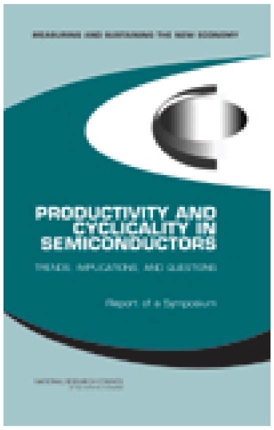

Productivity and Cyclicality in Semiconductors: Trends, Implications, and Questions -- Report of a Symposium

Dale W. Jorgenson and Charles W. Wessner, Editors, Committee on Measuring and Sustaining the New Economy, National Research Council

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Report of a Symposium

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Committee on Measuring and Sustaining the New Economy

Board on Science, Technology, and Economic Policy

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For the National Research Council (NRC), this project was overseen by the Board on Science, Technology and Economic Policy (STEP), a standing board of the NRC established by the National Academies of Sciences and Engineering and the Institute of Medicine in 1991. The mandate of the STEP Board is to integrate understanding of scientific, technological, and economic elements in the formulation of national policies to promote the economic well-being of the United States. A distinctive characteristic of STEP's approach is its frequent interactions with public and private-sector decision makers. STEP bridges the disciplines of business management, engineering, economics, and the social sciences to bring diverse expertise to bear on pressing public policy questions. The members of the STEP Board* and the NRC staff are listed below:

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Contents

Preface

This report is the first in a series designed to improve our understanding of the technological and economic trends underlying the growth and productivity increases that have created what many refer to as the New Economy. Led by the National Research Council's Board on Science, Technology, and Economic Policy (STEP), the goal of this analytical effort is to improve national policy making by improving our understanding of the sources of gains in growth and productivity and our understanding of the policies required to sustain the benefits of this New Economy for the nation.

Even the casual observer is aware of the ongoing revolution in communications, computing, and information management.[1] In the mid-1990s, this technological revolution contributed to a distinct rise in the long-term growth trajectory of the United States.[2] The term "New Economy" captures this new reality and has now become widely accepted by leading economists as a long-term pro-

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[1]This is especially so for the computer hardware sector and perhaps for the Internet 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, *U.S. Productivity Growth 1995-2000, Understanding the Contribution of Information Technology Relative to Other Factors.* Washington, D.C.: McKinsey & Co., October 2001.

[2]See Dale Jorgenson and Kevin Stiroh, "Raising the Speed Limit: U.S. Economic Growth in the Information Age," in National Research Council, *Measuring and Sustaining the New Economy,* D. Jorgenson and C. Wessner, eds, Washington, D.C.: National Academy Press, 2002.

ductivity shift of major significance.[3] What is less widely appreciated is that much of this progress is derived from the significant and sustained increases in semiconductor productivity, predicted over 30 years ago by Gordon Moore and known as Moore's Law.[4]

In approaching a phenomenon as complex as the New Economy, it is important to understand—and sort out—diverse elements of technological innovation, structural change, and the impact of public policy as well as issues of measurement.

- Technological innovation—more accurately, the rapid rate of technological innovation in information technology (including semiconductors, computers, software, and telecommunications) and the rapid growth of the Internet—are seen as the sources of the productivity gains that characterize the New Economy. These productivity gains derive first from the exponential growth in semiconductor performance at ever lower cost.[5] In addition, the use of information technologies in the production of computers has greatly increased the productivity of this industry while having substantial positive effects (albeit with a lag) on the productivity of other important sectors of the economy such as banking, retail, and transportation.[6] Many therefore believe that the productivity gains of the New Economy are closely linked to this unprecedented rate of technological innovation.[7]

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[3]The introduction of advanced productivity-enhancing technologies obviously does not eliminate the business cycle. See Organisation for Economic Cooperation and Development, *Is There a New Economy? A First Report on the OECD Growth Project*, Paris: Organisation for Economic Cooperation and Development, June 2000, p. 17. For an early discussion, 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>.

[4]Academic and policy interest in the New Economy was highlighted by the "Roundtable on the New Economy and Growth in the United States" at the 2003 annual meetings of the American Economic Association, held in Washington, D.C. Roundtable participants included Martin Baily, Martin Feldstein, Robert J. Gordon, Dale Jorgenson, Joseph Stiglitz, and Lawrence Summers.

[5]Price declines, for higher performance, have remained on the order of 17 to 20 percent per annum. See the presentation by Kenneth Flamm in this volume.

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

[7]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. Kenneth Flamm compares favorably the economic impact of semiconductors today with the impact of railroads in the nineteenth century.

- 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.[8] 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[9] and its discretion in setting and enforcing the rules by which technology firms, among others, compete.[10] 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.[11] It supports national research capacities, providing incentives (or disincentives) to promote education and training in key disciplines, and funds most of the nation's basic research.[12] The government also plays a major role in stimulating innovation. It does this most broadly through the patent system.[13] In addition, government procurement and innovation awards have

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

[9]Dr. Vint Cerf notes 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." See comments by Dr. Cerf in National Research Council, *Measuring and Sustaining the New Economy, op. cit*. Also in the same volume, see the presentation by Dr. Shane Greenstein on the evolution of the Internet from academic and government-related applications to the commercial world.

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

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

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

[13]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 *Capitalizing on New Needs and New Opportunities: Government-Industry Partnerships in Biotechnology and Information Technologies*, Washington, D.C.: National Academy Press, 2002.

> played key roles in the development of new technologies to fulfill national missions in defense, agriculture, health, and the environment.[14]

This report seeks to explore the economics underpinning Moore's Law, to identify current R&D challenges and analyze new trends in the semiconductor industry, to discuss how cyclical swings in the industry might be better understood, and to discuss the policy responses available to sustain the benefits of the New Economy.

THE CONTEXT OF THIS REPORT

Since 1991 the National Research Council's Board on Science, Technology, and Economic Policy (STEP) has undertaken a program of activities to improve policy makers' 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 derives directly from its mandate.[15] The STEP Board's activities have corresponded with an increased recognition by policy makers of the importance of technology to economic growth.[16]

This mandate is reflected in an earlier STEP study, titled *U.S. Industry in 2000,* which assesses the determinants of competitive performance in a wide range of manufacturing and service industries, including those relating to information technology.[17] The Board also undertook a major study, chaired by Gordon Moore, Chairman Emeritus of Intel, on how government-industry partnerships support the growth of new technologies.[18] Reflecting a growing recognition of the impact of new information technologies on the surge in productivity since 1995, the Board launched this assessment of the New Economy phenomenon, designed to explore the sources of growth, measurement challenges, and the policy frame-

[14]For example, government support played a critical role in the early development of computers. See K. Flamm, *Creating the Computer*, Washington, D.C.: The Brookings Institution, 1988. For an overview of government-industry collaboration and a discussion of one effective collaborative program, 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. Washington, D.C.: National Academy Press, 2001.

[15]See the Front Matter in this volume.

[16]See Gene Grossman and Elhannan Helpman, *Innovation and Growth in the Global Economy*, Cambridge, MA: MIT Press, 1993.

[17]National Research Council, *U.S. Industry in 2000, Studies in Competitive Performance,* David C. Mowery, ed., Washington, D.C.: National Academy Press, 1999.

[18]For a summary of this multivolume study, See National Research, *Government-Industry Partnerships for the Development of New Technologies, Summary Report,* Charles W. Wessner, ed., Washington, D.C.: The National Academies Press, 2003.

work required to sustain the New Economy. The first exploratory volume was published in 2002.[19] Subsequent workshops and ensuing reports in this series include *Deconstructing the Computer* and *Productivity and Cyclicality in Semiconductors: Trends, Implications, and Questions*—the present report. Future reports in the series will address the software sector, as well as the policies required to sustain the New Economy.

SYMPOSIUM AND DISCUSSIONS

The Committee on Measuring and Sustaining the New Economy convened this symposium to explore how the growth and increased productivity in the semiconductor industry are linked to the economic gains and productivity growth associated with the New Economy. Understanding these trends is important to understanding how to better measure this growth and how to develop the appropriate policy mix to support it. The symposium, convened at Harvard University on September 24, 2001, 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. Three papers complete the volume. The first, "Information Technology and the U.S. Economy," by Dale W. Jorgenson, provides economic underpinning for the symposium discussion and served as the basis for his presentation. The second, "International Technology Roadmaps: The U.S. Semiconductor Experience" by William J. Spencer and T. E. Seidel of SEMATECH, also provided information for the symposium proceedings and was available to participants. The third paper, "Moore's Law and the Economics of Semiconductor Price Trends," by Kenneth Flamm of the University of Texas at Austin, was also distributed at the symposium and was the basis of his presentation. 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. The lessons from this symposium and others in this series will contribute to the Committee's final consensus report on measuring and sustaining the New Economy.

ACKNOWLEDGMENTS

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

[19]National Research Council, *Measuring and Sustaining the New Economy, op.cit*.

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, the National Science Foundation, and Sandia National Laboratories.

Several members of the STEP staff and consultants to STEP deserve recognition for their contributions to the preparation of this report. We are indebted to Alan Anderson for his preparation of the meeting summary. We wish to thank Sujai Shivakumar 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, in preparing this report for publication.

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 and evidence. 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: Ana Aizcorbe, Federal Reserve Bank; Ellen Dulberger, IBM; David Hodges, University of California at Berkeley; Larry Sumney, Semiconductor Research Corporation; and Larry Thompson, Ultratech Stepper, Inc.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the content of the report, nor did they see the final draft before its release. The review of this report was overseen by R. Stephen Berry, University of Chicago, and Gerald P. Dinneen. Appointed by the National Research Council, they were 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.

This report is one step in a major research effort by the Board on Science, Technology, and Economic Policy to advance our understanding of the factors shaping the New Economy in order to better understand it and thereby improve our ability to maintain and develop the policies best suited to sustaining the greater productivity and prosperity that it promises.

Dale W. Jorgenson Charles W. Wessner

I

PROCEEDINGS

Welcome

Ira A. Jackson
Harvard University

Dr. Jackson welcomed the participants from the National Research Council, the business sector, several universities, and other organizations, and he offered a brief description of the mission of the Center for Business and Government at Harvard University's Kennedy School of Government. He said that the Center tries to align business with industry and to match market efficiencies with society's other, competing demands "for equitable outcomes in a process that gains legitimacy and trust."

He praised Dale Jorgenson for his contributions to this area of study and for leading a program in technology, economy, and productivity at the Kennedy School for the past 17 years. Over that period, he said, Dr. Jorgenson's program had produced some "20 serious volumes which have had an impact on intellectual and academic understanding of markets, productivity, efficiency, and tax policy," as well as an important impact on the private sector and on public-sector decision making. He noted that the topic of the day, the semiconductor industry, is critical to all of these areas and has been driving the efficiency, productivity, and growth of the U.S. economy. That economy, he noted, appeared to have lost momentum, and so "we need to apply as much productivity and technological innovation as ever before."

Introduction

Dale W. Jorgenson
Harvard University

Dr. Jorgenson, Chairman of the National Academies Board on Science, Technology, and Economic Policy (STEP), gave a brief history of the organization. STEP was formed a decade ago for the purpose of bringing economics to the National Research Council more directly. Economics had been part of the National Academies' structure for about 25 years, but studies done at the National Research Council—which has a mandate to advise the federal government on issues related to science and technology—did not exploit the potential of economics. Creation of the Board was proposed by Dr. Jorgenson, George Hatsopoulos, long-time Chairman of Thermo-Electron Corporation, and Ralph Landau, a leading chemical engineer who is a faculty member at Stanford University and a fellow at the Kennedy School.

Since its formation under the chairmanship of Michael Spence, a 2001 Nobel laureate in economics, STEP has published more than 20 volumes, including *U.S. Industry in the Year 2000: Studies in Competitive Performance*, edited by Dr. David Mowery of the University of California at Berkeley. This volume, said Dr. Jorgenson, provided a healthy antidote to "declinism," which he described as a literature of the mid-1980s in economics and history that focused on the perceived decline of U.S. industry. Declinism was the focus of a major study of U.S. industry at MIT, resulting in a book entitled *Made in America*.[1] The thesis of the book was that the United States had lost much of its edge in manufacturing, had been surpassed by Japan and other countries, and had entered a period of decline.

[1] Robert M. Solow, Michael Dertouzos, and Richard Lester, *Made in America,* Cambridge, MA:MIT Press, 1989.

By the time *U.S. Industry in 2000* was published, said Dr. Jorgenson, the dozen or so industries it surveyed had regained lost ground or avoided decline altogether. The U.S. semiconductor industry was conspicuous among these and had by then attained a very strong position relative to its counterparts abroad. That industry was the subject of a chapter written by Dr. Mowery and two colleagues. They showed that the industry had come under severe competitive attack in the mid-1980s. By the end of the decade of the 1990s, however, it had returned to international pre-eminence. The speed of that recovery, said Dr. Jorgenson, was "a very important reason for focusing now on that industry."

Dr. Jorgenson introduced Dr. Kenneth Flamm of the University of Texas as the person who had taken the lead in studying the economic impact of the semiconductor industry. Dr. Flamm had demonstrated "to the satisfaction of economists" that the semiconductor industry had been the key force in the revival of the competitive strength of industries related to information technology. Of the successful industries identified in *U.S. Industry in 2000*, well over half had been transformed by the use of information technology, which, in turn, depends on developments in semiconductor technology. This, he said, is another reason to try to understand the semiconductor industry and its future contribution to the economy.

Dr. Jorgenson then turned to his own research and that of colleagues at the Federal Reserve Board of Governors and the Brookings Institution. He described a "growing realization" that information technology is a driving force in the U.S. economy, and he said that the revival of the U.S. economy from its current recession depends heavily on the future of the semiconductor industry. He noted that the semiconductor industry was in the midst of its own severe cyclical contraction, which was even more pronounced than the slowdown of the economy. It had experienced at least three, and possibly four, other downturns during the business expansion that began around 1991 and ended at the end of 2000.

During a 10-year period in which the U.S. economy was generally expanding and the unemployment rate falling, the semiconductor industry was subject to severe cyclical downturns, with the present one being the deepest. One assumption about these downturns is that they are related to a special feature of the industry: its exceptionally high rate of technical progress. The growth of the industry periodically exceeds the capacity of the economy to absorb its products[2]—until this overhang eventually self-corrects in a painful fashion. Hence the industry creates complex challenges for its managers and substantial ripple effects throughout the economy.

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[2] This excess in manufacturing capacity results partially from the fact that the increases in manufacturing capacity—units of clean rooms, for example—are quantum in nature. Another factor contributing to excess in manufacturing capacity is that companies put additional capacity in place to capture a greater market share for new products and technologies. Additionally, ramping up a new technology introduces uncertainties—e.g., uncertainty as to yield—that can exacerbate these issues.

Panel I

Productivity Trends in the Semiconductor Industry

INTRODUCTION

W. Clark McFadden
Dewey Ballantine

Mr. McFadden introduced Robert Doering of Texas Instruments as a man "with a long and distinguished history as a technologist in the semiconductor industry." Dr. Doering is the U.S. Delegate to the International Technology Roadmap Committee for Semiconductors; he has also been very active in the Semiconductor Research Corporation (SRC) and in SEMATECH, the semiconductor industry consortium. He was a central figure in the development and maintenance of the technology roadmap for semiconductors.

PHYSICAL LIMITS OF SILICON CMOS AND SEMICONDUCTOR ROADMAP PREDICTIONS

Robert R. Doering
Texas Instruments

Dr. Doering began by describing the basic features of CMOS, a technology based on a Complementary Metal Oxide Silicon capacitor structure. Through patterning and associated processes, the capacitors are transformed into transistors. Today, the metal layer has been largely replaced by a polysilicon top plate on the capacitor, acting as a gate. Beneath the top plate is an insulating layer—which is normally silicon dioxide, sometimes doped with nitrogen—and below that is the "bulk" silicon crystal.

He showed an illustration of the basic features of the transistor superimposed on a transmission electron micrograph to indicate the scale used in building transistors today. Small dots visible in the silicon substrate represented individual atoms of the transistor. This device, still in development, showed a separation between the source and the drain, called the "channel length," which was only about 30 nanometers, or billionths of a meter. The smallest transistors in production today have channels about twice that long. Along the channel of the research transistor were only about 80 columns of silicon atoms, again about half as many as in products being made today. Given these tiny dimensions, said Dr. Doering, "we are rapidly approaching a scale where it is feasible and appropriate to talk about transistor structure in terms of counting the number of atoms."

When a positive (for NMOS) voltage is placed on the gate, some electrons are attracted out of the substrate into a relatively thin layer near the surface called an "inversion layer." This creates a conductive path between the source and the drain. If another voltage is then applied between the source and drain, a current is pulled through the device; when the gate voltage is off, there is (ideally) no current for any drain to source voltage. In this way, the transistor acts as an on-off control switch.

Decreasing Size, Increasing Sales

He suggested that one way to summarize the history of the industry was to track the continual diminution of the transistors and the wires that connect them into integrated circuits—a process that has been under way since the integrated circuit (IC) was invented in 1958. The IC feature sizes in 1962 were about a millimeter–25 microns, a micron equaling one-millionth of a meter. Today the feature sizes are described in nanometers, or billionths of a meter. We have currently reached interconnect and transistor feature sizes of about 130 nm and 70 nm, respectively, he said. IC makers hope to continue along this path within the next decade or so, toward feature sizes approaching 10 nm. Such infinitesimally small sizes mean that engineers are working with a small number of atoms, something that will soon present problems associated with quantum effects.

Integrated Circuit Sales

A parallel and related trend, he said, is one that economists are familiar with: the growth in integrated circuit sales. Once the cyclicality of the semiconductor industry is "smoothed" on a plot of prices against time, the annual growth of sales is seen to be roughly 15 percent over the long term. He said that total sales were currently in the range of $200 billion a year and estimated that they would move to "an appreciable fraction of a trillion dollars" in the next 10 years.

This decades-long, rapid rise in revenues has been made possible to a large extent by the ability to make features smaller and thereby to place more transistors on a given area of silicon. The manufacturing cost of a square centimeter of silicon for large-volume product such as Dynamic RAM (DRAM) memory does rise slowly, but its rate of increase has so far remained small in comparison to the rate at which engineers have been able to gain efficiency/economy by "scaling down" the feature size of transistors, diodes, capacitors, thyristors, and other individual components built into integrated circuits. For example, transistors are often used in groups of four, corresponding to logic gates.

With feature size—specifically metal half-pitch, as defined by the International Technology Roadmap for Semiconductors (ITRS)—expected to reach 100 nm by 2003, transistor density will have reached about 100 million per square centimeter of silicon, or 25 million logic gates. Firms will benefit from these trends by the ability to market these huge gains in density and performance with very little increase in their own manufacturing costs per the same output of silicon area for high-volume products.

However, low-volume integrated circuits are now deriving less advantage, since the cost of photomasks, which must be amortized over the volume of production for a particular product, has been rapidly rising as feature scaling continues into the deep-sub-micron regime. This factor is becoming increasingly significant. Unless a technical breakthrough (e.g., some relatively low-cost form of "maskless lithography") emerges which solves this issue, Dr. Doering predicted, low-volume integrated circuits at state-of-the-art feature sizes will eventually become more expensive than their predecessors. To some extent, this can be addressed by sharing mask costs via multiple-product masks, but this is obviously less effective for large-area chips.

Costs and Productivity

He then discussed a projection of the cost of transistors based primarily on the semiconductor roadmap. This projection shows unit costs in dollars per square centimeter of silicon increasing gradually from 1999, when the last complete update of the roadmap was done, to the roadmap horizon in 2014. The increase in cost/area is more than offset by the density increase, yielding a decrease in cost per transistor of roughly 18 percent per year. In the revised roadmap for 2001, scheduled to be published shortly, there was to be a more up-to-date projection indicating an even a faster descent in cost per transistor.

He summarized the preceding trends in terms of overall productivity, which showed an exponential trend in technology, such as the ability to make transistors smaller and place more of them on a square centimeter, and the ability to operate faster at lower power. Those trends generate the ability to market new products, or to market the same products at greatly reduced cost, and to create an expanding market. As fuel to power these trends the semiconductor industry invests about 15 percent of the value of sales in research and development.

When Will the Trend End?

It is natural to ask when this favorable trend might end, he said, and the answers vary widely. The reason for this variation is the complexity of the technology. The semiconductor industry has a history of overcoming limitations with new solutions. For example, said Dr. Doering, when he first came to Texas Instruments, the feature size of integrated circuits was about 2 microns; engineers were then predicting that the effectiveness of optical lithography would end when a feature size of about 1 micron was reached. Since that time, feature size has shrunk to about 0.1 micron and, as a result of many ingenious solutions to technical problems, the industry is still using optical lithography.

Hybridization with other technologies in system-on-chip fashion will also extend the phaseout of CMOS. For this reason, CMOS itself will not disappear quickly even as new, miniature system technologies are developed. It will probably support other mechanical, optical, biological, and “nanoelectronic” components placed on the chip or in the package of the same system for a long time.

Yet another factor that complicates predictions is affordability. It is entirely likely, he said, that progress on CMOS technology will end not because engineers run out of ways to make it still smaller or faster, but because the cost of manufacturing outstrips the advantages.

The Future of CMOS

Optimizing the System

CMOS itself represents a vast array of different products: microprocessors, memories, digital signal processors, and other kinds of chips, some of which are optimized more for low power and others more for high performance. Within the overall technology are many parameters and complicated tradeoffs for optimizing the system. A complicating factor is that designers are just beginning to seriously contemplate how to better optimize the technologies at both the circuit and system levels.

Many possible tradeoffs and new ideas at these high levels could mitigate the physical barriers that threaten to slow progress at the fundamental level of transistors and interconnects. For example, until recently few circuits were able to power themselves off when they were not being used; this capacity requires some technique to “wake up” the system. This simple design feature, which could save a great deal of power, is now being increasingly used as one way of optimizing the whole system as we begin to approach the limits of CMOS scaling.

A Question of Tradeoffs

Dr. Doering reviewed the question of tradeoffs in more detail. Basically, he said, CMOS scaling comes down to a set of relationships that have been studied for over 20 years as researchers have tried to make features smaller. Scaling applies to all the simple linear dimensions of the device: the thickness of the oxide, the length of the gate, the width of the transistor and the wire, and so on. Each of these dimensions drops by half each time scaling is doubled. This has typically happened approximately every 4 to 6 years for decades.

In order for the rate of scaling to continue at this pace, each component must function optimally as it shrinks or runs faster. For example, switching speed scales well; as transistors get smaller, they switch faster. This is known as "good scaling behavior." Good scaling behavior also holds true for transistor capacitance, current, and switching power. Voltage scaling introduces some challenges, however; engineers are less confident that lower voltages can continue to be used effectively as thermal noise levels and other voltage limits are approached.

A more serious scaling problem is presented by interconnects—the wires that run between transistors and other components. The speed of interconnects tends to be constant. For chips of the same size, which have wires extending from one side of the chip to the other, speed does not scale well because the resistance of the wires rises as the cross-sectional area falls. This problem can be addressed through designs that arrange the interconnects in hierarchical fashion. That is, wires that must run at high speeds can be very short, while longer wires can be those where high speeds are not as important. This is one simple example of potential tradeoffs and design innovation opportunities.

How a Tradeoff Can Work

A tradeoff at the device level can be seen in the case of a simple circuit called a ring oscillator, which is used to measure the speed of transistors. When a transistor is turned off, some current still leaks from the source to the drain, and that leakage worsens as the size of the transistor shrinks. For a particular technology node, each chip manufacturer will typically design a family of transistors, and within any one family is a tradeoff curve. If lower leakage is desired, the transistor speed must be lower as well. In the same way, if transistor operating voltage or another feature is changed, other parameters must be adjusted to accommodate it. Most companies that sell integrated circuits have processes that are aimed at a number of points along such curves. A customer making a device that runs off wall current, for example, may be interested in high performance but not in whether the standby power is kept low. Another customer, making hand-held devices, does need to worry about power efficiency to prolong battery life.

The Tunneling Problem

There are several ways to increase the performance and reduce the standby power of transistors, and a common one is to reduce the thickness of the gate insulator. This technique has already been pushed to extremes, as in a demonstration by Intel last year of an experimental device with a channel length of 30 nm and a gate-oxide thickness of only 0.8 nm. This is a thickness of less than three atomic layers, which is clearly approaching a limit, especially for an amorphous material such as silicon dioxide. The downside of making a gate oxide so thin is that it loses most of its insulating ability and becomes a new leakage path through the transistor. This current flow is dominated by quantum mechanical "tunneling" of electrons through the barrier, which cannot be prevented in extremely thin layers of any insulator. A possible solution to this problem is to use a material with a higher dielectric constant, such as particular metal oxides or silicates, which can be thicker than silicon dioxide for the same electrical performance. But whether any such material has the reliability and other desirable features of silicon dioxide is not yet known.

Another uncertainty has to do with device structure. Several laboratories are building devices with silicon-on-insulator (SOI) technology, which places the transistor into a thin layer of silicon above a much thicker layer of silicon dioxide to reduce parasitic capacitance. Most technologists, said Dr. Doering, believe that CMOS will go a little farther than basic SOI with double-gate devices that have a gate on the bottom as well as on the top. Simulations with these devices seem to suggest that they may be candidates for feature sizes as small as 10 nm, although they will still require a high dielectric constant gate insulator.

Predicting Limits

He then illustrated how hard it is to predict limits for these devices. Even for double-gate devices, one limit is a drop in the threshold voltage as a function of the gate length. With a given structure, as the gate length becomes smaller and smaller, the transistor must maintain a certain threshold voltage at which it turns on. This voltage should be stable and independent of small variations in the gate length. As a certain gate length is approached, however, the threshold voltage begins to drop rapidly. With one set of materials and thicknesses, that "roll-off" occurs with a gate length of about a 50 nm; for another set that behaves more favorably, the system works well until the gate length is about 20 nm. Researchers must discover how much instability can be tolerated and what techniques can offset this kind of roll-off in a parameter that should be well controlled.

On the other side of the coin, some advances in technology are beneficial but require little in the way of a breakthrough. One class of relatively obvious but cost-effective improvements is called "optical proximity correction," which involves small pattern adjustments in the lithography process. Adding small features or tabs at the corners or other places of the patterns may squeeze small improvements out of the performance of the optical system at relatively little cost. This is another reason why it is so difficult to predict the exact limits of lithography.

The Semiconductor Roadmap

Dr. Doering turned then to a discussion of the semiconductor roadmap, which is now organized around five regions of the world: the United States, Taiwan, Japan, Korea, and Europe. Most major producers of integrated circuits, as well as their suppliers, universities, and government research agencies, send representatives to roadmap committees. These working groups, hierarchically organized at the international and regional levels, actually make the charts and write the chapters of the roadmap itself.

History of the Roadmap

The first edition of the roadmap was drawn up in 1992—a "pretty rushed job compared to how we do it now," said Dr. Doering. In part, it was written in response to the government's request for information about the most urgent research and development needs of the industry. Lithography was a contentious issue then, with competing suggestions about the kind of technology that would succeed the incumbent technology. The Semiconductor Industry Association (SIA) organized the National Technology Roadmap for Semiconductors, and the format was basically shaped during a two-day workshop in Dallas. This format was followed for an update in 1994 and a second update in 1997.

After that, the group decided to open its membership to international companies, beginning with a partial step in 1998 when the first ones were invited both to attend as observers and to critique the process. In 1999 the name was changed to the International Technology Roadmap for Semiconductors and full international participation began. The ITRS has adopted a schedule of biennial updates alternating with semi-annual full revisions. The previous full revision was done in 2001, following a mid-term update in 2000. The International Technology Roadmap for Semiconductors had about 200 participants in the United States—almost half from chip makers, about 30 percent from the supplier community, and the rest from SEMATECH, the Semiconductor Research Corporation, other consortia, universities, government, and other institutions.

Features of the Current Roadmap

He turned to what the roadmap that was then being updated would have to say about continued scaling. From discussions at a workshop in July 2001, he described in two different ways the projected minimum feature size. The first was what could be printed lithographically, the second was one particular feature—the gate length of the transistor. Because the gate length is important to performance, he said, techniques have been developed to make it even smaller than features that can be printed lithographically, so that it is essentially a "sub-lithographic feature." Sub-lithographic techniques take advantage of the fact that transistors are not usually patterned at the lithographic minimum pitch. He said that it was probably best to view overall IC progress in terms of circuit density, the diversity of function being integrated, and Moore's Law.[3] The most important density consideration, he said, is how close together metal wires can be placed on circuits. Another, which is more relevant to speed, is how short the gates of transistors can be.

Potential Solutions

One of the objectives of the roadmap is to indicate potential solutions. He said that there is no lack of ideas on how to stretch optical lithography technology farther through many evolutionary improvements. The next big step in lithography, most people agreed, would be extreme ultraviolet (EUV) technology, which was just entering the research demonstration phase. By 2008 or earlier, he said, a commercial system may have been developed that will bring feature sizes below 50 nm and guide the technology all the way to the end of the roadmap: 2016, according to the 2001 edition. If these systems can be cost effective, lithography won't likely be the limiting factor in IC scaling.

He again raised the question of what comes after CMOS, affirming that there will be other kinds of technologies. The roadmap working groups, which are attempting to anticipate how these technologies will affect speed, cost, and other parameters, assume that silicon CMOS will remain in use for many years, both hybridized with and complemented by other techniques.

He concluded by saying that the consensus now on purely physical limits is that the industry can expect at least 10 more years of CMOS scaling and perhaps 15 years, which represents the current horizon of the roadmap. Beyond that horizon loom a number of technologies, most of them in the very early stages of research, which have the potential to complement CMOS and to allow it to accomplish even more in future integrated circuits.

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[3]The original statement of "Moore's Law" can be found in Gordon E. Moore, "Cramming More Components Onto Integrated Circuits," *Electronics,* 38(8), April 19, 1965. Moore wrote: "The 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." This pattern has held true for a quarter century beyond Dr. Moore's hesitant original suggestion.

DISCUSSANTS

Mr. McFadden thanked Dr. Doering and suggested that the symposium had just heard "a very optimistic view of the challenges we face in trying to deal with continuing productivity gains in the semiconductor industry."

George M. Scalise
Semiconductor Industry Association

Realizing Roadmaps

George Scalise commented that he had participated in the first roadmap meeting in 1991, along with Gordon Moore and several others. Part of what motivated them to meet, he said, was the need to rethink the function of SEMATECH, which lacked a roadmap that could provide guidance for the industry. They made a preliminary outline for such a roadmapping process, and this outline became the starting point for the workshop in Dallas.

The group also realized that the way the new, international version of the roadmapping groups was structured would be critical, and decided that a structure on the model of the United Nations, with a new leader and new forms of governance each year, would not work efficiently. Instead, they agreed that the most effective system would be for the SIA to continue to provide the leadership. There was resistance to this idea at first, but Mr. Scalise and the others prevailed, and in his opinion the SIA leadership has contributed to the smooth working of the first few international iterations.

Collaboration Among Firms

Mr. McFadden then asked Mr. Scalise to respond to the issues of challenges to productivity gains in light of existing business models, and of what the industry might expect as it restructures and continues to tighten its operations in light of the current, constrained economic conditions. Mr. Scalise focused on two aspects of the question. The first was the ability of competing firms in the industry to collaborate, which he described as "one of the things that has really helped to shape the industry over the last many years." Collaboration began with the formation of the Semiconductor Research Corporation in 1982; it continued with SEMATECH in 1987 and then with the ITRS in 1999. We have reached a state, he said, where worldwide collaboration is becoming even more important, and "we have yet to figure out how to do that well. Building an international consortium is a far tougher thing to do than SEMATECH." He expressed optimism, however, that it could be done.

The Foundry Phenomenon

He also commented on the emerging new "fabless" business model in the semiconductor industry, where large, efficient, fabrication-only plants produce custom chips for firms that design the chips. He put this in the context of the industry as a whole, in which firms traditionally have to invest about 23 percent of revenues in manufacturing and facilities in order to maintain "equilibrium" with the 17 percent compounded annual rate of growth. The foundries, he said, have been investing approximately 100 percent of revenues, which is "far beyond anything that can be tolerated in terms of a reasonable business environment."

The consequence of the recent surge in manufacturing capacity, said Mr. Scalise, is "excessive price attrition," well beyond what the traditional integrated firms can compete with. Beyond that, he said, is a new environment that could well be dominated by the success of the foundry model. The question is whether the foundries will become not only the manufacturers but also begin to do design work. If so, what would that mean for the integrated device manufacturers (IDMs)? Will the IDMs move toward the foundry model and stop investing in captive fabs? If they do, who will drive the equipment industry, and who will invest in it?

The old structure, led by IDMs, had been well defined for many years, especially in the United States, which had held a firm grip on the leading edge of every aspect of the business. The U.S.-based suppliers control about 50 percent of the worldwide market. The foundries are now approaching the ability to handle roughly 20 percent of total fabrication, and they are concentrated geographically in Taiwan, Korea, Malaysia, and Singapore, so that the industry is moving toward a new balance.

The Impact of China

He noted that this new balance will certainly include China, which is rapidly surging toward the forefront of the semiconductor universe. This follows its entry into the World Trade Organization (WTO), which the SIA has strongly supported. Now the Taiwanese foundries are moving into China with their technology, aiding the rapid growth taking place there. Current projections are that mainland China will within this decade become number two in the world both as a market and as a manufacturer of semiconductors. Its resulting influence means that it will have a major impact on how the industry functions, something the United States cannot ignore.

"Rest assured that we will not be the same industry either structurally or geographically in a few years, the way things are unfolding today," said Mr. Scalise. He concluded by saying that the country may have to make another concerted effort to maintain its leadership, as it did when the industry lost momentum in the mid-1980s. At that point, many people predicted that the "U.S. industry is finished." The industry once again faces the challenge of responding quickly to a new challenge to its leadership. "If we don't address that," concluded Mr. Scalise, "a panel sitting here in 2010 will have a very different discussion than we're having today."

Charles W. Wessner
National Research Council

An Unanswered Challenge

Dr. Wessner thanked Mr. Scalise for articulating the extent of the challenge—and previous success—yet noted some "asymmetry" among the points made by the first three speakers:

1. The industry is very important to the American economy.
2. The industry faces steep technical challenges but is probably up to them.
3. The industry may be "outflanked" by the sudden recent competition from offshore.

In light of those points, he posed three questions:

1. Does U.S. industry have the resources in place to meet the technical challenges and regain leadership?
2. In light of the overbuild of manufacturing capacity during the current downturn in the business cycle, it is harder for companies to maintain profits. Does that cede advantage to companies focused more on market share than on quarterly profit?
3. Does the U.S. industry have the mechanisms through the MARCO program, the SRC, or SEMATECH to address these technical challenges cooperatively?

Finally, he asked whether a generalized, undefined call for more basic research is an adequate response, given the challenges faced by the industry.

DISCUSSION

Mr. McFadden noted, in regard to the last point, that the industry at its inception in the 1960s used the results of fundamental research done in the 1940s and 1950s to develop its technologies. "Yet we see the federal government reducing the amount of funding in the basic sciences," he said, "at the same time the industry is pressed to maintain its level of capital spending and investment. We need the underlying basic research that's going to allow the U.S. industry to meet these challenges."[4]

[4]Proponents argue that research consortia can efficiently address most of the basic research needs of the semiconductor industry, as articulated in the ITRS, by focusing on precompetitive research needs, providing financial leveraging, and controlling redundancy.

Mr. Scalise added that the concern about basic research is so great that the board of the SIA has made increasing federal funding for university research in mathematics and science its number-one priority for the next year.

Coordinating Fab Investments?

Dr. Pakes asked why the industry had been so effective at coordinating research among the members of SEMATECH and of the SIA, and yet had not been able to coordinate investments in fabs or foundries. Mr. Scalise answered that the purpose of collaboration so far had been to provide the technical capability for innovators to compete vigorously with process technology as well as manufacturing equipment. Manufacturing, to this point, had been one of the competitive tools. In some cases, one company had led the way and others had benefited, as when IBM blazed a trail in moving from four- to six-inch wafers. The following generation of wafers had been driven largely by Intel. But the industry hasn't yet reached the point of collaborating on manufacturing capability. He noted that this question has to be addressed very soon with regard to the foundries.

Dealing with 'Showstoppers' and 'Choke Points'

Dr. Flamm suggested that the international roadmap is often described as a descriptive or predictive process, but that it is really more than either. It involves a complex technology with different pieces from different suppliers, and it has to be coordinated. "What you really have is people identifying technical challenges they call 'showstoppers,'" he said, "and trying to mobilize people to address those 'choke points.'" He said that the situation was the first example he knew of a competitive industry, rather than organizing as a cartel or monopoly, collaborating on the technology-investment aspect of the business only. He added that the practice was explicitly legal because of the Limbert antitrust exemption that had been granted to joint research cartels in 1984. Dr. Pakes seconded that there was no illegality in the activity, and Mr. McFadden said that the activity would be governed by the rule of reason and would not be liable to treble damages.

Mr. McFadden continued that it is important to understand that the roadmap is not a solution to technological problems. It describes various options, challenges, and gaps, and it communicates that information to the industry in ways that suppliers, manufacturers, and customers can appreciate and use. The collaboration still depends on individual competitive actions. In its consortium activity, the industry has been unique not only in establishing roadmaps, but also in having collaborative industry support for university research. The industry invests nearly $100 million a year in university research. It also collaborates on programs like SEMATECH that focus on specific technological problems. "This has always been an activist industry," he said. "The question is, in the kind of economic conditions we're facing now, can we maintain this progress when government investment in university research is declining?"

Faster Cycles

Dr. Jorgenson asked what had caused the roadmap to underestimate the speed at which successive generations of technology are evolving. The roadmap had projected successive generations at about three-year intervals, but in fact new generations have been evolving recently at intervals of closer to two years.

Dr. Doering responded that the adoption of the two-year cycle had been purely competitive. He suggested that the roadmap may even have given some impetus to the faster cycle just by putting "a stake in the ground" that people could try to pass. Aside from that, he said, two years is about the smallest feasible amount of time in which the industry can complete the R&D for a technology generation, and it may not be quite enough time to produce uniform improvements. For example, gate length may come down faster than other parameters. "But from a business standpoint, what's important is to come out with something that is a new technology generation on a two-year cycle, which is just about as fast as it can be done."

More on the New Foundry Model

In response to a question, Mr. Scalise said that it had once been possible for a single company to drive a transition in wafer size from one generation to the next, but this is no longer possible. Moving from the 8-inch to the 12-inch wafer, for example, is far too costly for any one company to accomplish alone. The industry is promoting this transition on an international basis, guided largely by the international roadmap. Similarly, unlike 5 years ago, today only a few of the traditional integrated device manufacturers, who integrate design and manufacture, can afford to invest in wafer fabs. The industry is moving toward the foundry business model, and the capacity coming online at present is dominated by the foundries, not the IDMs. The important question, said Mr. Scalise, is whether this development will continue in the same direction over the next several years and the new foundries will come to represent the dominant new business model of the industry.

Dr. Flamm pointed out that the foundry-based companies spend a smaller percentage of their sales on R&D than do the IDMs, and Mr. Scalise agreed that virtually all of the research in the industry is being performed by the companies on the boards of the SIA, the SRC, and SEMATECH.

Dr. Mowery asked whether the foundry phenomenon is partly a reaction to expanded research activities on the part of the equipment manufacturers, which often produce complete modules with their hardware. These firms sell modules to the other foundries as well as to the IDMs. Mr. Scalise agreed with this assessment and said that the development flowed largely from the activities of the ITRS and SEMATECH in planning for this transition toward a new and evolving business model that includes the specialized foundries.

A Problem for Equipment Suppliers

Mr. McFadden commented that the roadmap may have recently complicated the challenge of the equipment suppliers, who anticipated a more rapid movement into new equipment for large wafers than actually occurred. Dr. Mowery agreed with this point. He said that the roadmap is indeed an important contribution, and that it has facilitated specialized coordination, but that the equipment makers had mistakenly based the timing of their move toward 300-mm wafer technology on the roadmap. This caused them to take on the cost of developing a new generation of equipment that in a sense was not timed properly.

Dr. Mowery emphasized that the timing problem was not the fault of the roadmap. A roadmap cannot eliminate uncertainty. At the same time, it does bring some risk to the industry in that a consensus may suppress less orthodox alternatives and impose higher costs on firms that interpret the time line of the roadmap literally. In the case of some equipment firms, these conditions resulted in higher costs. Mr. Scalise agreed, emphasizing that a "roadmap is just a roadmap—not an architectural blueprint." In this case, he said, the delay in moving from 200-mm to 300-mm wafers unfolded as a consequence of competing elements in the economy, including the industry's own cyclicality.

The Question of Government Support

Dr. Wessner noted that STEP would soon be releasing a report based on a semiconductor conference held late last year.[5] Participants included members of semiconductor consortia from Europe, Japan, and Taiwan, all of whom reported substantial government support. He asked whether it did not seem logical for our government to support the industry as well, given the latter's strategic importance to the nation.

Dr. Doering agreed that U.S. industry had depended heavily on government-supported R&D in the past. If the present falloff in support for fundamental R&D were to continue, it would curtail the industry's ability to address the limits of CMOS technology as well as potential "post-CMOS" breakthroughs. "Based on physical limits," he said, "we need a big R&D effort, on many levels, to come up with new ideas and take them to a point—even in academic research—where

[5]National Research Council, *Securing the Future: Regional and National Programs to Support the Semiconductor Industry,* Charles W. Wessner, ed., Washington D.C.: The National Academies Press, 2003.

they can be picked up by industry. Where that point of transition between academia and industry is located has shifted today toward academia, because we don't have as many large industrial labs that work at the breadth and depth they used to."

Because of industry's reduced ability to do long-term research, he suggested additional government investments in the university research community for programs that can move the technology closer to the commercialization stage than was the practice 10 to 20 years ago. If this is not done, he projected, some of the innovations that will be needed probably won't appear—"at least not in this country."

Panel II

Cyclicality: Comparisons by Industry

INTRODUCTION

Dale W. Jorgenson
Harvard University

Dr. Jorgenson noted that Dr. Flamm, when he began to experiment with mathematical models of the semiconductor industry a decade ago, was one of the few economists in that specialty. Many others are now applying dynamic modeling techniques to the industry.

A MODELING STRATEGY FOR INDUSTRY

Ariel Pakes
Harvard University

Dr. Pakes said that one of the goals of his research was to devise a modeling strategy that can be used to model whole industries. He said that part of this strategy was to construct a framework for dynamic analysis. This approach followed earlier efforts with simple models, which proved to be inadequate to handle the complexity of such large, changing entities as the semiconductor industry.

Constructing the Model

He began by using data from the industry itself to create inputs called "primitives." These are rich enough to determine each firm's profits conditional on the qualities of the products marketed, the costs of production, and the prices charged by all firms. They also determine the likely impacts of investments, the likelihood of potential entrants' appearing, and the costs or benefits generated by an exit decision. The framework assembles the primitives in a coherent fashion and uses them to numerically analyze problems that could not be analyzed with simpler theoretical models. The primitives must be realistic, he emphasized, which means that the person working with the model must have direct access to information about the industry. The user can then use the framework to generate quantitative responses to changes in the business environment or in a policy.

Then he discussed the simplest form of the framework, which he said was a publicly available program found on his web site.[6] The simple form is used mostly for teaching. "The world is a complicated place," he said, "and we want to show students what can happen if you change a tax, a tariff, or an entry barrier and let the whole industry evolve differently." When used for research, the framework needs to be extended to incorporate the major institutional features of the industry being studied. The framework has a static portion and a dynamic portion.

An Equilibrium Assumption

Each static model consists of a demand system and a set of cost functions, one for each producer, along with an equilibrium assumption. In the simple applications, this allows one to solve for reasonable pricing or quantity-setting decisions of firms that are faced with the demand and cost primitives. If we were using a Nash equilibrium pricing assumption, for example, the program would solve for a set of prices at which each firm is doing its best, given the prices of other firms. This is a reasonable "textbook" equilibrium assumption.

Computing Profits

This static pricing assumption will determine the prices, and through the prices the quantity, of each product sold. This plus the cost functions enables the program to compute the profits of each firm as well as consumer benefits. The profits of each firm are calculated as a function of the characteristics of the firm's and its competitors' products and cost functions. The program computes profits for each of the firms for all possible characteristic combinations.

Producing Investment Decisions

The dynamic model goes a step further and feeds these profit functions into another program, which analyzes the investments in developing the characteris-

[6] See <http://post.economics.harvard.edu/faculty/pakes/pakes.html>.

tics of the product or in reducing cost. The goal of the larger program is to produce the likely investment decisions that result from those profit estimates and their likely impact on the industry and consumers.

Extending the Model

The simplest version of the model, said Dr. Pakes, can be extended in many ways. One is to include multiple states per firm, where firms differ in the quality of the product and cost of production. For the semiconductor industry, one would want multiproduct firms, with each firm producing more than one kind of chip. The model can also allow for mergers and make more complicated pricing decisions. In addition, pricing decisions can be based not simply on how prices affect current profits, but also on an independent effect of prices on future profits through their effect on future demand, on future costs, or on future equilibrium prices. A pricing decision that affects future equilibrium can be used to generate various forms of coordination, which is also relevant to the semiconductor industry. It does so by choosing price to ensure that the coordination is "incentive compatible." That is, it ensures that coordinated action will be in each firm's interest; no firm can deviate from the coordination without decreasing its own value.

Dr. Pakes then went through the core version and several extensions of the model in slightly more detail, and he illustrated several challenges in applying it .[7] The simplest version contains one product per firm and one characteristic per product: product quality. The higher the quality of the product, the more people like it. When all the firms producing a product with a certain quality level are combined into a vector, the result is how many firms are producing this quality level. Given investment decisions, the distribution of future quality is independent of price- or quantity-setting decisions. This assumption makes the model easy to work with; dynamic pricing does not have to be considered.

A Program in Three Modules

The Value of a Firm

He said that the *first module* in the program includes only the demand functions, cost functions, and an equilibrium assumption. It is able to calculate the profits of each firm for every possible vector of quality of products in the industry. He then explained the Bellman equation for incumbent behavior. This calculates the value of a firm as the expected discounted value of future net cash flow.

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[7]This model derives from R. Ericson and A. Pakes, "Markov-Perfect Industry Dynamics: A Framework for Empirical Work," *Review of Economic Studies* 62:53-82, 1995.

The actual value will depend on the random outcomes of these investments. However, it is this expected value that one assumes the firm is trying to maximize.

Dynamic Behavior

The Bellman equation is solved in the following way: The firm can either exit or continue. If it continues, it receives current profits and chooses a quantity of investment. The investment improves the probability of having a higher-quality (or lower-cost) product in the next period. The value of the firm in the next period is not known because it depends on the outcome of the random outcomes of the firm's investments and of those of the firm's competitors.

The distribution of tomorrow's quality, given today's quality and the amount invested today, is a primitive. The increment in the quality of the product depends on two things. One is a probability distribution which tells that the value of the increment will depend stochastically on the amount invested. The larger the amount invested, the more likely the outcome is to be good. The second is an exogenous shock that concerns the competitiveness to the industry, or demand.

Reaching an Entry and Exit Strategy

To solve for the firm's investment we require one more factor: the firm's perception of where its competitors will be tomorrow (the profits it is likely to make from any given outcome depend on where its competitors will be). These perceptions must, in some sense, be consistent with the actions of those competitors. An equilibrium occurs when each agent chooses the best of the actions available to it, given perceptions of competitors' behavior that are consistent with what the competitors actually do.

To find an equilibrium in this model assume we know the distribution of where the firm's competitors will be tomorrow. If a firm knows where its competitors are likely to be in future years, the firm can calculate what it should do. That is, an incumbent can determine whether it should exit or continue and what its investment should be if it continues, and a potential entrant can decide whether it should enter. Once all determine what they will do, there is a real distribution of outcomes from all the primitives. When the realized distribution is the same as the belief distribution, equilibrium is reached. In the equilibrium, given a firm's perceptions of what all firms will be doing tomorrow, the firm is doing the best it can. Moreover, the firm's perceptions of where other firms will be tomorrow are stochastically correct. That is, in equilibrium, the distribution a firm perceives is in fact the distribution that derives when all are doing the best they can for themselves. In the *second module* of the program, the computer in effect solves for investment entry and exit strategies.

Comparing Outcomes

The *third module* of the program allows the analyst to simulate outcomes from an initial position. By entering information about where all firms are today, the program can simulate the most likely path for the industry over time. It also answers questions about the likely trends in market structure, investment, etc., and will do another simulation to calculate producer profits and consumer benefits over time. Users can specify a starting point, then change a policy, or demand, or an environmental parameter and compare the two outcomes. The objective is to have a coherent framework in which to work in a dynamic setting.

Examples

The Hospital Industry

He then touched on several extensions of the module that have been developed by others. One was developed for the hospital industry. When the Clinton administration proposed changes in health care, it never analyzed how changing the nature of reimbursement would also change the structure of the hospital industry. When the model was run, the change in reimbursement was predicted to change the equilibrium of the industry, and it was shown that the new equilibrium might not be desirable. This turned out to be the case, with some hospitals merging, others going out of business, and prices actually rising instead of falling in different parts of the country. These things happened, said Dr. Pakes, partly because planners never took into consideration the dynamic impact of changes in the structure of demand.[8]

Analyzing Coordination

Another extension was applied to analysis of the effects of coordinated activities on the part of firms. The perception of coordination differs in Europe, Asia, and the United States. Here, price coordination is traditionally regarded as a form of collusion, in which any coordination on pricing is presumed to be per se illegal. The argument behind this presumption is that higher prices are worse for consumers than lower prices. This presumption, he said, ignores the dynamics involved. If firms collude and raise prices, the higher prices may in fact induce more firms to enter, or firms to produce a more favorable range of quality products, and investment can be more productive.[9]

[8]G. Gowrisankaran, 1998, "Issues and Prospects for Payment System Deregulation," working paper, University of Minnesota.

[9]C. Fershtman and A. Pakes, "A Dynamic Game with Collusion and Price Wars," *RAND Journal of Economics*, 31(2):207-36, 2000.

Other Model Exercises

Dr. Pakes and a collaborator wrote a paper in which they showed that consumers could be better off with collusion than without it. They chose an industry with a very small number of products; the simplest case is an industry where there is a monopoly without collusion. In this case, an active antitrust authority would allow only one firm. If collusion were allowed, it would be optimal for a second firm to enter because prices would be higher. Consumers would then receive both a lower-priced product and more variety to choose from. This argues for price collusion to be subject to the rule of reason, as in Europe. In this case price collusion would not be per se illegal, and the court would decide whether collusion is bad or good for consumers.

Similar exercises can be used to formulate merger policy. With a static horizontal merger model, the reason to merge is to raise prices. When the dynamics of the situation are considered, the merger changes the incentive to enter along with investment incentives.

This discussion seems relevant to the semiconductor industry. It has coordinated interactions in research and development but not in investment. We might want to ask, if we did coordinate our investment strategies, could we get to an equilibrium that would be better for everyone? What would be the implications for consumers, and for the industry itself? This can be done in principle, he said, although further study would have to be done to determine whether it could produce useful answers for the semiconductor industry.

Computational Challenges

He concluded by saying that his modeling technique still has computational problems, but that solutions to these problems now appeared likely. One that seems to be working well is an artificial-intelligence algorithm that acts in a way similar to the self-teaching function of computers. By keeping information on periods when the industry was in a similar situation in the past, and including an examination of what happened then as a result of various actions, the computer is enabled to choose today what would have given the best response yesterday. If these solutions do emerge as expected, dynamic modeling could be a useful analytic and predictive tool for many industries.

THE CASE OF THE AIRCRAFT INDUSTRY

C. Lanier Benkard
Stanford University

Dr. Benkard opened by saying that the aircraft and semiconductor industries have several things in common, including a "learning-by-doing" function. Both industries also respond better to the kind of dynamic model that Dr. Pakes described than to the older type of static model.

Differences and Similarities—Aircraft and Semiconductors

The Learning Curve

There are differences, however. In referring to the learning curve of the industry, he displayed data for the L-1011 airplane, produced by Lockheed from 1972 through 1984. These data demonstrated the direct labor requirement for every plane manufactured, which totaled about 250 units. The first plane required about 1.5 million man-hours to complete, a figure that was quickly reduced by about 80 percent, to about 200,000 hours. This reduction took about 4 years to accomplish, out of a manufacturing lifetime of 14 to 15 years. That product lifetime is near the industry median; the Boeing 747 was brought out in 1969 and is still being manufactured three decades later. By contrast, he said, the semiconductor industry has a much shorter product cycle and learning curve.

Difference in Pricing Behavior

Another difference between the two industries can be seen in pricing behavior. Compared to the steadily declining prices of semiconductor products, real aircraft prices tend to remain largely flat; he illustrated this with a series of prices set between 1958 and 1997. Price rises that did occur for aircraft usually reflected the introduction of a new, more expensive model, as did the progression from the Boeing 747-100 to the 747-400, which was 20 percent larger. He said that the traditional, static business model cannot explain the concurrence of two of the trends— one that showed the cost of labor falling 80 percent, another that showed flat prices for aircraft. Static models tend to produce a "cost-plus" pattern: the cost plus a markup of approximately 100 percent. This is why Dr. Benkard began, like Dr. Pakes, to work with the dynamic model.

Using the Model[10]

The Use of Primitives

His overall modeling approach begins with estimates of model primitives, or static profits. The goal is to estimate profits for each period by knowing, for

[10]For additional details of the model, see C. Lanier Benkard, "A Dynamic Analysis of the Market for Wide-Bodied Commercial Aircraft," NBER Working Paper 7710, National Bureau of Economic Research.

example, the set of products in the market. He then uses a computer to calculate the model equilibrium—what happens in the dynamic model—from these primitives. The model primitives are a set of variables that summarize the "state of the world"—for example, a list of the products in their market and their qualities. The primitives also include a set of control variables, such as quantity or price.

Profit Function

The second objective is to calculate profits. This entails entering a profit function that calculates how the firm's profits will respond as the world changes from period to period, based on the actions of the firm. For aircraft the most important feature, or "state variable," is that planes are differentiated products—that is, they are not all the same. This is probably much more important for aircraft than for semiconductors.[11] As shown by the wide variations in the number of seats and range, some planes have close competitors while others do not.

Dr. Benkard models this by writing down the variables of different planes being produced today and their qualities. Then he enters the firm's experience in producing that plane in period "t"—the learning curve—which determines the cost of producing the plane. He uses a "common state," which is the state of demand in the world. In each period, a firm has to make decisions, such as whether to exit a product it currently produces and how much of that product to produce. Other firms as well will be deciding whether to enter. All these control variables can actually be observed.

Calculating Profits

In working with the model primitives, the next step is to ask how to calculate profits as a function of those variables. This profit function is very simple and standard: price times quantity minus cost. Quantity is simply the amount of product. The price is what the aircraft will bring in the market, using standard techniques of predicting demand with a nested logic model, and the costs are the expense of producing the aircraft. For the other side of the model—cost—a standard learning-curve formulation is used for production costs. The engineers in semiconductor firms are familiar with finding costs in the same way. Of these inputs to the model the most important is profit function.

The other input needed is how the world changes from today to tomorrow. This value turns out to be straightforward, and it is derived from what has already been done. If a firm with a given experience level produces quantity "q," its

[11]This is a matter of opinion. It can be argued that there are more fundamental and significant differentiators among types of integrated circuits than among aircraft, which vary by seats and range. For example, analog integrated circuits are fundamentally different in design, process, and function from digital integrated circuits.

experience tomorrow is its past experience plus the quantity it produces today. Based on what firms have done, the model suggests what products to exit, what products to enter, and so on.

Quantity Today = Investment Tomorrow

One key feature of the aircraft industry that differentiates it slightly from the base-case model of Dr. Pakes is dynamic pricing. The learning curve not only determines profits today, but also the cost of production tomorrow. This gives firms an incentive to produce more and price more aggressively. Expanded quantity resembles a form of cost-reducing investment: The amount a firm produces and sells today is also an investment in tomorrow.

One lesson the model can teach is that it is possible to predict prices, markups, and quantities. He showed a graph plotting the predicted price of the L-1011 from 1972 to 1986 vs. the actual price, and they were very similar. Also similar were the predicted and actual price-to-cost ratios for the same period. This shows that Lockheed's pricing behavior was reasonably close to what it should have been, given the situation. Lockheed's financial losses, he said, were probably caused by the two major oil shocks during the period. The airplane was never sold at a price below cost.

Initial Selling at a Loss

Next he showed a simulation by the model over a 20-year period. At the starting point, four new planes were coming to market. Because they were new, workers still had to learn their tasks, and the costs of all four were high, though at different levels. As the workers progressed along the learning curve, costs declined steeply. This, he said, looks at first like the semiconductor industry, where everyone starts out with products on the same roadmap and the technology is more or less synchronized. In the aircraft industry, by contrast, a new plane may enter the market populated by competitors that are already efficient. The newcomer, with high initial costs, cannot compete if it sells the planes at that cost and must begin by selling planes at a loss. This is an important difference between the two industries.

He showed two more graphs to give the flavor of the model. One graph showed a simulation over the same 20-year period for unit sales. During some years all planes did well, and in others they did not; there were wide fluctuations indicating boom times and recessions.

The second graph showed the firms' realized discounted cash flow for 20 years. At first each firm lost money, then started making it—which is generally what happens in reality. He said that he had experimented with an antitrust policy model, also, which showed that firm antitrust regulations usually have a negative impact on the consumer. He concluded by saying that cooperation among firms in industries like the aircraft and semiconductor industries might be beneficial from an economic point of view.

SEMICONDUCTOR INDUSTRY

Minjae Song
Harvard University

Mr. Song said that he is writing his economics thesis on the microprocessor industry, and that he chose that industry because he believed it offered the most dramatic and rapid innovations in the economy. He has developed a dynamic model to help understand this industry and certain of its features that lend themselves to modeling.

High Costs to Firms

A distinctive feature of this industry, he said, is its continuous introduction of new generations of semiconductor chips, and the dramatic difference in performance from one generation to the next. The cost of rapid innovation is very high, and it has been increasing over time. The costs consist of building new fabrication plants, or fabs, upgrading existing fabs, buying new equipment, and performing research and development, which is very expensive in this industry.

Standard models of the industry have used marginal costs, he said, but his objective is to include sunk costs to firms, a factor of predominant importance in this industry. One cause of high sunk costs is the very short life span of products. For example, the longest life span of a single chip, according to his data, has been 8 to 10 quarters. The average life span of the technology is 2 to 3 years. Over the past ten years, the industry has produced five to six different generations of semiconductors.

Basic Model Features

"These are the basic features that I want in my model," Mr. Song said.

'Frontier' and 'non-Frontier' Products

The model allows for two firms in the market producing two types of products. The "frontier" product and the "non-frontier" product coexist in the industry at the same time, with the former having better technology than the latter. When a firm introduces the frontier product, the previous frontier product becomes a non-frontier product. Thus frontier and non-frontier are relative terms. For example, when both Pentium 2 and Pentium 3 processors were in the market, Pentium 3 was used as the frontier product for the model. Then Pentium 3 became the non-frontier product with the introduction of Pentium 4.

The "Entry" of a Plant

The firm produces each product in a separate plant, so that a plant represents a particular type of product. The entry of a firm into the production of a new product can be expressed as the "entry" of a new plant. But the plant does not have to represent a single fab; it can represent a group of fabs that use the same technology. There are at most four plants in this industry shared by two firms, with one plant producing one type of product or two plants producing both types of the product at the same time. In the model, the sunk cost to the firm is introduced by the entry cost of each plant.

In his model are two state variables. First, efficiency variables for each firm are present in the standard dynamic model. To this a second state variable called the "technology variable" is added to represent whether the product is a frontier or non-frontier product. Quality here is defined as a certain value plus other attributes the firm tries to improve.

Choosing Among Strategies

The firm can then choose among several strategies. Along with entry into and exit from the market and average period of investment, another strategy choice for firms is the entry and exit of the plant. A firm with one plant can keep producing its one product, or introduce a frontier product by setting up a new plant, or exit the market. A firm with two plants can keep producing two products, or choose one and exit the other, or introduce another frontier product and take the non-frontier product out of the market. Thus a single firm uses this kind of decision tree, depending on where the firm is. It computes the value of each strategy at given points and chooses the one that gives the firm the highest value. That value is not just current profit, but the sum of all net cash flow and the option value of having or not having plants in the market.The model can also include other features of industry. One is increasing firm cost over time. For example, it is reasonable to allow the entry cost of a plant to increase over time. The entry cost of introducing a new type of product yesterday was lower than it is today. Another feature of the model is that it allows firms to be asymmetric in terms of the entry costs, so that one firm is more efficient than others at introducing a new product. The model can also introduce spillover effects in the market. When one firm is first to introduce a frontier product in the market, it is easier for the other firms to follow suit. So the entry costs of a new plant depend on whether it is producing a frontier product or not.

Outputs of the Model

Measuring Value and Benefits

From this model, one can expect to measure the value of a firm's innovations and investments. It is also possible to measure the benefit of the innovations to society. This measurement of welfare is based on demand, which is estimated outside the model. This estimate involves collecting product-level data for the microprocessors, making an estimate of demand, and incorporating that demand into the model to make it as realistic as possible.

The entry and exit of the plant may represent the product cycle for this model. The entry of the plant may represent the beginning point for one generation of product, and the exit of that plant may represent the ending point. The model allows a study of whether the plant is more likely to enter or to exit.

Market Outcomes and Policy Questions

The model can also simulate the market outcomes of various market structures. If this industry were a monopoly, for example, how would market outcomes change? What if social planners made a certain decision that affected this industry—what would happen? One can also ask policy questions, such as: If we want more spillovers in this market, does the government have to do something? One can also evaluate the role of SEMATECH or other mechanisms that affect the industry.

DISCUSSION

Questions on Aircraft

Dr. Wessner asked several questions:

- Did the Boeing 747 in effect have a monopoly on the large-airplane market?
- Could the model, in the case of the European Airbus, take into account government subsidies?
- Do aircraft manufacturers make money on aircraft-body maintenance contracts, as engine manufacturers are said to?
- Is the initial low pricing of aircraft a form of forward pricing or dumping which is designed to drive a competitor out of business?

Dr. Benkard responded that the Boeing 747 has a monopoly in certain markets because it has a very long range. But its size does not create a monopoly, because a competitor can compete by flying two smaller planes. This is a condition the model can create.

Second, he said that a desire to evaluate the question of subsidies was one of the reasons for developing the model. He said that it is difficult to quantify the value of Airbus subsidies, however, because they take the form of low-cost loans for new-product investment, along with what seems to be a small output subsidy when state-run airlines purchase the plane.

Third, he said he knew of no case where a company had been able to use forward pricing to drive competitors out of business. The primary reason for low initial pricing is that it is the only way a company can sell its planes into a market already occupied by competitors' products. The market simply adapts in a way that allows this pricing behavior: It must be profitable for a producer to bring in a plane at a low initial price and eventually to make the money back. Otherwise, all the companies would go out of business, whether state-owned or privately owned. He pointed out that this held true even during the postwar years, when the industry was truly competitive, with 22 aircraft producers. Since then, pricing behavior does not seem to have changed, even at a time when the global industry has only two firms manufacturing a relatively small number of products.

The Advantage of the Dynamic Model

Dr. Pakes pursued the idea of when it makes sense to price forward: i.e., for manufacturers to market goods at prices lower than marginal costs. One reason for a company to do that, he said, is to get down its learning curve faster, decrease its cost tomorrow, and perhaps force its competitors out of business. That is in fact what happened in the competition for wide-bodied aircraft, where Lockheed was eventually forced out of the business. A dynamic model is needed to rationalize this order of behavior, which does not appear in the standard static models that economists generally use. If costs tomorrow did not depend on pricing conditions today, a company would never price something at less than marginal variable costs. It would lose money, and there would be no gain tomorrow. Dr. Benkard's model, he said, showed that it makes sense in the aircraft industry to price below cost in the early stages of marketing the good. A company may not recover those costs, as in the case of Lockheed, or it may recover them and much more, as in the case of the Boeing 747.

Strong Demand Expands Markets

David Morgenthaler offered several points about the semiconductor industry and cyclicality. He emphasized Dr. Doering's point about the long-term dynamics of the demand side in the semiconductor industry, which is the declining cost per function. This has the effect of expanding markets, and presumably also of expanding the diversity of markets—the number of different end-use applications. One anomaly is why this increased diversity of end-users does not seem to translate into smoother cycles, especially if all the different markets are moving synchronously.

Opportunity Behind the Frontier

Second, it is important that in the industry as a whole much of the expansion of foundry capacity is really inframarginal capacity. Foundry products are slightly behind the technological frontier. In this behavior, the semiconductor industry differs both from the aircraft industry and the microprocessor subsegment. He suggested that what is really happening is that the expanding diversity of the market for semiconductors is creating opportunities for short product runs that are one or sometimes two generations behind the frontier. This is where foundries have historically done very well, at least partly because semiconductors constitute input for many diverse products.

Leasing

Third, he discussed the practice of leasing for both industries. For aircraft, leasing of the product has been an important and growing source of demand. Lease companies in some cases take advantage of cyclicality by buying aircraft in down cycles. In the semiconductor industry, leasing in the equipment segment is also growing fairly rapidly. This may be driven partly by increased cost of capacity and partly by increased diversity of demand for equipment. It has interesting implications for entry into the industry, for capacity extension, for demand cycles, and for the cyclical behavior of markets for semiconductor equipment.

Do the Models Begin at Equilibrium?

Dr. Flamm complimented the modelers for the realism of their results and asked a question about calibrating the models to actual data: Did the modelers assume that the observed histories reflected equilibrium positions, or did they begin out of equilibrium and move toward it?

Dr. Benkard said that he could take either approach. His own approach, which was to estimate demand and cost and to use them as inputs, did not rely on the real world being in equilibrium. It took the inputs and then asked what the equilibrium would be. However, he said, he could also use the model in such a way that it required the real world to be in equilibrium.

Dr. Pakes agreed. He said that the preferred way of modeling is to have estimates for cost and estimates for demand. However, this is difficult for some parameters, such as the cost of entry. As a technical matter, it is virtually impossible to estimate all the parameters by using the equilibrium behavior. For parameters that were difficult to get at, he suggested gathering data from people in the industry and using a range of reasonable values.

Luncheon Address: The Industry Perspective on Semiconductors

George M. Scalise
Semiconductor Industry Association

Mr. Scalise prefaced his talk by addressing the unfortunate events of September 11 and their impact on the semiconductor industry. Then he offered a quote from Alan Greenspan, chairman of the Federal Reserve Board, made a year and a half earlier: "An economy that 20 years ago seemed to have seen its better days has enjoyed a remarkable run of economic growth that appears to have its roots in the ongoing advances in technology." He agreed, saying that that observation was still valid and would continue to be valid for a long period.

THE NEAR-TERM OUTLOOK

He began with the near-term outlook, showing a chart on which worldwide semiconductor revenues were down about 37 percent as of July 2001. He called that decline "dramatic" but said it was slightly better than it had been on a month-to-month basis in the prior period. He said that the industry seemed to be dealing with a cyclical issue largely inventory-driven, rather than a structural change in industry. One of the reasons for the decline, he suggested, is related to the investment in capital equipment over the last several years. In the year 2000 worldwide investment in capital equipment nearly doubled, from $25 billion to $48 billion, over the preceding year—"a very large increase." The forecast for the year 2001 was $31 billion, still roughly 20 percent higher than the investment of 1999. He said that this suggested considerable "excess investment," most of which had gone to the foundries.

He then compared the integrated device manufacturers[12] with the foundries.[13] The IDMs traditionally invest about 23 percent of sales to maintain a 17 percent compound annual growth rate (CAGR). Capital investment for the industry as a whole was then well above that range, which he attributed to heavy spending on new plants by the foundry groups—a trend that he said would soon come "back into balance."

Another "piece of good news" that might bring the industry back into balance in the relatively near term is the book-to-bill ratio for equipment, as opposed to that for semiconductors. Although the ratio had been unfavorable (below unity) since February 2001, it had more recently been moving steadily closer to unity.

Capacity utilization rates, at an average of about 72 percent, were unfavorable and not showing improvement. However, he said, if the companies were broken down into IDMs and foundries, the rates for IDMs were 82 to 84 percent, whereas the foundries were between 30 and 40 percent and had not yet stabilized.

Prices and Inventory

A point that had been discussed late in the morning session concerned functionality and price, measured by the chip price/performance index. This index comprehends not just microprocessors and memory, but a broad spectrum of products. The index is moving at a rate slightly below what Moore's Law would "require," which seemed to reflect the excess manufacturing capacity and the resulting price pressures. However, Mr. Scalise said that prices were beginning to return to the 30-percent-per-year rate of decline of recent years. He turned then to excess inventory, which at the beginning of 2001 was at about $15 billion worth of product. That amount had been reduced by nearly half during the year, while demand had grown—"a combination that bodes well for the outlook from here."

A Turn in the Cycle?

One piece of justification for that optimism was that consumption had begun to exceed shipments for the first time since about April 2001, which was beginning to bring down the inventory in the channel. In the view of the SIA, that meant that the September quarter would be the last down quarter of the current semiconductor cycle, and that the December quarter would be the first growth quarter of the next cycle. As a consequence of September 11, he said, the Septem-

[12]The IDMs, which include IBM, Intel, and Texas Instruments, are companies that integrate multiple functions, including research, design, and manufacture, in one company.

[13]"Foundries," such as Taiwan Semiconductor Manufacturing Co. and United Microelectronics Co., focus almost exclusively on manufacturing for IDMs and "fabless" customers that lack manufacturing facilities.

ber quarter would be a little lower than anticipated, and the growth in the December quarter would be a little less. Fourth-quarter growth had originally been projected at 5 to 7 percent over the third quarter, and that projection had been lowered to 1 to 5 percent. "But what is important," he said, "is that we are still on that same track."

Industry Megatrends

He turned then to several "megatrends" for the industry. The first was that about 70 percent of all semiconductors were used for communication and computation. These products would be needed in the immediate future to deal with the "terrorist world that we now face"; the government would need hand-held devices for communication and computation, numerous kinds of GPS devices, and faster core memory for transportable PCs. Wireless communication, in particular, was projected to become a much larger market. He concluded that the near-term outlook was not quite as robust as it was before September 11 but still had the "same dynamic." He referred to a large number of new semiconductor-based products due on the market by the Christmas shopping season, including Blackberry-based devices and miniaturized digital audio products, some of which would replace portable CD players.

LONG-TERM TRENDS

For the longer term, he said that information technology (IT) would be the number-one driver of the U.S. economy. While IT represented about 8 percent of the economy, he said, it had provided 30 to 35 percent of economic growth over the previous 5 years. It had also lowered inflation by about 0.5 percent during that period and helped to nearly double productivity.

He said that a shift was taking place in the pattern of semiconductor consumption. In 1995, 56 percent of semiconductors went into computers and 14 percent into communication devices; in 2001 those figures had changed to 46 and 24 percent, respectively, with communications growing rapidly. Consumer products had held steady at around 15 percent. In response to a question, he said that the auto industry consumed about 5 percent of semiconductors.

SEMICONDUCTORS AND STRUCTURAL CHANGES

Impact on the Economy of Computers and the Internet

He described a change in the economy in the mid-1990s, when a host of technologies—including the Internet and e-commerce—converged. Since then the Internet had become more functional, PCs faster, operating systems more reliable, memory and microprocessors cheaper, communications better, and hand-held devices more numerous. All have converged, he said, to bring new elements that will impact the economy for the long term, in terms both of growth and of making major contributions to the deflationary forces in the economy.

To illustrate this change, he showed the changes in the average retail desktop PC from August 1995 to 2001. It had become 18 times as powerful, its clock rate had risen 12 to 15 times, disk storage had increased 50 to 60 times, and memory had increased more than a dozen times. Computers now had a new dimension of connectivity, beginning with built-in modems, and the price was about half of what it had been. That is the real contribution of this industry, he said, and under Moore's Law it may be able to continue this contribution for 10 to 15 years. If the industry can move beyond scaling, he said, the impact on the economy will continue to be as strong as it has been for last several years.

The Value of Free Trade

Continued advances will be driven by free trade and globalization, he said. The trade agreements over last three decades, for which the SIA lobbied hard, had "made trade work." In particular, the U.S.-Japan Semiconductor Trade Agreement of 1986 successfully addressed two major issues: dumping and market access. Foreign suppliers' share of the Japanese market had grown from 8 percent in the mid-1980s to between 30 and 35 percent today. U.S. suppliers' share of the world market had recovered from a low of about 34 percent in the mid-1980s to about 52 percent.

A more recent international agreement saved U.S. companies about $1.5 billion in tariffs.[14] "Convincing the rest of the world to adopt that treaty was not easy," he said, "but eventually even the Europeans agreed that tariffs are just a cost that adds nothing to the ability to compete in the markets." Another result of trade agreements was that innovators were allowed to reap the rewards of their work.

A major international event, he said, is the entry of China into the WTO. As a market for semiconductors, the Chinese have moved into the third or fourth position, and in the next decade are expected to be number two. They are expected to become second in the world in manufacturing as well, at around the same time.

Legal Protection for Bits

Urgently needed in both international trade and e-commerce, continued Mr. Scalise, is an agreement on legal protections covering all digital products, including software, that are as effective as the legal protections covering physical goods. The key to this transformation, he said is to achieve "technological neutrality" so that "bits and atoms" are treated equally under tax and tariff regula-

[14]The Information Technology Agreement of 1997, signed by 52 countries, eliminated all IT tariffs.

tions. "Our view is that a good is a good, whether you buy it in a package or download it from the Internet. That's going to be an important principle for e-commerce."

CHALLENGES AHEAD

Major R&D Needs

Turning to the R&D needs of the industry, he saw a "big problem." He said that federal spending on basic research as a percentage of the overall federal budget had declined by about 60 percent since 1992. While overall R&D spending had remained nearly constant at about 2.5 percent of GDP, the mix had changed dramatically. The federal share had dropped from a high in the 1960s of about 2 percent to about 0.8 percent, while the industrial share had increased from about 0.5 percent to nearly 2 percent.

He expressed concern that even though the total is roughly the same, it represents "a much less stable investment environment." That is, during economic downturns, companies tend to cut their investments in R&D, whereas a government can maintain a more even funding rate.

He noted that among all the disciplines mathematics and science had suffered large cuts, while the medical area was receiving large increases.[15] He noted that medical advances depend not only on health research, but also on diagnostics, metrics, instrumentation, and other fields that are built on a foundation of basic physical science and technology.

Workforce Challenges

He noted challenges in the area of workforce trends as well. He cited the example of TIMSS scores, in which U.S. students are performing below world levels, and said that much more needs to be done for K-12 students in mathematics and science.[16] The number of bachelor's degrees awarded in electrical engineering has fallen about 40 percent over the last several years. While the decline

[15]He quoted an excerpt of a letter from John Hennessey, president of Stanford University, to President Bush: "The initiative to double the budget of the National Institutes of Health is opening frontiers in life sciences, a wise and productive federal investment. But as Dr. Harold Varmus, former director of NIH, stated correctly in an opinion piece in the *Washington Post* last fall, 'Scientists can wage an effective war only if we as a nation and as a scientific community harness the energies of many disciplines, not just biology and medicine.' Now is the time to further open and explore the frontiers of the physical sciences and engineering by making comparable R&D investments in the Department of Energy's Office of Science, the National Science Foundation, the Department of Defense, and NASA."

[16]For twelfth graders in the most recent TIMSS exams, the average score of international students was 500 vs. 461 for U.S. students.

seems to have flattened out, the numbers are still disappointing. "This industry is growing fast, and it is 30 percent of the economy, so we can't afford to have fewer engineers available." He showed a chart indicating that the number of engineering graduates in other parts of the world is higher than in the United States. In Europe, for example, the number is 140,000 vs. 60,000 in this country. "That," he said, "is going to be a competitive problem."

A Call for Federal Research Funding

To address this challenge, he suggested, federal funding needs to support more IT research. In 1998, 30 percent of industrial R&D went toward work in IT, but only 6 percent of federal R&D was done in IT. "If it's having a 30 percent impact on the economy, we have to invest more at the federal level. That's the number-one message: Invest in the basic research of math and science that will be the driver of the economy one and two decades from now."

Growth and Prices

He then turned to the industry as a whole, which historically has grown at a 17 percent compound annual growth rate. Although that figure had dipped during the downturn, he predicted that the industry would keep to that pace for the next 10 to 15 years—"as long as we make some of the key investments we'll have to make."

He again referred to Moore's Law, saying that the price per bit is continuing to remain on track. A bit of memory cost about 5 percent of what it did in 1995 while providing more functionality. The combination of 17 percent growth and 30 percent decline in prices, he added, translates to about a 55 percent compound annual growth rate in the number of transistors produced. In the year 2000, about 60 million transistors were produced for every person in the world, a figure projected to rise to 1 billion by 2008. He suggested that this would translate into real benefits for countries with poor infrastructure, where enhanced wireless communications would allow people much greater capabilities in not only communication but also computation, health care, and other fields.

Technological Roadblocks

On the horizon, he said, the roadmap indicates some substantial technological problems—most likely arising between 2005 and 2008—if the industry is to maintain the pace of Moore's Law. Most of those roadblocks will begin to emerge as the feature sizes of chips shrink to the range of 100 to 70 nanometers; we are now in the 200-nm range. He said that current plans, which include more investment in R&D, should be sufficient to address these challenges.

RESPONSES BY INDUSTRY

Precompetitive Research by Industry

The first plan is the precompetitive work being funded by the Semiconductor Research Corporation. This program spends $40 million per year on directed research carried out in universities by over 700 graduate students worldwide. In addition, International SEMATECH, in close partnership with its member firms, is supporting research on manufacturing technologies at a level of $140 million annually. Third, the Focus Center Research Program, created in 1998, sponsors a multi-university effort to address major basic research challenges identified by the ITRS.

There are now four Focus programs: a design and test program, led by the University of California at Berkeley; an interconnect team, led by the Georgia Institute of Technology; a circuit systems and software program, led by Carnegie Mellon; and a materials and devices program, the most recently formed, led by MIT. Each program has seven to eight partners, and funding for the four programs totals $22 million a year, which will grow to $60 million a year over the next several years. These programs are designed to solve the problems that are already visible in the short term. "We think we can handle the next several years," said Mr. Scalise. "The issue is what we can do beyond that in the way of basic research."

Policy Suggestions from SIA

He summarized the SIA's suggestions under three categories, as follows:

To ensure adequate Federal funding for basic university research, the SIA proposes:

- A Federal R&D strategy to guide funding, including a commitment to organizations that fund basic research, such as the National Science Foundation.
- A commitment to strengthening research infrastructure to ensure that university labs are adequately equipped and staffed.

To retain the competitive advantage we gain by employing the best and brightest engineers, the SIA proposes:

- Fundamental reform of the H-1B visa process to exempt those who earn master's and Ph.D. degrees in the hard sciences at U.S. universities.

To ensure that the evolution of the Internet is not hindered, the SIA proposes:

- Uniform national and international standards for all public policies, including issues such as taxation, tariffs, access, and privacy.

In addition, the SIA has proposed workforce and education initiatives, a partnership with SECME, and a minority pre-college success program that provides professional development for teachers.[17]

Other SIA Initiatives

The SIA also sponsors a program for technicians with the Maricopa Advanced Technology Education Center (MATEC) to support community college programs for developing fab employees, including undergraduate program assistantships and a program for foundry employees who want to learn design. The SRC has provided support through contract research for master's and Ph.D. students since its founding in 1982.

He described the industry's environmental health and safety emphasis, which has earned it a number-two ranking out of 208 manufacturing industries, according to the Bureau of Labor Statistics. The number-one industry, which assembles communications equipment, does not work with the chemicals and gases that are part of the semiconductor industry. The objective of the semiconductor industry is to move to the number-one ranking, and, more broadly, for all companies once a year to share best practices and to achieve the same worker health standards worldwide.

A POSITIVE OUTLOOK

He closed by stating that the outlook for the industry remains positive. "In our view, it continues to be as strong today as it was 10 to 15 years ago."

In response to a question about funding, he added that the SRC has minimal government involvement—by design. The industry, he said, felt that it needs to provide the funding for the SRC because the research is mainly precompetitive. It has also been internationalized because investments benefit companies around the world. The SRC would like more industrial support, not more federal support; federal funds, it feels, should be devoted to basic research.[18] He also said that funding for the Focus Centers is shared among the SIA (50 percent), the equipment companies (25 percent), and DARPA (25 percent) for the support largely of crosscutting technologies, such as metrology. One option is to include other industries in this support, since the research is often broadly based.

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[17]The SECME (Science, Engineering, Communications, Mathematics Enrichment) program seeks to help historically under-represented and under-served students embark upon and complete post-secondary studies in science, mathematics, engineering, and technology.

[18]The SIA has recently assisted the SRC in establishing a partnership with the NSF to expand university-based ITRS research. Pointing out that financial leverage on an individual company's research investment in the SRC is important, the SRC is now seeking both U.S. and non-U.S. companies to become members and share the responsibility to increase investment in precompetitive, university-based research. Also, because the gap of what needs to be funded vs. what is being funded is ever increasing, the SRC would like government agencies to fund research in partnership with it in order to exploit the SRC's infrastructure, core competencies, and interfaces with industry. According to the SRC, this not only helps to close the funding gap but also provides leverage to both the government and SRC members.

Panel III

Economic Growth and Semiconductor Productivity

INTRODUCTION

Kenneth Flamm
University of Texas at Austin

Dr. Flamm opened Panel II by asking, what is the impact of semiconductor price/performance improvement on user industries? He said that the answer depends on three general factors:

1. The composition of semiconductor input varies greatly across user industries.
2. Price changes vary greatly by chip type.
3. Differences in semiconductor input price changes across the industry may play a significant role in explaining differences in quality-adjusted price declines across user sectors.

Moore's 'Self-fulfilling Prophecy'?

He then reviewed Moore's Law in its original form. In 1965 Gordon Moore noted that the number of devices per chip was doubling every 12 months. Then, in 1975, he revised this observation slightly to say that the number of devices was doubling every 18 months—a "law" that has remained substantially in place to the present. This observation was never intended as a law, of course; Dr. Flamm suggested it might have been a "self-fulfilling prophecy" that "happened because everyone believed it was going to happen." Whatever the mechanism, the Moore's

Law phenomenon included a continuing process of technological innovation that effectively pushed ahead of it the technological "brick wall," that moment when technological roadblocks would slow or halt the pace of doubling.

He then described an "economist's default corollary" to Moore's Law, which describes processing cost in dollars per device. Because lithographic and other advances have produced twice as many features per "technology node" every three years, and the cost of wafer processing has remained roughly constant, the processing cost in dollars per device has shown a compound annual decline rate (CADR) of 21 percent.

An 'Ingenuity Corollary'

Then he added an "ingenuity corollary," consisting of several observations:

- Instead of doubling chip size, the industry has used technological ingenuity to increase chip size by only Z ($Z < 2$) times.
  —A recent example is DRAM size, which has increased by only Z=1.37.
  —Another example is 3-D device structures.
- The use of ingenuity has several implications:
  —For DRAMs recently, CADR has equaled minus-30 percent.
  —For DRAMs in the 1970s and 1980s, the wafer-processing cost also fell, so that CADR equaled approximately minus-37 percent.
  —The Japan/VLSI project has had a competition impact.
- Another example is ASICs (application-specific integrated circuits), which represent rapid, leading-edge technology adoption.
- This has a transitory impact on CADR.

He added that the differences in semiconductor price movements are huge (see Figure 1). The prices declining fastest are those of microprocessors, DRAMs, other MOS logic, and other MOS memory. Prices have declined little for analog devices, bipolar devices, and light-emitting diodes.

The implications for input prices in different user industries are also great, he said. Input prices are much higher for automobiles and all of industry than for computers, "all end-user sectors," and communications.

Tinkering with Moore's Law

Then he looked at the consequences of "tinkering with Moore's Law" so as to change the time required for doubling the number of devices on a chip. In fact, the roadmap committee did just that in the late 1990s, changing the doubling time from every 3 years to every 2 years. This was a consequence partly of technological abilities and partly of competitive pressures. This raised the compound annual decline rate for processing prices from minus-21 percent to minus-29 percent, for

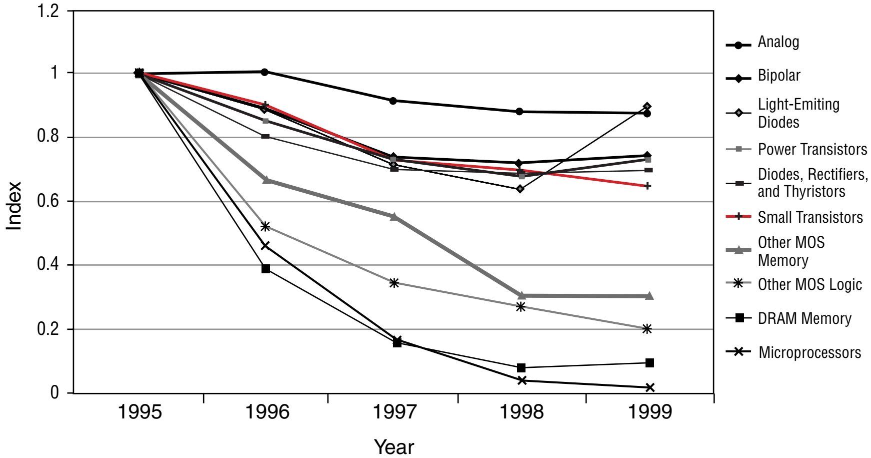

FIGURE 1 Not Everything is DRAMs: Differences in Semiconductor Price Movements are huge.
SOURCE: Aizcorbe, Flamm, and Khushid (2001).

DRAMs from minus-30 percent to minus-41 percent, and for the constant chip size to minus-50 percent.

A Temporary Point of Inflection?

He then discussed the "point of inflection" for price performance, which accelerated sharply between 1995 and 1999, with memory prices falling at a rate of 60 percent a year. This behavior was so anomalous, he suggested, that it would probably prove to be temporary. He examined some of the factors that seemed to have caused the point of inflection, including shorter product lives, intensified competition, and more rapid adoption of leading-edge processors in other products. All of these conditions, he said, were unlikely to persist, and in the future the rate of price declines was likely to return to the historical rate of minus-40 percent. "This rate of minus-60 percent," he concluded," does not seem to be sustainable."

SEMICONDUCTOR PRODUCTIVITY AND COMMUNICATIONS

Mark Pinto
Agere

Dr. Pinto opened by saying that within the semiconductor market communications is growing more rapidly than other subsectors, moving from 17 percent of the $151 billion market in 1995 to 26 percent of a $228 billion market in 2000.

Within communications, such rapid growth has been made possible by optoelectronics, where photonics is outstripping electronics, bringing increased amounts of both data and voice transmission. Within this category, data transmission is growing faster than voice transmission. The demand in the United States for capacity is growing by about 80 percent per year. At this rate, capacity will reach 1 petabit per second by 2006-2007. This would represent a capacity of 5 megabytes per person in the United States, always-on. Business-to-business (B2B) and intranet usage dominate present usage.

Growing Capacity

Optoelectronics

The capacity trend in optoelectronics resembles that described by Moore's Law, which is the doubling of the number of transistors on a chip every 18 months. The total capacity for a single optical fiber has risen a thousand-fold since 1981, for a CAGR of 40 percent. Since 1995 capacity has increased even faster, doubling every 9 months (a 140 percent CAGR). Much of this gain was caused by the advent of wave division multiplexing. "Light-speed," said Dr. Pinto, "is faster than Moore's Law."

Increasing Productivity

The real driver of increased capacity, he said, is productivity. He listed device-cost learning curves, one of which showed a decline of 47 percent per year in silicon transistor costs over a period of four decades. The cost of optical components decreased by up to 35 percent per year in most key segments. System cost reductions have amounted to 120 percent since 1997 for dense wavelength division multiplexing (DWDM).[19] Scalable DWDM systems are important because they enable service providers to accommodate consumer demand for ever-increasing amounts of bandwidth. DWDM allows the transmission of e-mail, video, multimedia, data, and voice information. He added that the same phenomenon is to be seen in the electronic space, where the fundamental issue is to drive down cost as network capacity increases.

[19] DWDM is a fiber-optic transmission technique that employs light wavelengths to transmit data parallel-by-bit or serial-by-character.

Communications Perspectives on Systems Integration

Communications Across Nine Orders of Magnitude

He then showed a communications perspective on systems integration that demonstrated a "distance" of nine orders of magnitude "from IC interconnect to TAT-4"—from the center of a single chip to a fiber-optic system spanning the Atlantic Ocean. Costs rise with distance as one moves to progressively larger structures: the center of a switch, an integrated circuit, an IC package, a circuit board, a box, and finally a network or long-distance cable. At the IC scale, the cost of interconnects can be reduced by monolithic integration; at the network end, the challenge is to establish higher bandwidths through cheaper "effective" interconnects for DWDM and 3G[20] systems.

He illustrated some examples of communications systems that use integrated circuits, including the cordless phone, GPRS wireless terminal, ADSL (asymmetric digital subscriber line) client, Ethernet network information center, and multi-channel wireless infrastructure.

Shrinking Wireless Handsets

Dr. Pinto then illustrated the evolution of the wireless handset since 1978. During that period, the total volume of a wireless handset has shrunk from 2,000 cubic inches, requiring 130 ICs, to 2 cubic inches for a PCMCIA card-driven device. By 2002 the smallest wireless handset, a "soft radio," will occupy just 1 cubic inch, with only two ICs.[21] He said a single small card would be able to carry both a wireless local area network connection and a GPS device.

He mentioned also high data rate wireless communications as an example of "where could we go." One version is known as BLAST, for Bell Labs Layered Space-Time, an architecture for realizing very high data rates over fading wireless channels.[22] This uses a compact antenna array and is the same size as a palm-held portable device. He also discussed module-level optoelectronics integration, which has evolved from a discrete board (1997), to a subsystem in a package (1999), to an OE-IC multichip module (2000). This evolution has been accompanied by gains in size reduction of more than 10 times, in power reduction of more than three times, and in cost reduction through advanced packaging.

[20]3G, or third-generation, systems feature a high degree of commonality of design worldwide, compatibility of services, the use of small pocket terminals with worldwide roaming capability, Internet and other multimedia applications, and a wide range of services and terminals.

[21]A software radio is a radio whose channel modulation waveforms are defined in software. That is, waveforms are generated as sampled digital signals and then converted from digital to analog sound signals.

[22]In more technical terms, BLAST is an extraordinarily bandwidth-efficient approach to wireless communication that takes advantage of the spatial dimension by transmitting and detecting a number of independent co-channel data streams using multiple, essentially co-located antennas.

Advanced Technologies

In other advanced technologies, he briefly discussed monolithic III-V optoelectronic integration, an electroabsorption modulator, and an integrated optical preamp in a detector that cleans up the signal. He discussed heterogeneous integration of various elements (III-V actives, waveguide passives, and optical discretes) into a single SiOB (silicon optical bench). SiOB technology is a fabrication platform for integrated optical device components under development at Bell Laboratories. Devices made using SiOB technology will find application in optical networks, especially those where wavelength division multiplexing (WDM) is used to increase the capacity of the system. Finally, he demonstrated some of the newer silicon MEMS (microelectromechanical systems) in optical networking that had just been shipped in the previous 12 months.

Rapid Evolution of Optical Networking

He then discussed the evolution of optical networking, which has been rapid. Between 1996 and 2002 it had been changing: from WDM transmission, to WDM transmission with the ability to add or drop signals, to WDM rings with node addressing, to WDM rings with full connectivity, and finally to interconnected rings and mesh topologies. This evolution had taken the technology from pure connectivity with discrete components to content and traffic management featuring intelligent subsystems and high-volume, low-cost manufacturing. The area of most intense interest is "metro" systems that bring optics into the public space, if not all the way to the home.

The "Last-mile" Challenge

He returned to the cost of networks vs. the distance from the center of an integrated circuit, updating the work of Mayo to span 18 orders of magnitude in cost. The actual networks of fiber-optic lines are still expensive because of the cost of burying cable, he said. So while the cost of sending gigabits per second per meter is going down sharply, thanks to the use of MEMS and other productivity-enhancing technologies, the cost of the "last mile" of connection is going up just as sharply, especially at distances of more than 100 km from the chip center.

Exponential Improvements—for How Long?

The performance of optoelectronic components has been growing exponentially—a rate that cannot continue indefinitely, he said. In other words, we cannot count on the following trends for much longer: IC capacity increasing at 60 percent per year, computation increasing at 25 percent per year, cost/function decreasing at 30 percent per year, optical network capacity increasing at 140 percent per year, and optical network cost decreasing at 120 percent per year. Among the barriers to these trends, he said, might be the laws of physics, manufacturability, economics, design complexity, and lack of applications.

Are there fundamental limits to fiber optics? He said that a transparency window in fiber optics had been broadened by using materials science to eliminate a source of decibel loss called the "red peak" or "water peak." There may be further improvements of materials possible through coding techniques. But the larger issue here is that once the fiber is in ground, it cannot be replaced whenever a new advance in technology makes replacement desirable.

A View of Future Markets

He offered a view from the year 2001 of the end-user marketplace ahead. One important issue is that capital expenditures by service providers were projected to drop 10 to 30 percent year-over-year from 2000 to 2002, then to grow by 5 to 10 percent per year. To a large extent, service depends on what consumers are willing to spend. He also gave an overview of growth in the network business. Since the beginning of 1998, network capacity has grown by 80 percent per year. Accompanying this growth have been price reductions in the cost of bandwidth of about 80 percent per year.

Some people question whether the applications exist to continue to drive this bandwidth growth. He noted that computing has faced this question for more than 50 years, and the answer has always been "yes." It is logical to suppose, he concluded, that communications, too, will find a continual stream of new applications driven by better networking.

The Key is Productivity

The key in all semiconductor applications is to deliver better productivity. Applications in the foreseeable future are likely to include high-performance computing, virtual conferencing, faster and more intelligent networks, ubiquitous sensing and computing, games and entertainment, interconnected intelligent appliances, and better human interfaces.

SEMICONDUCTOR PRODUCTIVITY AND COMPUTERS

Randall D. Isaac
International Business Machines

Dr. Isaac addressed the complex question of whether computer productivity will continue beyond the range of CMOS scaling. He began by noting that in terms of how many computations per second $1,000 will buy, progress is achieved by migrating to new technologies. The only technology that has made substantial progress without migrating, he said, is the semiconductor, which has leapt ahead in performance by nine orders of magnitude since 1960. The questions he posed are how much life is left in the semiconductor and what will replace it.

Economics as the Driver of Moore's Law

He reviewed the original Moore's Law proposal, affirming Dr. Moore's original statement that increased integration and the consequent gains in performance have been driven primarily by economics. If that ceases to be true, he said, those gains will slow or stop.

He then looked more closely at the factors underlying the improvement of integration. Lithography was by far the most important, accounting for 50 percent of the gains in integration, which is why it has dominated the national discussion about Moore's Law. The other factors were device and circuit innovations, accounting for 25 percent of the gain, and increased chip size (manufacturability), accounting for the remaining 25 percent of the gain. Performance gains were caused by improved transistor performance, interconnect density and delay, packaging and cooling, and circuit level and system level gains. He also said that the evolution of memory density in megabits per chip is one of the fundamental influences on the direction of the industry. Historically the density of megabits per chip had increased four times every 3 years on a consistent basis. That is now changing to a doubling every 3 years.

Trends on the Roadmap

Such trends are the subject of the ITRS lithography roadmap, which attempts to describe the minimum feature size in nanometers for each successive generation of chips. Since 1994 the curve toward smaller size has become steeper, partly because the transition to deep ultraviolet lithography was easier than first thought. It was also accompanied by significant innovations, such as the chemically amplified photo resist, optical proximity correction, off-axis illumination, and additional elements. Implementing all of them at the same time turned out to be much easier than many in industry expected.

Doubts about EUV

The combination of deep UV and its set of accompanying improvements resulted in a surge of improvement in performance. That surge, however, is probably not sustainable. It is already proving to be more difficult to move to 193 nm, and 157 nm is even more of a challenge. He said that signs are emerging already that extreme ultraviolet (EUV) lithography, the next expected technology, may not be as pervasive as its predecessor, partly because the depth of focus may be too small to efficiently pattern levels such as contact holes. At between $40 million and $50 million per tool, the economic challenges of the technology are daunting. It will not be known until the latter part the decade whether lithographic improvement will continue to spurt, will return to its historical level, or to some other level.

He examined the average price of data storage since 1980 in dollars per megabyte and showed that it has decreased even faster than the price of DRAMs. He said that much of the increased use of storage has been drawn by the decrease in prices.

A Tailing off of Scaling

In terms of performance, he noted, scaling would not be able to move technology much further. He said that he would slightly revise Dr. Doering's earlier comment in that he did not think that CMOS device scaling would continue for 10 to 15 years. He predicted that progress in logic performance would come less from scaling than from moving from one kind of device to another, such as the double-gate devices described by Dr. Doering. For a particular transistor, he said, the advantages of scaling would probably tail off, but productivity would continue by jumping from one type of device to another.

He listed a collection of items his company has been working on, including copper technologies, silicon-on-insulator, silicon-germanium, strained silicon, and low-k dielectric. The objective is not to stick too long with a particular scaling paradigm that is flattening out, he said, but to move from one transistor to another to reset the scaling direction.

Pursuing Enhancements

Using Twin Processors that Check Each Other

From a system point of view, technical enhancements, in terms of both area reduction and performance enhancement, had brought his company a year previously to a point where it was able to implement a 64-bit system S/390 microprocessor. This series uses a 175-sq-mm chip with 47 million transistors and seven layers of copper interconnect. It has been possible to run a 1-gigahertz processor on a 20-way system with enough productivity to put two processors on a single chip. The two processors carry out the same function and check each other. If the two do not agree, they retry the instruction and re-check with the other. This capability is a powerful testament to the levels of cost and effectiveness that makers of processors can achieve today.

Incremental Improvements

Modern system-level performance is also efficient because it depends on a large range of factors. Surprisingly, there is a long list of incremental improvements that are far more important than the traditional and better-known CMOS scaling.[23] For a 60 to 90 percent compound annual growth rate in system-performance improvements, both the technology and every one of these improvements are needed. The small improvements account for 80 percent of CAGR, while traditional CMOS scaling accounts for 20 percent of CAGR. And the list of improvements has been growing steadily.

The importance of this concept for productivity is linked to the fact that if one of the improvements slows down, there are more than enough others to take up the slack, especially as regards software. In mathematics, the combinatorial function of the number of components is much faster than exponential. So with hundreds of millions of components on a chip, the number of possibilities that can be combined for large numbers of devices is infinite.

Power Density: the Fly in the Ointment

The Issue of Power Density

He then turned to a "fly in the ointment" which had become an industry-wide concern over the last 12 months: the issue of power at the system level. First he looked at a variety of functions and compared the expectations based in Moore's Law with what had actually happened over the past decade. The expectation for lithography had been an improvement in resolution by a factor of two every six years. In fact, it has moved faster than that. And the impact? Primarily reduction in chip area, he said, which in turn was driven by economics. The cost of a chip is roughly proportional to the chip's area. Because the processing cost per unit area had increased slowly, there was tremendous economic pressure to reduce chip size.

The number of transistors was supposed to follow Moore's Law closely, doubling every 18 months, but the doubling time for microprocessors has been closer to 1.9 years. For performance, which might be supposed to follow Moore's Law as well, doubling had occurred approximately every 18 months. Frequency had not been increasing as fast, doubling about every 2 years, with signs of an upturn in the last 2 years.

[23]The list includes application tuning; middleware tuning; OS tuning/scalability; compilers; multiway systems; motherboard design: electrical, debug; memory subsystem: latency/bandwidth; packaging: more pins, better electrical, cooling; tools/environment/designer productivity; architecture/microarchitecture/logic design; circuit design; new device structures; and other process technology.

Signs of Trouble

The power curve, however, was what brought signs of trouble. Power density should have remained roughly flat, or constant. The only reason for any increase in power density was the 25 percent increase in innovation, which increased the density of the circuit without changing the power. In fact, power density was actually found to rise rather steeply. "This is an important issue," he said. "The fact that power density is going up much faster than classical scaling tells us that as we pack more chips together, we're getting into a power issue."

He displayed some specific examples. On April 10, 1989, Intel released the first 486 chip, a 1-micron technology that held 1.2 million transistors on a 165-sq-mm chip. The 486 used about 4 to 5 W of power at a power density of 2.5 W per square centimeter. If these features were changed only by scaling at the same rate as lithography, then 12 years later, in 2001, one would expect a one-quarter-micron technology using 0.25 W on a 10-sq-mm chip, with the same power density: 2.5 W per square centimeter. If these changes were made at the rate dictated by Moore's Law, one would still reach one-quarter-micron technology, with 300 million transistors on a 660-sq-mm chip. But the chip would use about 66 W of power and 10 W per square centimeter—four times the power density expected from scaling.

What actually happened was much worse. On April 23, 2001, Intel announced the first member of the Pentium 4 family, and it had a power density of *29.5 W per square centimeter*, three times larger than predicted by Moore's Law. How had this happened? The number of transistors was actually much lower than predicted and the power was about the same, but the voltage was much higher, which drove higher performance. If classical scaling had held true, designers could have used many more transistors without causing power problems. The root cause of the problem was that the technology did not follow classical scaling. As a result the power density, due to technology alone, had actually risen not by the predicted factor of three but by a factor of 10.

The Culprit: Operating Temperature

The fundamental reason for this, said Dr. Isaac, is that the one feature not following the scaling pattern is the operating temperature. The ambient temperature should be lowered by a factor of about three to accommodate the decrease in threshold voltage, keeping the "off-current" (the leakage current at zero gate voltage) at negligible levels. "Because the temperature doesn't go down," he said, "the subthreshold current kills us. You can't drop the threshold voltage, so you can't drop the supply voltages." Therefore the power, which is the square of the supply voltage, stays too high. The technology is violating classical scaling, keeping the power density very high.

The consequences are waste heat and high power consumption. Few technologists or economists have factored in the cost of the power for computing; it has been considered trivial. Today, however, the energy consumption of server farms is increasing exponentially. Already, a server farm uses more watts per square foot than a semiconductor or automobile manufacturing plant.[24] Energy needs for server farms are 60 percent of costs.

Too Much Focus on Performance and Frequency

The underlying factor, said Dr. Isaac, is not that chip designs are wasteful, although they could be much more efficient. Rather, the cause is that the industry has been following a high-performance scaling law rather than a low-power scaling law. As a consequence, power density has been rising since 1995, and increases in power density are now inherent in the technology. As engineers place more components more closely together, the power consumption and heat generation have become systemic problems.

A second factor behind the power problem, he said, is the focus on frequency. Even though frequency doesn't affect system performance in linear fashion, it has a large impact on power. For example, a 600-megahertz processor uses more than three times as much power as a 300-megahertz processor. When a design is optimized for frequency, as opposed to system performance, power use rises sharply.

"Been Here Before"

He pointed out that the industry has "been here before." In the early 1990s, the industry hit an early brick wall in terms of power. This technological block was avoided primarily by moving from bipolar to CMOS technology. CMOS technology uses some 100 times fewer parts, 15 times less weight, and 30 times less power than bipolar technology. Bipolar technology is much faster: The industry had to move from a faster building block to a slower building block that was more power efficient. This presented an option for the current situation, he said: to find other building blocks that are more power efficient. This option at first did not seem promising, because there is no known circuit technology ready to replace CMOS, nor is any on the horizon.

A Solution: Parallel Systems

Instead, Dr. Isaac suggested that the industry will move toward massively parallel systems, which use slower but more efficient processors to build a system

[24]Before the recent technology slowdown, many companies were already encountering power shortages. At one point, 27 server farms were proposed for south King County, Washington, where they would require as much energy as Seattle. In Santa Clara, California, a single communications company applied for permission to build a 250-megawatt power plant to power its server farm.

that is, on balance, better. This is done without replacing the circuit. For example, one could replace a Unix processor using 50 to 60 watts of power with one that is much slower but 30 times more power efficient to produce a "higher" system at lower power. The leading technology here is the supercomputer, which has taken exactly this route. The supercomputer roadmap shows a progression over the years, as follows:

- use slower processors with much greater power efficiency;
- scale the technology to desired performance with parallel systems;
- design workload scaling efficiency to sustain power efficiency; and
- keep physical distances small to use less communication power.

One of the productivity challenges in the future, said Dr. Isaac, is to design for the total picture, not just for computations per second. Now that the power issue is no longer negligible, the industry will need to find new solutions. The most promising approach, he concluded, is to make use of solutions with multiple components each of which is so power efficient that the overall system is more productive.

PRODUCTIVITY AND GROWTH: ALTERNATIVE SCENARIOS

Dale W. Jorgenson
Harvard University

Dr. Jorgenson said that his objective in his talk would be to link the two "conversations" of the conference: first, the economics of the industry and its relationship to performance, and second, the issue of price. Economists tend to focus on price, he said, and instead of looking at performance he would examine prices in information technology and show how they were related to trends in the semiconductor industry. He would also discuss the role of IT in the recent U.S. economic boom and its potential for moving that economy in the future. Finally, he would try to relate the issue of prices to the technological issues that had been discussed.

An Amazing Regularity

Moore's Law

He began with a review of Moore's Law and said that the progression from the Intel 4004 processor to the Pentium 4 "has a regularity to it that is amazing to economists as well as technologists." What is interesting from an economic point of view, he said, is the closely related but distinct subject of price behavior. He showed a graphical representation of prices, which required complex calculations to produce, indicating that the price of computing had declined steadily from 1959 to 2001 at a rate of about 16 percent a year. A phenomenon visible in that diagram was a sharp acceleration in the rate of decline of computer prices in the mid-1990s, when the rate of decrease doubled to about 32 percent a year.

The diagram also showed the price declines of memory chips and microprocessors. This information had become available only recently. Prior to 1998, semiconductor prices were not available from the official national accounts. The price of storage devices had declined by about 40 percent a year, and the price of microprocessors by about 50 percent a year. He pointed out the same point of inflection for both products in 1995, although the change was more pronounced for microprocessors than for storage devices.

Shift to the Two-year Cycle

He then displayed the lithography part of the semiconductor roadmap for 2000, which showed a similar change. That is, until 1995 successive generations of these products moved on a three-year cycle, and in 1994 the roadmap committee extrapolated that trend for the next decade or more.

Technology continually outruns the roadmap, however, and beginning in 1995 the map changed to a two-year cycle. The roadmap construction team doubted that this would be permanent, so they planned for a two-year cycle for another two years and then called for a reversion to a three-year cycle. "Reality intruded," however, and the two-year cycle continued. This was then estimated to continue for one more two-year cycle, followed by a region of uncertainty.

Economic Consequences of the Two-year Cycle

The shift to a two-year cycle had important economic consequences. Dr. Jorgenson showed a semi-logarithmic chart that indicated the point of inflection in computer prices more clearly. Unfortunately, the price data for software are incomplete. Only the prepackaged portion—including preinstalled or "shrink-wrapped" software—was part of the national accounts. The rest, including custom software,was not priced in the same way. Even the data for the prepackaged software have only been in the national accounts as investments since 1999.

The price data for communications equipment are also incomplete, including only central office switching equipment and omitting routers, transmission gear, and fiber optics. Nonetheless, to an economist this was a dramatic story, since economists expect price indexes to rise, not fall.

IT and GDP Growth

The Data on Software

He moved on to the implications of this price information for the recent growth resurgence and future economic growth. The share of information technology in GDP is now a little under 7 percent. Software, as measured in the national accounts, has emerged as the most important form of information technology. Computing has had a very important role and up until the end of the 1980s was about equal in importance to software.

A Disproportionate Share of Growth from IT

An important part of the story is how a sector that is only 7 percent of the GDP can play such a large role in the nation's growth. The contribution of IT to growth from 1995 to 1999 was about 1.3 percent; by comparison, the annual growth of the U.S. economy from 1995 to 1999 was about 4 percent. A third of that was due to IT, so that 7 percent of the economy accounts for about a third of its economic growth. The growth rate of IT is equal to its share of the total, about 7 percent, multiplied by the growth rate of its components. The growth rate of the components reflects the fact that prices were declining dramatically and the dollar values were going up. Therefore the quantities were increasing even more rapidly than the prices were falling.

Dr. Jorgenson said that IT has been a very important part of growth for some time, accounting for about half a percentage point during the early 1990s. This tremendous surge at the end of the 1990s, however, pushed the role of IT into the "major leagues" and made it about a quarter of the total. The rate of economic growth increased by about 1.75 percent between the middle and late 1990s. About half a percent of that increase was accounted for by IT, so the contribution of IT was a very important part of the growth.

The Role of IT in Productivity

Within overall economic growth, IT plays a key role in productivity. Dr. Jorgenson discussed the economy in terms of both IT and non-IT inputs and outputs. Productivity growth was relatively rapid in the postwar period, from 1948 to 1973, and IT did not have a very important role. After 1973 productivity grew slowly, by about 0.25 percent per year, but by then the predominant share belonged to IT. From 1990 to 1995 the productivity growth in the non-IT part of the economy was small and negative. Then IT productivity jumped substantially toward the middle of the 1990s. Productivity in general, however, never got back to what economists think of as the Golden Age after the war.

Morals of the IT Story

From this he drew "a number of morals." One is that IT has been a factor in the economy for a long time. Even when the IT industry was only 2 percent of the economy, it accounted for about 80 percent of productivity growth. During the early 1990s, a time when productivity growth was not very substantial, it accounted for basically all productivity growth. During the resurgence of the late 1990s, the escalation in IT productivity growth that appears in the price trends accounts for the total productivity.

For the big picture, therefore, economic growth during the latter 1990s was comparable to the growth of the Golden Age: slightly better than 4 percent a year. By then, IT had become extremely important for both input and productivity. Productivity had always been extremely important, and IT as an input had also been important for decades. But the surge in productivity toward the end of the period was clearly related to the price trend.

The prices of IT are driven primarily by prices of semiconductors, fiber optics, and other components. The surge in the contribution of IT to productivity growth is associated with maintaining the acceleration in the rate of price decline. The authors of the roadmap estimate that that acceleration should continue through 2003. If that is the case, the resurgence should continue. After 2003, they hedged their bets, and there is a possibility of a return to a three-year cycle. There is some division of opinion in the industry. Those who side with the conservative faction behind the roadmap exercise and assume a reversion to a three-year cycle beginning around 2003 can expect the rate of acceleration of productivity to return to previous levels.

The most recent surge in economic growth was not sustainable, because this included an extraordinary gain in the labor force as unemployment declined from 7.3 percent to 4 percent. After taking that into account, however, the growth rate is likely to be relatively rapid, on the order of 3.5 percent a year. If there is a return to the three-year cycle, however, the growth rate is likely to be closer to 2.9 percent. If one splits the difference—assuming a two-year cycle to the year 2003 and then a somewhat longer cycle—the growth figure for the next decade would be about 3.3 percent, which is the estimate of the Congressional Budget Office.

Prices have 'Momentous' Importance

"The moral of this story," said Dr. Jorgenson, "is that the prices of IT and the prices of semiconductors, in particular, are of "momentous" importance to our economy." This importance reaches not only the people concerned with the fate of the industry, but also the people responsible for framing future economic policy for our country.

To estimate the potential growth of our national product, it is necessary to understand both the technology and the economics of this industry. The technology had been discussed in detail at the symposium, he said; for the economics, however, we have to understand how prices and product quality in the industry are determined.

The roadmap describes the opportunities and a possible scenario. Without telling us what is actually going to happen, this does provide the factual basis for an economic analysis of product cycles in this industry. Depending on the outcome, the nation will see a different outcome for the growth of our economy.

In Conclusion, a Call for Better Data

He called attention in closing to the serious gaps in data that prevent a full accounting of semiconductor-related prices. He reiterated that software had been part of our national accounts for only 2 years. Telecom equipment was included in the national accounts, as it had been for many years, but the prices did not include fiber optics, which is fundamental to the future of the industry. He concluded with a call for more and better data in order to assist a better understanding of the nation's productivity and growth.

Panel IV

Roundtable on Models for Cyclical Industries

INTRODUCTION

David C. Mowery
University of California at Berkeley

Dr. Mowery said that one of the motivations for the agenda of the meeting was to try for a better understanding of cyclical behavior, especially in the semiconductor industry, which was then in a severe downturn. He said that he had asked the next three speakers to address at least four issues:

1. the kinds of data or evidence needed to address causes and characteristics of cycles in these industries over time, including changes in the cycles' amplitude and duration, as well as data that allow one to develop time series or longitudinal analyses of these cycles;
2. the linkages, if any, between cyclical behavior in a given industry and the behavior of other forms of investment, particularly in physical capital or innovation R&D;
3. the managerial strategies developed in these industries to deal with these cyclical fluctuations, and how these strategies are influencing the evolution of industry structure and investment in areas such as physical capital and R&D; and
4. keeping in mind that the conference was organized by the STEP Board, the implications for public policy of the analysis of cyclical behavior in a given industry, and whether there is a role for government in dealing with the causes or consequences of industry cycles.

Kenneth Flamm
University of Texas at Austin

Dr. Flamm said he would address the "stylized facts" that should be considered in trying to model the semiconductor industry, as well as some of the modeling work under way at SEMATECH and the University of California at Berkeley. He began by listing some key economic features of the semiconductor industry that might be associated with deep cyclical swings.

FACTORS UNDERPINNING CYCLICALITY IN THE SEMICONDUCTOR INDUSTRY

Rapid Technical Progress

The first is rapid technical progress. This means that holding inventories as a way of smoothing out demand fluctuations is not productive; because of the short lifetimes of semiconductor products, the inventories will lose value and even become obsolete if they are held too long. Instead, firms must sell what they have as quickly as they can.

Scale of R&D Investments

Second, very large R&D investments are required to enter this industry—typically, as much as 10 to 15 percent of annual sales. This R&D is often specific to the segment of the market that the firm is entering.

Nature of Learning Curves

Learning economies are very important. For military aircraft, a learning curve of 85 to 90 percent is estimated, which means a doubling of output drops unit costs by 10 to 15 percent. In semiconductors this curve is closer to 70 percent, quite a bit steeper. In addition, the source of the learning economy in semiconductors is different from that in aircraft.

The curve is not caused necessarily by labor productivity. Instead, improvements come from two sources. One is *die-shrinks*: Over the cost of a product cycle, the number of chips on a wafer increases. Over any product's life, this happens typically two or three times, essentially increasing the product on each silicon wafer. The other source is *yield learning*: The number of good chips on the wafer increases over time as a percentage of the total number of chips. Together these sources generate the steep learning curve. This curve is thought to have flattened somewhat, but good evidence of this is difficult to come by.

High Sunk Costs

Capital intensity is very high and rising. A mid-sized fab today costs $1.5 billion to $2 billion, or even more. Furthermore, if a firm decided to build a fab and then wanted to exit the industry, the resale value would be low. Also, it typically takes 1 to 2 years to build a new fabrication facility. This long gestation time is often overlooked in addressing cyclicality. A spike in demand might prompt a decision to build a fab, but it would not be ready for mass production for a year and a half or two years. This lag time plays a significant role in the very wide swings in the industry, because demand might be fading just as new capacity reaches the market.

Capacity Constraints in Production

The importance of capacity constraints, too, is often overlooked. The output of the semiconductor industry is really a mixed bag including both old, trailing products and new, leading-edge products. Typically, the leading-edge product is produced in the most modern facilities, which are run at full capacity. A modeling strategy that approaches an optimization problem is likely to run up against a constraint boundary. This is important for anyone trying to use interior first-order conditions to make inferences about, say, marginal costs.

The Importance of Technology Shocks

Finally, the sources of deep cyclical swings are difficult to quantify, but conversations with people in the industry indicate that periodic technology shocks have been important in explaining spurts of robust demand. In the early 1990s, for example, the PC market experienced a boom, and this in turn created an unprecedented demand for memory chips that lasted approximately three years. Again, the dawning of the Internet era around 1995 created additional demand for semiconductors that only now appears to have tapered off. Wireless communications also propelled the market forward in a way that had not been anticipated.

PERSPECTIVES ON CAPACITY UTILIZATION

Previously, said Dr. Flamm, most published data on capacity utilization of semiconductors were misleading. Typically, published capacity numbers referred to the entire semiconductor industry. The problem with such numbers is that it mixes older and newer products. The older products are typically produced in depreciated, older fabs that run far below capacity.

It has been common to hear that "the industry is running at a capacity utilization of between 40 and 80 percent" and to assume that capacity constraints were not an issue. In fact, between 1997 and 2001 plants manufacturing semiconductors at feature sizes of 0.4 micron and below, close to the technological frontier, were typically running at 90 to 97 percent of capacity during a period of robust demand.

Another way to view the capacity issue is by analyzing 8-inch wafer starts. This wafer size represented the frontier in 1997, when plants were running at levels above 90 percent of capacity. With the downturn in 2001, the numbers of wafer starts at leading-edge technologies dropped to the 70- to 80-percent range of capacity utilization. But the latest-generation technologies, with features smaller than 0.2 micron, were running as close to capacity as they could.

The reason for this is that the brand-new fabs are the ones that can produce the highest quantities of leading-edge product and do so economically. Even in periods of declining overall capacity utilization, the leading-edge plants are almost always running at essentially full capacity, minus that small fraction of plant equipment that must always be down for upgrade and service purposes.

MODELING THE SEMICONDUCTOR INDUSTRY

An I/O Model for SEMATECH

He then reviewed a project undertaken for SEMATECH to create an economic I/O-style model. To do this, he assumed a vector of demand for semiconductors that was disaggregated into product classes and technology nodes. He worked backward from that vector to detailed requirements for materials, which were driven by an assumption about demand. One goal was to put prices and demand into the model, and another was to create a more realistic investment model, where the amount invested depended on the return on investment (ROI). He also wanted to incorporate some of the influences that produce cyclical behavior, including the general state of the economy. A final goal was to convert the SEMATECH model to an investment algorithm that was based on ROI and could deal with such factors as gestation lag and expectations.

Using an Optimal-control Model

He reviewed a simpler approach to modeling the industry by a deterministic optimal-control model, devised in 1996. That approach assumed that investment in the industry proceeded in two stages. The first was a capacity-investment stage when, at the outset, a firm would invest the amount required to enter the industry, sink resources into capacity, and begin production. This was a relatively simple, open-loop, optimal-control model where every entrant was equal. He found interesting regularities according to the segment of the industry where he applied the model. For DRAMs, the Hirfendahl Hirschman index was strikingly constant from the 1970s through the 1990s at about a level of about 0.1—that is, for a symmetric industry of about 10 equally sized players. That shape seemed to have changed recently as the industry had become more concentrated. But he completed a prototype version of a Nash equilibrium finder that ran with the Excel solver and hoped eventually to integrate that model with the SEMATECH model, which is also programmed in Excel. So far, he concluded, there has been some success in seeing how changes in some of the parameters affect the determination of equilibrium in the industry.

DISCUSSION

Asked whether his work had produced any predictions for the industry, Dr. Flamm said that the rates of technological improvement in the semiconductor industry witnessed in the late 1990s did not seem to be sustainable. "I think we may go back to a rate that is somewhat above previous levels," he said, "but not back to the 60 percent zone we were seeing."

Dr. Jorgenson asked whether the product cycle can be modeled by Dr. Flamm's technique—more specifically, whether the model is capable of explaining the product cycle, which appears to drive both the technology and the price, and therefore the demand.

Dr. Flamm replied that he had so far looked only at the small piece of the model representing demand. But he thought that the model might be applied to the business cycle as follows: Suppose a demand function, and suppose that the amount of product demanded will depend on the price per function. That price, coupled with the amount of capacity investment that determines output, would be essentially fixed in the short run, given the output of all firms. This would give some level of return on an incremental investment in output. The return would include not just current price but also an expectation about future prices.

One could think of an iterative algorithm, he said, that would allow calculation of the rate of return on investment. If that rate of return were above the hurdle rate, the firm would want to increase investment. As investment increased, output would increase at every moment in the future, price would tend to decline as all the identical firms in the industry increased their investment, and at some point the rate of return on investment would drop. Investment would essentially cease as it approached the hurdle rate. In this way the model had a mechanism that could take expectations into account.

C. Lanier Benkard
Stanford University

Dr. Benkard talked briefly about cyclicality in the aircraft industry, including a review of some possible similarities with the semiconductor industry.

COMPARING THE AIRLINE AND SEMICONDUCTOR INDUSTRIES

Rapid Technological Progress

The first possible similarity he considered was rapid technological progress, to which he said, "Not really." For aircraft, he said, the basic technology had not changed for many years. One major innovation came in the late 1960s, when high-bypass jet engines were introduced; these essentially made it possible for large modern jets to fly. More recently, the smaller innovation of fly-by-wire technology had not had a large impact to date, although it may enable the next generation of aircraft design.

Size of R&D Investments

To a second possible similarity between aircraft and semiconductors, large R&D investments, he said, "Absolutely." Bringing out a new aircraft product typically requires from $5 billion to $10 billion, which is often more than the market value of the company. Both industries also require ongoing R&D investment.[25] Both have learning economies as well. For aircraft the consensus number is 80 percent, he said; the number for Lockheed was about 75 percent.

High Fixed Costs

Both industries have large fixed costs: the cost of buying a plant.

Effect of Capacity Constraints

Capacity constraints are very important for aircraft, as for semiconductors, typically increasing during industry booms. These booms do not always coincide with economic expansion, however.

He noted the surprising fact that the largest output year for the commercial aircraft industry was 1991, a year of worldwide recession. This boom was quickly followed by a steep sales slump, then another recovery. Industry sales typically lag the economy, partly because orders must be placed in advance of delivery and partly because labor productivity is low at the beginning of a new product cycle while workers learn their tasks and managers refine production techniques.

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[25]It is possible that R&D investments in the semiconductor industry would seem to reduce the research costs of the aircraft industry.

Shapes of the Learning Cycle

One important difference between the semiconductor and aircraft industries is the shape of the learning cycle. The semiconductor production process is capital intensive, and the learning process is primarily a matter of making small, incremental adjustments to the automated technology.

Aircraft, by contrast, are largely "handmade"—that is, they are put together piece by piece. Plants use the labor-intensive practice of training workers to go from station to station and carry out multiple tasks. The reason for this is that the very low unit output rates—plants produce as few as 20 to 40 planes of a given type per year—do not justify the design and purchase of automated machinery for every phase. This means that the learning curve is a function primarily of labor.

CYCLICALITY EFFECTS OF INDUSTRY FEATURES

Productivity Losses Late in the Cycle

One consequence of this labor-based learning cycle in the aircraft industry is that productivity drops late in the cycle. Lockheed, for example, went from a productive level of about 220,000 man-hours per unit to about 450,000 man-hours per unit—a 50 percent drop in productivity.

The explanation for this productivity loss for Lockheed is actually one of cyclicality in output. When output goes down, the company has to lay off workers or reassign them to other work stations. Some of the knowledge they have of making aircraft is lost. This "knowledge forgetting" may occur when a manager walks out and doesn't write down what he knows, or when information that was written down is lost.

A Countercycle of Learning and Unlearning

He showed a graph that demonstrated the cyclicality for Lockheed. In 1971 the company produced four aircraft. The oil shock of 1973-1974 dragged demand for aircraft down as the price of fuel rose, to claim 50 to 60 percent of the cost of operating aircraft (that portion is now about 25 percent). Demand crashed, and as it started to pick up again, another the oil shock struck in 1979, taking demand down again. In the background of this cyclicality, the productivity of man-hours per unit was highest when output was low, because output had recently been high and workers had reached high proficiency. During low output, they lost proficiency—which had to be regained when sales picked up. This is a countercycle of learning and then unlearning.

Depreciations of Knowledge and Experience

Dr. Benkard said he could model Lockheed's cyclicality with a traditional model of the learning curve. In that model, experience was the equivalent of cumulative past production—the last period's experience plus the last period's quantity. He allowed experience to depreciate by a factor *delta*. When he calculated for *delta*, he found it to be quite high: about 4 percent per month, or 40 percent per year.

He found several explanations for this high cyclical forgetting. One was that orders are made in advance. Another had to do with capacity constraints. The company would receive orders, ramp up its production lines, and become very efficient through learning. That would have been the most favorable time, when efficiency was high, to maximize production.

Another pattern was shown in the case of Boeing in the 1990s, when the firm's production fell off in the face of many orders. The company could not increase production because it lacked sufficient experienced workers. The response was to hire even more workers than the company had had before, and this drove its stock price down. The lack of trained workers acted as an implicit capacity restraint.

COUNTERCYCLICAL STRATEGIES

Dr. Benkard closed by describing how the industry tries to manage these extreme fluctuations by the simple strategy of diversifying into the defense industry. Defense contracts tend to be longer term, and defense production can be accelerated when commercial production is down.

DISCUSSION

Purchaser Strategies

Dr. Mowery asked whether one motive for companies that lease aircraft to enter their orders during the down cycle is to get a better position in the delivery queue. Dr. Benkard agreed that they would get both quicker delivery and a better price. Aircraft are priced through options contracts, with the price depending on the lead time of the order. An option exercised at 24 months has a better price than one exercised at 12 months.

A Strategy Guided by Inventory Costs

Dr. Wessner noted the labor unions' argument that Boeing weakens its efficiency when it reduces the labor force so quickly, and that it could better compete with Airbus by maintaining a more stable workforce. Dr. Benkard said he had studied that question and had concluded that Boeing is actually following the most economical practice by ramping up during booms, producing as many planes as it can while orders are heavy, and laying off workers when the boom ends. This is because the inventory costs of large aircraft are so high that the company needs to move each unit out as quickly as it can, even if it means hiring too many workers and having to release some later.

A Learning Challenge

Philip Auerswald asked about the primitives in the model from the standpoint of modeling the innovation process—especially the issue of sequential innovation leading to a technological crisis that needs to be resolved. The aircraft industry had a sequence of related products that were tracing out an industry-wide performance curve. Each of those products needed factory-level and product-level learning-by-doing, which would be a component of the price change. At the same time it had to deal with forgetting, and with the per-unit costs going up, as it went from one model to four models. He asked whether trying both to learn on existing products and to diversify over a range of products didn't create a particularly severe learning and productivity challenge.

Dr. Benkard agreed. He added that he thinks that the story about "productivity waves," or moving along a product frontier, also holds for the aircraft industry, but over a longer term. In 1956 the first aircraft with jet engines came out. In 1969 high-bypass jet engines were introduced and basically changed the industry. Today the technology is almost the same as it was in 1969, improved by smaller productivity increases. But he said he saw suggestions that additional, significant change is imminent. New technologies are usually tested out in the defense industry, where the technology is much higher, and some of these—including composite materials, fly-by-wire controls, and new wing designs—may trigger basic innovations in commercial aircraft in the next 10 years.

Dr. Mowery said that the negative effects of forgetting, or learning deficits, are important in semiconductors as well. Managers who are introducing a new process in a fab often find that much of the learning in yield improvement depends on engineering and managerial talent that is scarce and is spread thinly across multiple processes that all need to be debugged at the same time.

Modeling a Complex Industry

Dr. Auerswald suggested that the structural models discussed by Dr. Pakes form a framework for thinking about the evolution of an industry that has different firms, supply-and-demand questions, and people who are trying to predict the outcome of different investments. The modeler needs to get information from industry about what type of structure can be placed on that innovation process that makes sense. A limitless number of structures could be examined mathematically, but only a few can make sense for a staging of projects that go from one step to the next. In order to put the story together, he suggested, the model had best include the next generation of a discontinuous chain, incremental changes on a range of products, and new learning on an existing fixed product.

Aircraft Spinoffs

Mr. Morgenthaler noted his own involvement in the development and production of high-value components for jet engines from 1950 to 1957—the period of rapid buildup discussed by Dr. Benkard. He said that after it went to huge production, it ultimately made the transition to a huge spare-parts business. He noted that NASA is constantly developing new technology for spacecraft but lamented that the space agency is unproductive in promoting innovation for other industrial areas.

Dr. Benkard continued the discussion of spinoffs by saying that the airframe industry had a "parallel" industry, which was the defense industry, where much innovation is done. Fly-by-wire technology has already been spun off to commercial aircraft, which allows the use of airframes with advanced wing designs that would not otherwise fly commercially.

Future Tasks for the Model

He also responded to Dr. Auerswald's question about the learning curve. The industry starts out in a short-term mode to produce a certain amount of product and advance the learning curve. This is followed by a medium-term mode, concerned with product, how it is treated marginally, and perhaps the ability to bring in new products. He said that Dr. Auerswald was talking about either a longer-term investment process or an extreme outcome of the regular investment process. He said that that level had not yet been built into the models. So far, the models make use of the kinds of features with sufficient data, which are the types of investment processes that go on every year.

Ariel Pakes
Harvard University

Dr. Pakes said that in his summary he would offer more questions than answers.

COORDINATING INVESTMENTS IN SOCIETY'S INTEREST

He began with a question about the concept of coordinating investments by different firms. He noted that federal regulations are not clear about this subject. For example, the merger guidelines, which are designed to offer a legal framework on such issues, are essentially vacant on forms of coordination of anything except pricing. One result from his experience with merger models is that the ability to coordinate the investment of both merging firms often generates an improvement for society. That is, if one asks the question of whether the new, multiproduct firm merged with full coordination is better for society, the answer is often "yes," for a simple reason: A firm will invest to the point that the benefit of its investment equals the marginal cost of the investment. Part of that benefit is the gain of share from other firms.

A social planner does not count that share as a net increase. He concluded that some kinds of coordination, such as coordination of investment, might be in society's interest, and that in this case the Department of Justice might not object to the practice. He said that although this area is not at the center of his expertise, he thought that the semiconductor industry was one of the few that had been successful in coordinating at least one kind of investment, namely, R&D investment.

An Example of Coordination

Dr. Isaac agreed on the importance of this point and offered an example. From 1990 to 1995 he served as project manager for IBM's 64-megabit DRAM development program, which was conducted jointly with Infineon and Toshiba. Of the two kinds of DRAM, the stack-capacitor type and the trench type, this collaboration was the only group working on the deep-trench type. Because the companies had considerable flexibility through subsidiaries and different formats, they were able to design joint research investments, joint manufacturing investments, and spinoffs. Today the deep-trench DRAM holds 40 percent of the world DRAM market. He said that neither IBM nor Infineon would have continued in the DRAM business past 1993 if they had not formed that alliance. "It enabled us to be productive in a manner that none of us could afford by ourselves," said Dr. Isaac. "That kind of coordinated investment has been going on over this past decade to a very high degree and has indeed been central to the progress of the whole industry."

CYCLICALITY IN SEMICONDUCTORS AND DURABLE GOODS

Dr. Pakes raised a second set of questions regarding cyclicality. Most industries that sell durable goods, such as autos and airplanes, are cyclical. Some semiconductors go into durable goods, but he had not seen a demand analysis that takes this into account. One reason that a firm's demand goes down tomorrow is that sales are heavy today. At a large auto manufacturer, the firm is aware that demand next year is linked to sales this year. He said he was surprised that the semiconductor industry did not anticipate a sales cycle in the same way.

DISCUSSION

Signs of a Fragmenting Market?

Dr. Wessner cited recent signs that suggest global shifts in the market for semiconductors, with concentrated efforts by the Japanese to invest in wireless technologies and by the Europeans to focus on embedded appliances as well as wireless, based on standards that are unique to Europe. These trends, he said, may suggest that the market for semiconductors may fragment over the next few years.

Other Cyclical Industries

Dr. Mowery pointed out that industries outside the durable-goods category also have cycles. He cited the paper industry and its "enormous, investment-driven cycles." People invest in capacity in the good times, which are followed by down times. Over the past 15 to 20 years, he said, paper companies have consolidated, primarily through merger and acquisition.

He also mentioned the aluminum industry, which is characterized by "terrible" capacity and demand cycles. It also receives state support in the form of investment underwriting, which might be relevant to the semiconductor experience with the first years of SEMATECH, which was partly funded by government.

Finally, he said that the independent firms of the aircraft industry had responded to their inability to manage cycles by choosing strategies of merger, acquisition, or exit.

Dr. Pakes noted that mergers are the one practice virtually sure to draw the attention of the Department of Justice and Federal Trade Commission, largely because mergers have both price and demand implications for current products. He said that a merger is an "almost perfect coordination mechanism." He restated his interest in better understanding the practice of the semiconductor industry in coordinating parts of its R&D work without merging. He wondered whether it might not be a model that could be applied in other industries, and whether it could be modified to apply to other forms of investment.

Modeling Semiconductors and Aircraft

Dr. Wessner asked whether it was misleading to draw analogies between the semiconductor and airline industries, given their many differences. Dr. Mowery replied that there are both similarities and differences, with the differences most prominent at the technology level. He did see analogies in dealing with the problems of managing capacity and production in an industry facing wide swings in demand.

Dr. Pakes said that the reason for discussing aircraft was not so much to make a case for the similarities of the two industries. It was to explore the usefulness of modeling whole industries, and, given some years of experience in modeling the aircraft industry, to demonstrate the level of detail needed for productive modeling of the semiconductor industry.

Dr. Benkard closed this discussion by agreeing that the aspects that are central to the aircraft industry differ from those that are central to the semiconductor industry. He also refuted the point that semiconductor products reach the market faster than aircraft. He noted that experimental work with semiconductor products, such as chips with 8-nm separation, begins many years before a product reaches the market. Conversely, the first high-bypass jet engine was developed concurrently with the airframe it powered.

The Chip is the Product, Not the Transistor

Dr. Pinto made the point that, in the semiconductor business, "transistors aren't the product. The product is the chip that has 50 million transistors and the integrated circuit that goes with it." The market lifetime of these products varies widely, from 9 months or less for the disk drive business to eight or ten years for an infrastructure chip.

Diverse Product Lifetimes

Dr. Isaac seconded that point, and he reminded the group not to think of the semiconductor industry in monolithic terms, but to separate process technology, as seen in the foundry, from more integrated activities that bring products to market. He said that in the realm of process technology it may take 15 or more years to develop a useable new technology, such as copper, SOI (silicon on insulator), or silicon-germanium. Complex individual products may be somewhat quicker, such as IBM's new Unix chip, which had been defined four years earlier. For discrete, specialized products, the tempo may be much more rapid; a chip for a storage drive may have to be designed, manufactured, and ready in nine months. In short, the industry is more diverse in terms of product lifetimes than many people realize.

Closing Remarks

Dale W. Jorgenson
Harvard University

Dr. Jorgenson concluded the symposium by declaring it a success and expressing his gratitude to the participants. In organizing the discussion, he said, the objective of the STEP board had been to initiate a dialogue among economists who had been interested in the semiconductor industry for some time, and who had been inspired by the knowledge that it had recently played an even more strategic role than before in the performance of the economy. The topic was accessible, he said, because the economics of this industry can "be understood without understanding the technology." At the same time, the technology of semiconductors is driven largely by the economics. In short, he said, there is a community of interest between the technological and economic communities and an obvious need for collaboration on questions that neither group can answer on its own.

II

RESEARCH PAPERS

Accounting for Growth in the Information Age

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1. THE INFORMATION AGE*

1.1. Introduction

The resurgence of the American economy since 1995 has outrun all but the most optimistic expectations. Economic forecasting models have been seriously off track and growth projections have been revised repeatedly to reflect a more sanguine outlook.[1] It is not surprising that the unusual combination of more rapid growth and slower inflation touched off a strenuous debate about whether improvements in America's economic performance could be sustained.

The starting point for the economic debate is the thesis that the 1990s are a

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NOTE: Tables and figures appear at the end of this paper, pp. 114-134. An earlier version of this paper was published under the title "Information Technology and the U.S. Economy" in the *American Economic Review*, 90:1, in March 2001.

[1]See Congressional Budget Office (2000) on official forecasts and Economics and Statistics Administration (2000), p. 60, on private forecasts.

mirror image of the 1970s, when an unfavorable series of "supply shocks" led to stagflation—slower growth and higher inflation.[2] In this view, the development of information technology (IT) is one of a series of positive, but *temporary*, shocks. The competing perspective is that IT has produced a fundamental change in the U.S. economy, leading to a *permanent* improvement in growth prospects.[3] The resolution of this debate has been the "killer application" of a new framework for productivity measurement summarized in Paul Schreyer's (2001) OECD Manual, *Measuring Productivity*.

A consensus has emerged that the development and deployment of information technology is the foundation of the American growth resurgence. A mantra of the "new economy"—*faster, better, cheaper*—captures the speed of technological change and product improvement in semiconductors and the precipitous and continuing fall in semiconductor prices. The price decline has been transmitted to the prices of products that rely heavily on semiconductor technology, like computers and telecommunications equipment. This technology has also helped to reduce the cost of aircraft, automobiles, scientific instruments, and a host of other products.

Swiftly falling IT prices provide powerful economic incentives for the substitution of IT equipment for other forms of capital and for labor services. The rate of the IT price decline is a key component of the cost of capital, required for assessing the impacts of rapidly growing stocks of computers, communications equipment, and software. Constant quality price indexes are essential for identifying the change in price for a given level of performance. Accurate and timely computer prices have been part of the U.S. National Income and Product Accounts (NIPA) since 1985. Unfortunately, important information gaps remain, especially on trends in prices for closely related investments, such as software and communications equipment.

Capital input has been the most important source of U.S. economic growth throughout the postwar period. More rapid substitution toward information technology has given much additional weight to components of capital input with higher marginal products. The vaulting contribution of capital input since 1995 has boosted growth by close to a percentage point. The contribution of investment in IT accounts for more than half of this increase. Computers have been the predominant impetus to faster growth, but communications equipment and software have made important contributions as well.

The accelerated information technology price decline signals faster productivity growth in IT-producing industries. In fact, these industries have been a rapidly rising source of aggregate productivity growth throughout the 1990s. The IT-producing industries generate less than 5 percent of gross domestic income,

[2]Gordon (1998, 2000); Bosworth and Triplett (2000).
[3]Greenspan (2000).

but have accounted for nearly half the surge in productivity growth since 1995. However, it is important to emphasize that faster productivity growth is not limited to these industries.

The dramatic effects of information technology on capital and labor markets have already generated a substantial and growing economic literature, but many important issues remain to be resolved. For capital markets the relationship between equity valuations and growth prospects merits much further study. For labor markets more research is needed on investment in information technology and substitution among different types of labor.

1.2. Faster, Better, Cheaper

Modern information technology begins with the invention of the *transistor*, a semiconductor device that acts as an electrical switch and encodes information in binary form. A binary digit or *bit* takes the values zero and one, corresponding to the off and on positions of a switch. The first transistor, made of the semiconductor germanium, was constructed at Bell Labs in 1947 and won the Nobel Prize in Physics in 1956 for the inventors—John Bardeen, Walter Brattain, and William Shockley.[4]

The next major milestone in information technology was the co-invention of the *integrated circuit* by Jack Kilby of Texas Instruments in 1958 and Robert Noyce of Fairchild Semiconductor in 1959. An integrated circuit consists of many, even millions, of transistors that store and manipulate data in binary form. Integrated circuits were originally developed for data storage and retrieval and semiconductor storage devices became known as *memory chips*.[5]

The first patent for the integrated circuit was granted to Noyce. This resulted in a decade of litigation over the intellectual property rights. The litigation and its outcome demonstrate the critical importance of intellectual property in the development of information technology. Kilby was awarded the Nobel Prize in Physics in 2000 for discovery of the integrated circuit; regrettably, Noyce died in 1990.[6]

1.2.1. Moore's Law

In 1965 Gordon Moore, then Research Director at Fairchild Semiconductor, made a prescient observation, later known as *Moore's Law*.[7] Plotting data on

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[4]On Bardeen, Brattain, and Shockley, see: http://www.nobel.se/physics/laureates/1956/.

[5]Petzold (1999) provides a general reference on computers and software.

[6]On Kilby, see: http://www.nobel.se/physics/laureates/2000/. On Noyce, see: Wolfe (2000), pp. 17-65.

[7]Moore (1965). Ruttan (2001), pp. 316-367, provides a general reference on the economics of semiconductors and computers. On semiconductor technology, see: http://euler.berkeley.edu/~esrc/csm.

memory chips, he observed that each new chip contained roughly twice as many transistors as the previous chip and was released within 18-24 months of its predecessor. This implied exponential growth of chip capacity at 35-45 percent per year! Moore's prediction, made in the infancy of the semiconductor industry, has tracked chip capacity for 35 years. He recently extrapolated this trend for at least another decade.[8]

In 1968 Moore and Noyce founded Intel Corporation to speed the commercialization of memory chips.[9] Integrated circuits gave rise to *microprocessors* with functions that can be programmed by software, known as *logic chips*. Intel's first general purpose microprocessor was developed for a calculator produced by Busicom, a Japanese firm. Intel retained the intellectual property rights and released the device commercially in 1971.

The rapidly rising trends in the capacity of microprocessors and storage devices illustrate the exponential growth predicted by Moore's Law. The first logic chip in 1971 had 2,300 transistors, while the Pentium 4 released on November 20, 2000, had 42 million! Over this 29 year period the number of transistors increased by 34 percent per year. The rate of productivity growth for the U.S. economy during this period was slower by two orders of magnitude.

1.2.2. Semiconductor Prices

Moore's Law captures the fact that successive generations of semiconductors are *faster* and *better*. The economics of semiconductors begins with the closely related observation that semiconductors have become *cheaper* at a truly staggering rate! Figure 1.1 gives semiconductor price indexes constructed by Bruce Grimm (1998) of the Bureau of Economic Analysis (BEA) and employed in the U.S. National Income and Product Accounts since 1996. These are divided between memory chips and logic chips. The underlying detail includes seven types of memory chips and two types of logic chips.

Between 1974 and 1996 prices of memory chips *decreased* by a factor of 27,270 times or at 40.9 percent per year, while the implicit deflator for the gross domestic product (GDP) *increased* by almost 2.7 times or 4.6 percent per year! Prices of logic chips, available for the shorter period 1985 to 1996, *decreased* by a factor of 1,938 or 54.1 percent per year, while the GDP deflator *increased* by 1.3 times or 2.6 percent per year! Semiconductor price declines closely parallel Moore's Law on the growth of chip capacity, setting semiconductors apart from other products.

Figure 1.1 also reveals a sharp acceleration in the decline of semiconductor prices in 1994 and 1995. The microprocessor price decline leapt to more than 90

[8]Moore (1997).
[9]Moore (1996).

percent per year as the semiconductor industry shifted from a three-year product cycle to a greatly accelerated two-year cycle. This is reflected in the *2000 Update* of the International Technology Road Map for Semiconductors,[10] prepared by a consortium of industry associations. Ana Aizcorbe, Stephen Oliner, and Daniel Sichel (2003) have identified and analyzed break points in prices of microprocessors and storage devices.

1.2.3. Constant Quality Price Indexes

The behavior of semiconductor prices is a severe test for the methods used in the official price statistics. The challenge is to separate observed price changes between changes in semiconductor performance and changes in price that hold performance constant. Achieving this objective has required a detailed understanding of the technology, the development of sophisticated measurement techniques, and the introduction of novel methods for assembling the requisite information.

Ellen Dulberger (1993) introduced a "matched model" index for semiconductor prices. A matched model index combines price relatives for products with the same performance at different points of time. Dulberger presented constant quality price indexes based on index number formulas, including the *Fisher* (1922) *ideal index* used in the in the U.S. national accounts.[11] The Fisher index is the geometric average of the familiar Laspeyres and Paasche indexes.

Erwin Diewert (1976) defined a *superlative* index number as an index that *exactly* replicates a *flexible* representation of the underlying technology (or preferences). A flexible representation provides a second-order approximation to an arbitrary technology (or preference system). A. A. Konus and S. S. Byushgens (1926) first showed that the Fisher ideal index is superlative in this sense. Laspeyres and Paasche indexes are not superlative and fail to capture substitutions among products in response to price changes accurately.

Grimm (1998) combined matched model techniques with hedonic methods, based on an econometric model of semiconductor prices at different points of time. A hedonic model gives the price of a semiconductor product as a function of the characteristics that determine performance, such as speed of processing and storage capacity. A constant quality price index isolates the price change by holding these characteristics of semiconductors fixed.[12]

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[10]On International Technology Roadmap for Semiconductors (2000), see: http://public.itrs.net/.

[11]See Landefeld and Parker (1997).

[12]Triplett (2003) has drafted a manual for the OECD on constructing constant quality price indexes for information technology and communications equipment and software.

Beginning in 1997, the Bureau of Labor Statistics (BLS) incorporated a matched model price index for semiconductors into the Producer Price Index (PPI) and since then the national accounts have relied on data from the PPI. Reflecting long-standing BLS policy, historical data were not revised backward. Semiconductor prices reported in the PPI prior to 1997 do not hold quality constant, failing to capture the rapid semiconductor price decline and the acceleration in 1995.

1.2.4. Computers

The introduction of the Personal Computer (PC) by IBM in 1981 was a watershed event in the deployment of information technology. The sale of Intel's 8086-8088 microprocessor to IBM in 1978 for incorporation into the PC was a major business breakthrough for Intel.[13] In 1981 IBM licensed the MS-DOS operating system from the Microsoft Corporation, founded by Bill Gates and Paul Allen in 1975. The PC established an Intel/Microsoft relationship that has continued up to the present. In 1985 Microsoft released the first version of Windows, its signature operating system for the PC, giving rise to the Wintel (Windows-Intel) nomenclature for this ongoing collaboration.

Mainframe computers, as well as PC's, have come to rely heavily on logic chips for central processing and memory chips for main memory. However, semiconductors account for less than half of computer costs and computer prices have fallen much less rapidly than semiconductor prices. Precise measures of computer prices that hold product quality constant were introduced into the NIPA in 1985 and the PPI during the 1990s. The national accounts now rely on PPI data, but historical data on computers from the PPI, like the PPI data on semiconductors, do not hold quality constant.

Gregory Chow (1967) pioneered the use of hedonic techniques for constructing a constant quality index of computer prices in research conducted at IBM. Chow documented price declines at more than twenty percent per year during 1960-1965, providing an initial glimpse of the remarkable behavior of computer prices. In 1985 the Bureau of Economic Analysis incorporated constant quality price indexes for computers and peripheral equipment constructed by IBM into the NIPA. Triplett's (1986) discussion of the economic interpretation of these indexes brought the rapid decline of computer prices to the attention of a very broad audience.

The BEA-IBM constant quality price index for computers provoked a heated exchange between BEA and Edward Denison (1989), one of the founders of national accounting methodology in the 1950s and head of the national accounts at BEA from 1979 to 1982. Denison sharply attacked the BEA-IBM methodology

[13] See Moore (1996).

and argued vigorously against the introduction of constant quality price indexes into the national accounts.[14] Allan Young (1989), then Director of BEA, reiterated BEA's rationale for introducing constant quality price indexes.

Dulberger (1989) presented a more detailed report on her research on the prices of computer processors for the BEA-IBM project. Speed of processing and main memory played central roles in her model. Triplett (1989, 2003) has provided exhaustive surveys of research on hedonic price indexes for computers. Gordon (1989, 1990) gave an alternative model of computer prices and identified computers and communications equipment, along with commercial aircraft, as assets with the highest rates of price decline.

Figure 1.2 gives BEA's constant quality index of prices of computers and peripheral equipment and its components, including mainframes, PCs, storage devices, other peripheral equipment, and terminals. The decline in computer prices follows the behavior of semiconductor prices presented in Figure 1.1, but in much attenuated form. The 1995 acceleration in the computer price decline parallels the acceleration in the semiconductor price decline that resulted from the changeover from a three-year product cycle to a two-year cycle in 1995.

1.2.5. Communications Equipment and Software

Communications technology is crucial for the rapid development and diffusion of the Internet, perhaps the most striking manifestation of information technology in the American economy.[15] Kenneth Flamm (1989) was the first to compare the behavior of computer prices and the prices of communications equipment. He concluded that the communications equipment prices fell only a little more slowly than computer prices. Gordon (1990) compared Flamm's results with the official price indexes, revealing substantial bias in the official indexes.

Communications equipment is an important market for semiconductors, but constant quality price indexes cover only a portion of this equipment. Switching and terminal equipment rely heavily on semiconductor technology, so that product development reflects improvements in semiconductors. Grimm's (1997) constant quality price index for digital telephone switching equipment, given in Figure 1.3, was incorporated into the national accounts in 1996. The output of communications services in the NIPA also incorporates a constant quality price index for cellular phones.

Much communications investment takes the form of the transmission gear, connecting data, voice, and video terminals to switching equipment. Technolo-

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[14]Denison cited his 1957 paper, "Theoretical Aspects of Quality Change, Capital Consumption, and Net Capital Formation," as the definitive statement of the traditional BEA position.

[15]General references on the economics of the Internet are Choi and Whinston (2000) and Hall (2002). On Internet indicators see: http://www.internetindicators.com/.

gies such as fiber optics, microwave broadcasting, and communications satellites have progressed at rates that outrun even the dramatic pace of semiconductor development. An example is dense wavelength division multiplexing (DWDM), a technology that sends multiple signals over an optical fiber simultaneously. Installation of DWDM equipment, beginning in 1997, has doubled the transmission capacity of fiber optic cables every 6-12 months.[16]

Mark Doms (2004) has provided comprehensive price indexes for terminals, switching gear, and transmission equipment. These have been incorporated into the Federal Reserve's Index of Industrial Production, as described by Carol Corrado (2003), but are not yet included in the U.S. National Income and Product Accounts. The analysis of the impact of information technology on the U.S. economy described below is based on the national accounts and remains incomplete.

Both software and hardware are essential for information technology and this is reflected in the large volume of software expenditures. The eleventh comprehensive revision of the national accounts, released by BEA on October 27, 1999, re-classified computer software as investment.[17] Before this important advance, business expenditures on software were treated as current outlays, while personal and government expenditures were treated as purchases of nondurable goods. Software investment is growing rapidly and is now much more important than investment in computer hardware.

Parker and Grimm (2000) describe the new estimates of investment in software. BEA distinguishes among three types of software—prepackaged, custom, and own-account software. Prepackaged software is sold or licensed in standardized form and is delivered in packages or electronic files downloaded from the Internet. Custom software is tailored to the specific application of the user and is delivered along with analysis, design, and programming services required for customization. Own-account software consists of software created for a specific application. However, only price indexes for prepackaged software hold performance constant.

Parker and Grimm (2000) present a constant quality price index for prepackaged software, given in Figure 1.3. This combines a hedonic model of prices for business applications software and a matched model index for spreadsheet and word processing programs developed by Oliner and Sichel (1994). Prepackaged software prices decline at more than ten percent per year over the period 1962-1998. Since 1998 the BEA has relied on a matched model price index for all prepackaged software from the PPI; prior to 1998 the PPI data do not hold quality constant.

[16]Rashad (2000) characterizes this as the "demise" of Moore's Law. Hecht (1999) describes DWDM technology and provides a general reference on fiber optics.

[17]Moulton (2000) describes the 11th comprehensive revision of NIPA and the 1999 update.

BEA's prices for own-account and custom software are based on programmer wage rates. This implicitly assumes no change in the productivity of computer programmers, even with growing investment in hardware and software to support the creation of new software. Custom and own-account software prices are a weighted average of prepackaged software prices and programmer wage rates with arbitrary weights of 75 percent for programmer wage rates and 25 percent for prepackaged software. These price indexes do not hold the software performance constant and present a distorted picture of software prices, as well as software output and investment.

1.2.6. Research Opportunities

The official price indexes for computers and semiconductors provide the paradigm for economic measurement. These indexes capture the steady decline in IT prices and the recent acceleration in this decline. The official price indexes for central office switching equipment and prepackaged software also hold quality constant. BEA and BLS, the leading statistical agencies in price research, have carried out much of the best work in this area. However, a critical role has been played by price research at IBM, long the dominant firm in information technology.[18]

It is important to emphasize that information technology is not limited to applications of semiconductors. Switching and terminal equipment for voice, data, and video communications have come to rely on semiconductor technology and the empirical evidence on prices of this equipment reflects this fact. Transmission gear employs technologies with rates of progress that far outstrip those of semiconductors. This important gap in our official price statistics has been filled by constant quality price indexes for all types of communications equipment constructed by Doms (2004), but these indexes have not been incorporated into the national accounts.

Investment in software is more important than investment in hardware. This was essentially invisible until BEA introduced new measures of prepackaged, custom, and own-account software investment into the national accounts in 1999. This is a crucial step in understanding the role of information technology in the American economy. Unfortunately, software prices are a statistical blind spot with only prices of prepackaged software adequately represented in the official system of price statistics. The daunting challenge that lies ahead is to construct constant quality price indexes for custom and own-account software.

[18]See Chandler (2000), Table 1.1, p. 26.

1.3. Impact of Information Technology

In Section 2, I consider the "killer application" of the new framework for productivity measurement—the impact of information technology (IT) on economic growth. Despite differences in methodology and data sources, a consensus has emerged that the remarkable behavior of IT prices provides the key to the surge in U.S. economic growth after 1995. The relentless decline in the prices of information technology equipment and software has steadily enhanced the role of IT investment. Productivity growth in IT-producing industries has risen in importance and a productivity revival is under way in the rest of the economy.

A substantial acceleration in the IT price decline occurred in 1995, triggered by a much sharper acceleration in the price decline of semiconductors, the key component of modern information technology. Although the decline in semiconductor prices has been projected to continue for at least another decade, the recent acceleration may be temporary. This can be traced to a shift in the product cycle for semiconductors from 3 years to 2 years as a consequence of intensifying competition in markets for semiconductor products.

In Section 3, I show that the surge of IT investment in the United States after 1995 has counterparts in all other industrialized countries. It is essential to use comparable data and methodology in order to provide rigorous international comparisons. A crucial role is played by measurements of IT prices. The U.S. national accounts have incorporated measures of IT prices that hold performance constant since 1985. Schreyer (2000) has extended these measures to other industrialized countries by constructing "internationally harmonized prices."[19]

I have shown that the acceleration in the IT price decline in 1995 triggered a burst of IT investment in all of the G7 nations–-Canada, France, Germany, Italy, Japan, the U.K., as well as the U.S.[20] These countries also experienced a rise in productivity growth in the IT-producing industries. However, differences in the relative importance of these industries have generated wide disparities in the impact of IT on economic growth. The role of the IT-producing industries is greatest in the U.S., which leads the G7 in output per capita. Section 3 concludes.

2. AGGREGATE GROWTH ACCOUNTING

2.1. The Role of Information Technology

At the aggregate level IT is identified with the outputs of computers, communications equipment, and software. These products appear in the GDP as investments by businesses, households, and governments along with net exports to

[19]The measurement gap in IT prices between the U.S. and other OECD countries was first identified by Wyckoff (1995).

[20]See Jorgenson (2003).

the rest of the world. The GDP also includes the services of IT products consumed by households and governments. A methodology for analyzing economic growth must capture the substitution of IT outputs for other outputs of goods and services.

While semiconductor technology is the driving force behind the spread of IT, the impact of the relentless decline in semiconductor prices is transmitted through falling IT prices. Only net exports of semiconductors, defined as the difference between U.S. exports to the rest of the world and U.S. imports appear in the GDP. Sales of semiconductors to domestic manufacturers of IT products are precisely offset by purchases of semiconductors and are excluded from the GDP.

Constant quality price indexes, like those reviewed in the previous section, are a key component of the methodology for analyzing the American growth resurgence. Computer prices were incorporated into the NIPA in 1985 and are now part of the PPI as well. Much more recently, semiconductor prices have been included in the NIPA and the PPI. The official price indexes for communications equipment do not yet reflect the important work of Doms (2004). Unfortunately, evidence on the price of software is seriously incomplete, so that the official price indexes are seriously misleading.

2.1.1. Output

The output data in Table 2.1 are based on the most recent benchmark revision of the national accounts, updated through 2002.[21] The output concept is similar, but not identical, to the concept of gross domestic product used by the BEA. Both measures include final outputs purchased by businesses, governments, households, and the rest of the world. Unlike the BEA concept, the output measure in Table 2.1 also includes imputations for the service flows from durable goods, including IT products, employed in the household and government sectors.

The imputations for services of IT equipment are based on the cost of capital for IT described in more detail below. The cost of capital is multiplied by the nominal value of IT capital stock to obtain the imputed service flow from IT products. In the business sector this accrues as capital income to the firms that employ these products as inputs. In the household and government sectors the flow of capital income must be imputed. This same type of imputation is used for housing in the NIPA. The rental value of renter-occupied housing accrues to real estate firms as capital income, while the rental value of owner-occupied housing is imputed to households.

Current dollar GDP in Table 2.1 is $11.3 trillions in 2002, including imputations, and real output growth averaged 3.46 percent for the period 1948-2002. These magnitudes can be compared to the current dollar value of $10.5 trillions in

[21] See Jorgenson and Stiroh (2000b), Appendix A, for details on the estimates of output.

2002 and the average real growth rate of 3.36 percent for period 1948-2002 for the official GDP. Table 2.1 presents the current dollar value and price indexes of the GDP and IT output. This includes outputs of investment goods in the form of computers, software, communications equipment, and non-IT investment goods. It also includes outputs of non-IT consumption goods and services as well as imputed IT capital service flows from households and governments.

The most striking feature of the data in Table 2.1 is the rapid price decline for computer investment, 15.8 percent per year from 1959 to 1995. Since 1995 this decline has increased to 31.0 percent per year. By contrast the relative price of software has been flat for much of the period and began to fall only in the 1980s. The price of communications equipment behaves similarly to the software price.

The top panel of Table 2.2 summarizes the growth rates of prices and quantities for major output categories for 1989-1995 and 1995-2002. Business investments in computers, software, and communications equipment are the largest categories of IT spending. Households and governments have also spent sizable amounts on computers, software, communications equipment and the services of information technology. Figure 2.1 shows that the share of software output in the GDP is largest, followed by the shares of computers and communications equipment.

2.1.2. Capital Services

This section presents capital estimates for the U.S. economy for the period 1948 to 2002.[22] These begin with BEA investment data; the perpetual inventory method generates estimates of capital stocks and these are aggregated, using service prices as weights. This approach, originated by Jorgenson and Zvi Griliches (1967), is based on the identification of service prices with marginal products of different types of capital. The service price estimates incorporate the cost of capital.[23]

The cost of capital is an annualization factor that transforms the price of an asset into the price of the corresponding capital input. This includes the nominal rate of return, the rate of depreciation, and the rate of capital loss due to declining prices. The cost of capital is an essential concept for the economics of information technology,[24] due to the astonishing decline of IT prices given in Table 2.1.

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[22]See Jorgenson and Stiroh (2000b), Appendix B, for details on the estimates of capital input.

[23]Jorgenson and Yun (2001) present the model of capital input used in the estimates presented in this section. BLS (1983) describes the version of this model employed in the official productivity statistics. For recent updates, see the BLS multifactor productivity website: http://www.bls.gov/mfp/home.htm. Hulten (2001) surveys the literature.

[24]Jorgenson and Stiroh (1995), pp. 300-303.

The cost of capital is important in many areas of economics, especially in modeling producer behavior, productivity measurement, and the economics of taxation.[25] Many of the important issues in measuring the cost of capital have been debated for decades. The first of these is incorporation of the rate of decline of asset prices into the cost of capital. The assumption of perfect foresight or rational expectations quickly emerged as the most appropriate formulation and has been used in almost all applications of the cost of capital.[26]

The second empirical issue is the measurement of economic depreciation. The stability of patterns of depreciation in the face of changes in tax policy and price shocks has been carefully documented. The depreciation rates presented by Jorgenson and Stiroh (2000b) summarize a large body of empirical research on the behavior of asset prices.[27] A third empirical issue is the description of the tax structure for capital income. This depends on the tax laws prevailing at each point of time. The resolution of these issues has cleared the way for detailed measurements of the cost of capital for all assets that appear in the national accounts, including information technology equipment and software.[28]

The definition of capital includes all tangible assets in the U.S. economy, equipment and structures, as well as consumers' and government durables, land, and inventories. The capital service flows from durable goods employed by households and governments enter measures of both output and input. A steadily rising proportion of these service flows are associated with investments in IT. Investments in IT by business, household, and government sectors must be included in the GDP, along with household and government IT capital services, in order to capture the full impact of IT on the U.S. economy.

Table 2.3 gives capital stocks from 1948 to 2002, as well as price indexes for total domestic tangible assets and IT assets—computers, software, and communications equipment. The estimate of domestic tangible capital stock in Table 2.3 is $45.9 trillions in 2002, considerably greater than the estimate by BEA. The most important differences reflect the inclusion of inventories and land in Table 2.3.

Business IT investments, as well as purchases of computers, software, and communications equipment by households and governments, have grown spectacularly in recent years, but remain relatively small. The stocks of all IT assets

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[25]Lau (2000) surveys applications of the cost of capital.

[26]See, for example, Jorgenson, Gollop, and Fraumeni (1987), pp. 40-49, and Jorgenson and Griliches (1967).

[27]Jorgenson and Stiroh (2000b), Table B4, pp. 196-197 give the depreciation rates employed in this section. Fraumeni (1997) describes depreciation rates used in the NIPA. Jorgenson (1996) surveys empirical studies of depreciation.

[28]See Jorgenson and Yun (2001) for details on the U.S. tax structure for capital income. Diewert and Lawrence (2000) survey measures of the price and quantity of capital input.

combined account for only 3.79 percent of domestic tangible capital stock in 2002. Table 2.4 presents estimates of the flow of capital services and corresponding price indexes for 1948-2002.

The difference between growth in capital services and capital stock is the improvement in capital quality. This represents the substitution towards assets with higher marginal products. The shift toward IT increases the quality of capital, since computers, software, and communications equipment have relatively high marginal products. Capital stock estimates fail to account for this increase in quality and substantially underestimate the impact of IT investment on growth.

The growth of capital quality is slightly less than 20 percent of capital input growth for the period 1948-2002. However, improvements in capital quality have increased steadily in relative importance. These improvements jumped to 46.1 percent of total growth in capital input during the period 1995-2002, reflecting very rapid restructuring of capital to take advantage of the sharp acceleration in the IT price decline. Capital stock has become progressively less accurate as a measure of capital input and is now seriously deficient.

Figure 2.2 gives the IT capital service flows as a share of gross domestic income. The second panel of Table 2.2 summarizes the growth rates of prices and quantities of capital inputs for 1989-1995 and 1995-2002. Growth of IT capital services jumps from 12.58 percent per year in 1989-1995 to 18.33 percent in 1995-2002, while growth of non-IT capital services increases from 1.91 percent to 3.01 percent. This reverses the trend toward slower capital growth through 1995.

2.1.3. Labor Services

This section presents estimates of labor input for the U.S. economy from 1948 to 2002. These incorporate individual data from the Censuses of Population for 1970, 1980, and 1990, as well as the annual Current Population Surveys. Constant quality indexes for the price and quantity of labor input account for the heterogeneity of the workforce across sex, employment class, age, and education levels. This follows the approach of Jorgenson, Gollop, and Fraumeni (1987).[29]

The distinction between labor input and labor hours is analogous to the distinction between capital services and capital stock. The growth in labor quality is 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. Table 2.5 presents estimates of labor input, hours worked, and labor quality.

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[29]See Jorgenson and Stiroh (2000b), Appendix C, for details on the estimates of labor input. Gollop (2000) discusses the measurement of labor quality.

The value of labor expenditures in Table 2.5 is \$6.6 trillions in 2002, 58.7 percent of the value of output. This share accurately reflects the concept of gross domestic income, including imputations for the value of capital services in household and government sectors. As shown in Table 2.7, the growth rate of labor input decelerated to 1.50 percent for 1995-2002 from 1.64 percent for 1989-1995. Growth in hours worked rose from 1.08 percent for 1989-1995 to 1.16 percent for 1995-2002 as labor force participation increased and unemployment rates declined.

The growth of labor quality has declined considerably since 1995, dropping from 0.55 percent for 1989-1995 to 0.33 percent for 1995-2002. This slowdown captures well-known demographic trends in the composition of the workforce, as well as exhaustion of the pool of available workers. Growth in hours worked does not capture these changes in labor quality growth and is a seriously misleading measure of labor input.

2.2. The American Growth Resurgence

The American economy has undergone a remarkable resurgence since the mid-1990s with accelerating growth in output, labor productivity, and total factor productivity. The purpose of this section is to quantify the sources of growth for 1948-2002 and various sub-periods. An important objective is to account for the sharp acceleration in the growth rate since 1995 and, in particular, to document the role of information technology.

The appropriate framework for analyzing the impact of information technology is the production possibility frontier, giving outputs of IT investment goods as well as inputs of IT capital services. An important advantage of this framework is that prices of IT outputs and inputs are linked through the price of IT capital services. This framework successfully captures the substitutions among outputs and inputs in response to the rapid deployment of IT. It also encompasses costs of adjustment, while allowing financial markets to be modeled independently.

As a consequence of the swift advance of information technology, a number of the most familiar concepts in growth economics have been superseded. The aggregate production function heads this list. Capital stock as a measure of capital input is no longer adequate to capture the rising importance of IT. This completely obscures the restructuring of capital input that is such an important wellspring of the growth resurgence. Finally, hours worked must be replaced as a measure of labor input.

2.2.1. Production Possibility Frontier

The production possibility frontier describes efficient combinations of outputs and inputs for the economy as a whole. Aggregate output Y consists of outputs of investment goods and consumption goods. These outputs are produced from aggregate input *X*, consisting of capital services and labor services.

Productivity is a "Hicks-neutral" augmentation of aggregate input. The production possibility frontier takes the form:

$$Y(I_n, I_c, I_s, I_t, C_n, C_c) = A \cdot X(K_n, K_c, K_s, K_t, L),$$

where the outputs include non-IT investment goods I_n and investments in computers I_c, software I_s, and communications equipment I_t, as well as non-IT consumption goods and services C_n and IT capital services to households and governments C_c. Inputs include non-IT capital services K_n and the services of computers K_c, software K_s, and telecommunications equipment K_t, as well as labor input *L*.[30] Productivity is denoted by *A*.

The most important advantage of the production possibility frontier is the explicit role that it provides for constant quality prices of IT products. These are used as deflators for nominal expenditures on IT investments to obtain the quantities of IT outputs. Investments in IT are cumulated into stocks of IT capital. The flow of IT capital services is an aggregate of these stocks with service prices as weights. Similarly, constant quality prices of IT capital services are used in deflating the nominal values of consumption of these services.

Another important advantage of the production possibility frontier is the incorporation of costs of adjustment. For example, an increase in the output of IT investment goods requires foregoing part of the output of consumption goods and non-IT investment goods, so that adjusting the rate of investment in IT is costly. However, costs of adjustment are external to the producing unit and are fully reflected in IT prices. These prices incorporate forward-looking expectations of the future prices of IT capital services.

The aggregate production function employed, for example, by Kuznets (1971) and Solow (1957, 1960, 1970) and, more recently, by Jeremy Greenwood, Zvi Hercowitz, and Per Krusell (1997, 2000), Hercowitz (1998), and Arnold Harberger (1998) is a competing methodology. The production function gives a single output as a function of capital and labor inputs. There is no role for separate prices of investment and consumption goods and, hence, no place for constant quality IT price indexes for outputs of IT investment goods.

Another limitation of the aggregate production function is that it fails to incorporate costs of adjustment. Robert Lucas (1967) presented a production model with internal costs of adjustment. Fumio Hayashi (2000) shows how to identify these adjustment costs from Tobin's Q-ratio, the ratio of the stock market value of the producing unit to the market value of the unit's assets. Implementation of

[30]Services of durable goods to governments and households are included in both inputs and outputs.

this approach requires simultaneous modeling of production and asset valuation. If costs of adjustment are external, as in the production possibility frontier, asset valuation can be modeled separately from production.[31]

2.2.2. Sources of Growth

Under the assumption that product and factor markets are competitive producer equilibrium implies that the share-weighted growth of outputs is the sum of the share-weighted growth of inputs and growth in total factor productivity:

$$\bar{w}_{I,n}\Delta\ln I_n + \bar{w}_{I,c}\Delta I_c + \bar{w}_{I,s}\Delta I_s + \bar{w}_{I,t}\Delta I_t + \bar{w}_{C,n}C_n + \bar{w}_{C,c}\Delta\ln C_c =$$
$$\bar{v}_{K,n}\Delta\ln K_n + \bar{v}_{K,c}\Delta\ln K_c + \bar{v}_{K,s}\Delta\ln K_s + \bar{v}_{K,t}\Delta\ln K_t + \bar{v}_L\Delta\ln L + \Delta\ln A$$

where $\bar{v}$ and $\bar{w}$ denote average value shares. The shares of outputs and inputs add to one under the additional assumption of constant returns,

$$\bar{w}_{I,n} + \bar{w}_{I,c} + \bar{w}_{I,s} + \bar{w}_{I,t} + \bar{w}_{C,n} + \bar{w}_{C,c} = \bar{v}_{K,n} + \bar{v}_{K,c} + \bar{v}_{K,s} + \bar{v}_{K,t} + \bar{v}_L = 1.$$

The growth rate of output is a weighted average of growth rates of investment and consumption goods outputs. The contribution of each output is its weighted growth rate. Similarly, the growth rate of input is a weighted average of growth rates of capital and labor services and the contribution of each input is its weighted growth rate. The contribution of productivity, the growth rate of the augmentation factor A, is the difference between growth rates of output and input.

Table 2.6 presents results of a growth accounting decomposition for the period 1948-2002 and various sub-periods, following Jorgenson and Stiroh (1999, 2000b). Economic growth is broken down by output and input categories, quantifying the contribution of information technology to investment and consumption outputs, as well as capital inputs. These estimates identify computers, software, and communications equipment as distinct types of information technology.

The results can also be presented in terms of average labor productivity (ALP), defined as $y = Y/H$, the ratio of output Y to hours worked H, and $k = K/H$ is the ratio of capital services K to hours worked:

$$\Delta\ln y = \bar{v}_k\Delta\ln k + \bar{v}_L(\Delta\ln L - \Delta\ln H) + \Delta\ln A.$$

This equation allocates ALP growth among three sources. The first is capital deepening, the growth in capital input per hour worked, and reflects the capital-labor substitution. The second is improvement in labor quality and captures the

[31]See, for example, Campbell and Shiller (1998).

rising proportion of hours by workers with higher marginal products. The third is total factor productivity growth, which contributes point-for-point to ALP growth.

2.2.3. Contributions of IT Investment

Figure 2.5 depicts the rapid increase in the importance of IT services, reflecting the accelerating pace of IT price declines. In 1995-2002 the capital service price for computers fell 26.09 percent per year, compared to an increase of 32.34 percent in capital input from computers. While the value of computer services grew, the current dollar value was only 1.44 percent of gross domestic income in 2002.

The rapid accumulation of software appears to have different sources. The price of software services has declined only 1.72 percent per year for 1995-2002. Nonetheless, firms have been accumulating software very rapidly, with real capital services growing 14.27 percent per year. A possible explanation is that firms respond to computer price declines by investing in complementary inputs like software. However, a more plausible explanation is that the price indexes used to deflate software investment fail to hold quality constant. This leads to an overstatement of inflation and an understatement of growth.

Although the price decline for communications equipment during the period 1995-2002 is greater than that of software, investment in this equipment is more in line with prices. However, prices of communications equipment also fail to hold quality constant. 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. This leads to an underestimate of the growth rates of investment, capital stock, capital services, and the GDP, as well as an overestimate of the rate of inflation.

Figures 2.3 and 2.4 highlight the rising contributions of IT outputs to U.S. economic growth. Figure 2.3 shows the breakdown between IT and non-IT outputs for sub-periods from 1948 to 2002, while Figure 2.4 decomposes the contribution of IT into its components. Although the importance of IT has steadily increased, Figure 2.3 shows that the recent investment and consumption surge nearly doubled the output contribution of IT. Figure 2.4 shows that computer investment is the largest single IT contributor in the late 1990s, but that investments in software and communications equipment are becoming increasingly important.

Figures 2.5 and 2.6 present a similar decomposition of IT inputs into production. The contribution of these inputs is rising even more dramatically. Figure 2.5 shows that the contribution of IT now accounts for more than 48.0 percent of the total contribution of capital input. Figure 2.6 reveals that computer hardware is the largest component of IT, reflecting the growing share and accelerating growth rate of computer investment in the late 1990s.

Private business investment predominates in the output of IT, as shown by Jorgenson and Stiroh (2000b) and Oliner and Sichel (2000).[32] Household purchases of IT equipment and services are next in importance. Government purchases of IT equipment and services, as well as net exports of IT products, must be included in order to provide a complete picture. Firms, consumers, governments, and purchasers of U.S. exports are responding to relative price changes, increasing the contributions of computers, software, and communications equipment.

Table 2.2 shows that the price of computer investment fell by 30.99 percent per year, the price of software fell by 1.31 percent, and the price of communications equipment dropped by 4.16 percent during the period 1995-2002, while non-IT investment and consumption prices rose by 2.02 and 1.79 percent, respectively. In response to these price changes, firms, households, and governments have accumulated computers, software, and communications equipment much more rapidly than other forms of capital.

2.2.4. Productivity

The price or "dual" approach to productivity measurement employed by Triplett (1996) makes it possible to identify the role of IT production as a source of productivity growth at the industry level.[33] 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 with value shares of the inputs as weights. For the computer industry this expression is dominated by two terms: the decline in the price of computers and the contribution of the price of semiconductors. For the semiconductor industry the expression is dominated by the decline in the price of semiconductors.[34]

Jorgenson, Gollop, and Fraumeni (1987) have employed Domar's (1961) model to trace aggregate productivity growth to its sources at the level of individual industries.[35] More recently, Harberger (1998), William Gullickson and Michael Harper (1999), and Jorgenson and Stiroh (2000a, 2000b) have used the model for similar purposes. Productivity growth for each industry is weighted by the ratio of the gross output of the industry to GDP to estimate the industry contribution to aggregate productivity growth.

If semiconductor output were only used to produce computers, then its contribution to computer industry productivity growth, weighted by computer indus-

[32]Bosworth and Triplett (2000) and Baily (2002) compare the results of Jorgenson and Stiroh with those of Oliner and Sichel, who incorporate data from the BLS measures of multifactor productivity.

[33]The dual approach is presented by Jorgenson, Gollop, and Fraumeni (1987), pp. 53-63.

[34]Models of the relationships between computer and semiconductor industries presented by Dulberger (1993), Triplett (1996), and Oliner and Sichel (2000) are special cases of the Domar (1961) aggregation scheme.

[35]See Jorgenson, Gollop, and Fraumeni (1987), pp. 63-66, 301-322.

try output, would precisely offset its independent contribution to the growth of aggregate productivity. This is the ratio of the value of semiconductor output to GDP, multiplied by the rate of semiconductor price decline. In fact, semiconductors are used to produce telecommunications equipment and many other products. However, the value of semiconductor output is dominated by inputs into IT production.

The Domar aggregation formula can be approximated by expressing the declines in prices of computers, communications equipment, and software relative to the price of gross domestic income, an aggregate of the prices of capital and labor services. The rates of relative IT price decline are weighted by ratios of the outputs of IT products to the GDP. Table 2.8 reports details of this decomposition of productivity for 1989-1995 and 1995-2002; the IT and non-IT contributions are presented in Figure 2.7. The IT products contribute 0.47 percentage points to productivity growth for 1995-2002, compared to 0.23 percentage points for 1989-1995. This reflects the accelerating decline in relative price changes resulting from shortening the product cycle for semiconductors.

2.2.5. Output Growth.

This section presents the sources of GDP growth for the entire period 1948 to 2002. Capital services contribute 1.75 percentage points, labor services 1.05 percentage points, and productivity growth only 0.67 percentage points. Input growth is the source of nearly 80.6 percent of U.S. growth over the past half century, while productivity has accounted for 19.4 percent. Figure 2.8 shows the relatively modest contributions of productivity in all sub-periods.

More than four-fifths of the contribution of capital reflects the accumulation of capital stock, while improvement in the quality of capital accounts for about one-fifth. Similarly, increased labor hours account for 68 percent of labor's contribution; the remainder is due to improvements in labor quality. Substitutions among capital and labor inputs in response to price changes are essential components of the sources of economic growth.

A look at the U.S. economy before and after 1973 reveals familiar features of the historical record. After strong output and productivity growth in the 1950s, 1960s and early 1970s, the U.S. economy slowed markedly through 1989, with output growth falling from 3.99 percent to 2.97 percent and productivity growth declining from 1.00 percent to 0.29 percent. The contribution of capital input also slowed from 1.94 percent for 1948-1973 to 1.53 percent for 1973-1989. This contributed to sluggish ALP growth—2.93 percent for 1948-1973 and 1.36 percent for 1973-1989.

Relative to the period 1989-1995, output growth increased by 1.16 percent in 1995-2002. The contribution of IT production jumped by 0.27 percent, relative to 1989-1995, but still accounted for only 17.8 percent of the increased growth of output. Although the contribution of IT has increased steadily throughout the period 1948-2002, there has been a sharp response to the acceleration in the IT price decline in 1995. Nonetheless, more than 80 percent of the increased output growth can be attributed to non-IT products.

Between 1989-1995 and 1995-2002 the contribution of capital input jumped by 0.80 percentage points, the contribution of labor input declined by 0.10 percent, and productivity accelerated by 0.45 percent. Growth in ALP rose 1.03 percent as more rapid capital deepening and growth in productivity offset slower improvement in labor quality. Growth in hours worked rose as labor markets tightened, while labor force participation rates increased.[36]

The contribution of capital input reflects the investment boom of the late 1990s as businesses, households, and governments poured resources into plant and equipment, especially computers, software, and communications equipment. The contribution of capital, predominantly IT, is considerably more important than the contribution of labor. The contribution of IT capital services has grown steadily throughout the period 1948-2002, but Figure 2.6 reflects the impact of the accelerating decline in IT prices.

After maintaining an average rate of 0.29 percent for the period 1973-1989, productivity growth dipped to 0.26 percent for 1989-1995 and then vaulted to 0.71 percent per year for 1995-2002. This is a major source of growth in output and ALP for the U.S. economy (Figures 2.8 and 2.9). Productivity growth for 1995-2002 is considerably higher than the rate of 1948-1973 and the U.S. economy is recuperating from the anemic productivity growth of the past two decades. More than half of the acceleration in productivity from 1989-1995 to 1995-2002 can be attributed to IT production, and this is far greater than the 3.80 percent share of IT in the GDP in 2002.

2.2.6. Average Labor Productivity

Output growth is the sum of growth in hours and average labor productivity. Table 2.7 shows the breakdown between growth in hours and ALP for the same periods as in Table 2.6. For the period 1948-2002, ALP growth predominated in output growth, increasing 2.23 percent per year, while hours worked increased 1.23 percent per year. As shown above, ALP growth depends on capital deepening, a labor quality effect, and overall productivity growth.

Figure 2.9 reveals the well-known productivity slowdown of the 1970s and 1980s, emphasizing the sharp acceleration in labor productivity growth in the late 1990s. The slowdown through 1989 reflects reduced capital deepening, declining labor quality growth, and decelerating growth in total factor productivity. The growth of ALP recovered slightly during the early 1990s with a slump in capital

[36]Katz and Krueger (1999) analyze the recent performance of the U.S. labor market.

deepening more than offset by a revival in labor quality growth and an up-tick in total factor productivity growth. A slowdown in hours combined with middling ALP growth during 1989-1995 to produce a further slide in the growth of output. In previous cyclical recoveries during the postwar period, output growth accelerated during the recovery, powered by more rapid growth of hours and ALP.

Accelerating output growth during 1995-2002 reflects modest growth in labor hours and a sharp increase in ALP growth.[37] Comparing 1989-1995 to 1995-2002, the rate of output growth jumped by 1.16 percent—due to an increase in hours worked of 0.14 percent and an upward bound in ALP growth of 1.03 percent. Figure 2.9 shows the acceleration in ALP growth is due to capital deepening as well as faster total factor productivity growth. Capital deepening contributed 0.74 percentage points, counterbalancing a negative contribution of labor quality of 0.13 percent. The acceleration in total factor productivity growth added 0.45 percentage points.

2.2.7. Research Opportunities

The use of computers, software, and communications equipment must be carefully distinguished from the production of IT.[38] Massive increases in computing power, like those experienced by the U.S. economy, have two effects on growth. First, as IT producers become more efficient, more IT equipment and software is produced from the same inputs. This raises productivity in IT-producing industries and contributes to productivity growth for the economy as a whole. Labor productivity also grows at both industry and aggregate levels.

Second, investment in information technology leads to growth of productive capacity in IT-using industries. Since labor is working with more and better equipment, this increases ALP through capital deepening. If the contributions to aggregate output are captured by capital deepening, aggregate productivity growth is unaffected.[39] Increasing deployment of IT affects productivity growth only if there are spillovers from IT-producing industries to IT-using industries.

Jorgenson, Ho, and Stiroh (2004) trace the increase in aggregate productivity growth to its sources in individual industries. Jorgenson and Stiroh (2000a, 2000b) present the appropriate methodology and preliminary results. Stiroh (2002) shows that aggregate ALP growth can be attributed to productivity growth in IT-producing and IT-using industries.

[37] Stiroh (2002) shows that ALP growth is concentrated in IT-producing and IT-using industries.
[38] Economics and Statistics Administration (2000), Table 3.1, p. 23, lists IT-producing industries.
[39] Baily and Gordon (1988).

2.3. Demise of Traditional Growth Accounting

2.3.1. Introduction

The early 1970s marked the emergence of a rare professional consensus on economic growth, articulated in two strikingly dissimilar books. Kuznets summarized his decades of empirical research in *Economic Growth of Nations* (1971).[40] Solow's book *Growth Theory* (1970), modestly subtitled "An Exposition," contained his 1969 Radcliffe Lectures at the University of Warwick. In these lectures Solow also summarized decades of theoretical research, initiated by the work of Roy Harrod (1939) and Domar (1946).[41]

Let me first consider the indubitable strengths of the perspective on growth that emerged victorious over its many competitors in the early 1970s. Solow's neo-classical theory of economic growth, especially his analysis of steady states with constant rates of growth, provided conceptual clarity and sophistication. Kuznets generated persuasive empirical support by quantifying the long sweep of historical experience of the United States and thirteen other developed economies. He combined this with quantitative comparisons among a developed and developing economies during the postwar period.

With the benefit of hindsight the most obvious deficiency of the traditional framework of Kuznets and Solow was the lack of a clear connection between the theoretical and the empirical components. This lacuna can be seen most starkly in the total absence of cross references between the key works of these two great economists. Yet they were working on the same topic, within the same framework, at virtually the same time, and in the very same geographical location—*Cambridge, Massachusetts*!

Searching for analogies to describe this remarkable coincidence of views on growth, we can think of two celestial bodies on different orbits, momentarily coinciding from our earth-bound perspective at a single point in the sky and glowing with dazzling but transitory luminosity. The indelible image of this extraordinary event has been burned into the collective memory of economists, even if the details have long been forgotten. The resulting professional consensus, now ob-

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[40]The enormous impact of this research was recognized in the same year by the Royal Swedish Academy of Sciences in awarding the third Bank of Sweden Prize in Economic Sciences in Memory of Alfred Nobel to Kuznets "for his empirically founded interpretation of economic growth which has led to new and deepened insight into the economic and social structure and process of development." See Lindbeck (1992), p. 79.

[41]Solow's seminal role in this research, beginning with his brilliant and pathbreaking essay of 1956, "A Contribution to the Theory of Economic Growth," was recognized, simply and elegantly, by the Royal Swedish Academy of Sciences in awarding Solow the Nobel Prize in Economics in 1987 "for his contributions to the theory of economic growth." See Maler (1992), p. 191. Solow (1999) presents an updated version of his exposition of growth theory.

solete, remained the guiding star for subsequent conceptual development and empirical observation for decades.

2.3.2. Human Capital

The initial challenge to the framework of Kuznets and Solow was posed by Denison's magisterial study, *Why Growth Rates Differ* (1967). Denison retained NNP as a measure of national product and capital stock as a measure of capital input, adhering to the conventions employed by Kuznets and Solow. Denison's comparisons among nine industrialized economies over the period 1950-1962 were cited extensively by both Kuznets and Solow.

However, Denison departed from the identification of labor input with hours worked by Kuznets and Solow. He followed his earlier study of U.S. economic growth, *The Sources of Economic Growth in the United States and the Alternatives Before Us*, published in 1962. In this study he had constructed constant quality measures of labor input, taking into account differences in the quality of hours worked due to the age, sex, and educational attainment of workers.

Kuznets (1971), recognizing the challenge implicit in Denison's approach to measuring labor input, presented his own version of Denison's findings.[42] He carefully purged Denison's measure of labor input of the effects of changes in educational attainment. Solow, for his part, made extensive references to Denison's findings on the growth of output and capital stock, but avoided a detailed reference to Denison's measure of labor input. Solow adhered instead to hours worked (or "man-hours" in the terminology of the early 1970s) as a measure of labor input.[43]

Kuznets showed that "... with one or two exceptions, the contribution of the factor inputs per capita was a minor fraction of the growth rate of per capita product."[44] For the United States during the period 1929 to 1957, the growth rate of productivity or output per unit of input exceeded the growth rate of output per capita. According to Kuznets' estimates, the contribution of increases in capital input per capita over this extensive period was negative!

2.3.3. Solow's Surprise

The starting point for our discussion of the demise of traditional growth accounting is a notable but neglected article by the great Dutch economist Jan

[42]Kuznets (1971), Table 9, part B, pp. 74-75.

[43]Solow (1970), pp. 2-7. However, Solow (1988), pp. 313-314, adopted Denison's perspective on labor input in his Nobel Prize address. At about the same time this view was endorsed by Becker (1993a), p. 24, in his 1989 Ryerson Lecture at the University of Chicago. Becker (1993b) also cited Denison in his Nobel Prize address.

[44]Kuznets (1971), p. 73.

Tinbergen (1942), published in German during World War II. Tinbergen analyzed the sources of U.S. economic growth over the period 1870-1914. He found that efficiency accounted only a little more than a quarter of growth in output, while growth in capital and labor inputs accounted for the remainder. This was precisely the opposite of the conclusion that Kuznets (1971) and Solow (1970) reached almost three decades later!

The notion of efficiency or "total factor productivity" was introduced independently by George Stigler (1947) and became the starting point for a major research program at the National Bureau of Economic Research. This program employed data on output of the U.S. economy from earlier studies by the National Bureau, especially the pioneering estimates of the national product by Kuznets (1961). The input side employed data on capital from Raymond Goldsmith's (1962) system of national wealth accounts. However, much of the data was generated by John Kendrick (1956, 1961), who employed an explicit system of national production accounts, including measures of output, input, and productivity for national aggregates and individual industries.[45]

The econometric models of Paul Douglas (1948) and Tinbergen were integrated with data from the aggregate production accounts generated by Abramovitz (1956) and Kendrick (1956) in Solow's justly celebrated 1957 article, "Technical Change and the Aggregate Production Function." Solow identified "technical change" with shifts in the production function. Like Abramovitz, Kendrick, and Kuznets, he attributed almost all of U.S. economic growth to "residual" growth in productivity.[46]

Kuznets' (1971) international comparisons strongly reinforced the findings of Abramovitz (1956), Kendrick (1956), and Solow (1957), which were limited to the United States.[47] According to Kuznets, economic growth was largely attributable to the Solow residual between the growth of output and the growth of capital and labor inputs, although he did not use this terminology. Kuznets' assessment of the significance of his empirical conclusions was unequivocal:

> (G)iven the assumptions of the accepted national economic accounting framework, and the basic demographic and institutional processes that control labor supply, capital accumulation, and initial capital-output ratios, this major conclusion—that the distinctive feature of modern economic growth, the high rate of growth of per capita product is for the most part attributable to a high rate of growth in productivity—is inevitable.[48]

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[45]Updated estimates based on Kendrick's framework are presented by Kendrick (1973) and Kendrick and Grossman (1980).

[46]This finding is called "Solow's Surprise" by Easterly (2001) and is listed as one of the "stylized facts" about economic growth by King and Rebelo (1999).

[47]A survey of international comparisons, including Tinbergen (1942) and Kuznets (1971), is given in my paper with Christensen and Cummings (1980), presented at the forty-fourth meeting of the Conference on Research and Wealth, held at Williamsburg, Virginia, in 1975.

[48]Kuznets (1971), p. 73; see also, pp. 306-309.

The empirical findings summarized by Kuznets have been repeatedly corroborated in investigations that employ the traditional approach to growth accounting. This approach identifies output with real NNP, labor input with hours worked, and capital input with real capital stock.[49] Kuznets (1971) interpreted the Solow residual as due to exogenous technological innovation. This is consistent with Solow's (1957) identification of the residual with technical change. Successful attempts to provide a more convincing explanation of the Solow residual have led, ultimately, to the demise of the traditional framework.[50]

2.3.4. Radical Departure

The most serious challenge to the traditional approach growth accounting was presented in my 1967 paper with Griliches, "The Explanation of Productivity Change." Griliches and I departed far more radically than Denison from the measurement conventions of Kuznets and Solow. We replaced NNP with GNP as a measure of output and introduced constant quality indexes for both capital and labor inputs.

The key idea underlying our constant quality index of labor input, like Denison's, was to distinguish among different types of labor inputs. We combined hours worked for each type into a constant quality index of labor input, using the index number methodology Griliches (1960) had developed for U.S. agriculture. This considerably broadened the concept of substitution employed by Solow (1957). While he had modeled substitution between capital and labor inputs, Denison, Griliches and I extended the concept of substitution to include different types of labor inputs as well. This altered, irrevocably, the allocation of economic growth between substitution and technical change.[51]

Griliches and I introduced a constant quality index of capital input by distinguishing among types of capital inputs. To combine different types of capital into a constant quality index, we identified the prices of these inputs with rental prices, rather than the asset prices used in measuring capital stock. For this purpose we used a model of capital as a factor of production I had introduced in my 1963 article, "Capital Theory and Investment Behavior." This made it possible to incorporate differences among depreciation rates on different assets, as well as

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[49]For recent examples, see Dertouzos, Solow, and Lester (1989) and Hall (1988, 1990).

[50]A detailed survey of research on sources of economic growth is given in my 1990 article, "Productivity and Economic Growth," presented at the The Jubilee of the Conference on Research in Income and Wealth, held in Washington, D.C., in 1988, commemorating the fiftieth anniversary of the founding of the Conference by Kuznets. More recent surveys are presented in Griliches' (2000) posthumous book, *R&D, Education, and Productivity,* and Hulten's (2001) article, "Total Factor Productivity: A Short Biography."

[51]Constant quality indexes of labor input are discussed detail by Jorgenson, Gollop, and Fraumeni (1987), Chapters 3 and 8, pp. 69-108 and 261-300, and Jorgenson, Ho, and Stiroh (2004).

variations in returns due to the tax treatment of different types of capital income, into our constant quality index of capital input.[52]

Finally, Griliches and I replaced the aggregate production function employed by Denison, Kuznets, and Solow with the production possibility frontier introduced in my 1966 paper, "The Embodiment Hypothesis." This allowed for joint production of consumption and investment goods from capital and labor inputs. I had used this approach to generalize Solow's (1960) concept of embodied technical change, showing that economic growth could be interpreted, equivalently, as "embodied" in investment or "disembodied" in productivity growth. My 1967 paper with Griliches removed this indeterminacy by introducing constant quality price indexes for investment goods.[53]

Griliches and I showed that changes in the quality of capital and labor inputs and the quality of investment goods explained most of the Solow residual. We estimated that capital and labor inputs accounted for 85 percent of growth during the period 1945-1965, while only fifteen percent could be attributed to productivity growth. Changes in labor quality explained thirteen percent of growth, while changes in capital quality another eleven percent.[54] Improvements in the quality of investment goods enhanced the growth of both investment goods output and capital input; the net contribution was only two percent of growth.[55]

2.3.5. The Rees Report

The demise of the traditional framework for productivity measurement began with the Panel to Review Productivity Statistics of the National Research Council, chaired by Albert Rees. The Rees Report of 1979, *Measurement and*

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[52]I have presented a detailed survey of empirical research on the measurement of capital input in my 1989 paper, "Capital as a Factor of Production." Earlier surveys were given in my 1973 and 1980 papers and Diewert's (1980) contribution to the forty-fifth meeting of the Conference on Income and Wealth, held at Toronto, Ontario, in 1976. Hulten (1990) surveyed conceptual aspects of capital measurement in his contribution to the Jubilee of the Conference on Research in Income and Wealth in 1988.

[53]As a natural extension of Solow's (1956) one-sector neo-classical model of economic growth, his 1960 model of embodiment had only a single output and did not allow for the introduction of a separate price index for investment goods. Recent research on Solow's model of embodiment is surveyed by Greenwood and Jovanovic (2001) and discussed by Solow (2001). Solow's model of embodiment is also employed by Whelan (2002).

[54]See Jorgenson and Griliches (1967), Table IX, p. 272. We also attributed 13 percent of growth to the relative utilization of capital, measured by energy consumption as a proportion of capacity; however, this is inappropriate at the aggregate level, as Denison (1974), p. 56, pointed out. For additional details, see Jorgenson, Gollop, and Fraumeni (1987), especially pp. 179-181.

[55]Using Gordon's (1990) estimates of improvements in the quality of producers' durables, Hulten (1992) estimated this proportion as 8.5 percent of the growth of U.S. manufacturing output for the period 1949-1983.

Interpretation of Productivity, became the cornerstone of a new measurement framework for the official productivity statistics. This was implemented by the Bureau of Labor Statistics (BLS), the U.S. government agency responsible for these statistics.

Under the leadership of Jerome Mark and Edwin Dean the BLS Office of Productivity and Technology undertook the construction of a production account for the U.S. economy with measures of capital and labor inputs and total factor productivity, renamed multifactor productivity.[56] The BLS (1983) framework was based on GNP rather than NNP and included a constant quality index of capital input, displacing two of the key conventions of the traditional framework of Kuznets and Solow.[57]

However, BLS retained hours worked as a measure of labor input until July 11, 1994, when it released a new multifactor productivity measure including a constant quality index of labor input as well. Meanwhile, BEA (1986) had incorporated a constant quality price index for computers into the national accounts—over the strenuous objections of Denison (1989). This index was incorporated into the BLS measure of output, completing the displacement of the traditional framework of economic measurement by the conventions employed in my papers with Griliches.[58]

The official BLS (1994) estimates of multifactor productivity have overturned the findings of Abramovitz (1956) and Kendrick (1956), as well as those of Kuznets (1971) and Solow (1970). The official statistics have corroborated the findings summarized in my 1990 survey paper, "Productivity and Economic Growth." These statistics are now consistent with the original findings of Tinbergen (1942), as well as my paper with Griliches (1967), and the results I have presented in Section 2.2.

The approach to growth accounting presented in my 1987 book with Gollop and Fraumeni and the official statistics on multifactor productivity published by the BLS in 1994 has now been recognized as the international standard. The new framework for productivity measurement is presented in *Measuring Productivity*, a Manual published by the Organisation for Economic Co-Operation and Development (OECD) and written by Schreyer (2001). The expert advisory group for this manual was chaired by Dean, former Associate Commissioner for Productivity at the BLS, and leader of the successful effort to implement the Rees Report (1979).

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[56]A detailed history of the BLS productivity measurement program is presented by Dean and Harper (2001).

[57]The constant quality index of capital input became the international standard for measuring productivity in Blades' (2001) OECD manual, *Measuring Capital*.

[58]The constant quality index of labor input became the international standard in the United Nations (1993) *System of National Accounts*.

3. ECONOMICS ON INTERNET TIME

The steadily rising importance of information technology has created new research opportunities in all areas of economics. Economic historians, led by Chandler (2000) and Moses Abramovitz and Paul David (1999, 2001),[59] have placed the information age in historical context. Abramovitz and David present sources of U.S. economic growth for the nineteenth and twentieth centuries. Their estimates, beginning in 1966, are based on the official productivity statistics published by the Bureau of Labor Statistics (1994).

The Solow (1987) Paradox, that we see computers everywhere but in the productivity statistics,[60] has been displaced by the economics of the information age. Computers have now left an indelible imprint on the productivity statistics. The remaining issue is whether the breathtaking speed of technological change in semiconductors differentiates this resurgence from previous periods of rapid growth?

Capital and labor markets have been severely impacted by information technology. Enormous uncertainty surrounds the relationship between equity valuations and future growth prospects of the American economy.[61] One theory attributes rising valuations of equities since the growth acceleration began in 1995 to the accumulation of intangible assets, such as intellectual property and organizational capital. An alternative theory treats the high valuations of technology stocks as a bubble that burst during the year 2000.

The behavior of labor markets also poses important puzzles. Widening wage differentials between workers with more and less education has been attributed to computerization of the workplace. A possible explanation could be that high-skilled workers are complementary to IT, while low-skilled workers are substitutable. An alternative explanation is that technical change associated with IT is skill-biased and increases the wages of high-skilled workers relative to low-skilled workers.[62]

Finally, information technology is altering product markets and business organizations, as attested by the large and growing business literature,[63] but a fully satisfactory model of the semiconductor industry remains to be developed.[64] Such

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[59]See also: David (1990, 2000) and Gordon (2000).

[60]Griliches (1994), Brynjolfsson and Yang (1996), and Triplett (1999) discuss the Solow Paradox.

[61]Campbell and Shiller (1998) and Shiller (2000) discuss equity valuations and growth prospects. Kiley (1999), Brynjolfsson and Hitt (2000), and Hall (2000, 2001), present models of investment with internal costs of adjustment.

[62]Acemoglu (2002) and Katz (2000) survey the literature on labor markets and technological change.

[63]See, for example, Grove (1996) on the market for computers and semiconductors and Christensen (1997) on the market for storage devices.

[64]Irwin and Klenow (1994), Flamm (1996), pp. 305-424, and Helpman and Trajtenberg (1998), pp. 111-119, present models of the semiconductor industry.

a model would derive the demand for semiconductors from investment in information technology in response to rapidly falling IT prices. An important objective is to determine the product cycle for successive generations of new semiconductors endogenously.

The semiconductor industry and the information technology industries are global in their scope with an elaborate international division of labor.[65] This poses important questions about the American growth resurgence. Where is the evidence of a new economy in other leading industrialized countries? I have shown in Section 3 that the most important explanation is the relative paucity of constant quality price indexes for semiconductors and information technology in national accounting systems outside the U.S.

The stagflation of the 1970s greatly undermined the Keynesian Revolution, leading to a New Classical Counter-revolution led by Lucas (1981) that has transformed macroeconomics. The unanticipated American growth revival of the 1990s has similar potential for altering economic perspectives. In fact, this is already foreshadowed in a steady stream of excellent books on the economics of information technology.[66] We are the fortunate beneficiaries of a new agenda for economic research that will refresh our thinking and revitalize our discipline.

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[65]The role of information technology in U.S. economic growth is discussed by the Economics and Statistics Administration (2000); comparisons among OECD countries are given by the Organisation for Economic Co-operation and Development (2000, 2003).

[66]See, for example, Carl Shapiro and Hal Varian (1999), Brynjolfsson and Kahin (2000), and Choi and Whinston (2000).

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TABLE 2.1 Information Technology Output and Gross Domestic Product

	Computer		Software	
Year	Value	Price	Value	Price
1948				
1949				
1950				
1951				
1952				
1953				
1954				
1955				
1956				
1957				
1958				
1959	0.0	1,635.07		
1960	0.2	1,635.07	0.1	1.25
1961	0.3	1,226.30	0.2	1.22
1962	0.3	817.53	0.2	1.18
1963	0.8	572.27	0.5	1.14
1964	1.0	490.52	0.6	1.11
1965	1.3	408.77	0.8	1.08
1966	1.9	283.63	1.1	0.99
1967	2.1	228.43	1.4	1.02
1968	2.1	194.16	1.5	1.01
1969	2.7	176.76	2.1	1.07
1970	3.0	158.80	2.8	1.14
1971	3.2	142.57	2.9	1.11
1972	4.1	128.28	3.4	1.10
1973	4.2	142.83	3.9	1.12
1974	4.8	128.86	4.8	1.18
1975	4.6	152.47	5.9	1.25
1976	5.6	125.12	6.4	1.25
1977	7.2	98.56	6.8	1.27
1978	9.7	60.47	8.0	1.27
1979	13.2	45.21	10.2	1.30
1980	17.3	34.17	12.2	1.35
1981	22.6	25.95	14.9	1.42
1982	25.3	25.83	17.7	1.45
1983	34.8	20.42	20.9	1.44
1984	43.4	18.70	25.9	1.43
1985	46.0	15.41	30.1	1.41
1986	45.7	13.64	32.7	1.36
1987	48.6	12.40	37.8	1.36
1988	54.0	12.15	44.7	1.35
1989	56.8	12.01	54.2	1.30
1990	52.3	10.86	62.3	1.26

Communications		Total IT		Gross Domestic Product	
Value	Price	Value	Price	Value	Price
1.7	0.90	1.7	4.26	321.0	0.19
1.5	0.90	1.5	4.28	322.0	0.19
1.7	0.92	1.7	4.37	343.4	0.19
2.0	0.96	2.0	4.55	382.1	0.19
2.5	0.93	2.5	4.39	395.1	0.19
2.8	0.89	2.8	4.22	436.6	0.20
2.5	0.90	2.5	4.26	428.1	0.20
2.7	0.89	2.7	4.24	471.8	0.20
3.4	0.91	3.4	4.30	493.7	0.21
4.0	0.95	4.0	4.49	537.2	0.22
3.5	0.95	3.5	4.52	512.6	0.21
4.3	0.95	4.4	4.52	556.9	0.21
4.8	0.93	5.1	4.42	573.1	0.22
5.3	0.91	5.9	4.28	587.6	0.22
5.8	0.91	6.4	4.18	631.3	0.22
5.9	0.90	7.1	3.99	675.9	0.23
6.5	0.88	8.0	3.86	737.6	0.23
7.6	0.87	9.8	3.71	806.8	0.24
9.1	0.85	12.1	3.43	881.7	0.25
10.0	0.86	13.4	3.35	928.7	0.25
10.7	0.87	14.3	3.31	981.9	0.26
12.1	0.89	16.9	3.33	1,052.5	0.27
13.4	0.92	19.2	3.38	1,111.2	0.28
13.7	0.94	19.8	3.36	1,182.5	0.29
14.4	0.96	21.9	3.35	1,323.8	0.31
16.9	0.97	25.0	3.45	1,509.2	0.33
18.4	1.02	28.0	3.52	1,628.7	0.36
19.7	1.09	30.2	3.82	1,808.8	0.40
22.0	1.12	34.0	3.78	2,054.9	0.43
26.0	1.10	40.0	3.59	2,270.7	0.46
30.3	1.13	48.0	3.33	2,547.6	0.49
35.7	1.16	59.0	3.19	2,878.4	0.53
40.7	1.22	70.2	3.10	3,011.1	0.56
45.1	1.29	82.6	3.01	3,341.7	0.61
46.9	1.34	90.0	3.07	3,532.2	0.66
50.4	1.35	106.1	2.87	3,886.1	0.69
57.8	1.36	127.0	2.79	4,375.0	0.73
64.1	1.35	140.1	2.60	4,624.7	0.74
57.9	1.37	136.4	2.50	4,753.7	0.73
58.4	1.35	144.7	2.40	5,118.9	0.76
63.9	1.32	162.6	2.36	5,702.9	0.81
66.5	1.31	177.5	2.32	6,028.4	0.83
69.5	1.31	184.1	2.23	6,339.7	0.85

continues

TABLE 2.1 Continued

	Computer		Software	
Year	Value	Price	Value	Price
1991	52.5	10.77	70.8	1.25
1992	55.3	9.76	76.7	1.16
1993	56.3	8.57	86.1	1.14
1994	60.4	8.19	93.4	1.11
1995	74.9	5.61	102.0	1.09
1996	84.8	3.53	115.4	1.05
1997	94.2	2.43	142.3	1.00
1998	96.6	1.69	162.5	0.97
1999	101.9	1.22	194.7	0.97
2000	109.9	1.00	222.7	1.00
2001	98.6	0.79	219.6	1.01
2002	88.4	0.64	212.7	1.00

NOTES: Values are in billions of current dollars. Prices are normalized to one in 2000. Information technology output is gross domestic product by type of product.

Communications		Total IT		Gross Domestic Product	
Value	Price	Value	Price	Value	Price
66.9	1.33	190.3	2.23	6,464.4	0.87
70.5	1.31	202.5	2.10	6,795.1	0.89
76.7	1.29	219.1	2.00	7,038.5	0.89
84.3	1.26	238.1	1.94	7,579.5	0.93
94.4	1.21	271.2	1.72	7,957.2	0.95
107.8	1.18	307.9	1.48	8,475.4	0.97
119.2	1.17	355.7	1.31	8,961.0	0.98
124.1	1.11	383.1	1.15	9,346.9	0.98
134.0	1.05	430.5	1.05	9,824.2	0.98
152.6	1.00	485.2	1.00	10,399.6	1.00
146.5	0.95	464.7	0.94	10,628.5	1.01
127.4	0.90	428.6	0.88	11,279.4	1.04

TABLE 2.2 Growth Rates of Outputs and Inputs

	1989-1995		1995-2002	
	Prices	Quantities	Prices	Quantities
		Outputs		
Gross Domestic Product	2.20	2.43	1.39	3.59
Information Technology	–4.95	12.02	–9.58	16.12
Computers	–12.69	17.30	–30.99	33.37
Software	–2.82	13.34	–1.31	11.82
Communications Equipment	–1.36	7.19	–4.16	8.44
Non-Information Technology Investment	2.05	1.10	2.02	2.01
Non-Information Technology Consumption	2.52	2.40	1.79	3.35
		Inputs		
Gross Domestic Income	2.45	2.17	2.10	2.88
Information Technology Capital Services	–3.82	12.58	–10.66	18.33
Computer Capital Services	–10.46	20.22	–26.09	32.34
Software Capital Services	–4.40	15.03	–1.72	14.27
Communications Equipment Capital Services	0.99	5.99	–5.56	9.83
Non-Information Technology Capital Services	1.71	1.91	1.72	3.01
Labor Services	3.37	1.64	3.42	1.50

NOTES: Average annual percentage rates of growth.

TABLE 2.3 FOLLOWS

TABLE 2.3 Information Technology Capital Stock and Domestic Tangible Assets

	Computer		Software		Communications		Total IT		Total Domestic Tangible Assets	
Year	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price
1948					4.6	0.93	4.6	1.99	754.9	0.11
1949					5.7	0.93	5.7	2.00	787.1	0.11
1950					7.0	0.95	7.0	2.04	863.5	0.11
1951					8.6	0.99	8.6	2.13	990.4	0.12
1952					10.0	0.96	10.0	2.05	1,066.5	0.12
1953					11.5	0.92	11.5	1.97	1,136.3	0.13
1954					12.9	0.93	12.9	1.99	1,187.7	0.13
1955					14.3	0.92	14.3	1.98	1,279.3	0.13
1956					16.4	0.94	16.4	2.01	1,417.8	0.14
1957					19.4	0.98	19.4	2.09	1,516.9	0.14
1958					21.1	0.98	21.1	2.11	1,586.0	0.14
1959	0.2	2,389.62	0.1	1.16	23.1	0.98	23.4	2.11	1,682.5	0.15
1960	0.2	2,389.62	0.1	1.16	24.9	0.96	25.2	2.06	1,780.8	0.15
1961	0.4	1,792.22	0.3	1.14	27.1	0.94	27.8	2.02	1,881.0	0.15
1962	0.5	1,194.81	0.4	1.10	29.9	0.94	30.8	2.00	2,007.2	0.16
1963	1.0	836.37	0.7	1.06	32.0	0.92	33.7	1.94	2,115.4	0.16
1964	1.6	716.89	1.0	1.04	34.5	0.91	37.1	1.90	2,201.2	0.16
1965	2.2	597.41	1.5	1.02	37.8	0.89	41.5	1.86	2,339.3	0.16
1966	2.9	414.53	2.1	0.94	42.1	0.88	47.1	1.78	2,534.9	0.17
1967	3.7	333.84	2.9	0.97	47.9	0.89	54.5	1.78	2,713.9	0.17
1968	4.3	283.77	3.4	0.96	54.4	0.91	62.1	1.79	3,004.5	0.18
1969	5.3	258.34	4.6	1.01	61.7	0.93	71.6	1.82	3,339.1	0.20
1970	6.3	232.09	6.2	1.09	70.0	0.96	82.5	1.87	3,617.5	0.21
1971	6.3	176.08	7.0	1.06	77.3	0.98	90.7	1.86	3,942.2	0.22
1972	7.4	142.24	8.1	1.05	85.2	1.01	100.7	1.87	4,463.6	0.24

1973	8.7	134.90	9.6	1.07	93.8	1.02	112.0	1.89	5,021.4	0.26
1974	9.2	110.16	11.7	1.12	105.8	1.07	126.7	1.94	5,442.4	0.27
1975	9.8	101.69	14.4	1.19	120.6	1.14	144.8	2.06	6,242.6	0.30
1976	10.5	85.07	16.3	1.19	133.0	1.18	159.8	2.09	6,795.1	0.32
1977	12.5	73.95	18.1	1.21	142.2	1.16	172.8	2.04	7,602.8	0.35
1978	14.2	50.03	20.4	1.21	160.3	1.19	194.9	2.03	8,701.7	0.38
1979	19.4	41.48	24.5	1.24	181.9	1.22	225.8	2.05	10,049.5	0.43
1980	24.4	32.35	29.6	1.29	210.5	1.28	264.4	2.09	11,426.5	0.47
1981	33.9	28.42	36.2	1.35	243.4	1.36	313.5	2.17	13,057.6	0.53
1982	42.7	25.37	43.2	1.39	270.5	1.40	356.4	2.20	14,020.9	0.55
1983	53.0	21.01	50.3	1.38	293.3	1.41	396.5	2.16	14,589.5	0.57
1984	66.7	17.08	60.1	1.37	320.6	1.42	447.3	2.11	15,901.1	0.60
1985	78.3	14.59	70.5	1.36	348.1	1.42	497.0	2.05	17,616.4	0.64
1986	86.8	12.46	79.3	1.31	374.1	1.40	540.2	1.96	18,912.3	0.67
1987	95.0	10.66	91.2	1.31	402.9	1.39	589.0	1.91	20,263.5	0.70
1988	108.3	9.90	105.4	1.30	432.9	1.37	646.5	1.87	21,932.4	0.74
1989	122.4	9.27	121.9	1.25	461.6	1.36	705.9	1.83	23,678.3	0.78
1990	123.6	8.30	140.6	1.22	487.5	1.35	751.7	1.77	24,399.0	0.79
1991	125.7	7.38	163.2	1.22	508.1	1.34	797.0	1.73	24,896.4	0.79
1992	129.7	6.20	175.0	1.12	528.8	1.32	833.5	1.64	25,218.3	0.79
1993	138.9	5.22	199.2	1.11	550.7	1.30	888.8	1.58	25,732.9	0.79
1994	155.5	4.59	218.2	1.08	578.0	1.28	951.8	1.52	26,404.3	0.79
1995	178.3	3.80	242.7	1.07	605.5	1.24	1,026.5	1.44	28,003.7	0.82
1996	192.5	2.85	269.7	1.04	637.6	1.20	1,099.8	1.34	29,246.9	0.83
1997	212.5	2.15	312.4	1.00	678.7	1.18	1,203.6	1.25	31,146.2	0.86
1998	227.4	1.55	360.6	0.97	704.3	1.11	1,292.2	1.13	33,888.5	0.91
1999	252.1	1.18	433.7	0.97	741.3	1.05	1,427.1	1.05	36,307.6	0.95
2000	288.2	1.00	515.5	1.00	805.2	1.00	1,609.0	1.00	39,597.1	1.00
2001	279.5	0.80	563.7	1.01	844.3	0.95	1,687.6	0.94	42,566.8	1.05
2002	281.8	0.67	583.9	1.00	874.0	0.91	1,739.7	0.89	45,892.0	1.11

NOTES: Values are in billions of current dollars. Prices are normalized to one in 2000. Domestic tangible assets include fixed assets and consumer durable goods, land, and inventories.

TABLE 2.4 Information Technology Capital Services and Gross Domestic Income

	Computer		Software		Communications		Total IT		Gross Domestic Income	
Year	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price
1948					1.7	1.21	1.7	8.44	321.0	0.14
1949					1.4	0.87	1.4	6.12	322.0	0.13
1950					1.7	0.86	1.7	6.04	343.4	0.14
1951					2.0	0.91	2.0	6.36	382.1	0.14
1952					2.6	0.97	2.6	6.78	395.1	0.14
1953					3.1	0.98	3.1	6.85	436.6	0.15
1954					2.5	0.70	2.5	4.88	428.1	0.15
1955					3.5	0.87	3.5	6.08	471.8	0.16
1956					4.0	0.89	4.0	6.24	493.7	0.16
1957					3.5	0.69	3.5	4.84	537.2	0.17
1958					3.9	0.70	3.9	4.88	512.6	0.16
1959	0.2	1,843.00	0.1	1.54	4.9	0.81	5.2	5.66	556.9	0.17
1960	0.2	1,801.01	0.1	1.51	5.1	0.76	5.3	5.33	573.1	0.17
1961	0.3	2,651.36	0.1	1.53	5.3	0.72	5.7	5.15	587.6	0.17
1962	0.5	2,221.38	0.2	1.59	6.3	0.77	7.0	5.41	631.3	0.18
1963	0.7	1,301.76	0.3	1.40	6.2	0.68	7.1	4.63	675.9	0.19
1964	0.8	749.35	0.4	1.32	6.8	0.69	8.0	4.40	737.6	0.20
1965	1.2	680.70	0.6	1.36	8.7	0.80	10.5	4.95	806.8	0.21
1966	2.2	675.44	1.0	1.43	9.2	0.75	12.4	4.72	881.7	0.22
1967	2.4	424.81	1.1	1.14	9.4	0.68	12.8	3.96	928.7	0.22
1968	2.6	329.85	1.5	1.27	9.8	0.64	14.0	3.66	981.9	0.22
1969	2.7	253.51	1.7	1.12	10.9	0.64	15.3	3.44	1,052.5	0.23
1970	3.6	246.33	2.3	1.17	12.7	0.68	18.5	3.58	1,111.2	0.24
1971	5.2	274.21	3.5	1.52	14.3	0.70	23.0	3.87	1,182.5	0.26
1972	4.9	182.44	3.7	1.37	16.0	0.73	24.5	3.58	1,323.8	0.28

1973	4.4	124.14	4.1	1.32	21.7	0.92	30.2	3.91	1,509.2	0.30
1974	6.6	145.93	4.9	1.34	19.5	0.76	30.9	3.56	1,628.7	0.32
1975	5.9	107.43	6.2	1.46	22.3	0.82	34.4	3.56	1,808.8	0.36
1976	6.6	97.74	7.0	1.44	23.9	0.82	37.5	3.51	2,054.9	0.39
1977	7.0	78.00	7.8	1.43	39.4	1.26	54.2	4.54	2,270.7	0.42
1978	11.8	84.61	9.0	1.50	33.6	0.98	54.4	3.92	2,547.6	0.45
1979	11.6	50.14	10.4	1.50	44.9	1.19	66.8	4.00	2,878.4	0.49
1980	16.6	44.40	12.2	1.51	40.0	0.96	68.8	3.41	3,011.1	0.51
1981	17.6	29.68	13.7	1.45	38.6	0.84	69.9	2.84	3,341.7	0.55
1982	19.7	22.39	15.2	1.39	41.4	0.83	76.3	2.61	3,532.2	0.58
1983	26.6	20.57	18.0	1.40	46.4	0.87	91.1	2.61	3,886.1	0.64
1984	36.5	18.42	22.4	1.46	53.9	0.93	112.8	2.64	4,375.0	0.68
1985	40.0	14.01	26.7	1.46	60.3	0.96	127.0	2.45	4,624.7	0.69
1986	43.6	11.46	31.0	1.44	67.3	0.98	141.9	2.32	4,753.7	0.70
1987	54.0	11.00	36.5	1.46	78.9	1.06	169.3	2.38	5,118.9	0.72
1988	53.4	8.69	44.6	1.54	97.2	1.20	195.2	2.39	5,702.9	0.77
1989	58.6	7.83	54.3	1.57	98.8	1.14	211.6	2.27	6,028.4	0.79
1990	65.9	7.57	60.0	1.45	102.5	1.10	228.3	2.17	6,339.7	0.81
1991	65.8	6.65	62.7	1.29	97.1	0.99	225.6	1.93	6,464.4	0.82
1992	73.2	6.22	82.4	1.45	105.4	1.02	261.0	1.99	6,795.1	0.85
1993	79.4	5.38	80.0	1.21	118.2	1.09	277.5	1.85	7,038.5	0.86
1994	84.0	4.46	97.3	1.29	132.6	1.14	313.8	1.83	7,579.5	0.90
1995	105.2	4.18	102.7	1.21	150.2	1.20	358.0	1.80	7,957.2	0.91
1996	133.1	3.73	116.3	1.20	144.2	1.07	393.5	1.66	8,475.4	0.94
1997	144.0	2.77	134.4	1.17	147.6	1.01	426.0	1.46	8,961.0	0.96
1998	162.4	2.12	152.5	1.10	184.4	1.15	499.3	1.37	9,346.9	0.96
1999	166.5	1.48	165.7	1.00	188.1	1.06	520.2	1.15	9,824.2	0.98
2000	156.9	1.00	193.9	1.00	201.4	1.00	552.2	1.00	10,399.6	1.00
2001	175.6	0.88	219.0	1.01	199.5	0.88	594.1	0.92	10,628.5	1.00
2002	162.9	0.67	247.2	1.07	202.4	0.82	612.5	0.86	11,279.4	1.06

NOTES: Values are in billions of current dollars. Prices are normalized to one in 2000.

TABLE 2.5 Labor Services

	Labor Services							
Year	Price	Quantity	Value	Quality	Employment	Weekly Hours	Hourly Compensation	Hours Worked
1948	0.06	2,324.8	150.1	0.73	61,536	40.6	1.2	129,846
1949	0.07	2,262.8	165.5	0.73	60,437	40.2	1.3	126,384
1950	0.08	2,350.6	181.3	0.75	62,424	39.8	1.4	129,201
1951	0.08	2,531.5	210.7	0.76	66,169	39.7	1.5	136,433
1952	0.09	2,598.2	222.5	0.77	67,407	39.2	1.6	137,525
1953	0.09	2,653.0	238.5	0.79	68,471	38.8	1.7	138,134
1954	0.09	2,588.7	240.7	0.79	66,843	38.4	1.8	133,612
1955	0.09	2,675.7	252.7	0.80	68,367	38.7	1.8	137,594
1956	0.10	2,738.0	272.4	0.80	69,968	38.4	1.9	139,758
1957	0.11	2,740.9	293.0	0.81	70,262	37.9	2.1	138,543
1958	0.12	2,671.8	307.4	0.82	68,578	37.6	2.3	134,068
1959	0.11	2,762.8	316.9	0.82	70,149	37.8	2.3	137,800
1960	0.12	2,806.6	341.7	0.83	71,128	37.6	2.5	139,150
1961	0.12	2,843.4	352.1	0.84	71,183	37.4	2.5	138,493
1962	0.13	2,944.4	374.1	0.85	72,673	37.4	2.6	141,258
1963	0.13	2,982.3	382.7	0.86	73,413	37.3	2.7	142,414
1964	0.13	3,055.7	412.0	0.86	74,990	37.2	2.8	144,920
1965	0.14	3,149.7	448.1	0.86	77,239	37.2	3.0	149,378
1966	0.15	3,278.8	494.8	0.87	80,802	36.8	3.2	154,795
1967	0.16	3,327.2	518.9	0.87	82,645	36.3	3.3	156,016
1968	0.17	3,405.4	582.6	0.88	84,733	36.0	3.7	158,604
1969	0.18	3,491.1	641.4	0.88	87,071	35.9	3.9	162,414
1970	0.20	3,439.2	683.1	0.88	86,867	35.3	4.3	159,644
1971	0.22	3,439.5	740.7	0.89	86,715	35.2	4.7	158,943
1972	0.23	3,528.8	813.3	0.89	88,838	35.3	5.0	162,890
1973	0.25	3,672.4	903.9	0.89	92,542	35.2	5.3	169,329

1974	0.27	3,660.9	979.2	0.89	94,121	34.5	5.8	168,800
1975	0.29	3,606.4	1,055.2	0.90	92,575	34.2	6.4	164,460
1976	0.32	3,708.0	1,182.6	0.90	94,922	34.2	7.0	168,722
1977	0.34	3,829.8	1,321.1	0.90	98,202	34.1	7.6	174,265
1978	0.37	3,994.9	1,496.8	0.90	102,931	34.0	8.2	181,976
1979	0.40	4,122.6	1,660.4	0.90	106,463	33.9	8.9	187,589
1980	0.44	4,105.6	1,809.7	0.90	107,061	33.4	9.7	186,202
1981	0.47	4,147.7	1,934.6	0.91	108,050	33.3	10.4	186,887
1982	0.50	4,110.2	2,056.5	0.92	106,749	33.1	11.2	183,599
1983	0.54	4,172.3	2,234.7	0.92	107,810	33.2	12.0	186,175
1984	0.56	4,417.4	2,458.3	0.93	112,604	33.3	12.6	195,221
1985	0.58	4,531.7	2,646.2	0.93	115,201	33.3	13.3	199,424
1986	0.64	4,567.5	2,904.1	0.93	117,158	33.0	14.4	200,998
1987	0.64	4,736.5	3,017.3	0.94	120,456	33.1	14.6	207,119
1988	0.65	4,888.8	3,173.3	0.94	123,916	33.0	14.9	212,882
1989	0.68	5,051.3	3,452.4	0.95	126,743	33.2	15.8	218,811
1990	0.71	5,137.6	3,673.2	0.96	128,290	33.0	16.7	220,475
1991	0.75	5,086.7	3,806.3	0.96	127,022	32.7	17.6	216,281
1992	0.80	5,105.9	4,087.4	0.97	127,100	32.8	18.8	216,873
1993	0.82	5,267.6	4,323.8	0.97	129,556	32.9	19.5	221,699
1994	0.83	5,418.2	4,472.4	0.98	132,459	33.0	19.7	227,345
1995	0.84	5,573.2	4,661.5	0.98	135,297	33.1	20.0	232,675
1996	0.86	5,683.6	4,878.5	0.99	137,571	33.0	20.7	235,859
1997	0.89	5,843.3	5,186.5	0.99	140,432	33.2	21.4	242,242
1998	0.92	6,020.8	5,519.5	0.99	143,557	33.3	22.2	248,610
1999	0.96	6,152.1	5,908.2	1.00	146,468	33.3	23.3	253,276
2000	1.00	6,268.5	6,268.5	1.00	149,364	33.1	24.4	257,048
2001	1.05	6,250.6	6,537.4	1.00	149,020	32.9	25.6	255,054
2002	1.06	6,188.7	6,576.2	1.01	147,721	32.9	26.1	252,399

NOTES: Value is in billions of current dollars. Quantity is in billions of 2000 dollars. Price and quality are normalized to one in 2000. Employment is in thousands of workers. Weekly hours is hours per worker, divided by 52. Hourly compensation is in current dollars. Hours worked are in millions of hours.

TABLE 2.6 Sources of Gross Domestic Product Growth

	1948-2002	1948-1973	1973-1989	1989-1995	1995-2002
			Outputs		
Gross Domestic Product	3.46	3.99	2.97	2.43	3.59
Contribution of Information Technology	0.28	0.12	0.34	0.37	0.64
Computers	0.13	0.03	0.18	0.15	0.34
Software	0.07	0.02	0.08	0.15	0.19
Communications Equipment	0.08	0.07	0.08	0.08	0.11
Contribution of Non-Information Technology	3.18	3.87	2.63	2.05	2.95
Contribution of Non-Information Technology Investment	0.69	1.04	0.45	0.21	0.41
Contribution of Non-Information Technology Consumption	2.49	2.82	2.18	1.85	2.55
			Inputs		
Gross Domestic Income	2.79	2.99	2.68	2.17	2.88
Contribution of Information Technology Capital Services	0.36	0.15	0.38	0.49	0.93
Computers	0.17	0.04	0.20	0.22	0.52
Software	0.08	0.02	0.07	0.16	0.23
Communications Equipment	0.11	0.09	0.11	0.10	0.18
Contribution of Non-Information Technology Capital Services	1.39	1.79	1.15	0.71	1.07
Contribution of Labor Services	1.05	1.04	1.15	0.98	0.88
Total Factor Productivity	0.67	1.00	0.29	0.26	0.71

NOTES: Average annual percentage rates of growth. The contribution of an output or input is the rate of growth, multiplied by the value share.

TABLE 2.7 Sources of Average Labor Productivity Growth

	1948-2002	1948-1973	1973-1989	1989-1995	1995-2002
Gross Domestic Product	3.46	3.99	2.97	2.43	3.59
Hours Worked	1.23	1.06	1.60	1.02	1.16
Average Labor Productivity	2.23	2.93	1.36	1.40	2.43
Contribution of Capital Deepening	1.23	1.49	0.85	0.78	1.52
Information Technology	0.33	0.14	0.34	0.44	0.88
Non-Information Technology	0.90	1.35	0.51	0.34	0.64
Contribution of Labor Quality	0.33	0.43	0.23	0.36	0.20
Total Factor Productivity	0.67	1.00	0.29	0.26	0.71
Information Technology	0.17	0.05	0.20	0.23	0.47
Non-Information Technology	0.50	0.95	0.09	0.03	0.24
Addendum					
Labor Input	1.81	1.83	1.99	1.64	1.50
Labor Quality	0.58	0.77	0.39	0.61	0.33
Capital Input	4.13	4.49	3.67	2.92	4.92
Capital Stock	3.29	4.13	2.77	1.93	2.66
Capital Quality	0.84	0.36	0.90	0.99	2.27

NOTES: Average annual percentage rates of growth. Contributions are defined in Equation (3) of the text.

TABLE 2.8 Sources of Total Factor Productivity Growth

	1948-2002	1948-1973	1973-1989	1989-1995	1995-2002
Total Factor Productivity Growth	0.67	1.00	0.29	0.26	0.71
Contributions to TFP Growth					
Information Technology	0.17	0.05	0.20	0.23	0.47
Computers	0.10	0.02	0.13	0.13	0.33
Software	0.02	0.00	0.03	0.06	0.06
Communications Equipment	0.04	0.03	0.05	0.04	0.08
Non-Information Technology	0.50	0.95	0.09	0.03	0.24
Relative Price Changes					
Information Technology	–6.72	–4.1	–8.5	–7.4	–11.7
Computers	–22.50	–22.0	–21.5	–15.1	–33.1
Software	–4.87	–5.1	–5.1	–5.3	–3.4
Communications Equipment	–3.79	–2.9	–4.1	–3.8	–6.3
Non-Information Technology	–0.51	–1.0	–0.1	0.0	–0.3
Average Nominal Shares					
Information Technology	2.03	1.00	2.35	3.04	4.10
Computers	0.46	0.10	0.64	0.83	1.00
Software	0.53	0.07	0.49	1.13	1.78
Communications Equipment	1.04	0.83	1.22	1.09	1.33
Non-Information Technology	97.97	99.00	97.65	96.96	95.90

NOTES: Average annual rates of growth. Prices are relative to the price of gross domestic income. Contributions are relative price changes, weighted by average nominal output shares.

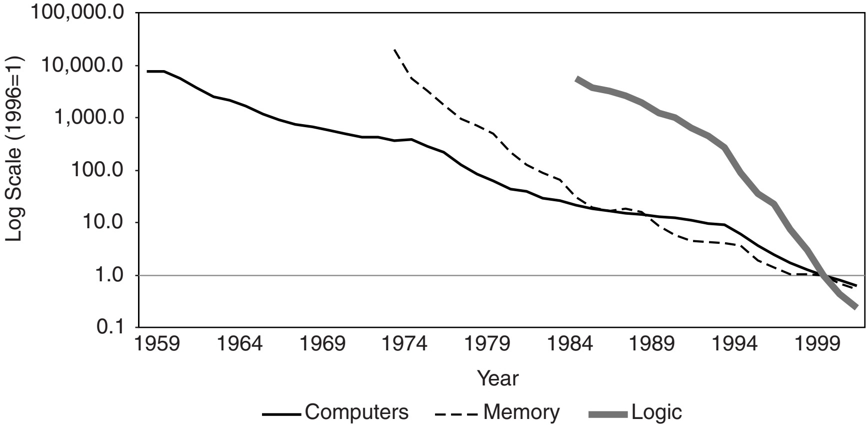

FIGURE 1.1 Relative Prices of Computers and Semiconductors, 1959-2002. NOTE: All price indexes are divided by the output price index.

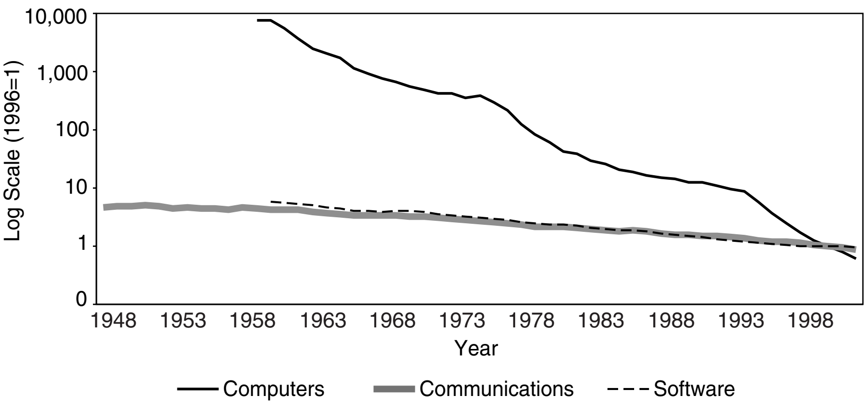

FIGURE 1.2 Relative Prices of Computers, Communications, and Software, 1948-2002. NOTE: All price indexes are divided by the output price index.

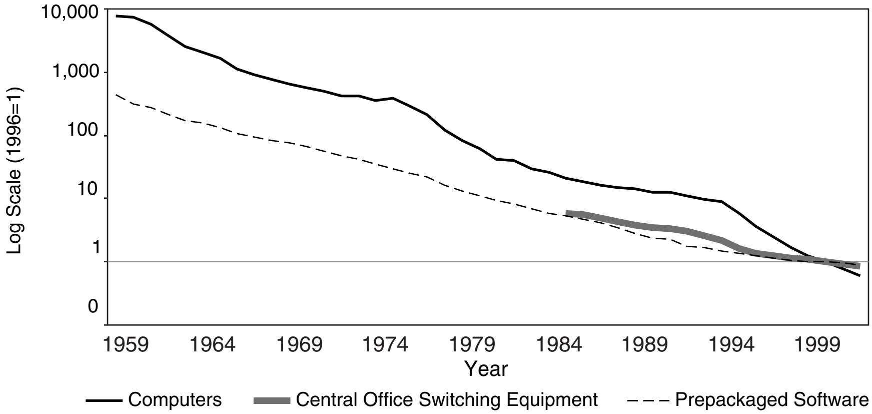

FIGURE 1.3 Relative Prices of Computers, Central Office Switching Equipment, and Prepackaged Software, 1959-2002.
NOTE: All price indexes are divided by the output price index.

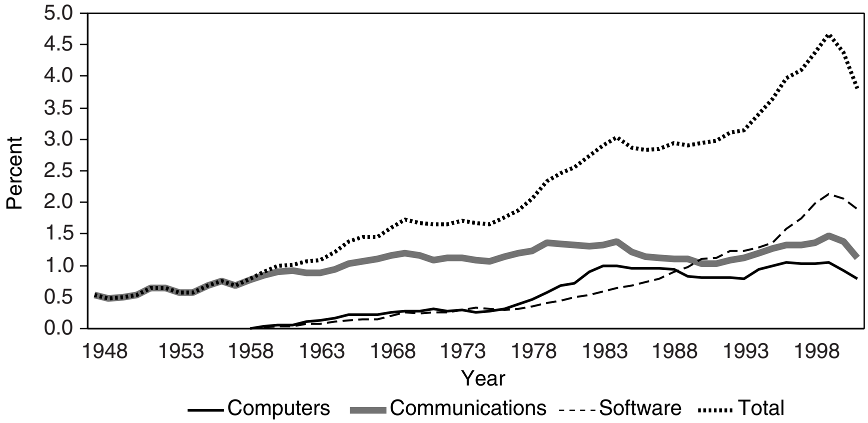

FIGURE 2.1 Output Shares of Information Technology by Type, 1948-2002.
NOTE: Share of current dollar gross domestic product.

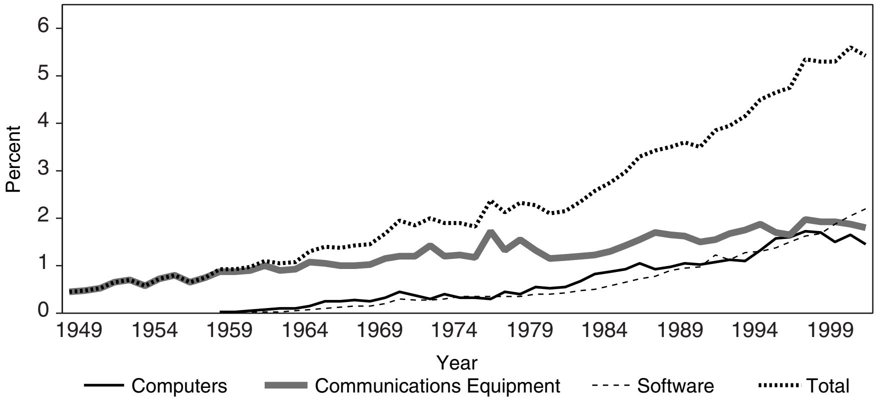

FIGURE 2.2 Input Shares of Information Technology by Type, 1948-2002.
NOTE: Share of current dollar gross domestic income.

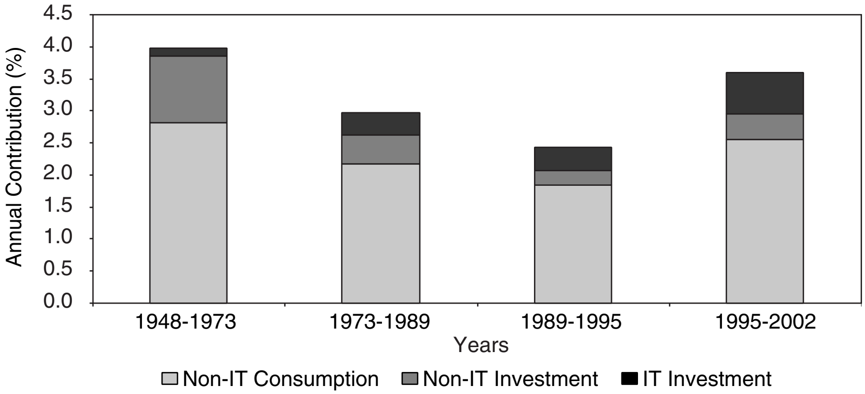

FIGURE 2.3 Output Contribution of Information Technology.
NOTE: Output contributions are the average annual growth rates, weighted by the output shares.

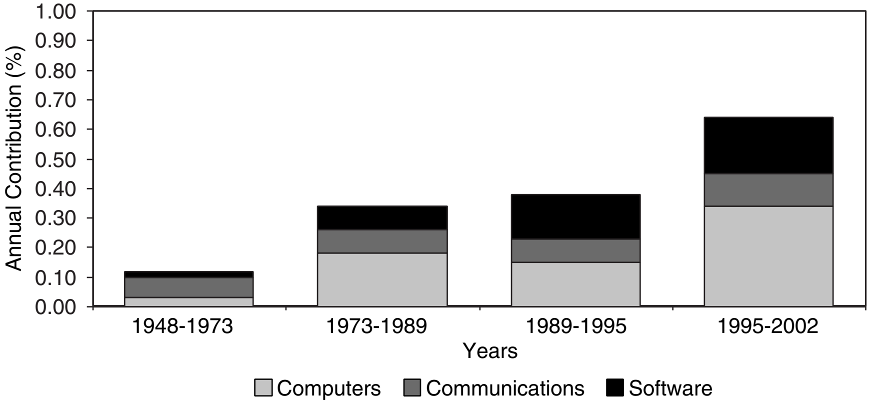

FIGURE 2.4 Output Contribution of Information Technology by Type.
NOTE: Output contributions are the average annual growth rates, weighted by the output shares.

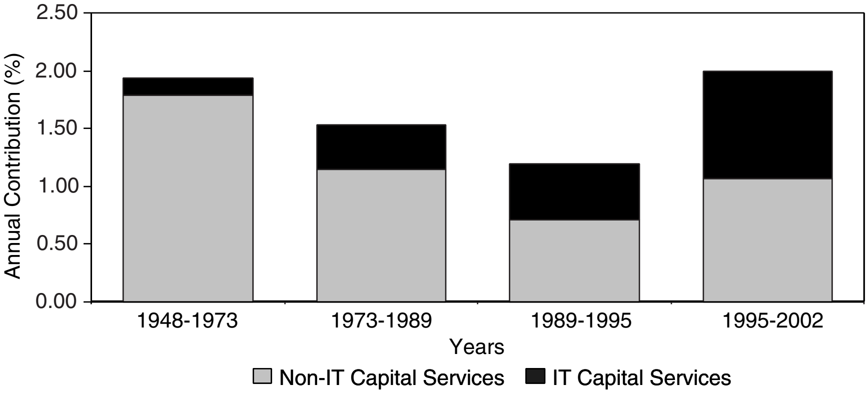

FIGURE 2.5 Capital Input Contribution of Information Technology.
NOTE: Input contributions are the average annual growth rates, weighted by the income shares.

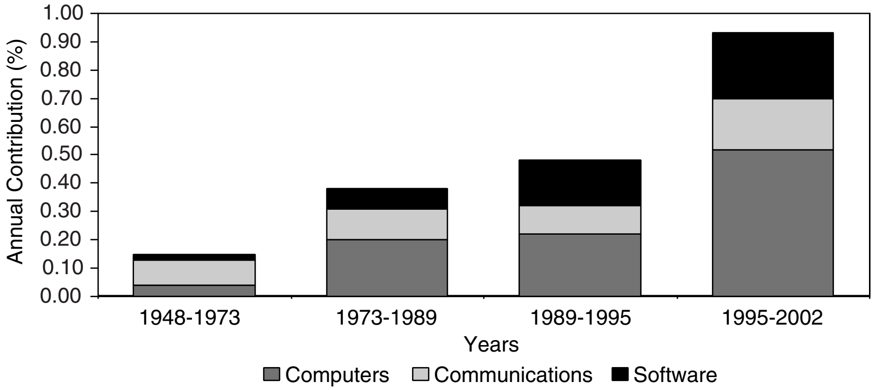

FIGURE 2.6 Capital Input Contribution of Information Technology by Type.
NOTE: Input contributions are the average annual growth rates, weighted by the income shares.

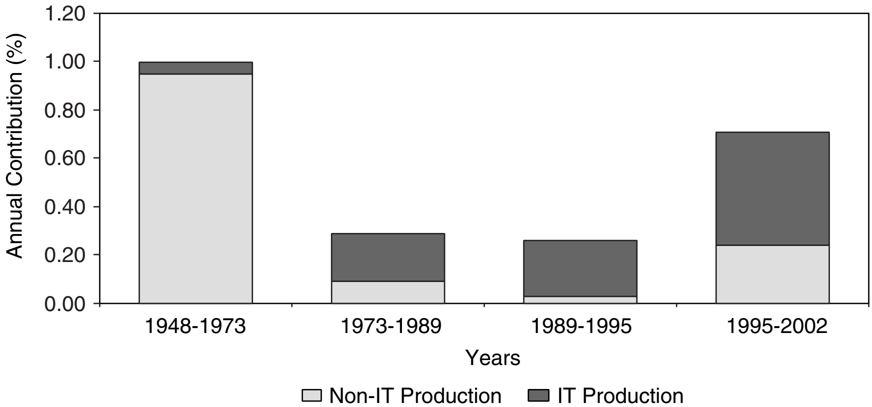

FIGURE 2.7 Contributions of Information Technology to Total Factor Productivity Growth.
NOTE: Contributions are average annual relative price changes, weighted by average nominal output shares from Table 2.8.

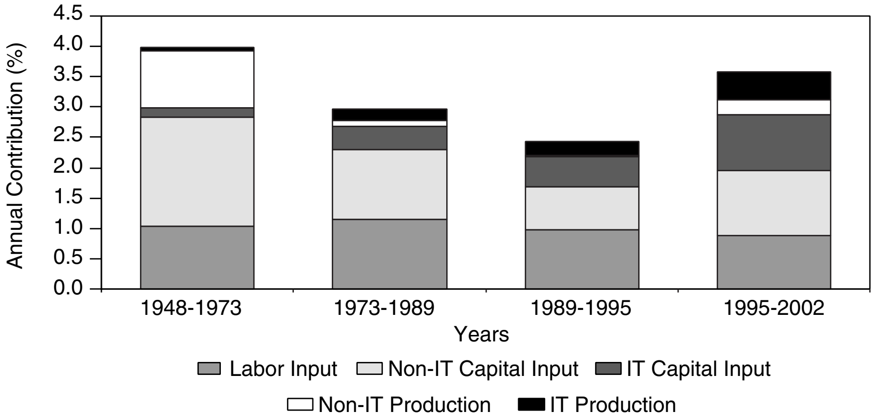

FIGURE 2.8 Sources of Gross Domestic Product Growth.

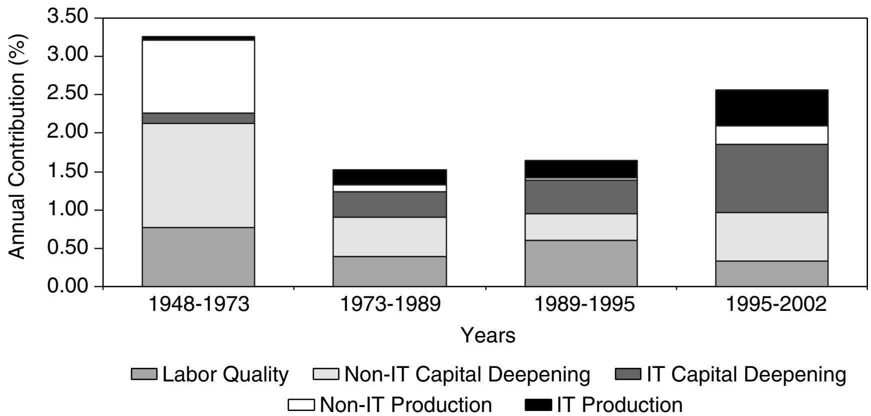

FIGURE 2.9 Sources of Average Labor Productivity Growth.

International Technology Roadmaps: The U.S. Semiconductor Experience

W. J. Spencer and T. E. Seidel
International SEMATECH

INTRODUCTION

"It is difficult to predict, especially the future!"
—Ancient Chinese Proverb

The semiconductor industry was born in 1947 with the invention of the point contact transistor on germanium material. The industry got a tremendous impetus to its growth with the development of the integrated circuit (IC) in the late 1950s. Germanium was replaced by silicon, and the technology to manufacture hundreds of millions of individual components on silicon microchips has led to a worldwide industry that will exceed $135 billion in sales in 1995. The semiconductor industry has undergone a compound annual growth rate of over 15 percent for several decades. The worldwide growth of the industry exceeded 25 percent per year in 1993 and 1994; it is expected to do the same in 1995.

The reason that the semiconductor industry has grown so dramatically—and is in fact the economic driving force for the Information Age—is a year-over-year increase in productivity of 25 to 30 percent. This productivity increase has been going on for nearly three decades and shows up as either a 30-percent-per-year reduction in cost of components on silicon or a 30-percent-per-year increase in the complexity of functions that can be performed in silicon. This productivity improvement is demonstrated clearly in the continual decrease in cost of semiconductor memory from the first introduction of 1,000-bit chips in around 1970 to today's production of 4- and 16-megabit dynamic random access memories (DRAMs), and it is expected to continue well into the twenty-first century (see Figure 1).

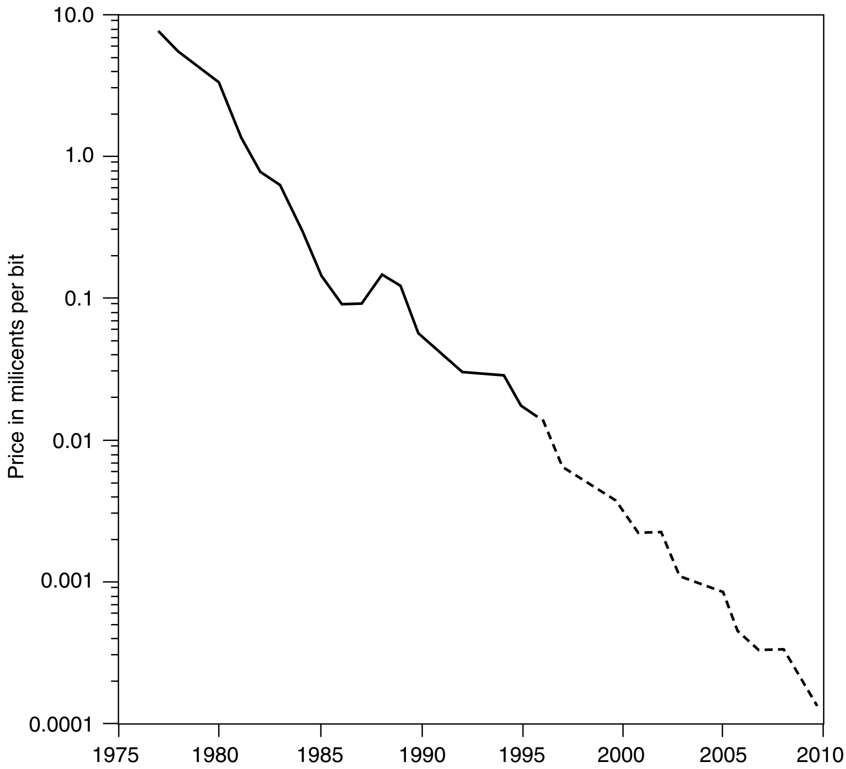

FIGURE 1 Dynamic RAM Best-Bit Prices.
SOURCE: ICE and National Technology Roadmap.

There appear to be no major physical limitations to improving productivity in silicon integrated circuits for the next 15 to 20 years. Today's 16-megabit DRAMs and associated microprocessor and logic chips are manufactured using 0.5-μm technology. The manufacturing facilities currently under construction will produce 0.35-μm and 0.25-μm products before the end of the decade. Table 1 shows a summary of the technologies projected by the National Technology Roadmap for Semiconductors ("Roadmap") out through the year 2007. Behind this projection for the technology for the next 15 years are complete roadmaps for each of the major technologies in support of the manufacture of silicon integrated circuits. This work was the result of hundreds of scientists and engineers from universities, industry, and government working together to develop a set of industry requirements for silicon technology. The history of this roadmap process, the methods used to develop the National Technology Roadmap for Semiconductors, some of the overall requirements of the Roadmap, and finally, some sugges-

TABLE 1 Overall Roadmap Technology Characteristics

	1992	**1995**	**1998**	**2001**	**2004**	**2007**
Feature Size (μm)	0.5	0.35	0.25	0.18	0.12	0.10
Gate/chip	300K	800K	2Mb	5Mb	10Mb	20Mb
Bits/chip						
—DRAM	16Mb	64Mb	256Mb	1Gb	4Gb	16Gb
—SRAM	4Mb	16Mb	64Mb	256Mb	1Gb	4Gb
Wafer processing cost ($\$/cm^2$)	$4.00	$3.90	$3.80	$3.70	$3.60	$3.50
Chip size (mm^2)						
—logic/μprocessor	250	400	600	800	1000	1250
—DRAM	132	200	320	500	700	1000
Wafer diameter (mm)	200	200	200/400	200-400	200-400	200-400

tions for international cooperation and roadmaps in other technologies are the subject of this paper.

Technology roadmaps are not new to the semiconductor industry. The first semiconductor technology roadmaps were developed by SEMATECH in 1987. Earlier technology predictions were developed by the National Academy of Sciences' Committee on Science and Public Policy (COSEPUP). Studies were initiated by COSEPUP in the early 1960s. In 1968 Philip Handler, who was then the President of the National Academy of Sciences, edited a book entitled *Biology and the Future of Man.*[1] A survey of physics was done by the National Research Council under the chairmanship of George E. Pake in 1966.[2] This study was updated in 1972[3] and again in 1986.[4] Today, to the author's knowledge, there is no plan to further update these surveys of fundamental science.

EARLY SEMATECH ROADMAP

The early planning of SEMATECH was greatly influenced by a set of industry-wide roadmap workshops held from June 1987 through March 1988. The latter month was coincident with the consortium's occupation of its Austin,

[1]Philip Handler, *Biology and the Future of Man,* London: Oxford University Press, 1970.
[2]G. E. Pake, *Physics Survey and Outlook,* Washington, D.C.: National Academy Press, 1966.
[3]D. Alan Bromley, *Physics in Perspective,* Washington, D.C.: National Academy Press, 1972.
[4]W. F. Brinkman, *Physics Through the 1990s*, Washington, D.C.: National Academy Press, 1986.

Texas, site. These early workshops were driven by a group of about 20 planners from the future member companies of SEMATECH; leaders included Turner Hasty, who was later to serve as Chief Operating Officer. The first "organizing" workshop was held in Monterey, California; it provided a global competitive overview and developed planning guidelines for additional technology roadmapping to reach a competitive technology position for U.S. semiconductor manufacturers by 1990-1993. The workshop also identified topics for about 30 detailed workshops. Workshop topics included Lithography, Manufacturing Systems, Thermal Processes, Implant, Etch, Deposition and Etch Technologies, Manufacturing Facilities, Packaging, Metrology, Silicon Epi, Robotics & Automation, Test, Cleaning, and Process Architecture.

The Lithography workshop recognized that new exposure-tool technology required long development times, so planning decisions had to be developed quickly to meet 1993 goals for 0.35 μm. However, a vision to extend I-line to 0.35 μm was not developed at this time; in fact, history has shown the industry only made that decision as late as 1994. This early Lithography workshop scoped a list of options that included 1 × X-ray for use at 0.35 μm. It also used a systems approach for each lithographic technology option, considering mask, resist, and metrology needs for various exposure technologies.

Among the identification of general needs were architectures for factory data systems, improvement of defect densities (100x improvement was called for for the 0.5-μm generation), equipment specifications (later this evolved into a qualification methodology), defect-detection/metrology needs, and improved manufacturing cycle time, equipment, and reliability.

Specific technology requirements in the important Interconnect area include the development of tungsten plugs, a comparison of metal-physical and vapor-deposition schemes, and the characterization of electromigration. At the 0.5-μm Process Architecture workshop, the vision was set for the need for planarization of interlevel dielectrics when more than two levels of metal were required. This had an early influence that drove SEMATECH's focus on chemical-mechanical planarization.

The Process Architecture workshops not only set roadmap process requirements and options but also made some operational recommendations. They included an evolutionary migration from the 0.8-μm AT&T process (which was the process incubator for SEMATECH) to generic 0.5- to 0.35-μm processes and the recommendation to delay a 200-mm demonstration until 150-mm equipment was further qualified. SEMATECH ultimately developed its own 0.35-μm processes and demonstrated 200-mm tool performance on 0.35-μm technology by the end of 1993.

Many of the organizers and leaders of the early workshops later served SEMATECH in management or advisory roles. They included Belani (NSC), Castrucci (IBM), Dehmel (Intel), Ferrell (Motorola), Hanson (NSC), Hasty (TI), Mackiewicz (AT&T), Oberai (IBM), Reilly (IBM), Seidel (UC-Santa Barbara),

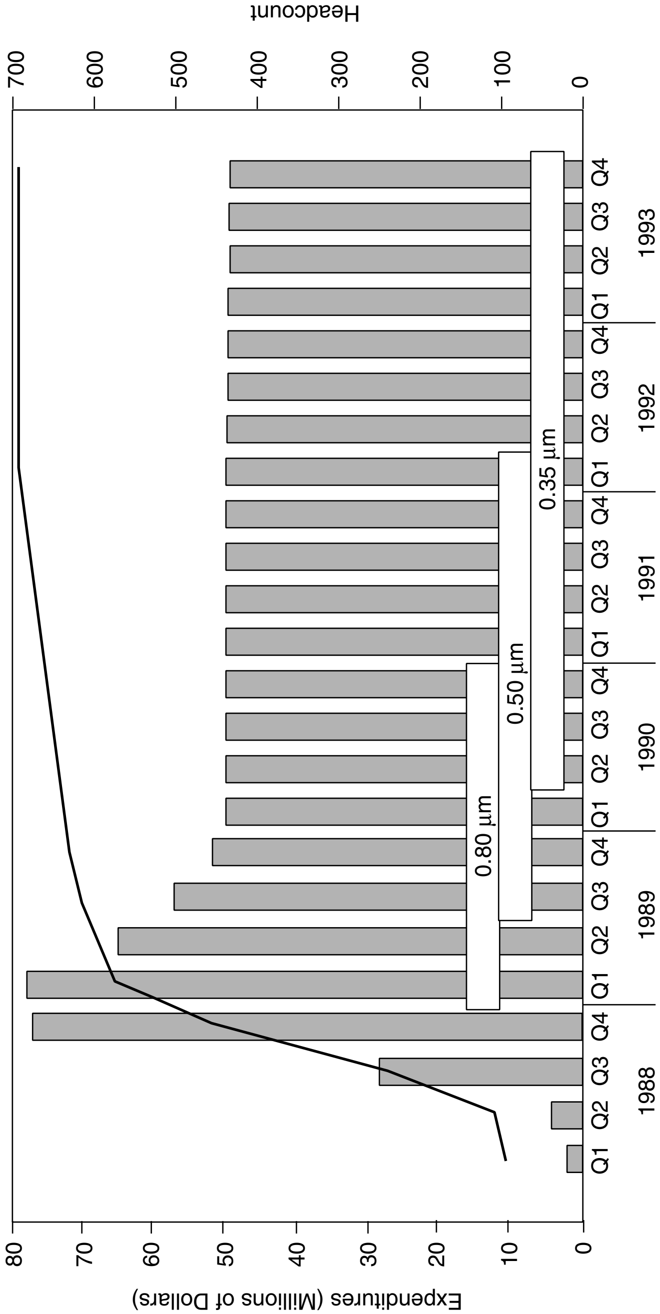

FIGURE 2 SEMATECH Five-Year Operational Plan.

and Sinha (AT&T). These workshops provided the basis for SEMATECH's first five-year operational plan. Figure 2 shows three components of the five-year plan: manpower, budget, and technology generations. The curve represents manpower and the bars represent the quarterly budget.

MICROTECH 2000—DEVELOP A 1-GIGABIT STATIC RANDOM ACCESS MEMORY CHIP BY 2000

The 100th Congress of the United States established a National Advisory Committee on Semiconductors (NACS) in 1988. This was part of a Semiconductor Research and Development Act. The objectives of the Presidential Committee were to "devise and promulgate a national semiconductor strategy." The committee included leaders from both industry and government. Between 1989 and 1992 the NACS published a series of recommendations for strengthening the U.S. semiconductor industry, including the equipment and materials suppliers.[5] These reports were submitted to the President of the United States and resulted in additional funding for R&D in the U.S. semiconductor industry, principally from the Department of Defense. In addition, the NACS convened several ad hoc working groups in markets, environment, and technology. The Technology Committee was chaired by Dr. John A. Armstrong, who was then Vice President for Science and Technology at the IBM Corporation.

In April 1991 the Technology Committee of NACS and the U.S. federal government, through the Office of Science and Technology Policy, co-sponsored a workshop at Research Triangle Park in North Carolina. Nearly 100 representatives of U.S. semiconductor manufacturers, equipment makers, research institutions, universities, materials suppliers, and the federal government participated in the workshop. The objectives of the workshop were "to determine if the MicroTech 2000 technical goal of developing a competitive 0.12 micron semiconductor manufacturing process ahead of current forecasts is feasible, to identify the most critical efforts that should be undertaken to develop the manufactur-

[5]National Advisory Committee on Semiconductors, *A Strategic Industry At Risk,* Washington, D.C.: National Advisory Committee on Semiconductors, 1989; National Advisory Committee on Semiconductors, *Preserving the Vital Base: America's Semiconductor Materials and Equipment Industry,* Washington, D.C.: National Advisory Committee on Semiconductors, 1990; National Advisory Committee on Semiconductors, *Capital Investment in Semiconductors: The Lifeblood of the U.S. Semiconductor Industry,* Washington, D.C.: National Advisory Committee on Semiconductors, 1990; National Advisory Committee on Semiconductors, *Toward a National Semiconductor Strategy,* vols. 1 and 2, Washington, D.C.: National Advisory Committee on Semiconductors, 1991; National Advisory Committee on Semiconductors, *A National Strategy for Semiconductors: An Agenda for the President, the Congress, and the Industry,* Washington, D.C.: National Advisory Committee on Semiconductors, 1992; and National Advisory Committee on Semiconductors, *Competing in Semiconductors,* Washington, D.C.: National Advisory Committee on Semiconductors, 1992.

TABLE 2 Microtech 2000 Architecture Roadmap

Year Required	1993	1996	1998	2000
			SRAM	
Maximum	16Mb	64Mb	256Mb	1Gb
Minimum design rules (µm)	0.35	0.25	0.18	0.12
Access time (ns)	10	6	4	2.5
Burst clock (Mhz)	100	300	500	1200
			SYSTEM-ON-A-CHIP	
Minimum design rules (µm)		0.35	0.25	0.18
On-chip SRAM		8Mb	64Mb	256Mb

ing process and to produce engineering samples of a product using the process, and to determine when resources would have to be made available to reach the goal by the year 2000."

The outcome of the workshop was a report to the full NACS in August 1991.[6] The workshop met its goal of developing a technology roadmap that would advance semiconductor technology by roughly one generation by the year 2000. This would make possible the manufacture of a 1-Gigabit static random access memory (SRAM) chip in early production phase by that time frame. The architecture roadmap is shown in Table 2.

The workshop report received wide circulation, and a great deal of discussion, within the U.S semiconductor industry. There was a general sense that the technology could be accelerated. There was a question in the industry as to whether the economics of this acceleration were worthwhile.

The NACS was a three-year committee activity that ended in 1992. In 1991, in preparation for its final report, the NACS asked the U.S. Semiconductor Industry Association (SIA) to take over some of its activities, including the implementation of the MicroTech 2000 workshop report. The SIA formed a Technology Committee under the leadership of Dr. Gordon Moore, who was then Chairman of the Board at Intel Corporation. Several meetings and telephone discussions between Dr. Moore and one of the authors led to the formation of a group to update the MicroTech 2000 report in 1992.

[6]National Advisory Committee on Semiconductors, *MICROTECH 2000 Workshop Report,* Washington, D.C.: National Advisory Committee on Semiconductors, 1991.

SEMICONDUCTOR INDUSTRY ASSOCIATION 1992 ROADMAP

The SIA, recognizing the United States must maintain its leadership in the semiconductor industry, which is enabling for the Information Age, sponsored the 1992 Semiconductor Technology Workshop to develop a comprehensive 15-year roadmap. Unlike the MicroTech 2000 report, which set the challenges for a particular technology generation (1G SRAM) circa the year 2000, the 1992 Roadmap assessed the current status and then set down the needs for each of five succeeding generations, looking out 15 years from 1992, to 2007. It was also the first time that industry, government, and academia worked together and broadly contributed expertise and insights to the effort.

Gordon Moore, chair of the SIA Technology Committee and general chair of the workshop, provided the keynote address and the leadership to make the workshop a success. The organizational leadership for this meeting, provided by the Semiconductor Research Corporation (SRC) and SEMATECH, formed a variety of management committees. They included a Framework Committee (led by Oberai Industry) and a Steering Committee (Burger [SRC]); these were composed of membership from industry, academia, and government. A Technology Committee (chaired by Bill Howard) was also formed to coordinate the efforts of each of the Technical Working Groups (lithography, interconnect, etc.).

The process that the groups followed was to develop the Roadmap "strawman," or draft, and iterate it with their individual committee members. A revised draft of the Roadmap was issued before the workshop, and the key issues were highlighted for review at the actual workshop.

The charter of the workshop was to evaluate likely progress in key areas relative to expected industry requirements and to identify resources that might best be used to ensure that the industry would have the necessary technology for success in competitive world markets. One underlying assumption of the Semiconductor Technology Roadmap is that it refers to mainstream silicon Complimentary Metal-Oxide Silicon (CMOS) technology and does not include nonsilicon technologies.

This workshop consisted of 11 Technical Working Groups (TWGs): Chip Design & Test, chaired by Richard Howard; Process Integration, chaired by Dirk Bartelink; Lithography, chaired by Gordon McMillan; Interconnect, chaired by Thomas Seidel; Materials & Bulk Processes, chaired by Dyer Matlock; Environment, Safety & Health, chaired by Phyllis Pei; Manufacturing Systems, chaired by Hal Bogardus; Manufacturing Facilities, chaired by Craig Schackleton; Process Device Structure/CAD, chaired by Don Scharfetter; Packaging, chaired by John Kelly; and Equipment Modeling & Design, chaired by Edward Hall.

Altogether there were about 200 participants in the three-day workshop, which was held in Irving, Texas, in November 1992. The format included a general session followed by breakout sessions that featured cross-coordination of information among various technical working groups. For example, it was neces-

TABLE 3 Cost Targets

Lithography	35%
Multilevel Metals and Etch	25%
Furnaces/Implants	15%
Cleans/Strips	20%
Metrology	5%

NOTE: Numbers are percentages of the wafer-processing cost. Percentages exclude packaging, test, and design costs.

sary for the Lithography group to communicate with Interconnect and with Materials & Bulk Processes. Joint and breakout sessions alternated until consensus was reached or the final joint general session was held, at which time there was debate in an open forum.

The working groups defined critical success factors and core competencies needed for progress. Common themes and elements led to the set of overall key challenges that is shown in Table 1. In this table, the progression of feature sizes and chip complexity follows historical trends. Entries are organized by date of introduction of production startup; however, some entries reflect attributes of each technology generation at maturity. These characteristics were starting points for working-group deliberations.

For the first time, an industry technical roadmapping process prioritized the "cost-to-produce" as a key metric. The cost/cm^2 was taken as a benchmark metric against which budget targets were developed for the various fab production technologies. For example, lithography was allocated 35 percent of the total, multilevel metal and etch 25 percent, and so forth (see Table 3).

Technical characteristics of note are increasing logic complexity (gates/chip) and chip frequency and decreasing power-supply voltage. These specific characteristics set the vision for requirements for dynamic power for CMOS. They also set in place additional implications for engineering the capabilities to achieve or manage those requirements.

Many organizations have used the Roadmap to set up their own development plans, to prioritize investments, and to act as resource material for discussion of technology trends at various forums, including those of international character. In the United States, one of the most significant results of the workshop was to reinforce a culture of cooperation. The intent to renew the Roadmap on a periodic basis was established.

One of the key conclusions of the 1992 Roadmap was the recognition that the infrastructure was unbalanced in its investments among fab technologies and design, test, packaging, and Technology Computer Aided Design (TCAD). This conclusion influenced SEMATECH's board of directors to order the startup of these silicon-to-systems activities in 1993. Two documents were published in 1993 to represent the 1992 Roadmap: *Semiconductor Technology Workshop Conclusions*[7] and *Semiconductor Technology Workshop Working Group Reports.*[8,9] Those documents were published and provided worldwide on a cost-free basis.

1994 UPDATE

The success of the 1992 Roadmap prompted the renewal of the Roadmap in 1994. A central assumption of the 1994 process was that Moore's Law (a 4x increase in complexity every three years) would again extend over the next 15 years. Many experts have challenged this assumption because maintaining the pace of technology and cost reduction is an exceedingly difficult task. Nonetheless, no expectation or algorithm for slowing was agreed upon, and the coordinating committee framed the workshop against extension of Moore's Law. A 15-year outlook was again taken, this time reaching to 0.07-μm CMOS technology in 2010. A proof of concept exists for low-leakage CMOS transistors near a 0.07-μm gate length. There appears to be no fundamental limit to fabrication of quality 0.07-μm CMOS transistors.

Unlike during the first roadmapping exercise, the management committees were consolidated into one committee: the Roadmap Coordinating Group (RCG), which played the roles of the former Framework, Steering, and Technology committees. The RCG was chaired by Owen Williams (Motorola), while different members fulfilled a mentoring responsibility for the various working groups, and several members (Burger, Seidel, and Wollensen) owned the creation and iteration of the overall (framing) characteristics. The RCG owned communication to the TWGs and the SIA's Technology Committee (see Figure 3).

Again, all sectors of the U.S. semiconductor technology base participated: industry, universities, and government organizations. The theme of the 1994 Roadmap became the creation of a cooperative culture that builds a sense of "urgency without crises."

The 1994 workshop, a one-day meeting, was held in Boulder, Colorado. Almost 300 participants met in a format that was condensed because the prework was carried out in such a way as to reach consensus within the various Technical Working Groups before the meeting. The meeting was an open forum where each chair and co-chair presented their summary of the Roadmap and then the entire audience held open debate on the issues that the proposed Roadmap presented.

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[7]Semiconductor Industry Association, *Semiconductor Technology Workshop Conclusions,* San Jose, CA: Semiconductor Industry Association, 1993.

[8]Semiconductor Industry Association, *Semiconductor Technology Workshop Working Group Reports,* San Jose, CA: Semiconductor Industry Association, 1993.

[9]1993 International Electron Device Meeting Technical Digest, Piscataway, NJ: WEE, 1993.

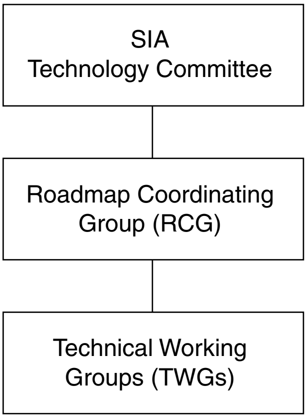

FIGURE 3 Roadmap coordinating committee structure.

In the 1994 workshop, there were only eight Technical Working Groups: Design & Test, chaired by R. Howard; Process Integration & Device Structure (PIDS), chaired by D. Bartelink; Environment, Safety & Health (ESH), chaired by R. Kirby; Lithography, chaired by G. McMillan; Interconnect, chaired by J. Martin; Materials & Bulk Processes (MBP), chaired by F. Robertson; Assembly & Packaging, chaired by A. Oscilowski; and Factory Integration, chaired by G. Gettel.

The consolidation of TCAD with PIDS and of Manufacturing Facilities, Manufacturing Systems, and Equipment Modeling & Design into Factory Integration accounts for the reduction from 11 groups in 1992 to eight. However, although it was recognized that Contamination-Free Engineering was a key part of MBP, all groups assessed contamination, materials, metrology, modeling, standards, and quality/reliability requirements. These latter technology areas cut across all eight technical working groups. The key summaries from each TWG are abstracted here:

- Design & Test is dealing with an increase in complexity that threatens the ability to economically manage the design of higher complexity.
- Process Integration & Device Structure is faced with power, performance, signal integrity, and complexity issues that require lower voltage, process simplification, and cross-functional coordination.
- Environment, Safety & Health finds that future requirements mandate concurrent-engineering efforts to ensure ESH integrity (harmony with society).
- Lithography forecasts the extension of optical technologies while predicting a future move to non-optical technologies, among which there is no preferred choice now.

- Interconnect expresses needs in cost, density, performance, and reliability; this requires the engineering and integration of new materials and architectures, and a focus on productivity.
- Materials & Bulk Processes is challenged by large wafers, thinner dielectrics, shallow junctions, process control, and contamination-free manufacturing.
- Assembly & Packaging faces a variety of requirements paced by a proliferation of products in the market place but has special challenges in power and frequency requirements.
- Factory Integration identifies productivity, complexity, flexibility, and cost as major issues.

The overall Roadmap characteristics in 1994 (see Table 4) were iterated with each of the TWGs and were developed in a self-consistent manner. The first three rows in the table are Major Market Product descriptions. The cost per function metrics for DRAM and microprocessors (μP) and the nonrecurring engineering cost for low-volume application-specific integrated circuits (ASICs) are listed. Similar overall characteristic charts include: number of Chip I/0s, number of wiring levels on chip (appropriate to Interconnect and Assembly & Packaging), defect density, mask count, wafer size (Factory Integration), power-supply voltage and maximum logic power (Process Integration & Device Structure and Design & Test).

In general, the trends between 1992 and 1994 overall characteristics are very similar. There is some acceleration in the migration to lower power supply voltage, and wafer size has now been standardized at 300 mm for the 0.18- to 0.13-μm generations.

The 1994 Roadmap has again been a useful vehicle for many forums. An electronic version has been piloted on the Internet, and there is discussion of renewal again in 1996 or 1997. One document was published in 1994, *The National Technology Roadmap for Semiconductors,*[10] and again globally distributed.

INTERNATIONAL ROADMAPS

"If you don't know where you're going, any road will take you there."
—Anonymous

The development of a National Technology Roadmap for Semiconductors has had a profound impact on semiconductor R&D in the United States. The Roadmap forms the basis for many technology discussions. The Roadmap results

[10]Semiconductor Industry Association, *The National Technology Roadmap for Semiconductors,* San Jose, CA: Semiconductor Industry Association, 1994.

TABLE 4 Overall Roadmap Technology Characteristics Major Markets

Year of First DRAM Shipment	1995	1998	2001	2004	2007	2010	
Minimum Feature Size (μm)	0.35	0.25	0.18	0.13	0.10	0.07	**Driver**
Memory							D
Bits/Chip (DRAM/Flash)	64Mb	256Mb	1Gb	4Gb	16Gb	64Gb	
Cost/Bit @ volume (millicents)	0.017	0.007	0.003	0.001	0.0005	0.0002	
Logic (High-Volume: Microprocessor)							L (μP)
Logic Transistors/cm^2 (packed)	4Mb	7Mb	13Mb	25Mb	50Mb	90Mb	
Bits/cm^2 (cache SRAM)	2Mb	6Mb	20Mb	50Mb	100Mb	300Mb	
Cost/Transistor @ volume (millicents)	1	0.5	0.2	0.1	0.05	0.02	
Logic (Low-Volume: ASIC)							L (A)
Transistors/cm^2 (auto layout)	2Mb	4Mb	7Mb	12Mb	25Mb	40Mb	
Non-recurring engineering	0.3	0.1	0.05	0.03	0.02	0.01	
Cost/Transistor (millicents)							

have been widely reported at international technical society meetings. The U.S. government uses the Roadmap to help determine funding priorities for its semiconductor R&D. The Roadmap has become the strategic plan for SEMATECH, the U.S. government-industry consortium in Austin, Texas. In fact, SEMATECH's programs today are managed in an organization that reflects the technologies outlined in the National Technology Roadmap.

The roadmapping process was not unique to the semiconductor industry. The National Research Council (NRC) and the National Academy of Sciences have commissioned earlier studies of status and direction in fundamental sciences.

Today, with research and development budgets under pressure in every nation, it is important that redundancy in noncompetitive research and development be minimized wherever possible. This is particularly true in major basic research programs in physics; biology; chemistry; and, probably, computer science. It certainly has been a major help to the U.S. semiconductor industry's and the equipment supplier industry's cooperation in precompetitive-technology development. One step to setting priorities in international cooperation in R&D would be to develop additional roadmaps for science and technology.

There are, of course, inherent problems with roadmaps. As soon as they are written, they are out of date and, by definition, incorrect. Scientists involved in basic research believe their work cannot be predicted well enough to develop a roadmap. Most universities—U.S. universities in particular—believe that individual investigators and their graduate students are best suited to choose directions for academic research. Roadmaps are expensive and time-consuming. The process involves many people, several months, and, in the case of Semiconductor Roadmap, an annual cost of approximately $1 million. The 1986 physics effort cost approximately $750,000 for an eight-volume report.

However, there seem to be many areas where setting international priorities might make sense. The clearly international interest in continuing to study the world of subatomic physics generally leads to large investments in high-energy physics. There is a continued interest in developing exploration and understanding of the universe outside our own planet. There are major problems that require studies in biology and chemistry that will ultimately lead to better disease control and quality of life. There are major health, safety, and environmental issues that need to be addressed. There is no group of people better suited to set priorities and determine the resources required to study them than the scientists and engineers themselves. If our community does not set its own priorities and directions, some one will set them for us.

There are a number of issues that must be addressed. Scientists must become more realistic in determining budgets and in setting schedules for project development. Governments must be willing to fund programs on a long-term basis. Changes in national politics cannot be used as an excuse to start and stop funding both large and small projects. The credibility of the scientific community has been damaged in the past and needs to be rebuilt. It is imperative that scientists and engineers learn to communicate why they require large resources and what the benefit for the general good will be from the successful outcome of these endeavors. Many of these issues have been extremely well discussed by the NRC and Phillip Griffiths.[11] There are undoubtedly other advantages and disadvantages to trying to set directions in each science and technology area.

The natural leaders for doing this work in the basic sciences area are the academies of science and engineering around the world. These groups of talented individuals already have communication networks. They usually represent the best scientific and engineering talent in each country. The resources needed would represent a modest investment by individual governments. The development of these science and technology roadmaps should not be a one-time effort but a continuing effort by the best science and technology talent in the world. The roadmaps for particular technologies should be led by industry with international participation. The coordination of the National Technology Roadmap for Semiconductors has been handled through a consortium of U.S. semiconductor corporations that has been a model for other industries.

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[11]National Academy of Sciences, National Academy of Engineering, Institute of Medicine, *Science, Technology and the Federal Government. National Goals for a New Era,* Washington, D.C.: National Academy Press, 1993; and P. Griffith, "Science and the Public Interest," *The Bridge, p.16,* Washington, D.C.: National Academy of Engineering, Fall 1993.

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Moore's Law and the Economics of Semiconductor Price Trends

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In 1965, just 5 years after the construction of the first integrated circuit (IC), Gordon E. Moore (then at Fairchild Semiconductor) predicted that the number of devices on a single integrated circuit would double every year.[1] Later modifications of that early prediction have passed into the everyday jargon of our high-tech society as "Moore's Law."

Moore's Law is nowadays invoked to explain just about anything pertaining to high technology: the explosion in Internet use of the late 1990s: rapid improvement in price-performance in semiconductors, computers, communications, and just about everything electronic; the continuing rapid improvement in the technical capabilities of information technology; and the productivity rebound of the late 1990s in the U.S. economy. All of these things, indeed, may be connected to Moore's Law, but "explaining" them with a reference to Moore's Law may obscure more than it illuminates.

This paper creates a framework for interpreting the economic implications of Moore's Law. I first describe the history of Moore's Law predictions and explain why they have such potentially wide-ranging consequences. I then show how a Moore's Law prediction must be coupled with other assumptions in order to produce an economically meaningful link to what is the key economic variable of the information age: the cost or price of electronic functionality, as implemented in a semiconductor integrated circuit. I then relate the historical evolution of semiconductor prices through the mid-1990s to developments in several key parameters

[1]I am grateful for useful conversations about some of the ideas in this paper with Alan Allen, Denis Fandel, Dale Jorgenson, Paul Landler, Bill Spencer, and Phillip Webre. Responsibility for the errors is mine alone.

TABLE 1 Changing Size: U.S. Semiconductor Manufacturing Value Added vs. GDP

Year	Percent of GDP
1958	0.04
1965	0.09
1975	0.13
1985	0.26
1995	0.70
1997	0.77

SOURCE: U.S. Census of Manufactures, Bureau of Economic Analysis, U.S. Department of Commerce.

over this historical period. I then link acceleration in the rate of decline in leading-edge semiconductor prices to changes in these underlying parameters in the mid-1990s, and explain why measured historical rates of decline over this period seem unlikely to persist. Finally, I explore the nature of the man-made historical and institutional economic processes that made these technical accomplishments possible, and argue that their consequence has been an unappreciated but radical transformation of the industrial framework in which R&D is undertaken within the global semiconductor industry.

BACKGROUND

In 1965, when Gordon Moore enunciated the first version of this "law," semiconductor manufacturing accounted for about 0.09 percent of U.S. GDP. (See Table 1.) Thirty-five years later semiconductor manufacturing's relative size had increased tenfold, and it accounted for almost 1 percent of U.S. GDP. Semiconductors were the single largest manufacturing industry in the United States (more precisely, they were the four-digit industrial code with the largest value added). Furthermore, while in 1965 the United States accounted for the vast bulk of global output, at the dawn of the twenty-first century it only accounted for roughly a third of total world production. The rapid growth of semiconductor manufacturing within the United States must be part of an even steeper rise relative to the size of the global economy.

Perhaps more importantly, semiconductors are a critical input to the industries at the heart of information technology: computers and communications. These two industries have had a particularly significant role in U.S. economic and productivity growth over the last decade.[2] Together with consumer electron-

[2]See Dale Jorgenson, "Information Technology and the U.S. Economy," *American Economic Review*, 91(1):1-32, 2001.

ics, this cluster of user industries also accounted for about seven-eighths of global semiconductor consumption in 2000.[3]

Rough calculations suggest that improvement in price-performance in semiconductors has been a major (if not *the* major) source of price-performance improvement in information technology.[4] Thus, declines in cost for electronics functionality embedded in semiconductors are the linchpin of improvement in price-performance for computers and communications, which in turn has been a major factor in recent economic performance. To the extent that Moore's Law is connected to these phenomena, it is of great importance.

THE HISTORY OF MOORE'S LAW

In 1965, Gordon Moore first noted the developing industry trends that were to become Moore's Law.[5] In a now-famous diagram, Moore plotted a trend line for components per integrated circuit over the previous seven years and projected its continuing for another decade, out to 1975. (See Figure 1.)

Moore described this figure as showing the "minimum cost per component"-sized IC (note that Moore uses "component" to refer to what can also be referred to as function or device—i.e., a transistor or elemental unit of electronic functionality). Moore also noted that IC costs were at this point dominated by packaging costs, not the costs of fabricating the silicon semiconductor to be packaged—so that, up so some limit, costs per function/device effectively declined as the inverse of the number of devices per chip. The effective limit to placing more functions/devices on a chip came from sharply decreased manufacturing yields—and sharply higher costs per device—on larger chips past some critical size, defined in terms of devices per chip. The Moore's Law graph basically plotted Moore's projection of how this critical "minimum cost" number of devices per chip was likely to change over time.

It is important to point out that continually decreasing the size of circuit features by means of technical improvements in the photolithographic processes

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[3]Author's calculations based on data from World Semiconductor Trade Statistics, *Annual Consumption Survey*, 2000.

[4]See Jack E. Triplett, "High-Tech Productivity and Hedonic Price Indexes," in Organisation for Economic Co-operation and Development, *Industry Productivity*, Paris: OECD, 1996; Kenneth Flamm, "Technological Advance and Costs: Computers vs. Communications," in Robert C. Crandall and Kenneth Flamm, eds., *Changing the Rules: Technological Change, International Competition, and Regulation in Communications*, Washington, D.C.: The Brookings Institution, 1989; Ana Aizcorbe, Kenneth Flamm, and Anjum Khurshid, "The Role of Semiconductor Inputs in IT Hardware Price Declines: Computers vs. Communications," *Finance and Economics Discussion Series*. Washington, D.C.: Board of Governors of the Federal Reserve System, December 2001.

[5]Gordon E. Moore, "Cramming More Components onto Integrated Circuits," *Electronics*, 38(8): 114-117, April 19, 1965.

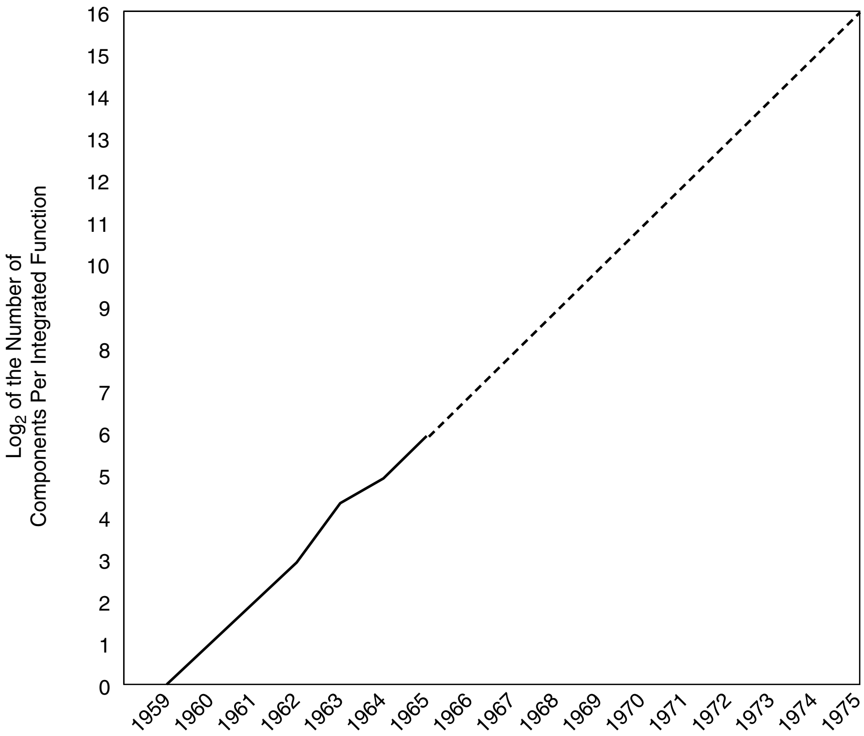

FIGURE 1 The Original "Moore's Law" Plot from *Electronics*, April 1965.

used to pattern silicon wafers with integrated circuits did *not* play any role in this first version of Moore's Law. To the contrary, Moore went to great pains to point out that the ICs he was predicting could be manufactured using existing feature sizes and manufacturing technology. Indeed, after Moore notes that his graph implies a single IC with 65,000 components on it by 1975, he states: "I believe that such a large circuit can be built on a single wafer."[6] The integrated circuits projected for the out-years of Figure 1 were visualized as being about the same size as snack-type mini-pizzas.

[6]*Ibid*. Moore notes that the silicon wafers then in use were "usually an inch or more in diameter," with "ample room for such a structure if the components can be closely packed with no space wasted for interconnection." He notes that this density "can be achieved by present optical techniques and does not require the more exotic techniques, such as electron beam operations, which are being studied to make even smaller structures."

In 1975, the endpoint of his original prediction, Moore produced a significant revision to his original prediction.[7] Most importantly, Moore noted that rather than simply increasing the size of the chip to achieve the greater number of devices (components) per chip, manufacturers had instead used "finer scale microstructures" to engineer a higher density of components per chip. Noting that area per component on a chip was essentially proportional to the minimum dimension per component squared, Moore effectively proposed that

(1) components per chip = k * area of chip / area per component

where constant k is a residual factor that has been added to reflect "device and circuit cleverness"—i.e., factors above and beyond decreases in the size of the features patterned on a chip and the size of the chip. Equation (1) allows the sources of Moore's Law to be decomposed into a contribution of component-dimension reduction (1/area per component), a contribution of increased chip size, and a contribution of all other things ("cleverness," k). The first two can be estimated from technical data and the last calculated as a residual. Using data from the period from 1960 to 1975, Moore calculated that components per chip had increased by about 65,000, that density (1/area per component) had improved by a factor of 32 historically, that chip area had increased by a factor of 20, and that "cleverness" must therefore have improved components per chip by a factor of about 100 over the same period.

Moore then went on to argue that, based on current developments, there was no reason to expect that future trends in chip area or density would deviate from the historical pace. "Cleverness," however, was apparently being exhausted, and Moore proposed that all future contributions from this source could not much exceed another factor of four. Accordingly, Moore revised his law by suggesting that, by the end of decade of the 1970s, increases in components per chip "might approximate a doubling every 2 years, rather than every year."[8]

In later years, it became clear that the real world was actually doing better than this 1975 prediction. The de facto barometer for Moore's Law became the Dynamic Random Access Memory chip (DRAM), first produced in 1970 with 1,024 binary digits ("bits") of memory on a single chip. New generations of DRAMs typically multiplied the capacity of an older generation by a factor of four every 3 years. Moore's Law was informally modified and assimilated by the technology community—and the press—as a prediction that components per chip would double every 18 months, the mean of the optimistic Moore of 1965 and the excessively pessimistic Moore of 1975.

[7]Gordon E. Moore, "Progress in Digital Integrated Circuits," *Proceedings of the 1975 International Electron Devices Meeting*, pp. 11-13, Picataway, NJ: IEEE, 1975.

[8]*Ibid*., p. 13.

There are, however, no economic predictions embedded in these calculations. Moore's original 1965 article did project that cost per component would fall to a tenth of its current level by 1970 (which works out to a compound annual decline rate [CADR] of 37 percent). This follows from the assumption that costs per chip were dominated by packaging costs and were assumed to remain constant on a per-chip basis. The 1965 Moore's Law would predict a tenfold increase in components per chip by 1970 and, therefore, a cost per component of a tenth of 1965 levels by 1970.

By 1975, however, chip costs were no longer dominated by packaging of the silicon chip; processes carried out to make the chips themselves in increasingly expensive, high-tech, capital-intensive fabrication plants accounted for the vast bulk of the cost, and packaging for relatively little.

THE ECONOMICS OF DECLINING INTEGRATED-CIRCUIT PRICES

To understand how continuing technological innovation in semiconductors affects chip costs—and, ultimately, prices—it is helpful to sketch out a stylized description of the principal elements driving the technology and cost structure. To begin, leading-edge semiconductor production is dominated by the costs of fabricating microstructures on silicon wafers: so-called wafer-processing or front-end costs. Assembly and packaging—so-called back-end costs—are relatively small for advanced, leading-edge products, and they will be ignored in the analysis of high-level trends that follows.[9]

A substantial number of the chips coming out of a wafer-fabrication facility have manufacturing defects and are scrapped. What is left—"yielded" good product—is what gets sold. Typically, the fraction of the chips that is good, as a share of the chips starting down the line on silicon wafers, increases with experience in manufacturing the chip. This so-called learning curve generates increased yields over time and results in the sharp increase over time of yielded good output coming off a fully utilized fabrication line. Again, because we are mainly concerned with long-term trends, we will ignore the impact of learning on yields and assume some fixed, idealized yield of good chips as a fraction of all chips on silicon of some given generation of technology starting down the fabrication line.

Integrated-circuit fabrication requires the coordination of many different pieces of technology that have to work together in a very complex manufacturing

[9]For a more comprehensive discussion of IC manufacturing and cost structures, see Kenneth Flamm, "Measurement of DRAM Prices: Technology and Market Structure," in Murray F. Foss, Marilyn E. Manser, and Allan H. Young, eds., *Price Measurements and Their Uses*, Chicago: University of Chicago Press, 1993; Kenneth Flamm, *Mismanaged Trade? Strategic Policy and the Semiconductor Industry*, Washington, D.C.: The Brookings Institution, 1996, chapter 6.

process. In many respects, the pacing technology for the entire process has been photolithography, the critical set of tools used to define and fabricate features on a chip. (Other key techniques combined with lithography to produce microstructures on a silicon wafer include: various methods for deposition and etching of a variety of materials on a silicon substrate; annealing; polishing surfaces; and the creation and maintenance of ultra-clean, contaminant-free spaces in which these advanced processes are carried out.) In recent decades, a new "technology node"—consisting of a new generation of lithographic equipment and the related equipment and materials required for its application—has typically been introduced every three years. The fact that this cycle is the same as that observed historically for the arrival of a new generation of DRAM is no coincidence. DRAMs historically were the highest-volume leading-edge product sold in the marketplace, and new manufacturing technology was typically first implemented in leading-edge memory chip production facilities.

Finally I note that, historically, every generation of lithographic equipment has typically shrunk minimum feature size by about 30 percent relative to the minimum feature size produced by the prior generation of equipment. As a result, area per chip feature, or area per component, has declined by 50 percent with each new technology node.

We can now derive a relationship between Moore's Law and cost trends for integrated circuits. The key identity is

$$(2)\ \$/\text{component} = \frac{\dfrac{\$\ \text{processing cost}}{\text{area "yielded" good silicon}} \times \text{silicon area/chip}}{\text{Components/chip}}$$

where each of the variables on the right-hand side has a well defined economic or technical meaning.

Moore's Law, strictly speaking, is about the denominator only—a prediction that components per chip would quadruple every three years. (This is the recent folklore incarnation of Moore's Law; the published 1965 version would have quadrupled components per chip every 2 years, and the published 1975 version every 4 years.) The chip containing the increasing numbers of components could conceivably be the size of a full-sized pizza—and costs per component might well rise rather than fall.

However, the introduction of 30 percent smaller feature dimensions every three years would result in 50 percent smaller areas per component. With four times the components on a next-generation chip, then, the silicon area per chip would only double, rather than quadruple.

Finally, average processing cost per total wafer area processed has increased only slightly in recent years; wafer-processing costs have increased greatly, but so have wafer sizes and areas.[10] If we also factor in a trend to steadily rising yields as successive generations of products reach volume production, it seems conservative to propose that wafer-fabrication costs per area of good silicon have remained roughly constant.[11]

If we now substitute in these stylized trends—a wafer-processing cost per area of silicon that is constant, silicon area per chip that doubles as components per chip quadruple, and a new technology node that is introduced every three years—we can do some simple math using Equation (2). The calculation suggests that every three years, the cost of producing a component in silicon will fall by 50 percent, for a CADR of 21 percent annually. To summarize, if we further assume a new technology node shrinking area per component by 50 percent every three years, constant wafer-processing costs per area of good silicon, and prices roughly tracking unit costs in the long run, an economist's corollary to Moore's Law would be a 21 percent annual decline in price-performance for leading-edge semiconductors.

THE INGENUITY (DRAM) COROLLARY

If we actually survey economists' attempts to measure price-performance in semiconductors, however, we discover something remarkable. Our impressive forecasts of large improvements in price-performance for microelectronic components are far too stingy when compared with the actual historical record. Table 2 shows some recent estimates of quality-adjusted price indexes for what are probably the two most important types of leading-edge ICs, DRAMs and microprocessors. Over the 22 years from 1974 to 1995, both DRAMs and microprocessors fell at an annual rate of roughly 30 percent.[12]

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[10]Over the 1983-1998 period, one estimate is that overall wafer-processing cost per square centimeter of silicon increased at a compound annual growth rate of 5.5 percent. See Carl Cunningham, Denis Fandel, Paul Landler, and Robert Wright, "Silicon Productivity Trends," International SEMATECH Technology Transfer #00013875A-ENG, February 29, 2000, p. 5. Note that this estimate is per total silicon area processed, not cost per good yielded area. Since good yielded area appears to have increased over time as a fraction of total wafer area processed, with improved processing yields, it seems safe to assume that wafer processing cost per good yielded silicon area was roughly constant over time.

[11]For solid evidence that DRAM yields have increased steadily over time, for successive generations of DRAMs, see Charles H. Stapper and Raymond J. Rosner, "Integrated Circuit Yield Management and Yield Analysis: Development and Implementation," *IEEE Transactions on Semiconductor Manufacturing*, 8(2), 1995, p. 100; Rainier Cholewa, "16M DRAM Manufacturing Cooperation IBM/SIEMENS in Corbeil Essonnes in France," *Proceedings of the 1996 IEEE/SEMI Advanced Semiconductor Manufacturing Conference*, Piscataway, NJ: IEEE, 1996, p. 222.

[12]See Kenneth Flamm, *More For Less: The Economic Impact of Semiconductors*, San Jose, CA: Semiconductor Industry Association, 1997, Appendix 2.

TABLE 2 Decline Rates in Price-Performance

		Percent/Year
Microprocessors	1975-1985	–37.5
Hedonic Index	1985-1994	–26.7
DRAM Memory	1975-1985	–40.4
Fisher Matched Model	1985-1994	–19.9
	DRAMs, Fisher Matched Model, Quarterly Data	
	91:2-95:4	–11.9
	95:4-98:4	–64.0
	Intel Microprocessors, Fisher Matched Model, Quarterly Data	
	93:1-95:4	–47.0
	95:4-99:4	–61.6

SOURCES: Flamm (1997); Aizcorbe, Corrado, and Doms (2000).

Remarkably, then, both DRAMs and microprocessors were falling at a rate roughly 50 percent greater than that we just calculated in our economic corollary to Moore's Law! In fact, for the first half of this period, these rates are almost identical to those projected by Moore I for the late 1960s and early 1970s. Moreover, this was over the period 1975-1985, when Moore II suggested a significant slowing in the pace of technical innovation in semiconductors.

The much-anticipated slowdown seems instead to have occurred a decade later, over 1985-1995. This was an exceptional period in the history of the industry, rife with international trade frictions, government policy activism, and—near its end—an unprecedented burst in world demand for chip-guzzling personal computers.

How did this first pass at a simple economic corollary to Moore's Law go wrong over these decades? The most obvious candidate inaccuracy seems to be its assumption that chip size would double from one technology node to the next. In fact, chip size seems to have increased by substantially less than a factor of two from one technology node to the next. In the case of the DRAM, over this period average chip size seems to have increased by a factor of about 1.4 from one node to the next.[13]

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[13]One calculates a factor of 1.37 based on chip area for first versions of six generations of DRAMs. The increase in size is calculated from the data shown in Figure 6.2 in Betty Prince, *Semiconductor Memories: A Handbook of Design, Manufacture and Application, 2nd Edition*, Chichester, UK: John Wiley and Sons, 1991, p. 209. A similar estimate is implicit in Cunningham, Fandel, Landler, and Wright, *op.cit.,* p. 11, who estimate that area/bit has fallen at a rate of 29 percent annually over a long period. That works out to an increase in chip size of 41 percent with every three-year quadrupling in bits per DRAM.

DRAM chip sizes increased by less than what is implied by shrinkage of features owing exclusively to improved lithographic equipment because of the old standby of Moore's 1975 paper: cleverness. In fact, there was considerable further ingenuity applied in the design of DRAMs. In particular, after roughly a decade in which further generations of DRAMs in essence scaled down the basic DRAM design of the mid-1970s to smaller dimensions, a period of vigorous innovation began in the late 1980s during which three-dimensional memory cells were developed.[14] In addition to 3-D features in memory cells, use of additional interconnect levels allowed tighter packing of components on a chip, and other types of products moved closer to the leading edge in their use of advanced manufacturing process technology.[15] The net result was an average chip size that increased significantly less than that associated with reduced feature size due to introduction of a new technology node alone. In the case of DRAMs, the increase in chip size was about 30 percent less than that predicted on the basis of lithography improvement alone.[16]

We can incorporate this ingenuity factor as an additional variable, K, in Equation (2) by noting that "silicon area/chip" in Equation (2), rather than doubling every three years (as it would were area/chip altered by the lithography innovation associated with a new technology node alone), increases by $2K$ where K (<1) denotes an additional reduction factor in chip size due to other design and process innovation. With the historical pattern of design innovation in DRAMs we have just seen, K equals approximately 0.7.

If we then redo the math based on Equation (2) with a new technology node every three years, constant wafer-processing cost, and chip size increasing by multiple $2K$ (=1.4), we produce an annual decline rate of 30 percent. That this is the historical rate of decline in DRAM price (quality-adjusted) over the 1974-1995 period is not completely surprising, since we have in effect used the DRAM to calibrate our estimated impact of design ingenuity, parameter K. What is more reassuring is that the methodology used for calculating quality-adjusted prices over this period makes no use of the technical parameters and predictions embedded in Equation (2) yet gives us completely consistent and congruent descriptions of trends in costs and prices.[17]

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[14] See Prince, *op. cit.*, pp. 209-210, for an overview.

[15] Cunningham, Fandel, Landler, and Wright, *op. cit.*, p. 4.

[16] I.e., chip size increased by about 1.4 rather than 2, for about a 30 percent reduction in chip size relative to that predicted by lithography alone.

[17] The methodology used for producing the price indexes cited in Flamm, *More for Less*, takes weighted averages of "matched model" DRAM chip market prices from one period to the next, with the weights calculated from market revenue shares for each model according to the so-called Fisher ideal index number formula. It does not use any information on price per bit or any other direct calculation of price per electronic element or function. Interestingly, though not a perfect correlation, the Fisher ideal price index and a simple calculation of average price per aggregate bit shipped for all generations of chips produced at any moment are a close match over time. See Flamm, *Mismanaged Trade*, pp. 10 and 238-239.

What remains intriguing is that the decline in DRAM prices was substantially greater than this (a CADR of 37 percent) over the subperiod 1975-1985. One possible explanation is that Equation (2) captures some notion of long-run average cost, and that a lot of other factors—fluctuations in demand, entry by new competitors, exit by others, the impacts of trade and industrial policy—have shorter-term impacts on market price quite separate from long-term cost fundamentals.

This is certainly true, but an additional explanation is that processing cost per silicon area was not really constant over this early, data-deficient period—that it was instead declining in a way not captured in the above calculations. In the late 1970s, Japan's government, in close cooperation with national semiconductor producers, launched a series of cooperatively funded R&D projects: the so-called VLSI Projects, which were perceived in the United States (and in Japan, for that matter) as having greatly advanced the technological and manufacturing competence of Japanese semiconductor producers.[18] A 1987 Defense Science Board report pointing to deterioration in the relative position of American semiconductor manufacturers as a possible national security issue played an important role in a U.S.-government decision to have the Defense Department pay half of the cost of a joint industry consortium, dubbed SEMATECH (for *se*miconductor *ma*nufacturing *tech*nology) and budgeted at $200 million annually.

Thus, it can be argued that the early 1980s were a period in which Japanese equipment manufacturers and IC producers were significantly improving semiconductor manufacturing technology, building in part on the technical successes of the VLSI Projects. Indeed, U.S. semiconductor manufacturers in later years acknowledged that they were lagging Japanese producers in manufacturing technology over this period, and that the formation of SEMATECH was part of their recognition of this problem.[19] It is not unreasonable to suggest that the Japanese entry into the global semiconductor market in the late 1970s and early 1980s was at least in part based on improvements in semiconductor manufacturing techniques which may well have been associated with significant declines in wafer-processing costs—in sharp contrast with the apparent stability of these costs in later decades that has been documented.

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[18]See Flamm, *Mismanaged Trade*, chapter 2; J. Sigurdson, *Industry and State Partnership in Japan: The Very Large Scale Integrated Circuits (VLSI) Project*, Lund, Sweden: Research Policy Institute, 1986; for detailed discussions of the Japanese VLSI projects and their impact. A "revisionist" assessment can be found in M. Fransman, *The Market and Beyond: Cooperation and Competition in Information Technology Development in the Japanese System*, Cambridge, UK: Cambridge University Press, 1992.

[19]See Flamm, *Mismanaged Trade*, pp. 144-146, on this point.

TINKERING WITH MOORE'S LAW: THE TECHNOLOGY ROADMAP PROCESS

While the objective of improving American semiconductor manufacturing technology was fairly clear, the specific means by which SEMATECH was to meet it were the subject of considerable debate, and SEMATECH's focus zigged and zagged in its first few years of existence. It was restricted to American companies; Japanese producer NEC, which had a U.S. production plant, was turned away when it sought to join in 1988.[20]

SEMATECH underwent significant changes in structure and research direction in the early 1990s. Even in the early years, there had been a growing emphasis on projects designed to improve the equipment and materials used by U.S. semiconductor makers but purchased from upstream equipment and materials producers. In 1992, after a new CEO had been brought on board and an internal reorganization undertaken, a new long-range plan (SEMATECH II) was adopted.[21] One new emphasis was on a significant reduction in the elapsed time between introductions of new technologies. Coinciding with this new emphasis on more rapid introduction of new technologies at SEMATECH was the institutionalization and acceptance within the U.S. semiconductor industry of a so-called roadmap process: a systematic attempt by all major players both in the U.S. IC industry and among its materials and equipment suppliers to jointly work out details of a complex array of likely new technologies required for manufacturing next-generation chips, coordinate the required timing for their introduction, and intensify R&D efforts on the pieces of technology that were likely to be "showstoppers" and required further work if the overall schedule was to succeed.

The first such "national technology roadmap" was published in 1992, and the next one, issued in 1994, still had new technology nodes being introduced at the historical three-year intervals.[22] But the so-called 250-nanometer technology node was introduced a year earlier than called for in the 1994 Roadmap, and the 1997 National Technology Roadmap called for the next technology node (at 180

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[20]Good resources on the history of SEMATECH are SEMATECH's own web pages (at <www.SEMATECH.org>), and the corporate chronology contained within; W. J. Spencer and P. Grindley, "SEMATECH After Five Years: High Technology Consortia and U.S. Competitiveness," *California Management Review*, 35, 1993; P. Grindley, D. C. Mowery, and B. Silverman, "SEMATECH and Collaborative Research: Lessons in the Design of a High-Technology Consortia," *Journal of Policy Analysis and Management*, 13, 1994; L. D. Browning and J. C. Shetler, *SEMATECH, Saving the U.S. Semiconductor Industry*, College Station, TX: Texas A&M Press, 2000; John Brendan Horrigan, "Cooperation Among Competitors in Research Consortia," unpublished doctoral dissertation, University of Texas at Austin, December 1996.

[21]See Browning and Shetler, *op. cit.,* chapter 8.

[22]See Semiconductor Industry Association, *The National Technology Roadmap for Semiconductors, 1994*, San Jose, CA: Semiconductor Industry Association, 1994.

nm) to follow after another two-year interval rather than reverting to the three-year pattern.[23]

It is far from clear that this acceleration of technological improvement in the semiconductor industry was solely the result of decisions taken within the membership of the U.S. SEMATECH consortium and the broader industry, government, and academic coalition participating in the U.S. national technology roadmap process. Korean producers had become major players on the world semiconductor scene, and Taiwanese manufacturers were rapidly becoming a significant force. Accelerating competitive pressures were certainly being felt by U.S. chip producers, and intensified efforts to more rapidly deploy new technology were a logical economic response. But the identification of R&D needs and explicit coordination of R&D efforts through an industry-wide program was a novel and important development.[24]

Other institutional changes coincided with this industry-wide shift toward a two-year technology node pace. In 1995 a decision was made by SEMATECH to partner with foreign companies in a project aimed at accelerating the development of technology designed for use with 300-mm (12-in.) silicon wafers. In fiscal 1996 U.S. government funding for SEMATECH ended by mutual agreement. In 1998 a separate organization, International SEMATECH, was formed as the umbrella for an increasing number of projects in which non-U.S. chip producers were involved, and in 1999 the original SEMATECH restructured itself into International SEMATECH. Interestingly, International SEMATECH in 2002 has 13 corporate members (eight American, five foreign), the same number as the parent SEMATECH had when founded. The share of world semiconductor sales accounted for by the consortium's membership is now substantially greater than was the case in 1987.[25]

SEMATECH was also certainly perceived as a major force in Japan, where the SEMATECH model greatly influenced the formation of a new generation of semiconductor industry R&D consortia in the mid-1990s.[26] The Japanese semiconductor industry's R&D consortium, known as SELETE, was joined by Korean producer Samsung, and there are in effect two rival international R&D orga-

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[23]See Semiconductor Industry Association, *The National Technology Roadmap for Semiconductors, Technology Needs, 1997 Edition*, San Jose, CA: Semiconductor Industry Association, 1997.

[24]The existence of the National Cooperative Research Act of 1984, which granted partial antitrust exemption to registered U.S. R&D consortia—like SEMATECH, the operational home for the U.S. roadmap—undoubtedly played an important role in making this roadmap coordination process feasible for the industry.

[25]It is claimed that prior to its internationalization, the SEMATECH membership never accounted for less than 75 percent of U.S. semiconductor industry sales. Shetler and Brown, *op. cit.,* p. 197.

[26]See Kenneth Flamm, "Japan's New Semiconductor Technology Programs," *Asia Technology Information Program Report No. ATIP 96.091*, Tokyo, November 1996.

nizations within the global semiconductor industry today: SELETE, headquartered in Japan, and International SEMATECH, with headquarters in the United States.

The 1997 roadmap was the last "national" technology roadmap. Later roadmaps are "International Technology Roadmaps" sponsored and coordinated through the two global R&D consortia and through national semiconductor industry associations headquartered in the United States, Europe, Japan, Korea, and Taiwan.[27] A two-year cycle for the introduction of new technology nodes remains a feature of recent roadmaps, though they also call for a reversion to the slower-paced three-year cycle after 2005.[28] An earlier call for reversion to a longer cycle (in the 1999 international roadmap), incidentally, was ignored when the 130-nm technology node was introduced in 2001, just two years after the 180-nm node had come online.

THE IMPACT OF FASTER INNOVATION ON IC COST

Let us now consider the economic impact of the move from a three-year cycle to a two-year cycle in the introduction of a new technology node. If we assume that Moore's Law obliges with a similar acceleration (i.e., a quadrupling of components per chip in two years—the original Moore 1965 pace) on the same schedule as a new technology node, as was historically the case in DRAMs, then the default calculation (no further application of ingenuity in reducing chip size, $K=1$) of declines in cost per component based on Equation (2) produces a CADR of 29 percent.

With the historical dose of ingenuity a la DRAM continuing (i.e., $K=0.7$, chip size shrinking an additional 30 percent above and beyond the size associated with the lithography introduced over the faster two-year cycle), the CADR improves to 41 percent annually. If we were to heroically assume that chip size were to remain constant, reflecting even greater applications of ingenuity—which some in the industry have publicly called for as a new target in R&D roadmaps (i.e., $K=0.5$)—then a decline in cost per component as high as 50 percent annually would result.

These are impressively large numbers. Incredibly, even with the most generous assumptions about technological acceleration and further ingenuity in design and manufacturing, they fall short of the actual historical record for quality-adjusted DRAM and microprocessor prices in the late 1990s, which fell at rates exceeding 60 percent per year! (See Table 2.)

[27] They may be accessed through a link found at the International SEMATECH web site, at <www.sematech.org>.

[28] According to the 2000 International Technology Roadmap.

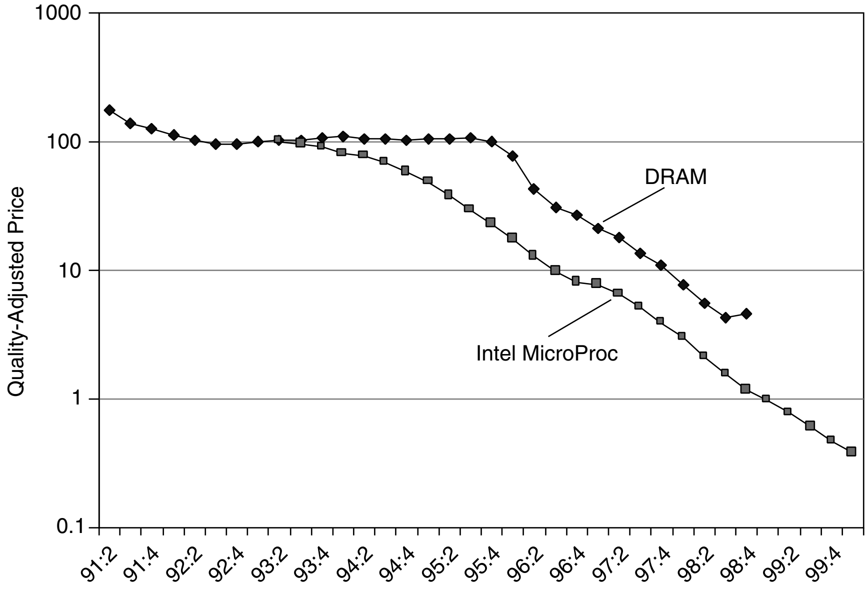

FIGURE 2 Quality-adjusted price change in DRAMS and microprocessors.
SOURCE: Author's calculations based on Aizcorbe, Corrado, and Doms (2000).

CAUSES AND CONSEQUENCES OF DECLINING COSTS

This acceleration in the decline of semiconductor prices has been noted by economists and credited with playing a significant role in the macroeconomic productivity growth acceleration of the late 1990s, as well as an important role in more rapidly declining prices for the underlying computer and communications capabilities which fueled the technology contribution to resurgent productivity.[29] It is also tempting to speculate that this decline in the cost of computing and communications capabilities played a significant role in the boom in Internet-related activities that occurred over this same period.

Indeed, the graphical evidence of price movements over the decade of the 1990s seems to support the notion of a "point of inflection" in the pace of technological advance in leading-edge semiconductors in the mid-1990s. Figure 2 shows one set of measurements of quality-adjusted price change in DRAMs and microprocessors over this period.

[29]Jorgenson, *op. cit.*; Aizcorbe, Flamm, and Khurshid, *op. cit*.

But this analysis suggests that while some of the more rapid technological advance and more rapidly declining prices in semiconductors are attributable to identifiable long-term changes in the pace of technical innovation in semiconductors, a substantial portion of the more rapid decline in semiconductor prices in the late 1990s must be due to more transitory changes. Likely candidates include cyclical fluctuations in product demand, intensified competition (which may well end in some consolidation within this global industry as the least successful exit the industry), a shift of manufacturing processes for some products closer to the leading edge in technology, and a shortening of product lives accompanying more frequent introductions of new versions of certain products. All of these would have some transitory impact in accelerating declines in price, but they will likely dissipate as the industry approaches a new "steady state."

In short, if one accepts this analysis of the technical and economic fundamentals determining cost on the "supply side," the pace of price declines of the late 1990s cannot be sustained. Leading-edge semiconductors may well drop in price at much faster rates than in the past as the result of faster introduction of new technology nodes over the long term, but the increase will be from 30 percent annually to a number in the 40 percent-plus range, *not* in a range exceeding 60 percent annual declines. One would also expect productivity improvement flowing directly and indirectly from the sharp price declines for information technology of the late 1990s to fall to more moderate—but sustainable—levels in future years.

THE DYNAMICS OF MOORE'S LAW

Finally, it is worth noting that Moore's Law can be interpreted as an interesting case of an informal institutional framework for analyzing technical change that gradually evolved into a more formally structured process for organizing technical change in a major global industry. There was nothing inevitable about Moore's Law—no underlying technical or physics-based reason for the phenomenon. (In fact, as already noted, the original 1965 Moore's Law did not rely on any significant technical change!)

Instead, Moore's Law through the 1980s can perhaps be interpreted as a self-reinforcing expectations mechanism. Companies believed something approximating Moore's prediction, and as it continued to more or less hold true, companies made their technical plans around sticking to a Moore's Law timetable. This was probably not because that schedule would necessarily have maximized their profit had everyone else not innovated on the same timetable, but because they believed that all their competitors would be introducing new products and technology on the Moore's Law schedule and that, therefore, they too had to stick to the plan in order to stay competitive. This certainly seems to have been the case in DRAMs, the pacing product for new semiconductor manufacturing technology, where a three-year next generation product introduction schedule became an accepted characteristic of the market.

Then, in the 1990s, as the U.S. SEMATECH consortium finally defined itself, a new and more formal coordination mechanism for R&D came into play. Rather than simply accepting a historical norm, a decision was made to alter the norm by trying to explicitly coordinate the now-complex array of decentralized pieces of technology that had to be simultaneously improved in order to bring a new generation of manufacturing systems online. It may be impossible to determine the extent to which the coordination process played a role, or the extent to which the simple act of a major group of IC producers announcing new and very specific technology targets created a credible reason for the various suppliers of technology to believe that the technology cycle really was about to accelerate, and therefore caused it to accelerate. What is clear is that the industry roadmap—the ultimate descendent of Moore's Law—has now become an organizing and coordinating framework for private and public R&D in what is the largest, most important, and most globalized manufacturing industry in the world.

The executive agents for this organizing framework were originally national in character. The U.S.'s SEMATECH consortium and Semiconductor Industry Association originally treated the whole process as a national endeavor, designed to give national producers a leg up over the global competition. But reality —that U.S. companies were not necessarily the leaders in all of the many bits of technology that had to be coordinated for the next-generation manufacturing line to work, and that both semiconductor producers and their suppliers were thoroughly international in all aspects of their business operations, from R&D, to manufacturing, to sales—led the U.S. industry to reach out to global partners.

First SEMATECH, then the roadmap, added the prefix "International" to their name. Today, the roadmap process is thoroughly global in character. Interestingly, there are two competing multinational R&D consortia—International SEMATECH, with no Japanese members, and SELETE, with just one, very large non-Japanese member— that manage to balance nationalist dynamics and international coalitions within a single, overarching international R&D roadmap coordination process.

Economists are largely accustomed to thinking of the speed of technological change as something that is exogenous, dropping in gracefully from outside their models. Ultimately, one moral of this story is that the pace of technological change in the semiconductor industry may have an endogenous component as important as its exogenous scientific foundations. Particularly where many complex items of technology secured from a broad variety of sources must be coordinated in a fairly precise manner in order to create economically viable new technological alternatives, vague and diffuse factors like expectations and even political coalitions may play an important role.

CONCLUSIONS

This paper has constructed a simple framework for explaining how technological trends in the semiconductor industry are ultimately reflected in the dynamics of costs and—in the long run, in a competitive industry—leading edge chip prices. The framework does a reasonable job of tracking real-world, quality-adjusted price trends for leading-edge products over the 1975-1995 period. Moore's Law governs one of the three key technical and economic variables that drive the calculation.

Moreover, the same framework suggests that an acceleration in the introduction of new technology nodes in the late 1990s had a significant and predictable impact in further increasing the rate of decline in leading edge chip prices that took place at that time. These calculations, however, indicate that the actual fall in these prices over this period substantially exceeded the decline attributable to sustainable, long-term cost trends, suggesting that the extraordinary price declines of the late 1990s—in excess of 60 percent for memory chips and microprocessors—were transitory in nature. Even with optimistic assumptions about further innovation, I conclude that price declines must moderate significantly from these stratospheric rates over the long haul. To the extent that macroeconomic productivity growth and robust sales of information technology over this period were based on these component cost foundations, they too must fall back to more moderate rates in the future.

Finally, I noted that Moore's Law was more of an expectation than a physical law, and I pointed out that an informal benchmark for coordinating R&D has since been replaced with a formal, globalized technology roadmap process. Here we must also end on a note of caution. We now have—with little fanfare or publicity—a situation in which what has become the most important manufacturing industry in the world, an industry made up of fierce competitors from all over the globe, calls a truce and jointly negotiates a set of global targets for private and public R&D efforts.

What the roadmap gives, the roadmap can also take away. Recent roadmaps, while continuing to call for two-year technology nodes in the near term, have perhaps wistfully or nostalgically also called for a return to an older, slower pace of technological change toward the end of this decade. Recent roadmaps have also suggested slowing down the pace of new-product introductions in DRAMs in the future, calling for a quadrupling of memory bits on a chip every four years instead of the historical three-year interval. While these choices may be dictated by technical issues, the roadmaps provide a framework in which economic implications can be discussed when technical choices are set cooperatively.

The current roadmap process seems to be open and transparent. But because the roadmap framework for guiding technological change in this thoroughly global industry is international, the role of national governments in drawing the fine line between acceptable cooperation and unacceptable collusion may at some point need to be revisited. Whether or not this becomes an issue, we cannot ignore the emergence of a pioneering new model for international R&D cooperation within the largest global high-tech industry.

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III

APPENDIXES

Appendix A

Biographies of Speakers*

C. LANIER BENKARD

Lanier Benkard received his B.S. in economics from University of Toronto in 1991 and his Ph.D. in economics from Yale University in 1998. Since 1998 he has been an Assistant Professor of Economics at the Stanford University Graduate School of Business. Since 1999 he has been a Faculty Research Fellow at the National Bureau of Economics. For the academic year 2001-2002, he was named a National Fellow at the Hoover Institution. Prior to receiving his Ph.D., he worked as an Associate Economist at WEFA Inc.

Dr. Benkard's recent papers and publications include "Learning and Forgetting: The Dynamics of Aircraft Production" (2000), *A Dynamic Analysis of the Market for Wide-Bodied Commercial Aircraft* (2001), and "Demand Estimation with Heterogeneous Consumers and Unobserved Product Characteristics: A Hedonic Approach" (2001).

At Stanford Dr. Benkard teaches graduate courses in industrial organization, applied microeconomics and econometrics.

ROBERT R. DOERING

Robert Doering is a Senior Fellow in Silicon Technology Development at Texas Instruments (TI). His primary area of responsibility is Technology Strategy. His previous positions at TI include Manager of Future-Factory Strategy, Director of Scaled-Technology Integration, and Director of the Microelectronics

*As of September 2001.

Manufacturing Science and Technology (MMST) Program. The MMST Program was a five-year R&D effort, funded by DARPA, the U.S. Air Force, and Texas Instruments, which developed a wide range of new technologies for advanced semiconductor manufacturing. The major highlight of the program was the demonstration in 1993 of sub-three-day cycle time for manufacturing 0.35-μm CMOS integrated circuits. This was principally enabled by the development of 100 percent single-wafer processing.

Dr. Doering received a B.S. degree in physics from the Massachusetts Institute of Technology in 1968 and a Ph.D. in physics from Michigan State University in 1974. He joined TI in 1980 after several years on the faculty of the Physics Department at the University of Virginia. His physics research was on nuclear reactions and was highlighted by the discovery of the Giant Spin-Isospin Resonance in heavy nuclei in 1973. His early work at Texas Instruments was on SRAM, DRAM, and NMOS/CMOS device physics and process-flow design. Management responsibilities during his first 10 years at TI included advanced lithography and plasma etch as well as CMOS and DRAM technology development.

Dr. Doering is a member of the American Physical Society, the Institute of Electrical and Electronics Engineers (IEEE), and the American Association for the Advancement of Science. He represents TI on many industry committees, including: the Technology Strategy Committee of the Semiconductor Industry Association, the Board of Directors of the Semiconductor Research Corporation, the Semiconductor Manufacturing Technical Committee of the IEEE Electron Device Society, and the Corporate Associates Advisory Committee of the American Institute of Physics. Dr. Doering is also one of the two U.S. representatives to the International Roadmap Committee, which governs the International Technology Roadmap for Semiconductors. He has authored over 130 published/conference papers and has 19 U.S. patents.

KENNETH FLAMM

Kenneth Flamm, who joined the Lyndon B. Johnson School of Public Affairs of the University of Texas at Austin in fall 1998, is a 1973 honors graduate of Stanford University and received a Ph.D. in economics from MIT in 1979.

From 1993 to 1995 Dr. Flamm served as Principal Deputy Assistant Secretary of Defense for Economic Security and as Special Assistant to the Deputy Secretary of Defense for Dual-Use Technology Policy. He was awarded the Department’s Distinguished Public Service Medal in 1995 by Defense Secretary William J. Perry. Prior to his service at the Defense Department, he spent 11 years as a Senior Fellow in the Foreign Policy Studies Program at the Brookings Institution.

Dr. 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 Crandall, 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.

Dr. Flamm, an expert on international trade and high-technology industry, teaches classes in microeconomic theory, international trade, and defense economics.

RANDALL D. ISAAC

Randall D. Isaac is the Vice President, Science and Technology, for the IBM Research Division. He has worldwide responsibility for the Research Division's strategy in the areas of Physical Sciences and Technology, including semiconductor, packaging, communications and display technologies. He was formerly the Director of the newly formed IBM Austin Research Laboratory in Austin, Texas. The focus of the lab is high-performance microprocessor design. Prior to his current role, Dr. Isaac was a senior manager in the Semiconductor Research and Development Center of the IBM Microelectronics Division in Burlington, Vermont. In this capacity, he was the project manager for the 64Mb DRAM development joint program with Siemens and Toshiba. Dr. Isaac previously worked at the IBM Thomas J. Watson Research Center in Yorktown Heights, New York, as the Director of Silicon Technology. He also managed the bipolar technology group and the silicon processing facility, and he was active in advanced silicon facility planning. Dr. Isaac received his B.S. degree in physics from Wheaton College in Wheaton, Illinois, in 1972 and his M.S. and Ph.D. degrees in physics from the University of Illinois at Urbana-Champaign in 1974 and 1977, respectively. Dr. Isaac joined IBM in 1977 at IBM Research, Yorktown. Dr. Isaac is a Senior Member of Institute of Electrical and Electronics Engineers and an American Physical Society Fellow.

IRA A. JACKSON

Ira A. Jackson, Lecturer in Public Policy and Management, is Director of the Center for Business and Government (CBG) of Harvard University's John F. Kennedy School of Government (KSG). Jackson came to CBG from BankBoston, a large multinational commercial bank, where for a dozen years he was an executive vice president and where he helped to shape an unusual business strategy of "managing for value with values." Previously, Jackson served as Commissioner of Revenue in Massachusetts, where he tried to implement entrepreneurial strategies to improve the accountability and performance of a traditional governmental bureaucracy. From 1976-1982 he served as Associate Dean of the Kennedy School. Earlier, he was a top aide to Newark, New Jersey, Mayor Kenneth Gibson and Boston Mayor Kevin White. He holds an undergraduate degree from Harvard College and an MPA from KSG, and he is a graduate of the Advanced Management Program at the Harvard Business School. Jackson is active in civic and community affairs, and he played a role in launching CityYear and a number of other innovative, local, not-for-profit institutions. His interests focus on making government more accountable and business more responsible, and on leveraging competencies and concerns from the public, private, and NGO sectors in advancing economic progress and promoting social justice.

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.

Dr. Jorgenson was elected to membership in the American Philosophical Society in 1998, the Royal Swedish Academy of Sciences in 1989, the U.S. 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. He was awarded honorary doctorates by Uppsala University and the University of Oslo in 1991.

Dr. 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.

Dr. Jorgenson received the prestigious John Bates Clark Medal of the American Economic Association in 1971. This Medal is awarded every 2 years to an economist under 40 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.

Dr. Jorgenson is the author of more than 200 articles and the author and editor of 20 books in economics. His collected papers have been published in nine volumes by The MIT Press, beginning in 1995. The most recent volume, *Econometrics and Producer Behavior*, was published in 2000.

Prior to Dr. Jorgenson's appointment at Harvard he was 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 Dr. Jorgenson on published research. An important feature of Dr. 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.

Dr. Jorgenson was born in Bozeman, Montana, in 1933 and attended public schools in Helena, Montana. He is married to Linda Mabus Jorgenson, who is a partner in the law firm of Spero and Jorgenson in Cambridge, Massachusetts. Professor and Mrs. Jorgenson reside in Cambridge. Their daughter Kari, 25, is an honors graduate of Harvard College, Class of 1997, and is an associate with Primark Decision Economics in Boston. Their son Eric, 27, is a graduate of Duke University, Class of 1995, and is a graduate student in human genetics at Stanford University.

W. CLARK MCFADDEN

W. Clark McFadden is a partner of Dewey Ballantine LLP, resident in the Washington, D.C. office. Mr. McFadden represents corporate clients in government contract matters and international trade, encompassing work in litigation, regulation, and legislation. He also specializes in international corporate transactions, especially the formation of joint ventures and consortia, as well as in international investigations and enforcement proceedings. Mr. McFadden has a broad background in foreign affairs and international trade, having experience with Congressional committees, the U.S. Department of Defense, and the National Security Council.

In 1986 he was appointed General Counsel, President's Special Review

Board ("Tower Commission"), to investigate the National Security Council system and the Iran-Contra Affair. In 1979 Mr. McFadden served as Special Counsel to the Senate Foreign Relations Committee on the Strategic Arms Limitations Treaty (SALT II). From 1973 to 1976, he worked as General Counsel, Senate Armed Services Committee, and was responsible to the Committee for all legislative, investigatory, and oversight activities.

He holds degrees from: Western Reserve Academy, 1964; Williams College, B.A., 1968, Economics (cum laude); Harvard University, M.B.A., 1972 (first class honors); Harvard University, J.D., 1972.

DAVID C. 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 United States 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, on the Causes and Consequences of the Internationalization of U.S. Manufacturing, on the Federal Role in Civilian Technology Development, on U.S. Strategies for the Children's Vaccine Initiative, and on 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 Organization for Economic Cooperation and Development, various federal agencies, and industrial firms.

Dr. Mowery has published numerous academic papers and has written or edited a number of books, including Paths of Innovation: Technological Change in 20th-Century America; The International Computer Software Industry: A Comparative Study of Industry Evolution and Structure; Paths of Innovation: Technological Change in 20th-Century America; The Sources of Industrial Leadership; Science and Technology Policy in Interdependent Economies; Technology and the Pursuit of Economic Growth; Alliance Politics and Economics: Multinational Joint Ventures in Commercial Aircraft; Technology and Employment: Innovation and Growth in the U.S. Economy; The Impact of Technological Change on Employment and Economic Growth; Technology and the Wealth of Nations; and International Collaborative Ventures in U.S. Manufacturing. His academic awards include the Raymond Vernon Prize from the Association for Public Policy Analysis and Management, the Economic History Association's Fritz Redlich Prize, the *Business History Review*'s Newcomen Prize, and the Cheit Outstanding Teaching Award.

ARIEL PAKES

Ariel Pakes is a Professor of Economics in the Department of Economics at Harvard University, where he teaches courses in Industrial Organization and in Econometrics. Before coming to Harvard in 1999, he was the Charles and Dorothea Dilley Professor of Economics at Yale University (1997-1999). He has held other tenured positions, at Yale (1988-1997), the University of Wisconsin (1986-1988), and the University of Jerusalem (1985-1986). Dr. Pakes received his doctoral degree from Harvard University in 1980, and he stayed at Harvard as a Lecturer until he took a position in Jerusalem in 1981. Dr. Pakes received the award for the best graduate student adviser at Yale in 1996, and his past students are now on the faculties of several leading economics departments.

Dr. Pakes was the recipient of the Frisch Medal of the Econometric Society in 1986 and was elected as a fellow of that society in 1988. He is currently co-chair of the AEA Census Advisory Panel, an Editor of the *RAND Journal of Economics*, an associate editor of *Economic Letters* and of the *Journal of Economic Dynamics and Control*, a research associate of the NBER and a member of the AEA Committee on Government Statistics. In the past Dr. Pakes has been an Associate Editor of *Econometrica*, the *Journal of Econometrics*, the *International Journal of Industrial Organization*, and *Economics of Innovation and New Technology*. He also co-edited a *Proceedings of the National Academy of Sciences* issue on "Science, Technology and the Economy."

Dr. Pakes has given symposium lectures to several broad professional groups, including the National Academy of Sciences, the Econometric Society, the American Academy of Arts and Sciences, and the National Council on Research and Development in Israel. He has also served on numerous National Science Foundation panels, including the Economics Advisory Panel, Global Change, Computational Economics, Data Opportunities, and the Presidential Fellow Advisory Board. In addition Dr. Pakes has done work for a number of consultancies, government agencies, and large firms.

Professor Pakes's research has been in Industrial Organization (I.O.), the Economics of Technological Change, and Econometric Theory. He and his co-authors have recently focused on developing techniques which allow empirical analysis of I.O. models. This includes: theoretical work on how to estimate demand and cost systems, and then to use the estimated parameters to analyze equilibrium responses to policy and environmental changes; empirical work which uses these techniques to analyze the implications of alternative events in different industries; and the development of a framework for the numerical analysis of dynamic oligopolies (with and without collusive possibilities).

The recent empirical work includes an analysis of the impact of the breakup of AT&T on productivity in the telecommunication equipment industry, an analysis of the impact of Voluntary Export Restrictions on the profits and consumer welfare generated by the sales of new cars, and an analysis of the impact of the entry and exit of goods on the price index for personal computers. His previous work outside I.O. proper included the co-development of simulation estimators (in Econometric Theory), and the development of measures of the costs and returns to research and patenting activities (in Technological Change).

Dr. Pakes is married to Juliana Rojas Pakes and has two children.

MARK PINTO

Mark Pinto is the Chief Technical Officer of Agere Systems, formerly the Microelectronics Group of Lucent Technologies, and also serves as Agere's Vice President of Integrated Circuit Technology. Dr. Pinto's responsibilities include defining Agere's technology strategy; directing research activities formerly in Bell Laboratories related to semiconductor devices, integrated circuit design, and software and systems; and leading the company's efforts to deliver process and interconnect technologies, system-on-a-chip hardware cores, communications software elements, development software, and design methodologies.

Dr. Pinto had been with Bell Laboratories since 1985, serving as Director of the Silicon Electronics Research Laboratory in the Bell Laboratories Research Division, which was responsible for advanced R&D of materials, processes, devices, and IC designs. He was selected as a Bell Laboratories Distinguished Member of Technical Staff in 1991 and a Bell Labs Fellow in 1995, both for work in semiconductor device physics and computational simulation. Dr. Pinto has authored or co-authored more than 150 journal and professional conference papers and has eight patents in semiconductor devices. He is a Fellow of the Institute of Electrical and Electronics Engineers.

Dr. Pinto received bachelor's degrees in electrical engineering and computer science from Rensselaer Polytechnic Institute, and a master's degree and doctorate in electrical engineering from Stanford University. As part of his doctoral work at Stanford, Dr. Pinto developed the semiconductor device simulation program PISCES-II, which was a standard tool in the integrated-circuit industry for more than a decade.

GEORGE M. SCALISE

George Scalise is President of the Semiconductor Industry Association (SIA), the premier trade association representing the microchip industry. As President, Mr. Scalise directs and oversees SIA programs focused on public policy, technology, workforce, international trade and government affairs, environment safety and health, and communications.

Mr. Scalise has had a long career in the semiconductor and related industries, bringing with him over 35 years of industry experience. Prior to joining the SIA in June 1997, Mr. Scalise served as the executive vice president of operations at Apple Computer. Preceding Apple, he worked in numerous executive positions at National Semiconductor Corporation, Maxtor Corporation, Advanced Micro Devices, Fairchild Semiconductor, and Motorola Semiconductor.

Mr. Scalise is a highly respected technology and public policy spokesperson for the industry. He has a special interest and expertise in international-trade and competition issues. For over eight years Mr. Scalise was the chairman of SIA's Public Policy Committee, shaping and implementing the semiconductor industry's agenda on major policy issues. Additionally, he was a founder, a member, and the chairman of the Board of the Semiconductor Research Corporation (SRC), an industry-funded organization that provides resources for precompetitive semiconductor research at American universities. For three years he also served on the Board of Directors of SEMATECH, a research consortium created to improve manufacturing technology in the semiconductor industry.

Mr. Scalise is active on many boards and advisory committees. In December 1999 he was elected to the Board of Directors of the Federal Reserve Bank of San Francisco, the Twelfth Federal Reserve District, to represent non-banking interests in the District's nine states. In October 2000 he was appointed Deputy Chairman of the Bank for the year 2001 by the Board of Governors of the Federal Reserve Bank.

He also serves on the boards of Cadence Design Systems and Network Equipment Technologies. Mr. Scalise has served on a number of university and government boards, including: the University of Southern California School of Engineering Board of Councilors; the Santa Clara University Leavey School of Business Advisory Board; the University of Texas at Austin Engineering Foundation Advisory Committee; the Purdue University Engineering Visiting Committee; the Secretary of Energy Advisory Board for the U.S. Department of Energy, as chairman; and the Joint High Level Advisory Panel of the U.S.-Israel Science and Technology Committee.

Mr. Scalise graduated from Purdue University with a B.S. in mechanical engineering.

MINJAE SONG

Minjae Song is a 1996 honors graduate of Seoul National University with a B.A. in economics and, since 1998, has been a student in the Ph.D. program in economics at Harvard University, focusing on industrial organization and econometrics. His current research interests focus on demand estimation with heterogeneous consumers, vertical innovation in high-tech industry, and dynamic games with multiple plants.

His past work in includes "Demand estimation for the personal computer:

U.S. domestic market from 1995 to 1999." Work currently in progress includes "Demand estimation for the microprocessor chip: 1993-2000," and "Vertical innovation and the product cycle: the microprocessor industry."

CHARLES W. WESSNER

Charles Wessner has served with three different federal agencies in positions of increasing responsibility, bringing a unique perspective on Washington policy developments and international cooperation to science and technology policy. He has extensive overseas experience, both with the OECD and as a senior officer with the U.S. Diplomatic Corps. Since joining the National Research Council, the operational arm of the U.S. National Academy of Sciences, he has led several major studies, produced a rapidly growing list of publications, and works closely with the senior levels of the U.S. government. His policy interests focus on the linkages between science-based economic growth, new technology development and commercialization, including conditions to encourage entrepreneurship, and international investment and trade in high technology industries. His current portfolio of work centers on government measures to support the development of new technologies which have contributed to the productivity gains which characterize the New Economy. Dr. Wessner frequently lectures and testifies on United States technology policy and its role in the global economy. He has testified to Congressional Committees and before national commissions such as the U.S. Trade Deficit Review Commission and the Presidential Aerospace Offsets Commission. Dr. Wessner also lectures at leading universities in the United States such as Harvard, The College of William & Mary, and Georgetown, as well as foreign universities such as Nottingham, Potsdam, and Helsinki University of Technology. Dr. Wessner holds degrees in International Affairs from Lafayette College (Phi Beta Kappa) and the Fletcher School of Law and Diplomacy where he obtained an M.A., an M.A.L.D. and a Ph.D. as a Shell Fellow.

Appendix B

Participants List*

Alan Anderson
National Research Council

Philip Aspden
National Research Council

Philip Auerswald
Harvard University

C. Lanier Benkard
Stanford University

McAlister Clabaugh
National Research Council

Amy Christofer
Harvard University

Robert R. Doering
Texas Instruments

Kenneth Flamm
University of Texas at Austin

Daryl Hatano
Semiconductor Industry Association

Christopher Hayter
National Research Council

David Hsu
Massachusetts Institute of Technology

Randall D. Isaac
International Business Machines

Ira A. Jackson
Harvard University

Dale W. Jorgenson
Harvard University

Richard Lugg
CIE Group

W. Clark McFadden
Dewey Ballantine

*Speakers in italics

David Morgenthaler
Morgenthaler

David C. Mowery
University of California at Berkeley

Ariel Pakes
Harvard University

Mark Pinto
Agere

George M. Scalise
Semiconductor Industry Association

Sujai Shivakumar
National Research Council

Minjae Song
Harvard University

Philip Webre
Congressional Budget Office

Charles W. Wessner
National Research Council

Appendix C

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