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The Economics of Productivity

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Introduction

Dale W. Jorgenson

The resurgence of the American economy since 1995 has survived the dot-com crash of 2000, the short recession of 2001, and the 'jobless' recovery that followed. The financial and economic crisis resulting from the collapse of sub-prime mortgage lending has generated a strenuous debate: Can the improvements in America's economic performance be sustained? A consensus has emerged that the investment in information technology (IT) provides a strong foundation for the future growth of the American economy.[1]

The information technology mantra – faster, better, cheaper – characterizes the speed of technological change and product improvement in semiconductors, the key enabling technology. The economics of IT begins with the precipitous and continuing fall in semiconductor prices. The rapid price decline has been transmitted to the prices of a range of products that rely on this technology, like computers and telecommunications equipment. Semiconductor technology has also reduced the costs of aircraft, automobiles, scientific instruments and a host of other products.[2]

Swiftly falling IT prices have provided powerful economic incentives for the rapid diffusion of information technology through investment in IT hardware and software. A substantial acceleration in the IT price decline occurred in 1995, triggered by a much sharper acceleration in the price decline for semiconductors. The accelerated IT price decline after 1995 signaled even faster innovation in the main IT-producing industries – semiconductors, computers, communications equipment and software.

Productivity growth is the key economic indicator of innovation. Economic growth can take place without innovation through replication of established technologies. Investment increases the availability of these technologies, while the labor force expands as population grows. With only replication and without innovation, output will increase in proportion to capital and labor inputs. By contrast the successful introduction of new products and new or altered processes, organization structures, systems, and business models generates growth of output that exceeds the growth of capital and labor inputs. This results in growth in productivity or output per unit of input.[3]

The industries responsible for much of IT hardware – computers and semiconductors – display truly extraordinary rates of productivity growth, as well as substantial accelerations after 1995. Together with telecommunications equipment and software, these IT-producing industries make up less than 3 percent of the US economy, but generated almost all of the increase in economy-wide productivity growth in 1995–2000. The dot-com crash in 2000 resulted in a return to more sustainable productivity growth rates in the four IT-producing industries.

Surprisingly, productivity growth in the US economy has continued at a rapid pace since the dot-com crash, indicating a high rate of innovation. This has been accomplished by a striking shift in the locus of innovation to IT-using industries. These are the industries particularly intensive in the utilization of information technology hardware and software. The IT-users are primarily trade and service industries – communications services, business services, and wholesale trade – altogether more than a quarter of the US economy. This is the core of the New Economy that is only gradually penetrating sectors traditionally resistant to innovation – health care, education and government.[4]

The flood of IT investment in the United States after 1995 has counterparts throughout the world. The burst of IT investment in industrialized economies after 1995 was unmistakable. The world economy has undergone a powerful growth resurgence and investment in IT is rising sharply in the major developing and transition economies – Brazil, China, India and Russia. However, differences in the rates of innovation in the IT-using industries have generated wide disparities in the impact of IT on economic growth. Among the industrialized countries rates of innovation in the IT-using industries are greatest in the US.

Highly volatile IT production is giving way to a broadly diversified advance in IT applications. These applications now spawn innovation in almost a quarter of the US economy, but well under half this proportion of the world economy. Globalization is creating enormous new opportunities for the application of information technology. The source of international competitiveness in the New World Economy will be the successful exploitation of information technology-based business models, systems and organizational structures.

This introduction begins with a brief history of productivity measurement. The traditional approach of Kuznets (1971) and Solow (1970), discussed in Section 1,[5] has been replaced by the new framework presented in the OECD (2001) manual, *Measuring Productivity* and outlined in Section 2.[6] The OECD productivity manual has established international standards followed by Jorgenson, Ho and Stiroh (2005) and the EU (European Union) KLEMS (capital, labor, energy, materials and services) study completed on 30 June 2008.[7] This landmark study presents industry-level productivity measurements for 25 of the 27 EU members and Australia, Canada, Japan, Korea and the US.

The hallmark of the new framework for productivity measurement is the concept of capital services, including the services provided by information technology (IT) equipment and software, presented in Section 3. Modern information technology is based on semiconductor technology used in computers and telecommunications equipment. The economics of information technology begins with the staggering rates of decline, outlined in Section 4, in the prices of IT equipment used for storage of information and computing. The 'killer application' of the new framework for productivity measurement is the impact of IT investment. This is the main topic of the book and is presented in Section 5.

The economics of productivity remains central to understanding the forces driving world economic growth, as outlined in Section 6. The international productivity comparisons presented in this volume reveal the emergence of a New World Economy, rooted in information technology-based business models, systems and organizational structures. However, the arena for innovation is shifting away from IT-producing industries toward IT-intensive trade and service industries such as telecommunications, wholesale trade and air transportation.

1. A Brief History of Productivity Measurement

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).[8] Solow's book *Economic Growth* (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 Evsey Domar (1946).[9]

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 13 other developed economies. He combined this with quantitative comparisons among 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 obsolete, remained the guiding star for subsequent conceptual development and empirical observation for decades.

The initial challenge to the framework of Kuznets and Solow was posed by Denison's magisterial study, *Why Growth Rates Differ* (1967).[10] 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 US economic growth, *The Sources of Economic Growth in the United States and the Alternatives Before Us*, published in 1962.[11] 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.[12] 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.[13]

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'.[14] 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!

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 Tinbergen (1942), published in German during World War II.[15] Tinbergen analyzed the sources of US economic growth over the period 1870–1914. He found that efficiency accounted for 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.[16] This program employed data on output of the US economy from earlier studies by the National Bureau, especially the pioneering estimates of the national product by Kuznets (1961).[17] The input side employed data on capital from Raymond Goldsmith's (1962) system of national wealth accounts.[18] 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.[19]

The econometric models of Paul Douglas (1948) and Tinbergen were integrated with data from the aggregate production accounts generated by Moses 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.[20] Like Abramovitz, Kendrick and Kuznets, Solow attributed almost all of US economic growth to 'residual' growth in productivity.[21]

Kuznets' (1971) international comparisons strongly reinforced the findings of Abramovitz (1956), Kendrick (1956), and Solow (1957), which were limited to the United States.[22] 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.[23]

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.[24] Kuznets (1978) interpreted the Solow residual as due to exogenous technological innovation.[25] 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.[26]

2. The New Framework for Productivity Measurement

The most serious challenge to the traditional approach to productivity measurement was presented in my 1967 paper with Griliches, 'The Explanation of Productivity Change'.[27] 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 US agriculture.[28] 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.[29]

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'.[30] This made it possible to incorporate differences among depreciation rates on different assets, as well as variations in returns due to the tax treatment of different types of capital income, into our constant quality index of capital input.[31]

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'.[32] 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.[33]

Nicholas Oulton (2007) shows that Solow's model of embodiment is a special case of the model I proposed in 1966.[34] He also compares the empirical results of a standard two-sector neo-classical growth model with outputs of consumption and investment with Solow's one-sector model. Jeremy Greenwood and Per Krussell (2007) have continued to employ Solow's one-sector model, replacing constant quality prices for investment goods by 'investment-specific' or embodied technical change, as defined by Solow.[35] The deflator for the single output, consumption, is then used to deflate investment, conflicting with the most elementary requirement of the systems of national accounts discussed below, namely, separate deflators for consumption and investment.

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 15 percent could be attributed to productivity growth. Changes in labor quality explained 13 percent of growth, while changes in capital quality another 11 percent.[36] Improvements in the quality of investment goods enhanced the growth of both investment goods output and capital input; the net contribution was only 2 percent of growth.

The final 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 Interpretation of Productivity*, became the cornerstone of a new measurement framework for the official productivity statistics.[37] This was implemented by the Bureau of Labor Statistics (BLS), the US government agency responsible for these statistics.

Under the leadership of Jerome Mark and Dean the BLS Office of Productivity and Technology undertook the construction of a production account for the US economy with measures of capital and labor inputs and total factor productivity, renamed multifactor productivity.[38] 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.[39]

However, BLS retained hours worked as a measure of labor input until 11 July 1994, when it released a new multifactor productivity measure including a constant quality index of labor input as well.[40] Meanwhile, BEA (1986) had incorporated a constant quality price index for computers into the national accounts – over the strenuous objections of Denison (1989).[41] 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.

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 consistent with the original findings of Tinbergen (1942), as well as my paper with Griliches (1967), and the results presented by Jorgenson, Ho, Samuels and Stiroh (2007) in Chapter 18, this volume.

The approach to growth accounting 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 outlined in *Measuring Productivity*, a manual published by the Organisation for Economic Co-Operation and Development (OECD) and written by Paul Schreyer (2001). The expert advisory group for this manual was chaired by Dean, former Associate Commissioner for Productivity at the BLS, and a leader of the successful effort to implement the Rees Report (1979).

The transition to the new framework for productivity measurement, represented by Jorgenson, Ho and Stiroh (2005) and the studies in this volume, has been very abrupt. This has precipitated the sudden obsolescence of earlier productivity research employing the conventions of Kuznets and Solow. All the studies of productivity reprinted in this volume conform to the new international standards presented in the OECD productivity manual. The 'killer application' of the new framework is the impact of information technology on economic growth, so that these studies have focused on the impact of information technology on economic growth in a variety of settings.

Jorgenson and Steven Landefeld have developed a new architecture for the US national accounts that includes prices and quantities of capital services for all productive assets in the

US economy.[42] The incorporation of the price and quantity of capital services into the revision of the 1993 System of National Accounts (SNA) was approved by the United Nations Statistical Commission at its February–March 2007 meeting. A draft of Chapter 20 of the revised SNA, 'Capital Services and the National Accounts', is undergoing final revisions and will be published in 2009.[43] Schreyer, now head of national accounts at the OECD, has prepared an OECD manual, *Measuring Capital*, published in 2009. This provides detailed recommendations on methods for the construction of prices and quantities of capital services.

In Chapter 20 of the revised 1993 SNA, estimates of capital services are described as follows: 'By associating these estimates with the standard breakdown of value added, the contribution of labor and capital to production can be portrayed in a form ready for use in the analysis of productivity in a way entirely consistent with the accounts of the System.' The measures of capital and labor inputs in the prototype system of US national accounts are consistent with the OECD productivity manual, the revised 1993 SNA, and the OECD manual, *Measuring Capital*. The volume measure of input is a quantity index of capital and labor services, while the volume measure of output is a quantity index of investment and consumption goods. Productivity is the ratio of output to input.

The new architecture for the US national accounts has been endorsed by the Advisory Committee on Measuring Innovation in the 21st Century Economy to the former US Secretary of Commerce, Carlos Guttierez.[44] The first recommendation of the Advisory Committee is:

> Develop annual, industry-level measures of total factor productivity by restructuring the NIPAs to create a more complete and consistent set of accounts integrated with data from other statistical agencies to allow for the consistent estimation of the contribution of innovation to economic growth.[45]
> The Advisory Committee endorses the new architecture in the following words:
> The proposed new 'architecture' for the NIPAs would consist of a set of income statements, balance sheets, flow of funds statements, and productivity estimates for the entire economy and by sector that are more accurate and internally consistent. The new architecture will make the NIPAs much more relevant to today's technology-driven and globalizing economy and will facilitate the publication of much more detailed and reliable estimates of innovation's contribution to productivity growth.[46]

In response to the Advisory Committee's recommendations, BEA and BLS have produced a set of estimates integrating multifactor productivity with the NIPAs. The results were reported at a special session on economic statistics at the Annual Meeting of the American Economic Association in San Francisco on 4 January 2009.[47] This is the crucial step in implementing the new architecture. Estimates of productivity are essential for projecting the potential growth of the US economy, as demonstrated by Jorgenson, Ho and Stiroh (2008), Chapter 22, this volume. The omission of productivity statistics from the NIPAs and the 1993 SNA is a serious barrier to application of the national accounts in assessing potential economic growth.

Although it will eventually be desirable to provide a breakdown of the prototype system of US national accounts by industrial sectors, the prototype system constructed by Jorgenson and Landefeld is limited to aggregates for the US economy as a whole. Disaggregating the production account by industrial sector will require a fully integrated system of input–output accounts and accounts for gross product originating by industry, as described by Ann Lawson, et al. (2006), and Brian Moyer, et al. (2006).[48] This can be combined with the measures of capital, labor and intermediate inputs by industry presented by Jorgenson, et al. (2005), to generate production accounts by sector.[49] The principles for constructing these production accounts are discussed by Fraumeni, et al. (2006).[50]

3. 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.[51]

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 billions, 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*.

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.[52]

In 1965 Gordon Moore, then Research Director at Fairchild Semiconductor, made a prescient observation, later known as Moore's Law.[53] Plotting data on 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 more than 40 years. He recently extrapolated this trend well into the future.[54]

In 1968 Moore and Noyce founded Intel Corporation to speed the commercialization of memory chips.[55] 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 2300 transistors. In 2009 Intel plans to release the Tukwila microprocessor with more than two billion transistors! Over this 38 year period the number of transistors on a chip will have increased by 36 percent per year. The rate of productivity growth for the US economy during this period was slower by two orders of magnitude.

4. Prices of Information Technology

Moore's Law captures the fact that successive generations of semiconductors are faster and better. The economics of semiconductors begins with Moore's closely related observation that semiconductors have become cheaper at a truly staggering rate. Semiconductor price indexes, constructed by Bruce Grimm (1998) of the Bureau of Economic Analysis (BEA) and employed in the US National Income and Product Accounts (NIPAs) since 1996,[56] are divided between memory chips and logic chips.

Between 1974 and 1996 prices of memory chips *decreased* by a factor of 27 270 times or 40.9 percent per year, while the implicit deflator for the US 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 1938 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 chip capacity, setting semiconductors apart from other products.

A sharp acceleration in the rate of decline of semiconductor prices took place in 1994 and 1995. The microprocessor price decline leapt to more than 90 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 2005 Update of the International Technology Road Map for Semiconductors,[57] prepared by a consortium of industry associations. However, the accelerated decline of semiconductor prices proved to be transitory and has reverted to more sustainable rates since the dot-com crash of 2000.

The behavior of semiconductor prices is a severe test for the methods used in the official price statistics. The challenge is to decompose observed price declines between changes in semiconductor performance and declines in prices 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) of IBM introduced a 'matched model' index for semiconductor prices.[58] A matched model index combines price relatives for products with the same performance at different points of time. Grimm (1998) combined matched model techniques with hedonic methods, based on an econometric model of semiconductor prices. 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.[59]

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.[60] 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 PCs, 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. In 1985 the Bureau of Economic Analysis incorporated constant quality price indexes for computers and peripheral equipment constructed by IBM into the NIPAs. Dulberger (1989) presented a more detailed report on her research on the prices of computer processors for the BEA-IBM project.[61] Speed of processing and main memory played central roles in her model. Triplett (2005) has provided an exhaustive survey of research on hedonic price indexes for computers.[62]

BEA's constant quality index of prices of computers and peripheral equipment and its components include mainframes, PCs, storage devices and other peripheral equipment. The decline in computer prices follows the behavior of semiconductor prices, but in much attenuated form. The 1995 acceleration in the computer price decline parallels the acceleration in the semiconductor price decline. Like the decline of semiconductor prices, this reverted to historical rates after the dot-com crash of 2000.

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.[63] 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.[64]

Much communications investment takes the form of the transmission gear, connecting data, voice and video terminals to switching equipment. Technologies 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.[65]

Both software and hardware are essential for information technology and this is reflected in the large volume of software expenditures. The 1999 revision of the US national accounts first classified software as investment.[66] Before this, business expenditures on software were treated as current outlays, while personal and government expenditures were treated as purchases of non-durable goods. Software investment is growing rapidly and is now much more important than investment in computer hardware.

The national accounts distinguish 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. Only price indexes for prepackaged software hold performance constant.[67]

5. Economic Impact of Information Technology

Finally, we arrive at the main subject of this book, the impact of information technology (IT) on economic growth. This is the 'killer application' of the new framework for growth accounting presented in Section 2. The key papers were published within a few months of each other by Jorgenson and Stiroh (2000), reprinted as Chapter 1 in this volume, and Oliner and Sichel (2000), reprinted as Chapter 2. I summarized the results in my Presidential Address to the American Economic Association, presented in New Orleans, Louisiana, on 6 January 2001, and reprinted as Chapter 3. Martin Neil Baily (2002) surveyed these papers and closely related work at the Council of Economic Advisers, which he chaired from 1999–2001. His 'Distinguished Lecture on Economics in Government' to the American Economic Association is published as Chapter 4.

Nicholas Oulton (2002), reprinted as Chapter 5 in this volume, published the first paper on the impact of information technology on economic growth in the United Kingdom using the methodology of Jorgenson and Stiroh (2000). Susanto Basu, John Fernald, Nicholas Oulton and Sylaja Srinivasan (2003), reprinted as Chapter 8 in this volume, extended this to the industry level and included comparisons with the United States. This work arose from a research project on productivity measurement at the Bank of England.

The American growth resurgence after 1995 has been traced to sources within the individual industries by Jorgenson, Ho, Samuels, and Stiroh (2007), reprinted as Chapter 18 in this volume. Stiroh (2002), reprinted as Chapter 6 in this volume, had generated measures of output and labor productivity for the four information technology-producing (IT-producing) industries – semiconductors, computers, communications equipment and software. He divided the remaining industries between the IT-using industries, those that are particularly intensive in the utilization of information technology equipment and software, and the non-IT industries. Bart van Ark, Robert Inklaar and Robert McGuckin (2003), reprinted as Chapter 7 in this volume, used data on labor productivity growth for the US and the European Union (EU) to show that US labor productivity growth was faster because of the larger employment share of the IT-producing industries and higher productivity growth in the IT-using industries.

The most distinctive features of IT assets are the rapid declines in prices of these assets, as well as relatively high rates of depreciation. The price of an asset is transformed into the price of the corresponding capital input by an annualization factor known as the cost of capital. The cost of capital includes the nominal rate of return, the rate of depreciation, and the rate of capital loss due to declining prices. The distinctive characteristics of IT prices – high rates of price decline and rates of depreciation – imply that prices of IT capital inputs are very large by comparison with prices of IT capital assets.

The annualized prices of capital inputs are essential for assessing the contribution of investment in IT equipment and software to economic growth.[68] This contribution is the relative share of IT equipment and software in the value of output, multiplied by the rate of growth of IT capital inputs. A substantial part of the growing contribution of capital input in the US can be traced to the change in composition of investment associated with the growing importance of IT equipment and software.

The contribution of college-educated and non-college-educated workers to US economic growth is the relative shares of these workers in the value of output, multiplied by the growth rates of their hours worked.[69] Personnel with a college degree or higher level of education coincide closely with 'knowledge workers' who deal with information. Of course, not every knowledge worker is college-educated and not every college graduate is a knowledge worker.

The growth of productivity or output per unit of input is the key economic indicator of innovation. Although the role of innovation is often described as the predominant source of economic growth, the growth of productivity was far less important than the contributions of capital and labor inputs to US economic growth. The contribution of productivity growth is comparable in magnitude to the contribution of investment in IT equipment and software alone.

The great bulk of economic growth is due to replication of established technologies. Innovation is obviously far more challenging and subject to much greater risk. The diffusion of successful innovation requires mammoth financial commitments. These fund the investments that replace outdated products and processes and establish new organization structures, systems and business models. Although innovation accounts for a relatively minor portion of economic growth, this portion is vital for maintaining gains in the standard of living in the long run.

Turning to the sources of the US growth acceleration after 1995, Jorgenson, Ho, Samuels and Stiroh (2007), reprinted as Chapter 18 in this volume, find that the contribution of capital input was by far the most significant. Growth increased by almost a full percentage point in 1995–2000. The outpouring of IT investment in response to the sharp decline in IT prices after 1995 contributed almost three-quarters of this growth. Many industries substituted IT equipment and software for non-IT investment, leading to a decline in the contribution of non-IT investment to growth.

The increased contribution of labor input in 1995–2000 was almost evenly divided between college and non-college workers, but the contribution of knowledge workers continued to predominate. Innovation also rose during the IT investment boom. Although the pace of innovation clearly accelerated, the contribution of productivity was comparable to that of non-college workers and well below IT investment.

Jorgenson, Ho and Stiroh (2008), Chapter 22, this volume, have shown that the rapid pace of US economic growth after 1995 was not sustainable. After the dot-com crash in 2000 the overall growth rate dropped to well below the long-term average of 1960–1995. The contribution of investment also declined below the 1960–1995 average, but the powerful shift from non-IT to IT capital input continued. The contribution of labor input dropped precipitously, accounting for most of the decline in economic growth during the 'jobless' recovery that followed. The contribution to growth by knowledge workers continued at a reduced rate, but that of non-college workers was negative.

The most remarkable feature of the recovery after 2000 was a spectacular climb in productivity growth, indicating a renewed surge of innovation. The sources of this outpouring of innovation are analyzed in detail by Oliner, Sichel and Stiroh (2007), reprinted as Chapter 20 in this volume. Jorgenson, Ho, Samuels and Stiroh (2007) decompose productivity growth into the contributions of the four IT-producing industries, 28 IT-using industries,[70] and 53 non-IT industries. The four IT-producing industries generate about 3 percent of the GDP, the IT-using industries a little over a quarter, and non-IT industries 71 percent.

During 1960–1995 the IT-producing industries accounted for almost 40 percent of innovation, far out of proportion to their 3 percent of the GDP. In the IT investment boom of 1995–2000 these industries accounted for more than 60 percent of the substantially increased contribution of innovation. After the dot-com crash the contribution of the IT-producing industries to innovation approached the long-term average of 1960–1995. How, then, did innovation accelerate after 2000?

Jorgenson, Ho, Samuels and Stiroh (2007) show a steady increase in rates of innovation in the non-IT industries, making up more than 70 percent of the GDP. The rate of productivity growth in these industries nearly doubled after 1995 and increased by a slightly smaller proportion after 2000. The emergence of innovation in the IT-using industries, making up a little over a quarter of the economy, was the main source of the jump in productivity growth in 2000–2005. Innovation in these industries had been almost negligible from 1960–1995 and was actually negative in 1995–2000 as IT-using industries were nearly swamped by investments in IT equipment and software.

A radical shift in the locus of US innovation following the dot-com crash is revealed by the difference in the contribution of productivity to US economic growth between 2000–2005 and the 35 year period 1960–1995 for 28 IT-using industries. Not all of these differences are positive; the total contribution of IT-using industries to the overwhelming surge of innovation in the US economy is concentrated in eight of the 28 industries. Communications services, the industry providing the hardware and software support for the vast expansion of the Internet, heads the list. The remaining seven industries are in services and trade.

We have now identified the foundations of the New Economy that emerged from the dot-com crash and the recovery that followed. The IT-using industries were nearly inundated by the flood of investment in IT equipment and software after 1995. These industries not only recovered, but actually replaced outmoded organization structures, systems, and business models with new services and new processes for delivering these services. For example, voice, data and video communications moved onto the Internet as broadband services become available to households along with mobile and landline communications services.

Insurance carriers, like banks before them, completed the transfer of their immense volume of transactions – sales, premiums, claims and cash disbursements – onto the Internet, displacing face-to-face transactions, voice communications and paper records. Airlines, long-time leaders in applications of IT equipment and software, adopted new business systems for electronic load management. Wholesale trade, including industry leaders like Wal-Mart and Cisco, integrated supply chains around the world, linking electronic cash registers at retail outlets and business-to-business ordering systems with order dispatch and transportation scheduling at remote factories.

The long reach of globalization is evident in the surge in IT investment and acceleration in growth of productivity in the IT-producing sectors of the world economy after 1995. Van Ark and Marcin Piatkowski (2004), reprinted as Chapter 9 in this volume, documented this for Old Europe, the EU prior to enlargement in May 2004, and New Europe, the countries of Central and Eastern Europe that were added to the EU in 2004. Marcel Timmer and van Ark (2005), reprinted as Chapter 12 in this volume, compared the EU and the US. These comparisons were extended to the industry level for France, Germany, the Netherlands, the United Kingdom and the United States by Inklaar, Mary O'Mahony and Timmer (2005), reprinted as Chapter 11 in this volume.

Inklaar and Timmer (2007), Chapter 16 in this volume, show that productivity trends in IT-producing industries are similar for France, Germany, the Netherlands, the United Kingdom and the United States, but productivity growth in IT-using industries differs between France, Germany and the Netherlands, on the one hand, and the 'Anglo-Saxon' countries, the United Kingdom and the United States, on the other. This reflects much greater levels of IT investment in the two Anglo-Saxon countries. Inklaar, Timmer and van Ark, reprinted as Chapter 17 in this volume, extend these comparisons to include Australia and Canada and show that differences in productivity growth and productivity levels can be traced primarily to market services, rather than goods-producing industries such as manufacturing. As the name suggests, market services are those bought and sold in markets, as opposed to non-market services, such as health, education and general government services.

Jorgenson (2005), reprinted as Chapter 10 in this volume, compares IT investment and growth in productivity in the IT-producing industries among the G7 countries – Canada, France, Germany, Italy, Japan, the United Kingdom and the United States. Jorgenson and Motohashi (2005), reprinted as Chapter 13 in this volume, focused more specifically on Japan and the US at the aggregate level, constructing fully comparable data sets for the two countries. Japan and the US have similar rates of productivity growth in the IT-producing sectors, but Japan invests much less in information technology equipment and software.

Jorgenson and Koji Nomura (2005), reprinted as Chapter 14, have extended the Japanese data on investment in information technology to the industry level. They take Nomura's data set from the Keio Economic Observatory (KEO), maintained at Keio University in Tokyo, as a point of departure.[71] This is augmented by incorporating detailed data on investment in information technology and software for individual Japanese industries. Jorgenson and Nomura (2007), reprinted as Chapter 19, compare productivity growth and productivity levels for Japanese and US industries, revealing similarities among IT-producing industries in the two countries and important differences among IT-using industries, especially trade and services. Japanese industries have invested much less in information technology equipment and software and show much lower rates of growth after 1990, the beginning of the so-called 'Lost Decade' in Japan.

Jorgenson and Khuong Vu (2007), reprinted as Chapter 15 in this volume, have shown that the pattern of IT investment in the G7 and non-G7 industrialized economies mirrors that in the US, but on a substantially reduced scale. Beginning from much lower levels in 1989–1995, the contribution of IT investment in Developing Asia after 2000 is comparable to G7 levels. The transformation of the US economy by the new wave of innovation has counterparts, especially in the relatively small Scandinavian economies, Ireland and Israel.

Jorgenson and Vu (2007) show that the acceleration of US innovation has been accompanied by a marked deceleration in productivity growth in the four major economies of the European Union – France, Germany, Italy and the UK. These countries are homes to many of the leading competitors for US multinationals.[72] Applications of information technology have encountered formidable obstacles in many economies, due to deeply entrenched policies of market and job protection.

The EU KLEMS project, completed on 30 June 2008 and summarized by van Ark, O'Mahony and Timmer (2008) in Chapter 23 of this volume, provides industry-level productivity measurements based on the new framework for growth accounting for the economies of 25 of the 27 member countries of the European Union. For major EU countries this project includes accounts for 72 industries, covering the period 1970–2005. Similar data sets have been compiled for Australia, Canada, Japan, Korea and the US. These data will greatly facilitate international comparisons and the impact of globalization on the major industrialized countries.

Inklaar, Timmer and van Ark (2008), reprinted as Chapter 21 in this volume, employ the EU KLEMS data for comparisons of productivity growth in market services in the EU and the United States. They find that investment in IT and human capital has generated substantial gains in labor productivity in market services in both the EU and the US. However, substantial differences have emerged in productivity growth in market services with the US undergoing the acceleration documented by Jorgenson, Ho, Samuels and Stiroh (2007), while Europe has experienced a deceleration. This accounts for the marked differences between growth of output and productivity in Europe and the United States discussed by van Ark, O'Mahony and Timmer in Chapter 23 of this volume.

6. The New World Economy

Efforts are underway to extend the EU KLEMS framework to important developing and transition economies, such as Brazil, China, India and Russia. This will open important new opportunities for research on the impact of globalization on developing and transition economies. Unfortunately, policies of market and job protection are not limited to industrialized economies. Jorgenson and Vu (2007) show that the contribution of investment in information technology equipment and software has risen steadily in Brazil, China, India, Russia and South Korea, while Indonesia and Mexico have been left behind. Brazil, Indonesia and Mexico give little evidence of sustained innovation, while China and India are slowly catching up with other Asian economies. Russia is only now fully recovered from the economic collapse of the 1990s and South Korea's rate of productivity growth has declined since the Asian financial crisis.

The production of information technology equipment and software has proved to be highly volatile; the great IT investment boom of 1995–2000 was followed by the dot-com crash and the slow and painful recovery of 2000–2005. The boom of 1995–2000 was generated by an unsustainable deluge of innovation in the production of semiconductors and semiconductor-intensive computer and telecommunications equipment. By contrast the wave of innovation that followed in 2000–2005 was spread across a much broader spectrum of trade and service industries. This has created a diversified advance in the applications of information technology in almost a quarter of the US economy.

Successful applications of information technology require new organizational structures to manage the steady procession of new generations of equipment and software. These organizational structures themselves rapidly become antiquated, so that executive-level management of information technology-based businesses must direct a continuous process of restructuring. Business systems have become imbedded in software that requires incessant updating as business needs evolve. Business models for innovation are selected by the market in a process of 'creative destruction' first described by Joseph A. Schumpeter nearly 100 years ago.[73]

Globalization through trade in goods, especially manufactured goods and natural resource products like oil and gas, has steadily advanced with the opening of the major economies of Brazil, China, India and Russia. However, globalization of services is only beginning, accompanied by a chorus of populist attacks on 'outsourcing' and 'offshoring'. The European Union, founded on the principle of a single market, has utterly failed to create a single market in trade and services, which make up 70–80 percent of activity in most industrialized economies. A central feature of the US economy now powering innovation is the gradual extension of a single market in trade and services through broadening the scope of application of the Interstate Commerce clause of the US Constitution.

The removal of impediments to trade in information technology equipment and software has progressed steadily under the Information Technology Agreement of the World Trade

Organization.[74] Since 2000 all tariff and non-tariff barriers to information technology trade have been removed among the more than 70 countries that adhere to this Agreement. Free trade in information technology is opening new business prospects on a daily basis, not only in industrialized economies, but also in developing and transition economies like Brazil, China, India and Russia. Some of these economies are already major participants in information technology production. However, the arena for competition has shifted to IT-using trade and service industries. International competitiveness in the New World Economy will be rooted in the information technology-based business models, systems and organizational structures that emerged phoenix-like from the ruins of the dot-com crash of 2000.

Notes

1. The emergence of this consensus is discussed by Dale W. Jorgenson, Mun S. Ho and Kevin J., Stiroh (2008) and is reprinted as Chapter 22 in this volume.
2. The role of information technology in the American growth resurgence is discussed in detail by Jorgenson, Ho and Stiroh (2005), *Information Technology and the American Growth Resurgence*, Cambridge: The MIT Press.
3. A survey of growth accounting is presented by Jorgenson (2005), 'Accounting for Growth in the Information Age, in Philippe Aghion and Steven Durlauf (eds), *Handbook of Economic Growth*, **1A**, Amsterdam: North-Holland, pp. 743–815. On measuring innovation, see 'Advisory Committee on Measuring Innovation in the 21st Century Economy' (2008), *Innovation Measurement: Tracking the State of Innovation in the American Economy*, report to the Secretary of Commerce, January.
4. More details are given by Jorgenson, Ho, Jon D. Samuels, and Stiroh, 'Industry Origins of the American Productivity Resurgence,' *Economic Systems Research*, Vol. 19, **3**, September 2007, pp. 229–252, reprinted as Chapter 18. On productivity growth and the New Economy, see: Jorgenson and Charles W. Wessner (2007), eds., *Enhancing Productivity Growth in the Information Age*, Washington: National Academy Press.
5. Simon Kuznets (1971), *Economic Growth of Nations*, Cambridge, MA: Harvard University Press; Robert M. Solow (1970), *Growth Theory: An Exposition*, New York: Oxford University Press.
6. Paul Schreyer (2001), *Productivity Manual: A Guide to the Measurement of Industry-Level and Aggregate Productivity Growth*, Paris: Organisation for Economic Co-Operation and Development, March.
7. For more information, see the EU KLEMS website: www.euklems.net.
8. 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 Assar Lindbeck (ed.) (1992), *Nobel Lectures in Economic Science, 1969–1980*, River Edge, NJ: World Scientific Publishing Company, p. 79.
9. See Harrod (1939), 'An Essay in Dynamic Theory', *Economic Journal*, **49** (194), March, pp. 14–33, and Domar (1946), 'Capital Expansion, Rate of Growth, and Employment', *Econometrica*, **14** (2), April, pp. 127–47. Solow's seminal role in this research, beginning with his brilliant and pathbreaking essay of 1956, 'A Contribution to the Theory of Economic Growth', *Quarterly Journal of Economics*, **70** (1), February, pp. 65–94, 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 Karl-Goran Maler (ed.) (1992), *Nobel Lectures in Economic Sciences, 1981–1990*, River Edge, NJ: World Scientific Publishing Company, p. 191. Solow (1999), 'Neo-Classical Growth Theory', in John B. Taylor and Michael Woodford (eds), *Handbook of Macroeconomics*, Volume 1A, Amsterdam: North-Holland, pp. 637–68, presents an updated version of his exposition of growth theory.

10. Denison (1967), *Why Growth Rates Differ*, Washington: The Brookings Institution Press.
11. Denison (1962), *The Sources of Economic Growth in the United States and the Alternatives Before Us*, New York: Committee on Economic Development.
12. Kuznets (1971), Table 9, part B, pp. 74–5.
13. Solow (1970), pp. 2–7. However, Solow (1988), 'Growth Theory and After', *American Economic Review*, **78** (3), June, pp. 313–14, adopted Denison's perspective on labor input in his Nobel Prize address. At about the same time this view was endorsed by Gary S. Becker (1993), *Human Capital*, 3rd edn, Chicago, IL: University of Chicago Press (1st edn, 1964, 2nd edn, 1975), p. 24, in his 1989 Ryerson Lecture at the University of Chicago. Becker (1993), 'Nobel Lecture: The Economic Way of Looking at Behavior', *Journal of Political Economy*, **101** (3), June, pp. 385–409, also cited Denison.
14. Kuznets (1971), p. 73.
15. Tinbergen (1959), 'On the Theory of Trend Movements', in *Selected Papers of Jan Tinbergen*, Amsterdam: North-Holland, pp. 182–221, translated from 'Zur Theorie der Langfristigen Wirtschaftswicklung', *Weltwirtschafliches Archiv*, **55** (1), 1942, 511–49.
16. Stigler (1947), *Trends in Output and Employment*, New York: National Bureau of Economic Research.
17. Kuznets (1961), *Capital in the American Economy*, Princeton, NJ: Princeton University Press.
18. Goldsmith (1962), *The National Wealth of the United States in the Postwar Period*, New York: National Bureau of Economic Research.
19. See Kendrick (1956), 'Productivity Trends: Capital and Labor', *Review of Economics and Statistics*, **38** (3), August, pp. 248–57, and Kendrick (1961), *Productivity Trends in the United States*, Princeton: Princeton University Press. Updated estimates based on Kendrick's framework are presented by Kendrick (1973), *Postwar Productivity Trends in the United States*, New York: National Bureau of Economic Research, and Kendrick and Eliot Grossman (1980), *Productivity in the United States: Trends and Cycles*, Baltimore, MD: The Johns Hopkins Press.
20. See Douglas (1948), 'Are There Laws of Production?', *American Economic Review*, **38** (1), March, pp. 1–41: Abramovitz (1956), 'Resources and Output Trends in the United States since 1870', *American Economic Review*, **46** (1), March, pp. 5–23; and Solow (1957), 'Technical Change and the Aggregate Production Function', *Review of Economics and Statistics*, **39** (3), August, pp. 312–20.
21. This finding is called 'Solow's Surprise' by William Easterly (2001), *The Elusive Quest for Growth*, Cambridge, MA: The MIT Press, and is listed as one of the 'stylized facts' about economic growth by Robert King and Sergio Rebelo (1999), 'Resuscitating Real Business Cycles', in John B. Taylor and Michael Woodford (eds), *Handbook of Macroeconomics*, **1B**, Amsterdam: North-Holland, pp. 927–1008.
22. A survey of international comparisons, including Tinbergen (1942) and Kuznets (1971), is given in my paper with Laurits Christensen and Dianne Cummings (1980), 'Economic Growth, 1947–1973: An International Comparison', in John W. Kendrick and Beatrice Vaccara (eds), *New Developments in Productivity Measurement and Analysis*, Chicago, IL: University of Chicago Press. This paper was presented at the forty-fourth meeting of the Conference on Research and Wealth, held at Williamsburg, Virginia, in 1975.
23. Kuznets (1971), p. 73; see also, pp. 306–9.
24. For more recent examples, see Michael Dertouzos, Solow and Richard Lester (1989), *Made in America: Regaining the Productive Edge*, Cambridge, MA: The MIT Press, and Robert E. Hall (1988), 'The Relation between Price and Marginal Cost in U.S. Industry', *Journal of Political Economy*, **96** (4), July–August, pp. 921–47, and Hall (1990), 'Invariance Properties of Solow's Residual', in Peter A. Diamond (ed.), *Growth/Productivity/Employment*, Cambridge, MA: The MIT Press.
25. See Simon Kuznets (1978), 'Technological Innovations and Economic Growth', in Patrick Kelly and Melvin Kranzberg (eds), *Technological Innovation: A Critical Review of Current Knowledge*, San Francisco: San Francisco Press, pp. 335–56.
26. A detailed survey of research on sources of economic growth is given in my article, 'Productivity and Economic Growth', in Ernst R. Berndt and Jack E. Triplett (eds) (1990), *Fifty Years of Economic*

Measurement, Chicago, IL: University of Chicago Press, pp. 19–118. This paper was presented at the Jubilee of the Conference on Research in Income and Wealth, held in Washington, DC, in 1988, commemorating the fiftieth anniversary of the founding of the Conference by Kuznets. More recent surveys are presented in Zvi Griliches' (2000) posthumous book, *R&D, Education, and Productivity*, Cambridge, MA: Harvard University Press, and Charles Hulten's (2001) article, 'Total Factor Productivity: A Short Biography', in Hulten, Edwin R. Dean and Harper (eds), *New Developments in Productivity Analysis*, Chicago, IL, University of Chicago Press, pp. 1–47.

27. Jorgenson and Griliches (1967), 'The Explanation of Productivity Change', *Review of Economic Studies*, **34** (99), July, pp. 249–80.
28. Griliches (1960), 'Measuring Inputs in Agriculture: A Critical Survey', *Journal of Farm Economics*, **40** (5), December, pp. 1398–427.
29. Constant quality indexes of labor input are discussed detail by Jorgenson, Gollop and Fraumeni (1987), *Productivity and U.S. Economic Growth*, Cambridge, MA: Harvard University Press, Chapters 3 and 8, pp. 69–108 and 261–300, and Jorgenson, Ho and Stiroh (2005), Chapter 6, pp. 201–90.
30. Jorgenson (1963), 'Capital Theory and Investment Behavior', *American Economic Review*, **53** (2), May, pp. 247–59.
31. I have presented a detailed survey of empirical research on the measurement of capital input in my paper, 'Capital as a Factor of Production', in Jorgenson and Ralph Landau (eds) (1989), *Technology and Capital Formation*, Cambridge, MA: MIT Press, pp. 1–36. Earlier surveys were given in my paper, 'The Economic Theory of Replacement and Depreciation', in Willy Sellekaerts (ed.) (1973), *Econometrics and Economic Theory*, New York: Macmillan, pp. 189–221, and Erwin Diewert (1980), 'Aggregation Problems in the Measurement of Capital', in Daniel Usher (ed.), *The Measurement of Capital*, Chicago, IL, University of Chicago Press, pp. 433–528, presented to the forty-fifth meeting of the Conference on Income and Wealth, held at Toronto, Ontario, in 1976. Charles Hulten (1990), 'The Measurement of Capital', in Berndt and Triplett (eds) 'Fifty Years of Economic Measurement', Chicago IL, University of Chicago Press, pp. 119–52 surveyed conceptual aspects of capital measurement in his contribution to the Jubilee of the Conference on Research in Income and Wealth in 1988.
32. Jorgenson (1966), 'The Embodiment Hypothesis', *Journal of Political Economy*, **74** (1), February, pp. 1–17.
33. As a natural extension of the one-sector neo-classical model of Solow (1956), Solow's (1960), 'Investment and Technical Progress', in Kenneth J. Arrow, Samuel Karlin and Patrick Suppes (eds), *Mathematical Methods in the Social Sciences, 1959*, Stanford: Stanford University Press, pp. 89–194, 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 Jeremy Greenwood and Boyan Jovanovic, 'Accounting for Growth', in Hulten, Dean and Harper (eds) (2001), pp. 179–222, and discussed by Solow, 'After Technical Progress and the Aggregate Production Function', in Hulten, Dean and Harper (eds) (2001), pp. 173–8.
34. See Oulton (2007), 'Investment-Specific Technological Change and Growth Accounting,' *Journal of Monetary Economics*, **54** (4), May, pp. 1290–99.
35. See Greenwood and Krussell (2007), 'Growth Accounting with Investment-Specific Technological Progress,' *Journal of Monetary Economics*, **54** (4), May, pp. 1300–1310.
36. 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. 179–81.
37. See Albert Rees (ed.) (1979), *The Measurement and Interpretation of Productivity*, Washington, DC: The National Academy Press.
38. A detailed history of the BLS productivity program is given by Dean and Harper, 'The BLS Productivity Measurement Program', in Hulten, Dean and Harper (eds) (2001), pp. 55–84.
39. See BLS (1983), *Trends in Multifactor Productivity, 1948–81*, Bulletin No. 2178, Washington, DC: U.S. Government Printing Office. The constant quality index of capital input became the

international standard for measuring productivity in Schreyer's (2009), OECD manual, *Measuring Capital*, Paris, Organisation for Economic Co-Operation and Development, January.

40. See BLS (1994), *Labor Composition and U.S. Productivity Growth, 1948–90*, Bulletin No. 2426, Washington, DC: U.S. Department of Labor.
41. See BEA (1986), 'Improved Deflation of Purchase of Computers', *Survey of Current Business*, **66** (3), March, pp. 7–9, and Denison (1989), *Estimates of Productivity Change by Industry*, Washington, DC: The Brookings Institution Press.
42. See Jorgenson and J. Steven Landefeld (2006), 'Blueprint for Expanded and Integrated U.S. Accounts: Review, Assessment, ands Next Steps', in Jorgenson, Landefeld and William D. Nordhaus (eds), *A New Architecture for the U.S. National Accounts*, Chicago: University of Chicago Press; Dale W. Jorgenson (2009), 'A New Architecture for the U.S. National Accounts', *Review of Income and Wealth*, **55** (1), March, pp. 1–42; and Jorgenson and Landefeld (2009), 'Implementation of a New Architecture for the U.S. National Accounts', *American Economic Review*, **99** (2), May, forthcoming.
43. See Intersecretariat Working Group on the National Accounts (2009), 'Capital Services and the National Accounts', Chapter 20 in *Revision 1, 1993 System of National Accounts*, **2**, forthcoming.
44. The Advisory Committee on Measuring Innovation in the 21st Century Economy (2008). The Advisory Committee was established on 6 December 2007, with ten members from the business community, including Carl Schramm, President and CEO of the Kauffman Foundation and chair of the Committee, Sam Palmisano, Chairman and CEO of IBM, and Steve Ballmer, President of Microsoft. The Committee also had five academic members, including Jorgenson. The Advisory Committee met on 22 February and 12 September 2007, to discuss its recommendations. The final report was released on 18 January 2008.
45. The Advisory Committee on Measuring Innovation in the 21st Century Economy (2008, p. 7).
46. The Advisory Committee on Measuring Innovation in the 21st Century Economy. (2008, p. 8).
47. Harper, Brent Moulton, Steven Rosenthal and David Wasshausen (2009), 'Integrated GDP-Productivity Accounts', *American Economic Review*, **99** (2), May, forthcoming.
48. See Ann Lawson, Brian Moyer, Sumiye Okubo and Mark A. Planting, 'Integrating Industry and National Economic Accounts: First Steps and Future Improvements', in Jorgenson, Landefeld and Nordhaus (eds) (2006), pp. 215–62, and Brian Moyer, Marshall B. Reinsdorf and Robert E. Yuskavage, 'Aggregation Issues in Integrating and Accelerating the BEA's Accounts: Improved Methods for Calculating GDP by Industry', in Jorgenson, Landefeld and Nordhaus (eds) (2006), pp. 263–87.
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61. Dulberger, 'The Application of Hedonic Model to a Quality-Adjusted Price Index for Computer Processors', in Jorgenson and Ralph Landau (eds) (1989), pp. 37–76.
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63. On the economics of electronic commerce, see Efraim Turban, David King, Judy McKay, Peter Marshall, Jae Lee and Dennis Viehland (2007), *Electronic Commerce 2008*, Englewood Cliffs, NJ: Prentice-Hall.
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69. For details on the contribution of labor input to economic growth, see Jorgenson, Ho and Stiroh (2005), Ch. 6, pp. 201–90.
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