it is closely studied by government agencies. This section examines the impact of the recent success of the U.S. economy on official growth forecasts.

(a) A Brief Review of Forecast Methodologies

The importance of economic growth for the U.S. government is evident in the considerable effort expended on projecting future growth. No fewer than five government agencies—the Congressional Budget Office (CBO), the Social Security Administration (SSA), the Office of Management and Budget (OMB), the Council of Economic Advisors (CEA), and the General Accounting Office (GAO) —report estimates of future growth for internal use or public discussion. This section briefly discusses the methodologies used by these agencies.[35]

All forecasts are based on models that rest securely on neoclassical foundations. While the details and assumptions vary, all employ an aggregate production model similar to Equation (1), either explicitly or implicitly. In addition, they all incorporate demographic projections from the SSA as the basic building block for labor supply estimates. CBO (1995, 1997, 1999a, 1999b, 2000) and GAO (1995, 1996) employ an aggregate production function and describe the role of labor growth, capital accumulation, and technical progress explicitly. SSA (1992, 1996), OMB (1997, 2000), and CEA (2000) on the other hand, employ a simplified relationship where output growth equals the sum of growth in hours worked and labor productivity. Projections over longer time horizons are driven by ag-

[35]Stiroh (1998b) provides details and references to supporting documents.

gregate supply with relatively little attention to business cycle fluctuations and aggregate demand effects.

Given the common framework and source data, it is not surprising that the projections are quite similar. Reporting on estimates released in 1997, Stiroh (1998b) finds that SSA and GAO projections of per capita GDP in 2025 were virtually identical, while CBO was about 9% higher due to economic feedback effects from the improving government budget situation. More recently, CBO (2000) projects real GDP growth of 2.8% and OMB (2000) projects 2.7% for 1999-2010, while CEA (2000) reports 2.8% for 1999-2007. Although the timing is slightly different—CBO projects faster growth than OMB earlier in the period and CEA reports projections only through 2007—the estimates are virtually identical. All three projections identify the recent investment boom as a contributor to rising labor productivity and capital deepening as a source of continuing economic growth. We now consider the CBO projections in greater detail.

(b) CBO's Growth Projections

CBO utilizes a sophisticated and detailed, multi-sector growth model of the U.S. economy.[36] The core of this model is a two-factor production function for the non-farm business sector with CBO projections based on labor force growth, national savings and investment, and exogenous TFP growth. Production function parameters are calibrated to historical data, using a Cobb-Douglas model:

$$(6) \quad Y = A \cdot H^{0.7} \cdot K^{0.3}$$

where Y is potential output, H is potential hours worked, K is capital input, and A is potential total factor productivity.[37]

CBO projects hours worked on the basis of demographic trends with separate estimates for different age and sex classifications. These estimates incorporate SSA estimates of population growth, as well as internal CBO projections of labor force participation and hours worked for the different categories. However, CBO does not use this demographic detail to identify changes in labor quality. Capital input is measured as the service flow from four types of capital stocks—producers' durable equipment excluding computers, computers, nonresidential structures, and inventories. Stocks are estimated by the perpetual inventory method and weighted by rental prices, thereby incorporating some changes in capital quality. TFP growth is projected on the basis of recent historical trends, with labor quality growth implicitly included in CBO's estimate of TFP growth.

[36]The five sectors—nonfarm business, farm, government, residential housing, and households and nonprofit institutions—follow the breakdown in Table 1.7 of the NIPA.

[37]See CBO (1995, 1997) for details on the underlying model and the adjustments for business cycle effects that lead to the potential series.

Turning to the most recent CBO projections, reported in CBO (2000), we focus on the non-farm business sector, which drives the GDP projections and is based on the most detailed growth model. Table 6 summarizes CBO's growth rate estimates for the 1980s and 1990s, and projections for 1999-2010. We also present estimates from BLS (2000) and our results.[38]

CBO projects potential GDP growth of 3.1% for 1999-2010, up slightly from 3.0% in the 1980s and 2.9% in the 1990s. CBO expects actual GDP growth to be somewhat slower at 2.8%, as the economy moves to a sustainable, long-run growth rate. Acceleration in potential GDP growth reflects faster capital accumulation and TFP growth, partly offset by slower growth in hours worked. Projected GDP growth is 0.4% higher than earlier estimates (CBO (1999b)) due to an upward revision in capital growth (0.1%), slightly more rapid growth in hours (0.1%), and faster TFP growth, reflecting the benchmark revisions of NIPA, and other technical changes (0.2%).[39]

CBO's estimates for the non-farm business sector show strong potential output growth of 3.5% for 1999-2010. While projected output growth is in line with experience of the 1990s and somewhat faster than the 1980s, there are significant differences in the underlying sources. Most important, CBO projects an increasing role for capital accumulation and TFP growth over the next decade, while hours growth slows. This implies that future output growth is driven by ALP growth, rather than growth in hours worked.

CBO projects potential non-farm business ALP growth for 1999-2010 to rise to 2.3%, powered by capital deepening (3.2%) and TFP growth (1.4%). This represents a marked jump in ALP growth, relative to 1.5% in the 1980s and 1.9% in the 1990s. In considering whether the recent acceleration in ALP growth represents a trend break, CBO "gives considerable weight to the possibility that the experience of the past few years represents such a break (CBO (2000), pg. 43)." This assumption appears plausible given recent events, and low unemployment and high labor force participation make growth in hours worked a less likely source of future growth. Falling investment prices for information technology make capital deepening economically attractive, while the recent acceleration in TFP growth gives further grounds for optimistic projections.

As the investment boom continues and firms substitute toward more information technology in production, CBO has steadily revised its projected growth rates of capital upward. It is worthwhile noting just how much the role of capital accumulation has grown in successive CBO projections, rising from a projected growth rate of 3.6% in January 1999 (CBO (1999a)) to 4.1% in July 1999 (CBO

[38]Note the growth rates in Table 6 do not exactly match Table 2 due to differences in calculating growth rates. All growth rates in Table 6 follow CBO's convention of calculating discrete growth rates as $g = \left[(X_t / X_0)^{1/t} - 1 \right] * 100$, while growth rates in Table 2 are calculated as $g = \left[\ln(X_t / X_0) / t \right] * 100$.

[39]See CBO (2000, pg. 25 and pg. 43) for details.

(1999b)) to 4.4% in January 2000 (CBO (2000)). This reflects the inclusion of relatively fast-growing software investment in the benchmark revision of NIPA, but also extrapolates recent investment patterns.

Similarly, CBO has raised its projected rate of TFP growth in successive estimates—from 1.0% in January 1999 to 1.1% in July 1999 to 1.4% in January 2000.[40] These upward revisions reflect methodological changes in how CBO accounts for the rapid price declines in investment, particularly computers, which added 0.2%. In addition, CBO adjustments for the benchmark revision of NIPA contributed another 0.1%.

Table 6 also reports our own estimates of growth for roughly comparable periods. While the time periods are not precisely identical, our results are similar to CBO's. We estimate slightly faster growth during the 1980s, due to rapidly growing consumers' durable services, but slightly lower rates of capital accumulation due to our broader measure of capital. Our growth of hours worked is higher, since we omit the cyclical adjustments made by CBO to develop their potential series.[41] Finally, our TFP growth rates are considerably lower, due to our labor quality adjustments and inclusion of consumers' durables. If we were to drop the labor quality adjustment, our estimate would rise to 1.0% per year from 1990 to 1998, compared to 1.2% for CBO for 1990-99. The remaining difference reflects the fact that we do not include the rapid TFP growth of 1999, but do include the services of consumers' durables, which involve no growth in TFP.

(c) Evaluating CBO's Projections

Evaluating CBO's growth projections requires an assessment of their estimates of the growth of capital, labor, and TFP. It is important to emphasize that this is not intended as a criticism of CBO, but rather a description of "best practice" in the difficult area of growth projections. We also point out comparisons between our estimates and CBO's estimates are not exact due to our broader output concept and our focus on actual data series, as opposed the potential series that are the focus of CBO.

We begin with CBO's projections of potential labor input. These data, based on the hours worked from BLS and SSA demographic projections, show a decline in hours growth from 1.5% in the 1990s to 1.2% for the period 1999-2010. This slowdown reflects familiar demographic changes associated with the aging of the U.S. population. However, CBO does not explicitly estimate labor quality, so that labor composition changes are included in CBO's estimates of TFP growth and essentially held constant.

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[40]Earlier upward revisions to TFP growth primarily reflect "technical adjustment…for methodological changes to various price indexes" and "increased TFP projections (CBO (1999b), pg. 3)."

[41]See CBO (1995) for details on the methodology for cyclical adjustments to derive the "potential" series.

We estimate growth in labor quality of 0.57% per year for 1990-98, while our projections based on demographic trends yield a growth rate of only 0.32% for the 1998-2010 period. Assuming CBO's labor share of 0.70, this implies that a decline in the growth contribution from labor quality of about 0.18 percentage points per year over CBO's projection horizon. Since this labor quality effect is implicitly incorporated into CBO's TFP estimates, we conclude their TFP projections are overstated by this 0.18 percentage point decline in the labor quality contribution.

TFP growth is perhaps the most problematical issue in long-term projections. Based on the recent experience of the U.S. economy, it appears reasonable to expect strong future productivity performance. As discussed above and shown in Table 2, TFP growth has increased markedly during the period 1995-98. However, extrapolation of this experience runs the risk of assuming that a temporary productivity spurt is a permanent change in trend.

Second, the recent acceleration of TFP growth is due in considerable part to the surge in productivity growth in IT-producing industries. This makes the economy particularly vulnerable to slowing productivity growth in these industries. Computer prices have declined at extraordinary rates in recent years and it is far from obvious that this can continue. However, acceleration in the rate of decline reflects the change in the product cycle for semi-conductors, which has shifted from three years to two and may be permanent.

We conclude that CBO's projection of TFP growth is optimistic in assuming a continuation of recent productivity trends, but nonetheless reasonable. However, we reduce this projection by only 0.18 percent per year to reflect the decline in labor quality growth, resulting in projected TFP growth of 1.22% per year. To obtain a projection of labor input growth we add labor quality growth of 0.32% per year to CBO's projection of growth in hours of 1.2% per year. Multiplying labor input growth of 1.52% per year by the CBO labor share of 0.7, we obtain a contribution of labor input of 1.06%.

CBO's projected annual growth of capital input of 4.4% is higher than in any other decade, and 0.8% higher than in the 1990s.[42] This projection extrapolates recent increases in the relative importance of computers, software, and communications equipment. Continuing rapid capital accumulation is also predicated on the persistence of high rates of decline in asset prices, resulting from rapid productivity growth in the IT producing sectors. Any attenuation in this rate of decline would produce a double whammy—less TFP growth in IT-producing industries and reduced capital deepening elsewhere.

Relative to historical trends, CBO's capital input growth projection of 4.4% seems out of line with the projected growth of potential output of 3.5%. During the 1980s capital growth exceeded potential output growth by 0.4%, according to

[42]These comparisons are from CBO (2000, Table 2-6).

their estimates, or 0.1% in our estimates. In the 1990s, capital growth exceeded output growth by only 0.2%, again according to their estimates, and 0.1% in our estimates. This difference jumps to 0.9% for the period of CBO's projections, 1999-2010.

Revising the growth of capital input downward to reflect the difference between the growth of output and the growth of capital input during the period 1995-98 of 0.2% would reduce the CBO's projected output growth to 3.35% per year. This is the sum of the projected growth of TFP of 1.22% per year, the contribution of labor input of 1.06% per year, and the contribution of capital input of 1.07% per year. This is a very modest reduction in output growth from CBO's projection of 3.5% per year and can be attributed to the omission of a projected decline in labor quality growth.

We conclude that CBO's projections are consistent with the evidence they present, as well as our own analysis of recent trends. We must emphasize, however, that any slowdown in technical progress in information technology could have a major impact on potential growth. Working through both output and input channels, the U.S. economy has become highly dependent on information technology as the driving force in continued growth. Should productivity growth in these industries falter, the projections we have reviewed could be overly optimistic.

IV. INDUSTRY PRODUCTIVITY

We have explored the sources of U.S. economic growth at the aggregate level and demonstrated that accelerated TFP growth is an important contributor to the recent growth resurgence. Aggregate TFP gains—the ability to produce more output from the same inputs—reflects the evolution of the production structure at the plant or firm level in response to technological changes, managerial choices, and economic shocks. These firm- and industry-level changes then cumulate to determine aggregate TFP growth. We now turn our attention to industry data to trace aggregate TFP growth to its sources in the productivity growth of individual industries, as well as reallocations of output and inputs among industries.

Our approach utilizes the framework of Jorgenson, Gollop, and Fraumeni (1987) for quantifying the sources of economic growth for U.S. industries. The industry definitions and data sources have been brought up-to-date. The methodology of Jorgenson, Gollop, and Fraumeni for aggregating over industries is based on Domar's (1961) approach to aggregation. Jorgenson and Stiroh (2000) have presented summary data from our work; other recent studies of industry-level productivity growth include BLS (1999), Corrado and Slifman (1999), and Gullickson and Harper (1999). The remainder of this section summarizes our methodology and discusses the results.

(a) Methodology

As with the aggregate production model discussed in Section II, we begin with an industry-level production model for each industry. A crucial distinction, however, is that industry output Q_i is measured using a "gross output" concept, which includes output sold to final demand as well as output sold to other industries as intermediate goods. Similarly, inputs include all production inputs, including capital services K_i and labor services L_i, as well as intermediate inputs, energy E_i and materials M_i, purchased from other industries.[43] Our model is based on the industry production function:

$$(7) \quad Q_i = A_i \cdot X_i(K_i, L_i, E_i, M_i)$$

where time subscripts have been suppressed for clarity.

We can derive a growth accounting equation similar to Equation (2) for each industry to measure the sources of economic growth for individual industries. The key difference is the use of gross output and an explicit accounting of the growth contribution of intermediate inputs purchased from other industries. This yields:

$$(8) \quad \Delta \ln Q_i = \overline{w}_{K_i} \Delta \ln K_i + \overline{w}_{L_i} \Delta \ln L_i + \overline{w}_{E_i} \Delta \ln E_i + \overline{w}_{M_t} \Delta \ln M_i + \Delta \ln A_i$$

where $\overline{w}_i$ is the average share of the subscripted input in the *i*th industry and the assumptions of constant returns to scale and competitive markets imply $\overline{w}_{K_i} + \overline{w}_{L_i} + \overline{w}_{E_i} + \overline{w}_{M_i} = 1$.

The augmentation factor ΔlnA_i represents the growth in output not explained by input growth and is conceptually analogous to the TFP concept used above in the aggregate accounts. It represents efficiency gains, technological progress, scale economies, and measurement errors that allow more measured gross output to be produced from the same set of measured inputs. We refer to this term as *industry productivity* or simply *productivity* to distinguish it from TFP, which is estimated from a value-added concept of output.[44]

Domar (1961) first developed an internally consistent methodology that linked industry level productivity growth in Equation (8) with aggregate TFP growth in Equation (2). He showed that aggregate TFP growth can be expressed as a weighted average of industry productivity growth:

[43]This is analogous to the sectoral output concept used by BLS. See Gullickson and Harper (1999), particularly pp. 49-53 for a review of the concepts and terminology used by the BLS.

[44]BLS refers to this concept as *multi-factor productivity* (MFP).

$$(9) \quad \Delta \ln A = \sum_{i=1}^{37} \overline{w}_i \cdot \Delta \ln A_i, \quad \overline{w}_i = \frac{1}{2}\left(\frac{P_{i,t} \cdot Q_{i,t}}{P_{Y,t} \cdot Y} + \frac{P_{i,t-1} \cdot Q_{i,t-1}}{P_{Y,t-1} \cdot Y_{t-1}} \right)$$

where $\overline{w}_i$ is the "Domar weight," $P_i \cdot Q_i$ is current dollar gross output in sector i, and $P_Y \cdot Y$ is current dollar aggregate value-added. This simplified version of the aggregation formula given by Jorgenson, Gollop, and Fraumeni (1987), excludes re-allocations of value added, capital input, and labor input by sector. Jorgenson and Stiroh (2000) show that these terms are negligible for the period 1958-1996, which is consistent with the results of Jorgenson, Gollop, and Fraumeni (1987) and Jorgenson (1990) for periods of similar duration.

Domar weights have the notable feature that they do not sum to unity. This reflects the different output concepts used at the aggregate and industry levels in Equations (1) and (7), respectively. At the aggregate level, only primary inputs are included, while both primary and intermediate inputs are included in the industry production functions. For the typical industry, gross output considerably exceeds value added, so the sum of gross output across industries exceeds the sum of value added. This weighting methodology implies that economy-wide TFP growth can grow faster than productivity in any industry, since productivity gains are magnified as they work their way through the production process.[45]

In addition to providing an internally consistent aggregation framework, industry-level gross output allows an explicit role for intermediate goods as a source of industry growth. For example, Triplett (1996) shows that a substantial portion of the price declines in computer output can be traced to steep price declines in semi-conductors, the major intermediate input in the computer-producing industry. Price declines in semi-conductors reflect technological progress—Moore's law in action. This should be measured as productivity growth in the industry that produces semi-conductors. By correctly accounting for the quantity and quality of intermediate inputs, the gross output concept allows aggregate TFP gains to be correctly allocated among industries.

(b) Data Sources

Our primary data include a set of inter-industry transactions accounts developed by the Employment Projections office at the BLS. These data cover a relatively short time period from 1977 to 1995. We linked the BLS estimates to industry-level estimates back to 1958, described by Stiroh (1998a), and extrapo-

[45]Jorgenson, Gollop, and Fraumeni (1987), particularly Chapter 2, provide details and earlier references; Gullickson and Harper (1999, pg. 50) discuss how aggregate productivity can exceed industry productivity in the Domar weighting scheme.

lated to 1996 using current BLS and BEA industry data.[46] This generated a time series for 1958 to 1996 for 37 industries, at roughly the two-digit Standard Industrial Classification (SIC) level, including Private Households and General Government.[47] Table 7 lists the 37 industries, the relative size in terms of 1996 value-added and gross output, and the underlying SIC codes for each industry.

Before proceeding to the empirical results, we should point out two limitations of this industry-level analysis. Due to the long lag in obtaining detailed inter-industry transactions, investment, and output data by industry, our industry data are not consistent with the BEA benchmark revision of NIPA published in December 1999; they correspond to the NIPA produced by BEA in November 1997. As a consequence, they are not directly comparable to the aggregate data described in Tables 1 through 6. Since the impact of the benchmark revision was to raise output and aggregate TFP growth, it is not surprising that the industry data show slower output and productivity growth. Second, our estimates of rental prices for all assets in this industry analysis are based on the industry-wide asset revaluation terms, as in Stiroh (1998a). They are not directly comparable to the aggregate data on capital input, where asset-specific revaluation terms are included in the rental price estimates. The use of industry-wide revaluation terms tends to reduce the growth in capital services since assets with falling relative prices, such as computers, have large service prices and rapid accumulation rates.

(c) Empirical Results

i) Sources of Industry Growth

Table 8 reports estimates of the components of Equation (8) for the period 1958-1996. For each industry, we show the growth in output, the contribution of each input (defined as the nominal share-weighted growth rate of the input), and productivity growth. We also report average labor productivity (ALP) growth, defined as real gross output per hour worked, and the Domar weights calculated from Equation (9). We focus the discussion of our results on industry productivity and ALP growth.

Industry productivity growth was the highest in two high-tech industries, Industrial Machinery and Equipment, and Electronic and Electric Equipment, at 1.5% and 2.0% per year, respectively. Industrial Machinery includes the production of computer equipment (SIC #357) and Electronic Equipment includes the production of semi-conductors (SIC #3674) and communications equipment (SIC #366). The enormous technological progress in the production of these high-tech capital goods has generated falling prices and productivity growth, and fueled the substitution towards information technology.

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[46] We are grateful to Mun Ho for his extensive contributions to the construction of the industry data.
[47] Appendix D provides details on the component data sources and linking procedures.

An important feature of these data is that we can isolate productivity growth for industries that produce intermediate goods, for example, Electronic and Electric Equipment.[48] Consider the contrast between computer production and semiconductor production. Computers are part of final demand, sold as consumption and investment goods, and can be identified in the aggregate data, as we did in Table 2. Semi-conductors, on the other hand, do not appear at the aggregate level, since they are sold almost entirely as an input to computers, telecommunications equipment, and an increasingly broad range of other products such as machine tools, automobiles, and virtually all recent vintages of appliances. Nonetheless, improved semiconductor production is an important source of aggregate TFP growth since it is ultimately responsible for the lower prices and improved quality of goods like computers produced for final demand.

The enormous price declines in computer equipment and the prominent role of investment in computers in the GDP accounts have led Gordon (1999b), Whelan (1999), and others to emphasize technological progress in the production of computers. Triplett (1996), however, quantifies the role of semi-conductors as an intermediate input and estimates that falling semi-conductor prices may account for virtually all of the relative price declines in computer equipment. He concludes, "productivity in the computer industry palls beside the enormous increases in productivity in the semi-conductor industry (Triplett (1996), pg. 137)."[49]

The decline in prices of semi-conductors is reflected in the prices of intermediate input into the computer industry, effectively moving productivity away from computers and toward semi-conductor production. Building on this observation, Oliner and Sichel (2000) present a model that includes three sectors—semi-conductor production, computer production, and other goods—and shows that semiconductor productivity is substantially more important than computer productivity. Our complete industry framework with Domar aggregation over all industries captures the contributions of productivity growth from all industries.

The impact of intermediate inputs can be seen in Table 8 in the large contribution of material inputs in the Industrial Machinery industry. Since a substantial portion of these inputs consists of semi-conductors purchased from the Electronic Equipment industry, productivity gains that lower the price of semi-conductors increase the flow of intermediate inputs into the Industrial Machinery industry. By correctly accounting for these inputs, industry productivity growth in the In-

[48]Our industry classification is too broad to isolate the role of semi-conductors.

[49]This conclusion rests critically on the input share of semi-conductors in the computer industry. Triplett reports Census data estimates of this share at 15% for 1978-94, but states industry sources estimate this share to be closer to 45%. This has an important impact on his results. At one end of the spectrum, if no account is made for semiconductor price declines, the relative productivity in computer equipment increases 9.1% for 1978-94. Assuming a 15% share for semi-conductors causes this to fall to 9%; assuming a 45% share causes a fall to 1%.

dustrial Machinery industry falls, and we can rightly allocate technological progress to the Electronic Equipment industry, which produces semi-conductors. While this type of industry reallocation does not affect aggregate productivity growth, it is important to identify the sources of productivity growth and allocate this among industries in order to assess the sustainability of the recent acceleration.

The two high-tech industries also show high rates of average labor productivity (ALP) growth of 3.1% and 4.1% per year. This reflects an underlying relationship similar to Equation (3) for the aggregate data, where industry ALP growth reflects industry productivity growth, labor quality growth, and increases in input intensity, including increases in capital as well as intermediate inputs per hour worked. As implied by Table 8, these industries showed rapid accumulation of capital and intermediate inputs, which raised ALP growth above productivity growth. It is also worthwhile to note that Communications, another high-tech industry, shows ALP growth much faster than industry productivity growth due to the rapid accumulation of inputs, notably intermediate materials. These results highlight the crucial importance of accounting for all inputs when examining the sources of industry growth.

Productivity growth in information technology provides a final perspective on the conclusions of Greenwood, Hercowitz, and Krusell (1997) and Hercowitz (1998). They argue that some 60% of postwar U.S. growth can be attributed to investment-specific (embodied) productivity growth, which they distinguish from input accumulation and (disembodied) productivity growth. As evidence, they note the relative price of equipment in the U.S. has fallen 3% per year, which they interpret as evidence of technical change that affects capital goods, but not consumption goods. Our decomposition, however, reveals that declines in the prices of investment goods are the consequence of improvements in industry (disembodied) productivity. Domar aggregation shows how these improvements contribute directly to aggregate TFP growth. There is no separate role for investment-specific technical change.

Other industries that show relatively strong productivity growth include Agriculture, Textile Mill Products, Rubber and Plastic, Instruments, Trade. All of these industries experienced productivity growth in the 1.0% per year range, and ALP growth in the 2-3% range. Industries with the slowest productivity growth include Petroleum and Gas, Construction, Printing and Publishing, and Government Enterprises, all of which showed a decline in productivity of nearly 0.5% per year.

It is worth emphasizing that nine industries showed negative productivity growth for the entire period, a counter-intuitive result, if we were to interpret productivity growth solely as technological progress. It is difficult to envision technology steadily worsening for a period of nearly 40 years as implied by these estimates. The perplexing phenomenon of negative technical progress was a primary motivation for the work of Corrado and Slifman (1999) and Gullickson and

Harper (1999), who suggest persistent measurement problems as a plausible explanation. Corrado and Slifman (1999) conclude, "a more likely statistical explanation for the implausible productivity, profitability, and price trends…is that they reflect problems in measuring prices (pg. 331)." If prices are systematically overstated because quality change is not accurately measured, then output and productivity are correspondingly understated. We do not pursue this idea here, but simply point out that measurement problems are considered a reasonable explanation by some statistical agencies.[50]

An alternative interpretation for negative productivity growth is the possibility of declines in efficiency that have no association with technology. These might include lower quality of management and worsening of industrial organization through the growth of barriers to entry. This appears to be a plausible explanation, given the widespread occurrence of negative productivity growth for extended periods of time. Until more careful research linking firm- and plant-level productivity to industry productivity estimates has been done, it would be premature to leap to the conclusion that estimates of economic performance should be adjusted so as to eliminate negative productivity growth rates, wherever they occur.

Low productivity growth rates are surprising in light of the fact that many of the affected industries are heavy investors in information technology. Stiroh (1998a), for example, reports nearly 80% of computer investment in the early 1990s was in three service-related industries, Trade, FIRE, and Services. Triplett (1999) reports a high concentration in service industries using the BEA's capital use survey. The apparent combination of slow productivity growth and heavy computer-use remains an important obstacle for new economy proponents who argue that the use of information technology is fundamentally changing business practices and raising productivity throughout the U.S. economy.

ii) Comparison to Other Results

Before proceeding to the Domar aggregation results, it is useful to compare these results to three other recent studies—BLS (1999), Corrado and Slifman (1999) and Gullickson and Harper (1999). BLS (1999) reports industry productivity growth ("industry multifactor productivity" in their terminology) for 19 manufacturing industries for 1949-96. Corrado and Slifman (1999) report estimates of ALP growth for selected one- and two-digit SIC industries for the period 1977-97. Gullickson and Harper (1999) report industry productivity growth for certain one and two-digit SIC industries based on two output series for the period 1947-1992. Similar to BLS (1999), Gullickson and Harper use a "sectoral output"

[50]Dean (1999) summarizes the BLS view on this issue. McGuckin and Stiroh (2000) attempt to quantify the magnitude of the potential mismeasurement effects.

concept estimated by the Employment Projections staff at BLS and also, for 1977-92, use BEA's gross output series, "adjusted for consistency."[51] Note that none of these studies reflect the BEA benchmark revision of NIPA.

Time period, industry classification, and methodological differences make a definitive reconciliation to our results impossible. For example, BLS (1999) reports detailed manufacturing industries; Corrado and Slifman (1999) use a value-added concept, BEA's "gross product originating," for output; Gullickson and Harper (1999) use the same data sources as we do, but make different adjustments for consistency and do not account for labor quality growth. Nonetheless, it is useful to compare broad trends over similar time periods to assess the robustness of our findings.

We first consider the ALP estimates from Corrado and Slifman (1999). We can compare similar time periods, but there are relatively few overlapping industries since our industry breakdown focuses on manufacturing industries, while they provide details primarily for service industries. For comparable industries, however, the results are quite similar. For seven industries with comparable definitions, five show differences in ALP growth of less than 0.25% when we compare our estimates for 1977-96 to Corrado and Slifman's estimates for 1977-97 (Corrado and Slifman (1999, Table 2).[52] Our ALP growth rates for Communication and Trade are below theirs by 1.3% and 0.4%, respectively, for these periods.

Our productivity estimates for 1977-92 for the majority of industries are similar to those of Gullickson and Harper (1999). The range of discrepancies is somewhat greater due to the difficulty of linking the various data sets needed to estimate intermediate inputs and industry productivity growth. For 7 of the 11 comparable industries productivity differences are below 0.5%, while we found larger discrepancies for Metal Mining, Coal Mining, Petroleum and Gas, and Services.[53] Similar differences can also be seen in Gullickson and Harper's comparison of productivity growth estimated from the BLS and BEA gross output series, where they find differences of 0.5 percentage points or more in 17 out of 40 industries and aggregates. Methodological differences, such as the inclusion of labor quality growth in our estimates of labor input growth, contribute to this divergence, as do different methods for linking data sets.

Neither Corrado and Slifman (1999) nor Gullickson and Harper (1999) break out ALP growth or industry productivity growth for detailed manufacturing industries. To gauge these results, we have compared our manufacturing results to the manufacturing industry estimates in BLS (1999). For the 18 industries that are

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[51]See Gullickson and Harper (1999), particularly pp. 55-56, for details.

[52]These five industries are Agriculture, Construction, Transportation, FIRE and Services. Note that our estimates for 1977-1996 are not given in Table 10.

[53]These seven other industries that are comparable are Agriculture, Nonmetallic Mining, Construction, Transportation, Communications, Trade, and FIRE.

comparable, ten showed productivity differences of less than 0.25% for 1979-96; two showed differences between 0.25% and 0.5%; and the remaining six industries, Textile Mills, Lumber and Wood, Petroleum Refining, Leather, Stone, Clay and Glass, and Instruments, showed differences greater than 0.5.[54]

iii) Domar Aggregation

We now turn to the aggregation of industry productivity growth described by Equation (9). This is not directly comparable to our estimates of aggregate productivity, due to different vintages of data and a broader definition of output. Nonetheless, it is useful to quantify an industry's contribution to aggregate TFP growth and to trace aggregate productivity growth back to its sources at the level of the individual industry. These results update the earlier estimates of Jorgenson, Gollop, and Fraumeni (1987). Gordon (1999b) presents a similar decomposition for ALP growth, although he focuses exclusively on the contribution from computer production.

We present our estimates of each industry's contribution to aggregate TFP growth for the period 1958-96 in Chart 11. This follows Equation (9) by weighting industry productivity growth by the "Domar weight," defined as industry gross output divided by aggregate value added. Summing across industries gives an estimate of aggregate TFP growth of 0.48 for 1958-96. This is lower than the number implied by Table 2 for two reasons. First, the data are prior to the BEA benchmark revision, which raised output and TFP growth. Second, these estimates include a broader output concept that includes Government Enterprises, which we estimate has negative industry productivity growth, and the General Government, which has zero productivity growth by definition. The estimate is consistent, however, with the estimates in Ho, Jorgenson, and Stiroh (1999) and Jorgenson and Stiroh (1999), which are based on the same vintage of data.

The most striking feature of Chart 11 is the wide range of industry contributions. Trade, Industrial Machinery, and Electronic Equipment make the largest contribution, although for different reasons. Trade has solid, but not exceptionally strong productivity growth of almost 1% per year, but makes the largest contribution due to its large relative size; Trade receives a Domar weight of nearly 0.20. Industrial Machinery and Electronic Equipment, on the other hand, make important contributions due to their rapid productivity growth, 1.5% and 2.0%, respectively, in spite of their relative small sizes with Domar weights of 0.05 and

[54]The 10 industries with small differences are Food Products, Apparel, Furniture and Fixtures, Paper Products, Printing and Publishing, Chemical Products, Primary Metals, Industrial and Commercial Machinery, Electronic and Electric Machinery, and Miscellaneous Manufacturing. The two industries with slightly larger differences are Rubber and Plastic, and Fabricated Metals.

0.04, respectively. An industry's contribution to aggregate productivity growth depends on both productivity performance and relative size.

Chart 11 also highlights the impact of the nine industries that experienced negative productivity growth over this period. Again, both performance and relative size matter. Services makes a negative contribution of 0.07 due to its large weight and productivity growth of –0.19%. Construction, on the other hand, shows even slower industry productivity growth, –0.44% per year, but makes a smaller negative contribution, since it is so much smaller than Services. We can also do a "thought experiment" similar to Corrado and Slifman (1999) and Gullickson and Harper (1999) and imagine that productivity growth is zero in these nine industries rather than negative. By zeroing out the negative contributions, we find aggregate TFP growth would have been 0.22% higher, an increase of nearly half.[55] Clearly, negative productivity growth in these industries is an important part of the aggregate productivity story.

Finally, these data enable us to provide some new perspective on an argument made by Gordon (1999b), who decomposes trend-adjusted ALP growth into a portion due to computer production and a residual portion for the rest of the economy.[56] He finds the former accounts for virtually all of the productivity acceleration since 1997. While we cannot comment directly on his empirical estimates since our industry data end in 1996 and we examine TFP growth rather than ALP growth, we can point to an important qualification to his argument. The U.S. economy is made up of industries with both positive and negative productivity growth rates, so that comparing one industry to the aggregate of all others necessarily involves aggregation over off-setting productivity trends. The fact that this aggregate does not show net productivity growth does not entail the absence of gains in productivity in any of the component industries, since these gains could be offset by declines in other industries.

Consider our results for 1958-96 and the importance of the negative contributions. The five industries with the largest, positive contributions—Trade, Electronic Equipment, Agriculture, Industrial Machinery, and Transport—cumulatively account for the sum across all industries, about 0.5% per year. Nonetheless, we find sizable productivity growth in some remaining industries that are offset by negative contributions in others. This logic and the prevalence of negative productivity growth rates at the industry level, in BLS (1999), Corrado and

[55]This aggregate impact is smaller than that estimated by Gullickson and Harper (1999), partly because our shares differ due to the inclusion of a Household and Government industry. Also, as pointed out by Gullickson and Harper, a complete re-estimation would account for the change in intermediate inputs implied by the productivity adjustments.

[56]Oliner and Sichel (2000) argue that Gordon's conclusion is weakened by the new NIPA data released in the benchmark revision, which allow a larger role for ALP growth outside of computer production.

Slifman (1999), and Gullickson and Harper (1999), suggest that a similar argument could hold for ALP and for the most recent period. This raises the question of whether off-setting productivity growth rates are responsible for Gordon's finding that there is "*no* productivity growth in the 99 percent of the economy located outside the sector which manufactures computer hardware (Gordon (1999b, pg. 1, italics in original))." Assessing the breadth of recent productivity gains and identifying the sources in productivity growth at the industry level remains an important question for future research.

V. CONCLUSIONS

The performance of the U.S. economy in the late 1990s has been nothing short of phenomenal. After a quarter century of economic malaise, accelerating total factor productivity growth and capital deepening have led to a remarkable growth resurgence. The pessimism of the famous Solow (1987) paradox, that we see computers everywhere but in the productivity statistics, has given way to optimism of the information age. The productivity statistics, beginning in 1995, have begun to reveal a clearly discernible impact of information technology. Both labor productivity and TFP growth have jumped to rates not seen for such an extended period of time since the 1960s. While a substantial portion of these gains can be attributed to computers, there is growing evidence of similar contributions from software and communications equipment—each equal in importance to computers.

The forces shaping the information economy originate in the rapid progress of semiconductor technology—Moore's Law at work. These gains are driving down relative prices of computers, software, and communications equipment and inducing massive investments in these assets by firms and households. Technological progress and the induced capital deepening are the primary factors behind accelerating output growth in recent years. The sustainability of recent growth trends therefore hinges to a great degree on prospects for continuing progress, especially in the production of semi-conductors. While this seems plausible and perhaps even likely, the contribution of high-tech assets to the growth resurgence remains subject to considerable uncertainty, owing to incomplete information on price trends for these assets.

The strong performance of the U.S. economy has not gone unnoticed. Forecasters have had to raise their projected growth rates and raise them again. The moderate speed limits set by Blinder (1997) and Krugman (1997), reflecting the best evidence available only a few years ago, have given way to the optimism of the ordinarily conservative community of official forecasters. Our review of the evidence now available suggests that the official forecasters are relying very heavily on a continuation of the acceleration in U.S. economic growth since 1995.

What are the risks to the optimistic view of future U.S. economic growth in the information age? Upward revision of growth projections seems a reasonable response as evidence accumulates of a possible break in trend productivity growth. Nonetheless, caution is warranted until productivity patterns have been observed for a longer time period. Should the pace of technological progress in high-tech industries diminish, economic growth would be hit with a double whammy—slower total factor productivity growth in important industries that produce high-tech equipment and slower capital accumulation in other sectors that invest in and use the high-tech equipment. Both factors have made an important contribution to the recent success of the U.S. economy, so that any slowdown would retard future growth potential.

At the same time we must emphasize that the uncertainty surrounding intermediate term projections has become much greater as a consequence of widening gaps in our knowledge, rather than changes in the volatility of economic activity. The excellent research that underlies estimates of prices and quantities of computer investment in NIPA has provided much needed illumination of the impact of information technology. But this is only part of the contribution of information technology to economic growth and may not be the largest part. As the role of technology continues to increase, ignorance of the most basic empirical facts about the information economy will plague researchers as well as forecasters. The uncertainties about past and future economic growth will not be resolved quickly. This is, of course, a guarantee that the lively economic debate now unfolding will continue for the foreseeable future.

The first priority for empirical research must be constant-quality price indexes for a wider variety of high-tech assets. These assets are becoming increasingly important in the U.S. economy, but only a small portion have constant-quality price deflators that translate the improved production characteristics into accurate measures of investment and output. This echoes the earlier findings of Gordon (1990), who reported that official price measures substantially overstate price changes for capital goods. In fact, Gordon identified computers and communications equipment as two assets with the largest overstatements, together with aircraft, which we have not included.[57] Much remains to be done to complete Gordon's program of implementing constant-quality price deflators for all components of investment in NIPA.

The second priority for research is to decompose the sources of economic growth to the industry level. Fortunately, the required methodology is well established and increasingly familiar. Domar aggregation over industries underlies back-of-the-envelope calculations of the contribution of information technology to economic growth in Section III, as well as the more careful and comprehensive view of the contributions of industry-level productivity that we have presented in Section IV. This view will require considerable refinement to discriminate among

[57]Gordon (1990), Table 12.3, p. 539.

alternative perspectives on the rapidly unfolding information economy. However, the evidence already available is informative on the most important issue. This is the "new economy" view that the impact of information technology is like phlogiston, an invisible substance that spills over into every kind of economic activity and reveals its presence by increases in industry-level productivity growth across the U.S. economy. This view is simply inconsistent with the empirical evidence.

Our results suggest that while technology is clearly the driving force in the growth resurgence, familiar economic principles can be applied. Productivity growth in the production of information technology is responsible for a sizable part of the recent spurt in TFP growth and can be identified with price declines in high-tech assets and semi-conductors. This has induced an eruption of investment in these assets that is responsible for capital deepening in the industries that use information technology. Information technology provides a dramatic illustration of economic incentives at work! However, there is no corresponding eruption of industry-level productivity growth in these sectors that would herald the arrival of phlogiston-like spillovers from production in the information technology sectors.

Many of the goods and services produced using high-tech capital may not be adequately measured, as suggested in the already classic paper of Griliches (1994). This may help to explain the surprisingly low productivity growth in many of the high-tech intensive, service industries. If the official data are understating both real investment in high-tech assets and the real consumption of commodities produced from these assets, the under-estimation of U.S. economic performance may be far more serious than we have suggested. Only as the statistical agencies continue their slow progress towards improved data and implementation of state-of-the art methodology will this murky picture become more transparent.

APPENDIX A - ESTIMATING OUTPUT

We begin with the National Income and Product Accounts (NIPA) as our primary source data. These data correspond to the most recent benchmark revision published by the Bureau of Economic Analysis (BEA) on October 29, 1999. These data provide measures of investment and consumption, in both current and chained 1996 dollars. The framework developed by Christensen and Jorgenson (1973), however, calls for a somewhat broader treatment of output than in the national accounts. Most important, consumers' durable goods are treated symmetrically with investment goods, since both are long-lived assets that are accumulated and provide a flow of services over their lifetimes. We use a rental price to impute a flow of consumers' durables services included in both consumption output and capital input. We also employ a rental price to make relatively small imputations for the service flows from owner-occupied housing and institutional equipment.

Table A-1 presents the time series of total output in current dollars and the corresponding price index from 1959-98. The table also includes the current dollar value and price index for information technology output components—computer investment, software investment, communications investments, computer and software consumption, and the imputed service flow of computer and software consumer durables—as described in Equation (4) in the text.

APPENDIX B - ESTIMATING CAPITAL SERVICES

i) Capital Services Methodology

We begin with some notation for measures of investment, capital stock, and capital services, for both individual assets and aggregates. For individual assets:

$I_{i,t}$ = quantity of investment in asset i at time t
$P_{i,t}$ = price of investment in asset i at time t
δ_i = geometric depreciation rate for asset i
$S_{i,t}$ = quantity of capital stock of asset i at time t
$P_{i,t}$ = price of capital stock of asset i at time t
$K_{i,t}$ = quantity of capital services from asset i at time t
$c_{i,t}$ = price of capital services from asset i at time t

where the i subscript refers to different types of tangible assets—equipment and structures, as well as consumers' durable assets, inventories, and land, all for time period t.

For economy-wide aggregates:

I_t = quantity index of aggregate investment at time t
$P_{I,t}$ = price index of aggregate investment at time t
S_t = quantity index of aggregate capital stock at time t
$P_{S,t}$ = price index of aggregate capital stock at time t
K_t = quantity index of aggregate capital services at time t
c_t = price of capital services at time t
$q_{K,t}$ = quality index of aggregate capital services at time t

Our starting point is investment in individual assets. We assume that the price index for each asset measures investment goods in identically productive "efficiency units" over time. For example, the constant-quality price deflators in the NIPA measure the large increase in computing power as a decline in price of computers.[58] Thus, a faster computer is represented by more $I_{i,t}$ in a given period and a larger accumulation of $S_{i,t}$, as measured by the perpetual inventory equation:

$$\text{(B}-1) \quad S_{i,t} = S_{i,t-1}(1-\delta_i) + I_{i,t} = \sum_{\tau=0}^{\infty}(1-\delta_i)^{\tau} I_{i,t-\tau}$$

where capital is assumed to depreciate geometrically at the rate δ_i .

Equation (B-1) has the familiar interpretation that the capital stock is the weighted sum of past investments, where weights are derived from the relative efficiency profile of capital of different ages. Moreover, since $S_{i,t}$ is measured in base-year efficiency units, the appropriate price for valuing the capital stock is simply the investment price deflator, $P_{i,t}$. Furthermore, $S_{i,t}$ represents the installed stock of capital, but we are interested in $K_{i,t}$, the flow of capital services from that stock over a given period. This distinction is not critical at the level of individual assets, but becomes important when we aggregate heterogeneous assets.

For individual assets, we assume the flow of capital services is proportional to the average of the stock available at the end of the current and prior periods:

$$\text{(B-2)} \quad K_{i,t} = q_i \frac{(S_{i,t} + S_{i,t-1})}{2}$$

where q_i denotes this constant of proportionality, set equal to unity. Note that this differs from our earlier work, e.g., Jorgenson (1990), Jorgenson and Stiroh (1999), and Ho, Jorgenson, and Stiroh (1999), where capital service flows were assumed proportional to the lagged stock for individual assets.

Our approach assumes any improvement in input characteristics, such as a faster processor in a computer, is incorporated into investment $I_{i,t}$, via deflation of the nominal investment series. That is, investment deflators transform recent vintages of assets into an equivalent number of efficiency units of earlier vintages. This is consistent with the perfect substitutability assumption across vintages and our use of the perpetual inventory method, where vintages differ in productive characteristics due to the age-related depreciation term.

We estimate a price of capital services that corresponds to the quantity flow of capital services via a rental price formula. In equilibrium, an investor is indifferent between two alternatives: earning a nominal rate of return, i_t, on a different

[58]See BLS (1997), particularly Chapter 14, for details on the quality adjustments incorporated into the producer prices indexes that are used as the primary deflators for the capital stock study. Cole et al. (1986) and Triplett (1986, 1989) provide details on the estimation of hedonic regressions for computers.

investment or buying a unit of capital, collecting a rental fee, and then selling the depreciated asset in the next period. The equilibrium condition, therefore, is:

$$\text{(B-3)} \quad (1+i_t)P_{i,t-1} = c_{i,t} + (1-\delta_i)P_{i,t}$$

and rearranging yields a variation of the familiar cost of capital equation:

$$\text{(B-4)} \quad c_{i,t} = (i_t - \pi_{i,t})P_{i,t-1} + \delta_i P_{i,t}$$

where the asset-specific capital gains term is $\pi_{i,t} = (P_{i,t} - P_{i,t-1})/\mathrm{P}_{\mathrm{i,t-1}}$.

This formulation of the cost of capital effectively includes asset-specific revaluation terms. If an investor expects capital gains on his investment, he will be willing to accept a lower service price. Conversely, investors require high service prices for assets like computers with large capital losses. Empirically, asset-specific revaluation terms can be problematic due to wide fluctuations in prices from period to period that can result in negative rental prices. However, asset-specific revaluation terms are becoming increasingly important as prices continue to decline for high-tech assets. Jorgenson and Stiroh (1999), for example, incorporated economy wide asset revaluation terms for all assets and estimated a relatively modest growth contribution from computers.

As discussed by Jorgenson and Yun (1991), tax considerations also play an important role in rental prices. Following Jorgenson and Yun, we account for investment tax credits, capital consumption allowances, the statutory tax rate, property taxes, debt/equity financing, and personal taxes, by estimating an asset-specific, after-tax real rate of return, $r_{i,t}$, that enters the cost of capital formula:

$$\text{(B-5)} \quad c_{i,t} = \frac{1 - ITC_{i,t} - \tau_t Z_{i,t}}{1-\tau_t}\left[r_{i,t}P_{i,t-1} + \delta_i P_{i,t}\right] + \tau_p P_{i,t-1}$$

where $ITC_{i,t}$ is the investment tax credit, τ_t is the statutory tax rate, $Z_{i,t}$ is the capital consumption allowance, τ_p is a property tax rate, all for asset i at time t, and $r_{i,t}$ is calculated as:

$$\text{(B-6)} \quad r_{i,t} = \beta\left[(1-\tau_t)i_t - \pi_{i,t}\right] + (1-\beta)\left[\frac{\rho_t - \pi_{i,t}(1-t_q^g)}{(1-t_q^e)\alpha + (1-t_q^g)(1-\alpha)}\right]$$

where β is the debt/capital ratio, i_t is the interest cost of debt, ρ_t is the rate of return to equity, α is the dividend payout ratio, and t_q^g and t_q^e are the tax rates on capital gains and dividends, respectively. $\pi_{i,t}$ is the inflation rate for asset *i*, which allows $r_{i,t}$ to vary across assets.[59]

Equations (B-1) through (B-6) describe the estimation of the price and quantity of capital services for individual assets: $P_{i,t}$ and $I_{i,t}$ for investment; $P_{i,t}$ and $S_{i,t}$ for capital stock; and $c_{i,t}$ and $K_{i,t}$ for capital services. For an aggregate production function analysis, we require an aggregate measure of capital services, $K_t = f(K_{1,t}, K_{2,t}, \ldots K_{n,t})$, where *n* includes all types of reproducible fixed assets, consumers' durable assets, inventories, and land. We employ quantity indexes to generate aggregate capital services, capital stock, and investment series.[60]

The growth rate of aggregate capital services is defined as a share-weighted average of the growth rate of the components:

$$\text{(B-7)} \quad \Delta \ln K_t = \sum_i \bar{v}_{i,t} \Delta \ln K_{i,t}$$

where weights are value shares of capital income:

$$\text{(B-8)} \quad \bar{v}_{i,t} = \frac{1}{2}\left(\frac{c_{i,t} K_{i,t}}{\sum_i c_{i,t} K_{i,t}} + \frac{c_{i,t-1} K_{i,t-1}}{\sum_i c_{i,t-1} K_{i,t-1}} \right)$$

and the price index of aggregate capital services is defined as:

$$\text{(B-9)} \quad c_t = \frac{\sum_i c_{i,t} K_{i,t}}{K_t}$$

Similarly, the quantity index of capital stock is given by:

$$\text{(B-10)} \quad \Delta \ln S_t = \sum_i \bar{w}_{i,t} \Delta \ln S_{i,t}$$

where the weights are now value shares of the aggregate capital stock:

[59]A complication, of course, is that ρ_t is endogenous. We assume the after-tax rate of return to all assets is the same and estimate ρ_t as the return that exhausts the payment of capital across all assets in the corporate sector. In addition, tax considerations vary across ownership classes, e.g., corporate, non-corporate, and household. We account for these differences in our empirical work, but do not go into details here. See Jorgenson and Yun (1991, Chapter 2).

[60]See Diewert (1980) and Fisher (1992) for details.

$$\text{(B-11)} \quad \overline{w}_{i,t} = \frac{1}{2}\left(\frac{P_{i,t}S_{i,t}}{\sum_i P_{i,t}S_{i,t}} + \frac{P_{i,t-1}S_{i,t-1}}{\sum_i P_{i,t-1}S_{i,t-1}}\right)$$

and the price index for the aggregate capital stock index is:

$$\text{(B-12)} \quad P_{s,t} = \frac{\sum_i P_{i,t}S_{i,t}}{S_t}$$

Finally, the aggregate quantity index of investment is given by:

$$\text{(B-13)} \quad \Delta \ln I_t = \sum_i \overline{u}_{i,t} \Delta \ln I_{i,t}$$

where the weights are now value shares of aggregate investment:

$$\text{(B-14)} \quad \overline{u}_{i,t} = \frac{1}{2}\left(\frac{P_{i,t}I_{i,t}}{\sum_i P_{i,t}I_{i,t}} + \frac{P_{i,t-1}I_{i,t-1}}{\sum_i P_{i,t-1}I_{i,t-1}}\right)$$

and the price index for the aggregate investment index is:

$$\text{(B-15)} \quad P_{I,t} = \frac{\sum_i P_{i,t}I_{i,t}}{I_t}$$

The most important point from this derivation is the difference between the growth rate of aggregate capital services, Equation (B-7), and the growth rate of capital stock, Equation (B-10); this reflects two factors. First, the weights are different. The index of aggregate capital services uses rental prices as weights, while the index of aggregate capital stock uses investment prices. Assets with rapidly falling asset prices will have relatively large rental prices. Second, as can be seen from Equation (B-2), capital services are proportional to a two-period average stock, so the timing of capital services growth and capital stock growth differ for individual assets. In steady-state with a fixed capital to output ratio, this distinction is not significant, but if asset accumulation is either accelerating or decelerating, this timing matters.

A second point to emphasize is that we can define an "aggregate index of capital quality," $q_{K,t}$, analogously to Equation (B-2). We define the aggregate index of capital quality as $q_{K,t} = Kt/((S_t+S_{t-1})/2)$, and it follows that the growth of capital quality is defined as:

$$\text{(B-16)} \quad \Delta \ln q_{K,t} = \Delta \ln K_t - \Delta \ln\left(\frac{(S_t + S_{t-1})}{2}\right) = \sum_i \left(\overline{v}_{i,t} - \overline{w}_{i,t}\right) \Delta \ln\left(\frac{(S_{t,i} + S_{t-1,i})}{2}\right)$$

Equation (B-16) defines growth in capital quality as the difference between the growth in capital services and the growth in average capital stock. This difference reflects substitution towards assets with relatively high rental price weights and high marginal products. For example, the rental price for computers is declining rapidly as prices fall, which induces substitution towards computers and rapid capital accumulation. However, the large depreciation rate and large negative revaluation term imply that computers have a high marginal product, so their rental price weight greatly exceeds their asset price weight. Substitution towards assets with higher marginal products is captured by our index of capital quality.

ii) Investment and Capital Data

Our primary data source for estimating aggregating the flow of capital services is the "Investment Estimates of Fixed Reproducible Tangible Wealth, 1925-1997" (BEA (1998b, 1998c)). These data contain historical cost investment and chain-type quantity indices for 47 types of non-residential assets, 5 types of residential assets, and 13 different types of consumers' durable assets from 1925 to 1997. Table B-1 shows our reclassification of the BEA data into 52 non-residential assets, 5 residential assets, and 13 consumers' durable assets.[61]

Table B-2 presents the value and price index of the broadly defined capital stock, as well as individual information technology assets. Table B-3 presents similar data, but for capital service flows rather than capital stocks.[62] The price of capital stocks for individual assets in Table B-2 is the same as the investment price in Table A-1, but the prices differ for aggregates due to differences between weights based on investment flows and those based on asset stocks. The price index for investment grows more slowly than the price index for assets, since short-lived assets with substantial relative price declines are a greater proportion of investment.

[61]Katz and Herman (1997) and Fraumeni (1997) provide details on the BEA methodology and underlying data sources.

[62]Note that these price indices have been normalized to equal 1.0 in 1996, so they do not correspond to the components of the capital service formula in Equation (B-5).

An important caveat about the underlying investment data is that it runs only through 1997 and is not consistent with the BEA benchmark revision in October 1999. We have made several adjustments to reflect the BEA revision, make the data consistent with our earlier work, and extend the investment series to 1998. First, we have removed the Tangible Wealth series on "computers and peripherals equipment" and replaced it with the NIPA investment series for "computers and peripherals equipment," in both current and chained 1996 dollars. These series were identical in the early years and differed by about 5% in current dollars in 1997. Similarly, we used the new NIPA series for investment in "software," "communications equipment," and for personal consumption of "computers, peripherals, and software" in both current and chained 1996 dollars. These NIPA series enable us to maintain a complete and consistent time series that incorporates the latest benchmark revisions and the expanded output concept that includes software.

Second, we have combined investment in residential equipment with "other equipment," a form of non-residential equipment. This does not change the investment or capital stock totals, but reallocates some investment and capital from the residential to the non-residential category.

Third, we control the total value of investment in major categories—structures, equipment and software, residential structures, and total consumers' durables—to correspond with NIPA aggregates. This adjustment maintains a consistent accounting for investment and purchases of consumers' durables as inputs and outputs. Computer investment, software investment, communications investment, and consumption of computers, peripherals, and software series are not adjusted.

Fourth, we extended the investment series through 1998 based on NIPA estimates. For example, the 1998 growth rate for other fabricated metal products, steam engines, internal combustion engines, metalworking machinery, special industry machinery, general industrial equipment, and electrical transmission and distribution equipment was taken from the "other" equipment category in NIPA. The growth rate of each type of consumers' durables was taken directly from NIPA.

These procedures generated a complete time series of investment in 57 private assets (29 types of equipment and software, 23 types of non-residential structures, and 5 types of residential structures) and consumption of 13 consumers' durable assets in both current dollars and chained-1996 dollars from 1925 to 1998. For each asset, we created a real investment series by linking the historical cost investment and the quantity index in the base-year 1996. Capital stocks were then estimated using the perpetual inventory method in Equation (B-1) and a geometric depreciation rate, based on Fraumeni (1997) and reported in Table B-1.

Important exceptions are the depreciation rates for computers, software, and autos. BEA (1998a) reports that computer depreciation is based on the work of

Oliner (1993, 1994), is nongeometric, and varies over time. We estimated a best-geometric approximation to the latest depreciation profile for different types of computer assets and used an average geometric depreciation rate of 0.315, which we used for computer investment, software investment, and consumption of computers, peripherals, and software. Similarly, we estimated a best geometric approximation to the depreciation profile for autos of 0.272.

We also assembled data on investment and land to complete our capital estimates. The inventory data come primarily from NIPA in the form of farm and non-farm inventories. Inventories are assumed to have a depreciation rate of zero and do not face an investment tax credit or capital consumption allowance, so the rental price formula is a simplified version of Equation (B-5).

Data on land are somewhat more problematic. Through 1995, the Federal Reserve Board published detailed data on land values and quantities in its "Balance Sheets for the U.S. Economy" study (Federal Reserve Board (1995, 1997)), but the underlying data became unreliable and are no longer published. We use the limited land data available in the "Flow of Funds Accounts of the United States" and historical data described in Jorgenson (1990) to estimate a price and a quantity of private land. As a practical matter, this quantity series varies very little, so its major impact is to slow the growth of capital by assigning a positive weight to the zero growth rate of land. Like inventories, depreciation, the investment tax credit, and capital consumption allowances for land are zero.

A final methodological detail involves negative service prices that sometimes result from the use of asset-specific revaluation terms. As can be seen from the simplified cost of capital formula in Equation (B-5), an estimated service price can be negative if asset inflation is high relative to the interest and depreciation rates. Economically, this is possible, implying capital gains were higher than expected. Negative service prices make aggregation difficult so we made adjustments for several assets. In a small number of cases for reproducible assets and inventories, primarily structures in the 1970s, we used smoothed inflation for surrounding years rather than the current inflation in the cost of capital calculation. For land, which showed large capital gains throughout and has no depreciation, we used the economy-wide rate of asset inflation for all years.

APPENDIX C - ESTIMATING LABOR INPUT

i) Labor Input Methodology

We again begin with some notation for measures of hours worked, labor inputs, and labor quality for worker categories:

$H_{j,t}$ = quantity of hours worked by worker category j at time t
$w_{j,t}$ = price of an hour worked by worker category j at time t

$L_{j,t}$ = quantity of labor services from worker category j at time t and for economy-wide aggregates:
H_t = quantity of aggregate hours worked at time t
W_t = average wage of hours worked at time t
L_t = quantity index of labor input at time t
$P_{L,t}$ = price index of labor input at time t
$q_{L,t}$ = quality index of labor input at time t

In general, the methodology for estimating labor input parallels capital services, but the lack of an investment-type variable makes the labor input somewhat more straightforward. For each individual category of worker, we begin by assuming the flow of labor service is proportional to hours worked:

$$\text{(C-1)} \quad L_{j,t} = q_{L,j} H_{j,t}$$

where $q_{L,j}$ is the constant of proportionality for worker category j, set equal to unity.

The growth rate of aggregate labor input is defined as the share-weighted aggregate of the components as:

$$\text{(C-2)} \quad \Delta \ln L_t = \sum_j \bar{v}_{j,t} \Delta \ln L_{j,t}$$

where weights are value shares of labor income:

$$\text{(C-3)} \quad \bar{v}_{j,t} = \frac{1}{2}\left(\frac{w_{j,t} L_{j,t}}{\sum_j w_{j,t} L_{j,t}} + \frac{w_{j,t-1} L_{j,t-1}}{\sum_j w_{j,t-1} L_{j,t-1}} \right)$$

and the price of aggregate labor input is defined as:

$$\text{(C-4)} \quad P_{L,t} = \frac{\sum_j w_{j,t} L_{j,t}}{L_t}$$

We define the "aggregate index of labor quality", $q_{L,t}$, $q_{L,t} = L_t / H_t$, where H_t is the unweighted sum of labor hours:

$$\text{(C-5)} \quad H_t = \sum_j H_{j,t}$$

The growth in labor quality is then defined as:

$$(\text{C-6}) \quad \Delta \ln q_{L,t} = \sum_j \bar{v}_{j,t} \Delta \ln H_{j,t} - \Delta \ln H_t$$

Equation (C-6) defines growth in labor quality as the difference between weighted and unweighted growth in labor hours. As with capital, this reflects substitutions among heterogeneous types of labor with different characteristics and different marginal products. As described by Ho and Jorgenson (1999), one can further decompose labor quality into components associated with different characteristics of labor, such as age, sex, and education.

ii) Labor Data

Our primary data sources are individual observations from the decennial Censuses of Population for 1970, 1980, and 1990, the NIPA, and the annual Current Population Survey (CPS). The NIPA provides totals for hours worked and the Census and CPS allow us to estimate labor quality growth. Details on the construction of the labor data are in Ho and Jorgenson (1999). Table C-1 reports the primary labor used in this study, including the price, quantity, value, and quality of labor input, as well as employment, weekly hours, hourly compensation, and hours worked.

Briefly, the Censuses of Population provide detailed data on employment, hours, and labor compensation across demographic groups in census years. The CPS data are used to interpolate similar data for intervening years and the NIPA data provide control totals. The demographic groups include 168 different types of workers, cross-classified by sex (male, female), class (employee, self-employed or unpaid), age (16-17, 18-24, 25-34, 45-54, 55-64, 65+), and education (0-8 years grade school, 1-3 years high school, 4 years high school, 1-3 years college, 4 years college, 5+ years college).[63] Adjustments to the data include allocations of multiple job-holders, an estimation procedure to recover "top-coded" income data, and bridging to maintain consistent definitions of demographic groups over time.

These detailed data cover 1959 to 1995 and are taken from Ho and Jorgenson (1999). This allows us to estimate the quality of labor input for the private business sector, general government, and government enterprises, where only the private business sector index is used in the aggregate growth accounting results. For the years 1996-98, we estimate labor quality growth by holding relative wages across labor types constant, and incorporating demographic projections for the labor force. Hours worked by employees are taken from the latest data in the NIPA; hours worked by the self-employed are estimated by Ho and Jorgenson (1999).

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[63]There is also an industry dimension, which we do not exploit in this aggregate framework, but is used in the industry productivity analysis discussed below.

APPENDIX D - ESTIMATING INDUSTRY-LEVEL PRODUCTIVITY

Our primary data are annual time series of inter-industry transactions in current and constant prices, including final demands by commodity, investment and labor inputs by industry, and output by industry. The first building block is a set of inter-industry transactions produced by the Employment Projections Office at the Bureau of Labor Statistics (BLS). These data report intermediate inputs and total value-added (the sum of capital and labor inputs and taxes) for 185 industries from 1977 to 1995. A major advantage of this BLS inter-industry data is that they provide the necessary interpolations between benchmark years.

We aggregate the data from the "Make" and "Use" tables to generate inter-industry transactions for 35 private business industries at approximately the two-digit Standard Industrial Classification (SIC) level. These tables enable us to generate growth rates of industry outputs, growth rates of intermediate inputs, and shares of intermediate inputs as needed in Equation (29). They also provide control totals for value-added in each industry, the sum of the values of capital and labor services and taxes.

Estimation of capital services and labor input follows the procedures described above for each industry. We collected information from three sources to estimate prices and quantities of capital and labor inputs by industry. An industry-level breakdown of the value of capital and labor input is available in the "gross product originating" series described in Lum and Yuskavage (1997) of the BEA. Investments by asset classes and industries are from the BEA Tangible Wealth Survey (BEA (1998a), described by Katz and Herman (1997)). Labor data across industries are from the decennial Census of Population and the annual Current Population Survey. We use the prices and quantities of labor services for each industry constructed by Ho and Jorgenson (1999).

We also generate capital and labor services for a Private Household sector and the Government sector.[64] For Private Households, the value of labor services equals labor income in BLS's private household industry, while capital income reflects the imputed flow of capital services from residential housing, consumers' durables, and household land as described above. For Government, labor income equals labor compensation of general government employees and capital income is an estimate flow of capital services from government capital.[65] Note Government Enterprises are treated as a private business industry and are separate from the General Government.

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[64]The Private Household and Government sectors include only capital and labor as inputs. Output in these sectors is defined via a Tornqvist index of capital and labor inputs, so productivity growth is zero by definition.

[65]BEA includes a similar imputation for the flow of government capital services in the national accounts, but our methodology includes a return to capital, as well as depreciation as estimated by BEA.

APPENDIX E - EXTRAPOLATION FOR 1999

Table 2 presents primary growth accounting results through 1998 and preliminary estimates for 1999. The data through 1998 are based on the detailed methodology described in Appendixes A-D; the 1999 data are extrapolated based on currently available data and recent trends.

Our approach for extrapolating growth accounting results through 1999 was to estimate 1999 shares and growth rates for major categories like labor, capital, and information technology components, as well as the growth in output. The 1999 labor share was estimated from 1995-98 data, hours growth are from BLS (2000), and labor quality growth came from the projections described above. The 1999 growth rates of information technology outputs were taken from the NIPA, and shares were estimated from 1995-98 data. The 1999 growth rates of information technology inputs were estimated from recent investment data and the perpetual inventory method, and shares were estimated from 1995-98 data. The 1999 growth of other capital were estimates from NIPA investment data for broad categories like equipment and software, nonresidential structures, residential structures, as well as consumers' durable purchases; the income share was calculated from the estimated labor share. Output growth was estimated from growth in BLS business output and BEA GDP, with adjustment made for different output concepts. Finally, TFP growth for 1999 was estimated as the difference in the estimated output growth and share-weighted input growth.

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TABLE 1 Average Growth Rates of Selected Outputs and Inputs

	1990–95		1995–98	
	Prices	Quantities	Prices	Quantities
Outputs				
Private Domestic Output (Y)	1.70	2.74	1.37	4.73
Other (Y_n)	2.01	2.25	2.02	3.82
Computer and Software Consumption (C_c)	–21.50	38.67	–36.93	49.26
Computer Investment (I_c)	–14.59	24.89	–27.58	38.08
Software Investment (I_s)	–1.41	11.59	–2.16	15.18
Communications Investment (I_m)	–1.50	6.17	–1.73	12.79
Computer and Software CD Services (D_c)	–19.34	34.79	–28.62	44.57
Inputs				
Total Capital Services (K)	0.60	2.83	2.54	4.80
Other (K_n)	1.00	1.78	4.20	2.91
Computer Capital (K_c)	–10.59	18.16	–20.09	34.10
Software Capital (K_s)	–2.07	13.22	–0.87	13.00
Communications Capital (K_m)	3.10	4.31	–7.09	7.80
Total Consumption Services (D)	1.98	2.91	–0.67	5.39
Non-Computer and Software (D_n)	2.55	2.07	0.54	3.73
Computer and Software CD Services (D_c)	–19.34	34.79	–28.62	44.57
Labor (L)	2.92	2.01	2.80	2.81

Notes: CD refers to consumers' durable assets. All values are percentages.

TABLE 2 Growth in U.S. Private Domestic Output and the Sources of Growth, 1959-99

	1959-98	1959-73	1973-90	1990-95	1995-98	Preliminary* 1995-99
Growth in Private Domestic Output Growth (Y)	3.630	4.325	3.126	2.740	4.729	4.763
Contribution of Selected Output Components						
Other (Y_n)	3.275	4.184	2.782	2.178	3.659	3.657
Computer and Software Consumption (C_c)	0.035	0.000	0.023	0.092	0.167	0.175
Computer Investment (I_c)	0.150	0.067	0.162	0.200	0.385	0.388
Software Investment (I_s)	0.074	0.025	0.075	0.128	0.208	0.212
Communications Investment (I_m)	0.060	0.048	0.061	0.053	0.122	0.128
Computer and Software CD Services (D_c)	0.036	0.000	0.023	0.089	0.187	0.204
Contribution of Capital Services (K)	1.260	1.436	1.157	0.908	1.611	1.727
Other (K_n)	0.936	1.261	0.807	0.509	0.857	0.923
Computers (K_c)	0.177	0.086	0.199	0.187	0.458	0.490
Software (K_s)	0.075	0.026	0.071	0.154	0.193	0.205
Communications (K_m)	0.073	0.062	0.080	0.058	0.104	0.109
Contribution of CD Services (D)	0.510	0.632	0.465	0.292	0.558	0.608
Other (D_n)	0.474	0.632	0.442	0.202	0.370	0.403
Computers and Software (D_c)	0.036	0.000	0.023	0.089	0.187	0.204
Contribution of Labor (L)	1.233	1.249	1.174	1.182	1.572	1.438
Aggregate Total Factor Productivity (TFP)	0.628	1.009	0.330	0.358	0.987	0.991
Growth of Capital and CD Services	4.212	4.985	3.847	2.851	4.935	5.286
Growth of Labor Input	2.130	2.141	2.035	2.014	2.810	2.575
Contribution of Capital and CD Quality	0.449	0.402	0.405	0.434	0.945	1.041
Contribution of Capital and CD Stock	1.320	1.664	1.217	0.765	1.225	1.293
Contribution of Labor Quality	0.315	0.447	0.200	0.370	0.253	0.248
Contribution of Labor Hours	0.918	0.802	0.974	0.812	1.319	1.190
Average Labor Productivity (ALP)	2.042	2.948	1.437	1.366	2.371	2.580

Notes: A contribution of an output and an input is defined as the share-weighted, real growth rate. CD refers to consumers' durable assets. All values are percentages. 1995-99 results include preliminary estimates for 1999; see the Appendix for details on estimation and data sources.

TABLE 3 The Sources of ALP Growth 1959-98

Variable	1959-98	1959-73	1973-90	1990-95	1995-98
Growth of Private Domestic Output (Y)	3.630	4.325	3.126	2.740	4.729
Growth in Hours (H)	1.588	1.377	1.689	1.374	2.358
Growth in ALP (Y/H)	2.042	2.948	1.437	1.366	2.371
ALP Contribution of Capital Deepening	1.100	1.492	0.908	0.637	1.131
ALP Contribution of Labor Quality	0.315	0.447	0.200	0.370	0.253
ALP Contribution of TFP	0.628	1.009	0.330	0.358	0.987

Notes: ALP Contributions are defined in Equation (3). All values are percentages.

TABLE 4 FOLLOWS

TABLE 4 Impact of Alternative Deflation of Software and Communications Equipment on the Sources of U.S. Economic Growth, 1959-98

	Base Case				Moderate P
	1959-73	1973-90	1990-95	1995-98	1959-73
Growth in Private Domestic Output Growth (Y)	4.33	3.13	2.74	4.73	4.35
Contribution of Selected Output Components					
Other (Y_n)	4.18	2.78	2.18	3.66	4.12
Computer and Software Consumption (C_c)	0.00	0.02	0.09	0.17	0.00
Computer Investment (I_c)	0.07	0.16	0.20	0.39	0.07
Software Investment (I_s)	0.03	0.08	0.13	0.21	0.04
Communications Investment (I_m)	0.05	0.06	0.05	0.12	0.12
Computer and Software CD Services (D_c)	0.00	0.02	0.09	0.19	0.00
Contribution of Capital Services (K)	1.44	1.16	0.91	1.61	1.54
Other (K_n)	1.26	0.81	0.51	0.86	1.25
Computers (K_c)	0.09	0.20	0.19	0.46	0.09
Software (K_s)	0.03	0.07	0.15	0.19	0.05
Communications (K_m)	0.06	0.08	0.06	0.10	0.16
Contribution of CD Services (D)	0.63	0.47	0.29	0.56	0.63
Non-Computers and Software (D_n)	0.63	0.44	0.20	0.37	0.63
Computers and Software (D_c)	0.00	0.02	0.09	0.19	0.00
Contribution of Labor (L)	1.25	1.17	1.18	1.57	1.25
Aggregate Total Factor Productivity (TFP)	1.01	0.33	0.36	0.99	0.94
Growth of Capital and CD Services	4.99	3.85	2.85	4.94	5.24
Growth of Labor Input	2.14	2.04	2.01	2.81	2.14
Contribution of Capital and CD Quality	0.40	0.41	0.43	0.95	0.48
Contribution of Capital and CD Stock	1.66	1.22	0.77	1.23	1.68
Contribution of Labor Quality	0.45	0.20	0.37	0.25	0.45
Contribution of Labor Hours	0.80	0.97	0.81	1.32	0.80
Average Labor Productivity (ALP)	2.95	1.44	1.37	2.37	2.98

Notes: Base Case uses official NIPA price data. Moderate Price Decline uses pre-packaged software deflator for all software and annual price changes of –10.7% for communications equipment. Rapid Price Decline uses annual price changes of –16% for software and –17.9% for communications equipment. See text for details and sources. A contribution is defined as the share-weighted, real growth rate. CD refers to consumers' durable assets. All values are percentages.

ations

	Moderate Price Decline				Rapid Price Decline			
1995-98	1959-73	1973-90	1990-95	1995-98	1959-73	1973-90	1990-95	1995-98
4.73	4.35	3.30	2.90	4.89	4.36	3.38	3.03	5.07
3.66	4.12	2.76	2.17	3.66	4.08	2.75	2.16	3.66
0.17	0.00	0.02	0.09	0.17	0.00	0.02	0.09	0.17
0.39	0.07	0.16	0.20	0.39	0.07	0.16	0.20	0.39
0.21	0.04	0.14	0.22	0.29	0.05	0.17	0.29	0.40
0.12	0.12	0.19	0.13	0.21	0.16	0.25	0.19	0.27
0.19	0.00	0.02	0.09	0.19	0.00	0.02	0.09	0.19
1.61	1.54	1.39	1.15	1.83	1.61	1.51	1.32	2.09
0.86	1.25	0.80	0.51	0.86	1.25	0.79	0.51	0.85
0.46	0.09	0.20	0.19	0.46	0.09	0.20	0.19	0.46
0.19	0.05	0.15	0.28	0.29	0.06	0.18	0.36	0.45
0.10	0.16	0.25	0.18	0.23	0.22	0.34	0.27	0.33
0.56	0.63	0.46	0.29	0.56	0.63	0.46	0.29	0.56
0.37	0.63	0.44	0.20	0.37	0.63	0.44	0.20	0.37
0.19	0.00	0.02	0.09	0.19	0.00	0.02	0.09	0.19
1.57	1.25	1.17	1.18	1.57	1.25	1.18	1.18	1.57
0.99	0.94	0.27	0.27	0.93	0.88	0.22	0.23	0.85
4.94	5.24	4.40	3.43	5.44	5.41	4.70	3.84	6.02
2.81	2.14	2.04	2.01	2.81	2.14	2.04	2.01	2.81
0.95	0.48	0.59	0.63	1.11	0.54	0.70	0.78	1.34
1.23	1.68	1.26	0.82	1.28	1.69	1.27	0.84	1.31
0.25	0.45	0.20	0.37	0.25	0.45	0.20	0.37	0.25
1.32	0.80	0.97	0.81	1.32	0.80	0.98	0.81	1.32
2.37	2.98	1.61	1.52	2.53	2.99	1.69	1.65	2.72

TABLE 5 Information Technology Decomposition of TFP Growth for Alternative Deflation Cases, 1990–98

	Base Case		Moderate Price Decline		Rapid Price Decline	
	1990-95	1995-98	1990-95	1995-98	1990-95	1995-98
Aggregate TFP Growth	0.36	0.99	0.27	0.93	0.23	0.85
TFP Contribution						
Information Technology	0.25	0.44	0.46	0.64	0.64	0.86
Computers	0.16	0.32	0.16	0.32	0.16	0.32
Software	0.05	0.08	0.17	0.18	0.28	0.34
Communications	0.04	0.04	0.13	0.13	0.21	0.20
Non–Information Technology	0.11	0.55	–0.19	0.29	–0.41	–0.01
Relative Price Change						
Computers	–16.6	–29.6	–16.6	–29.6	–16.6	–29.6
Software	–3.4	–4.2	–11.3	–9.7	–18.0	–18.0
Communications	–3.5	–3.8	–12.7	–12.7	–19.9	–19.9
Average Nominal Share						
Computers	0.96	1.09	0.96	1.09	0.96	1.09
Software	1.54	1.88	1.54	1.88	1.54	1.88
Communications	1.05	1.02	1.05	1.02	1.05	1.02

Notes: Base Case uses official NIPA price data. Moderate Price Decline uses pre–packaged software deflator for all software and –10.7% for communications equipment. Rapid Price Decline uses –16% for software and –17.9% for communications equipment. See text for details and sources. A TFP contribution is defined as the shareweighted, growth rate of relative prices.

TABLE 6 FOLLOWS

TABLE 6 Growth Rates of Output, Inputs, and Total Factor Productivity: Comparison of BLS, CBO, and Jorgenson-Stiroh

	BLS Nonfarm Bus	CBO Overall Econmy			CBO Nonfarm E
	1990-99	1980-90	1990-99	1999-2010	1980-90
Real Output	3.74	3.0	2.9	3.1	3.2
Labor Input					
Hours Worked	1.68	1.6	1.2	1.1	1.6
Labor Quality					
Capital Input					3.6
TFP - not adjusted for labor quality					0.9
TFP - adjusted for labor quality					
ALP	2.06	1.4	1.7	1.9	1.5

Note: CBO estimates refer to "potential" series that are adjusted for business cycle effects. Growth rates do not exactly match Table 5 since discrete growth rate are used here for consistency with CBO's methodology. Hours worked for CBO Overall Economy refers to potential labor force.

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	CBO Nonfarm Business			Jorgenson-Stiroh	
1999-2010	1980-90	1990-99	1999-2010	1980-90	1990-98
3.1	3.2	3.4	3.5	3.48	3.55
				2.14	2.34
1.1	1.6	1.5	1.2	1.81	1.76
				0.33	0.58
	3.6	3.6	4.4	3.57	3.68
	0.9	1.2	1.4	0.91	0.97
				0.73	0.63
1.9	1.5	1.9	2.3	1.67	1.79

TABLE 7 1996 Value-Added and Gross Output by Industry

Industry	SIC Codes	Value-Added	Gross Output
Agriculture	01-02, 07-09	133.3	292.2
Metal Mining	10	8.8	10.7
Coal Mining	11-12	14.7	21.1
Petroleum and Gas	13	57.4	83.3
Nonmetallic Mining	14	10.5	17.0
Construction	15-17	336.0	685.5
Food Products	20	147.2	447.6
Tobacco Products	21	26.7	32.7
Textile Mill Products	22	19.9	58.9
Apparel and Textiles	23	40.7	98.5
Lumber and Wood	24	34.2	106.7
Furniture and Fixtures	25	23.4	54.5
Paper Products	26	68.3	161.0
Printing and Publishing	27	113.5	195.6
Chemical Products	28	184.0	371.2
Petroleum Refining	29	44.7	184.3
Rubber and Plastic	30	64.1	148.9
Leather Products	31	3.4	8.1
Stone, Clay, and Glass	32	40.4	79.1
Primary Metals	33	57.6	182.1
Fabricated Metals	34	98.4	208.8
Industrial Machinery and Equipment	35	177.8	370.5
Electronic and Electric Equipment	36	161.9	320.4
Motor Vehicles	371	84.9	341.6
Other Transportation Equipment	372-379	68.0	143.8
Instruments	38	81.3	150.0
Miscellaneous Manufacturing	39	24.8	49.3
Transport and Warehouse	40-47	258.6	487.7
Communications	48	189.7	315.8
Electric Utilities	491, 493	111.8	186.7
Gas Utilities	492, 493, 496	32.9	57.9
Trade	50-59	1,201.2	1,606.4
FIRE	60-67	857.8	1,405.1
Services	70-87, 494-495	1,551.9	2,542.8
Goverment Enterprises		95.2	220.2
Private Households	88	1,248.4	1,248.4
General Government		1,028.1	1,028.1

Note: All values are in current dollars. Value-added refers to payments to capital and labor; Gross output includes payments for intermediate inputs.

TABLE 8 FOLLOWS

TABLE 8 Sources of U.S. Economic Growth by Industry, 1958–96

Industry	Output Growth	Contributions of Inputs				Productivity Growth	ALP Growth	Domar Weight
		Capital	Labor	Energy	Materials			
Agriculture	1.70	0.19	–0.13	–0.04	0.51	1.17	3.21	0.062
Metal Mining	0.78	0.73	–0.07	–0.07	–0.26	0.44	0.99	0.003
Coal Mining	2.35	0.82	0.00	0.06	0.63	0.84	2.32	0.005
Petroleum and Gas	0.43	0.61	–0.01	0.06	0.20	–0.44	0.88	0.022
Nonmetallic Mining	1.62	0.59	0.18	0.06	0.34	0.46	1.52	0.003
Construction	1.43	0.07	0.87	0.02	0.91	–0.44	–0.38	0.113
Food Products	2.20	0.21	0.18	0.00	1.27	0.54	1.59	0.076
Tobacco Products	0.43	0.59	0.05	0.00	–0.01	–0.20	0.88	0.004
Textile Mill Products	2.23	0.12	0.02	0.01	0.86	1.23	2.54	0.013
Apparel and Textiles	2.03	0.24	0.17	0.00	0.82	0.80	2.01	0.022
Lumber and Wood	2.24	0.21	0.33	0.02	1.70	–0.02	1.55	0.015
Furniture and Fixtures	2.91	0.31	0.58	0.02	1.44	0.56	1.78	0.007
Paper Products	2.89	0.50	0.40	0.05	1.51	0.42	1.96	0.022
Printing and Publishing	2.51	0.55	1.20	0.02	1.19	–0.44	0.14	0.024
Chemical Products	3.47	0.74	0.47	0.09	1.58	0.58	2.02	0.048
Petroleum Refining	2.21	0.44	0.24	0.49	0.71	0.33	0.80	0.033
Rubber and Plastic	5.17	0.47	1.16	0.08	2.43	1.04	1.94	0.016

Leather Products	–2.06	–0.11	–1.13	–0.02	–1.08	0.28	2.08	0.004
Stone, Clay, and Glass	1.86	0.26	0.37	0.00	0.82	0.41	1.30	0.014
Primary Metals	1.14	0.13	0.05	–0.03	0.77	0.22	1.51	0.040
Fabricated Metals	2.28	0.26	0.28	0.00	1.09	0.65	1.88	0.035
Industrial Machinery and Equipment	4.79	0.52	0.75	0.02	2.04	1.46	3.15	0.048
Electronic and Electric Equipment	5.46	0.76	0.65	0.03	2.04	1.98	4.08	0.036
Motor Vehicles	3.61	0.28	0.29	0.02	2.78	0.24	2.28	0.043
Other Transportation Equipment	1.31	0.23	0.37	0.00	0.52	0.18	1.00	0.027
Instruments	5.23	0.65	1.44	0.03	1.99	1.12	2.57	0.017
Miscellaneous Manufacturing	2.53	0.34	0.41	0.00	0.95	0.82	2.08	0.008
Transport and Warehouse	3.25	0.20	0.72	0.12	1.34	0.86	1.74	0.061
Communications	5.00	1.62	0.53	0.02	1.95	0.88	3.93	0.033
Electric Utilities	3.22	1.01	0.20	0.67	0.83	0.51	2.52	0.026
Gas Utilities	0.56	0.66	–0.04	0.14	0.05	–0.24	0.94	0.016
Trade	3.66	0.62	0.83	0.04	1.19	0.98	2.49	0.195
FIRE	3.42	1.14	0.94	0.00	1.52	–0.18	0.66	0.131
Services	4.34	0.84	1.70	0.07	1.92	–0.19	0.92	0.208
Goverment Enterprises	2.86	1.24	1.08	0.23	0.83	–0.52	0.49	0.022
Private Households	3.50	3.55	–0.06	0.00	0.00	0.00	5.98	0.137
General Government	1.35	0.60	0.75	0.00	0.00	0.00	0.46	0.131

Output Growth is the average annual growth in real gross output. Contributions of Inputs are defined as the average, share–weighted growth of the input. Productivity Growth is defined in Equation (8). ALP Growth is the growth in average labor productivity. Domar Weight is the average ratio of industry gross output to aggregate value added as defined in Equation (9). All numbers except Domar Weights are percentages.

TABLE A-1 Private Domestic Output and High-Tech Assets

	Private Domestic Output		Computer Investment		Software Investment		Communic Investment
Year	Value	Price	Value	Price	Value	Price	Value
1959	484.1	0.25	0.00	0.00	0.00	0.00	1.80
1960	472.8	0.24	0.20	697.30	0.10	0.61	2.30
1961	490.1	0.24	0.30	522.97	0.20	0.62	2.70
1962	527.1	0.25	0.30	369.16	0.20	0.63	3.00
1963	562.1	0.25	0.70	276.29	0.40	0.63	2.90
1964	606.4	0.26	0.90	229.60	0.50	0.64	3.00
1965	664.2	0.26	1.20	188.74	0.70	0.65	3.50
1966	728.9	0.27	1.70	132.70	1.00	0.66	4.00
1967	763.1	0.28	1.90	107.71	1.20	0.67	4.20
1968	811.0	0.28	1.90	92.00	1.30	0.68	4.70
1969	877.7	0.29	2.40	83.26	1.80	0.70	5.80
1970	937.9	0.31	2.70	74.81	2.30	0.73	6.70
1971	991.5	0.32	2.80	56.98	2.40	0.73	6.80
1972	1,102.9	0.33	3.50	45.93	2.80	0.73	6.80
1973	1,255.0	0.36	3.50	43.53	3.20	0.75	8.40
1974	1,345.9	0.38	3.90	35.55	3.90	0.80	9.40
1975	1,472.7	0.42	3.60	32.89	4.80	0.85	9.70
1976	1,643.0	0.44	4.40	27.47	5.20	0.87	11.10
1977	1,828.1	0.47	5.70	23.90	5.50	0.89	14.40
1978	2,080.4	0.50	7.60	16.17	6.60	0.90	17.70
1979	2,377.8	0.56	10.20	13.40	8.70	0.95	21.40
1980	2,525.9	0.59	12.50	10.46	10.70	1.01	25.70
1981	2,825.6	0.65	17.10	9.19	12.90	1.07	29.00
1982	2,953.5	0.69	18.90	8.22	15.40	1.12	31.10
1983	3,207.7	0.72	23.90	6.86	18.00	1.13	31.90
1984	3,610.3	0.75	31.60	5.55	22.10	1.14	36.60
1985	3,844.1	0.76	33.70	4.72	25.60	1.13	39.90
1986	3,967.4	0.76	33.40	4.06	27.80	1.12	42.10
1987	4,310.8	0.79	35.80	3.46	31.40	1.12	42.10
1988	4,766.1	0.84	38.00	3.21	36.70	1.14	46.70
1989	5,070.5	0.86	43.10	3.00	44.40	1.11	46.90
1990	5,346.8	0.89	38.60	2.72	50.20	1.09	47.50
1991	5,427.2	0.91	37.70	2.45	56.60	1.10	45.70
1992	5,672.4	0.92	43.60	2.09	60.80	1.04	47.80
1993	5,901.8	0.93	47.20	1.78	69.40	1.04	48.20
1994	6,374.4	0.96	51.30	1.57	75.50	1.02	54.70
1995	6,674.4	0.97	64.60	1.31	83.50	1.02	60.00
1996	7,161.2	1.00	70.90	1.00	95.10	1.00	65.60
1997	7,701.8	1.02	76.70	0.78	106.60	0.97	73.00
1998	8,013.3	1.01	88.51	0.57	123.41	0.96	83.60

Notes: Values are in billions of current dollars. All price indexes are normalized to 1.0 in 1996.

	Communications Investment		Computer & Software Consumption		Computer & Software Consumption Services	
Price	Value	Price	Value	Price	Value	Price
0.00	1.80	0.47	0.00	0.00	0.00	0.00
0.61	2.30	0.47	0.00	0.00	0.00	0.00
0.62	2.70	0.47	0.00	0.00	0.00	0.00
0.63	3.00	0.46	0.00	0.00	0.00	0.00
0.63	2.90	0.46	0.00	0.00	0.00	0.00
0.64	3.00	0.47	0.00	0.00	0.00	0.00
0.65	3.50	0.47	0.00	0.00	0.00	0.00
0.66	4.00	0.47	0.00	0.00	0.00	0.00
0.67	4.20	0.49	0.00	0.00	0.00	0.00
0.68	4.70	0.51	0.00	0.00	0.00	0.00
0.70	5.80	0.54	0.00	0.00	0.00	0.00
0.73	6.70	0.57	0.00	0.00	0.00	0.00
0.73	6.80	0.60	0.00	0.00	0.00	0.00
0.73	6.80	0.62	0.00	0.00	0.00	0.00
0.75	8.40	0.64	0.00	0.00	0.00	0.00
0.80	9.40	0.69	0.00	0.00	0.00	0.00
0.85	9.70	0.76	0.00	0.00	0.00	0.00
0.87	11.10	0.80	0.00	0.00	0.00	0.00
0.89	14.40	0.78	0.00	0.00	0.00	0.00
0.90	17.70	0.81	0.10	33.68	0.02	17.84
0.95	21.40	0.83	0.10	32.81	0.07	19.01
1.01	25.70	0.88	0.20	22.11	0.20	25.93
1.07	29.00	0.96	0.40	18.79	0.25	13.90
1.12	31.10	1.01	1.40	15.12	0.74	11.96
1.13	31.90	1.03	2.90	10.71	2.07	10.39
1.14	36.60	1.07	3.00	9.41	2.37	6.07
1.13	39.90	1.09	2.90	8.68	2.70	4.93
1.12	42.10	1.10	5.20	6.54	4.84	5.61
1.12	42.10	1.10	6.20	5.91	4.91	3.54
1.14	46.70	1.10	8.20	5.41	6.65	3.24
1.11	46.90	1.10	8.30	5.02	7.89	2.85
1.09	47.50	1.11	8.90	4.22	10.46	2.97
1.10	45.70	1.11	11.90	3.53	11.66	2.44
1.04	47.80	1.10	12.10	2.68	14.96	2.25
1.04	48.20	1.09	14.50	2.07	16.26	1.71
1.02	54.70	1.07	18.00	1.81	16.14	1.17
1.02	60.00	1.03	21.00	1.44	22.64	1.13
1.00	65.60	1.00	23.60	1.00	30.19	1.00
0.97	73.00	0.99	26.20	0.69	33.68	0.71
0.96	83.60	0.97	30.40	0.48	36.53	0.48

n 1996.

TABLE B-1 Investment and Capital Stock by Asset Type and Class

Asset	Geometric Depreciation Rate	1998 Investment	1998 Capital Stock
Total Capital	na		27,954.7
Fixed Reproducible Assets	na	4,161.7	20,804.2
Equipment and Software		829.1	4,082.0
Household furniture	0.1375	2.3	13.1
Other furniture	0.1179	37.6	224.4
Other fabricated metal products	0.0917	15.9	134.5
Steam engines	0.0516	2.7	60.1
Internal combustion engines	0.2063	1.6	6.9
Farm tractors	0.1452	10.8	60.7
Construction tractors	0.1633	2.9	15.3
Agricultural machinery, except tractors	0.1179	13.1	89.2
Construction machinery, except tractors	0.1550	20.6	99.5
Mining and oilfield machinery	0.1500	2.4	15.6
Metalworking machinery	0.1225	37.1	228.6
Special industry machinery, n.e.c	0.1031	38.6	288.7
General industrial, including materials handling, equipment	0.1072	34.5	247.5
Computers and peripheral equipment	0.3150	88.5	164.9
Service industry machinery	0.1650	17.9	92.0
Communication equipment	0.1100	83.6	440.5
Electrical transmission, distribution, and industrial apparatus	0.0500	26.7	313.0
Household appliances	0.1650	1.5	6.9
Other electrical equipment, n.e.c.	0.1834	15.2	64.5
Trucks, buses, and truck trailers	0.1917	104.5	367.0
Autos	0.2719	19.4	70.2
Aircraft	0.0825	23.0	174.5
Ships and boats	0.0611	3.0	48.4
Railroad equipment	0.0589	5.3	69.1
Instruments (Scientific & engineering)	0.1350	30.9	172.6
Photocopy and related equipment	0.1800	22.6	103.0
Other nonresidential equipment	0.1473	35.4	184.3
Other office equipment	0.3119	8.4	24.5
Software	0.3150	123.4	302.4
Non-Residential Structures		2,271.3	5,430.6
Industrial buildings	0.0314	36.4	766.6
Mobile structures (offices)	0.0556	0.9	9.8
Office buildings	0.0247	44.3	829.8
Commercial warehouses	0.0222	0.0	0.0
Other commercial buildings, n.e.c.	0.0262	55.7	955.8
Religious buildings	0.0188	6.6	155.3
Educational buildings	0.0188	11.0	157.4
Hospital and institutional buildings	0.0188	17.76	355.12
Hotels and motels	0.0281	17.08	210.57

TABLE B-1 Continued

Asset	Geometric Depreciation Rate	1998 Investment	1998 Capital Stock
Amusement and recreational buildings	0.0300	9.14	103.55
Other nonfarm buildings, n.e.c.	0.0249	2.07	67.68
Railroad structures	0.0166	5.78	210.36
Telecommunications	0.0237	13.19	282.09
Electric light and power (structures)	0.0211	12.12	490.04
Gas (structures)	0.0237	4.96	170.98
Local transit buildings	0.0237	0.00	0.00
Petroleum pipelines	0.0237	1.11	39.20
Farm related buildings and structures	0.0239	4.59	202.73
Petroleum and natural gas	0.0751	22.12	276.99
Other mining exploration	0.0450	2.03	38.96
Other nonfarm structures	0.0450	6.39	107.70
Railroad track replacement	0.0275	0.00	0.00
Nuclear fuel rods	0.0225	0.00	0.00
Residential Structures		363.18	8,309.62
1-to-4-unit homes	0.0114	240.27	5,628.27
5-or-more-unit homes	0.0140	21.11	871.81
Mobile homes	0.0455	14.64	147.17
Improvements	0.0255	86.29	1,634.15
Other residential	0.0227	0.87	28.23
Consumers Durables		698.20	2,981.97
Autos	0.2550	166.75	616.53
Trucks	0.2316	92.53	327.85
Other (RVs)	0.2316	18.63	64.98
Furniture	0.1179	56.02	372.26
Kitchen Appliance	0.1500	29.83	161.75
China, Glassware	0.1650	29.65	141.44
Other Durable	0.1650	64.03	309.67
Computers and Software	0.3150	30.40	52.30
Video, Audio	0.1833	75.15	289.22
Jewelry	0.1500	44.58	228.38
Ophthalmic	0.2750	16.53	53.44
Books and Maps	0.1650	25.34	132.51
Wheel Goods	0.1650	48.76	231.66
Land	0.0000		5,824.18
Inventories	0.0000		1,326.31

Source: BEA (1998a, 1999b, 1999c) and author calculations.
Note: Values of investment and capital stock is in millions of current dollars. Equipment and Software and Other nonresidential equipment includes NIPA residential equipment.

TABLE B-2 Total Capital Stock and High-Tech Assets

	Total Stock of Capital and CD Assets		Computer Capital Stock		Software Capital Sto
Year	Value	Price	Value	Price	Value
1959	1,300.3	0.17	0.00	0.00	0.00
1960	1,391.0	0.18	0.20	697.30	0.10
1961	1,478.5	0.18	0.40	522.97	0.27
1962	1,583.6	0.19	0.50	369.16	0.39
1963	1,667.7	0.19	0.95	276.29	0.67
1964	1,736.0	0.19	1.44	229.60	0.97
1965	1,848.3	0.19	2.01	188.74	1.37
1966	2,007.7	0.20	2.67	132.70	1.95
1967	2,150.6	0.21	3.38	107.71	2.55
1968	2,394.9	0.22	3.88	92.00	3.09
1969	2,670.4	0.24	4.81	83.26	3.98
1970	2,874.8	0.24	5.66	74.81	5.12
1971	3,127.9	0.26	5.75	56.98	5.91
1972	3,543.0	0.28	6.68	45.93	6.86
1973	4,005.0	0.30	7.83	43.53	8.04
1974	4,250.3	0.31	8.28	35.55	9.77
1975	4,915.0	0.35	8.85	32.89	11.89
1976	5,404.1	0.37	9.46	27.47	13.52
1977	6,151.9	0.41	11.34	23.90	15.01
1978	7,097.4	0.45	12.86	16.17	17.00
1979	8,258.3	0.50	17.50	13.40	21.01
1980	9,407.4	0.56	21.85	10.46	25.93
1981	10,771.2	0.62	30.26	9.19	31.72
1982	11,538.6	0.66	37.45	8.22	38.14
1983	12,033.2	0.67	45.29	6.86	44.40
1984	13,247.3	0.71	56.70	5.55	52.68
1985	14,837.5	0.77	66.72	4.72	61.66
1986	15,985.5	0.81	72.77	4.06	69.38
1987	17,137.5	0.85	78.26	3.46	79.17
1988	18,632.2	0.90	87.79	3.21	91.54
1989	20,223.2	0.96	99.26	3.00	105.64
1990	20,734.0	0.96	100.29	2.72	121.57
1991	21,085.3	0.97	99.42	2.45	140.37
1992	21,296.9	0.96	101.84	2.09	151.41
1993	21,631.7	0.96	106.68	1.78	173.39
1994	22,050.0	0.96	115.74	1.57	191.63
1995	23,346.7	0.99	130.78	1.31	215.13
1996	24,300.2	1.00	139.13	1.00	239.73
1997	26,070.4	1.04	150.57	0.78	266.63
1998	27,954.7	1.08	164.87	0.57	302.41

Notes: Values are in billions of current dollars. Total capital stock includes reproducible assets, consumers' durable assets (CD), land, and inventories. All price indexes are normalized to 1.0 in 1996.

Software Capital Stock		Communications Capital Stock		Computer and Software CD Stock	
Value	Price	Value	Price	Value	Price
0.00	0.00	9.97	0.47	0.00	0.00
0.10	0.61	11.11	0.47	0.00	0.00
0.27	0.62	12.53	0.47	0.00	0.00
0.39	0.63	14.06	0.46	0.00	0.00
0.67	0.63	15.50	0.46	0.00	0.00
0.97	0.64	16.99	0.47	0.00	0.00
1.37	0.65	18.56	0.47	0.00	0.00
1.95	0.66	20.69	0.47	0.00	0.00
2.55	0.67	23.21	0.49	0.00	0.00
3.09	0.68	26.38	0.51	0.00	0.00
3.98	0.70	30.57	0.54	0.00	0.00
5.12	0.73	35.16	0.57	0.00	0.00
5.91	0.73	39.66	0.60	0.00	0.00
6.86	0.73	43.77	0.62	0.00	0.00
8.04	0.75	48.30	0.64	0.00	0.00
9.77	0.80	55.98	0.69	0.00	0.00
11.89	0.85	64.49	0.76	0.00	0.00
13.52	0.87	71.56	0.80	0.00	0.00
15.01	0.89	76.27	0.78	0.00	0.00
17.00	0.90	88.54	0.81	0.10	33.68
21.01	0.95	101.62	0.83	0.17	32.81
25.93	1.01	122.33	0.88	0.28	22.11
31.72	1.07	146.61	0.96	0.56	18.79
38.14	1.12	168.74	1.01	1.71	15.12
44.40	1.13	185.59	1.03	3.73	10.71
52.68	1.14	207.81	1.07	5.25	9.41
61.66	1.13	228.43	1.09	6.21	8.68
69.38	1.12	246.93	1.10	8.41	6.54
79.17	1.12	262.59	1.10	11.40	5.91
91.54	1.14	280.64	1.10	15.35	5.41
105.64	1.11	297.05	1.10	18.06	5.02
121.57	1.09	311.95	1.11	19.30	4.22
140.37	1.10	324.37	1.11	22.97	3.53
151.41	1.04	334.48	1.10	24.05	2.68
173.39	1.04	342.48	1.09	27.20	2.07
191.63	1.02	353.46	1.07	34.28	1.81
215.13	1.02	362.23	1.03	39.71	1.44
239.73	1.00	380.00	1.00	42.49	1.00
266.63	0.97	407.58	0.99	46.20	0.69
302.41	0.96	440.52	0.97	52.30	0.48

TABLE B-3 Total Capital Services and High-Tech Assets

Year	Total Service Flow from Capital and CD Assets		Computer Capital Service Flow		Software Capital Ser
	Value	Price	Value	Price	Value
1959	214.7	0.32	0.00	0.00	0.00
1960	183.7	0.26	0.05	407.59	0.02
1961	192.3	0.26	0.25	602.38	0.08
1962	211.9	0.28	0.41	480.68	0.15
1963	241.7	0.30	0.56	291.73	0.22
1964	260.2	0.31	0.77	196.86	0.34
1965	289.2	0.32	1.15	169.47	0.52
1966	315.4	0.33	1.99	161.83	0.74
1967	333.8	0.33	2.13	103.65	1.03
1968	330.2	0.31	2.40	81.43	1.29
1969	349.2	0.31	2.54	63.64	1.57
1970	382.5	0.33	3.27	61.40	2.09
1971	391.4	0.32	4.83	68.40	2.83
1972	439.6	0.35	4.44	45.09	3.01
1973	517.9	0.38	4.02	30.87	3.47
1974	546.6	0.38	6.04	36.38	3.99
1975	619.2	0.42	5.36	26.49	5.17
1976	678.1	0.44	6.01	24.25	5.60
1977	742.8	0.47	6.35	19.16	6.26
1978	847.5	0.51	10.71	20.84	7.31
1979	999.1	0.57	10.45	12.30	8.19
1980	1,026.9	0.56	15.03	10.96	9.99
1981	1,221.4	0.66	15.92	7.33	11.76
1982	1,251.7	0.65	17.29	5.47	12.54
1983	1,359.1	0.71	22.77	5.06	15.11
1984	1,570.1	0.79	30.79	4.54	19.02
1985	1,660.5	0.79	33.72	3.43	22.41
1986	1,559.9	0.71	36.44	2.82	25.88
1987	1,846.6	0.80	45.07	2.76	31.84
1988	2,185.3	0.89	43.85	2.18	37.72
1989	2,243.0	0.89	47.89	1.97	45.96
1990	2,345.0	0.90	53.28	1.89	51.07
1991	2,345.8	0.88	52.65	1.69	54.07
1992	2,335.4	0.86	57.69	1.60	69.11
1993	2,377.4	0.85	62.00	1.42	69.32
1994	2,719.5	0.94	63.16	1.17	84.14
1995	2,833.4	0.94	77.77	1.11	89.18
1996	3,144.4	1.00	96.36	1.00	101.46
1997	3,466.3	1.05	103.95	0.77	119.80
1998	3,464.8	0.99	118.42	0.61	128.32

Note: Values are in billions of current dollars. Service prices are normalized to 1.0 in 1996. Total service flows include reproducible assets, consumers' durable assets (CD), land, and inventories. All price indexes are normalized to 1.0 in 1996.

Software Capital Service Flow		Communications Capital Service Flow		Computer and Software CD Service Flow	
Value	Price	Value	Price	Value	Price
0.00	0.00	2.55	0.50	0.00	0.00
0.02	0.64	2.65	0.47	0.00	0.00
0.08	0.61	2.85	0.45	0.00	0.00
0.15	0.65	3.44	0.48	0.00	0.00
0.22	0.60	3.32	0.42	0.00	0.00
0.34	0.59	3.68	0.42	0.00	0.00
0.52	0.64	4.73	0.50	0.00	0.00
0.74	0.65	5.00	0.48	0.00	0.00
1.03	0.68	5.14	0.45	0.00	0.00
1.29	0.69	5.43	0.44	0.00	0.00
1.57	0.69	6.02	0.44	0.00	0.00
2.09	0.74	7.23	0.48	0.00	0.00
2.83	0.83	8.34	0.51	0.00	0.00
3.01	0.77	8.86	0.51	0.00	0.00
3.47	0.77	12.48	0.68	0.00	0.00
3.99	0.78	11.48	0.58	0.00	0.00
5.17	0.88	13.41	0.64	0.00	0.00
5.60	0.84	13.61	0.62	0.00	0.00
6.26	0.86	22.37	0.94	0.00	0.00
7.31	0.91	19.02	0.72	0.02	17.84
8.19	0.89	26.30	0.89	0.07	19.01
9.99	0.93	23.94	0.72	0.20	25.93
11.76	0.94	23.89	0.64	0.25	13.90
12.54	0.87	25.32	0.62	0.74	11.96
15.11	0.92	29.54	0.67	2.07	10.39
19.02	0.99	33.20	0.70	2.37	6.07
22.41	0.99	39.30	0.77	2.70	4.93
25.88	0.99	43.39	0.79	4.84	5.61
31.84	1.07	55.49	0.94	4.91	3.54
37.72	1.11	67.22	1.07	6.65	3.24
45.96	1.16	67.90	1.02	7.89	2.85
51.07	1.10	69.86	1.00	10.46	2.97
54.07	1.01	66.05	0.91	11.66	2.44
69.11	1.12	70.72	0.94	14.96	2.25
69.32	0.98	80.23	1.02	16.26	1.71
84.14	1.05	89.16	1.09	16.14	1.17
89.18	0.99	101.18	1.17	22.64	1.13
101.46	1.00	92.91	1.00	30.19	1.00
119.80	1.04	100.13	1.00	33.68	0.71
128.32	0.97	103.35	0.94	36.53	0.48

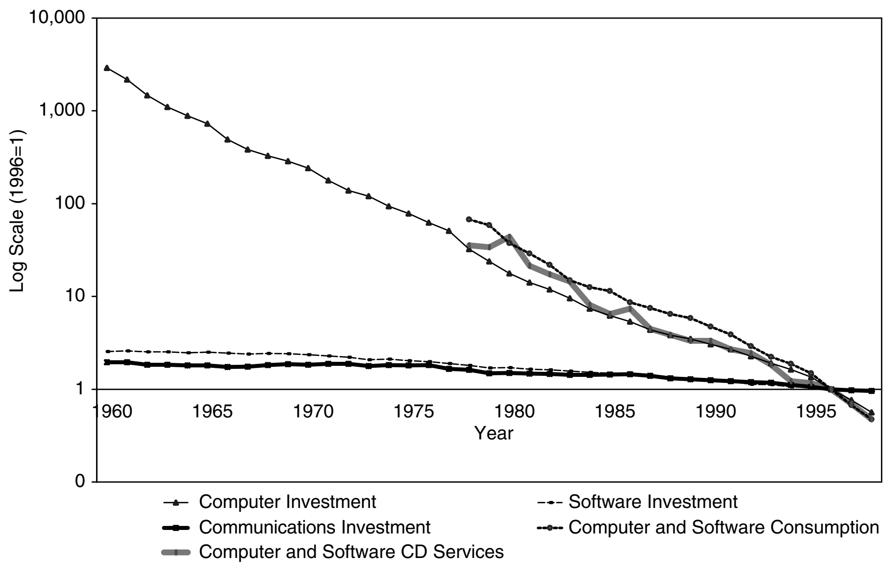
TABLE C-1 Labor Input

	Labor Input				
Year	Price	Quantity	Value	Quality	Employmer
1959	0.15	1,866.7	269.8	0.82	58,209
1960	0.15	1,877.5	289.1	0.82	58,853
1961	0.16	1,882.0	297.7	0.83	58,551
1962	0.16	1,970.7	315.3	0.86	59,681
1963	0.16	2,000.2	320.4	0.86	60,166
1964	0.17	2,051.4	346.2	0.87	61,307
1965	0.18	2,134.8	375.1	0.88	63,124
1966	0.19	2,226.9	413.7	0.89	65,480
1967	0.19	2,261.8	429.3	0.90	66,476
1968	0.21	2,318.8	480.8	0.91	68,063
1969	0.22	2,385.1	528.6	0.91	70,076
1970	0.24	2,326.6	555.6	0.90	69,799
1971	0.26	2,318.3	600.2	0.90	69,671
1972	0.28	2,395.5	662.9	0.91	71,802
1973	0.29	2,519.1	736.4	0.91	75,255
1974	0.32	2,522.2	798.8	0.91	76,474
1975	0.35	2,441.8	852.9	0.92	74,575
1976	0.38	2,525.6	964.2	0.92	76,925
1977	0.41	2,627.2	1,084.9	0.92	80,033
1978	0.44	2,783.7	1,232.4	0.93	84,439
1979	0.48	2,899.6	1,377.7	0.93	87,561
1980	0.52	2,880.8	1,498.2	0.94	87,788
1981	0.55	2,913.8	1,603.9	0.94	88,902
1982	0.60	2,853.3	1,701.6	0.94	87,600
1983	0.64	2,904.9	1,849.0	0.94	88,638
1984	0.66	3,095.5	2,040.2	0.95	93,176
1985	0.69	3,174.6	2,183.5	0.95	95,410
1986	0.75	3,192.8	2,407.1	0.95	97,001
1987	0.74	3,317.1	2,464.0	0.96	99,924
1988	0.76	3,417.2	2,579.5	0.96	103,021
1989	0.80	3,524.2	2,827.0	0.96	105,471
1990	0.84	3,560.3	3,001.9	0.97	106,562
1991	0.88	3,500.3	3,081.4	0.97	105,278
1992	0.94	3,553.4	3,337.0	0.98	105,399
1993	0.95	3,697.5	3,524.4	0.99	107,917
1994	0.96	3,806.4	3,654.6	0.99	110,888
1995	0.98	3,937.5	3,841.2	1.00	113,707
1996	1.00	4,016.8	4,016.8	1.00	116,083
1997	1.02	4,167.6	4,235.7	1.01	119,127
1998	1.06	4,283.8	4,545.7	1.01	121,934

Notes: Quantity of labor input is measured in billions of 1996 dollars; value of labor input is measured in billions of current dollars. Employment is thousands of workers, hourly compensation is in dollars, and hours worked is in millions. Price of labor input and index of labor quality are normalized to 1.0 in 1996.

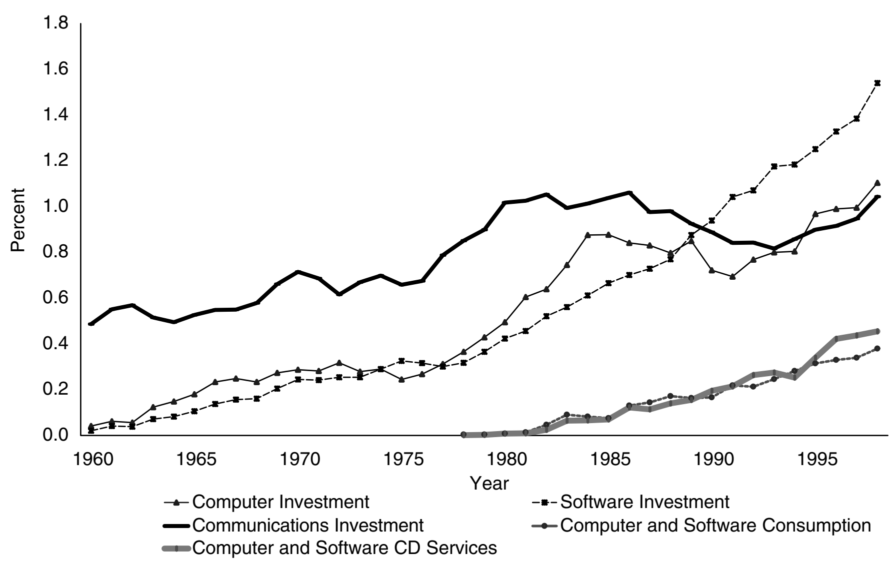
Employment	Weekly Hours	Hourly Compensation	Hours Worked
58,209	38.0	2.3	115,167
58,853	37.7	2.5	115,403
58,551	37.4	2.6	113,996
59,681	37.5	2.7	116,348
60,166	37.5	2.7	117,413
61,307	37.4	2.9	119,111
63,124	37.4	3.0	122,794
65,480	37.1	3.3	126,465
66,476	36.8	3.4	127,021
68,063	36.5	3.7	129,194
70,076	36.4	4.0	132,553
69,799	35.8	4.3	130,021
69,671	35.8	4.6	129,574
71,802	35.8	5.0	133,554
75,255	35.7	5.3	139,655
76,474	35.0	5.7	139,345
74,575	34.6	6.3	134,324
76,925	34.6	7.0	138,488
80,033	34.6	7.5	143,918
84,439	34.5	8.1	151,359
87,561	34.5	8.8	157,077
87,788	34.1	9.6	155,500
88,902	33.9	10.2	156,558
87,600	33.6	11.1	153,163
88,638	33.9	11.9	156,049
93,176	34.0	12.4	164,870
95,410	33.9	13.0	168,175
97,001	33.5	14.2	169,246
99,924	33.7	14.1	174,894
103,021	33.6	14.3	179,891
105,471	33.7	15.3	184,974
106,562	33.6	16.1	186,106
105,278	33.2	16.9	181,951
105,399	33.2	18.3	182,200
107,917	33.5	18.8	187,898
110,888	33.6	18.9	193,891
113,707	33.7	19.3	199,341
116,083	33.6	19.8	202,655
119,127	33.8	20.3	209,108
121,934	33.7	21.3	213,951

Chart 1: Relative Prices of Information Technology Outputs, 1960-1998



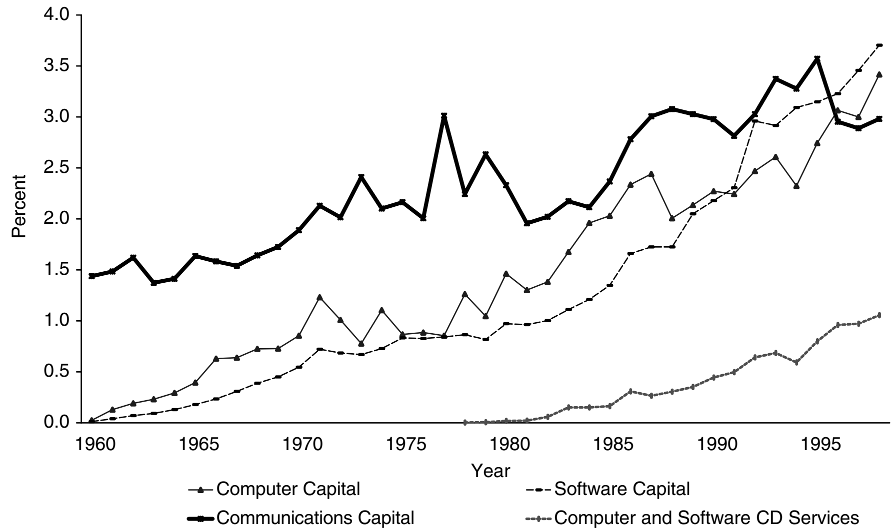
Notes: All prices indexes are relative to the output price index.
CD refers to Consumer Durables.

Chart 2: Output Shares of Information Technology, 1960-1998



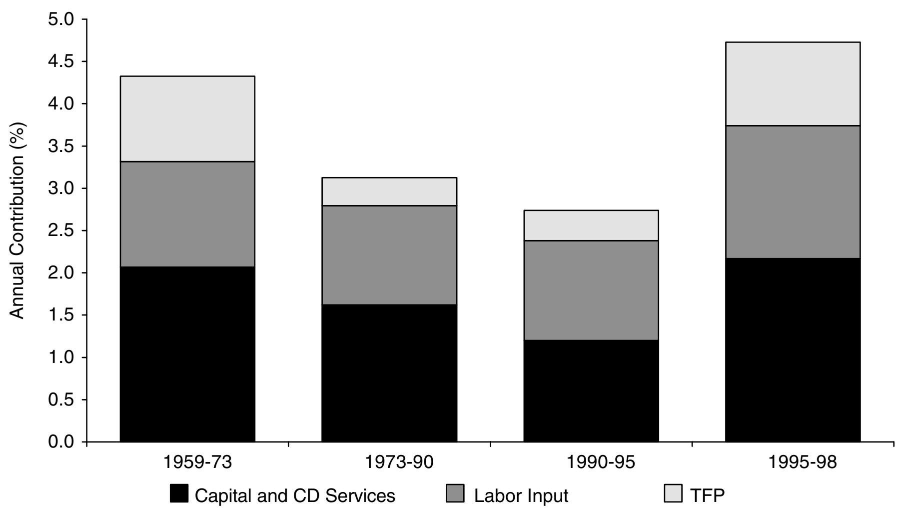
Notes: Share of current dollar output.
CD refers to Consumer Durables.

Chart 3: Input Shares of Information Technology, 1960-1998



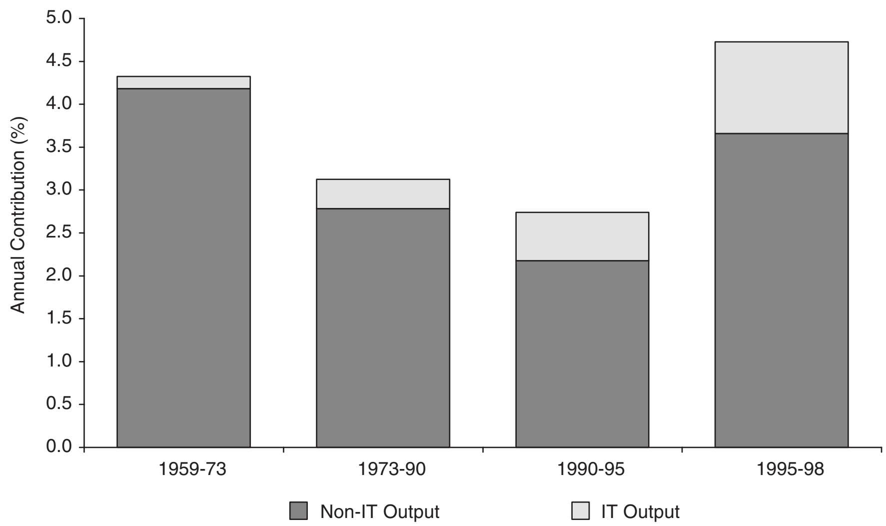
Notes: Share of current dollar capital and consumers' durable services.
CD refers to Consumer Durables.

Chart 4: Sources of U.S. Economic Growth, 1959-1998



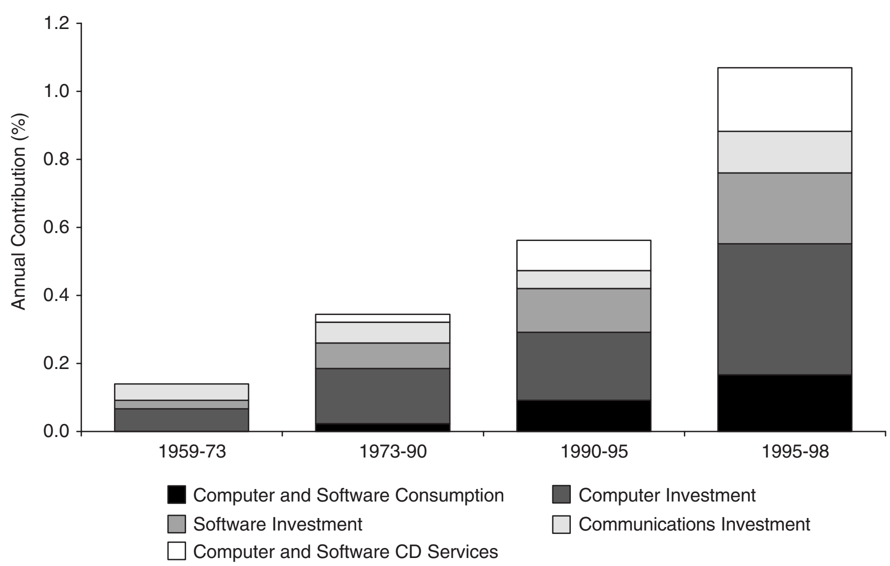
Notes: An input's contribution is the average share-weighted, annual growth rate.
CD refers to Consumer Durables.
TFP refers to Total Factor Productivity.

Chart 5: Output Contribution of Information Technology, 1959-1998



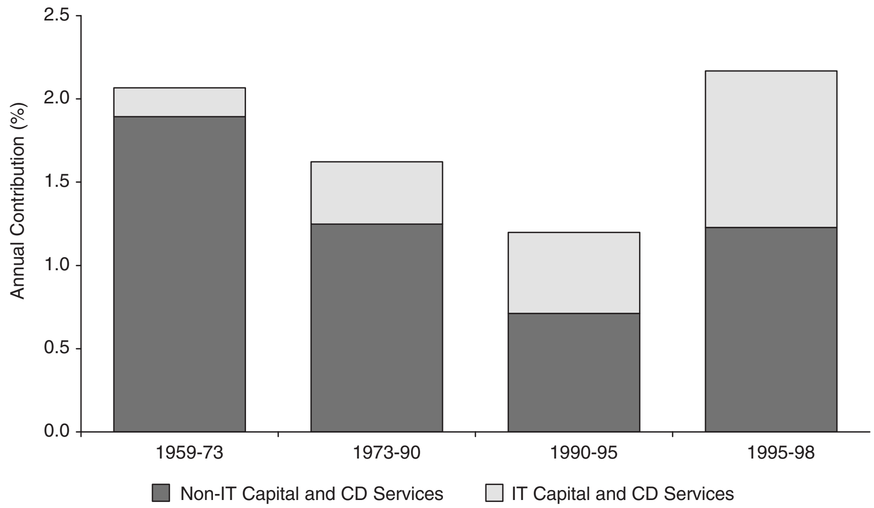
Notes: An output's contribution is the average share-weighted, annual growth rate.

Chart 6: Output Contribution of Information Technology Assets, 1959-1998



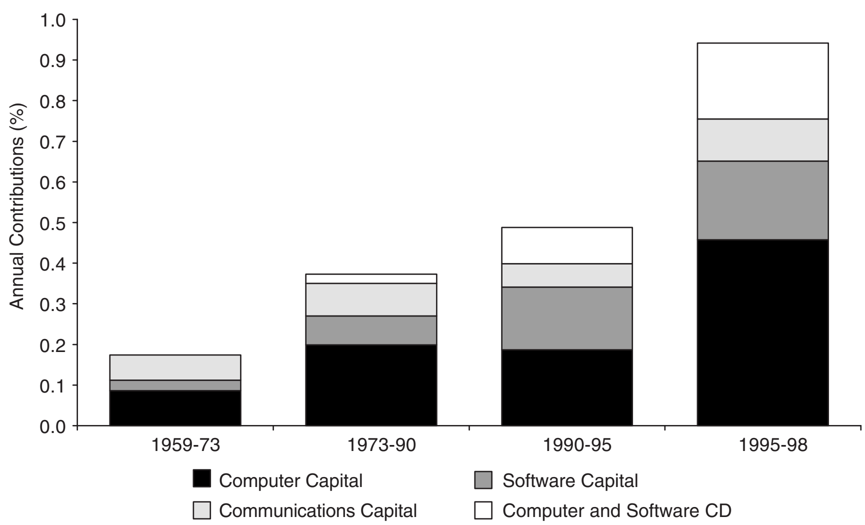
Notes: An output's contribution is the average share-weighted, annual growth rate.
CD refers to Consumer Durables.

Chart 7: Input Contribution of Information Technology, 1959-1998



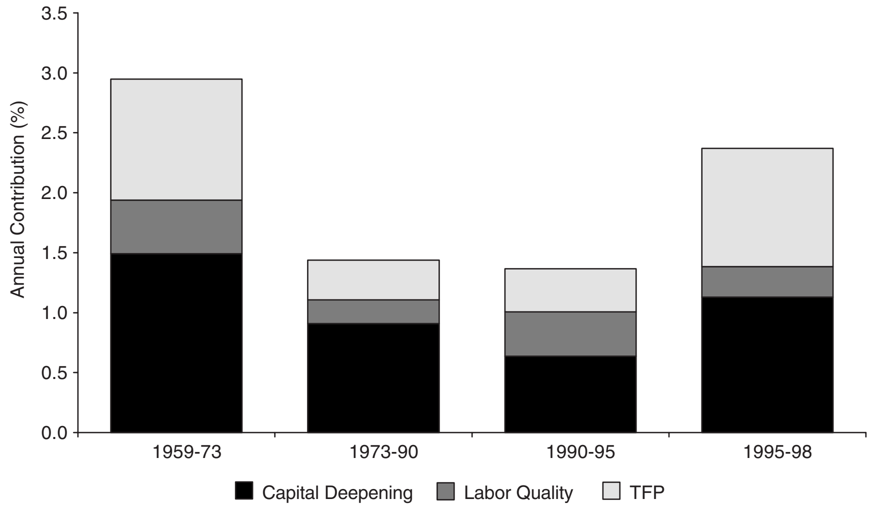
Notes: An input's contribution is the average share-weighted, annual growth rate.
CD refers to Consumer Durables.

Chart 8: Input Contribution of Information Technology, 1959-1998



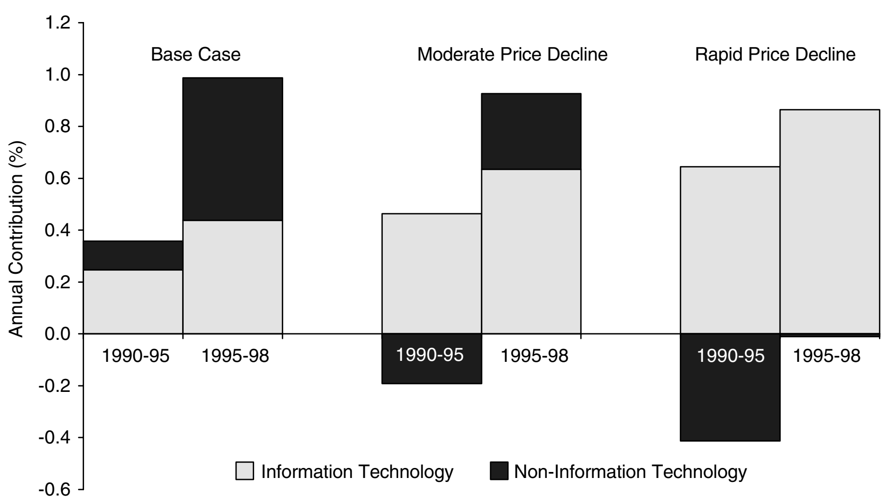
Notes: An input's contribution is the average share-weighted, annual growth rate.
CD refers to Consumer Durables.

Chart 9: Sources of U.S. Labor Productivity Growth, 1959-1998



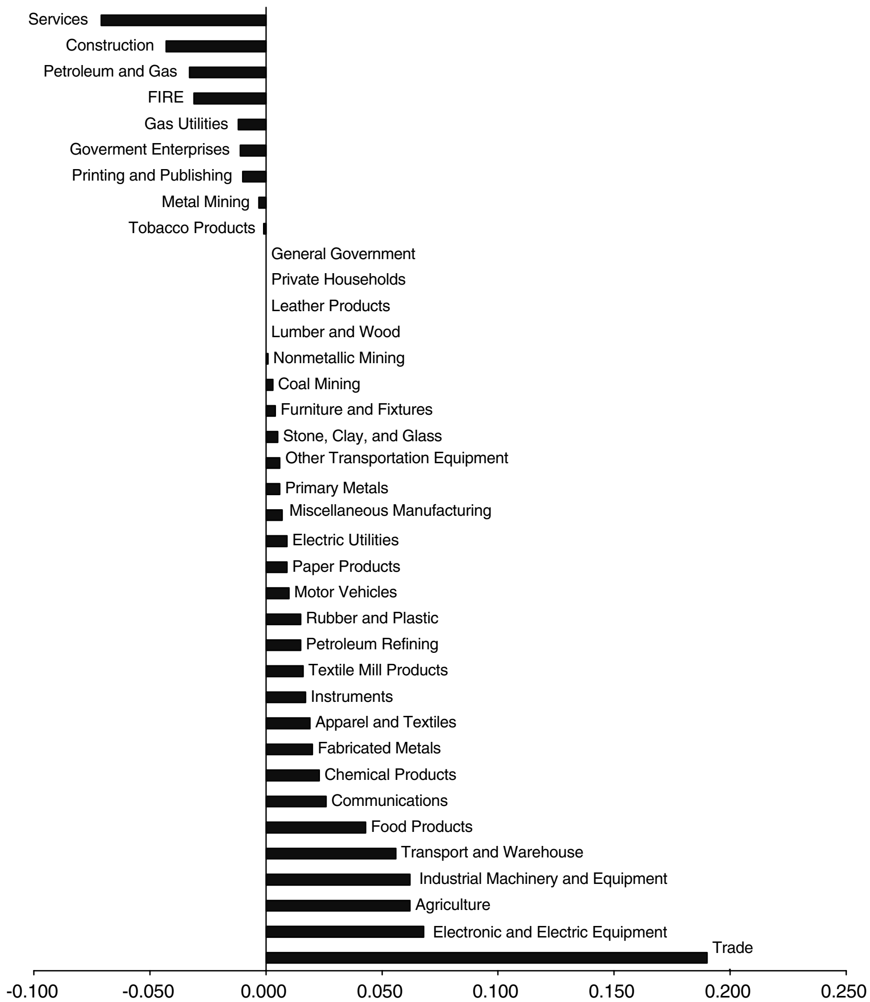
Notes: Annual contributions are defined in Equation (3) in text.
TFP refers to Total Factor Productivity.

Chart 10: TFP Decomposition for Alternative Deflation Cases



Notes: Annual contribution of information technology is the share-weighted decline in relative prices.

Chart 11: Industry Contributions to Aggregate Total Factor Productivity Growth, 1958-1996



Each industry's contribution is calculated as the product of industry productivity growth and the industry Domar weight, averaged for 1958-1996.

Appendix B
Biographies of Speakers*

SIDNEY ABRAMS

Sidney Abrams is currently a member of AT Kearney's North American E-Services Practice Leadership team with direct client and service development responsibilities.

Mr. Abrams has over sixteen years of North American, European, and Latin American consulting experience with Fortune 100 clients in areas such as corporate strategy development, revenue growth, post-acquisition integration, business restructuring, and e-business. Mr. Abrams has worked and led engagements in multiple industries including consumer products, chemicals, oil and gas, general manufacturing, and pharmaceuticals.

His accomplishments include leadership of an engagement for a $75-billion organization focused on creating the need for an e-business security strategy and defining the security architecture required; leadership of an engagement for a $5-billion multi-national cosmetic and beauty care company focused on the development of comprehensive business solutions associated with their dot-com business launch; leadership of an engagement for a $12-billion food service company including the development of an e-business competitive strategy and technology architecture, resulting in the creation of a new company focused on net markets; leadership of an engagement for an Internet freight transportation procurement company, including the assessment of competitive market strategies and required e-business applications; working with client senior management to aggressively pursue significant revenue growth and customer expansion; leadership of global

*As of October 2000.

supply chain restructuring program for a consumer-product company, focusing on North American, Latin American, and Asian markets; leadership of the first successful post-merger integration of a $1-billion chemical business into a Fortune 20 company; design and delivery of multiple complex restructuring programs on a Pan-European and global basis in the oil, gas, chemical, and consumer-product industries.

ALFRED V. AHO

Alfred V. Aho joined Lucent Technologies as Associate Research Vice President, Communications Sciences Research Division, in June 1997. He is currently Computing Sciences Research Vice President with responsibility for the Computing Sciences Research Center at Bell Laboratories in Murray Hill, New Jersey, and the Bell Labs Research Center in Beijing, China. The research work of these laboratories encompasses computer science, software, distributed systems, networking, network design and management, embedded systems, scientific computing, and quantum communication. The UNIX operating system and the C and C++ programming languages came from the Computing Sciences Research Center.

Prior to these appointments Dr. Aho was Professor and Chair of the Computer Science Department at Columbia University and from 1991 to 1995 the General Manager of the Information Sciences and Technologies Research Laboratory at Bellcore in Morristown, New Jersey. The work of this laboratory was directed at advancing the national information-networking infrastructure.

Dr. Aho received a B.A.Sc. in Engineering Physics from the University of Toronto and a Ph.D. in Electrical Engineering (Computer Science) from Princeton University. Upon graduating from Princeton Dr. Aho joined Bell Laboratories in 1967 as a member of the technical staff in the Computing Techniques Research Department, and in 1980 was appointed head of the Computing Principles Research Department. He has also been an adjunct professor of Computer Science at Stanford University and at the Stevens Institute of Technology.

Dr. Aho's personal research has focused on algorithms, compilers, database systems, and programming tools. He has written more than 60 research papers in these areas and has published 10 books that are widely used around the world in computer science research and education. He is a coinventor of the AWK programming language and several UNIX programming tools.

Dr. Aho is a member of the United States National Academy of Engineering. He is a fellow of the American Association for the Advancement of Science, the Association for Computing Machinery (ACM), Bell Laboratories, and the Institute of Electrical and Electronics Engineers. He has received honorary doctorates from the University of Helsinki and the University of Waterloo for his contributions to computer science research. He has been a distinguished lecturer at many of the world's leading universities.

Dr. Aho is active on a number of national and international advisory boards and committees. He has served as Chairman of the Advisory Committee for the Computer and Information Sciences and Engineering Directorate of the National Science Foundation. He has also been Chairman of ACM's Special Interest Group on Automata and Computability Theory and a member of the Computer Science and Telecommunications Board of the National Research Council.

ROBERT R. BORCHERS

Robert R. Borchers completed his Ph.D. in Nuclear Physics at the University of Wisconsin, Madison, in late 1961 under the supervision of Professor H. H. (Heinz) Barschall; he immediately started teaching the instrumentation electronics course and pursuing his research interests at that university. In the fall of 1963 he became an assistant professor and during the 1964-65 academic year took leave to do research at the Neils Bohr institute in Copenhagen, Denmark, on an Alfred P. Sloan fellowship.

Returning to Madison in 1965, he resumed his research and teaching duties and in 1966 received a W. H. Kieckhofer teaching award for his efforts in improving and teaching undergraduate laboratories. Also in 1966 he designed and installed a computer system to acquire and analyze data in the nuclear physics accelerator laboratory. This interest in computing led to a long involvement in computing and computing policy issues at the University of Wisconsin.

In 1970 the nuclear physics laboratories were badly damaged in a terrorist bombing. Borchers moved to the graduate school as Associate Dean for Physical sciences partly to aid in the reconstruction of the damaged labs. In 1972 he assumed the Directorship of the UW Physical Science Laboratory, a facility operated by the Graduate School to provide support to various research programs on campus. This included the design and construction of a variety of computer-based systems, including early use of microprocessors.

In 1976 he was selected as the Vice Chancellor for Academic Affairs at Madison, and in 1977 moved to the University of Colorado at Boulder as Vice Chancellor for Academic Affairs and Professor of Physics. One of his responsibilities at Boulder was the academic computing center.

In 1979 he moved to the Lawrence Livermore National Laboratory to become the leader of the planning and technology office in the magnetic fusion energy program. Among the programs managed by this office were all the fusion technology research and development, with an annual budget of roughly $20 million. This task included extensive interaction with the Department of Energy and the university research community that was active in fusion energy research. In 1982 he was named the Deputy Director of the fusion program and in 1983 was selected as the first Associate Director of the laboratory for computation.

The responsibilities of this position included management of the two large LLNL supercomputer centers, the computation department, and a variety of computing-related research and development programs. Overall, his responsibilities involved nearly 800 people and an annual budget of over $100 million. He also had extensive involvement with overall laboratory management and numerous interactions with the industrial and academic communities and government agencies. He chaired, for example, the Technical Review Committee that evaluated the initial round of proposals for the National Science Foundation (NSF) supercomputer centers and maintained a long-term interest in the program. He was also one of the founders of the annual supercomputing conferences and chaired the meeting in 1993. In 1992 Dr. Borchers established and managed the Lawrence Livermore National Laboratory University Relations Office to foster greater interaction between the laboratory and the University of California and other academic institutions.

In the summer of 1993 he was selected to be the Director of the Division of Advanced Scientific computing at NSF. This division manages the NSF supercomputer centers and several other programs. The Division Director also participates in the management of the CISE directorate. In 1995 he worked with the Hayes Task Force on the future of the supercomputer centers program and is currently managing the competition for the follow-on program, Partnerships in Advanced Computing Infrastructure.

TIMOTHY F. BRESNAHAN

Timothy F. Bresnahan is a professor in the Department of Economics at Stanford University. He holds a Ph.D. from Princeton University and a B.A. from Haverford College.

His research interests include industrial organization, applied econometrics, and the economics of technology. His current research focuses on competition in high-technology industries; technical change by users of information technologies; and employment and growth in the new economy. He teaches courses in econometrics, industrial organization, and microeconomics.

Recent Publications consist of (1) *The Economics of New Goods*, (edited with Robert J. Gordon), proceedings of a meeting of the Conference on Research in Income and Wealth, forthcoming, University of Chicago Press; (2) "The Competitive Crash in Large-Scale Commercial Computing," (with Shane Greenstein) forthcoming in *Growth & Development: The Economics of the 21st Century*, edited by Ralph Landau, Nathan Rosenberg, and Timothy Taylor, Stanford University Press; (3) "Technical Progress in Computing and in the Uses of Computers," (with Shane Greenstein) forthcoming in *Brookings Papers on Economic Activity* in *Micro*.

Professional affiliations include AEA, Econometric Society (fellow), National Bureau of Economic Research.

ERIK BRYNJOLFSSON

Erik Brynjolfsson is the codirector of the Center for eBusiness@MIT (http://ebusiness.mit.edu), professor at the MIT Sloan School, an award-winning researcher, and a Director or Advisor for numerous ecommerce firms. He lectures and consults worldwide on topics related to Internet strategy, pricing models, and intangible assets. Erik is an associate member of MIT's Lab for Computer Science, a member of *Time* magazine's Board of Economists and coeditor of *Understanding the Digital Economy* (MIT Press). He holds bachelor's and master's degrees from Harvard University and a Ph.D. from MIT.

VINTON G. CERF

Vinton G. Cerf is senior vice president of Internet Architecture and Technology for WorldCom. Cerf's team of architects and engineers design advanced Internet frameworks for delivering a combination of data, information, voice, and video services for business and consumer use.

Widely known as a "father of the Internet," Cerf is the codesigner of the TCP/IP protocols and the architecture of the Internet. In December 1997 President Clinton presented the U.S. National Medal of Technology to Cerf and his partner, Robert E. Kahn, for founding and developing the Internet. Prior to rejoining MCI in 1994, Cerf was vice president of the Corporation for National Research Initiatives (CNRI). As vice president of MCI Digital Information Services from 1982 to 1986, he led the engineering of MCI Mail, the first commercial e-mail service to be connected to the Internet. During his tenure from 1976 to 1982 with the U.S. Department of Defense's Advanced Research Projects Agency (DARPA), Cerf played a key role leading the development of Internet and Internet-related data packet and security technologies.

Cerf served as founding president of the Internet Society from 1992 to 1995 and recently completed his term as chairman of the board. He also is chairman of the newly created Internet Societal Task Force that will focus on making the Internet accessible to everyone and analysis of international, national, and local policies surrounding Internet use. In addition, Cerf is honorary chairman of the newly formed IPv6 Forum, dedicated to raising awareness and speeding introduction of the new Internet protocol. Cerf is a member of the U.S. Presidential Information Technology Advisory Committee (PITAC). He also sits on the Board of Directors for the Endowment for Excellence in Education, Gallaudet University, the MCI WorldCom Foundation, Nuance Corporation, Avanex Corporation, CoSine Corporation, 2BNatural Corporation, B2B Video Networks, Internet Corporation for Assigned Names and Numbers, the Internet Policy Institute and the Hynomics Corporation. Cerf is a fellow of the IEEE, ACM, and American Association for the Advancement of Science, American Academy of Arts and Sciences, International Engineering Consortium, and the National Academy of Engineering.

Cerf is a recipient of numerous awards and commendations in connection with his work on the Internet. These include the Marconi Fellowship, the Alexander Graham Bell Award presented by the Alexander Graham Bell Association for the Deaf, the NEC Computer and Communications Prize, the Silver Medal of the International Telecommunications Union, the IEEE Alexander Graham Bell Medal, the IEEE Koji Kobayashi Award, the ACM Software and Systems Award, the ACM SIGCOMM Award, the Computer and Communications Industries Association Industry Legend Award, the Yuri Rubinsky Web Award, the Kilby Award , the Yankee Group/Interop/Network World Lifetime Achievement Award, the George R. Stibitz Award, the Werner Wolter Award and the Library of Congress Bicentennial Living Legend medal. In December 1994 *People* magazine identified Cerf as one of that year's "25 most intriguing people."

In addition to his work on behalf of WorldCom and the Internet, Cerf serves as a technical advisor for the production of "Gene Roddenberry's Earth: Final Conflict," the number-one television show in first-run syndication. He also made a special guest appearance in May 1998. Cerf has appeared on the television programs NextWave with Leonard Nimoy and World Business Review with Alexander Haig. Cerf also holds an appointment as distinguished visiting scientist at the Jet Propulsion Laboratory, where he is working on the design of an interplanetary Internet.

Cerf holds a Bachelor of Science degree in Mathematics from Stanford University and Master of Science and Ph.D. degrees in Computer Science from the University of California, Los Angeles. He also holds honorary Doctorate degrees from the Swiss Federal Institute of Technology, Zurich; Lulea University of Technology, Sweden; University of the Balearic Islands, Palma; Capitol College, Maryland; Gettysburg College, Pennsylvania; George Mason University, Virginia; and Rovira i Virgili University, Tarragona, Spain.

KENNETH FLAMM

Kenneth Flamm joined the LBJ School at the University of Texas at Austin in the fall of 1998. He is a 1973 honors graduate of Stanford University and the recipient of a Ph.D. in economics from MIT in 1979.

From 1993 to 1995 Flamm served as principal Deputy Assistant Secretary of Defense for Economic Security and Special Assistant to the Deputy Secretary of Defense for Dual Use Technology Policy. He was awarded the Defense Department's Distinguished Public Service Medal in 1995. Prior to his service at the Defense Department he spent eleven years as a Senior Fellow in the Foreign Policy Studies program at the Brookings Institution.

Flamm has been a professor of economics at the Instituto Tecnológico A. de México in Mexico City, the University of Massachusetts, and George Washington University. He has also been an adviser to the Director General of Income

Policy in the Mexican Ministry of Finance and a consultant to the Organisation for Economic Co-operation and Development, the World Bank, the National Academy of Sciences, the Latin American Economic System, the U.S. Department of Defense, the U.S. Department of Justice, the U.S. Agency for International Development, and the Office of Technology Assessment of the U.S. Congress.

Among Dr. Flamm's publications are *Mismanaged Trade? Strategic Policy and the Semiconductor Industry* (1996), *Changing the Rules: Technological Change, International Competition, and Regulation in Communications* (ed., with Robert Crandell, 1989), *Creating the Computer* (1988), and *Targeting the Computer* (1987). He is currently working on an analytical study of the post-Cold-War defense industrial base.

Flamm, an expert on international trade and the high-technology industry, teaches classes in microeconomic theory, international trade, and defense economics.

ALAN G. GANEK

Alan Ganek is Vice President, Technical Strategy and Worldwide Operations, IBM Research, where he is responsible for the technical strategy of IBM's Research Division, a worldwide organization focused on research leadership in areas related to information technology and exploratory work in science and mathematics. This entails strategic and technology outlook, research portfolio management, and Research Division processes. In addition, Mr. Ganek oversees operational services supporting the division, including finance, information and library services, technical journals, and site operations.

Prior to joining IBM Research, Mr. Ganek was Director of Solutions Development, IBM Telecommunications and Media Industry Unit. In this capacity he was responsible for development activity supporting IBM's telecommunications and media industry customers worldwide, including regional and interexchange carriers, cable and wireless providers, broadcasters, entertainment companies, sports industry, and publishers. Project areas included the Internet and intranets, broadband, network management, customer service and billing, directory assistance, enhanced telephony services, operations support systems, digital broadcast and distribution, digital libraries, sports applications, and video transmission services.

Mr. Ganek joined IBM as a software engineer in 1978 in Poughkeepsie, New York, where he was involved in operating system design and development, computer addressing architecture, and parallel-systems architecture and design. He was the recipient of two Outstanding Innovation Awards for his work on Enterprise Systems Architecture/370 and System/390 Parallel Sysplex Design. In 1985 he was appointed manager of MVS Design and Performance Analysis, where he was responsible for the technical plan and content of the MVS control program.

Subsequently he was appointed VM/XA advanced-system manager, responsible for strategy, design, planning, customer support, system evaluation, and product delivery and control.

Mr. Ganek was appointed Director of Worldwide Software Manufacturing Strategy in 1990 and became responsible for IBM's strategy for manufacturing, distribution, and packaging of software, software service, and publications across all hardware platforms. In 1992 he was named Programming Systems Director, Quality and Development Operations, and led quality programs for the Programming Systems Division; he was also responsible for the software development process, including tools, technology, metrics, information development, and software service for IBM's software community.

He joined the Telecommunications and Media Industry Unit in 1994 and assumed his current responsibilities in January 1998. Mr. Ganek received his M.S. in Computer Science from Rutgers University in 1981. He holds 12 U.S. patents.

RALPH E. GOMORY

Ralph E. Gomory has been President of the Alfred P. Sloan Foundation since June 1989. Dr. Gomory received his B.A. from Williams College in 1950, studied at Cambridge University, and received his Ph.D. in mathematics from Princeton University in 1954. He served in the U.S. Navy from 1954 to 1957.

Dr. Gomory was Higgins lecturer and Assistant Professor at Princeton University, 1957-59. He joined the Research Division of IBM in 1959, was named an IBM fellow in 1964, and became Director of the Mathematical Sciences Department in 1965. He was made IBM Director of Research in 1970 with line responsibility for IBM's Research Division. He held that position until 1986, becoming IBM Vice President in 1973 and Senior Vice President in 1985. In 1986 he became IBM Senior Vice President for Science and Technology. In 1989 he retired from IBM and became President of the Alfred P. Sloan Foundation.

He has served in many capacities in academic, industrial, and government organizations, and is a member of both the National Academy of Science and the National Academy of Engineering. He has been awarded a number of honorary degrees and prizes, including the Lanchester Prize in 1963, the John von Neumann Theory Prize in 1984, the IEEE Engineering Leadership Recognition Award in 1988, the National Medal of Science awarded by the President in 1988, the Arthur M. Bueche Award of the National Academy of Engineering in 1993, the Heinz Award for Technology, the Economy and Employment in 1998, the Madison Medal award of Princeton University in 1999, and the Sheffield Fellowship Award of the Yale University Faculty of Engineering in 2000. He was named to the President's Council of Advisors on Science and Technology in 1990 and served until March 1993. Dr. Gomory is a director of the Washington Post Company, Lexmark International, and Polaroid Corporation.

Dr. Gomory's research interests have included integer and linear programming, network flow theory, nonlinear differential equations, and computers. In recent years he has written on the nature of technology and product development, research in industry, industrial competitiveness, technological change, and on economic models involving both economies of scale and technological change.

SHANE GREENSTEIN

Shane Greenstein is Associate Professor in the Management and Strategy Department of the Kellogg Graduate School of Management at Northwestern University. He teaches courses on strategy in technology-intensive industries and markets. He is also a Research Associate with the productivity group at the National Bureau of Economic Research. He is a regular columnist on the computer market for *Micro*, published by the Institute of Electronic and Electrical Engineers.

He received his B.A. from University of California, Berkeley, in 1983 and his Ph.D. from Stanford University in 1989, both in economics. He held a postdoctoral fellowship at the Center for Economic Policy Research at Stanford in 1989.

From 1990 to 1997 he was Assistant and then Associate Professor with the Department of Economics and the Institute of Government and Public Affairs at the University of Illinois, Urbana/Champaign. There he taught courses in the economics of technology, regulation, and industry. For the 1994-95 academic year he was Visiting Scholar with the Computer Industry Project at Stanford University and a Research Associate with the Institute for Management, Innovation, and Organizations in the Walter A. Haas School of Business at the University of California, Berkeley.

His research interests cover a wide variety of topics in the economics of high technology. He has studied buyer benefits from advances in computing and communication technology, structural change in information technology markets, standardization in electronics markets, investment in digital infrastructure at private and public firms, the spread of the commercial Internet business, and government procurement of computing services. This research is written for academic, policy, and business audiences.

DALE W. JORGENSON

Dale W. Jorgenson is the Frederic Eaton Abbe Professor of Economics at Harvard University. He has been a Professor in the Department of Economics at Harvard since 1969 and Director of the Program on Technology and Economic Policy at the Kennedy School of Government since 1984. He served as Chairman of the Department of Economics from 1994 to 1997. Jorgenson received his Ph.D.

degree in economics from Harvard in 1959 and his B.A. in economics from Reed College in Portland, Oregon, in 1955.

Jorgenson was elected to membership in the American Philosophical Society in 1998, the Royal Swedish Academy of Sciences in 1989, the National Academy of Sciences in 1978, and the American Academy of Arts and Sciences in 1969. He was elected to Fellowship in the American Association for the Advancement of Science in 1982, the American Statistical Association in 1965, and the Econometric Society in 1964. Uppsala University and the University of Oslo awarded him honorary doctorates in 1991.

Jorgenson is President of the American Economic Association. He has been a member of the Board on Science, Technology, and Economic Policy of the National Research Council since 1991 and was appointed to be Chairman of the Board in 1998. He is also Chairman of Section 54, Economic Sciences, of the National Academy of Sciences. He served as President of the Econometric Society in 1987. Jorgenson received the prestigious John Bates Clark Medal of the American Economic Association in 1971. This Medal is awarded every two years to an economist under forty for excellence in economic research. The citation for this award reads in part:

> Dale Jorgenson has left his mark with great distinction on pure economic theory (with, for example, his work on the growth of a dual economy); and equally on statistical method (with, for example, his development of estimation methods for rational distributed lags). But he is preeminently a master of the territory between economics and statistics, where both have to be applied to the study of concrete problems. His prolonged exploration of the determinants of investment spending, whatever its ultimate lessons, will certainly long stand as one of the finest examples in the marriage of theory and practice in economics.

Jorgenson is the author of more than 200 articles and the author and editor of 20 books on economics. The MIT Press, beginning in 1995, has published his collected papers in nine volumes. The most recent volume, *Econometrics and Producer Behavior*, was published in 2000.

Prior to Jorgenson's appointment at Harvard he was a Professor of Economics at the University of California, Berkeley, where he taught from 1959 to 1969. He has been Visiting Professor of Economics at Stanford University and the Hebrew University of Jerusalem and Visiting Professor of Statistics at Oxford University. He has also served as Ford Foundation Research Professor of Economics at the University of Chicago.

Forty-two economists have collaborated with Jorgenson on published research. An important feature of Jorgenson's research program has been collaboration with students in economics at Berkeley and Harvard, mainly through the supervision of doctoral research. This collaboration has often been the outgrowth of a student's dissertation research and has led to subsequent joint publications. Many of his former students are professors at leading academic institutions in the United States and abroad and several occupy endowed chairs.

DANIEL T. LING

Dr. Daniel T. Ling is currently vice president of Microsoft Research Redmond at Microsoft Corp. Microsoft Research is dedicated to basic and applied research in computer science. Its goal is to develop new technologies that will be key elements in the future of computing, including the creation of Microsoft's .Net platform.

Dan served as Director of the Redmond laboratory from 1995 until his promotion to vice president in April 2000. During this time the Redmond laboratory grew over threefold to include research in such new areas as networking, data mining, computer mediated collaboration, streaming media, devices, and new development tools.

Dan joined Microsoft Research in March 1992 as senior researcher in the area of user interfaces and computer graphics and was one of the founders of the laboratory. Previously he was senior manager at the IBM Thomas J. Watson Research Center. He initially worked on special-purpose VLSI chips for displays and was a coinventor of the video-RAM dynamic memory. He subsequently managed departments that conducted research on advanced microsystems based on 370 and RISC architectures, and the associated systems and VLSI design tools. One of these departments initiated work on a novel machine architecture, organization, and design code-named "America" that led to the IBM RS/6000 workstations. He subsequently managed the veridical user environments department that conducted research in virtual worlds technology, user interfaces, and data visualization.

Dan received his bachelor's, master's, and doctor's degrees in electrical engineering from Stanford University. Dr. Ling holds seven patents and is the author of a variety of publications. He was awarded an IBM Outstanding Innovation Award in 1986 for his coinvention of the video-RAM. He is a member of the Institute of Electrical and Electronics Engineers, the American Physical Society, and the Association for Computing Machinery. He also serves on advisory committees for the University of Washington and the University of California, Berkeley.

ELLIOT E. MAXWELL

Elliot E. Maxwell is presently Special Advisor to the Secretary of Commerce for the Digital Economy. He advises the Secretary on and coordinates Commerce Department activities regarding electronic commerce and the Internet. These include establishing a legal framework for electronic commerce, privacy, consumer protection, increasing access to bandwidth, digital inclusion, and the impact of electronic commerce on other aspects of the economy. He has participated in the U.S. government's Interagency Working Group on Electronic Commerce since its creation.

Prior to joining the administration he worked for a number of years as a consultant and as Assistant Vice President for Corporate Strategy of Pacific Telesis Group, where he combined business, technology, and public policy planning. Maxwell previously served at the Federal Communications Commission as Special Assistant to the Chairman, Deputy Chief of the Office of Plans and Policy, and Deputy Chief of the Office of Science and Technology, and as Director of International Technology Policy at the Department of Commerce. He was also senior counsel to the U.S. Senate Select Committee on Intelligence Activities.

Maxwell graduated from Brown University and Yale University Law School. He has written and spoken widely on issues involving electronic commerce, telecommunications, and technology policy.

DAVID MOWERY

David Mowery is Milton W. Terrill Professor of Business at the Walter A. Haas School of Business at the University of California, Berkeley, and Director of the Haas School's Ph.D. program. He received his undergraduate and Ph.D. degrees in economics from Stanford University and was a postdoctoral fellow at the Harvard Business School. Dr. Mowery taught at Carnegie Mellon University, served as the Study Director for the Panel on Technology and Employment of the National Academy of Sciences, and served in the Office of the U.S. Trade Representative as a Council on Foreign Relations International Affairs Fellow. He has been a member of a number of National Research Council panels, including those on the Competitive Status of the U.S. Civil Aviation Industry; Causes and Consequences of the Internationalization of U.S. Manufacturing; Federal Role in Civilian Technology Development; U.S. Strategies for the Children's Vaccine zInitiative; and Applications of Biotechnology to Contraceptive Research and Development. His research deals with the economics of technological innovation and with the effects of public policies on innovation; he has testified before congressional committees and served as an adviser for the Organisation for Economic Co-operation and Development, various federal agencies and industrial firms.

LEE PRICE

Lee Price is the Deputy Under Secretary for Economic Affairs at the Economics and Statistics Administration (ESA). The Deputy Under Secretary has management responsibility for ESA, which includes the Bureau of the Census, Bureau of Economic Analysis, Office of the Chief Economist, and the Office of Policy Development.

From 1996 until earlier this year Mr. Price was Chief Economist for the U.S. Department of Commerce, where he monitored and analyzed domestic and international economic developments as well as statistical policy issues. From June

1997 to April 1998 he served as the Acting Under Secretary for Economic Affairs at the Department of Commerce.

Mr. Price has overseen the production of the three annual "Digital Economy" reports since 1998. He authored the chapter "What is New in the New Economy?" for the "Digital Economy 2000" report. For the last year Mr. Price has been Vice Chair of the Working Party on the Information Economy at the Organisation for Economic Co-operation and Development.

Before his arrival at the Commerce Department Mr. Price worked at the Joint Economic Committee in Congress, where he held positions as staff director, deputy director, and chief economist. While at that committee Mr. Price worked on a variety of issues, including monetary and fiscal policy, labor and income distribution, and international trade and finance.

After receiving a B.A. in economics from Stanford University he entered the Joint Program in Law Economics at the University of Michigan, where he obtained a J.D. in law and an M.A. in economics. He has published research on a variety of economic topics, including trends in work and income distribution, Japan's trade imbalance, and the internationalization of the U.S. economy.

WILLIAM J. RADUCHEL

William J. Raduchel is Executive Vice President and Chief Technology Officer at AOL Time Warner. He joined AOL from Sun Microsystems, where he was chief strategy officer and a member of its executive committee. In his 11 years at Sun he was also chief information officer, chief financial officer, acting vice president of human resources, and vice president of corporate planning and development.

Prior to Sun he had senior executive roles at Xerox Corporation and McGraw-Hill. After receiving his undergraduate degree in economics from Michigan State, he earned A.M. and Ph.D. degrees in economics from Harvard. He is a director of Myriad International Holdings and a trustee of the Community College Foundation and works with several startup companies.

ROBERT J. SHAPIRO

Robert J. Shapiro serves as the Under Secretary for Economic Affairs at the U.S. Commerce Department. From the time of his nomination in November 1997 to his confirmation by the Senate on April 2, 1998, he acted as senior adviser to Secretary of Commerce William Daley. As Under Secretary, Dr. Shapiro is the senior economic adviser at the Commerce Department and oversees the nation's major statistical agencies, the Census Bureau and the Bureau of Economic Analysis.

Immediately prior to joining the Clinton-Gore Administration, Dr. Shapiro was Vice President of the Progressive Policy Institute and Director of Economic

Studies of the Progressive Foundation. In those capacities he published widely on the U.S. economy and economic policy, while also playing an influential role in public debates on tax and budget policy, the global economy, trade policy, social security reform, and industry subsidies.

While Dr. Shapiro was affiliated with the Progressive Policy Institute and the Progressive Foundation, he was an adviser to senior members of the Clinton-Gore Administration. He also served as President of the Committee on Free Trade and Economic Growth, as an adviser to members of Congress, and as a consultant to major U.S. corporations and financial institutions. In addition, he was a contributing editor to *The New Republic*, *International Economy*, and *Intellectual Capital.com* ; a trustee and advisory board member to educational and charitable organizations; and a lecturer at universities and research institutes.

Dr. Shapiro was principal economic adviser to then Governor William J. Clinton in his 1991-92 presidential campaign and senior adviser during the Clinton-Gore transition. In 1988 he was Deputy National Issues Director and Chief of Economic Policy in the Dukakis-Bentsen presidential campaign. Previously, Dr. Shapiro was Associate Editor of *U.S. News & World Report* and Legislative Director to Senator Daniel Patrick Moynihan of New York.

Dr. Shapiro has been a Fellow of Harvard University and of the National Bureau for Economic Research. He holds a Ph.D. and M.A. from Harvard University, an M.Sc. from the London School of Economics and Political Science, and an A.B. from the University of Chicago.

WILLIAM J. SPENCER

Bill Spencer recently retired as Chairman of SEMATECH, a research and development consortium consisting of 14 international corporations involved in semiconductor manufacturing. From 1990 to 1997 he served as President and Chief Executive Officer of SEMATECH. Prior to 1990 he was Group Vice President and Senior Technical Officer at Xerox Corporation in Stamford, Connecticut, as well as Vice President and Manager of the Xerox Palo Alto Research Center (PARC). He was Director of Systems Development and also Director of Microelectronics at Sandia National Laboratories from 1973 to 1981, prior to joining Xerox. He began his career at Bell Telephone Laboratories in 1959. He received his Ph.D. and M.S. from Kansas State University and an A.B. from William Jewell College in Missouri.

Dr. Spencer is also a Research Professor of Medicine at the University of New Mexico, where the first implantable electronic drug-delivery systems were developed jointly with Sandia National Labs. For this work he received the Regents Meritorious Service Medal and later a D.Sc. from William Jewell College. Until recently he served as a Director of Adobe Systems and a member of the Board of Trustees of the Computer Museum and the Austin Symphony. Currently Dr. Spencer is a Director of the Investment Corporation of America and SRI International. He is also a member of the Board of Trustees of William Jewell College.

Dr. Spencer has served on several National Research Council studies in the areas of technology, trade, cooperation, and competition. In 1998 he cochaired, with former Attorney General Richard Thornburgh, an NRC workshop on "Harnessing Technology for America's Future Economic Growth." In 1998-99 he served as a visiting professor at the Walter A. Haas School of Business and the College of Engineering at the University of California, Berkeley.

GARY STRONG

Gary Strong is a career program manager at the National Science Foundation. He began work at the NSF in January 1995 as an "IPA" (otherwise known as "rotator") and converted to a permanent position in November 1996. He received his Ph.D. from the University of Michigan in 1981 in both Anthropology and Computer and Communication Sciences. For the anthropology portion of his degree he did fieldwork in Japan. (The thesis won the AAAS Socio-psychological prize for 1981.) Before that he worked as an electrical engineer at Bell Labs during the years 17 B.D. (before divestiture) through 10 B.D. His master's degree is from Columbia University and his bachelor's degree is from Michigan, both in electrical engineering. This interdisciplinary background helps him greatly in managing the diverse program of interactive systems.

SAMUEL L. VENNERI

Samuel L. Venneri was appointed Associate Administrator for Aero-Space Technology in February 2000, while retaining his previous position as NASA's Chief Technologist. In the combined position, Venneri is the administrator's principal advisor on agency-wide technology issues. Under Venneri the Office of Aero-Space Technology is charged with developing integrated, long-term, innovative agency-level technology for aeronautics and space. Venneri will also be responsible for developing new commercial partnerships that exploit technology breakthroughs and for establishing and maintaining technology core competencies at the NASA centers.

Venneri was appointed Chief Technologist at NASA headquarters, Washington, D.C., in November 1996. He will report directly to the NASA administrator. He will serve as the principal advisor and advocate on matters concerning agency-wide technology policy and programs. As Chief Technologist Mr. Venneri also chairs NASA's Technology Leadership Council, whose members consist of the Enterprise Associate Administrators, the Chief Engineer and Chief Information Officer, the Comptroller and NASA Center Directors.

Before being named Chief Technologist Mr. Venneri served as Director of the Spacecraft Systems Division in the former Office of Space Access and Technology. In that position he was responsible for the planning, advocacy, and direction of all spacecraft and advanced instrument research and technology activities in that office.

Mr. Venneri started his career at NASA in 1981 as a Program Manager in the Materials and Structures Division, Office of Aeronautics and Space Technology. He was responsible for the technical direction, management, and coordination of programs in spacecraft design technology, structural dynamics, computational analysis and design methodology, and aircraft and engine materials and structures technology. Mr. Venneri was named Director of that office in 1984.

Prior to joining NASA Mr. Venneri was an aerospace consultant with Swales and Associates and principal engineer with Fairchild Space Electronics. In those positions he worked in a variety of areas relating to spacecraft structural design and analysis as well as launch vehicle systems.

Mr. Venneri received his B.S. in aerospace engineering from Pennsylvania State University in 1969 and M.S. in engineering science from George Washington University in 1975. He is presently completing a doctoral program in engineering at George Washington University.

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Appendix D
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