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Econometrics

VOLUME 3

Economic Growth in the Information Age

Dale W. Jorgenson

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Contents

List of Figures

List of Tables

Preface

Dale W. Jorgenson

The stagflation of the 1970s greatly undermined the Keynesian Revolution of the 1930s, leading to the New Classical Counterrevolution that has transformed the economics of the business cycle. The unanticipated American growth revival of the 1990s has similar potential for revolutionizing economists' perspectives on economic growth. It is not surprising that the combination of more rapid growth and lower inflation has touched off a strenuous debate about whether the improvements in America's economic performance can be sustained.

This volume presents my econometric studies of economic growth in the information age. The point of departure is my presidential address to the American Economic Association, "Information Technology and the U.S. Economy," delivered in New Orleans, Louisiana, on January 6, 2001. In chapter 1 I show that the remarkable behavior of information technology (IT) prices is the key to understanding the growth resurgence of the American economy. This can be traced to developments in semiconductor technology that are widely understood by technologists and economists.

The economics of information technology begins with the observation that semiconductors have become cheaper at a truly astonishing rate. Modeling the behavior of semiconductor prices is a severe test for the econometric methods used in the official price statistics. A hedonic model gives the price of semiconductor products 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 constant.

Mainframe and personal computers have come to rely heavily on semiconductor storage devices, or "memory chips," for main memory. Similarly, computers rely on microprocessors, or "logic chips," for central processing. 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 (BEA) introduced constant quality price indexes for computers and peripheral equipment into the U.S. National Income and Product Accounts (NIPA). Rosanne Cole et al. (1986) of IBM constructed the computer price indexes employed by BEA.

In 1985 the Program on Technology and Economic Policy that I direct at Harvard University organized a conference to discuss the BEA-IBM constant quality price indexes for computers. Ralph Landau and I edited the conference proceedings, *Technology and Capital Formation* (1989). This volume established the foundation for my research with Kevin Stiroh (1995) on the impact of computers on economic growth. In chapter 2 we show that the concept of the cost of capital, presented in my volume *Capital Theory and Investment Behavior* (1996), is the key to modeling the economic impact of information technology.

Swiftly falling IT prices provide a powerful economic incentive for substituting capital for labor, as well as substituting IT equipment for other forms of capital. The rate of the IT price decline is also a key component of the cost of capital, required for assessing the impacts of rapidly growing stocks of computers. Constant quality price indexes are used as deflators for investments in computers. These investments are cumulated into stocks of computer capital. Finally, constant quality service prices, incorporating the cost of capital, are employed to convert the stocks into flows of computer services.

The production possibility frontier was the principal innovation in "The Embodiment Hypothesis," chapter 2 in my volume, *Postwar U.S. Economic Growth* (1995). The most compelling advantage of this model is the explicit role that it provides for constant quality price indexes. The frontier captures substitution between capital and labor inputs, as well as substitution between investment and consumption outputs. Using this concept, Stiroh and I have generated evidence of massive substitutions of computers for outputs of consumption goods and other investment goods, as well as similar substitutions of services of computers for labor inputs and other capital inputs.

The eleventh set of comprehensive revisions of the U.S. national accounts, released by BEA in 1999, reclassified the output of software as an investment good. These revisions also incorporated a constant quality price index for prepackaged software developed by Steven Oliner and Daniel Sichel (1994). In chapter 3 Stiroh and I extend the production possibility frontier to include telecommunications equipment and software as well as computers. We employ a hedonic model of the prices of digital telephone switching equipment from the U.S. national accounts.

The rapid progress of econometric research on prices of information technology has left some significant gaps. While hedonic models of prices for computers and peripheral equipment now cover all forms of investment in these IT products, constant quality prices for telecommunications equipment and software cover only part of the investment. In chapter 3 Stiroh and I show that the impact of the resulting biases in IT price indexes is to underestimate the growth of output and overestimate the growth of total factor productivity.

In chapter 1 I include investments by the government sector, as well as investments by business and household sectors, in the measure of IT outputs. My output measure also includes the imputed value of IT services in the household and government sectors. (The value of these services employed in the business sector is included in business income and does not require a separate imputation.) This measure of output is similar to the concept of gross domestic product employed by BEA. However, my measure of IT services incorporates all the components of the cost of IT capital, while the BEA measure includes only depreciation.

A key innovation in the model of production employed in chapter 1 is the allocation of total factor productivity growth between information and non-information technology. I show that the contribution of information technology roughly doubled between the periods 1990–1995 and 1995–1999, but that the contribution of non-information technology increased even more. However, the rise in the growth of total factor productivity accounted for less than a third of the two percent jump in U.S. economic growth after 1995. Almost half the jump was due to a surge in the growth of capital input, while the rising contribution of labor input accounted for the rest.

As a consequence of the advance of information technology, many of the most familiar concepts in growth economics have been superseded. The aggregate production function employed by Robert M. Solow (1957, 1960) heads the list. 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 prices of information technology in measuring the output of investment goods.

Similarly, capital stock is no longer adequate to capture the rising importance of IT. This measure of capital input completely obscures the restructuring that is the wellspring of the American growth resurgence.

Accurate modeling of substitution among different types of capital input, especially information technology and other forms of capital, is essential in assessing the impact of investment. Finally, hours worked omits the rapid shifts in the evaluation of skills as a consequence of advances in information technology. This has been superseded by a measure of labor input that reflects substitution among workers with different skills.

The second major theme of this volume is international comparisons of patterns of economic growth in the information age. This is also the primary focus of my volume, *International Comparisons of Economic Growth* (1995). In chapter 5 Eric Yip and I present empirical support for a neo-classical growth model characterized by persistent differences in productivity, capital quality, labor quality, and hours worked per capita among countries. This can be contrasted with the econometric version of Solow's (1956) neo-classical model employed in the seminal paper by Gregory Mankiw, David Romer, and David Weil (1991) where these critical differences among countries are suppressed.

Yip and I assemble the empirical evidence for our neo-classical growth model by constructing consistent data on the sources of economic growth for the G7 countries, covering the period 1960–1995. Our methodology is based on the same innovations as those employed in modeling the U.S. economy in chapter 1. The cost of capital plays a central role in capturing the impact of investment in tangible assets. We employ a production possibility frontier for each country in order to incorporate the available data on investment in information technology.

Yip and I find that the United States has retained its lead in output per capita among the G7 countries throughout the period 1960-1995. The United States has also maintained its lead in input per capita, while relinquishing the lead in productivity to France. Investments in tangible assets and human capital account for the overwhelming proportion of economic growth in the G7 countries and also explain the predominant share of international differences in output per capita.

The third major theme of this book is the econometric modeling of economic growth in the information age. An econometric model of the production possibility frontier was the central contribution of "Transcendental Logarithmic Production Frontiers," chapter 4 in volume 1 of this set, *Econometric Modeling of Producer Behavior* (2000). This econometric model represents the technology of the U.S. economy in my book with Kun-Young Yun, *Lifting the Burden: Tax Reform, the Cost of Capi-*

tal, and U.S. Economic Growth (2001). We estimate the parameters of this model from a data set that includes the BEA-IBM constant quality price for computers.

In "Inflation-Proof Depreciation of Assets," chapter 8 in *Tax Policy and the Cost of Capital* (1996), Alan Auerbach and I augment the cost of capital framework by introducing the marginal effective tax rate. The cost of capital summarizes information about the future consequences of investment in tangible assets essential for current decisions. The marginal effective tax rate characterizes the consequence of investment decisions that is particularly suitable for comparisons among alternative tax policies. Efficient capital allocation requires the equalization of marginal effective tax rates on all assets.

Yun and I summarize the tax burden on capital income by means of marginal effective tax rates for all assets and all sectors of the U.S. economy. We show that the Tax Reform Act of 1986 significantly reduced differences in the tax burdens among corporate, non-corporate, and household sectors. Differences between short-lived and long-lived depreciable assets were almost eliminated by this legislation. However, substantial differences in marginal effective tax rates between household and corporate sectors still remain. These gaps reveal important opportunities for gains in efficiency through reallocation of capital by means of tax reform.

In chapter 6 I employ marginal effective tax rates to compare the effects of reforms of capital income taxation in the G7 countries, Australia, and Sweden during the 1980s and 1990s. In most countries these reforms reversed decades of erosion of the income tax base to provide incentives for saving and investment. Efforts were made to equalize tax rates on assets within the business sector. However, equalization of tax burdens on housing and business capital has proved to be extraordinarily difficult within the framework of the income tax. Although reforms have substantially reduced barriers to efficient allocation of capital, important opportunities for further gains in efficiency remain in all nine countries.

Yun and I focus on the determinants of investment in tangible assets, including investments in information technology. Our econometric model combines the production possibility frontier with an econometric representation of preferences. This representation was first presented in "Transcendental Logarithmic Utility Functions," chapter 1 of *Aggregate Consumer Behavior* (1997). Yun and I employ our econometric model of economic growth to simulate the impact of alternative tax reforms. We compare the level of social welfare for each tax reform with welfare in the absence of reform, translating these welfare comparisons into monetary terms.

In chapter 8 Mun S. Ho and I extend the econometric modeling of economic growth in the information age by incorporating a model of investment in human capital. We treat this investment as the output of the educational sector. Inputs of the sector include purchases of intermediate goods such as school supplies and energy by educational institutions, the services of tangible assets like buildings and equipment employed in these institutions, the services of human capital from teachers, and—most important of all—the services of human capital from students.

A detailed set of growth accounts for the educational sector is contained in my paper with Barbara Fraumeni, "The Output of the Educational Sector," chapter 7 of *Postwar U.S. Economic Growth* (1995). Our point of departure is that education is a service industry, but its output is investment in human capital. This is measured as increments to the lifetime incomes of all students enrolled in the educational system. The value of investment in education, measured in this way, is roughly equal to the value of the working time of the entire U.S. labor force.

Ho and I have evaluated alternative educational policies by transforming changes in welfare associated with policy changes into changes in wealth. We consider policies that would increase educational "quality" by increasing expenditures and taxes that finance them, while holding educational participation rates constant. We also consider policies that would hold expenditures and taxes constant, while increasing participation rates. We conclude that enhancing educational quality would reduce social welfare, while increasing participation rates would increase welfare.

In chapter 7 I describe the barriers to extending econometric models of economic growth to encompass intellectual capital. The standard model for investment in intellectual capital, formulated by Zvi Griliches (1973), treats this investment as an output of research and development. The services of intellectual capital are a factor of production, like the services of tangible assets and human capital in my model with Ho. While the output of the educational sector can be defined in terms of increments to lifetime incomes of students, there is no comparable measure for the output of research and development. Pricing this output remains a major barrier to incorporating intellectual capital into econometric models of economic growth.

The fourth major theme of this book is the econometric approach for measuring social welfare in the information age, also the focus of *Measuring Social Welfare* (1997). The essential idea is to recover measures of individual welfare from an econometric model of aggregate consumer behavior. These are combined into an indicator of welfare that reflects horizontal and vertical equity, as well as economic efficiency. The econometric approach is summarized in chapter 1 of the volume, "Aggregate Consumer Behavior and the Measurement of Social Welfare," my presidential address to the Econometric Society. Daniel Slesnick provides a much more detailed account in his book, *Consumption and Social Welfare* (2001).

Multi-million dollar budgets are involved in statistical reporting of measures of the cost of living, while millions more are spent on measures of poverty, inequality, and the standard of living. Unfortunately, these well-established programs give highly misleading results and require a complete overhaul. The key to revision of these programs is the effective exploitation of existing surveys of household consumption. In chapter 9 ("Did We Lose the War on Poverty?") I give a detailed example of econometric measures of the incidence of poverty based on consumption. I show that the War on Poverty was a success, while official estimates based on income rather than consumption purport to show the reverse.

In chapter 10, Slesnick and I present a new measure of the cost of living based on the econometric approach to measuring social welfare. This incorporates all the information employed in the Consumer Price Index (CPI) but preserves important features of the data ignored in constructing these price index numbers. For example, the econometric approach captures changes in household spending patterns in response to changes in prices and total expenditure. In addition, it includes the effects of changes in the demographic structure of the population on aggregate spending patterns.

Slesnick and I show that inflation rates over the period 1947–1995 are virtually identical for the econometric measure of the cost of living and the CPI. Over the first half of the period, the econometric approach generates slightly higher inflation rates, while the reverse is true for the second half. We find that group cost of living indexes are similar for white and nonwhite households, for female-headed and male-headed households, and for non-elderly households. The elderly have experienced slightly higher inflation rates since 1973. We recommend indexing government programs, such as Social Security, by group cost of living indexes rather than the CPI.

The fifth theme of this volume is econometric general equilibrium modeling in the information age. This is also the subject of *Energy, the Environment, and Economic Growth* (1998). In chapter 12 Peter J. Wilcoxen and I present an intertemporal general equilibrium model for analyzing the impact of tax policies in the United States. This preserves the key features of more highly aggregated models, like the one presented in chapter 8. However, Wilcoxen and I have disaggregated the representations of technology and preferences in order to provide a more detailed perspective on the impact of changes in tax policy.

One important dimension for disaggregation is to introduce a distinction between commodities and industries in order to model business responses to tax-induced price changes. We also distinguish among households by level of wealth and demographic characteristics so that we can model the responses of households to tax policies as well. Finally, we model demands for different types of capital services in each of thirty-five industrial sectors, as well as the household sector. These demands depend on tax policies through measures of the cost of capital that incorporate the characteristic features of U.S. tax law described in my book with Yun.

We consider the economic impact of substituting a tax on consumption for the existing system of income taxes in the United States. We first consider the Armey-Shelby Flat Tax. This proposal levies taxes on the difference between business receipts and the sum of business purchases from other firms and payrolls. Labor income is taxed at the individual level. An important feature of this proposal is a system of personal exemptions that have the effect of setting the marginal rates of taxation equal to zero up to the exempt amount of income. The purpose of the exemptions is to introduce progressivity into the rate structure, since average tax rates rise gradually from zero to the flat tax rate as household income increases.

The second tax reform proposal we consider is the National Retail Sales Tax. The tax base is the same as in our simulations of the Flat Tax. However, the method of collection is different. The Flat Tax preserves the existing structures of the corporate and individual income taxes but alters the tax base. The National Retail Sales Tax eliminates corporate and individual income taxes and relies on retail establishments to collect the taxes. This definition of retail establishments would include real estate developers and providers of professional services, such as legal and medical services. Most important, no personal exemptions would be provided.

The National Retail Sales tax would generate a substantial acceleration in economic growth, initially through a sharp rise in the labor supply, since capital stock is fixed in the short run. In the longer run a higher level of economic activity would be generated by added capital formation. By contrast, the Flat Tax would generate a very modest rise in the level of economic activity through increases in the labor supply. Capital formation would fall initially and would remain depressed, relative to levels that would prevail in the absence of tax reform.

In chapter 11 Richard Garbaccio, Ho, and I present an intertemporal general equilibrium model of the Chinese economy. The main features of the model are the same as those of the U.S. model given in Chapter 11. We account for the effects of population growth, capital accumulation, changes in technology, and changing patterns of demand in China. Our model of the Chinese economy reflects the fact that plan and market institutions continue to coexist. Although the scope of central planning has been drastically reduced for most commodities, it still affects the allocation of energy. In addition, capital markets are largely under government control, either directly through the state budget or indirectly through the state-owned banking system.

Although there is a wide range of forecasts of future emissions of carbon dioxide in China, they are unanimous in projecting that China will become the largest emitter within a few decades. In chapter 11 we show how carbon taxes could be used to control emissions. The extra revenue raised by a carbon tax is offset by reductions in all other taxes. The effect of a carbon tax would be to reduce household income and raise the retained earnings of enterprises. Spending would shift from consumption to investment and higher investment would lead to increases in future output. There would a "double dividend" from imposing a carbon tax, namely, reductions in carbon emissions combined with future increases in output and consumption.

An important issue is whether the coexistence of plan and market institutions reduces the responsiveness of energy demand to price changes. The price responsiveness of energy demand in the United States is analyzed in the companion volume, *Econometric General Equilibrium Modeling* (1998). Between 1978 and 1995 the energy-output ratio in China decreased by 55 percent as the Chinese economy expanded at double-digit rates. Using input-output tables for China for 1987 and 1992, Garbaccio, Ho, and I show in chapter 4 that this can be explained by declines in energy-output ratios within individual Chinese industries. Energy-intensive industries in China actually increased in relative importance from 1987 to 1992, raising the Chinese energy-output ratio. Increasing imports of energy-intensive products made a modest contribution to the decline in the energy-output ratio. We conclude that demands for energy are very responsive to the price changes that have accompanied the transition to a market economy in China. Accordingly, market-based approaches to environmental policy, such as a carbon tax, are not only feasible but also likely to be highly effective.

I conclude that the steadily rising importance of information technology has created new research opportunities in all areas of economics. Economic historians, led by Alfred Chandler (2000) and Paul David (2000), have made substantial progress in placing the Information Age in historical context. Chandler traces the development of information technology in America over the past two centuries, establishing persistent features of the advance of this technology. David emphasizes similarities and differences between the diffusion of information technology and the diffusion of innovations such as electricity generation.

Several models of the semiconductor industry exist, but none successfully account for the shift from a three-year product cycle to a two-year cycle that took place in 1995. In chapter 1 I show that this is the driving force behind the resurgence of American economic growth in the last half of the 1990s. A two-year cycle would continue to propel semiconductor prices on an accelerated downward course and produce rapid productivity growth in the IT-producing industries. Reversion to a three-year cycle would reduce this productivity growth to the more moderate pace that prevailed before 1995.

Capital and labor markets have been severely impacted by the advance of information technology. Enormous uncertainties surround the relationship between equity valuations and the future growth prospects of the American economy. One theory attributes rising valuations of equities after 1995 to the accumulation of intangible assets, such as intellectual property and organizational capital. A competing theory treats these high valuations as a bubble that burst in the year 2000. The behavior of labor markets impacted by the spread of information technology also poses important questions. Widening wage differentials by skill have been attributed to computerization of the workplace. In this view high-skilled workers are complementary to IT, while low-skilled workers are substitutable. An alternative explanation is that advances in information technology are skill-biased, raising the wages of skilled workers relative to the wages of the unskilled.

Finally, the semiconductor and information technology industries are global in their scope with an elaborate international division of labor. Where is the evidence of accelerated growth in other leading industrialized countries? An important limitation on the availability of this evidence is the lack of satisfactory price indexes for semiconductors and information technology products outside the U.S. Several of the most important participants in the information technology industry are the newly industrialized countries of Asia—Korea, Malaysia, Singapore, and Taiwan. What does this portend for growth in developing countries like India and China?

As policymakers attempt to fill the widening gaps between the available economic data and the information required for sound policy, the traditional division of labor between statistical agencies and policymaking bodies is breaking down. In the meantime monetary policymakers must set policies without accurate measures of price change. Similarly, fiscal policymakers must confront rising levels of uncertainty about future prospects for economic growth that drastically affect the outlook for future tax revenues and government spending. Resolving the uncertainties about future economic growth arising from advances in information technology is increasingly urgent. The practical need for better understanding of the impact of this technology is already generating a rising tide of research. This is sweeping away many older perspectives on economic growth, including some that were "new" only a decade ago. Economists are the fortunate beneficiaries of a fresh agenda for research that will revitalize economic thinking and enrich economics as a discipline.

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1

Information Technology and the U.S. Economy

Dale W. Jorgenson

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 to reflect a more sanguine outlook only recently.[1] It is not surprising that the unusual combination of more rapid growth and slower inflation in the 1990s has touched off a strenuous debate among economists about whether improvements in America's economic performance can be sustained.

The starting point for the economic debate is the thesis that the 1990s are a 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 relentless decline in the prices of information technology equipment has steadily enhanced the role of IT investment as a source of American economic growth. Productivity growth in IT-producing industries has gradually risen in importance and a productivity revival is now underway in the rest of the economy. Despite differences in methodology and data sources, a consensus is building that the remarkable behavior of IT prices provides the key to the surge in economic growth.

Section 1.1 illustrates that the foundation for the American growth resurgence is the development and deployment of semiconductors. The decline in IT prices is rooted in developments in semiconductor technology that are widely understood by technologists and economists. This technology has found its broadest applications in computing and communications equipment, but has reduced the cost of a wide variety of other products.

A substantial acceleration in the IT price decline occurred in 1995, triggered by a much sharper acceleration in the price decline of semiconductors in 1994. Although the decline in semiconductor prices has been projected to continue for at least another decade, the recent acceleration could be temporary. This can be traced to a shift in the product cycle for semiconductors from three years to two years that took place in 1995 as the consequence of intensifying competition in markets for semiconductor products.

In section 1.2, I outline a framework for analyzing the role of information technology in the American growth resurgence. Constant quality price indexes separate the change in the performance of IT equipment from 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.

The cost of capital is an essential concept for capturing the economic impact of information technology prices. Swiftly falling 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.

In section 1.3, I analyze the impact of the 1995 acceleration in the information technology price decline on U.S. economic growth. I introduce a production possibility frontier that encompasses substitutions between outputs of consumption and investment goods, as well as inputs of capital and labor services. This frontier treats IT equipment as part of investment goods output and the capital services from this equipment as a component of capital input.

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 nearly a full percentage point. The contribution of 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 the source of most of aggregate productivity growth throughout the 1990s. Before 1995 this was due to the decline of productivity growth elsewhere in the economy. The IT-producing industries have accounted for about half the surge in productivity growth since 1995, but faster growth is not limited to these industries.

I conclude that the decline in IT prices will continue for some time. This will provide incentives for the ongoing substitution of IT for other productive inputs. Falling IT prices also serve as an indicator of rapid productivity growth in IT-producing industries. However, it would be premature to extrapolate the recent acceleration in productivity growth in these industries into the indefinite future, since this depends on the persistence of a two-year product cycle for semiconductors.

In section 1.4, I outline research opportunities created by the development and diffusion of information technology. A voluminous and rapidly expanding business literature is testimony to the massive impact of IT on firms and product markets. Highest priority must be given to a better understanding of the markets for semiconductors. Although several models of the market for semiconductors already exist, none explains the shift from a three-year to a two-year product cycle.

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.

1.1 The Information Age

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.

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 Laboratories 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]

1.1.1 Moore's Law

In 1965 Gordon E. Moore, then Research Director at Fairchild Semiconductor, made a prescient observation, later known as *Moore's Law*.[7] 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 thirty-five 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 twenty-nine year period the number of transistors increased by thirty-four percent per year. The rate of productivity growth for the U.S. economy during this period was slower by two orders of magnitude.

1.1.2 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 T. 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

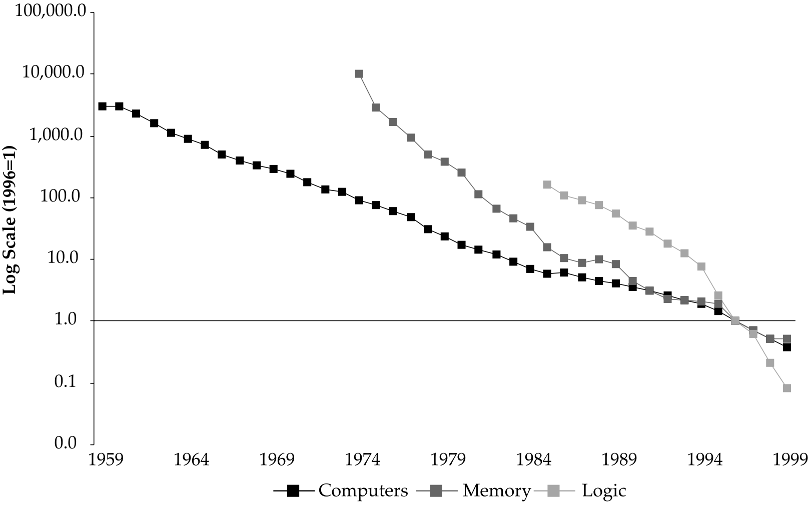

Figure 1.1
Relative prices of computers and semiconductors, 1959–1999. *Note:* All price indexes are divided by the output price index.

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 ninety 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.

1.1.3 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 R. Dulberger (1993) of IBM 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 [Irving] 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.

W. 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 preferences). 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.

Beginning in 1997, the U.S. 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 1994.

1.1.4 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.[12] 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. 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 C. 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.[13] In 1985 the Bureau of Economic Analysis incorporated constant quality price indexes for computers and peripheral equipment constructed by Rosanne Cole, Y. C. Chen, Joan A. Barquin-Stolleman, Ellen R. Dulberger, Nurthan Helvacian, and James H. Hodge (1986) of IBM into the NIPA. Jack E. Triplett (1986) discussed the economic interpretation of these indexes, bringing 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 F. 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 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) provided an exhaustive survey of research on hedonic price indexes for computers. Robert J. 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,

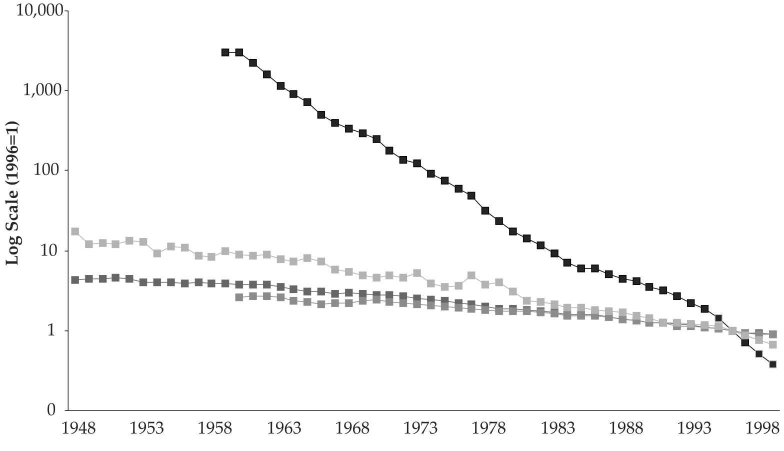

Figure 1.2
Relative prices of computers, communications, software, and services 1948–1999. *Note:* All price indexes are divided by the output price index.

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.

1.1.5 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.

Substantial 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.[16]

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, reclassified computer software as investment.[17] Before this important advance, business expenditures

Figure 1.3
Relative prices of computers, communications, and software, 1959–1999. *Note:* All price indexes are divided by the output price index.

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.

Robert P. Parker and Grimm (2000b) 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 (2000b) 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 Steven D. Oliner and Daniel E. 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.

BEA's prices for own-account 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 software prices are a weighted average of prepackaged and own-account software prices with arbitrary weights of 75 percent for own-account 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.

1.1.6 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 can only be filled by constant quality price indexes for all types of communications equipment.

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 another 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.

1.2 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 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. Unfortunately, evidence on the prices of communications equipment and software is seriously incomplete, so that the official price indexes are seriously misleading.

1.2.1 Output

The output data in table 1.1 are based on the most recent benchmark revision of the national accounts, updated through 1999.[19] 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 1.1 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 1.1 is $9.8 trillions in 1999, including imputations, and real output growth averaged 3.46 percent for the period 1948–1999. These magnitudes can be compared to the current dollar value of $9.3 trillions in 1999 and the average real growth rate of 3.40 percent for period 1948–1999 for the official GDP. Table 1.1 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 1.1 is the rapid price decline for computer investment, 17.1 percent per year from 1959 to 1995. Since 1995 this decline has almost doubled to 32.1 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 late 1980s. The price of communications equipment behaves similarly to the software price, while the consumption of capital services from computers and software by households and governments shows price declines similar to computer investment.

The top panel of table 1.2 summarizes the growth rates of prices and quantities for major output categories for 1990–1995 and 1995-1999. 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 1.4 shows that the output of software is the largest IT category as a share of GDP, followed by the outputs of computers and communications equipment.

1.2.2 Capital Services

This section presents capital estimates for the U.S. economy for the period 1948 to 1999.[20] 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 (1997), is based on the identification of

Table 1.1
Information technology output and Gross Domestic Product

	Computer		Software		Communi-cations		IT Services		Total IT		Gross Domestic Product	
Year	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price
1948					1.8	0.81	0.4	3.26	2.3	2.47	307.7	0.19
1949					1.7	0.81	0.4	2.19	2.0	2.29	297.0	0.18
1950					1.9	0.83	0.6	2.38	2.5	2.38	339.0	0.19
1951					2.2	0.86	0.8	2.30	3.0	2.43	370.6	0.19
1952					2.7	0.84	1.1	2.50	3.9	2.43	387.4	0.19
1953					3.0	0.80	1.5	2.56	4.5	2.38	418.2	0.20
1954					2.7	0.81	1.3	1.86	3.9	2.15	418.3	0.20
1955					3.0	0.81	1.8	2.25	4.7	2.30	461.3	0.20
1956					3.7	0.82	2.0	2.27	5.7	2.33	484.7	0.21
1957					4.3	0.85	1.9	1.79	6.2	2.22	503.6	0.21
1958					3.8	0.86	2.1	1.84	5.9	2.25	507.2	0.22
1959	0.0	662.98			4.7	0.86	2.7	2.14	7.4	2.37	551.9	0.22
1960	0.2	662.98	0.1	0.58	5.1	0.84	2.8	1.99	8.2	2.28	564.9	0.22
1961	0.3	497.23	0.2	0.59	5.6	0.82	2.8	1.88	9.0	2.19	581.8	0.22
1962	0.3	350.99	0.2	0.59	6.2	0.82	3.3	1.99	10.0	2.20	623.3	0.22
1963	0.8	262.69	0.5	0.59	6.2	0.81	3.3	1.81	10.8	2.08	666.9	0.23
1964	1.0	218.30	0.6	0.57	6.9	0.79	3.6	1.76	12.1	2.01	726.5	0.24
1965	1.3	179.45	0.9	0.58	8.1	0.78	4.7	1.99	15.0	2.03	795.1	0.25
1966	1.9	126.16	1.2	0.54	9.7	0.76	5.2	1.85	18.0	1.88	871.3	0.25
1967	2.1	102.41	1.5	0.58	10.7	0.76	5.0	1.50	19.3	1.75	918.2	0.26
1968	2.1	87.48	1.6	0.58	11.6	0.78	5.4	1.40	20.7	1.71	973.0	0.26
1969	2.7	79.16	2.3	0.63	13.0	0.79	5.8	1.31	23.8	1.70	1,045.8	0.27
1970	3.0	71.13	3.1	0.70	14.4	0.81	6.7	1.34	27.1	1.73	1,105.2	0.29
1971	3.1	54.17	3.2	0.69	14.7	0.83	8.1	1.47	29.0	1.73	1,178.8	0.30
1972	3.9	43.67	3.7	0.70	15.6	0.85	9.0	1.48	32.2	1.72	1,336.2	0.32
1973	3.9	41.39	4.3	0.72	18.2	0.86	12.1	1.78	38.4	1.82	1,502.5	0.34
1974	4.3	33.80	5.3	0.77	19.9	0.90	10.9	1.45	40.4	1.73	1,605.9	0.37
1975	4.0	31.27	6.6	0.83	21.3	0.96	12.0	1.46	43.9	1.79	1,785.8	0.41
1976	4.9	26.12	7.1	0.85	23.8	0.98	14.2	1.58	50.0	1.83	2,017.5	0.44
1977	6.3	22.72	7.5	0.87	28.1	0.97	22.5	2.28	64.4	2.02	2,235.7	0.46
1978	8.5	15.44	9.2	0.90	32.7	0.99	20.3	1.86	70.6	1.85	2,517.7	0.49
1979	11.4	12.81	11.9	0.94	38.4	1.02	26.5	2.18	88.2	1.92	2,834.9	0.54
1980	14.0	9.97	14.5	1.00	43.9	1.07	23.5	1.73	95.9	1.80	2,964.5	0.57
1981	19.2	8.75	17.8	1.08	48.6	1.13	22.4	1.46	108.0	1.76	3,285.2	0.62
1982	22.0	7.80	21.1	1.12	50.9	1.17	25.6	1.49	119.5	1.77	3,445.4	0.66
1983	28.8	6.44	24.9	1.13	55.0	1.17	29.5	1.50	138.1	1.71	3,798.8	0.70
1984	37.4	5.24	30.4	1.15	62.9	1.18	33.3	1.44	163.9	1.63	4,288.1	0.74

Table 1.1 (continued)

	Computer		Software		Communi-cations		IT Services		Total IT		Gross Domestic Product	
Year	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price
1985	39.6	4.48	35.2	1.15	69.9	1.17	38.5	1.44	183.1	1.57	4,542.6	0.75
1986	45.9	4.45	38.5	1.13	72.7	1.17	42.7	1.36	199.7	1.54	4,657.4	0.74
1987	48.6	3.93	43.7	1.14	74.9	1.15	50.3	1.37	217.5	1.50	5,078.1	0.78
1988	54.1	3.72	51.2	1.15	82.1	1.14	59.3	1.40	246.7	1.48	5,652.0	0.83
1989	56.9	3.52	61.4	1.13	85.1	1.13	63.0	1.31	266.3	1.43	5,988.8	0.85
1990	52.4	3.09	69.3	1.12	86.5	1.12	68.5	1.28	276.6	1.38	6,284.9	0.88
1991	52.6	2.85	78.2	1.13	83.9	1.12	67.5	1.13	282.2	1.32	6,403.3	0.90
1992	54.9	2.44	83.9	1.06	88.1	1.11	77.3	1.15	304.1	1.27	6,709.9	0.92
1993	54.8	2.02	95.5	1.06	92.6	1.09	84.7	1.11	327.6	1.21	6,988.8	0.93
1994	57.6	1.80	104.6	1.04	102.6	1.07	96.6	1.12	361.4	1.17	7,503.9	0.96
1995	70.5	1.41	115.7	1.03	112.4	1.03	108.7	1.10	407.2	1.11	7,815.3	0.97
1996	78.3	1.00	131.0	1.00	120.1	1.00	115.1	1.00	444.5	1.00	8,339.0	1.00
1997	86.0	0.73	158.1	0.97	131.5	0.98	123.0	0.90	498.7	0.91	9,009.4	1.04
1998	86.9	0.53	193.3	0.94	140.4	0.95	131.9	0.79	552.5	0.82	9,331.1	1.03
1999	92.4	0.39	241.2	0.94	158.1	0.92	140.9	0.69	632.6	0.75	9,817.4	1.04

Notes: Values are in billions of current dollars. Prices are normalized to one in 1996. Information technology output is gross domestic product by type of product.

service prices with marginal products of different types of capital. The service price estimates incorporate the cost of capital.[21]

The cost of capital is an annualization factor that transforms the price of an asset into the price of the corresponding capital input.[22] 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,[23] due to the astonishing decline of IT prices given in table 1.1.

The cost of capital is important in many areas of economics, especially in modeling producer behavior, productivity measurement, and the economics of taxation.[24] 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.[25]

The second empirical issue is the measurement of economic depreciation. The stability of patterns of depreciation in the face of changes in tax

Table 1.2
Growth rates of outputs and inputs

	1990–1995		1995–1999	
	Prices	Quantities	Prices	Quantities
		Outputs		
Gross domestic product	1.99	2.36	1.62	4.08
Information technology	−4.42	12.15	−9.74	20.75
Computers	−15.77	21.71	−32.09	38.87
Software	−1.62	11.86	−2.43	20.80
Communications equipment	−1.77	7.01	−2.90	11.42
Information technology services	−2.95	12.19	−11.76	18.24
Non-information technology investment	2.15	1.22	2.20	4.21
Non-information technology consumption	2.35	2.06	2.31	2.79
		Inputs		
Gross domestic income	2.23	2.13	2.36	3.33
Information technology capital services	−2.70	11.51	−10.46	19.41
Computer capital services	−11.71	20.27	−24.81	36.36
Software capital services	−1.83	12.67	−2.04	16.30
Communications equipment capital services	2.18	5.45	−5.90	8.07
Non-information technology capital services	1.53	1.72	2.48	2.94
Labor services	3.02	1.70	3.39	2.18

Note: Average annual percentage rates of growth.

policy and price shocks has been carefully documented. The depreciation rates presented by Jorgenson and Kevin J. Stiroh (2000b) summarize a large body of empirical research on the behavior of asset prices.[26] 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.[27]

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,

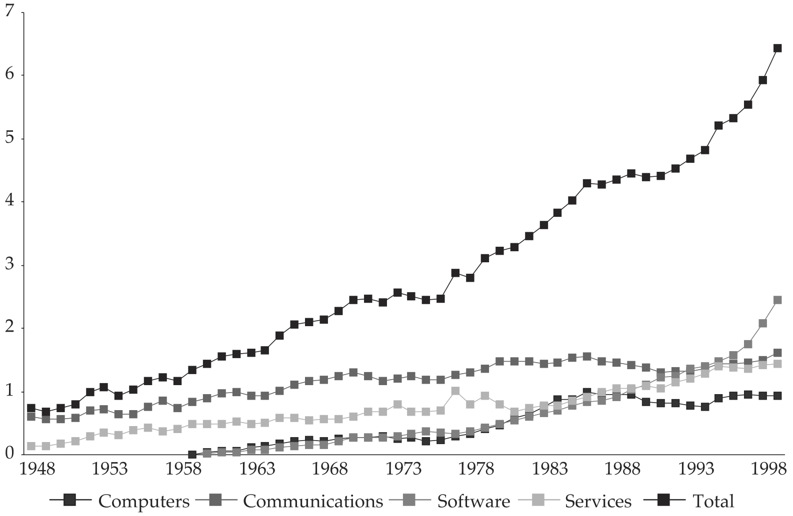

Figure 1.4
Output shares of information technology by type, 1948–1999. *Note:* Percent of current dollar gross domestic product.

along with household and government IT capital services, in order to capture the full impact of IT on the U.S. economy.

Table 1.3 gives capital stocks from 1948 to 1999, 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 1.3 is $35.4 trillions in 1999, considerably greater than the $27.9 trillions in fixed capital estimated by Shelby W. Herman (2000) of BEA. The most important differences reflect the inclusion of inventories and land in table 1.3.

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 combined account for only 4.35 percent of domestic tangible capital stock in 1999. Table 1.4 presents estimates of the flow of capital services and corresponding price indexes for 1948–1999.

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

Table 1.3
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					4.7	0.81	4.7	1.37	711.7	0.13
1949					5.9	0.82	5.9	1.37	750.5	0.13
1950					7.3	0.84	7.3	1.41	824.5	0.13
1951					9.0	0.87	9.0	1.46	948.1	0.14
1952					10.6	0.84	10.6	1.41	1,017.5	0.14
1953					12.2	0.81	12.2	1.36	1,094.9	0.15
1954					13.7	0.81	13.7	1.37	1,146.9	0.15
1955					15.2	0.81	15.2	1.36	1,238.4	0.15
1956					17.5	0.82	17.5	1.38	1,373.2	0.16
1957					20.7	0.86	20.7	1.44	1,494.1	0.17
1958					22.5	0.86	22.5	1.45	1,562.3	0.17
1959	0.2	752.87	0.1	0.54	24.7	0.86	25.0	1.45	1,655.7	0.18
1960	0.2	752.87	0.1	0.54	26.5	0.84	26.8	1.42	1,755.3	0.18
1961	0.5	564.66	0.3	0.55	28.8	0.83	29.5	1.39	1,854.8	0.18
1962	0.6	398.58	0.4	0.55	31.7	0.83	32.7	1.38	1,982.7	0.19
1963	1.1	298.31	0.8	0.56	33.8	0.81	35.7	1.34	2,088.5	0.19
1964	1.6	247.90	1.1	0.55	36.4	0.79	39.1	1.31	2,177.3	0.19
1965	2.2	203.79	1.6	0.55	40.0	0.78	43.8	1.28	2,315.4	0.20
1966	2.9	143.27	2.3	0.52	44.5	0.76	49.7	1.22	2,512.1	0.20
1967	3.7	116.30	3.2	0.56	50.8	0.77	57.6	1.22	2,693.3	0.21
1968	4.3	99.34	3.8	0.56	57.7	0.79	65.7	1.23	2,986.0	0.22
1969	5.3	89.90	5.1	0.61	65.4	0.80	75.7	1.25	3,319.1	0.24
1970	6.2	80.77	7.0	0.68	74.4	0.83	87.5	1.29	3,595.0	0.25
1971	6.3	61.52	7.9	0.67	82.1	0.84	96.3	1.28	3,922.6	0.26
1972	7.3	49.59	9.1	0.67	90.6	0.86	107.0	1.29	4,396.8	0.28
1973	8.6	47.00	10.7	0.69	99.9	0.88	119.2	1.31	4,960.3	0.31
1974	9.1	38.38	13.2	0.75	112.8	0.91	135.0	1.35	5,391.6	0.32
1975	9.7	35.51	16.3	0.80	128.7	0.98	154.6	1.43	6,200.5	0.36
1976	10.4	29.66	18.3	0.82	142.1	1.01	170.7	1.45	6,750.0	0.38
1977	12.4	25.81	20.4	0.84	152.3	0.99	185.1	1.42	7,574.4	0.41
1978	14.1	17.46	23.5	0.87	171.8	1.02	209.4	1.42	8,644.9	0.46
1979	19.3	14.47	28.7	0.91	195.0	1.04	243.0	1.43	9,996.7	0.51
1980	24.2	11.27	35.3	0.97	225.7	1.09	285.2	1.47	11,371.0	0.56
1981	33.6	9.90	43.6	1.04	260.9	1.15	338.1	1.53	13,002.5	0.63
1982	42.4	8.84	52.0	1.08	290.0	1.19	384.3	1.55	13,964.7	0.66
1983	52.6	7.32	60.6	1.09	314.3	1.20	427.5	1.53	14,526.0	0.68
1984	66.2	5.95	72.3	1.11	344.8	1.20	483.3	1.50	15,831.0	0.71

Table 1.3 (continued)

	Computer		Software		Communications		Total IT		Total domestic tangible assets	
Year	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price
1985	77.7	5.08	84.2	1.11	375.0	1.20	537.0	1.46	17,548.6	0.77
1986	86.0	4.34	94.9	1.10	404.3	1.18	585.1	1.41	18,844.3	0.80
1987	94.1	3.71	108.5	1.11	434.8	1.17	637.4	1.37	20,216.2	0.84
1988	107.2	3.45	125.2	1.12	467.7	1.16	700.0	1.35	21,880.1	0.89
1989	121.0	3.23	144.4	1.11	499.7	1.15	765.1	1.33	23,618.7	0.93
1990	122.3	2.89	165.2	1.10	527.1	1.14	814.5	1.29	24,335.1	0.94
1991	124.6	2.58	189.9	1.10	548.3	1.13	862.8	1.27	24,825.7	0.95
1992	128.2	2.17	203.8	1.04	569.7	1.11	901.7	1.21	25,146.8	0.95
1993	135.6	1.82	231.8	1.05	589.5	1.10	956.9	1.17	25,660.4	0.95
1994	150.4	1.61	255.8	1.02	612.8	1.07	1,019.0	1.13	26,301.0	0.95
1995	170.3	1.33	286.7	1.03	634.1	1.03	1,091.1	1.07	27,858.4	0.98
1996	181.6	1.00	318.1	1.00	659.3	1.00	1,158.9	1.00	29,007.9	1.00
1997	198.7	0.76	365.2	0.97	695.8	0.98	1,259.7	0.94	30,895.3	1.04
1998	210.0	0.55	431.2	0.95	730.9	0.94	1,372.1	0.87	32,888.5	1.07
1999	232.4	0.41	530.6	0.95	778.5	0.90	1,541.5	0.81	35,406.9	1.11

Notes: Values are in billions of current dollars. Prices are normalized to one in 1996. Domestic tangible assets include fixed assets and consumer durable goods, land, and inventories.

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 twenty percent of capital input growth for the period 1948–1995. However, improvements in capital quality have increased steadily in relative importance. These improvements jumped to 44.9 percent of total growth in capital input during the period 1995–1999 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 1.5 gives the IT capital service flows as a share of gross domestic income. The second panel of table 1.2 summarizes the growth rates of prices and quantities of capital inputs for 1990–1955 and 1995–1999. Growth of IT capital services jumps from 11.51 percent per year in 1990–1995 to 19.41 percent in 1995–1999, while growth of non-IT capital services increases from 1.72 percent to 2.94 percent. This reverses the trend toward slower capital growth through 1995.

Table 1.4
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	1.20	1.7	4.31	307.7	0.14
1949					1.3	0.79	1.3	2.83	297.0	0.14
1950					1.8	0.91	1.8	3.27	339.0	0.15
1951					2.1	0.90	2.1	3.21	370.6	0.15
1952					2.6	0.94	2.6	3.36	387.4	0.15
1953					3.2	0.96	3.2	3.46	418.2	0.15
1954					2.7	0.70	2.7	2.49	418.3	0.15
1955					3.6	0.85	3.6	3.05	461.3	0.16
1956					4.2	0.87	4.2	3.12	484.7	0.17
1957					3.7	0.68	3.7	2.44	503.6	0.17
1958					4.1	0.68	4.1	2.45	507.2	0.17
1959	0.2	444.36	0.1	0.63	5.2	0.80	5.5	2.87	551.9	0.18
1960	0.2	433.59	0.1	0.62	5.4	0.75	5.6	2.68	564.9	0.18
1961	0.3	637.21	0.1	0.58	5.6	0.71	6.0	2.59	581.8	0.18
1962	0.4	508.68	0.2	0.62	6.6	0.76	7.2	2.71	623.3	0.19
1963	0.6	311.81	0.3	0.58	6.5	0.67	7.3	2.34	666.9	0.20
1964	0.8	211.28	0.4	0.60	7.1	0.67	8.3	2.26	726.5	0.21
1965	1.3	182.17	0.6	0.59	9.1	0.78	11.0	2.52	795.1	0.22
1966	2.2	173.57	1.0	0.64	9.6	0.73	12.8	2.40	871.3	0.23
1967	2.3	110.97	1.1	0.50	9.8	0.66	13.2	2.01	918.2	0.23
1968	2.6	87.05	1.6	0.60	10.2	0.61	14.5	1.86	973.0	0.24
1969	2.8	68.23	1.7	0.52	11.3	0.61	15.8	1.76	1,045.8	0.25
1970	3.6	65.38	2.3	0.56	13.3	0.65	19.1	1.83	1,105.2	0.26
1971	5.2	72.48	3.7	0.77	14.9	0.67	23.9	1.99	1,178.8	0.27
1972	4.9	48.57	4.0	0.71	16.6	0.69	25.4	1.85	1,336.2	0.30
1973	4.4	33.06	4.5	0.71	22.8	0.88	31.7	2.04	1,502.5	0.32
1974	6.6	38.82	5.1	0.70	20.3	0.72	32.0	1.84	1,605.9	0.34
1975	5.9	28.43	6.7	0.80	23.2	0.77	35.7	1.85	1,785.8	0.37
1976	6.6	26.07	7.7	0.81	25.0	0.78	39.2	1.84	2,017.5	0.41
1977	7.0	20.69	8.4	0.82	41.8	1.20	57.2	2.40	2,235.7	0.44
1978	11.8	22.49	9.7	0.86	35.5	0.93	57.0	2.07	2,517.7	0.47
1979	11.6	13.33	11.6	0.90	47.9	1.14	71.1	2.15	2,834.9	0.51
1980	16.6	11.81	13.6	0.91	42.0	0.90	72.2	1.82	2,964.5	0.53
1981	17.7	7.89	15.5	0.90	40.5	0.79	73.6	1.53	3,285.2	0.58
1982	19.6	5.93	17.6	0.89	43.1	0.77	80.3	1.41	3,445.4	0.60
1983	26.4	5.46	20.6	0.91	49.4	0.82	96.4	1.43	3,798.8	0.66
1984	36.1	4.87	25.4	0.96	54.3	0.83	115.7	1.41	4,288.1	0.71

Table 1.4 (continued)

	Computer		Software		Communications		Total IT		Gross domestic income	
Year	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price
1985	39.6	3.70	30.6	0.99	63.1	0.89	133.3	1.35	4,542.6	0.73
1986	43.1	3.04	35.3	0.99	69.3	0.89	147.6	1.27	4,657.4	0.73
1987	53.4	2.93	42.1	1.04	86.5	1.02	181.9	1.36	5,078.1	0.77
1988	52.7	2.31	50.5	1.10	104.1	1.14	207.3	1.36	5,652.0	0.81
1989	57.6	2.08	60.4	1.13	105.8	1.07	223.8	1.29	5,988.8	0.84
1990	64.7	2.01	67.2	1.08	109.8	1.04	241.7	1.25	6,284.9	0.86
1991	64.2	1.76	70.8	1.00	104.2	0.93	239.2	1.12	6,403.3	0.88
1992	71.7	1.66	89.9	1.11	112.2	0.96	273.7	1.16	6,709.9	0.91
1993	77.8	1.45	90.4	0.98	126.9	1.03	295.1	1.11	6,988.8	0.92
1994	80.1	1.19	109.5	1.05	142.4	1.10	331.9	1.10	7,503.9	0.96
1995	99.3	1.12	115.5	0.99	160.7	1.16	375.6	1.09	7,815.3	0.96
1996	123.6	1.00	131.9	1.00	149.0	1.00	404.5	1.00	8,339.0	1.00
1997	134.7	0.76	156.2	1.02	157.1	0.98	448.1	0.92	9,009.4	1.04
1998	152.5	0.59	178.2	0.97	162.0	0.93	492.6	0.82	9,331.1	1.04
1999	157.7	0.42	204.4	0.91	175.3	0.91	537.4	0.72	9,817.4	1.06

Note: Values are in billions of current dollars. Prices are normalized to one in 1996.

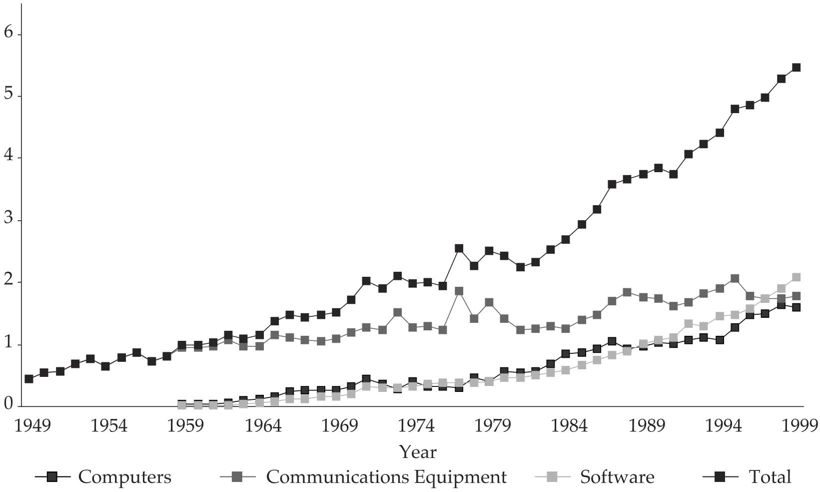

Figure 1.5
Input shares of information technology by type, 1948–1999. *Note:* Percent of current dollar domestic income.

1.2.3 Labor Services

This section presents estimates of labor input for the U.S. economy from 1948 to 1999. 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 work force across sex, employment class, age, and education levels. This follows the approach of Jorgenson, Frank M. Gollop, and Barbara M. Fraumeni (1987). The estimates have been revised and updated by Mun S. Ho and Jorgenson (2000).[28]

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 1.5 presents estimates of labor input, hours worked, and labor quality.

The value of labor expenditures in table 1.5 is $5.8 trillions in 1999, 59.3 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 1.2, the growth rate of labor input accelerated to 2.18 percent for 1995–1999 from 1.70 percent for 1990–1995. This is primarily due to the growth of hours worked, which rose from 1.17 percent for 1990–1995 to 1.98 percent for 1995–1999, as labor force participation increased and unemployment rates plummeted.

The growth of labor quality has declined considerably in the late 1990s, dropping from 0.53 percent for 1990–1995 to 0.20 percent for 1995–1999. This slowdown captures well-known demographic trends in the composition of the work force, 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.

1.3 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 1948–1999 and various subperiods. An important objective is to account for the sharp acceleration in the level of economic activity 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 now 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.

1.3.1 Production Possibility Frontier

The *production possibility frontier* describes efficient combinations of outputs and inputs for the economy as a whole.[29] 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:

$$Y(I_n, I_c, I_s, I_t, C_n, C_c) = A \cdot X(K_n, K_c, K_t, L), \tag{1.1}$$

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] *Total factor productivity* (TFP) is denoted by A.

Table 1.5
Labor Services

	Labor Services							
Year	Price	Quantity	Value	Quality	Employment	Weekly hours	Hourly compensation	Hours worked
1948	0.08	1,924.6	156.1	0.75	61,536	39.1	1.2	125,127
1949	0.09	1,860.0	171.5	0.75	60,437	38.5	1.4	121,088
1950	0.09	1,961.0	179.2	0.76	62,424	38.5	1.4	125,144
1951	0.10	2,133.0	214.4	0.78	66,169	38.7	1.6	133,145
1952	0.10	2,197.2	227.2	0.79	67,407	38.5	1.7	135,067
1953	0.11	2,254.3	241.8	0.80	68,471	38.3	1.8	136,331
1954	0.11	2,190.3	243.9	0.81	66,843	37.8	1.9	131,477
1955	0.11	2,254.9	256.7	0.81	68,367	37.8	1.9	134,523
1956	0.12	2,305.0	275.0	0.82	69,968	37.5	2.0	136,502
1957	0.13	2,305.1	295.5	0.83	70,262	37.0	2.2	135,189
1958	0.14	2,245.3	309.1	0.83	68,578	36.7	2.4	130,886
1959	0.14	2,322.1	320.1	0.84	70,149	36.8	2.4	134,396
1960	0.15	2,352.2	344.1	0.84	71,128	36.5	2.5	135,171
1961	0.15	2,378.5	355.0	0.86	71,183	36.3	2.6	134,451
1962	0.15	2,474.1	376.7	0.87	72,673	36.4	2.7	137,612
1963	0.15	2,511.4	386.2	0.88	73,413	36.4	2.8	139,050
1964	0.16	2,578.1	417.6	0.88	74,990	36.3	3.0	141,447
1965	0.17	2,670.6	451.9	0.89	77,239	36.3	3.1	145,865
1966	0.18	2,788.5	500.3	0.89	80,802	36.0	3.3	151,448
1967	0.19	2,842.4	525.5	0.90	82,645	35.7	3.4	153,345
1968	0.20	2,917.0	588.3	0.91	84,733	35.5	3.8	156,329
1969	0.22	2,992.1	646.6	0.91	87,071	35.4	4.0	160,174
1970	0.23	2,938.6	687.3	0.91	86,867	34.9	4.4	157,488
1971	0.26	2,924.9	744.5	0.90	86,715	34.8	4.7	156,924
1972	0.27	3,011.7	817.6	0.91	88,838	34.8	5.1	160,873
1973	0.29	3,135.0	909.4	0.91	92,542	34.8	5.4	167,271
1974	0.31	3,148.2	988.5	0.91	94,121	34.2	5.9	167,425
1975	0.35	3,082.9	1,063.9	0.92	92,575	33.8	6.5	162,879
1976	0.38	3,174.4	1,194.0	0.92	94,922	33.9	7.1	167,169
1977	0.41	3,277.4	1,334.5	0.92	98,202	33.8	7.7	172,780
1978	0.44	3,430.3	1,504.2	0.92	102,931	33.8	8.3	180,842
1979	0.47	3,554.7	1,673.2	0.92	106,463	33.7	9.0	186,791
1980	0.52	3,535.7	1,827.9	0.92	107,061	33.3	9.9	185,591
1981	0.55	3,563.8	1,968.8	0.93	108,050	33.2	10.6	186,257
1982	0.60	3,519.7	2,096.3	0.93	106,749	32.9	11.5	182,772
1983	0.63	3,586.7	2,269.8	0.94	107,810	33.1	12.2	185,457
1984	0.66	3,786.7	2,499.1	0.94	112,604	33.2	12.9	194,555

Table 1.5 (continued)

	Labor Services							
Year	Price	Quantity	Value	Quality	Employment	Weekly hours	Hourly compensation	Hours worked
1985	0.69	3,882.9	2,679.0	0.95	115,205	33.1	13.5	198,445
1986	0.75	3,926.3	2,931.1	0.95	117,171	32.9	14.6	200,242
1987	0.74	4,075.1	3,019.7	0.96	120,474	32.9	14.6	206,312
1988	0.75	4,207.7	3,172.2	0.96	123,927	32.9	15.0	211,918
1989	0.80	4,348.4	3,457.8	0.97	126,755	33.0	15.9	217,651
1990	0.84	4,381.5	3,680.8	0.97	128,341	32.9	16.8	219,306
1991	0.88	4,322.0	3,800.2	0.98	127,080	32.5	17.7	214,994
1992	0.94	4,353.9	4,086.9	0.98	127,238	32.6	19.0	215,477
1993	0.96	4,497.4	4,297.7	0.99	129,770	32.8	19.5	221,003
1994	0.96	4,628.3	4,453.1	0.99	132,799	32.9	19.6	226,975
1995	0.98	4,770.7	4,660.5	1.00	135,672	33.0	20.0	232,545
1996	1.00	4,861.7	4,861.7	1.00	138,018	32.8	20.6	235,798
1997	1.03	4,987.9	5,122.0	1.00	141,184	33.0	21.1	242,160
1998	1.08	5,108.8	5,491.5	1.00	144,305	33.0	22.2	247,783
1999	1.12	5,204.8	5,823.4	1.00	147,036	32.9	23.1	251,683

Notes: Value is in billions of current dollars. Quantity is in billions of 1996 dollars. Price and quality are normalized to one in 1996. 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.

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.

1.3.2 Aggregate Production Function

The aggregate production function employed by Robert M. Solow (1957, 1960) and, more recently, by Jeremy Greenwood, Zvi Hercowitz, and Per Krusell (1997, 2000), Hercowitz (1998), and Arnold C. 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.

Greenwood, Hercowitz, and Krusell employ a price index for consumption to deflate the output of all investment goods, including information technology. Confronted by the fact that constant quality prices of investment goods differ from consumption goods prices, they borrow the concept of *embodiment* from Solow (1960) in order to convert investment goods output into an appropriate form for measuring capital stock.[31] Investment has two prices, one used in the measuring output and the other used in measuring capital stock. This inconsistency can be removed by simply distinguishing between outputs of consumption and investment goods, as in the national accounts and equation (1.1). The concept of embodiment can then be dropped.

Perhaps inadvertently, Greenwood, Hercowitz, and Krusell have revisited the controversy accompanying the introduction of a constant quality price index for computers into the national accounts. They have revived Denison's (1993) proposal to use a consumption price index to deflate investment in the NIPA. Denison found this appealing as a means of avoiding the introduction of constant quality price indexes for computers. Denison's approach leads to a serious underestimate of GDP growth and an overestimate of inflation.

Another limitation of the aggregate production function is that it fails to incorporate costs of adjustment. Robert E. Lucas, Jr. (1967) presented a production model with internal costs of adjustment. Fumio Hayashi (2000) shows how to identify these adjustment costs from James Tobin's (1969) *Q*-ratio, the ratio of the stock market value of the producing unit to the market value of the unit's assets. Implementation of this approach requires simultaneous modeling of production and asset valuation. If costs of adjustment are external, as in the production possibility frontier (1.1), asset valuation can be modeled separately from production.[32]

1.3.3 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:

$$\begin{aligned}
&\overline{w}_{I,n}\Delta \ln I_n + \overline{w}_{I,c}\Delta \ln I_c + \overline{w}_{I,s}\Delta \ln I_s + \overline{w}_{I,t}\Delta \ln I_t + \overline{w}_{C,n}C_n + \overline{w}_{C,c}\Delta \ln C_c \\
&\quad = \overline{v}_{K,n}\Delta \ln K_n + \overline{v}_{K,c}\Delta \ln K_c + \overline{v}_{K,s}\Delta \ln K_s \\
&\qquad + \overline{v}_{K,t}\Delta \ln K_t + \overline{v}_{L}\Delta \ln L + \Delta \ln A
\end{aligned} \tag{1.2}$$

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

$$\begin{aligned}
&\overline{w}_{I,n} + \overline{w}_{I,c} + \overline{w}_{I,s} + \overline{w}_{I,t} + \overline{w}_{C,n} + \overline{w}_{C,c} \\
&\quad = \overline{v}_{K,n} + \overline{v}_{K,c} + \overline{v}_{K,s} + \overline{v}_{K,t} + \overline{v}_{L} = 1.
\end{aligned}$$

Equation (1.2) makes it possible to identify the contributions of outputs as well as inputs to U.S. economic growth. 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 TFP, the growth rate of the augmentation factor A in equation (1.2), is the difference between growth rates of output and input.

Table 1.6 presents results of a growth accounting decomposition, based on equation (1.2), for the period 1948–1999 and various subperiods, 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.

Rearranging equation (1.2), the results can 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:

$$\Delta \ln y = \overline{v}_K \Delta \ln k + \overline{v}_L(\Delta \ln L - \Delta \ln H) + \Delta \ln A. \tag{1.3}$$

Table 1.6
Sources of Gross Domestic Product growth

	1948–1999	1948–1973	1973–1990	1990–1995	1995–1999
			Outputs		
Gross domestic product	3.46	3.99	2.86	2.36	4.08
Contribution of information technology	0.40	0.20	0.46	0.57	1.18
Computers	0.12	0.04	0.16	0.18	0.36
Software	0.08	0.02	0.09	0.15	0.39
Commmunications equipment	0.10	0.08	0.10	0.10	0.17
Information technology services	0.10	0.06	0.10	0.15	0.25
Contribution of non-information technology	3.06	3.79	2.40	1.79	2.91
Contribution of non-information technology investment	0.72	1.06	0.34	0.23	0.83
Contribution of non-information technology consumption	2.34	2.73	2.06	1.56	2.08
			Inputs		
Gross domestic income	2.84	3.07	2.61	2.13	3.33
Contribution of information technology capital services	0.34	0.16	0.40	0.48	0.99
Computers	0.15	0.04	0.20	0.22	0.55
Software	0.07	0.02	0.08	0.16	0.29
Communications equipment	0.11	0.10	0.12	0.10	0.14
Contribution of non-information technology capital services	1.36	1.77	1.05	0.61	1.07
Contribution of labor services	1.14	1.13	1.16	1.03	1.27
Total factor productivity	0.61	0.92	0.25	0.24	0.75

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

Equation (1.3) 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 rising proportion of hours by workers with higher marginal products. The third is TFP growth, which contributes point-for-point to ALP growth.

1.3.4 Contributions of IT Investment

Figure 1.5 depicts the rapid increase in the importance of IT services, reflecting the accelerating pace of IT price declines. In 1995–1999 the capital service price for computers fell 24.81 percent per year, compared to an increase of 36.36 percent in capital input from computers. As a consequence, the value of computer services grew substantially. However, the current dollar value of computers was only 1.6 percent of gross domestic income in 1999.

The rapid accumulation of software appears to have different sources. The price of software services has declined only 2.04 percent per year for 1995–1999. Nonetheless, firms have been accumulating software very rapidly, with real capital services growing 16.30 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 1995–1999 is comparable to 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 1.6 and 1.7 highlight the rising contributions of IT outputs to U.S. economic growth. Figure 1.6 shows the breakdown between IT and non-IT outputs for subperiods from 1948 to 1999, while figure 1.7 decomposes the contribution of IT into its components. Although the importance of IT has steadily increased, figure 1.6 shows that the recent investment and consumption surge nearly doubled the output contribution of IT. Figure 1.7 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.

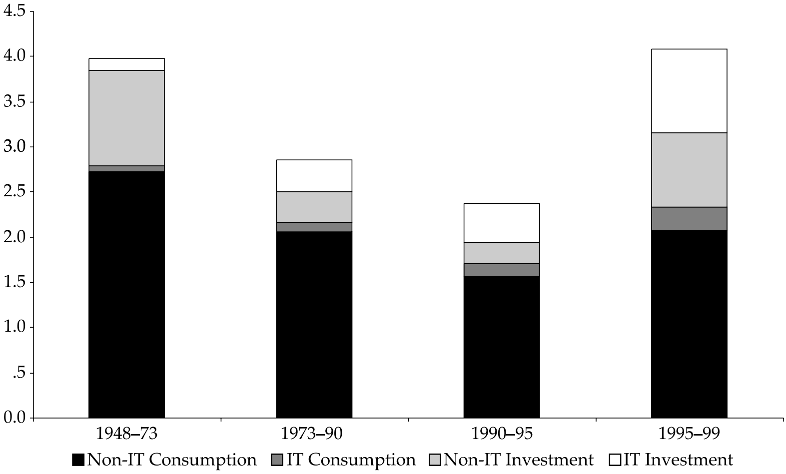

Figure 1.6
Output contribution of information technology. *Note:* Output contributions are the average annual (percentage) growth rates, weighted by the output shares.

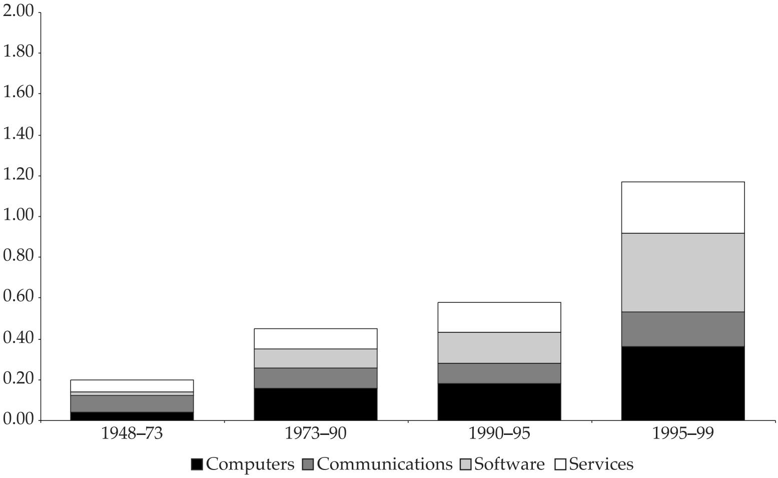

Figure 1.7
Output contribution of information technology by type. *Note:* Output contributions are the average annual (percentage) growth rates, weighted by the output shares.

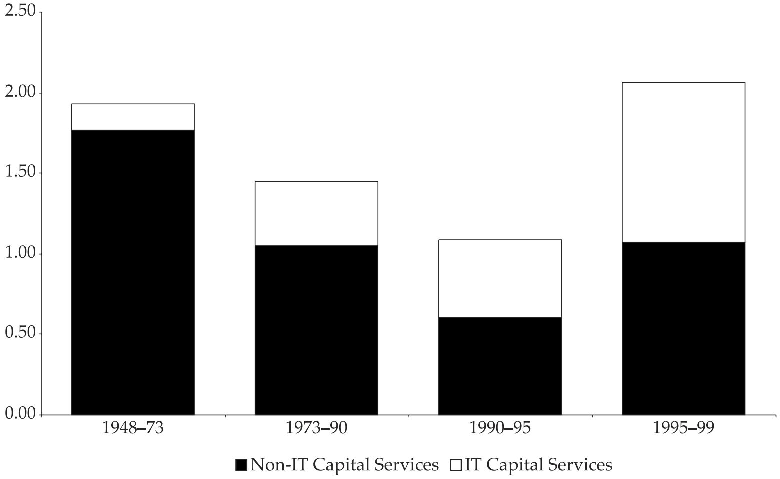

Figure 1.8
Capital input contribution of information technology. *Note:* Input contributions are the average annual (percentage) growth rates, weighted by the income shares.

Figures 1.8 and 1.9 present a similar decomposition of IT inputs into production. The contribution of these inputs is rising even more dramatically. Figure 1.8 shows that the contribution of IT now accounts for more than 48.1 percent of the total contribution of capital input. Figure 1.9 shows that computer hardware is the largest IT contributor on the input side, 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 (1999, 2000b).[33] 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 1.2 shows that the price of computer investment fell by more than 32 percent per year, the price of software 2.4 percent, and the price of communications equipment 2.9 percent, and the price of IT services 11.8 percent during the period 1995–1999, while non-IT prices rose 2.2 percent. In response to these price changes, firms, households, and

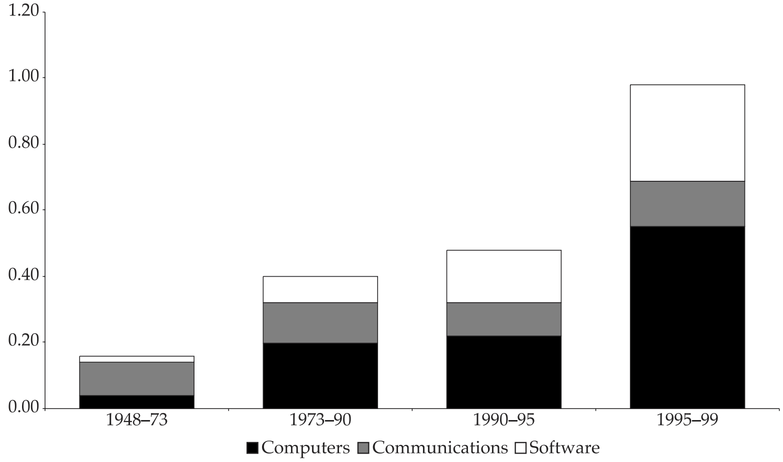

Figure 1.9
Capital input contribution of information technology by type. *Note:* Input contributions are the average annual (percentage) growth rates, weighted by the income shares.

governments have accumulated computers, software, and communications equipment much more rapidly than other forms of capital.

1.3.5 Total Factor Productivity

The price or "dual" approach to productivity measurement makes it possible to identify the role of IT production as a source of productivity growth at the industry level.[34] 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.[35]

Jorgenson, Gollop, and Fraumeni (1987) have employed Evsey Domar's (1961) model to trace aggregate productivity growth to its sources at the level of individual industries.[36] More recently, Harberger (1998), William Gullickson and Michael J. 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 TFP growth.

If semiconductor output were only used to produce computers, then its contribution to computer industry productivity growth, weighted by computer industry output, would precisely cancel its independent contribution to aggregate TFP growth. 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 1.7 reports details of this TFP decomposition for 1990–1995 and 1995–1999; the IT and non-IT contributions are presented in figure 1.10. The IT products contribute 0.50 percentage points to TFP growth for

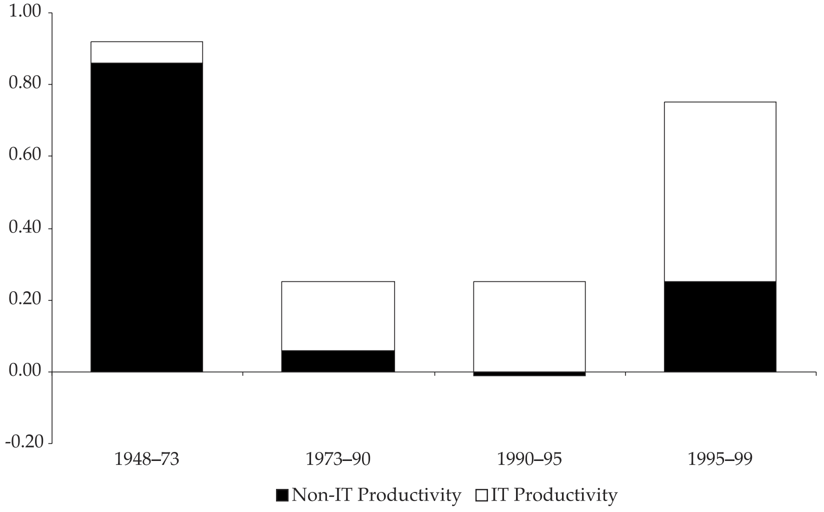

Figure 1.10
Contributions of information technology to total factor productivity growth. *Note:* Contributions are average annual (percentage) relative price changes, weighted by average nominal output shares from table 1.7.

Table 1.7
Sources of total factor productivity growth

	1948–99	1948–73	1973–90	1990–95	1995–99
Total factor productivity growth	0.61	0.92	0.25	0.24	0.75
	Contributions to TFP Growth				
Information technology	0.16	0.06	0.19	0.25	0.50
Computers	0.09	0.02	0.12	0.15	0.32
Software	0.02	0.00	0.02	0.05	0.09
Communications equipment	0.05	0.03	0.06	0.05	0.08
Non-information technology	0.45	0.86	0.06	−0.01	0.25
	Relative Price Changes				
Information technology	−6.16	−4.3	−7.4	−7.2	−11.5
Computers	−23.01	−23.5	−21.1	−18.0	−34.5
Software	−3.29	−3.0	−3.2	−3.9	−4.8
Communications equipment	−3.71	−3.1	−4.2	−4.0	−5.3
Non-information technology	−0.41	−0.9	0.0	0.1	−0.1
	Average Nominal Shares				
Information technology	2.07	1.09	2.60	3.46	4.26
Computers	0.40	0.10	0.61	0.81	0.94
Software	0.51	0.08	0.60	1.30	1.84
Communications equipment	1.16	0.91	1.39	1.34	1.48
Non-information technology	97.20	98.46	96.55	95.35	94.35

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.

1995–1999, compared to 0.25 percentage points for 1990–1995. This reflects the accelerating decline in relative price changes resulting from shortening the product cycle for semiconductors.

1.3.6 Output Growth

This subsection presents the sources of GDP growth for the entire period 1948 to 1999. Capital services contribute 1.70 percentage points, labor services 1.14 percentage points, and TFP growth only 0.61 percentage points. Input growth is the source of nearly 82.3 percent of U.S. growth over the past half century, while TFP has accounted for 17.7 percent. Figure 1.11 shows the relatively modest contributions of TFP in all subperiods.

More than three quarters of the contribution of capital reflects the accumulation of capital stock, while improvement in the quality of

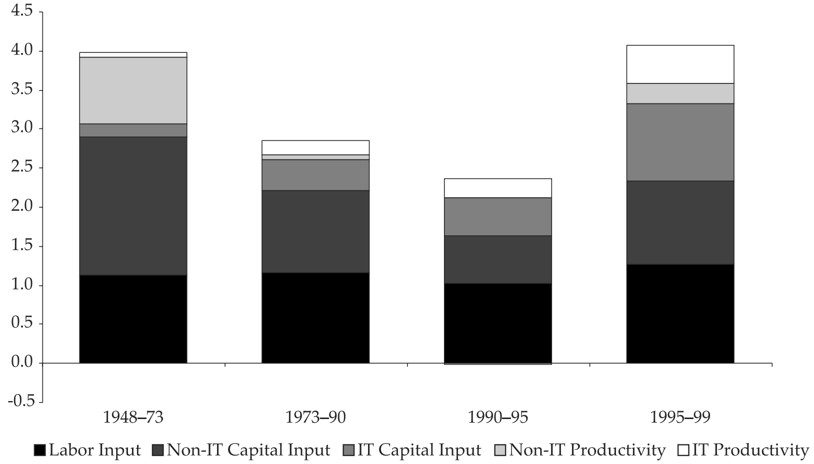

Figure 1.11
Sources of gross domestic product growth. *Notes:* Input contributions are average annual (percentage) rates of growth, weighted by average nominal income shares from table 1.6. Productivity contributions are from table 1.7.

capital accounts for about one quarter. Similarly, increased labor hours account for 80 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 TFP growth in the 1950s, 1960s and early 1970s, the U.S. economy slowed markedly through 1990, with output growth falling from 3.99 percent to 2.86 percent and TFP growth declining from 0.92 percent to 0.25 percent. Growth in capital inputs also slowed from 4.64 percent for 1948–1973 to 3.57 percent for 1973–1990. This contributed to sluggish ALP growth—2.82 percent for 1948–1973 and 1.26 percent for 1973–1990.

Relative to the early 1990s, output growth increased by 1.72 percent in 1995–1999. The contribution of IT production almost doubled, relative to 1990–1995, but still accounted for only 28.9 percent of the increased growth of output. Although the contribution of IT has increased steadily throughout the period 1948–1999, there has been a sharp response to the acceleration in the IT price decline in 1995. Nonetheless, more than 70 percent of the increased output growth can be attributed to non-IT products.

Between 1990–1995 and 1995-1999 the contribution of capital input jumped by 0.95 percentage points, the contribution of labor input rose by only 0.24 percent, and TFP accelerated by 0.51 percent. Growth in ALP rose 0.92 as more rapid capital deepening and growth in TFP offset slower improvement in labor quality. Growth in hours worked accelerated as unemployment fell to a 30-year low. Labor markets have tightened considerably, even as labor force participation rates increased.[37]

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 1948–1999, but figure 1.9 reflects the impact of the accelerating decline in IT prices.

After maintaining an average rate of 0.25 percent for the period 1973–1990, TFP growth fell to 0.24 percent for 1990–1995 and then vaulted to 0.75 percent per year for 1995–1999. This is a major source of growth in output and ALP for the U.S. economy (figures 1.11 and 1.12). While TFP growth for 1995–1999 is lower than the rate of 1948–1973, the U.S. economy is recuperating from the anemic productivity growth of the past two decades. Although only half of the acceleration in TFP from 1990–1995 to 1995–1999 can be attributed to IT production, this is far greater than the 4.26 percent share of IT in the GDP.

1.3.7 Average Labor Productivity

Output growth is the sum of growth in hours and average labor productivity. Table 1.8 shows the breakdown between growth in hours and ALP for the same periods as in table 1.6. For the period 1948–1999, ALP growth predominated in output growth, increasing just over 2 percent per year for 1948–1999, while hours increased about 1.4 percent per year. As shown in equation (1.3), ALP growth depends on capital deepening, a labor quality effect, and TFP growth.

Figure 1.12 reveals the well-known productivity slowdown of the 1970s and 1980s, emphasizing the acceleration in labor productivity growth in the late 1990s. The slowdown through 1990 reflects reduced capital deepening, declining labor quality growth, and decelerating growth in TFP. The growth of ALP slipped further during the early 1990s with a slump in capital deepening only partly offset by a revival in labor

Table 1.8
Sources of average labor productivity growth

	1948–1999	1948–1973	1973–1990	1990–1995	1995–1999
Gross domestic product	3.46	3.99	2.86	2.36	4.08
Hours worked	1.37	1.16	1.59	1.17	1.98
Average labor productivity	2.09	2.82	1.26	1.19	2.11
Contribution of capital deepening	1.13	1.45	0.79	0.64	1.24
Information technology	0.30	0.15	0.35	0.43	0.89
Non-information technology	0.83	1.30	0.44	0.21	0.35
Contribution of labor quality	0.34	0.46	0.22	0.32	0.12
Total factor productivity	0.61	0.92	0.25	0.24	0.75
Information technology	0.16	0.06	0.19	0.25	0.50
Non-Information technology	0.45	0.86	0.06	-0.01	0.25
			Addendum		
Labor input	1.95	1.95	1.97	1.70	2.18
Labor quality	0.58	0.79	0.38	0.53	0.20
Capital input	4.12	4.64	3.57	2.75	4.96
Capital stock	3.37	4.21	2.74	1.82	2.73
Capital quality	0.75	0.43	0.83	0.93	2.23

Notes: Average annual percentage rates of growth. Contributions are defined in equation (1.3) of the text.

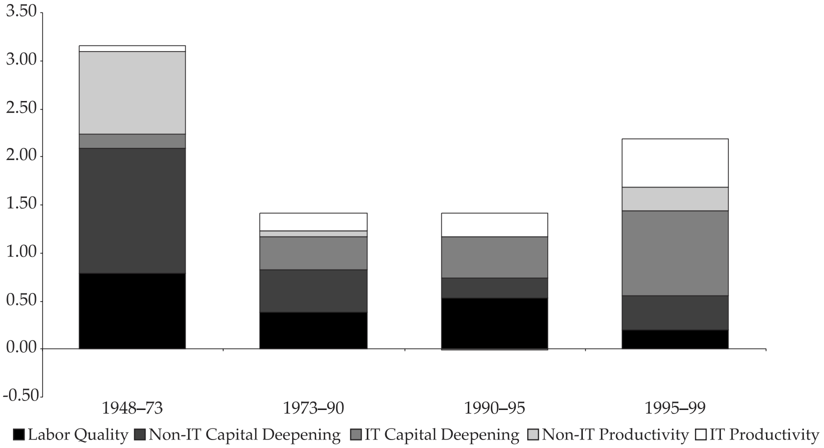

Figure 1.12
Sources of average labor productivity growth. *Note:* Contributions are from table 1.8.

quality growth and an uptick in TFP growth. A slowdown in hours combined with slowing ALP growth during 1990–1995 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 1995–1999 reflects growth in labor hours and ALP almost equally.[38] Comparing 1990–1995 to 1995–1999, the rate of output growth jumped by 1.72 percent—due to an increase in hours worked of 0.81 percent and another increase in ALP growth of 0.92 percent. Figure 1.12 shows the acceleration in ALP growth is due to capital deepening as well as faster TFP growth. Capital deepening contributed 0.60 percentage points, offsetting a negative contribution of labor quality of 0.20 percent. The acceleration in TFP added 0.51 percentage points.

1.3.8 Research Opportunities

The use of computers, software, and communications equipment must be carefully distinguished from the production of IT.[39] 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 TFP 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 TFP growth is unaffected.[40] Increasing deployment of IT affects TFP growth only if there are spillovers from IT-producing industries to IT-using industries.

Top priority must be given to identifying the impact of investment in IT at the industry level. Stiroh (1998a) has shown that this is concentrated in a small number of IT-using industries, while Stiroh (2000) shows that aggregate ALP growth can be attributed to productivity growth in IT-producing and IT-using industries. The next priority is to trace the increase in aggregate TFP growth to its sources in individual industries. Jorgenson and Stiroh (2000a, 2000b) present the appropriate methodology and preliminary results.

1.4 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 Alfred D. Chandler (2000) and Paul A. David (2000),[41] have placed the information age in historical context. The Solow (1987) Paradox, that we see computers everywhere but in the productivity statistics,[42] has provided a point of departure. Since 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.[43] 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.[44]

Finally, information technology is altering product markets and business organizations, as attested by the large and growing business literature,[45] but a fully satisfactory model of the semiconductor industry remains to be developed.[46] Such 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.[47] This poses important questions about the American growth resurgence. Where is the evidence of a new economy in other leading industrialized countries? An important explanation is the absence of constant quality price indexes for semiconductors and information technology in national accounting systems outside the United States.[48] Another conundrum is that several important participants—Korea, Malaysia, Singapore, and Taiwan—are "newly industrializing" economies. What does this portend for developing countries like China and India?

As policy-makers attempt to fill the widening gaps between the information required for sound policy and the available data, the traditional division of labor between statistical agencies and policy-making bodies is breaking down. In the mean time monetary policy-makers must set policies without accurate measures of price change. Similarly, fiscal policy-makers confront ongoing revisions of growth projections that drastically affect the outlook for future tax revenues and government spending.

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.[49] We are the fortunate beneficiaries of a new agenda for economic research that could refresh our thinking and revitalize our discipline.

Notes

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

2. Gordon (1998, 2000); Bosworth and Triplett (2000).

3. Greenspan (2000).

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

8. Moore (1997).

9. Moore (1996).

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

11. See Landefeld and Parker (1997).

12. See Moore (1996).

13. Further details are given by Berndt (1991), pp. 102–149.

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. A general reference on the Internet is Choi and Whinston (2000). On Internet indicators see: http://www.internetindicators.com/.

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 11-th comprehensive revision of NIPA and the 1999 update.

18. See Chandler (2000), table 1.1, p. 26.

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

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

21. Jorgenson (2000) presents a model of capital as a factor of production. BLS (1983) describes the version of this model employed in the official productivity statistics. For a recent update, see: http://www.bls.gov/ news.release/prd3.nr0.htm. Hulten (2001) surveys the literature.

22. Jorgenson and Yun (1991a), p. 7.

23. Jorgenson and Stiroh (1995), pp. 300–303.

24. Lau (2000) surveys applications of the cost of capital.

25. See, for example, Jorgenson, Gollop, and Fraumeni (1987), pp. 40–49, and Jorgenson and Griliches (1996).

26. Jorgenson and Stiroh (2000b), table B4, pp. 196–197 give the depreciation rates employed in this study. Fraumeni (1997) describes depreciation rates used in the NIPA. Jorgenson (2000) surveys empirical studies of depreciation.

27. See Jorgenson and Yun (2000). Diewert and Lawrence (2000) survey measures of the price and quantity of capital input.

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

29. The production possibility frontier was introduced into productivity measurement by Jorgenson (1996c), pp. 27–28.

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

31. Whelan (1999) also employs Solow's concept of embodiment.

32. See, for example, Campbell and Shiller (1998).

33. Bosworth and Triplett (2000) compare the results of Jorgenson and Stiroh (2000b) with those of Oliner and Sichel (2000).

34. The dual approach is presented by Jorgenson, Gollop, and Fraumeni (1987), pp. 53–63.

35. Dulberger (1993), Triplett (1996a), and Oliner and Sichel (2000) present models of the relationships between computer and semiconductor industries. These are special cases of the Domar (1961) aggregation scheme.

36. See Jorgenson, Gollop, and Fraumeni (1987), pp. 63–66, 301–322.

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

38. Stiroh (2000) shows that ALP growth is concentrated in IT-producing and IT-using industries.

39. Economics and Statistics Administration (2000), table 3.1, p. 23, lists IT-producing industries.

40. Baily and Gordon (1988).

41. See also: David (1990) and Gordon (2000).

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

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

44. Acemoglu (2000) and Katz (2000) survey the literature on labor markets and technological change.

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

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

47. 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 Cooperation and Development (2000).

48. The measurement gap between the U.S. and other OECD countries was first identified by Wykoff (1995). Schreyer (2000) has taken the initial steps to fill this gap.

49. See, for example, Shapiro and Varian (1999), Brynjolfsson and Kahin (2000), and Choi and Whinston (2000).

2

Computers and Growth

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The purpose of this chapter is to describe and measure the impact of computer investment on U.S. economic growth. Using a model of capital that is specific to computers, we estimate computer stocks and services flows for each type of computer equipment found in the NIPA. These estimates are then incorporated into a system of national accounts to determine the impact of computers as both an output and an input. The results show that computer inputs are steadily increasing as a source of growth and that the large price declines in computer investment have led to large pecuniary externalities.

2.1 Introduction

This chapter describes the impact of investment in computers on the growth of the U.S. economy. The economic literature on computers is relatively rich in information on the decline in computer prices and the growth of computer investment. Constant quality price indices for computers have been included in the U.S. National Income and Product Accounts (NIPA) since 1986. These indices employ state-of-the-art methodology to capture the rapid evolution of computer technology.

While the annual inflation rate for overall investment has been 3.66 percent for the period 1958 to 1992, computer prices have *declined* by 19.13 percent per year! Similarly, overall investment grew at 3.82 percent, while investment in computers increased at an astounding 44.34 percent! These familiar facts describe growth in the output of computers. The objective of this chapter is to complete the picture by analyzing the growth of computer services as inputs.

In a pioneering paper Bresnahan (1986) has focused on pecuniary externalities arising from the rapid decline in computer prices. Griliches

(1992, 1994) has emphasized the distinction between pecuniary and nonpecuniary externalities in the impact of computer investment on growth. This chapter is limited to pecuniary externalities or the impact of reductions in computer prices on the substitution of computer services for other inputs. As Griliches (1992) points out, this is an essential first step in identifying *nonpecuniary* externalities or "spill-overs" through the impact of a decline in computer prices on productivity growth.[1]

In two important papers Stephen D. Oliner (1993, 1994a) has introduced a model of computer technology that greatly facilitates the measurement of computer services as inputs. In this chapter we estimate computer stocks and flows of computer services for all forms of computer investment included in NIPA. We construct estimates of computer services parallel to NIPA data on computer investment by combining these data with information on computer inventories For example, the International Data Corporation (IDC) Census of Computer Processors includes an annual inventory of processors in the United States.

In section 2.2 we present data on investment in computers and constant quality price indices from NIPA. These data incorporate important innovations in modeling computer technology stemming from a joint study by IBM and the Bureau of Economic Analysis (BEA) completed in 1985. This study utilized a "hedonic" methodology for constructing an econometric model of computer prices that accurately reflects rapid changes in computer technology. This methodology generates an index of computer prices that holds the quality of computers constant.

In section 2.3 we present the model of computer services originated by Oliner (1993, 1994a). This differs in important respects from the model of capital services used in the previous studies of U.S. economic growth surveyed by Jorgenson (1989, 1990b). The model employed in previous studies is based on the decline in productive capacity with the chronological age of a capital good. Oliner assumes that computers maintain their productive capacity until they are retired. Decline in productive capacity occurs only through removal of used computers from the inventory through retirement.

In section 2.4 we construct estimates of stocks of computers that incorporate IDC data on computer inventories and derive the implied flow of computer services. While output of computer investments has grown very rapidly, the input of computer services has grown even faster. The price of these services has declined at 23.22 percent per year over the period 1958 to 1992, while the input of these services has grown at 52.82

percent! This is *prima facie* evidence of an important role for computer price declines as a source of pecuniary externalities.

In section 2.5 we combine computer services with the services of other types of capital to produce a measure of capital input into the U.S. economy. We link this with labor input to obtain the contributions of both inputs to U.S. economic growth, arriving at the growth of productivity as a residual. We find that the contribution of computer services to input into the U.S. economy is roughly equal to the contribution of computer investments to output. This is a significant step toward resolution of the Solow paradox: "We see computers everywhere except in the productivity statistics."[2] Declines in computer prices generate very sizable pecuniary externalities through the substitution of computer services for other inputs. By contrast Solow focuses on nonpecuniary externalities that would appear as productivity growth.

In section 2.6 we conclude that information on investment of computers is critical in quantifying the role of computer services as inputs. The constant quality price indices for computers incorporated into NIPA are also essential. A price index for computers that reflects only general trends in inflation would result in a highly distorted perspective on the growth of GDP and capital services, especially during the past decade. To capture the contribution of all forms of investment to U.S. economic growth, similar price indices should be included in NIPA for capital goods with rapidly evolving technologies, as proposed by Gordon (1990).

The long-term goal should be a unified system of income, product, and wealth accounts, like that proposed by Laurits Christensen and Jorgenson (1973) and Jorgenson (1980a). This incorporates capital stocks, capital services, and their prices. Achieving this goal will necessitate substantial greater elaboration of the accounting system described in section 2.4. These accounts would incorporate data on prices and quantities of investment, stocks of assets, and capital services for all forms of capital employed in the U.S. economy.

2.2 Computer Investment

The growth of investment in computers has been driven by a dramatic and continuing price decline. We have summarized information about investment in computers from NIPA in a series of tables and figures. In table 2.1 we present data on the prices of investment and quantities

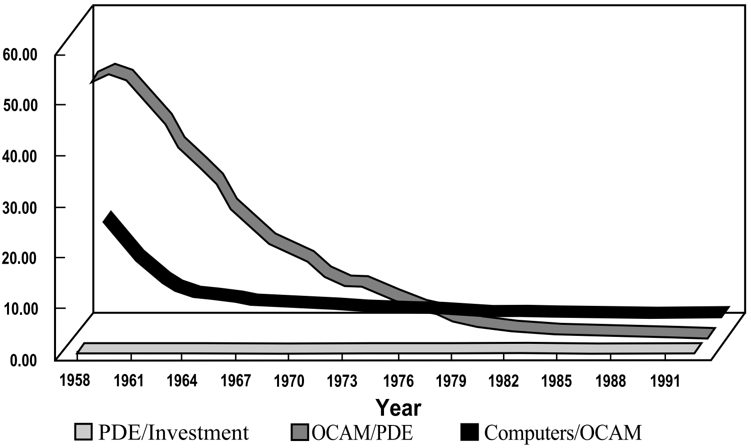
Table 2.1
Investment quantity in 1987 dollars

	Total Investment		Non-Res. PDE		OCAM		Computers	
Year	Quantity	Price	Quantity	Price	Quantity	Price	Quantity	Price
1958	319.9	0.318	69.7	0.367	0.078	18.730	0.000	374.070
1959	379.3	0.320	80.1	0.363	0.074	19.090	0.000	291.070
1960	376.5	0.325	82.5	0.368	0.083	18.815	0.001	215.110
1961	368.4	0.325	80.4	0.367	0.083	17.330	0.002	148.200
1962	408.9	0.330	88.9	0.368	0.088	15.926	0.004	100.910
1963	438.3	0.331	94.4	0.372	0.135	14.080	0.011	72.130
1964	474.9	0.334	105.0	0.376	0.158	13.038	0.016	60.869
1965	532.9	0.341	122.4	0.381	0.197	11.832	0.024	50.192
1966	574.1	0.346	138.4	0.389	0.331	9.825	0.051	35.350
1967	559.6	0.355	134.6	0.405	0.382	8.824	0.068	28.676
1968	595.4	0.371	140.3	0.424	0.415	8.007	0.082	24.499
1969	621.9	0.388	152.1	0.436	0.545	7.524	0.114	22.181
1970	585.3	0.403	149.5	0.453	0.596	7.118	0.143	19.910
1971	649.3	0.420	151.7	0.465	0.707	5.926	0.192	15.188
1972	717.0	0.441	169.5	0.47s	0.990	5.163	0.295	12.227
1973	800.1	0.459	203.3	0.477	1.149	5.056	0.316	11.597
1974	740.0	0.498	204.8	0.519	1.475	4.568	0.414	9.497
1975	646.0	0.558	184.5	0.593	1.419	4.453	0.423	8.790
1976	754.9	0.591	194.4	0.635	1.906	3.992	0.622	7.343
1977	852.3	0.635	220.9	0.684	2.402	3.719	0.905	6.393
1978	932.4	0.682	251.9	0.729	4.344	2.866	1.800	4.322
1979	934.5	0.743	269.1	0.786	6.359	2.523	2.911	3.581
1980	844.6	0.805	257.4	0.854	8.881	2.153	4.623	2.796
1981	884.8	0.889	261.8	0.934	12.312	1.975	7.202	2.456
1982	789.7	0.937	239.5	0.996	12.813	1.954	8.163	2.415
1983	886.2	0.927	254.3	0.989	19.217	1.693	12.157	1.999
1984	1,083.3	0.957	299.5	0.995	28.829	1.434	19.933	1.606
1985	1,110.6	0.961	324.1	0.974	34.301	1.252	24.955	1.357
1986	1,135.t	0.975	328.9	0.985	38.681	1.117	28.615	1.163
1987	1,153.0	1.000	332.3	1.000	42.800	1.000	35.805	1.000
1988	1,206.7	1.020	366.4	1.009	48.049	0.953	41.355	0.941
1989	1,224.0	1.055	368.7	1.034	51.465	0.890	46.018	0.869
1990	1,188.2	1.075	374.0	1.048	57.205	0.792	51.089	0.775
1991	1,093.3	1.093	356.5	1.067	63.628	0.701	58.516	0.663
1992	1,173.2	1.103	374.7	1.068	75.989	0.606	71.223	0.561
Annual Growth	3.82	3.66	4.95	3.14	20.24	(10.09)	44.34	(19.13)

of investment in constant prices. This table includes data on overall investment in the private sector, nonresidential producers' durable equipment (PDE), office, computing, and accounting machinery (OCAM), and computers.

The annual inflation rate for investment is 3.66 percent for the period 1958 to 1992, while investment in constant prices grows at 3.82 percent per year. Inflation for PDE is only 3.14 percent, while investment grows at 4.95 percent. For the period as a whole the prices of OCAM *decline* at 10.09 percent per year, while investment grows at 20.24 percent; by the end of the period investment in OCAM is primarily computer investment. Finally, computer prices *decline* at 19.13 percent and investment grows at 44.34 percent! We employ translog or Tornqvist price indices discussed, for example, by Jorgenson (1990b). The growth rate of a translog price index is a weighted average of the growth rates of its components. The weights are shares of the components in the value of the aggregate.[3]

We present information on investment prices in graphical form in figure 2.1. The prices of PDE, relative to prices of overall investment, are fairly stable. Movements in both prices are dominated by trends in inflation. The price of OCAM relative to PDE falls steadily throughout the period, reflecting the rising proportion of computers in OCAM investment. The price of computers relative to OCAM declines precipitously



Source: Survey of Current Business, BEA, and author's calculations

Figure 2.1
Relative price of investment, 1958–1992.

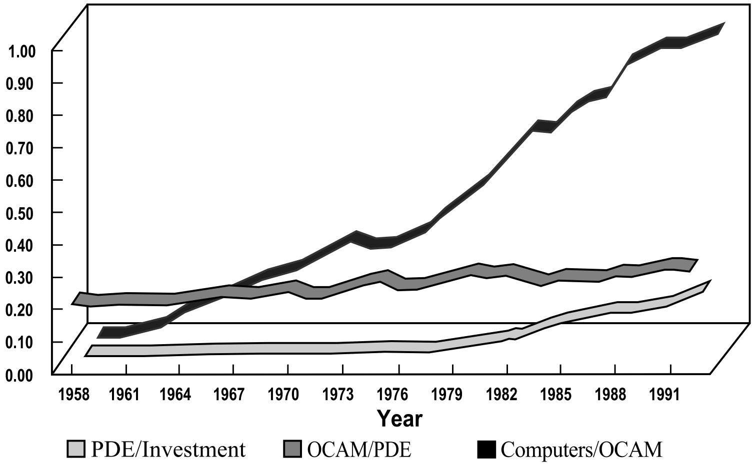


Figure 2.2
Share of investment quantity, 1958–1992.

at the beginning of the period, but falls at more moderate rates as computers come to dominate OCAM.

Finally, we provide information on constant dollar investment in graphical form in figure 2.2. The first panel shows that PDE rises relative to overall investment, especially during the 1980s and 1990s. The proportion of OCAM in PDE grows steadily throughout the period 1958 to 1992, while computer investment rises very substantially relative to the rest of OCAM. The computer proportion rises steadily, but not without interruptions, toward the theoretical upper limit of one hundred percent.

The NIPA price indices for computers utilize a "hedonic" methodology that holds the quality of computers constant, while the technical characteristics of computers change. This methodology was originated by Frederick Waugh (1929) to deal with the heterogeneity of agricultural commodities. It was successfully applied to automobile prices in an important study by Andrew Court (1939) for the General Motors Corporation. In a seminal article Zvi Griliches (1961) revived this methodology and applied it to postwar automobile prices.[4]

Gregory Chow (1967) first applied the hedonic methodology to computer prices in research conducted at IBM. Although Chow documented the rapid decline in computer prices in the 1950s and 1960s described in table 2.1, NIPA did not include specific price indices for computers until almost two decades later. Not surprisingly, this had become a highly controversial issue and was the subject of a heated exchange between BEA and Edward Denison (1989), one of the founders of NIPA methodology in the 1950s and head of national accounts at BEA from 1979 to 1982.

The exchange between the BEA and Denison was initiated by a detailed report by Rosanne Cole, Y.C. Chen, Joan Barquin-Stolleman, Ellen Dulberger, Nurthan Helvacian, and James Hodge (1986) of IBM on the results of a joint project conducted by BEA and IBM to construct a hedonic price index for computers for NIPA. Jack Triplett (1986), Chief Economist of BEA, discussed the economic interpretation of constant quality price indices in an accompanying article. Subsequently, BEA (1986a) described the introduction of hedonic price indices for computers into NIPA.[5]

A more detailed report on the research on computer processors resulting from the BEA-IBM project is presented by Dulberger (1989). The technical characteristics of processors that play a central role in Dulberger's econometric modeling are speed of processing, described in millions of instruction executions per second (MIPS), and main memory, described in units of 1,024 times eight binary digits (Megabytes).[6] An extensive survey of research on hedonic price indices for computers is given by Triplett (1989).

Denison (1989) attacked the BEA-IBM methodology and argued vigorously against the introduction of constant quality price indices into NIPA. He cited his 1957 paper, "Theoretical Aspects of Quality Change, Capital Consumption, and Net Capital Formation," as the definitive statement of the traditional BEA position against the introduction of constant quality price indices into NIPA. Denison argued specifically against constant quality price indices for investment, capital consumption, and capital stock.

Allan Young (1989), then the Director of BEA, answered Denison's objections and reiterated the BEA rationale for introducing constant quality price indices for computers. The price indices given in table 2.1 and represented in figure 2. 2 are based on hedonics, as described by BEA (1986). These indices are also employed in measuring capital consumption in NIPA and capital stock in the BEA (1987) study, *Fixed Reproducible Tangible Wealth in the United States, 1925–1985*.

2.3 A Model of Computer Services

Computer investment represents the acquisition of machines, for example, a certain number of processors with a given performance. The price of acquisition of a processor is the unit cost of purchasing a machine. An assumption implicit in this definition is that quantities and prices are measured in "efficiency units" of constant quality. This assumption is consistent with the econometric modeling reported by Dulberger (1989), where computer performance is represented as a function of MIPS and Megabytes.

Computers can be leased for days, months, or years. The rental price of computer services is the unit cost of renting a machine, rather than purchasing it. While computer investments are available in the commodity flows that underly NIPA, no comparable source of data on computer services is available. However, flows of computer services and their rental prices can be inferred from inventories of machines and constant quality price indices.

The price indices for computers from NIPA hold quality constant as computer technology changes. For example, price indices for processors reflect unchanging productive capacity from period to period, so that the drastic decline in processor prices reflects the reduced cost of acquiring this capacity. We take the constant quality price indices from NIPA as the prices of new assets for a perpetual inventory of asset prices.

Oliner (1993) has incorporated data on second hand acquisition prices for processors in modeling constant quality price indices. However, these prices are independent of the time at which the machine was originally sold by the manufacturer, so that the second hand price is independent of the chronological age of the machine. Oliner compares his constant quality price indices for processors with the BEA-IBM price indices included in NIPA and finds that the two are very similar.

We begin our description of the measurement of computer services with quantities of computer investment. We refer to computers acquired at different points of time as different *vintages*. To describe computer services in more detail we require the following notation:

A_t quantity of computers acquired at time t.

d_t proportion of computers installed prior to time t surviving at that time.

Q_t quantity of computer assets at time t.

$K_{t,v}$ quantity of computer services of vintage v at time t.

K_t quantity of computer services of all vintages at time t.

We also require notation for acquisition prices for computers and rental prices for computer services:

$p_{A,t}$ constant quality price of acquisition of computers at time t.

$p_{K,t}$ constant quality rental price of computer services at time t.

Finally, we require notation for the value of computers as assets:

W_t value of computer assets at time t.

The standard perpetual inventory method includes a system of vintage accounts for investment and the corresponding acquisition prices. This method is based on the assumption that the quantity of capital services is proportional to the initial level of investment. The constants of proportionality are given by the *relative efficiencies* of different vintages of investment. These efficiencies correspond to productive capacities and also determine the relative rental prices of different vintages.

If we assume that the flow of capital services, say K_t, is characterized by perfect substitutability among capital goods of different vintages, we can express this flow as a weighted sum:

$$\begin{aligned} K_t &= \sum_{v=0}^{t} k_{t,v} \, , \\ &= \sum_{v=0}^{t} d_{v,t} A_{t-v} \, , \end{aligned}$$

where $d_{v,t}$ is the relative efficiency of capital goods of vintage v at time t. This definition embodies the assumption that a capital good loses productivity capacity as it ages, so that relative efficiencies of different vintages of capital goods decline with chronological age.[7]

Oliner (1993, 1994a) has proposed a model of computer services with unchanging productive efficiency over the lifetime of a computer. At any point in time all units of a given technology family will provide the same flow of capital services. This flow is independent of the chronological age of the machine. Capital services from an entire vintage of investment goods decline only as individual units from that vintage are retired. Retirement begins only after a technology family is discontinued by the manufacturer, since arbitrage prevents new investment and retirement of a given type of assets at the same point of time.

More specifically, Oliner identifies technology families for processors corresponding to the IBM 360, 370, 30XX, and 4300 series. He obtains retirement distributions for all models within each family from the IDC censuses of equipment. He assumes that all investment in processors in any given year occurs in the model of the latest available technology family. Machines from the family that has been discontinued begin to be retired after a new family is introduced.

Although the productive capacity of a computer does not decline as it ages, the cost of maintaining equipment rises relative to the cost of new equipment as technology improves. Since these costs vary across users, retirement of old equipment will be distributed over all units still in the stock. Oliner assumes that retirements are distributed proportionately across all vintages of a given technology family and do not depend on chronological age.[8]

For the three types of peripherals considered by Oliner (1994a)—direct access storage drives (DASD), displays, and printers—we employ the same approach as for processors. Oliner has presented retirement distributions at five-year intervals, again based on inventories of peripherals from IDC censuses. We treat each five-year interval as a technology family, so that machines acquired before 1970 begin to be retired in 1970, machines acquired between1970 and 1974 begin to be retired in 1975, and so on. For the remaining peripherals and PCs we employ the perpetual inventory method from the simplified vintage accounting system introduced by Christensen and Jorgenson (1973) and Jorgenson (1980a) and outlined below.

Since units from all previous vintages of a given technology family are perfect substitutes and are retired in the same proportions, the stock of computers can be calculated from past investments and the retirement distribution:

$$Q_t = d_t \sum_{v=0}^{t} A_{t-v}.$$

Vintages of investment within the technology family in current production are not retired until the family is discontinued, so that the surviving proportion of these assets d_t is equal to unity.

We turn next to a description of the price data required for the measurement of the rental price of computer services. The model of computer services requires a system of vintage accounts containing data on the acquisition prices for computers of each vintage at each point of time. There is a one-to-one correspondence between this system of vintage accounts for asset prices and the vintage accounts for the inventories of assets. The system of vintage accounts comprises the perpetual inventory of assets and asset prices employed in accounting for wealth.

Under the assumptions of perfect substitutability and unchanging productive efficiency the rental prices for all vintages of computers are proportional to a single constant quality rental price. The price of acquisition of a computer is the sum of present values of future rental prices of the computer services, weighted by the conditional probability that the unit has not been retired:

$$p_{A,t} = \sum_{\tau=0}^{\infty} \prod_{s=1}^{\tau+1} \frac{1}{1+r_{t+s}} p_{K,t+\tau+1} \frac{d_{t+\tau+1}}{d_t}.$$

In this expression the ratio of $d_{t+\tau+1}$ to d_t is the probability that a computer will survive to time $t + \tau + 1$ given that it has survived until time t. The present values of future rental prices are obtained by applying a discount factor that depends on the sequence of discount rates r_{t+s}.

Weighting the acquisition price $p_{A,t}$ in period t by the discount factor in period $t - 1$ and dividing by the proportion of computers at time $t - 1$ that are still surviving at time t, we obtain the constant quality rental price:

$$p_{K,t} = [p_{A,t-1} r_1 + \delta_t p_{A,t} - (p_{A,t} - p_{A,t} - p_{A,t-1})] \frac{d_{t-1}}{d_t},$$

where r_t, is the *rate of return* and is equal to the discount rate, δ_t is the *rate of retirement*, where:

$$\delta_t = \frac{d_{t-1} - d_t}{d_{t-1}},$$

and the ratio of the first difference $p_{A,t} - p_{A,t-1}$ to the acquisition price $p_{A,t}$ is the *rate of revaluation* of computers. Note that the ratio of d_{t-1} to d_t, is equal to unity for a technology family that has not been discontinued.

Estimation of the capital service price requires data on current and lagged acquisition prices and the retirement distribution for each technology family. Since acquisition price data are available from BEA only for the current technology family, the capital service price can be estimated only for this family. Since computers do not lose productive capacity with age and the price index holds quality constant, arbitrage assures that all machines have the same service price. Oliner provides retirement distributions for all technology families, so that service prices can be determined at every point of time. Acquisition prices for assets from discontinued technology families can be estimated from these service prices.

The rental price formula for computers differs from the standard rental price formula in the interpretation of the retirement rate δ_t, and the presence of the ratio of the survival probability d_{t-1} to the probability d_t. The standard formula includes a term that represents economic depreciation, defined as the loss in the value of an asset with age. Depreciation for computers, defined in this way, is equal to zero, since acquisition prices are independent of age. A computer will lose value over time as the technology ages and retirement draws closer in time. Ignoring the effect of future retirement would lead to a censoring bias in estimating prices of acquisition for computers from discontinued families.

We combine the constant quality rental price for computers with an appropriate tax factor to obtain the pre-tax rental price:

$$p_{K,1} = \frac{1 - k_{t-1} - u_{t-1} z_{t-1}}{1 - u_{t-1}} [p_{A,t-1} r_t + \delta_t p_{A,t} - (p_{A,t} - p_{A,t-1})] \frac{d_{t-1}}{d_t},$$

where u_t is the *tax rate*, z_t is the *present value of capital consumption allowances on a new computer*, and k_t, is the *rate of the investment tax credit on computers*. Tax factors for OCAM are presented by Jorgenson and Yun (1991b). To construct a constant quality rental price index $p_{K,t}$ a system of vintage accounts containing data on constant quality acquisition prices of computers $p_{A,t}$ in every period is required. In addition, information on stocks of assets and rates of retirement of these assets is necessary. Finally, a constant quality rental price index requires data on tax rates, tax depreciation rules, and the availability of tax credits for investment in computers.

Oliner's framework of unchanging efficiency and retirement that is independent of age implies that all installed units of a given technology family must have the same price of acquisition. The value of all machines of a given family is defined as the sum of all vintages that remain at a given point of time, evaluated at the current acquisition price:

$$W_t = p_{A,t} d_t \sum_{v=0}^{t} A_{t-v},$$

where $p_{A,t}$ is the BEA price for the current technology family and is estimated for discontinued technology families. An index number approach is employed for aggregating over technology families to obtain the price and quantity indices presented below.

2.4 Computer Stocks and Services

In this section we present stocks and services of computers, together with the stocks and services of all office and accounting machinery (OCAM), in constant prices. We also give the stocks and services of nonresidential PDE and private tangible assets in the United States. The stocks are constant dollar magnitudes appropriate for the entries corresponding to these assets in the U.S. national wealth accounts. Stocks and services of tangible assets include structures, inventories, and land, as well as equipment including computers.

In table 2.2 we present constant quality price indices for stocks of tangible assets, PDE, OCAM, and computers. These price indices reflect the rapid decline in prices for new computers in table 2.1. Computer asset prices decline by 17.73 percent per year during the period 1958 to 1992, mirroring the corresponding fall in the prices of computer investment. Asset prices of OCAM decline at an annual rate of 8.99 percent, reflecting the increasing role of computers in the stock. Price indices of stocks of PDE and all tangible assets rise by 3.77 and 4.88 percent annually during this period.

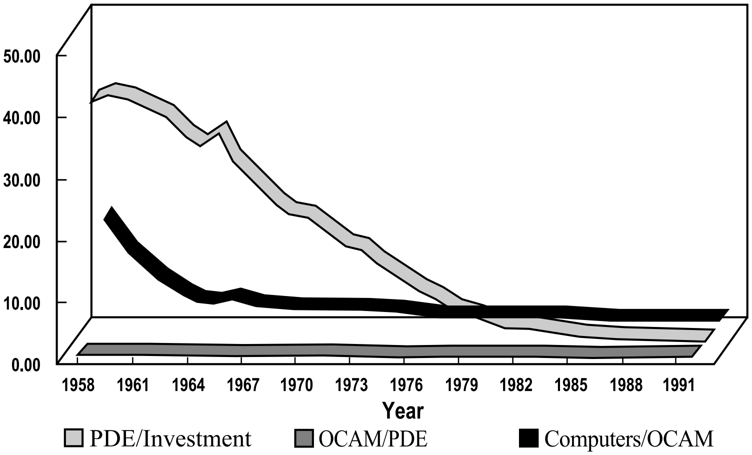
For each individual asset the acquisition prices come from two sources. For assets embodying current technology, the acquisition price given by BEA is presented in table 2.1. Acquisition prices for machines from discontinued technology families must be estimated from the model of capital as a factor of production outlined above. The price indices for groups of assets are obtained by applying an index number formula. The growth rate of the price is equal to a weighted average of the growth rates of its components. The weights are the shares of these components in the asset values.

We represent information on relative prices of computer stocks and stocks of OCAM, PDE, and tangible assets graphically in figure 2.3. As indicated in table 2.2, computer prices decline relative to OCAM, but at a diminishing rate as computer stocks come to dominate OCAM. The prices of OCAM fall steadily relative to those of PDE, reflecting the increasing importance of computers. Prices of PDE stocks decline slightly relative to those of tangible assets.

In figure 2.4 we graphically present stocks of computers in constant prices. Computer stocks rise rapidly in relation to OCAM stocks throughout the period, while OCAM stocks rise in relation to stocks of

Table 2.2
Capital stock quantity in 1987 dollars

	Total Investment		Non-Res. PDE		OCAM		Computers	
Year	Quantity	Price	Quantity	Price	Quantity	Price	Quantity	Price
1958	8,654.0	0.204	613.1	0.312	0.359	12.343	0.000	219.560
1959	8,869.9	0.207	631.1	0.309	0.374	12.603	0.000	172.780
1960	9,058.3	0.210	649.2	0.316	0.398	12.633	0.002	130.320
1961	9,250.8	0.212	662.2	0.314	0.416	12.071	0.005	94.250
1962	9,492.7	0.216	683.7	0.314	0.434	11.652	0.010	66.790
1963	9,761.4	0.219	708.3	0.316	0.508	10.822	0.026	47.585
1964	10,071.0	0.223	741.9	0.319	0.594	10.273	0.049	39.712
1965	10,437.0	0.229	791.2	0.323	0.606	11.145	0.052	50.428
1966	10,814.0	0.236	851.9	0.330	0.825	9.681	0.099	35.583
1967	11,165.0	0.244	899.5	0.343	1.046	8.981	0.158	29.416
1968	11,515.0	0.258	947.8	0.358	1.265	8.277	0.226	25.367
1969	11,851.0	0.276	1,003.1	0.369	1.590	7.836	0.322	23.119
1970	12,155.0	0.288	1,047.2	0.385	1.780	7.941	0.388	23.053
1971	12,330.0	0.305	1,088.7	0.397	1.838	7.463	0.415	20.835
1972	12,962.0	0.331	1,145.1	0.409	2.353	6.511	0.607	16.402
1973	13,400.0	0.362	1,230.8	0.416	2.951	6.430	0.811	15.736
1974	13,748.0	0.405	1,304.2	0.453	3.749	5.849	1.080	13.301
1975	13,985.0	0.450	1,343.6	0.529	4.152	5.736	1.228	12.581
1976	14,327.0	0.487	1,388.8	0.570	5.148	5.045	1.630	10.355
1977	14,746.0	0.531	1,456.0	0.614	6.424	4.627	2.217	8.880
1978	15,193.0	0.593	1,546.0	0.655	9.152	3.555	3.450	6.029
1979	15,556.0	0.668	1,639.6	0.708	13.132	3.137	5.421	5.030
1980	15,904.0	0.743	1,704.6	0.777	15.841	2.689	6.666	3.911
1981	16,209.0	0.810	1,764.8	0.857	23.650	2.420	11.673	3.290
1982	16,382.0	0.857	1,791.9	0.920	31.121	2.304	17.194	3.068
1983	16,697.0	0.880	1,831.1	0.935	43.872	2.038	25.935	2.594
1984	17,177.0	0.911	1,906.4	0.950	63.241	1.719	40.185	2.073
1985	17,632.0	0.937	1,989.1	0.954	85.959	1.278	58.556	1.412
1986	18,030.0	0.962	2,056.8	0.978	113.740	1.132	82.634	1.190
1987	18,436.0	1.000	2,113.2	1.000	143.480	1.000	113.240	1.000
1988	18,835.0	1.047	2,191.8	1.023	176.310	0.953	147.930	0.939
1989	19,207.0	1.096	2,257.1	1.054	210.730	0.854	185.820	0.822
1990	19,496.0	1.087	2,316.9	1.081	246.860	0.779	224.280	0.754
1991	19,736.0	1.088	2,349.5	1.110	282.350	0.669	263.260	0.625
1992	19,540.0	1.074	2,393.8	1.124	330.740	0.580	316.640	0.530
Annual Growth	2.40	4.88	4.01	3.77	20.07	(8.99)	47.16	(17.73)



Source: Survey of Current Business, BEA, and author's calculations

Figure 2.3
Relative price of capital stock, 1958–1992.

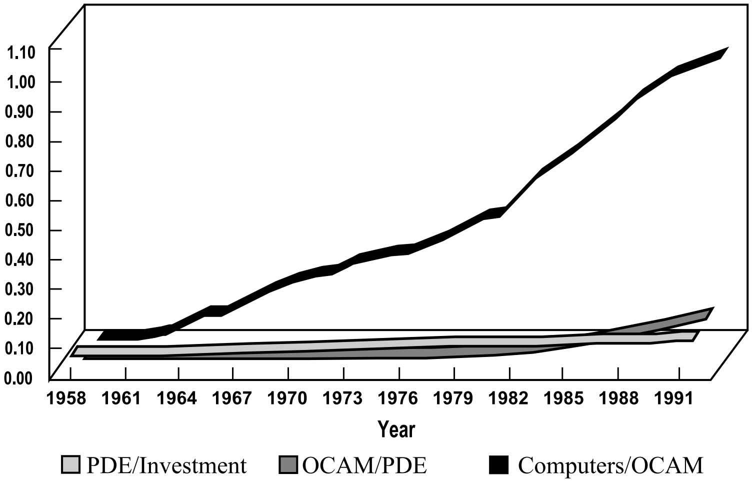


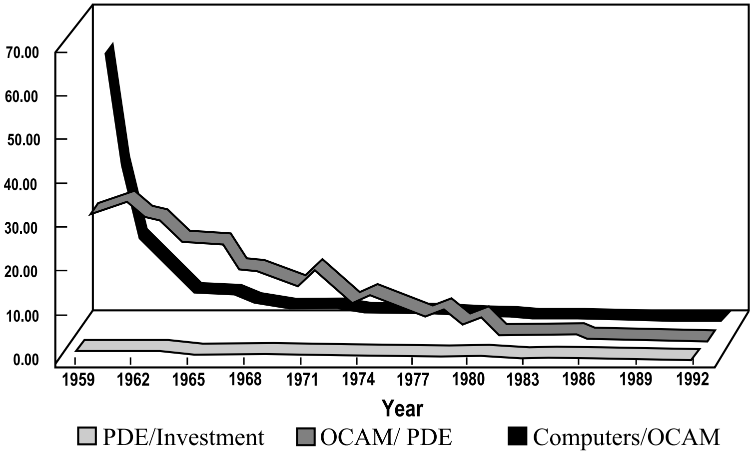
Figure 2.4
Share capital stock quantity, 1958–1992.

PDE toward the end of period. Finally, the ratio of PDE stocks to tangible assets increases only gradually.

In table 2.3 we present constant quality price indices for services of tangible assets, PDE, OCAM, and computers.

Table 2.3
Capital services quantity in 1987 dollars

	Total Investment		Non-Res. PDE		OCAM		Computers	
Year	Quantity	Price	Quantity	Price	Quantity	Price	Quantity	Price
1958	731.6	0.230	85.4	0.462	NA	NA	NA	NA
1959	740.9	0.272	84.1	0.490	0.039	14.126	0.000	857.520
1960	760.0	0.265	86.7	0.484	0.066	14.660	0.000	516.130
1961	776.0	0.268	89.5	0.484	0.090	15.377	0.000	286.020
1962	793.9	0.293	91.6	0.500	0.109	14.255	0.001	198.540
1963	818.5	0.312	95.4	0.476	0.126	12.827	0.002	128.140
1964	846.0	0.335	99.7	0.490	0.158	11.148	0.006	69.347
1965	880.7	0.366	105.4	0.516	0.191	11.736	0.011	72.845
1966	922.4	0.375	114.0	0.522	0.239	11.640	0.018	70.027
1967	966.6	0.361	124.8	0.525	0.341	8.699	0.035	37.546
1968	1008.3	0.359	132.7	0.540	0.430	8.616	0.055	30.134
1969	1,050.5	0.352	141.3	0.528	0.504	7.367	0.077	22.075
1970	1,091.4	0.337	151.1	0.538	0.611	6.723	0.106	20.651
1971	1,129.8	0.363	158.4	0.570	0.726	9.298	0.144	30.671
1972	1,178.0	0.387	167.1	0.554	0.885	6.700	0.198	19.257
1973	1,232.8	0.398	178.7	0.540	1.085	4.439	0.274	9.435
1974	1,287.1	0.382	195.0	0.541	1.296	5.749	0.351	13.671
1975	1,333.4	0.422	208.8	0.608	1.604	5.161	0.449	11.367
1976	1,366.6	0.476	215.7	0.656	1.853	4.785	0.549	9.736
1977	1,413.4	0.531	225.7	0.705	2.267	4.063	0.724	7.798
1978	1,469.6	0.571	241.0	0.737	2.777	5.282	0.960	10.479
1979	1,532.2	0.577	263.0	0.761	3.948	3.327	1.474	5.259
1980	1,582.1	0.595	284.9	0.797	5.669	4.285	2.290	8.093
1981	1,630.4	0.691	301.7	0.871	7.986	1.969	3.547	2.564
1982	1,672.8	0.744	316.5	0.849	10.832	1.447	5.529	1.630
1983	1,703.1	0.855	325.7	0.890	13.863	1.412	8.239	1.630
1984	1,756.4	0.941	342.9	0.939	19.271	1.550	12.409	1.775
1985	1,832.8	0.956	372.1	0.912	26.745	1.907	18.351	2.275
1986	1,911.5	0.939	403.4	0.881	35.314	0.935	25.340	0.958
1987	1,975.4	1.000	427.8	1.000	44.285	1.000	33.443	1.000
1988	2,040.6	1.039	449.3	1.020	53.741	0.740	44.336	0.629
1989	2,106.6	1.059	475.3	1.027	62.624	0.891	55.458	0.793
1990	2,163.6	1.134	496.8	1.026	72.333	0.598	68.510	0.461
1991	2,204.1	1.158	516.4	1.019	83.864	0.585	82.432	0.524
1992	2,226.9	1.234	528.9	1.060	95.996	0.493	97.124	0.403
Annual Growth	3.27	4.93	5.36	2.44	23.65	(10.17)	52.82	(23.22)



Source: Survey of Current Business, BEA, and author's calculations

Figure 2.5
Relative price of capital services, 1959–1992.

The price indices for these services are obtained by applying the translog index number formula we have already described with weights given by the shares of the components in the value of capital services. We give this information in graphic form in figure 2.5. The wide range of annual fluctuations in the values of capital services and the corresponding price indices is a reflection of changes in the acquisition prices of computers over time. The model of capital as a factor of production includes an asset pricing equation based on perfect foresight. Large capital losses associated with rapidly declining asset prices imply high rental prices.

Since the computer services provided by a given investment are proportional to the number of machines initially acquired, the services provided by different vintages at the same point of time are perfect substitutes in production. Under perfect substitutability the flow of computer services is proportional to the stock of computers and is a weighted sum of past investments. The weights correspond to the surviving proportions of past vintages of computers. In order to construct estimates of the quantities of computer services, a perpetual inventory containing data on computer investments of every age in every time period is essential.

The inventory of processors at each point of time consists of the unretired quantities of all prior vintages of investment. To generate the entries in a perpetual inventory in each time period we add new investment in processors and reduce the previous period's inventory by retirements. Technology families that have not been discontinued do not undergo retirement, so that the inventory of a given vintage is equal to the initial investment until the family is discontinued. After the family is no longer available from the manufacturer, all vintages are retired in the proportions implied by data on inventories of processors from the IDC censuses.

For assets included in the IDC censuses, the number of computers could be obtained, at least in principle, directly from the corresponding census. For other assets, the number of computers can be estimated from past investments. The estimates of computer stocks presented in table 2.2 are obtained from past investments by applying the perpetual inventory method we have described above to computer investment as they occur. Sums of these investments over all vintages of computers are reduced in accord with the distributions of retirements estimated from IDC inventory data by Oliner.

Since all vintages of computers receive the same price for capital services, the quantity of capital services is simply the sum over the unretired units from all technology families. An index number approach is used to generate the totals for computers and OCAM. In table 2.3 we present computer services in constant prices. The constant quality service price indices are calculated separately for each aggregate; for example, the quantity of computers is the ratio of the value of the computer service to the computer price index. In figure 2.6 we graphically present information on services in constant prices.

For computers with a full set of data for every time period, price and quantity indices for computer services can be constructed at each point of time. For computers with a less complete set of data a simplified set of price and quantity indices can be constructed on the basis of empirical evidence on the relative efficiencies of investment goods of different ages presented by Charles Hulten and Frank Wykoff (1981a, 1981b). The "hedonic" methodology employed for constructing constant quality price indices for investment goods was extended to capital goods of different ages or *vintages* by Robert Hall (1971). Hulten and Wykoff have estimated relative efficiences by age for all types of tangible assets included in NIPA from vintage price data for these assets.[9]

Hulten and Wykoff (1981a, 1981b) show that relative efficiencies for a wide range of assets decline geometrically at a constant rate. This is equal to the rate of depreciation and the rate of replacement. This finding has been corroborated by Hulten, Robertson, and Wykoff (1989). Jorgenson and Yun (1991b) have derived a depreciation rate equal to

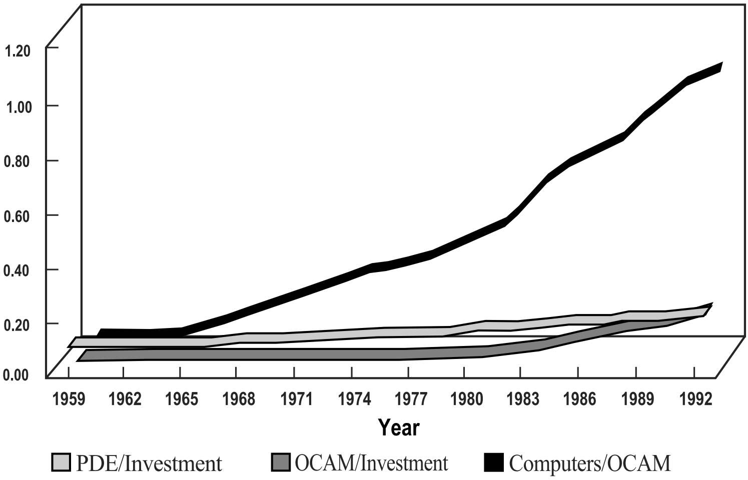


Figure 2.6
Share of capital services quantity, 1959–1992.

0.2729 for OCAM from the results of Hulten and Wykoff. Jorgenson and Christensen (1973) and Jorgenson (1980a) have introduced a simplified system of vintage accounts based on the assumption that the decline in relative efficiencies is geometric.

2.5 Computers and Growth

Jorgenson (1966) introduced a model of production based on an aggregate production possibility frontier as a generalization of Solow's (1960) concept of embodied technical change. This model also generalizes the aggregate production function by distinguishing between outputs of investment and consumption goods as well as inputs of capital and labor services. In the absence of constant quality price indices for investment goods, Jorgenson showed that economic growth could be interpreted, equivalently, as "embodied" in capital input or "disembodied" in the Solow (1957) residual.

Jorgenson and Griliches (1967) employed the production possibility frontier to link investment goods output and capital services input. For example, a constant quality price index for computers affects both the output of investment goods and the input of capital services. Jorgenson and Griliches identified embodiment with substitution between the output of investment goods and other outputs as well as substitution between capital input and other inputs. This required the introduction of constant quality price indices for investment goods, thereby removing the indeterminacy resulting from modeling embodiment by means of a time trend, as in Solow's model.[10]

To assess the impact of investment in computers on U.S. economic growth we employ an aggregate production possibility frontier with outputs of investment and consumption goods and inputs of capital and labor services. Computer investment from table 2.1 is a component of the output of investment goods and computer services from table 2.3 are a component of the input of capital services. Constant quality price indices for computers affect both the output of computer investment and the input of computer services. IDC inventory data for computers are incorporated into the measurement of stocks of computers in table 2.2 and flows of computer services in table 2.3.

At the aggregate level the output of the U.S. economy is represented by value added in constant dollars. Current dollar value added is the sum of the values of investment and consumption goods outputs. The price index for value added is constructed from price indices for outputs of investment and consumption goods. Constant dollar value added is the ratio of current dollar value added to this price index. The price index for investment goods includes the constant quality price index for computers presented in table 2.1. Growth rates of constant dollar value added is given for the period 1947–1992 in table 2.4. The average annual growth rate of value added is 3.42 percent per year for this period.

Table 2.4 also provides growth rates for nine subperiods: 1947–1953, 1953–1957, 1957–1960, 1960–1966, 1966–1969, 1969–1973, 1973–1979, 1979–1985, and 1985–1992. The endpoints of these subperiods, except for the last two, are years in which a cyclical peak occurred. The nine subperiods include two periods of relatively rapid growth, 1947–1953 and 1960–1966, and seven periods of relatively slow growth: 1953–1957, 1957–1960, 1966–1969, 1969–1973, 1973–1979, and 1979–1985, 1985–1992. Finally, table 2.4 gives growth rates of capital and labor inputs and productivity growth for the period 1947–1992 and the nine subperiods. Capital grows at an average annual rate of 3.41 percent per year, labor at 1.64 percent, and productivity at 1.03 percent for the period as a whole.

The contributions of capital and labor inputs to U.S. economic growth are obtained by weighting the corresponding growth rates by the shares of these inputs in value added. This produces the familiar allocation of growth to its sources. Capital input is by far the most important source of

Table 2.4
Growth rates of aggregate output, inputs, and productivity, 1947–1992

Variable	1947–1992	1947–1953	1953–1957	1957–1960	1960–1966	1966–1969	1969–1973	1973–1979	1979–1985	1985-1992
Value-Added	0.0342	0.0546	0.0214	0.0239	0.0538	0.0261	0.0367	0.0263	0.0289	0.0249
Non-computer Share	0.0333	0.0546	0.0214	0.0237	0.0530	0.0254	0.0360	0.0250	0.0265	0.0238
Computer Share	0.0009	0.0000	0.0000	0.0002	0.0008	0.0007	0.0008	0.0012	0.0024	0.0012
Capital Input	0.0341	0.0443	0.0331	0.0200	0.0323	0.0434	0.0400	0.0362	0.0299	0.0278
Labor Input	0.0164	0.0224	0.0036	(0.0001)	0.0263	0.0209	0.0126	0.0217	0.0154	0.0138
Contribution of Capital	0.0147	0.0192	0.0142	0.0083	0.0146	0.0193	0.0164	0.0145	0.0128	0.0126
Non-computer Share	0.0138	0.0192	0.0142	0.0083	0.0141	0.0185	0.0154	0.0135	0.0106	0.0109
Computer Share	0.0009	0.0000	0.0000	0.0000	0.0005	0.0009	0.0010	0.0010	0.0022	0.0017
Contribution of Labor	0.0092	0.0126	0.0019	(0.0001)	0.0144	0.0116	0.0074	0.0128	0.0083	0.0076
Productivity	0.0103	0.0227	0.0053	0.0157	0.0248	(0.0049)	0.0129	(0.0010)	0.0078	0.0047
Contribution of K Quality	0.0038	0.0051	0.0025	(0.0004)	0.0013	0.0057	0.0038	0.0045	0.0038	0.0060
Contribution of K Stock	0.0109	0.0142	0.0117	0.0088	0.0133	0.0136	0.0126	0.0100	0.0090	0.0066
Contribution of L Quality	0.0030	0.0070	0.0033	0.0007	0.0062	0.0031	(0.0002)	0.0017	0.0025	0.0012
Contribution of L Hours	0.0062	0.0056	(0.0014)	(0.0008)	0.0082	0.0086	0.0076	0.0111	0.0058	0.0064

growth in output, accounting for 43.0 percent of U.S. economic growth during the period 1947–1992, while labor input accounts for 26.9 percent of growth. Capital and labor inputs together account for 70.0 percent of growth and productivity growth accounts for 30.0 percent.

An important feature of the findings presented in table 2.4 is that the measure of capital input is based on the model of capital as a factor of production presented by Jorgenson (1989, 1990b) and summarized in section 2.2. The quantity of capital services is a weighted sum of past investments with relative efficiencies as weights The price of assets is the present value of future capital incomes, reflecting these same relative efficiencies. This model makes it possible to assimilate information on relative efficiencies from the empirical research of Hulten and Wykoff (1981a, 1981b) and Oliner (1993, 1994a).

The model of capital as a factor of production treats the flow of capital services for each type of asset as proportional to the stock of that asset. However, the price of capital input is a rental price rather than an asset price. This makes it possible to incorporate substitution among different types of capital inputs in response to changes in relative rental prices. These changes can be very dramatic, as we have shown by comparing constant quality rental prices of computers with those for other assets in table 2.3. However, changes in rental prices can also result from changes in tax policy, which affect the tax factors entering the pre-tax rental prices of capital inputs.

The growth rate of value added can be represented as the sum of contributions of computer and non-computer components. These contributions are obtained by weighting the corresponding growth rates by the shares of these components in value added. Although the growth rate of computer investment presented in table 2.1 is very large, the shares of computers in value added are very small, rising from zero in 1958 to a modest positive number at the end of the period in 1992.The contribution of computers to value added growth is only 0.09 percent per year or 2.63 percent of growth.

Alternatively, the growth rate of value added can be expressed as the sum of the contributions of capital and labor inputs and productivity growth. The contribution of capital input can be divided between computer and non-computer components. The contribution of computer services as an input is 0.09 percent per year or 2.63 percent of growth in value added. The contribution of computer services as an input is equal to the contribution of investment in computers as an output! The contribution of computer services as a proportion of the contribution of all capital input rises from zero in 1958 to more than twelve percent in 1992.

We can compare the constant quality measure of capital input employed in table 2.4 with an alternative measure based on capital stock. The contribution of capital input grows at an annual average rate of 1.47 percent, while the contribution of capital stock grows at only 1.09 percent per year. By omitting substitution among different types of capital services in response to changes in relative rental prices, the growth of capital stock underestimates the growth of capital input by 25.9 percent!

We refer to the difference between the contributions of capital input and capital stock as the contribution of capital quality. This difference reflects changes in the quality of an average unit of capital stock, viewed as an input into the U.S. economy. Just as we can hold the quality of the flow of computer investment output constant by introducing constant quality price indices for computers, we can hold the quality of the flow of computer services input constant by incorporating substitution in response to changes in constant quality rental prices. The growth of capital quality is a very significant component of the growth of a constant quality measure of capital services.

The measure of labor input presented in table 2.4 incorporates substitutions among different types of hours worked in response to changes in relative wages. These reflect differences in hourly wages for workers who differ in age, sex, and educational attainment. We refer to the difference between the contributions of labor input and hours worked as the contribution of labor quality. The contribution of labor input grows at an annual average rate of 0.92 percent, while the contribution of hours worked grows at only 0.62 percent. Omitting substitution among different types of labor services in response to changes in relative wages leads to underestimation of the growth of labor input by 32.6 percent!

Since productivity growth is calculated as a residual between the growth of output and the contributions of capital and labor inputs. it should include all alterations in production techniques that do not result from the growth of these inputs. If we were to employ a measure of computer output that fails to incorporate constant quality price indices for computers, this would lead to an underestimation of the growth of output and reduce residual productivity growth. However, it would also lead to underestimation of the growth of the input of computer services, increasing the growth of the residual.

Using the results presented in table 2.4, we can derive the implications of our constant quality measures of capital and labor inputs. The contribution of capital quality is 0.38 percent per year and the contribution of labor quality is 0.30 percent. If we were to add these changes to the residual, we would obtain a productivity growth rate of 1.71 percent per year. By failing to take account of substitutions among different components of capital stock we would reduce the contribution of capital input to 1.09 percent, while omitting substitutions among hours worked would reduce the contribution of labor input to 0.62 percent. The Solow (1957) residual would emerge as the most important source of U.S. economic growth.

Unfortunately, the Solow residual does not reflect the distinction between growth of inputs and productivity growth. By resorting to capital stock and hours worked in place of constant quality measures of capital and labor inputs we would transfer the substantial changes in the quality of capital stock and hours worked given in table 2.4 to the residual, leading to substantial underestimation of the growth of capital and labor inputs and overestimation of productivity growth. Substitution between capital and labor services can obviously take place, but it can equally well take place between computers and other forms of capital inputs, as we have shown in tables 2.3 and 2.4, above, or among different types of labor, as indicated in table 2.4.

In the model of production that underlies table 2.4 we have allowed for substitution between investment and consumption outputs and between capital and labor service inputs. We have also incorporated substitution among different types of investment goods including computer investment, as indicated in table 2.1, as well as substitution among different types of consumption goods. Finally, we have also incorporated substitution among capital inputs, including computer services, as indicated in table 2.3, as well as substitution among different types of labor inputs. By providing additional scope for modeling these substitutions we have arrived at the measure of productivity growth presented in table 2.4. *This differs from the Solow residual by 62.4 percent!*

An important limitation of the analysis of U.S. economic growth presented in table 2.4 is that Oliner (1993, 1994a) has provided retirement information from the IDC censuses of computer inventories only for processors and three types of peripherals—direct access storage drives (DASD), displays, and printers. For other types of peripherals and PCs we have employed the perpetual inventory method from the simplified accounting system based on geometric decline in efficiency. This system uses a single retirement rate of 0.2729 for all components of OCAM not modeled by Oliner. As Oliner (1993) points out, this is based on an econometric model of vintage prices for electric typewriters developed by Hulten and Wykoff (1981a, 1981b).

2.6 Conclusion

We conclude that the measures of computer investment included in NIPA and presented in table 2.1 can be incorporated into gross product of the U.S. economy. Using the model of computer technology introduced by Oliner (1993, 1994a), we have constructed measures of computer services as inputs into the U.S. economy. Unlike the capital stocks employed, for example, by Baily and Gordon (1988) Gordon (1990) and Baily and Schultze (1990) our capital input measures reflect substitution among capital inputs in response to changes in rental prices.

We have generated evidence of a massive substitution of computer services for other inputs in response to declines in computer prices. These pecuniary externalities, first identified by Bresnahan (1986) indicate that computer investment has had a very significant impact on U.S. economic growth. The apparent paradox that this impact does not appear in the form of nonpecuniary externalities can be resolved by focusing on the growth in inputs of computer services rather than "spillovers" that would appear as productivity growth.

While the introduction of constant quality price indices for computers into NIPA is a major achievement in economic measurement, a great deal remains to be done to capture fully the contribution of all forms of investment to U.S. economic growth. Gordon (1990) has demonstrated that price indices for noncomputer components of PDE in NIPA are subject to very substantial changes in quality over the period 1947–1983. For this period Gordon estimates the rate of quality change for all components of PDE, including computers, to be 2.96 percent per year.[11]

The largest quality changes estimated by Gordon are for OCAM at 9.32 percent per year, communications equipment, the category of PDE most closely related to OCAM, at 5.84 percent, and aircraft at 8.29 percent. By introducing constant quality price indices for all twenty-two components of PDE Gordon shows that the growth rate of private GNP rises from 3.17 percent per year for the period 1947–1983 to 3.40 percent. Capital stock growth rises from 3.51 percent per year for this period to 5.11 percent.

While Denison (1989, 1993) has recommended eliminating the constant quality price index for computers from NIPA in the interest of consistency, Gordon's results provide support for the conclusion reached by Baily and Gordon (1988) that Denison's recommendation should be reversed. Constant quality price indices should be introduced for all components of the national product, beginning with the remaining components of PDE.[12]

The next objective should be to revise the treatment of depreciation in NIPA to reflect information on inventories of assets prices like that compiled by Hulten and Wykoff (1981a, 1981b) and Oliner (1993, 1994a). This information is required for the valuation of stocks of capital, as in the BEA (1987) study, *Fixed Reproducible Tangible Wealth in the United States, 1925-1985*, and its successors. The information also provides the basis for estimates of the flows of capital services required for the analysis of sources of economic growth. Both constant quality price indices for investment goods and asset inventories will be needed for this purpose.

The ultimate objective of research on investment, capital stock, and capital services should be a unified system of income, production, and wealth accounts, like that originated by Christensen and Jorgenson (1973) and Jorgenson (1980a). The production account of such a system could provide the information required to implement the production approach to U.S. economic growth by decomposing growth in output among its sources, as in table 2.4 of the preceding section. The income account could generate the data on income, consumption, and saving needed to implement the welfare approach advocated by Denison (1989). A unified system would include information for all assets in the U.S. economy like that we have presented for computers.

Notes

1. Brynjolfsson (1993) has provided a detailed survey of studies of nonpecuniary externalities or "spill-overs." Recent studies include those of Brynjolfsson and Hitt (1994a. 1994b) and Lichtenberg (1993).

2. Robert M. Solow, quoted by Brynjolfsson (1993).

3. Erwin Diewert (1976) has shown that the indices utilized by Christensen and Jorgenson (1973) can be generated from the translog price functions introduced by Chrisstensen, Jorgenson and Lawrence Lau (1973).

4. The history of hedonic price indices is recounted by Ernst Berndt (1991).

5. Earlier, Richard Stone (1956), Griliches (1964), and Triplett (1983) had provided the rationale for introducing hedonic price indices into systems of national accounts.

6. Robert Gordon (1989, 1990b) has presented an alternative hedonic price index for computers.

7. For more details, see Jorgenson (1989, 1990b).

8. This is the "proportional retirement" assumption discussed by OIiner (1993); he also discusses an alternative "FIFO (first-in, first-out) retirement" assumption. However, only proportional retirement is consistent with Oliner's assumption that second hand prices are independent of chronological age.

9. Jorgenson (1994) surveys research on estimates of relative efficiencies from vintage price data. Recent research on this topic includes the papers by Hulten, James Robertson, and Wykoff (1989), and Wykoff (1989).

10. Hulten (1992) has estimated the proportion of U.S. economic growth accounted for within this framework, incorporating constant quality prices of all components of PDE in NIPA, including computers, from Gordon's (1990) magisterial study, *The Measurement of Durable Goods Prices*. Gordon (1990), Table 12.14, p. 557, presents a similar calculation.

11. A summary of Gordon's results is given in table 12.2, p. 536. The rate of quality change for all components of PDE is given in the line labeled, "Törnqvist."

12. Paul Pieper (1989, 1990) has provided constant quality price indices for the components of structures in NIPA.

3

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

Dale W. Jorgenson and
Kevin J. Stiroh

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

3.1 Introduction

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

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

The late 1990s have been exceptional in comparison with the growth experience of the U.S. economy over the past quarter century. While growth rates in the 1990s have not yet returned to those of the Golden Age of the U.S. economy in the 1960s, the data nonetheless clearly reveal a remarkable transformation of economic activity. Rapid declines in the prices of computers and semiconductors are well known and carefully documented, and evidence is accumulating that similar declines are taking place in the prices of software and communications equipment. Unfortunately, the empirical record is seriously incomplete, so much remains to be done before definitive quantitative assessments can be made about the complete role of these high-tech assets.

Despite the limitations of the available data, the mechanisms underlying the structural transformation of the U.S. economy are readily apparent. As an illustration, consider the increasing role that computer hardware plays as a source of economic growth.[3] For the period 1959 to 1973, computer inputs contributed less than one-tenth of one percent to U.S. economic growth. Since 1973, however, the price of computers has fallen at historically unprecedented rates and firms and households have followed a basic principle of economics—they have substituted towards relatively cheaper inputs. Since 1995 the price decline for computers has accelerated, reaching nearly 28 percent per year from 1995 to 1998. In response, investment in computers has exploded and the growth contribution of computers increased more than five-fold to 0.46 percentage points per year in the late 1990s.[4] Software and communications equipment, two other information technology assets, contributed an additional 0.30 percentage points per year for 1995–1998. Preliminary estimates through 1999 reveal further increases in these contributions for all three high-tech assets.

Next, consider the acceleration of average labor productivity (ALP) growth in the 1990s. After a 20-year slowdown dating from the early 1970s, ALP grew 2.4 per year for 1995–1998, more than a percentage point faster than during 1990–1995.[5] A detailed decomposition shows that capital deepening, the direct consequence of price-induced substitution and rapid investment, added 0.49 percentage points to ALP growth. Faster total factor productivity (TFP) growth contributed an additional 0.63 percentage points, largely reflecting technical change in the production of computers and the resulting acceleration in the price decline of computers. Slowing labor quality growth retarded ALP growth by 0.12 percentage points relative to the early 1990s, a result of exhaustion of the pool of available workers.

Focusing more specifically on TFP growth, this was an anemic 0.34 percent per year for 1973–1995, but accelerated to 0.99 percent for 1995–1998. After more than twenty years of sluggish TFP growth, four of the last five years have seen growth rates near 1 percent. It could be argued this represents a new paradigm. According to this view, the diffusion of information technology improves business practices, generates spillovers, and raises productivity throughout the economy. If this trend is sustainable, it could revive the optimistic expectations of the 1960s and overcome the pessimism of *The Age of Diminished Expectations,* the title of Krugman's (1990) influential book.

A closer look at the data, however, shows that gains in TFP growth can be traced in substantial part to information technology industries, which produce computers, semiconductors, and other high-tech gear. The evidence is equally clear that computer-using industries like finance, insurance, and real estate (FIRE) and services have continued to lag in productivity growth. Reconciliation of massive high-tech investment and relatively slow productivity growth in service industries remains an important task for proponents of the new economy position.[6]

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

In this respect, the recent experience provides grounds for caution, since much depends on productivity gains in high-tech industries. Ongoing technological gains in these industries have been a direct source of improvement in TFP growth, as well as an indirect source of more rapid capital deepening. Sustainability of growth, therefore, hinges critically on the pace of technological progress in these industries. As measured by relative price changes, progress has accelerated recently, as computer prices fell 28 percent per year for 1995–1998 compared to 15 percent in 1990–1995. There is no guarantee, of course, of continued productivity gains and price declines of this magnitude. Nonetheless, as long as high-tech industries maintain the ability to innovate and improve their productivity at rates comparable even to their long-term averages, relative prices will fall and the virtuous circle of an investment-led expansion will continue.[7]

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

The paper is organized as follows. Section 3.2 describes our methodology for quantifying the sources of U.S. economic growth. We present results for the period 1959–1998, and focus on the ″new economy″ era of the late 1990s. Section 3.3 explores the implications of the recent experience for future growth, comparing our results to recent estimates produced by the Congressional Budget Office, the Council of Economic Advisors, and the Office of Management and Budget. Section 3.4 moves beyond the aggregate data and quantifies the productivity growth at the industry level. Using methodology introduced by Domar (1961), we consider the impact of information technology on aggregate productivity. Section 3.5 concludes.

3.2 The Recent U.S. Growth Experience

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

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

3.2.1 Sources of Economic Growth

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

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

3.2.1.1 Production Possibility Frontier

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

$$Y(I_t, C_t) = A_t \cdot X(K_t, L_t). \tag{3.1}$$

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

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

$$\overline{w}_{I,t}\Delta \ln I_t + \overline{w}_{C,t}\Delta \ln C_t = \overline{v}_{K,t}\Delta \ln K_t + \overline{v}_{L,t} \ln L_t + \Delta \ln A_t, \tag{3.2}$$

where $\overline{w}_{I,t}$ is investment's average share of nominal output, $\overline{w}_{C,t}$ is consumption's average share of nominal input, $\overline{v}_{K,t}$ is capital's average share of nominal income, $\overline{v}_{K,t}$ is labor's average share of nominal income, $\overline{w}_{I,t} + \overline{w}_{C,t} = \overline{v}_{K,t} + \overline{v}_{L,t} = 1$ and Δ refers to a first difference. Note that we reserve the term *total factor productivity* for the augmentation factor in equation (3.1).

Equation (3.2) enables us to identify the contributions of outputs as well as inputs to economic growth. For example, we can quantify the contributions of different investments, such as computers, software, and communications equipment, to the growth of output by decomposing the growth of investment among its subcomponents. Similarly, we can quantify the contributions of different types of consumption, such as services from computers and software, by decomposing the growth of consumption. As shown in Jorgenson and Stiroh (1999), both computer investment and consumption of IT have made important contributions to U.S. economic growth in the 1990s. We also consider the output contributions of software and communications equipment as distinct high-tech assets. Similarly, we decompose the contribution of capital income to isolate the impact of computers, software, and communications equipment on input growth.

Rearranging equation (3.2) enables us to present results in terms of growth in *average labor productivity* (ALP), defined as $y_t = Y_t/H_t$, where Y_t is output, defined as an aggregate of consumption and investment goods, and $k_t = K_t/H_t$ is the ratio of capital services to hours worked H_t:

$$\Delta \ln y_t = \overline{v}_{K,t} \Delta \ln k_t + \overline{v}_{L,t}(\Delta \ln L_t - \Delta \ln H_t) + \Delta \ln A_t. \qquad (3.3)$$

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

3.2.1.2 Computers, Software, and Communications Equipment

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

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

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

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

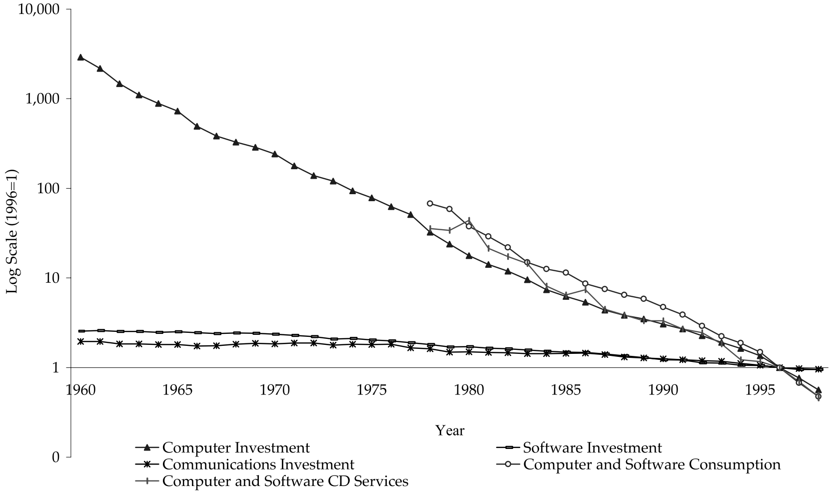
The remainder of this section provides empirical estimates of the variables in equations (3.1) through (3.3). We then employ equations (3.2) and (3.3) to quantify the sources of growth of output and ALP for 1959–1998 and various subperiods.

3.2.2 *Output*

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

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

The most striking feature of these data is the enormous price decline for computer investment, 18 percent per year from 1960 to 1995



Note: All prices indexes are relative to the output price index.

Figure 3.1
Relative prices of information technology outputs, 1960–1998.

(figure 3.1). Since 1995 this decline has accelerated to 27.6 percent per year. By contrast the relative price of software has been flat for much of the period and only began to fall in the late 1980s. The price of communications equipment behaves similarly to the software price, while consumption of computers and software shows declines similar to computer investment. The top panel of table 3.1 summarizes the growth rates of prices and quantities for major output categories for 1990–1995 and for 1995–1998.

In terms of current dollar output, investment in software is the largest IT asset, followed by investment in computers and communications equipment (figure 3.2). While business investments in computers, software, and communications equipment are by far the largest categories, households have spent more than $20B per year on computers and software since 1995, generating a service flow of comparable magnitude.

3.2.3 Capital Stock and Capital Services

This section describes our capital estimates for the U.S. economy from 1959 to 1998.[14] We begin with investment data from the Bureau of Economic Analysis, estimate capital stocks using the perpetual inventory method, and aggregate capital stocks using rental prices as weights.

Table 3.1
Average growth rates of selected outputs and inputs

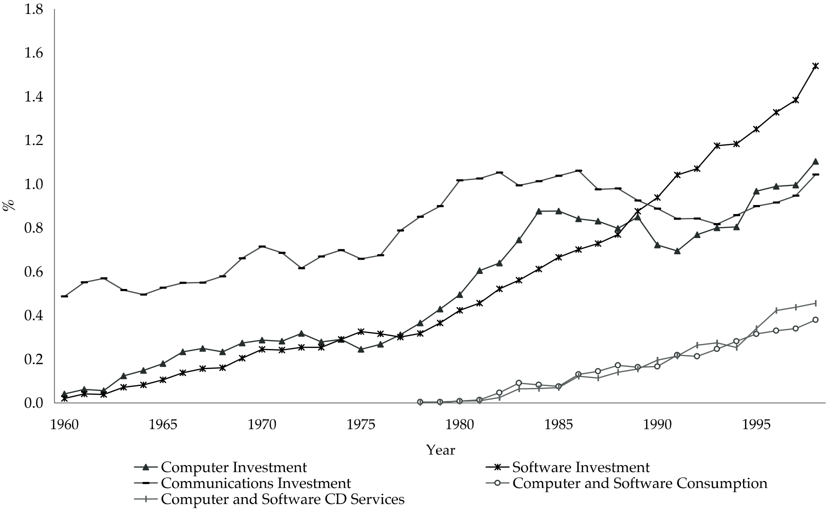
	1990–1995		1995–1998	
	Prices	Quantities	Prices	Quantities
		Outputs		
Private Domestic Output (Y)	1.70	2.74	1.37	4.73
Other (Y_n)	2.01	2.25	2.02	3.82
Computer and Software Consumption (C_c)	−21.50	38.67	−36.93	49.26
Computer Investment (I_c)	−14.59	24.89	−27.58	38.08
Software Investment (I_s)	−1.41	11.59	−2.16	15.18
Communications Investment (I_m)	−1.50	6.17	−1.73	12.79
Computer and Software CD Services (D_c)	−19.34	34.79	−28.62	44.57
		Inputs		
Total Capital Services (K)	0.60	2.83	2.54	4.80
Other (K_n)	1.00	1.78	4.20	2.91
Computer Capital (K_c)	−10.59	18.16	−20.09	34.10
Software Capital (K_s)	−2.07	13.22	−0.87	13.00
Communications Capital (K_m)	3.10	4.31	−7.09	7.80
Total Consumption Services (D)	1.98	2.91	−0.67	5.39
Non-Computer and Software (D_n)	2.55	2.07	0.54	3.73
Computer and Software CD Services (D_c)	−19.34	34.79	−28.62	44.57
Labor (L)	2.92	2.01	2.80	2.81

Notes: CD refers to consumers' durable assets. All values are percentages.

This approach, originated by Jorgenson and Griliches (1967), is based on the identification of rental prices with marginal products of different types of capital. Our estimates of these prices incorporate differences in asset prices, service lives and depreciation rates, and the tax treatment of capital incomes.[15]

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

We employ a broad definition of capital, including tangible assets such as equipment and structures, as well as consumers' durables, land, and inventories. We estimate a service flow from the installed stock of consumers' durables, which enters our measures of both output



Note: Share of current dollar output.

Figure 3.2
Output shares of information technology, 1960–1998.

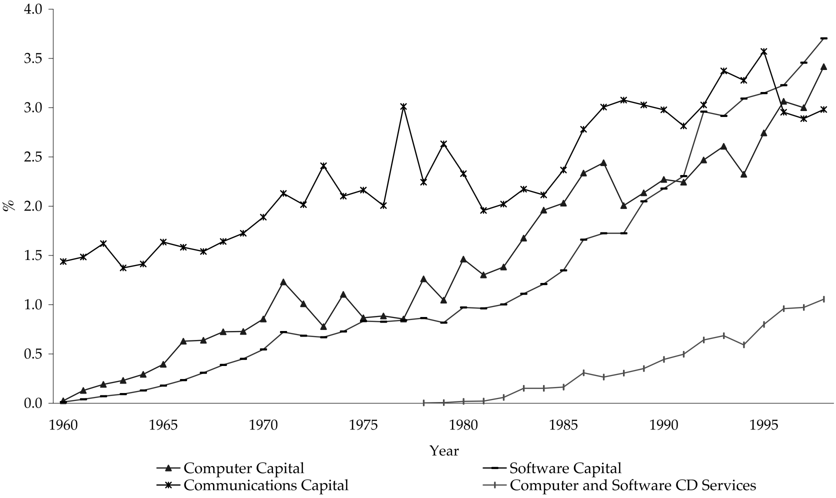
and input. It is essential to include this service flow, since a steadily rising proportion is associated with investments in IT by the household sector. In order to capture the impact of information technology on U.S. economic growth, investments by business and household sectors as well as the services of the resulting capital stocks must be included.

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

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

We now move to estimates of capital services flows, where capital stocks of individual assets are aggregated using rental prices as weights. Appendix table B.3 presents the current dollar service flows and corresponding price indexes for 1959–1998, and the second panel of table 3.1 summarizes the growth rates for prices and quantities of inputs for 1990–1955 and 1995–1998.

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



Note: Share of current dollar capital and consumers' durable services.

Figure 3.3
Input shares of information technology, 1960–1998.

Figure 3.3 highlights the rapid increase in the importance of IT assets, reflecting the accelerating pace of relative price declines. In the 1990s, the service price for computer hardware fell 14.2 percent per year, compared to an increase of 2.2 percent for non-information technology capital. As a direct consequence of this relative price change, computer services grew 24.1 percent, compared to only 3.6 percent for the services of non-IT capital in the 1990s. The current dollar share of services from computer hardware increased steadily and reached nearly 3.5 percent of all capital services in 1998 (figure 3. 3).[17]

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

A competing explanation is that the official price indexes used to deflate software investment omit a large part of true quality improvements. This would lead to a substantial overstatement of price inflation and a corresponding understatement of real investment, capital services, and economic growth. According to Moulton, Parker, and Seskin (1999) and Parker and Grimm (2000a), only prices for prepackaged software are calculated from constant-quality price deflators based on hedonic methods. Prices for business own-account software are based on input-cost indexes, which implicitly assume no change in the productivity of computer programmers. Custom software prices are a weighted average of prepackaged software and own-account software, with an arbitrary 75 percent weight for business own-account software prices. Thus, the price deflators for nearly two-thirds of recent software investment are estimated under the maintained assumption of no gain in productivity.[19] If the quality of own-account and custom software is improving at a pace even remotely close to packaged software, this implies a large understatement in investment in software.

Although the price decline for communications equipment during the 1990s is comparable to that of software, as officially measured in the NIPA, investment has grown at a rate that is more in line with prices. However, there are also possible measurement biases in the pricing of communications equipment. The technology of switching equipment, for example, is similar to that of computers; investment in this category is deflated by a constant-quality price index developed by BEA. Conventional price deflators are employed for transmission gear, such as fiber-optic cables, which also appear to be declining rapidly in price. This could lead to an underestimate of the rate of growth in communications equipment investment, capital stock, and capital services, as well as an overestimate of the rate of inflation.[20] We return to this issue at the end of section 3.2.

3.2.4 Measuring Labor Services

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

The distinction between labor input and labor hours is analogous to the distinction between capital services and capital stock. Growth in labor input reflects the increase in labor hours, as well as changes in the composition of hours worked as firms substitute among heterogeneous types of labor. We define the growth in labor quality as the difference between the growth in labor input and hours worked. Labor quality reflects the substitution of workers with high marginal products for those with low marginal products, while the growth in hours employed by Solow (1957) and others does not capture this substitution. Appendix table C.1 presents our estimates of labor input, hours worked, and labor quality.

Our estimates show a value of labor expenditures of $4,546B in 1998, roughly 57 percent of the value of output. This share accurately includes private output and our imputations for capital services. If we exclude these imputations, labor's share rises to 62 percent, in line with conventional estimates. As shown in table 3.1, the growth of the index of labor input L_t appropriate for our model of production in equation (3.1) accelerated to 2.8 percent for 1995–1998, from 2.0 percent for 1990–1995. This is primarily due to the growth of hours worked, which rose from 1.4 percent for 1990–1995 to 2.4 percent for 1995–1998, as labor force participation increased and unemployment rates plummeted.[22]

The growth of labor quality decelerated in the late 1990s, from 0.65 percent for 1990–1995 to 0.43 percent for 1995–1998. This slowdown captures well-known underlying demographic trends in the composition of the work force, as well as exhaustion of the pool of available workers as unemployment rates have steadily declined. Projections of future economic growth that omit labor quality, like those of CBO discussed in section 3.3, implicitly incorporate changes in labor quality into measured TFP growth. This reduces the reliability of projections of future economic growth. Fortunately, this is easily remedied by extrapolating demographic changes in the work force in order to reflect foreseeable changes in composition by characteristics of workers such as age, sex, and educational attainment.

3.2.5 *Quantifying the Sources of Growth*

Table 3.2 presents results of our growth accounting decomposition based on an extension of equation (3.2) for the period 1959 to 1998 and various subperiods, as well as preliminary estimates through 1999. As in Jorgenson and Stiroh (1999), we decompose economic growth by both output and input categories in order to quantify the contribution of information technology (IT) to investment and consumption outputs, as well as capital and consumers' durable inputs. We extend our previous treatment of the outputs and inputs of computers by identifying software and communications equipment as distinct IT assets.

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

$$Y(Y_n, C_c, I_c, I_s, I_m, D_c) = A \cdot X(K_n, K_c, K_s, K_m, D_n, D_c, L), \qquad (3.4)$$

where outputs include computer and software consumption C_c, computer investment I_c, software investment I_s, telecommunications investment I_m, the services of consumers' computers and software D_c, and other outputs Y_n. Inputs include the capital services of computers K_c, software K_s, telecommunications equipment K_m, and other capital assets K_n, services of consumers' computers and software D_c and other

Table 3.2
Growth in U.S. private domestic output and the sources of growth, 1959–1999

	1959–1998	1959–1973	1973–1990	1990–1995	1995–1998	Prelim. 1995–1999
Growth in Private Domestic Output Growth (Y)	3.630	4.325	3.126	2.740	4.729	4.763
Contribution of Selected Output Components						
Other (Y_n)	3.275	4.184	2.782	2.178	3.659	3.657
Computer and Software Consumption (C_c)	0.035	0.000	0.023	0.092	0.167	0.175
Computer Investment (I_c)	0.150	0.067	0.162	0.200	0.385	0.388
Software Investment (I_s)	0.074	0.025	0.075	0.128	0.208	0.212
Communications Investment (I_m)	0.060	0.048	0.061	0.053	0.122	0.128
Computer and Software CD Services (D_c)	0.036	0.000	0.023	0.089	0.187	0.204
Contribution of Capital Services (K)	1.260	1.436	1.157	0.908	1.611	1.727
Other (K_n)	0.936	1.261	0.807	0.509	0.857	0.923
Computers (K_c)	0.177	0.086	0.199	0.187	0.458	0.490
Software (K_s)	0.075	0.026	0.071	0.154	0.193	0.205
Communications (K_m)	0.073	0.062	0.080	0.058	0.104	0.109
Contribution of CD Services (D)	0.510	0.632	0.465	0.292	0.558	0.608
Other (D_n)	0.474	0.632	0.442	0.202	0.370	0.403
Computers and Software (D_c)	0.036	0.000	0.023	0.089	0.187	0.204
Contribution of Labor (L)	1.233	1.249	1.174	1.182	1.572	1.438
Aggregate Total Factor Productivity (TFP)	0.628	1.009	0.330	0.358	0.987	0.991
Growth of Capital and CD Services	4.212	4.985	3.847	2.851	4.935	5.286
Growth of Labor Input	2.130	2.141	2.035	2.014	2.810	2.575

Table 3.2 (continued)

	1959– 1998	1959– 1973	1973– 1990	1990– 1995	1995– 1998	Prelim. 1995– 1999
Contribution of Capital and CD Quality	0.449	0.402	0.405	0.434	0.945	1.041
Contribution of Capital and CD Stock	1.320	1.664	1.217	0.765	1.225	1.293
Contribution of Labor Quality	0.315	0.447	0.200	0.370	0.253	0.248
Contribution of Labor Hours	0.918	0.802	0.974	0.812	1.319	1.190
Average Labor Productivity (ALP)	2.042	2.948	1.437	1.366	2.371	2.580

Notes: A contribution of an output and an input is defined as the share-weighted, real growth rate. CD refers to consumers' durable assets. All values are percentages. 1995–1999 results include preliminary estimates for 1999; see the Appendix for details on estimation and data sources.

durables D_n, and labor input L.[23] As in equation (3.1), total factor productivity is denoted by A and represents the ability to produce more output from the same inputs. Time subscripts have been dropped for convenience.

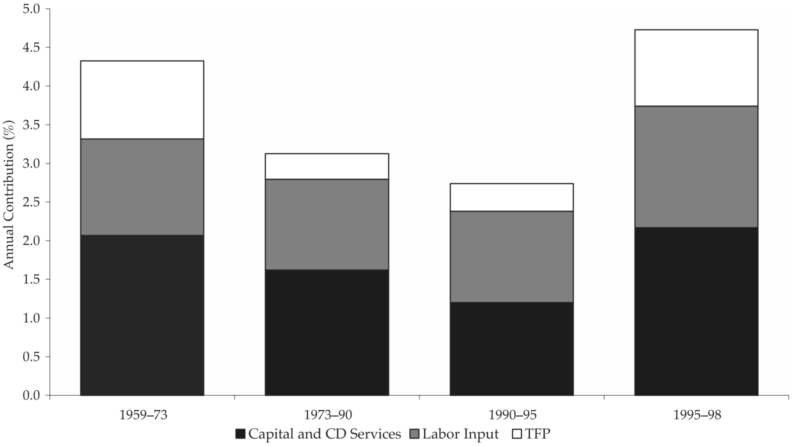
The corresponding extended growth accounting equation is:

$$\begin{aligned}
&\overline{w}_{Y_n}\Delta \ln Y_n + \overline{w}_{C_c}\Delta \ln C_c + \overline{w}_{I_c}\Delta \ln I_c + \overline{w}_{I_s}\Delta \ln I_c + \overline{w}_{I_s}\Delta \ln I_s \\
&\quad + \overline{w}_{I_m}\Delta \ln I_m + \overline{w}_{D_c}\Delta \ln D_c \\
&\quad = \overline{v}_{K_n}\Delta \ln K_n + \overline{v}_{K_c}\Delta \ln K_c + \overline{v}_{K_s}\Delta \ln K_s + \overline{v}_{K_m}\Delta \ln K_m \\
&\quad + \overline{v}_{D_n}\Delta \ln D_n + \overline{v}_{D_c}\Delta \ln D_c + \overline{v}_L\Delta \ln L + \Delta \ln A \qquad (3.5)
\end{aligned}$$

where $\overline{w}$ and $\overline{v}$ denote average shares in nominal income for the subscripted variable

$$\begin{aligned}
&\overline{w}_{Y_n} + \overline{w}_{C_c} + \overline{w}_{I_c} + \overline{w}_{I_s} + \overline{w}_{I_m} + \overline{w}_{D_c} \\
&\quad = \overline{v}_{K_n} + \overline{v}_{K_c} + \overline{v}_{K_s} + \overline{v}_{K_m} + \overline{v}_{D_n} + \overline{v}_{D_c}\overline{v}_L = 1,
\end{aligned}$$

and we refer to a share-weighted growth rate as the *contribution* of an input or output.



Note: An input's contribution is the average share-weighted, annual growth rate. TFP defined in equation (3.2) in text.

Figure 3.4
Sources of U.S. economic growth, 1959–1998.

3.2.5.1 Output Growth

We first consider the sources of output growth for the entire period 1959 to 1998. Broadly defined capital services make the largest growth contribution of 1.8 percentage point (1.3 percentage points from business capital and 0.5 from consumers' durable assets), labor services contribute 1.2 percentage points, and TFP growth is responsible for only 0.6 percentage points. Input growth is the source of nearly 80 percent of U.S. growth over the past 40 years, while TFP has accounted for approximately one-fifth. Figure 3.4 highlights this result by showing the relatively small growth contribution of the TFP residual in each subperiod.

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

A look at the U.S. economy before and after 1973 reveals some familiar features of the historical record. After strong output and TFP growth in the 1960s and early 1970s, the U.S. economy slowed markedly through

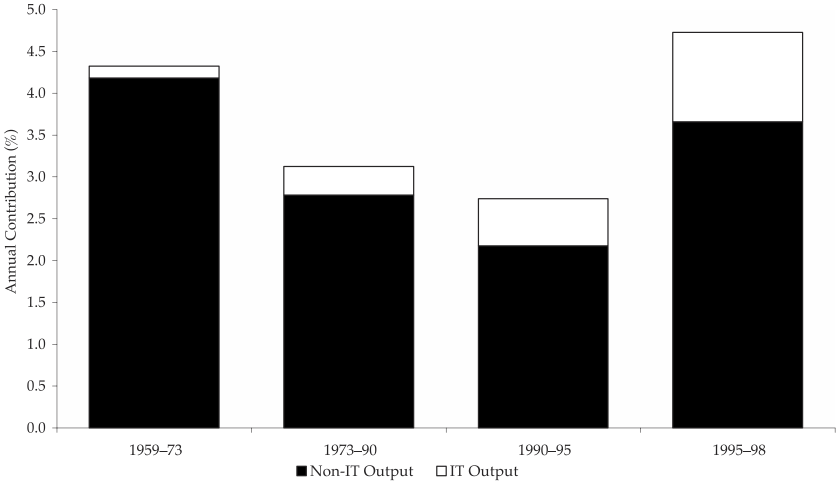
1990, with output growth falling from 4.3 percent to 3.1 percent and TFP growth falling almost two-thirds of a percentage point from 1.0 percent to 0.3 percent. Growth in capital inputs also slowed, falling from 5.0 percent for 1959–1973 to 3.8 percent for 1973–1990, which contributed to sluggish ALP growth, 2.9 percent for 1959–1973 to 1.4 percent for 1973–1990.

We now focus on the 1990s and highlight recent changes.[24] Relative to the early 1990s, output growth has increased by nearly two percentage points for 1995–1998. The contribution of capital jumped by 1.0 percentage point, the contribution of labor rose by 0.4 percentage points, and TFP growth accelerated by 0.6 percentage point. ALP growth rose 1.0 percentage point. The rising contributions of capital and labor encompass several well-known trends in the late 1990s. Growth in hours worked accelerated as labor markets tightened, unemployment fell to a 30-year low, and labor force participation rates increased.[25] The contribution of capital reflects the investment boom of the late 1990s as businesses poured resources into plant and equipment, especially computers, software, and communications equipment.

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

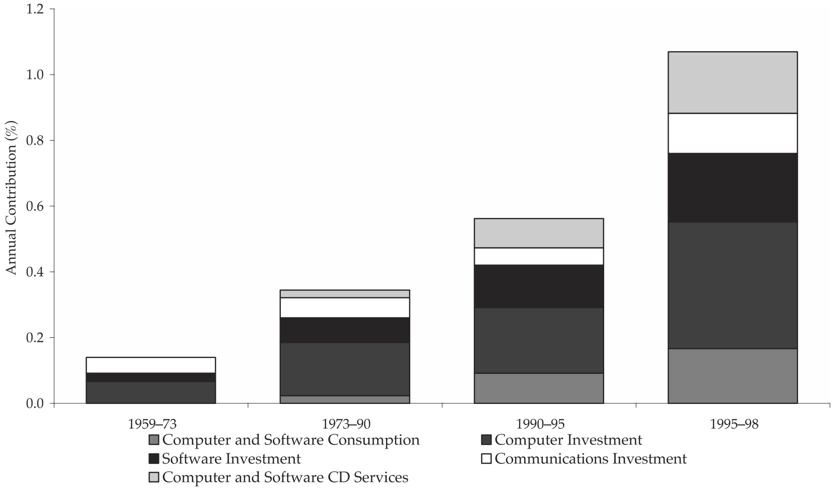
Figures 3.5 and 3.6 highlight the rising contributions of information technology (IT) outputs to U.S. economic growth. Figure 3.5 shows the breakdown between IT and non-IT outputs for the subperiods from 1959 to 1998, while figure 3.6 decomposes the contribution of IT outputs into the five components we identified above. Although the role of IT has steadily increased, figure 3.5 shows that the recent investment and consumption surge nearly doubled the output contribution of IT for 1995–1998 relative to 1990–1995. Figure 3.5 shows that computer investment is the largest single IT contributor in the late 1990s, and that consumption of computers and software is becoming increasingly important as a source of output growth.

Figures 3.7 and 3.8 present a similar decomposition of the role of IT as a production input, where the contribution is rising even more dramatically. Figure 3.7 shows that the capital and consumers' durable contribution from IT increased rapidly in the late 1990s, and now accounts for more two-fifths of the total growth contribution from broadly



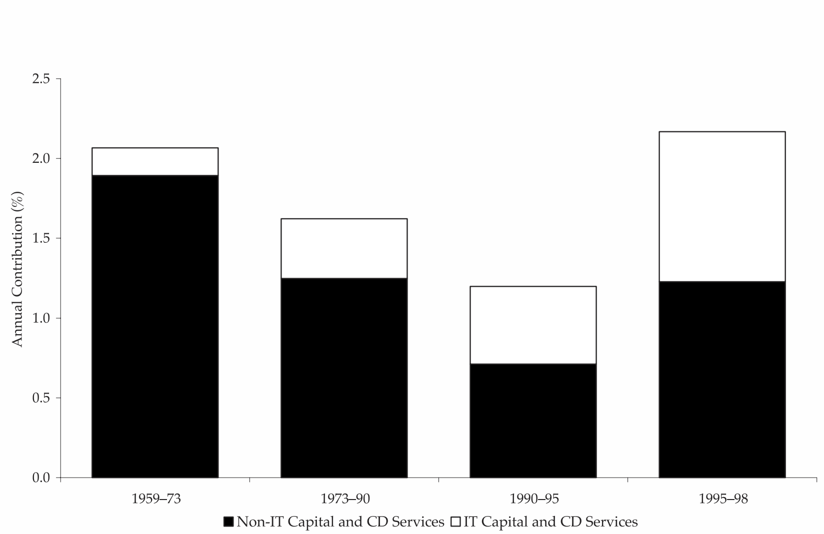
Note: An output's contribution is the average share-weighted, annual growth rate.

Figure 3.5
Output contribution of information technology, 1959–1998.



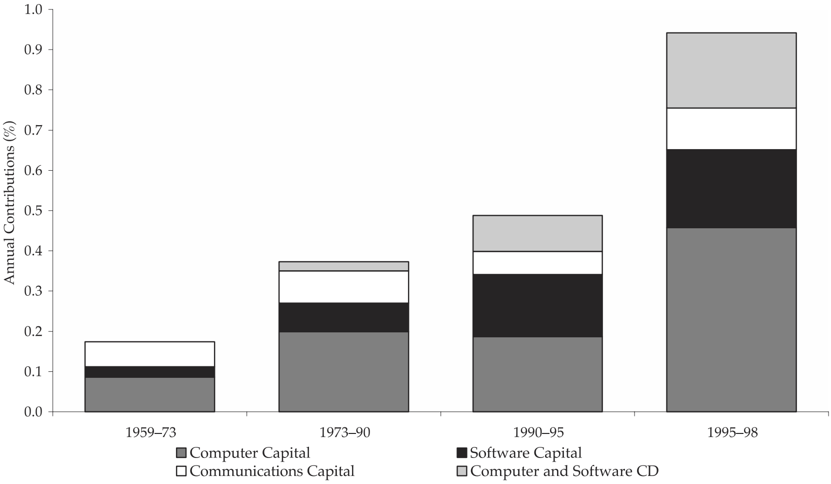
Note: An output's contribution is the average share-weighted, annual growth rate.

Figure 3.6
Output contribution of information technology assets, 1959–1998.



Note: An input's contribution is the average share-weighted, annual growth rate.

Figure 3.7
Input contribution of information technology, 1959–1998.



Note: An input's contribution is the average share-weighted, annual growth rate.

Figure 3.8
Input contribution of information technology assets, 1959–1998.

defined capital. Figure 3.8 shows that computer hardware is also the single largest IT contributor on the input side, which reflects the growing share and rapid growth rates of the late 1990s.

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

This large increase in the growth contribution of computers and software is consistent with recent estimates by Oliner and Sichel (2000), although their estimate of contribution is somewhat larger. They report that computer hardware and software contributed 0.93 percentage points to growth for 1996–1999, while communications contributed another 0.15. The discrepancy primarily reflects our broader output concept, which lowers the input share of these high-tech assets, and also minor differences in tax parameters and stock estimates. Whelan (1999) also reports a larger growth contribution of 0.82 percentage points from computer hardware for 1996–1998. The discrepancy also reflects our broader output concept. In addition, Whelan (1999) introduces a new methodology to account for retirement and support costs that generates a considerably larger capital stock and raises the input share and the growth contribution from computer capital.

Despite differences in methodology and data sources among studies, a consensus is building that computers are having a substantial impact on economic growth.[27] What is driving the increase in the contributions of computers, software, and communications equipment? As we argued in Jorgenson and Stiroh (1999), price changes lead to substitution toward

Table 3.3
The sources of ALP growth, 1959–1998

Variable	1959–1998	1959–1973	1973–1990	1990–1995	1995–1998
Growth of Private Domestic Output (Y)	3.630	4.325	3.126	2.740	4.729
Growth in Hours (H)	1.588	1.377	1.689	1.374	2.358
Growth in ALP (Y/H)	2.042	2.948	1.437	1.366	2.371
ALP Contribution of Capital Deepening	1.100	1.492	0.908	0.637	1.131
ALP Contribution of Labor Quality	0.315	0.447	0.200	0.370	0.253
ALP Contribution of TFP	0.628	1.009	0.330	0.358	0.987

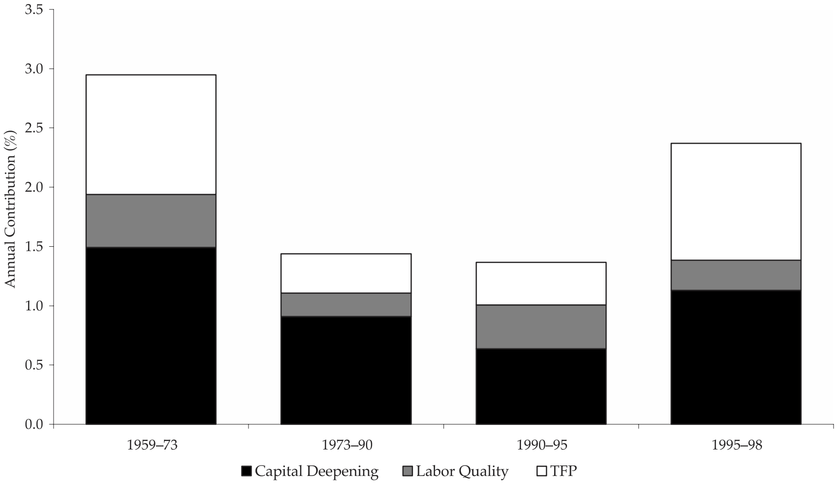
Notes: ALP contributions are defined in equation (3.3). All values are percentages.

capital services with lower relative prices. Firms and consumers are responding to relative price changes.

Table 3.1 shows the acquisition price of computer investment fell nearly 28 percent per year, the price of software fell 2.2 percent, and the price of communications equipment fell 1.7 percent during the period 1995–1998, while other output prices rose 2.0 percent. In response to these price changes, firms accumulated computers, software, and communications equipment more rapidly than other forms of capital. Investment other than information technology actually declined as a proportion of private domestic product. The story of household substitution toward computers and software is similar. These substitutions suggest that gains of the computer revolution accrue to firms and households that are adept at restructuring activities to respond to these relative price changes.

3.2.5.2 Average Labor Productivity Growth

To provide a different perspective on the sources of economic growth we can focus on ALP growth. By simple arithmetic, output growth equals the sum of hours growth and growth in labor productivity.[28] Table 3.3 shows the output breakdown between growth in hours and ALP for the same periods as in table 3.2. For the entire period 1959–1998, ALP growth was the predominant determinant of output growth, increasing just over 2 percent per year for 1959–1998, while hours increased about 1.6 percent per year. We then examine the changing importance of the factors determining ALP growth. As shown in equation (3.3), ALP growth depends on a capital deepening effect, a labor quality effect, and a TFP effect.



Note: Annual contributions are defined in equation (3.3) in text.

Figure 3.9
Sources of U.S. labor productivity growth, 1959–1998.

Figure 3.9 plots the importance of each factor, revealing the well-known productivity slowdown of the 1970s and 1980s, and highlighting the acceleration of labor productivity growth in the late 1990s. The slowdown through 1990 reflects less capital deepening, declining labor quality growth, and decelerating growth in TFP. The growth of ALP slipped further during the early 1990s with the serious slump in capital deepening only partly offset by a revival in the growth of labor quality and an uptick in TFP growth. Slow growth in hours combined with slow ALP growth during 1990–1995 to produce a further slide in the growth of output. This stands out from previous cyclical recoveries during the postwar period, when output growth accelerated during the recovery, powered by more rapid hours and ALP growth.

For the most recent period of 1995–1998, strong output growth reflects growth in labor hours and ALP almost equally. Comparing 1990–1995 to 1995–1998, output growth accelerated by nearly two percentage points due to a one percentage point increase in hours worked, and a 1.0 percentage point increase in ALP growth.[29] Figure 3.9 shows the acceleration in ALP growth is due to rapid capital deepening from the investment boom, as well as faster TFP growth. Capital deepening contributed 0.49 percentage points to the acceleration in ALP growth, while acceleration in TFP growth added 0.63 percentage points. Growth in labor quality slowed somewhat as growth in hours accelerated. This reflects the falling unemployment rate and tightening of labor markets as more workers with relatively low marginal products were drawn into the work force. Oliner and Sichel (2000) also show a decline in the growth contribution of labor quality in the late 1990s, from 0.44 for 1991–1995 to 0.31 for 1996–1999.

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

3.2.5.3 Total Factor Productivity Growth

Finally, we consider the remarkable performance of U.S. TFP growth in recent years. After maintaining an average rate of 0.33 percent for the period 1973–1990, TFP growth rose to 0.36 percent for 1990–1995 and then vaulted to 0.99 percent per year for 1995–1998. This jump is a major source of growth in output and ALP for the U.S. economy (figures 3.4 and 3.9). While TFP growth for the 1990s has yet to attain the peaks of some periods in the Golden Age of the 1960s and early 1970s, the recent acceleration suggests that the U.S. economy may be recuperating from the anemic productivity growth of the past two decades. Of course, caution is warranted until more historical experience is available.

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

3.2.6 Alternative Growth Accounting Estimates

Tables 3.1 through 3.3 and figures 3.1 through 3.9 report our primary results using the official data published in the NIPA. As we have already noted, however, there is reason to believe that the rates of inflation in official price indices for certain high-tech assets, notably software and telecommunications equipment, may be overstated. Moulton, Parker, and Seskin (1999) and Parker and Grimm (2000a), for example, report that only the prepackaged portion of software investment is deflated with a constant-quality deflator. Own-account software is deflated with an input cost index and custom software is deflated with a weighted average of the prepackaged and own-account deflator. Similarly, BEA reports that in the communications equipment category, only telephone switching equipment is deflated with a constant-quality, hedonic deflator.

This subsection incorporates alternative price series for software and communications equipment and examines the impact on the estimates of U.S. economic growth and its sources. Table 3.4 presents growth accounting results under three different scenarios. The Base Case repeats the estimates from table 3.2, which are based on official NIPA price data. Two additional cases, Moderate Price Decline and Rapid Price Decline, incorporate price series for software and communications equipment that show faster price declines and correspondingly more rapid real investment growth.[30]

The Moderate Price Decline case assumes that prepackaged software prices are appropriate for all types of private software investment, including custom and business own-account software. Since the index for prepackaged software is based on explicit quality adjustments, it falls much faster than the prices of custom and own-account software, −10.1 percent vs. 0.4 percent and 4.1 percent respectively, for the full period 1959–1998 according to Parker and Grimm (2000a). For communications equipment, the data are more limited and we assume prices fell 10.7 percent per year throughout the entire period. This estimate is the average annual "smoothed" decline for digital switching equipment for 1985–1996 reported by Grimm (1997). While this series may not be appropriate for all types of communications equipment, it exploits the best available information.

The Rapid Price Decline case assumes that software prices fell 16 percent per year for 1959–1998, the rate of quality-adjusted price decline reported by Brynjolfsson and Kemerer (1996) for microcomputer spreadsheets for 1987–1992. This is a slightly faster decline than the −15 percent for 1986–1991 estimated by Gandal (1994), and considerably faster than the 3 percent annual decline for word processors, spreadsheets, and databases for 1987–1993 reported by Oliner and Sichel (1994). For communications equipment, we used estimates from the most recent period from Grimm (1997), who reports a decline of 17.9 percent per year for 1992–1996.

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

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

The counter-balancing effects of increased output and increased input growth lead to an indirect effect on measured TFP growth. Depending on the relative shares of high-tech assets in investment and capital services, the TFP residual will increase if the output effect dominates or decrease if the effect on capital services dominates.[31] Following Solow (1957, 1960), Greenwood, Hercowitz, and Krusell (1997) omit the output effect and attribute the input effect to "investment-specific" (embodied) technical change. This must be carefully distinguished from the effects of industry-level productivity growth on TFP growth, discussed in section 3.4.

Table 3.4 reports growth accounting results from these three scenarios—Base Case, Moderate Price Decline, and Rapid Price Decline. The results are not surprising; the more rapid the price decline for software and communications, the faster the rate of growth of output and capital services. Relative to the Base Case, output growth increases by 0.16 percentage points per year for 1995–1998 in the Moderate Price Decline case and by 0.34 percentage points in the Rapid Price Decline case. Capital input growth shows slightly larger increases across the

Table 3.4
Impact of alternative deflation of software and communications equipment on the sources of U.S. economic growth, 1959–1998

	Base Case				Moderate Price Decline				Rapid Price Decline			
	1959–1973	1973–1990	1990–1995	1995–1998	1959–1973	1973–1990	1990–1995	1995–1998	1959–1973	1973–1990	1990–1995	1995–1998
Growth in Private Domestic Output Growth (Y)	4.33	3.13	2.74	4.73	4.35	3.30	2.90	4.89	4.36	3.38	3.03	5.07
Contribution of Selected Output Components												
Other (Y_n)	4.18	2.78	2.18	3.66	4.12	2.76	2.17	3.66	4.08	2.75	2.16	3.66
Computer and Software Consumption (C_c)	0.00	0.02	0.09	0.17	0.00	0.02	0.09	0.17	0.00	0.02	0.09	0.17
Computer Investment (I_c)	0.07	0.16	0.20	0.39	0.07	0.16	0.20	0.39	0.07	0.16	0.20	0.39
Software Investment (I_s)	0.03	0.08	0.13	0.21	0.04	0.14	0.22	0.29	0.05	0.17	0.29	0.40
Communications Investment (I_m)	0.05	0.06	0.05	0.12	0.12	0.19	0.13	0.21	0.16	0.25	0.19	0.27
Computer and Software CD Services (D_c)	0.00	0.02	0.09	0.19	0.00	0.02	0.09	0.19	0.00	0.02	0.09	0.19
Contribution of Capital Services (K)	1.44	1.16	0.91	1.61	1.54	1.39	1.15	1.83	1.61	1.51	1.32	2.09
Other (K_n)	1.26	0.81	0.51	0.86	1.25	0.80	0.51	0.86	1.25	0.79	0.51	0.85
Computers (K_c)	0.09	0.20	0.19	0.46	0.09	0.20	0.19	0.46	0.09	0.20	0.19	0.46
Software (K_s)	0.03	0.07	0.15	0.19	0.05	0.15	0.28	0.29	0.06	0.18	0.36	0.45
Communications (K_m)	0.06	0.08	0.06	0.10	0.16	0.25	0.18	0.23	0.22	0.34	0.27	0.33
Contribution of CD Services (D)	0.63	0.47	0.29	0.56	0.63	0.46	0.29	0.56	0.63	0.46	0.29	0.56
Non-Computers and Software (Dn)	0.63	0.44	0.20	0.37	0.63	0.44	0.20	0.37	0.63	0.44	0.20	0.37
Computers and Software (D_c)	0.00	0.02	0.09	0.19	0.00	0.02	0.09	0.19	0.00	0.02	0.09	0.19
Contribution of Labor (L)	1.25	1.17	1.18	1.57	1.25	1.17	1.18	1.57	1.25	1.18	1.18	1.57
Aggregate Total Factor Productivity (TFP)	1.01	0.33	0.36	0.99	0.94	0.27	0.27	0.93	0.88	0.22	0.23	0.85
Growth of Capital and CD Services	4.99	3.85	2.85	4.94	5.24	4.40	3.43	5.44	5.41	4.70	3.84	6.02
Growth of Labor Input	2.14	2.04	2.01	2.81	2.14	2.04	2.01	2.81	2.14	2.04	2.01	2.81

Table 3.4 (continued)

	Base Case				Moderate Price Decline				Rapid Price Decline			
	1959–1973	1973–1990	1990–1995	1995–1998	1959–1973	1973–1990	1990–1995	1995–1998	1959–1973	1973–1990	1990–1995	1995–1998
Contribution of Capital and CD Quality	0.40	0.41	0.43	0.95	0.48	0.59	0.63	1.11	0.54	0.70	0.78	1.34
Contribution of Capital and CD Stock	1.66	1.22	0.77	1.23	1.68	1.26	0.82	1.28	1.69	1.27	0.84	1.31
Contribution of Labor Quality	0.45	0.20	0.37	0.25	0.45	0.20	0.37	0.25	0.45	0.20	0.37	0.25
Contribution of Labor Hours	0.80	0.97	0.81	1.32	0.80	0.97	0.81	1.32	0.80	0.98	0.81	1.32
Average Labor Productivity (ALP)	2.95	1.44	1.37	2.37	2.98	1.61	1.52	2.53	2.99	1.69	1.65	2.72

Notes: Base Case uses official NIPA price data. Moderate Price Decline uses prepackaged software deflator for all software and annual price changes of −10.7 percent for communications equipment. Rapid Price Decline uses annual price changes of −16 percent for software and −17.9 percent for communications equipment. See text for details and sources. A contribution is defined as the share-weighted, real growth rate. CD refers to consumers' durable assets. All values are percentages.

three cases. Clearly, constant-quality price indexes for information technology are essential for further progress in understanding the growth impact of high-tech investment.

The acceleration in output and input growth reflects the increased contributions from IT, and determines the effect on the TFP residual. In particular, the output contribution from software for 1995–1998 increases from 0.21 percentage points in the Base Case to 0.29 percentage points under Moderate Price Decline to 0.40 percentage points with Rapid Price Decline. Similarly, the capital services contribution for software increase from 0.19 to 0.29 to 0.45 percentage points. The contribution of communications equipment shows similar changes. Residual TFP growth falls slightly during the 1990s, as the input effect outweighs the output effect, due to the large capital services shares of IT.

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

3.2.7 Decomposition of TFP Growth

We next consider the role of high-tech industries as a source of TFP growth. As discussed above, production of high-tech investment goods has made important contributions to aggregate growth. CEA (2000), for example, allocates 0.39 percentage points of aggregate TFP growth to the computer production, while Oliner and Sichel (2000) allocate 0.47 percentage points to the production of computers and computer-related semiconductor production for the period 1995–1999.[32]

We employ a methodology based on the price "dual" approach to measurement of productivity at the industry level. Anticipating our complete industry analysis section 3.4, below, it is worthwhile to spell out the decomposition of TFP growth by industry. Using the

Domar approach to aggregation, industry-level productivity growth is weighted by the ratio of the gross output of each industry to aggregate value added to estimate the industry contribution to aggregate TFP growth. In the dual approach, the rate of productivity growth is measured as the decline in the price of output, plus a weighted average of the growth rates of input prices.

In the case of computer production, this expression is dominated by two terms; namely, the price of computers and the price of semiconductors, a primary intermediate inputs into the computer-producing industry. If semiconductor industry output is used only as an intermediate good to produce computers, then its contribution to computer industry productivity growth, weighted by computer industry output, precisely cancels its independent contribution to aggregate TFP growth.[33] This independent contribution from the semiconductor industry, based on the complete Domar weighting scheme, is the value of semiconductor output divided by aggregate value added, multiplied by the rate of price decline in semiconductors.

We report details of our TFP decomposition for the three alternative cases described above for 1990–1995 and 1995–1998 in table 3.5, and summarize the IT vs. non-IT comparison in figure 3.10. In our Base Case, using official NIPA data, we estimate the production of information technology accounts for 0.44 percentage points for 1995–1998, compared to 0.25 percentage points for 1990–1995. This reflects the accelerating relative price changes prices due to radical shortening of the product cycle for semiconductors.[34]

As we have already suggested, the estimates of price declines for high-tech investments in our Base Case calculations may be conservative; in fact, these estimates may be *very* conservative. Consider the Moderate Price Decline Case, which reflects only part of the data we would require for constant-quality estimates of the information technology price declines. This boosts the contribution of information technology to TFP growth to 0.64 percentage points, an increase of 0.20 percentage points for 1995–1998. Proceeding to what may appear to be the outer limit of plausibility, but still consistent with the available evidence, we can consider the case of Rapid Price Decline. The contribution of information technology to TFP growth is now a robust 0.86 percentage points, accounting for all of TFP growth for 1995–1998.

As a final observation from the TFP decomposition, we note that the TFP acceleration in the late 1990s does not appear to be entirely located within IT-producing industries. While the actual growth rates

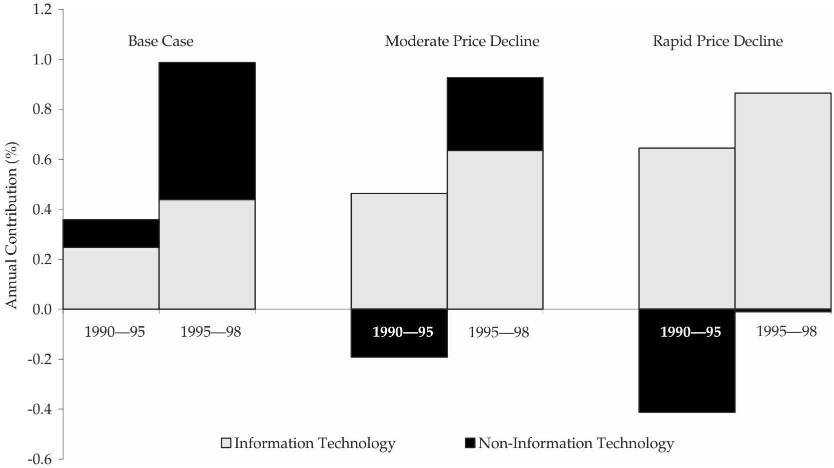
Table 3.5
Information technology decomposition of TFP growth for alternative deflation cases, 1990–1998

	Base Case		Moderate Price Decline		Rapid Price Decline	
	1990–1995	1995–1998	1990–1995	1995–1998	1990–1995	1995–1998
Aggregate TFP Growth	0.36	0.99	0.27	0.93	0.23	0.85
			TFP Contribution			
Information Technology	0.25	0.44	0.46	0.64	0.64	0.86
Computers	0.16	0.32	0.16	0.32	0.16	0.32
Software	0.05	0.08	0.17	0.18	0.28	0.34
Communications	0.04	0.04	0.13	0.13	0.21	0.20
Non-Information Technology	0.11	0.55	-0.19	0.29	-0.41	-0.01
			Relative Price Change			
Computers	-16.6	-29.6	-16.6	-29.6	-16.6	-29.6
Software	-3.4	-4.2	-11.3	-9.7	-18.0	-18.0
Communications	-3.5	-3.8	-12.7	-12.7	-19.9	-19.9
			Average Nominal Share			
Computers	0.96	1.09	0.96	1.09	0.96	1.09
Software	1.54	1.88	1.54	1.88	1.54	1.88
Communications	1.05	1.02	1.05	1.02	1.05	1.02

Notes: Base Case uses official NIPA price data. Moderate Price Decline uses prepackaged software deflator for all software and −10.7 percent for communications equipment. Rapid Price Decline uses −16 percent for software and −17.9 percent for communications equipment. See text for details and sources. A TFP contribution is defined as the share-weighted, growth rate of relative prices.

vary considerably across our three alternative cases, non-IT TFP growth increased markedly in each case when the early 1990s are compared to the late 1990s. This runs counter to the conclusion of Gordon (1999b), who reports the entire acceleration of labor productivity growth in the late 1990s reflects gains in IT-production. This divergence likely reflects Gordon's detrending procedure which attributes a sizable portion of recent productivity growth to cyclical factors, as well as his focus on labor productivity and our focus on TFP growth.

This acceleration of non-IT TFP growth could also be interpreted as evidence of a "new economy." If these productivity gains do indeed reflect spillovers from IT into non-IT industries, this would provide some missing evidence for the new economy side. Alternatively, however,



Note: Annual contribution of information technology is the share-weighted decline in relative prices.

Figure 3.10
TFP decomposition for alternative deflation cases.

this could reflect technological progress in non-IT industries that is entirely independent of the IT revolution. Differentiation between these two hypotheses is impossible at the aggregate level, and requires detailed industry data for the most recent period 1995–1998. Without these data, identification problems prevent us from drawing firm conclusions about the sources and implications of the acceleration of TFP in non-IT industries.

3.3 Setting the Speed Limit

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

3.3.1 A Brief Review of Forecast Methodologies

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

All forecasts are based on models that rest securely on neoclassical foundations. While the details and assumptions vary, all employ an aggregate production model similar to equation (3.1), either explicitly or implicitly. In addition, they all incorporate demographic projections from the SSA as the basic building block for labor supply estimates. CBO (1995, 1997, 1999a, 1999b, 2000) and GAO (1995, 1996a) employ an aggregate production function and describe the role of labor growth, capital accumulation, and technical progress explicitly. SSA (1992, 1996), OMB (1997, 2000), and CEA (2000) on the other hand, employ a simplified relationship where output growth equals the sum of growth in hours worked and labor productivity. Projections over longer time horizons are driven by aggregate supply with relatively little attention to business cycle fluctuations and aggregate demand effects.

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

3.3.2 *CBO's Growth Projections*

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

$$Y = A \cdot H^{0.7} \cdot K^{0.3}, \tag{3.6}$$

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

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

Turning to the most recent CBO projections, reported in CBO (2000), we focus on the non-farm business sector, which drives the GDP projections and is based on the most detailed growth model. Table 3.6 summarizes CBO's growth rate estimates for the 1980s and 1990s, and projections for 1999–2010. We also present estimates from BLS (2000) and our results.[38]

CBO projects potential GDP growth of 3.1 percent for 1999–2010, up slightly from 3.0 percent in the 1980s and 2.9 percent in the 1990s. CBO expects actual GDP growth to be somewhat slower at 2.8 percent, as the economy moves to a sustainable, long-run growth rate. Acceleration in potential GDP growth reflects faster capital accumulation and TFP growth, partly offset by slower growth in CBO projects potential GDP growth of 3.1 percent for 1999–2010, up slightly from 3.0 percent in the 1980s and 2.9 percent in the 1990s.

Table 3.6
Growth rates of output, inputs, and total factor productivity comparison of BLS, CBO, and Jorgenson-Stiroh

	BLS Nonfarm Business	CBO Overall Economy			CBO Nonfarm Business			Jorgenson–Stiroh	
	1990–1999	1980–1990	1990–1999	1999–2010	1980–1990	1990–1999	1999–2010	1980–1990	1990–1998
Real Output	3.74	3.0	2.9	3.1	3.2	3.4	3.5	3.48	3.55
Labor Input								2.14	2.34
Hours Worked	1.68	1.6	1.2	1.1	1.6	1.5	1.2	1.81	1.76
Labor Quality								0.33	0.58
Capital Input					3.6	3.6	4.4	3.57	3.68
TFP—not adjusted for labor quality					0.9	1.2	1.4	0.91	0.97
TFP—adjusted for labor quality								0.73	0.63
ALP	2.06	1.4	1.7	1.9	1.5	1.9	2.3	1.67	1.79

Notes: CBO estimates refer to "potential" series that are adjusted for business cycle effects. Growth rates do not exactly match table 3.5 since discrete growth rate are used here for consistency with CBO's methodology. Hours worked for CBO. Overall Economy refers to potential labor force.

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

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

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

As the investment boom continues and firms substitute toward more information technology in production, CBO has steadily revised its projected growth rates of capital upward. It is worthwhile noting just how much the role of capital accumulation has grown in successive CBO projections, rising from a projected growth rate of 3.6 percent in January 1999 (CBO, 1999a) to 4.1 percent in July 1999 (CBO, 1999b) to 4.4 percent in January 2000 (CBO, 2000). This reflects the inclusion of relatively fast-growing software investment in the benchmark revision of NIPA, but also extrapolates recent investment patterns.

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

Table 3.6 also reports our own estimates of growth for roughly comparable periods. While the time periods are not precisely identical, our results are similar to CBO's. We estimate slightly faster growth during the 1980s, due to rapidly growing consumers' durable services, but slightly lower rates of capital accumulation due to our broader measure of capital. Our growth of hours worked is higher, since we omit the cyclical adjustments made by CBO to develop their potential series.[41] Finally, our TFP growth rates are considerably lower, due to our labor quality adjustments and inclusion of consumers' durables. If we were to drop the labor quality adjustment, our estimate would rise to 1.0 percent per year from 1990 to 1998, compared to 1.2 percent for CBO for

1990–1999. The remaining difference reflects the fact that we do not include the rapid TFP growth of 1999, but do include the services of consumers' durables, which involve no growth in TFP.

3.3.3 Evaluating CBO's Projections

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

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

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

TFP growth is perhaps the most problematical issue in long-term projections. Based on the recent experience of the U.S. economy, it appears reasonable to expect strong future productivity performance. As discussed above and shown in table 3.2, TFP growth has increased markedly during the period 1995–1998. However, extrapolation of this experience runs the risk of assuming that a temporary productivity spurt is a permanent change in trend.

Second, the recent acceleration of TFP growth is due in considerable part to the surge in productivity growth in IT-producing industries.

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

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

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

Relative to historical trends, CBO's capital input growth projection of 4.4 percent seems out-of-line with the projected growth of potential output of 3.5 percent. During the 1980s capital growth exceeded potential output growth by 0.4 percent, according to their estimates, or 0.1 percent in our estimates. In the 1990s, capital growth exceeded output growth by only 0.2 percent, again according to their estimates, and 0.1 percent in our estimates. This difference jumps to 0.9 percent for the period of CBO's projections, 1999–2010.

Revising the growth of capital input downward to reflect the difference between the growth of output and the growth of capital input during the period 1995–1998 of 0.2 percent would reduce the CBO's projected output growth to 3.35 percent per year. This is the sum of the projected growth of TFP of 1.22 percent per year, the contribution of labor input of 1.06 percent per year, and the contribution of capital input of 1.07 percent per year. This is a very modest reduction in output growth from CBO's projection of 3.5 percent per year and can be attributed to the omission of a projected decline in labor quality growth.

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

3.4 Industry Productivity

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

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

3.4.1 Methodology

As with the aggregate production model discussed in section 3.2, we begin with an industry-level production model for each industry. A crucial distinction, however, is that industry output Q_i is measured using a "gross output" concept, which includes output sold to final demand as well as output sold to other industries as intermediate goods. Similarly, inputs include all production inputs, including capital services K_i and labor services L_i , as well as intermediate inputs, energy E_i and materials M_i, purchased from other industries.[43] Our model is based on the industry production function:

$$Q_i = A_i \cdot X_i(K_i, L_i, E_i, M_i), \tag{3.7}$$

where time subscripts have been suppressed for clarity.

We can derive a growth accounting equation similar to equation (3.2) for each industry to measure the sources of economic growth for individual industries. The key difference is the use of gross output and an explicit accounting of the growth contribution of intermediate inputs purchased from other industries. This yields:

$$\begin{aligned}\Delta \ln Q_i = {} & \overline{w}_{K_i} \Delta \ln K_i + \overline{w}_{L_i} \Delta \ln L_i \\ & + \overline{w}_{E_i} \Delta \ln E_i + \overline{w}_{M_i} \Delta \ln M_i + \Delta \ln A_i \end{aligned} \tag{3.8}$$

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

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

Domar (1961) first developed an internally consistent methodology that linked industry-level productivity growth in equation (3.8) with aggregate TFP growth in equation (3.2). He showed that aggregate TFP growth can be expressed as a weighted average of industry productivity growth:

$$\Delta \ln A = \sum_{i=1}^{37} \overline{w}_i \cdot \Delta \ln A_i, \quad \overline{w}_i = \frac{1}{2}\left(\frac{P_{i,t} \cdot Q_{i,t}}{P_{Y,t} \cdot Y_t} + \frac{P_{i,t-1} \cdot Q_{i,t-1}}{P_{Y,t-1} \cdot Y_{t-1}}\right), \tag{3.9}$$

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

Domar weights have the notable feature that they do not sum to unity. This reflects the different output concepts used at the aggregate and industry levels in equations (3.1) and (3.7), respectively. At the aggregate level, only primary inputs are included, while both primary and intermediate inputs are included in the industry production functions. For the typical industry, gross output considerably exceeds value added, so the sum of gross output across industries exceeds the sum of value added. This weighting methodology implies that economy-wide TFP growth can grow faster than productivity in any industry, since productivity gains are magnified as they work their way through the production process.[45]

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

3.4.2 *Data Sources*

Our primary data include a set of interindustry transactions accounts developed by the Employment Projections office at the BLS. These data cover a relatively short-time period from 1977 to 1995. We linked the BLS estimates to industry-level estimates back to 1958, described by Stiroh (1998a), and extrapolated to 1996 using current BLS and BEA industry data.[46] This generated a time series for 1958 to 1996 for 37 industries, at roughly the two-digit Standard Industrial Classification (SIC) level, including Private Households and General Government.[47] Table 3.7 lists the 37 industries, the relative size in terms of 1996 value added and gross output, and the underlying SIC codes for each industry.

Before proceeding to the empirical results, we should point out two limitations of this industry-level analysis. Due to the long lag in obtaining detailed interindustry transactions, investment, and output data by industry, our industry data are not consistent with the BEA benchmark revision of NIPA published in December 1999; they correspond to the NIPA produced by BEA in November 1997. As a consequence, they are not directly comparable to the aggregate data described in Tables 3.1 through 3.6. Since the impact of the benchmark revision was to raise output and aggregate TFP growth, it is not surprising that the industry data show slower output and productivity growth. Second, our estimates of rental prices for all assets in this industry analysis are based on the industry-wide asset revaluation terms, as in Stiroh (1998a). They are not directly comparable to the aggregate data on capital input, where asset-specific revaluation terms are included in the rental price estimates. The use of industry-wide revaluation terms tends to reduce the growth in capital services since assets with falling relative prices, such as computers, have large service prices and rapid accumulation rates.

3.4.3 Empirical Results

3.4.3.1 Sources of Industry Growth

Table 3.8 reports estimates of the components of equation (3.8) for the period 1958–1996. For each industry, we show the growth in output, the contribution of each input (defined as the nominal share-weighted growth rate of the input), and productivity growth. We also report average labor productivity (ALP) growth, defined as real gross output per hour worked, and the Domar weights calculated from equation (3.9). We focus the discussion of our results on industry productivity and ALP growth.

Industry productivity growth was the highest in two high-tech industries, Industrial Machinery and Equipment, and Electronic and Electric Equipment, at 1.5 percent and 2.0 percent per year, respectively. Industrial Machinery includes the production of computer equipment (SIC #357) and Electronic Equipment includes the production of semiconductors (SIC #3674) and communications equipment (SIC #366). The enormous technological progress in the production of these high-tech

Table 3.7
1996 value added and gross output by industry

Industry	SIC Codes	Value-Added	Gross Output
Agriculture	01–02, 07–09	133.3	292.2
Metal Mining	10	8.8	10.7
Coal Mining	11–12	14.7	21.1
Petroleum and Gas	13	57.4	83.3
Nonmetallic Mining	14	10.5	17.0
Construction	15–17	336.0	685.5
Food Products	20	147.2	447.6
Tobacco Products	21	26.7	32.7
Textile Mill Products	22	19.9	58.9
Apparel and Textiles	23	40.7	98.5
Lumber and Wood	24	34.2	106.7
Furniture and Fixtures	25	23.4	54.5
Paper Products	26	68.3	161.0
Printing and Publishing	27	113.5	195.6
Chemical Products	28	184.0	371.2
Petroleum Refining	29	44.7	184.3
Rubber and Plastic	30	64.1	148.9
Leather Products	31	3.4	8.1
Stone, Clay, and Glass	32	40.4	79.1
Primary Metals	33	57.6	182.1
Fabricated Metals	34	98.4	208.8
Industrial Machinery and Equipment	35	177.8	370.5
Electronic and Electric Equipment	36	161.9	320.4
Motor Vehicles	371	84.9	341.6
Other Transportation Equipment	372–379	68.0	143.8
Instruments	38	81.3	150.0
Miscellaneous Manufacturing	39	24.8	49.3
Transport and Warehouse	40–47	258.6	487.7
Communications	48	189.7	315.8
Electric Utilities	491, %493	111.8	186.7
Gas Utilities	492, %493, 496	32.9	57.9
Trade	50–59	1,201.2	1,606.4
FIRE	60–67	857.8	1,405.1
Services	70–87, 494–495	1,551.9	2,542.8
Government Enterprises		95.2	220.2
Private Households	88	1,248.4	1,248.4
General Government		1,028.1	1,028.1

Notes: All values are in current dollars. Value added refers to payments to capital and labor; Gross output includes payments for intermediate inputs.

capital goods has generated falling prices and productivity growth, and fueled the substitution towards information technology.

An important feature of these data is that we can isolate productivity growth for industries that produce intermediate goods, for example, Electronic and Electric Equipment.[48] Consider the contrast between computer production and semiconductor production. Computers are part of final demand, sold as consumption and investment goods, and can be identified in the aggregate data, as we did in table 3.2. Semiconductors, on the other hand, do not appear at the aggregate level, since they are sold almost entirely as an input to computers, telecommunications equipment, and an increasingly broad range of other products such as machine tools, automobiles, and virtually all recent vintages of appliances. Nonetheless, improved semiconductor production is an important source of aggregate TFP growth since it is ultimately responsible for the lower prices and improved quality of goods like computers produced for final demand.

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

The decline in prices of semiconductors is reflected in the prices of intermediate input into the computer industry, effectively moving productivity away from computers and toward semiconductor production. Building on this observation, Oliner and Sichel (2000) present a model that includes three sectors—semiconductor production, computer production, and other goods—and shows that semiconductors productivity is substantially more important than computer productivity. Our complete industry framework with Domar aggregation over all industries captures the contributions of productivity growth from all industries.

The impact of intermediate inputs can be seen in table 3.8 in the large contribution of material inputs in the Industrial Machinery industry. Since a substantial portion of these inputs consists of semiconductors purchased from the Electronic Equipment industry, productivity gains that lower the price of semiconductors increase the flow of intermediate inputs into the Industrial Machinery industry. By correctly accounting

Table 3.8
Sources of U.S. economic growth by industry, 1958–1996

Industry	Output Growth	Contributions of Inputs				Productivity Growth	ALP Growth	Domar Weight
		Capital	Labor	Energy	Materials			
Agriculture	1.70	0.19	−0.13	−0.04	0.51	1.17	3.21	0.062
Metal Mining	0.78	0.73	−0.07	−0.07	−0.26	0.44	0.99	0.003
Coal Mining	2.35	0.82	0.00	0.06	0.63	0.84	2.32	0.005
Petroleum and Gas	0.43	0.61	−0.01	0.06	0.20	−0.44	0.88	0.022
Nonmetallic Mining	1.62	0.59	0.18	0.06	0.34	0.46	1.52	0.003
Construction	1.43	0.07	0.87	0.02	0.91	−0.44	−0.38	0.113
Food Products	2.20	0.21	0.18	0.00	1.27	0.54	1.59	0.076
Tobacco Products	0.43	0.59	0.05	0.00	−0.01	−0.20	0.88	0.004
Textile Mill Products	2.23	0.12	0.02	0.01	0.86	1.23	2.54	0.013
Apparel and Textiles	2.03	0.24	0.17	0.00	0.82	0.80	2.01	0.022
Lumber and Wood	2.24	0.21	0.33	0.02	1.70	−0.02	1.55	0.015
Furniture and Fixtures	2.91	0.31	0.58	0.02	1.44	0.56	1.78	0.007
Paper Products	2.89	0.50	0.40	0.05	1.51	0.42	1.96	0.022
Printing and Publishing	2.51	0.55	1.20	0.02	1.19	−0.44	0.14	0.024
Chemical Products	3.47	0.74	0.47	0.09	1.58	0.58	2.02	0.048
Petroleum Refining	2.21	0.44	0.24	0.49	0.71	0.33	0.80	0.033
Rubber and Plastic	5.17	0.47	1.16	0.08	2.43	1.04	1.94	0.016
Leather Products	−2.06	−0.11	−1.13	−0.02	−1.08	0.28	2.08	0.004
Stone, Clay, and Glass	1.86	0.26	0.37	0.00	0.82	0.41	1.30	0.014
Primary Metals	1.14	0.13	0.05	−0.03	0.77	0.22	1.51	0.040
Fabricated Metals	2.28	0.26	0.28	0.00	1.09	0.65	1.88	0.035
Industrial Machinery and Equipment	4.79	0.52	0.75	0.02	2.04	1.46	3.15	0.048
Electronic and Electric Equipment	5.46	0.76	0.65	0.03	2.04	1.98	4.08	0.036
Motor Vehicles	3.61	0.28	0.29	0.02	2.78	0.24	2.28	0.043
Other Transportation Equipment	1.31	0.23	0.37	0.00	0.52	0.18	1.00	0.027
Instruments	5.23	0.65	1.44	0.03	1.99	1.12	2.57	0.017
Miscellaneous Manufacturing	2.53	0.34	0.41	0.00	0.95	0.82	2.08	0.008
Transport and Warehouse	3.25	0.20	0.72	0.12	1.34	0.86	1.74	0.061
Communications	5.00	1.62	0.53	0.02	1.95	0.88	3.93	0.033
Electric Utilities	3.22	1.01	0.20	0.67	0.83	0.51	2.52	0.026
Gas Utilities	0.56	0.66	−0.04	0.14	0.05	−0.24	0.94	0.016

Table 3.8 (continued)

Industry	Output Growth	Contributions of Inputs: Capital	Labor	Energy	Materials	Productivity Growth	ALP Growth	Domar Weight
Trade	3.66	0.62	0.83	0.04	1.19	0.98	2.49	0.195
FIRE	3.42	1.14	0.94	0.00	1.52	−0.18	0.66	0.131
Services	4.34	0.84	1.70	0.07	1.92	−0.19	0.92	0.208
Goverment Enterprises	2.86	1.24	1.08	0.23	0.83	−0.52	0.49	0.022
Private Households	3.50	3.55	−0.06	0.00	0.00	0.00	5.98	0.137
General Government	1.35	0.60	0.75	0.00	0.00	0.00	0.46	0.131

Notes: Output Growth is the average annual growth in real gross output. Contributions of Inputs are defined as the average, share-weighted growth of the input. Productivity Growth is defined in equation (3.8). ALP Growth is the growth in average labor productivity. Domar Weight is the average ratio of industry gross output to aggregate value added as defined in equation (3.9). All numbers except Domar Weights are percentages.

for these inputs, industry productivity growth in the Industrial Machinery industry falls, and we can rightly allocate technological progress to the Electronic Equipment industry, which produces semiconductors. While this type of industry reallocation does not affect aggregate productivity growth, it is important to identify the sources of productivity growth and allocate this among industries in order to assess the sustainability of the recent acceleration.

The two high-tech industries also show high rates of average labor productivity (ALP) growth of 3.1 percent and 4.1 percent per year. This reflects an underlying relationship similar to equation (3.3) for the aggregate data, where industry ALP growth reflects industry productivity growth, labor quality growth, and increases in input intensity, including increases in capital as well as intermediate inputs per hour worked. As implied by table 3.8, these industries showed rapid accumulation of capital and intermediate inputs, which raised ALP growth above productivity growth. It is also worthwhile to note that Communications, another high-tech industry, shows ALP growth much faster than industry productivity growth due to the rapid accumulation of inputs, notably intermediate materials. These results highlight the crucial importance of accounting for all inputs when examining the sources of industry growth.

Productivity growth in information technology provides a final perspective on the conclusions of Greenwood, Hercowitz, and Krusell

(1997) and Hercowitz (1998). They argue that some 60 percent of postwar U.S. growth can be attributed to investment-specific (embodied) productivity growth, which they distinguish from input accumulation and (disembodied) productivity growth. As evidence, they note the relative price of equipment in the United States has fallen 3 percent per year, which they interpret as evidence of technical change that affect capital goods, but not consumption goods. Our decomposition, however, reveals that declines in the prices of investment goods are the consequence of improvements in industry (disembodied) productivity. Domar aggregation shows how these improvements contribute directly to aggregate TFP growth. There is no separate role for investment-specific technical change.

Other industries that show relatively strong productivity growth include Agriculture, Textile Mill Products, Rubber and Plastic, Instruments, Trade. All of these industries experienced productivity growth in the 1.0 percent per year range, and ALP growth in the 2–3 percent range. Industries with the slowest productivity growth include Petroleum and Gas, Construction, Printing and Publishing, and Government Enterprises, all of which showed a declines in productivity of nearly 0.5 percent per year.

It is worth emphasizing that nine industries showed negative productivity growth for the entire period, a counter-intuitive result, if we were to interpret productivity growth solely as technological progress. It is difficult to envision technology steadily worsening for a period of nearly 40 years as implied by these estimates. The perplexing phenomenon of negative technical progress was a primary motivation for the work of Corrado and Slifman (1999) and Gullickson and Harper (1999), who suggest persistent measurement problems as a plausible explanation. Corrado and Slifman (1999) conclude, "a more likely statistical explanation for the implausible productivity, profitability, and price trends . . . is that they reflect problems in measuring prices (pg. 331)." If prices are systematically overstated because quality change is not accurately measured, then output and productivity are correspondingly understated. We do not pursue this idea here, but simply point out that measurement problems are considered a reasonable explanation by some statistical agencies.[50]

An alternative interpretation for negative productivity growth is the possibility of declines in efficiency that have no association with technology. These might include lower quality of management and worsening of industrial organization through the growth of barriers to entry. This appears to be plausible explanation, given the widespread occurrence of negative productivity growth for extended periods of time. Until more careful research linking firm- and plant-level productivity to industry productivity estimates has been done, it would be premature to leap to the conclusion that estimates of economic performance should be adjusted so as to eliminate negative productivity growth rates, wherever they occur.

Low productivity growth rates are surprising in light of the fact that many of the affected industries are heavy investors in information technology. Stiroh (1998a), for example, reports nearly 80 percent of computer investment in the early 1990s was in three service-related industries, Trade, FIRE, and Services. Triplett (1999b) reports a high concentration in service industries using the BEA's capital use survey. The apparent combination of slow productivity growth and heavy computer-use remains an important obstacle for new economy proponents who argue that the use of information technology is fundamentally changing business practices and raising productivity throughout the U.S. economy.

3.4.3.2 Comparison to Other Results

Before proceeding to the Domar aggregation results, it is useful to compare these results to three other recent studies—BLS (1999), Corrado and Slifman (1999) and Gullickson and Harper (1999). BLS (1999) reports industry productivity growth ("industry multifactor productivity" in their terminology) for 19 manufacturing industries for 1949–1996. Corrado and Slifman (1999) report estimates of ALP growth for selected one- and two-digit SIC industries for the period 1977–1997. Gullickson and Harper (1999) report industry productivity growth for certain one- and two-digit SIC industries based on two output series for the period 1947–1992. Similar to BLS (1999), Gullickson and Harper use a "sectoral output" concept estimated by the Employment Projections staff at BLS and also, for 1977–1992, use BEA's gross output series, "adjusted for consistency."[51] Note that none of these studies reflect the BEA benchmark revision of NIPA.

Time period, industry classification, and methodological differences make a definitive reconciliation to our results impossible. For example, BLS (1999) reports detailed manufacturing industries; Corrado and Slifman (1999) use a value added concept, BEA's "gross product originating," for output; Gullickson and Harper (1999) use the same data sources as we do, but make different adjustments for consistency and do not account for labor quality growth. Nonetheless, it is useful to compare broad trends over similar time periods to assess the robustness of our findings.

We first consider the ALP estimates from Corrado and Slifman (1999). We can compare similar time periods, but there are relatively few overlapping industries since our industry breakdown focuses on manufacturing industries, while they provide details primarily for service industries. For comparable industries, however, the results are quite similar. For seven industries with comparable definitions, five show differences in ALP growth of less than 0.25 percent when we compare our estimates for 1977–1996 to Corrado and Slifman's estimates for 1977–1997 (Corrado and Slifman, 1999, table 2).[52] Our ALP growth rates for Communication and Trade are below theirs by 1.3 percent and 0.4 percent, respectively, for these periods.

Our productivity estimates for 1977–1992 for the majority of industries are similar to those of Gullickson and Harper (1999). The range of discrepancies is somewhat greater due to the difficulty of linking the various data sets needed to estimate intermediate inputs and industry productivity growth. For 7 of the 11 comparable industries productivity differences are below 0.5 percent, while we found larger discrepancies for Metal Mining, Coal Mining, Petroleum and Gas, and Services.[53] Similar differences can also be seen in Gullickson and Harper's comparison of productivity growth estimated from the BLS and BEA gross output series, where they find differences of 0.5 percentage points or more in 17 out of 40 industries and aggregates. Methodological differences, such as the inclusion of labor quality growth in our estimates of labor input growth, contribute to this divergence, as do different methods for linking data sets.

Neither Corrado and Slifman (1999) nor Gullickson and Harper (1999) break out ALP growth or industry productivity growth for detailed manufacturing industries. To gauge these results, we have compared our manufacturing results to the manufacturing industry estimates in BLS (1999). For the 18 industries that are comparable, ten showed productivity differences of less than 0.25 percent for 1979–1996; two showed differences between 0.25 percent and 0.5 percent; and the remaining six industries, Textile Mills, Lumber and Wood, Petroleum Refining, Leather, Stone, Clay and Glass, and Instruments, showed differences greater than 0.5.[54]

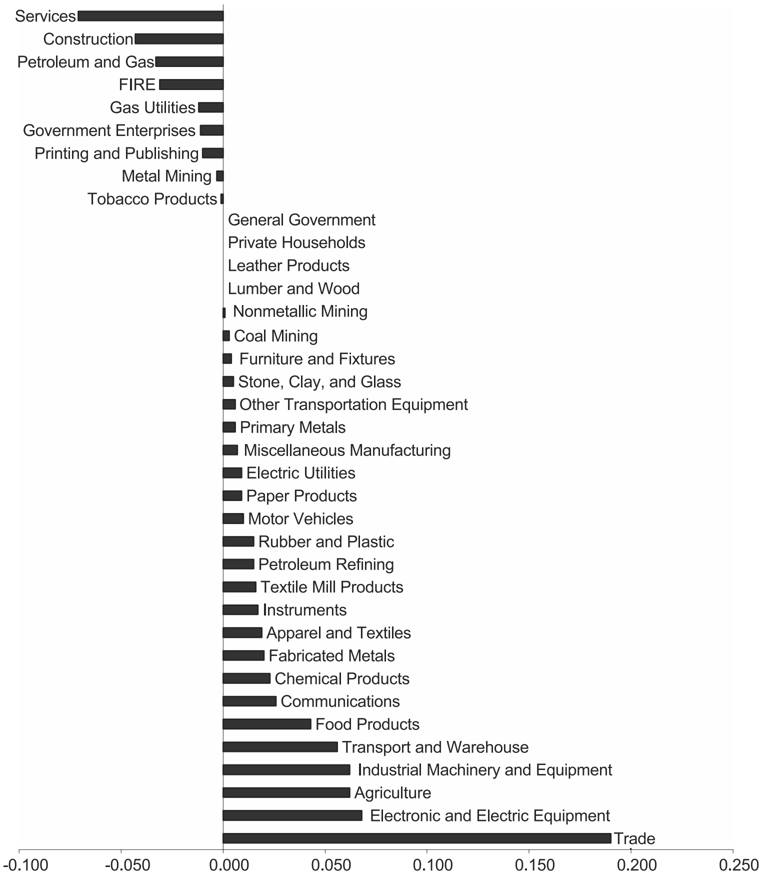
3.4.3.3 Domar Aggregation

We now turn to the aggregation of industry productivity growth described by equation (3.9). This is not directly comparable to our estimates of aggregate productivity, due to different vintages of data and a broader definition of output. Nonetheless, it is useful to quantify an industry's contribution to aggregate TFP growth and to trace aggregate productivity growth back to its sources at the level of the individual industry. These results update the earlier estimates of Jorgenson, Gollop, and Fraumeni (1987). Gordon (1999b) presents a similar decomposition for ALP growth, although he focuses exclusively on the contribution from computer production.

We present our estimates of each industry's contribution to aggregate TFP growth for the period 1958–1996 in Figure 3.11. This follows equation (3.9) by weighting industry productivity growth by the "Domar weight," defined as industry gross output divided by aggregate value added. Summing across industries gives an estimate of aggregate TFP growth of 0.48 for 1958–1996. This is lower than the number implied by table 3.2 for two reasons. First, the data are prior to the BEA benchmark revision, which raised output and TFP growth. Second, these estimates include a broader output concept that includes Government Enterprises, which we estimate has negative industry productivity growth, and the General Government, which has zero productivity growth by definition. The estimate is consistent, however, with the estimates in Ho, Jorgenson, and Stiroh (1999) and Jorgenson and Stiroh (1999), which are based on the same vintage of data.

The most striking feature of figure 3.11 is the wide range of industry contributions. Trade, Industrial Machinery, and Electronic Equipment make the largest contribution, although for different reasons. Trade has solid, but not exceptionally strong productivity growth of almost 1 percent per year, but makes the largest contribution due to its large relative size; Trade receives a Domar weight of nearly 0.20. Industrial Machinery and Electronic Equipment, on the other hand, make important contributions due to their rapid productivity growth, 1.5 percent and 2.0 percent, respectively, in spite of their relative small sizes with Domar weights of 0.05 and 0.04, respectively. An industry's contribution to aggregate productivity growth depends on both productivity performance and relative size.

Figure 3.11 also highlights the impact of the nine industries that experienced negative productivity growth over this period. Again, both



Note: Each industry's contribution is calculated as the product of industry productivity growth and the industry Domar weight, averaged for 1958–1996.

Figure 3.11
Industry contributions to aggregate total factor productivity growth, 1958–1996.

performance and relative size matter. Services makes a negative contribution of 0.07 due to its large weight and productivity growth of −0.19 percent. Construction, on the other hand, shows even slower industry productivity growth, −0.44 percent per year, but makes a smaller negative contribution, since it is so much smaller than Services. We can also do a "thought experiment" similar to Corrado and Slifman (1999) and Gullickson and Harper (1999) and imagine that productivity growth is zero in these nine industries rather than negative. By zeroing out the negative contributions, we find aggregate TFP growth would have been 0.22 percent higher, an increase of nearly half.[55] Clearly, negative productivity growth in these industries is an important part of the aggregate productivity story.

Finally, these data enable us to provide some new perspective on an argument made by Gordon (1999b), who decomposes trend-adjusted ALP growth into a portion due to computer production and a residual portion for the rest of the economy.[56] He finds the former accounts for virtually all of the productivity acceleration since 1997. While we cannot comment directly on his empirical estimates since our industry data end in 1996 and we examine TFP growth rather than ALP growth, we can point to an important qualification to his argument. The U.S. economy is made up of industries with both positive and negative productivity growth rates, so that comparing one industry to the aggregate of all others necessarily involves aggregation over offsetting productivity trends. The fact that this aggregate does not show net productivity growth does not entail the absence of gains in productivity in any of the component industries, since these gains could be offset by declines in other industries.

Consider our results for 1958–1996 and the importance of the negative contributions. The five industries with the largest, positive contributions—Trade, Electronic Equipment, Agriculture, Industrial Machinery, and Transport—cumulatively account for the sum across all industries, about 0.5 percent per year. Nonetheless, we find sizable productivity growth in some remaining industries that are offset by negative contributions in others. This logic and the prevalence of negative productivity growth rates at the industry level, in BLS (1999), Corrado and Slifman (1999), and Gullickson and Harper (1999), suggest that a similar argument could hold for ALP and for the most recent period. This raises the question of whether offsetting productivity growth rates are responsible for Gordon's finding that there is "no productivity growth in the 99 percent of the economy located outside the sector which manufactures computer hardware (Gordon (1999b, pg. 1, italics in original))." Assessing the breadth of recent productivity gains and identifying the sources in productivity growth at the industry level remains an important question for future research.

3.5 Conclusions

The performance of the U.S. economy in the late 1990s has been nothing short of phenomenal. After a quarter century of economic malaise, accelerating total factor productivity growth and capital deepening have led to a remarkable growth resurgence. The pessimism of the famous Solow (1987) paradox, that we see computers everywhere but in the productivity statistics, has given way to optimism of the information age. The productivity statistics, beginning in 1995, have begun to reveal a clearly discernible impact of information technology. Both labor productivity and TFP growth have jumped to rates not seen for such an extended period of time since the 1960s. While a substantial portion of these gains can be attributed to computers, there is growing evidence of similar contributions from software and communications equipment—each equal in importance to computers.

The forces shaping the information economy originate in the rapid progress of semi-conductor technology—Moore's Law at work. These gains are driving down relative prices of computers, software, and communications equipment and inducing massive investments in these assets by firms and households. Technological progress and the induced capital deepening are the primary factors behind accelerating output growth in recent years. The sustainability of recent growth trends therefore hinges to a great degree on prospects for continuing progress, especially in the production of semiconductors. While this seems plausible and perhaps even likely, the contribution of high-tech assets to the growth resurgence remains subject to considerable uncertainty, owing to incomplete information on price trends for these assets.

The strong performance of the U.S. economy has not gone unnoticed. Forecasters have had to raise their projected growth rates and raise them again. The moderate speed limits set by Blinder (1997) and Krugman (1997), reflecting the best evidence available only a few years ago, have given way to the optimism of the ordinarily conservative community of official forecasters. Our review of the evidence now available suggests that the official forecasters are relying very heavily on a continuation of the acceleration in U.S. economic growth since 1995.

What are the risks to the optimistic view of future U.S. economic growth in the information age? Upward revision of growth projections seems a reasonable response as evidence accumulates of a possible break in trend productivity growth. Nonetheless, caution is warranted until productivity patterns have been observed for a longer time period. Should the pace of technological progress in high-tech industries diminish, economic growth would be hit with a double whammy—lower total factor productivity growth in important industries that produce high-tech equipment and slower capital accumulation in other sectors that invest in and use the high-tech equipment. Both factors have made important contribution to the recent success of the U.S. economy, so that any slowdown would retard future growth potential.

At the same time we must emphasize that the uncertainty surrounding intermediate term projections has become much greater as a consequence of widening gaps in our knowledge, rather than changes in the volatility of economic activity. The excellent research that underlies estimates of prices and quantities of computer investment in NIPA has provided much needed illumination of the impact of information technology. But this is only part of the contribution of information technology to economic growth and may not be the largest part. As the role of technology continues to increase, ignorance of the most basic empirical facts about the information economy will plague researchers as well as forecasters. The uncertainties about past and future economic growth will not be resolved quickly. This is, of course, a guarantee that the lively economic debate now unfolding will continue for the foreseeable future.

The first priority for empirical research must be constant-quality price indexes for a wider variety of high-tech assets. These assets are becoming increasingly important in the U.S. economy, but only a small portion have constant-quality price deflators that translate the improved production characteristics into accurate measures of investment and output. This echoes the earlier findings of Gordon (1990), who reported that official price measures substantially overstate price changes for capital goods. In fact, Gordon identified computers and communications equipment as two assets with the largest overstatements, together with aircraft, which we have not included.[57] Much remains to be done to complete Gordon's program of implementing constant-quality price deflators for all components of investment in NIPA.

The second priority for research is to decompose the sources of economic growth to the industry level. Fortunately, the required methodology is well established and increasingly familiar. Domar aggregation over industries underlies back-of-the-envelope calculations of the contribution of information technology to economic growth in section 3.3, as well as the more careful and comprehensive view of the contributions of industry-level productivity that we have presented in section 3.4. This view will require considerable refinement to discriminate among alternative perspectives on the rapidly unfolding information economy. However, the evidence already available is informative on the most important issue. This is the "new economy" view that the impact of information technology is like phlogiston, an invisible substance that spills over into every kind of economic activity and reveals its presence by increases in industry-level productivity growth across the U.S. economy. This view is simply inconsistent with the empirical evidence.

Our results suggest that while technology is clearly the driving force in the growth resurgence, familiar economic principles can be applied. Productivity growth in the production of information technology is responsible for a sizable part of the recent spurt in TFP growth and can be identified with price declines in high-tech assets and semiconductors. This has induced an eruption of investment in these assets that is responsible for capital deepening in the industries that use information technology. Information technology provides a dramatic illustration of economic incentives at work! However, there is no corresponding eruption of industry-level productivity growth in these sectors that would herald the arrival of phlogiston-like spillovers from production in the information technology sectors.

Many of the goods and services produced using high-tech capital may not be adequately measured, as suggested in the already classic paper of Griliches (1994). This may help to explain the surprisingly low productivity growth in many of the high-tech intensive, service industries. If the official data are understating both real investment in high-tech assets and the real consumption of commodities produced from these assets, the underestimation of U.S. economic performance may be far more serious than we have suggested. Only as the statistical agencies continue their slow progress towards improved data and implementation of state-of-theart methodology will this murky picture become more transparent.

Appendix A: Estimating Output

We begin with the National Income and Product Accounts (NIPA) as our primary source data. These data correspond to the most recent benchmark revision published by the Bureau of Economic Analysis (BEA) on October 29, 1999. These data provide measures of investment and consumption, in both current and chained 1996 dollars. The framework developed by Christensen and Jorgenson (1973), however, calls for a

Table A.1
Private domestic output and high-tech assets

	Private Domestic Output		Computer Investment		Software Investment		Communications Investment		Computer & Software Consumption		Computer & Software Consumption Services	
Year	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price
1959	484.1	0.25	0.00	0.00	0.00	0.00	1.80	0.47	0.00	0.00	0.00	0.00
1960	472.8	0.24	0.20	697.30	0.10	0.61	2.30	0.47	0.00	0.00	0.00	0.00
1961	490.1	0.24	0.30	522.97	0.20	0.62	2.70	0.47	0.00	0.00	0.00	0.00
1962	527.1	0.25	0.30	369.16	0.20	0.63	3.00	0.46	0.00	0.00	0.00	0.00
1963	562.1	0.25	0.70	276.29	0.40	0.63	2.90	0.46	0.00	0.00	0.00	0.00
1964	606.4	0.26	0.90	229.60	0.50	0.64	3.00	0.47	0.00	0.00	0.00	0.00
1965	664.2	0.26	1.20	188.74	0.70	0.65	3.50	0.47	0.00	0.00	0.00	0.00
1966	728.9	0.27	1.70	132.70	1.00	0.66	4.00	0.47	0.00	0.00	0.00	0.00
1967	763.1	0.28	1.90	107.71	1.20	0.67	4.20	0.49	0.00	0.00	0.00	0.00
1968	811.0	0.28	1.90	92.00	1.30	0.68	4.70	0.51	0.00	0.00	0.00	0.00
1969	877.7	0.29	2.40	83.26	1.80	0.70	5.80	0.54	0.00	0.00	0.00	0.00
1970	937.9	0.31	2.70	74.81	2.30	0.73	6.70	0.57	0.00	0.00	0.00	0.00
1971	991.5	0.32	2.80	56.98	2.40	0.73	6.80	0.60	0.00	0.00	0.00	0.00
1972	1,102.9	0.33	3.50	45.93	2.80	0.73	6.80	0.62	0.00	0.00	0.00	0.00
1973	1,255.0	0.36	3.50	43.53	3.20	0.75	8.40	0.64	0.00	0.00	0.00	0.00
1974	1,345.9	0.38	3.90	35.55	3.90	0.80	9.40	0.69	0.00	0.00	0.00	0.00
1975	1,472.7	0.42	3.60	32.89	4.80	0.85	9.70	0.76	0.00	0.00	0.00	0.00
1976	1,643.0	0.44	4.40	27.47	5.20	0.87	11.10	0.80	0.00	0.00	0.00	0.00
1977	1,828.1	0.47	5.70	23.90	5.50	0.89	14.40	0.78	0.00	0.00	0.00	0.00
1978	2,080.4	0.50	7.60	16.17	6.60	0.90	17.70	0.81	0.10	33.68	0.02	17.84
1979	2,377.8	0.56	10.20	13.40	8.70	0.95	21.40	0.83	0.10	32.81	0.07	19.01

Table A.1 (continued)

	Private Domestic Output		Computer Investment		Software Investment		Communications Investment		Computer & Software Consumption		Computer & Software Consumption Services	
Year	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price
1980	2,525.9	0.59	12.50	10.46	10.70	1.01	25.70	0.88	0.20	22.11	0.20	25.93
1981	2,825.6	0.65	17.10	9.19	12.90	1.07	29.00	0.96	0.40	18.79	0.25	13.90
1982	2,953.5	0.69	18.90	8.22	15.40	1.12	31.10	1.01	1.40	15.12	0.74	11.96
1983	3,207.7	0.72	23.90	6.86	18.00	1.13	31.90	1.03	2.90	10.71	2.07	10.39
1984	3,610.3	0.75	31.60	5.55	22.10	1.14	36.60	1.07	3.00	9.41	2.37	6.07
1985	3,844.1	0.76	33.70	4.72	25.60	1.13	39.90	1.09	2.90	8.68	2.70	4.93
1986	3,967.4	0.76	33.40	4.06	27.80	1.12	42.10	1.10	5.20	6.54	4.84	5.61
1987	4,310.8	0.79	35.80	3.46	31.40	1.12	42.10	1.10	6.20	5.91	4.91	3.54
1988	4,766.1	0.84	38.00	3.21	36.70	1.14	46.70	1.10	8.20	5.41	6.65	3.24
1989	5,070.5	0.86	43.10	3.00	44.40	1.11	46.90	1.10	8.30	5.02	7.89	2.85
1990	5,346.8	0.89	38.60	2.72	50.20	1.09	47.50	1.11	8.90	4.22	10.46	2.97
1991	5,427.2	0.91	37.70	2.45	56.60	1.10	45.70	1.11	11.90	3.53	11.66	2.44
1992	5,672.4	0.92	43.60	2.09	60.80	1.04	47.80	1.10	12.10	2.68	14.96	2.25
1993	5,901.8	0.93	47.20	1.78	69.40	1.04	48.20	1.09	14.50	2.07	16.26	1.71
1994	6,374.4	0.96	51.30	1.57	75.50	1.02	54.70	1.07	18.00	1.81	16.14	1.17
1995	6,674.4	0.97	64.60	1.31	83.50	1.02	60.00	1.03	21.00	1.44	22.64	1.13
1996	7,161.2	1.00	70.90	1.00	95.10	1.00	65.60	1.00	23.60	1.00	30.19	1.00
1997	7,701.8	1.02	76.70	0.78	106.60	0.97	73.00	0.99	26.20	0.69	33.68	0.71
1998	8,013.3	1.01	88.51	0.57	123.41	0.96	83.60	0.97	30.40	0.48	36.53	0.48

Notes: Values are in billions of current dollars. All price indexes are normalized to 1.0 in 1996.

somewhat broader treatment of output than in the national accounts. Most important, consumers' durable goods are treated symmetrically with investment goods, since both are long-lived assets that are accumulated and provide a flow of services over their lifetimes. We use a rental price to impute a flow of consumers' durables services included in both consumption output and capital input. We also employ a rental price to make relatively small imputations for the service flows from owner-occupied housing and institutional equipment.

Table A.1 presents the time series of total output in current dollars and the corresponding price index from 1959–1998. The table also includes the current dollar value and price index for information technology output components—computer investment, software investment, communications investments, computer and software consumption, and the imputed service flow of computer and software consumer durables—as described in equation (3.4) in the text.

Appendix B: Estimating Capital Services

B.1 Capital Services Methodology

We begin with some notation for measures of investment, capital stock, and capital services, for both individual assets and aggregates. For individual assets:

$I_{i,t}$ = quantity of investment in asset i at time t

$P_{i,t}$ = price of investment in asset i at time t

δ_i = geometric depreciation rate for asset i

$S_{i,t}$ = quantity of capital stock of asset i at time t

$P_{i,t}$ = price of capital stock of asset i at time t

$K_{i,t}$ = quantity of capital services from asset i at time t

$c_{i,t}$ = price of capital services from asset i at time t

where the i subscript refers to different types of tangible assets—equipment and structures, as well as consumers' durable assets, inventories, and land, all for time period t.

For economy-wide aggregates:

I_t = quantity index of aggregate investment at time t

$P_{I,t}$ = price index of aggregate investment at time t

S_t = quantity index of aggregate capital stock at time t
$P_{S,t}$ = price index of aggregate capital stock at time t
K_t = quantity index of aggregate capital services at time t
c_t = price of capital services at time t
$q_{K,t}$ = quality index of aggregate capital services at time t.

Our starting point is investment in individual assets we assume that the price index for each asset measures investment goods in identically productive "efficiency units" over time. For example, the constant-quality price deflators in the NIPA measure the large increase in computing power as a decline in price of computers.[58] Thus, a faster computer is represented by more $I_{i,t}$ in a given period and a larger accumulation of $S_{i,t}$, as measured by the perpetual inventory equation:

$$S_{i,t} = S_{i,t-1}(1-\delta_i) + I_{i,t} = \sum_{\tau=0}^{\infty}(1-\delta_i)^{\tau} I_{i,t-\tau} \tag{B.1}$$

where capital is assumed to depreciate geometrically at the rate δ_i.

Equation (B.1) has the familiar interpretation that the capital stock is the weighted sum of past investments, where weights are derived from the relative efficiency profile of capital of different ages. Moreover, since $S_{i,t}$ is measured in base-year efficiency units, the appropriate price for valuing the capital stock is simply the investment price deflator, $P_{i,t}$. Furthermore, $S_{i,t}$ represents the installed stock of capital, but we are interested in $K_{i,t}$, the flow of capital services from that stock over a given period. This distinction is not critical at the level of individual assets, but becomes important when we aggregate heterogeneous assets.

For individual assets, we assume the flow of capital services is proportional to the average of the stock available at the end of the current and prior periods:

$$K_{i,t} = q_i \frac{(S_{i,t} + S_{i,t-1})}{2} \tag{B.2}$$

where q_i denotes this constant of proportionality, set equal to unity. Note that this differs from our earlier work, e.g., Jorgenson (1990b), Jorgenson and Stiroh (1999), and Ho, Jorgenson, and Stiroh (1999), where capital service flows were assumed proportional to the lagged stock for individual assets.

Our approach assumes any improvement in input characteristics, such as a faster processor in a computer, is incorporated into investment

$t_{i,t}$, via deflation of the nominal investment series. That is, investment deflators transform recent vintages of assets into an equivalent number of efficiency units of earlier vintages. This is consistent with the perfect substitutability assumption across vintages and our use of the perpetual inventory method, where vintages differ in productive characteristics due to the age-related depreciation term.

We estimate a price of capital services that corresponds to the quantity flow of capital services via a rental price formula. In equilibrium, an investor is indifferent between two alternatives: earning a nominal rate of return, i_t, on a different investment or buying a unit of capital, collecting a rental fee, and then selling the depreciated asset in the next period. The equilibrium condition, therefore, is:

$$(1+i_t)P_{i,t-1} = c_{i,t} + (1-\delta_i)\ P_{i,t} \tag{B.3}$$

and rearranging yields a variation of the familiar cost of capital equation:

$$c_{i,t} = (i_t - \pi_{i,t})P_{i,t-1} + \delta_i P_{i,t} \tag{B.4}$$

where the asset-specific capital gains term is $\pi_{i,t} = (P_{i,t} - P_{i,t-1})/P_{i,t-1}$.

This formulation of the cost of capital effectively includes asset-specific revaluation terms. If an investor expects capital gains on his investment, he will be willing to accept a lower service price. Conversely, investors require high service prices for assets-like computers with large capital losses. Empirically, asset-specific revaluation terms can be problematic due to wide fluctuations in prices from period to period that can result in negative rental prices. However, asset-specific revaluation terms are becoming increasingly important as prices continue to decline for high-tech assets. Jorgenson and Stiroh (1999), for example, incorporated economy-wide asset revaluation terms for all assets and estimated a relatively modest growth contribution from computers.

As discussed by Jorgenson and Yun (1991b), tax considerations also play an important role in rental prices. Following Jorgenson and Yun, we account for investment tax credits, capital consumption allowances, the statutory tax rate, property taxes, debt/equity financing, and personal taxes, by estimating an asset-specific, after-tax real rate of return, $r_{i,t}$, that enters the cost of capital formula:

$$c_{i,t} = \frac{1 - ITC_{i,t} - \tau_t Z_{i,t}}{1-\tau_t}[r_{i,t}P_{i,t-1} + \delta_i P_{i,t}] + \tau_p P_{i,t-1} \tag{B.5}$$

where $ITC_{i,t}$ is the investment tax credit, τ_t is the statutory tax rate, $Z_{i,t}$ is the capital consumption allowance, τ_p is a property tax rate, all for asset i at time t , and $r_{i,t}$ is calculated as:

$$r_{i,t} = \beta[(1-\tau_t)i_t - \pi_{i,t}] + (1-\beta)\left[\frac{\rho_t - \pi_{i,t}(1-t_q^g)}{(1-t_q^e)\alpha + (1-t_q^g)(1-\alpha)}\right] \tag{B.6}$$

where β is the debt/capital ratio, i_t is the interest cost of debt, ρ_t is the rate of return to equity, α is the dividend payout ratio, and t_q^g and t_q^e are the tax rates on capital gains and dividends, respectively. $\pi_{i,t}$ is the inflation rate for asset i, which allows $r_{i,t}$ to vary across assets.[59]

Equations (B.1) through (B.6) describe the estimation of the price and quantity of capital services for individual assets: $P_{i,t}$ and $I_{i,t}$ for investment; $P_{i,t}$ and $S_{i,t}$ for capital stock; and $c_{i,t}$ and $K_{i,t}$ for capital services. For an aggregate production function analysis, we require an aggregate measure of capital services, $K_t = f(K_{1,t}, K_{2,t}, \ldots, K_{n,t})$, where n includes all types of reproducible fixed assets, consumers' durable assets, inventories, and land. We employ quantity indexes of to generate aggregate capital services, capital stock, and investment series.[60]

The growth rate of aggregate capital services is defined as a share-weighted average of the growth rate of the components:

$$\Delta \ln K_t = \sum_i \overline{v}_{i,t} \Delta \ln K_{i,t} \tag{B.7}$$

where weights are value shares of capital income:

$$\overline{v}_{i,t} = \frac{1}{2}\left(\frac{c_{i,t}K_{i,t}}{\sum\limits_i c_{i,t}K_{i,t}} + \frac{c_{i,t-1}K_{i,t-1}}{\sum\limits_i c_{i,t-1}K_{i,t-1}}\right) \tag{B.8}$$

and the price index of aggregate capital services is defined as:

$$c_t = \frac{\sum_i c_{i,t}K_{i,t}}{K_t}. \tag{B.9}$$

Similarly, the quantity index of capital stock is given by:

$$\Delta \ln S_t = \sum_i \overline{w}_{i,t} \Delta \ln S_{i,t} \tag{B.10}$$

where the weights are now value shares of the aggregate capital stock:

$$\overline{w}_{i,t} = \frac{1}{2}\left(\frac{P_{i,t}S_{i,t}}{\sum\limits_{i} P_{i,t}S_{i,t}} + \frac{P_{i,t-1}S_{i,t-1}}{\sum\limits_{i} P_{i,t-1}S_{i,t-1}}\right) \tag{B.11}$$

and the price index for the aggregate capital stock index is:

$$P_{S,t} = \frac{\sum\limits_{i} P_{i,t}S_{i,t}}{S_t}. \tag{B.12}$$

Finally, the aggregate quantity index of investment is given by:

$$\Delta \ln I_t = \sum_{i} \overline{u}_{i,t} \Delta \ln I_{i,t} \tag{B.13}$$

where the weights are now value shares of aggregate investment:

$$\overline{u}_{i,t} = \frac{1}{2}\left(\frac{P_{i,t}I_{i,t}}{\sum\limits_{i} P_{i,t}I_{i,t}} + \frac{P_{i,t-1}I_{i,t-1}}{\sum\limits_{i} P_{i,t-1}I_{i,t-1}}\right) \tag{B.14}$$

and the price index for the aggregate investment index is:

$$P_{I,t} = \frac{\sum\limits_{i} P_{i,t}I_{i,t}}{I_t}. \tag{B.15}$$

The most important point from this derivation is the difference between the growth rate of aggregate capital services, equation (B.7), and the growth rate of capital stock, equation (B.10); this reflects two factors. First, the weights are different. The index of aggregate capital services uses rental prices as weights, while the index of aggregate capital stock uses investment prices. Assets with rapidly falling asset prices will have relatively large rental prices. Second, as can be seen from equation (B.2), capital services are proportional to a two-period average stock, so the timing of capital services growth and capital stock growth differ for individual assets. In steady-state with a fixed capital to output ratio, this distinction is not significant, but if asset accumulation is either accelerating or decelerating, this timing matters.

A second point to emphasize is that we can define an ″aggregate index of capital quality,″ $q_{K,t}$, analogously to equation (B.2). We define the aggregate index of capital quality as $q_{K,t} = K_t/((S_t + S_{t-1})/2)$, and it follows that the growth of capital quality is defined as:

$$\begin{aligned}\Delta \ln q_{K,t} &= \Delta \ln K_t - \Delta \ln \left(\frac{(S_t + S_{t-1})}{2} \right) \\ &= \sum_i (\overline{v}_{i,t} - \overline{w}_{i,t}) \Delta \ln \left(\frac{(S_{t,i} + S_{t-1,i})}{2} \right). \end{aligned} \tag{B.16}$$

Equation (B.16) defines growth in capital quality as the difference between the growth in capital services and the growth in average capital stock. This difference reflects substitution towards assets with relatively high rental price weights and high marginal products. For example, the rental price for computers is declining rapidly as prices fall, which induces substitution towards computers and rapid capital accumulation. However, the large depreciation rate and large negative revaluation term imply that computers have a high marginal product, so their rental price weight greatly exceeds their asset price weight. Substitution towards assets with higher marginal products is captured by our index of capital quality.

B.2 Investment and Capital Data

Our primary data source for estimating aggregating the flow of capital services is the "Investment Estimates of Fixed Reproducible Tangible Wealth, 1925–1997" (BEA, 1998b, 1998c).

These data contain historical cost investment and chain-type quantity indices for 47 types of non-residential assets, 5 types of residential assets, and 13 different types of consumers' durable assets from 1925 to 1997. Table B.1 shows our reclassification of the BEA data into 52 non-residential assets, 5 residential assets, and 13 consumers' durable assets.[61]

Table B.2 presents the value and price index of the broadly defined capital stock, as well as individual information technology assets. Table B.3 presents similar data, but for capital service flows rather than capital stocks.[62] The price of capital stocks for individual assets in table B.2 is the same as the investment price in table A.1, but the prices differ for aggregates due to differences between weights based on investment flows and those based on asset stocks. The price index for investment grows more slowly than the price index for assets, since short-lived assets with substantial relative price declines are a greater proportion of investment.

An important caveat about the underlying the investment data is that it runs only through 1997 and is not consistent with the BEA benchmark revision in October 1999. We have made several adjustments to reflect the BEA revision, make the data consistent with our earlier work, and extend the investment series to 1998. First, we have replaced the Tangible Wealth series on "computers and peripherals equipment" and replaced it with the NIPA investment series for "computers and peripherals equipment," in both current and chained 1996 dollars. These series were identical in the early years and differed by about 5 percent in current dollars in 1997. Similarly, we used the new NIPA series for investment in "software," "communications equipment," and for personal consumption of "computers, peripherals, and software" in both current and chained 1996 dollars. These NIPA series enable us to maintain a complete and consistent time series that incorporates the latest benchmark revisions and the expanded output concept that includes software.

Second, we have combined investment in residential equipment with "other equipment," a form of non-residential equipment. This does not change the investment or capital stock totals, but reallocates some investment and capital from the residential to the non-residential category.

Third, we control the total value of investment in major categories—structures, equipment and software, residential structures, and total consumers' durables—to correspond with NIPA aggregates. This adjustment maintains a consistent accounting for investment and purchases of consumers' durables as inputs and outputs. Computer investment, software investment, communications investment, and consumption of computers, peripherals, and software series not adjusted.

Fourth, we extended the investment series through 1998 based on NIPA estimates. For example, the 1998 growth rate for other fabricated metal products, steam engines, internal combustion engines, metalworking machinery, special industry machinery, general industrial equipment, and electrical transmission and distribution equipment were taken from the "other" equipment category in NIPA. The growth rate of each type of consumers' durables was taken directly from NIPA.

These procedures generated a complete time series of investment in 57 private assets (29 types of equipment and software, 23 types of non-residential structures, and 5 types of residential structures) and consumption of 13 consumers' durable assets in both current dollars and chained–1996 dollars from 1925 to 1998. For each asset, we created a real investment series by linking the historical cost investment and the

Table B.1
Investment and capital stock by asset type and class

Asset	Geometric Depreciation Rate	1998	
		Investment	Capital Stock
Total Capital	na		27,954.7
Fixed Reproducible Assets	na	4,161.7	20,804.2
Equipment and Software		829.1	4,082.0
Household furniture	0.1375	2.3	13.1
Other furniture	0.1179	37.6	224.4
Other fabricated metal products	0.0917	15.9	134.5
Steam engines	0.0516	2.7	60.1
Internal combustion engines	0.2063	1.6	6.9
Farm tractors	0.1452	10.8	60.7
Construction tractors	0.1633	2.9	15.3
Agricultural machinery, except tractors	0.1179	13.1	89.2
Construction machinery, except tractors	0.1550	20.6	99.5
Mining and oilfield machinery	0.1500	2.4	15.6
Metalworking machinery	0.1225	37.1	228.6
Special industry machinery, n.e.c.	0.1031	38.6	288.7
General industrial, including materials handling, equipment	0.1072	34.5	247.5
Computers and peripheral equipment	0.3150	88.5	164.9
Service industry machinery	0.1650	17.9	92.0
Communication equipment	0.1100	83.6	440.5
Electrical transmission, distribution, and industrial apparatus	0.0500	26.7	313.0
Household appliances	0.1650	1.5	6.9
Other electrical equipment, n.e.c.	0.1834	15.2	64.5
Trucks, buses, and truck trailers	0.1917	104.5	367.0
Autos	0.2719	19.4	70.2
Aircraft	0.0825	23.0	174.5
Ships and boats	0.0611	3.0	48.4
Railroad equipment	0.0589	5.3	69.1
Instruments (scientific & engineering)	0.1350	30.9	172.6
Photocopy and related equipment	0.1800	22.6	103.0
Other nonresidential equipment	0.1473	35.4	184.3
Other office equipment	0.3119	8.4	24.5
Software	0.3150	123.4	302.4
Non-Residential Structures		2,271.3	5,430.6
Industrial buildings	0.0314	36.4	766.6
Mobile structures (offices)	0.0556	0.9	9.8
Office buildings	0.0247	44.3	829.8
Commercial warehouses	0.0222	0.0	0.0
Other commercial buildings, n.e.c.	0.0262	55.7	955.8
Religious buildings	0.0188	6.6	155.3

Table B.1 (continued)

Asset	Geometric Depreciation Rate	1998 Investment	1998 Capital Stock
Educational buildings	0.0188	11.0	157.4
Hospital and institutional buildings	0.0188	17.76	355.12
Hotels and motels	0.0281	17.08	210.57
Amusement and recreational buildings	0.0300	9.14	103.55
Other nonfarm buildings, n.e.c.	0.0249	2.07	67.68
Railroad structures	0.0166	5.78	210.36
Telecommunications	0.0237	13.19	282.09
Electric light and power (structures)	0.0211	12.12	490.04
Gas (structures)	0.0237	4.96	170.98
Local transit buildings	0.0237	0.00	0.00
Petroleum pipelines	0.0237	1.11	39.20
Farm related buildings and structures	0.0239	4.59	202.73
Petroleum and natural gas	0.0751	22.12	276.99
Other mining exploration	0.0450	2.03	38.96
Other nonfarm structures	0.0450	6.39	107.70
Railroad track replacement	0.0275	0.00	0.00
Nuclear fuel rods	0.0225	0.00	0.00
Residential Structures		363.18	8,309.62
1-to-4-unit homes	0.0114	240.27	5,628.27
5-or-more-unit homes	0.0140	21.11	871.81
Mobile homes	0.0455	14.64	147.17
Improvements	0.0255	86.29	1,634.15
Other residential	0.0227	0.87	28.23
Consumers Durables		698.20	2,981.97
Autos	0.2550	166.75	616.53
Trucks	0.2316	92.53	327.85
Other (RVs)	0.2316	18.63	64.98
Furniture	0.1179	56.02	372.26
Kitchen Appliance	0.1500	29.83	161.75
China, Glassware	0.1650	29.65	141.44
Other Durable	0.1650	64.03	309.67
Computers and Software	0.3150	30.40	52.30
Video, Audio	0.1833	75.15	289.22
Jewelry	0.1500	44.58	228.38
Ophthalmic	0.2750	16.53	53.44
Books and Maps	0.1650	25.34	132.51
Wheel Goods	0.1650	48.76	231.66
Land	0.0000		5,824.18
Inventories	0.0000		1,326.31

Notes: Values of investment and capital stock is in millions of current dollars. Equipment and Software and Other nonresidential equipment includes NIPA residential equipment.
Source: BEA (1998a, 1999b, 1999c) and author calculations.

Table B.2
Total capital stock and high-tech assets

	Total Stock of Capital & CD Assets		Computer Capital Stock		Software Capital Stock		Communications Capital Stock		Computer & Software CD Stock	
Year	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price
1959	1,300.3	0.17	0.00	0.00	0.00	0.00	9.97	0.47	0.00	0.00
1960	1,391.0	0.18	0.20	697.30	0.10	0.61	11.11	0.47	0.00	0.00
1961	1,478.5	0.18	0.40	522.97	0.27	0.62	12.53	0.47	0.00	0.00
1962	1,583.6	0.19	0.50	369.16	0.39	0.63	14.06	0.46	0.00	0.00
1963	1,667.7	0.19	0.95	276.29	0.67	0.63	15.50	0.46	0.00	0.00
1964	1,736.0	0.19	1.44	229.60	0.97	0.64	16.99	0.47	0.00	0.00
1965	1,848.3	0.19	2.01	188.74	1.37	0.65	18.56	0.47	0.00	0.00
1966	2,007.7	0.20	2.67	132.70	1.95	0.66	20.69	0.47	0.00	0.00
1967	2,150.6	0.21	3.38	107.71	2.55	0.67	23.21	0.49	0.00	0.00
1968	2,394.9	0.22	3.88	92.00	3.09	0.68	26.38	0.51	0.00	0.00
1969	2,670.4	0.24	4.81	83.26	3.98	0.70	30.57	0.54	0.00	0.00
1970	2,874.8	0.24	5.66	74.81	5.12	0.73	35.16	0.57	0.00	0.00
1971	3,127.9	0.26	5.75	56.98	5.91	0.73	39.66	0.60	0.00	0.00
1972	3,543.0	0.28	6.68	45.93	6.86	0.73	43.77	0.62	0.00	0.00
1973	4,005.0	0.30	7.83	43.53	8.04	0.75	48.30	0.64	0.00	0.00
1974	4,250.3	0.31	8.28	35.55	9.77	0.80	55.98	0.69	0.00	0.00
1975	4,915.0	0.35	8.85	32.89	11.89	0.85	64.49	0.76	0.00	0.00
1976	5,404.1	0.37	9.46	27.47	13.52	0.87	71.56	0.80	0.00	0.00
1977	6,151.9	0.41	11.34	23.90	15.01	0.89	76.27	0.78	0.00	0.00
1978	7,097.4	0.45	12.86	16.17	17.00	0.90	88.54	0.81	0.10	33.68
1979	8,258.3	0.50	17.50	13.40	21.01	0.95	101.62	0.83	0.17	32.81
1980	9,407.4	0.56	21.85	10.46	25.93	1.01	122.33	0.88	0.28	22.11
1981	10,771.2	0.62	30.26	9.19	31.72	1.07	146.61	0.96	0.56	18.79
1982	11,538.6	0.66	37.45	8.22	38.14	1.12	168.74	1.01	1.71	15.12
1983	12,033.2	0.67	45.29	6.86	44.40	1.13	185.59	1.03	3.73	10.71
1984	13,247.3	0.71	56.70	5.55	52.68	1.14	207.81	1.07	5.25	9.41
1985	14,837.5	0.77	66.72	4.72	61.66	1.13	228.43	1.09	6.21	8.68
1986	15,985.5	0.81	72.77	4.06	69.38	1.12	246.93	1.10	8.41	6.54
1987	17,137.5	0.85	78.26	3.46	79.17	1.12	262.59	1.10	11.40	5.91
1988	18,632.2	0.90	87.79	3.21	91.54	1.14	280.64	1.10	15.35	5.41
1989	20,223.2	0.96	99.26	3.00	105.64	1.11	297.05	1.10	18.06	5.02
1990	20,734.0	0.96	100.29	2.72	121.57	1.09	311.95	1.11	19.30	4.22
1991	21,085.3	0.97	99.42	2.45	140.37	1.10	324.37	1.11	22.97	3.53
1992	21,296.9	0.96	101.84	2.09	151.41	1.04	334.48	1.10	24.05	2.68
1993	21,631.7	0.96	106.68	1.78	173.39	1.04	342.48	1.09	27.20	2.07
1994	22,050.0	0.96	115.74	1.57	191.63	1.02	353.46	1.07	34.28	1.81
1995	23,346.7	0.99	130.78	1.31	215.13	1.02	362.23	1.03	39.71	1.44
1996	24,300.2	1.00	139.13	1.00	239.73	1.00	380.00	1.00	42.49	1.00
1997	26,070.4	1.04	150.57	0.78	266.63	0.97	407.58	0.99	46.20	0.69
1998	27,954.7	1.08	164.87	0.57	302.41	0.96	440.52	0.97	52.30	0.48

Notes: Values are in billions of current dollars. Total capital stock includes reproducible assets, consumers' durable assets (CD), land, and inventories. All price indexes are normalized to 1.0 in 1996.

Table B.3
Total capital services and high-tech assets

	Total Service Flow from Capital & CD Assets		Computer Capital Service Flow		Software Capital Service Flow		Communications Capital Service Flow		Computer & Software CD Service Flow	
Year	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price
1959	214.7	0.32	0.00	0.00	0.00	0.00	2.55	0.50	0.00	0.00
1960	183.7	0.26	0.05	407.59	0.02	0.64	2.65	0.47	0.00	0.00
1961	192.3	0.26	0.25	602.38	0.08	0.61	2.85	0.45	0.00	0.00
1962	211.9	0.28	0.41	480.68	0.15	0.65	3.44	0.48	0.00	0.00
1963	241.7	0.30	0.56	291.73	0.22	0.60	3.32	0.42	0.00	0.00
1964	260.2	0.31	0.77	196.86	0.34	0.59	3.68	0.42	0.00	0.00
1965	289.2	0.32	1.15	169.47	0.52	0.64	4.73	0.50	0.00	0.00
1966	315.4	0.33	1.99	161.83	0.74	0.65	5.00	0.48	0.00	0.00
1967	333.8	0.33	2.13	103.65	1.03	0.68	5.14	0.45	0.00	0.00
1968	330.2	0.31	2.40	81.43	1.29	0.69	5.43	0.44	0.00	0.00
1969	349.2	0.31	2.54	63.64	1.57	0.69	6.02	0.44	0.00	0.00
1970	382.5	0.33	3.27	61.40	2.09	0.74	7.23	0.48	0.00	0.00
1971	391.4	0.32	4.83	68.40	2.83	0.83	8.34	0.51	0.00	0.00
1972	439.6	0.35	4.44	45.09	3.01	0.77	8.86	0.51	0.00	0.00
1973	517.9	0.38	4.02	30.87	3.47	0.77	12.48	0.68	0.00	0.00
1974	546.6	0.38	6.04	36.38	3.99	0.78	11.48	0.58	0.00	0.00
1975	619.2	0.42	5.36	26.49	5.17	0.88	13.41	0.64	0.00	0.00
1976	678.1	0.44	6.01	24.25	5.60	0.84	13.61	0.62	0.00	0.00
1977	742.8	0.47	6.35	19.16	6.26	0.86	22.37	0.94	0.00	0.00
1978	847.5	0.51	10.71	20.84	7.31	0.91	19.02	0.72	0.02	17.84
1979	999.1	0.57	10.45	12.30	8.19	0.89	26.30	0.89	0.07	19.01
1980	1,026.9	0.56	15.03	10.96	9.99	0.93	23.94	0.72	0.20	25.93
1981	1,221.4	0.66	15.92	7.33	11.76	0.94	23.89	0.64	0.25	13.90
1982	1,251.7	0.65	17.29	5.47	12.54	0.87	25.32	0.62	0.74	11.96
1983	1,359.1	0.71	22.77	5.06	15.11	0.92	29.54	0.67	2.07	10.39
1984	1,570.1	0.79	30.79	4.54	19.02	0.99	33.20	0.70	2.37	6.07
1985	1,660.5	0.79	33.72	3.43	22.41	0.99	39.30	0.77	2.70	4.93
1986	1,559.9	0.71	36.44	2.82	25.88	0.99	43.39	0.79	4.84	5.61
1987	1,846.6	0.80	45.07	2.76	31.84	1.07	55.49	0.94	4.91	3.54
1988	2,185.3	0.89	43.85	2.18	37.72	1.11	67.22	1.07	6.65	3.24
1989	2,243.0	0.89	47.89	1.97	45.96	1.16	67.90	1.02	7.89	2.85
1990	2,345.0	0.90	53.28	1.89	51.07	1.10	69.86	1.00	10.46	2.97
1991	2,345.8	0.88	52.65	1.69	54.07	1.01	66.05	0.91	11.66	2.44
1992	2,335.4	0.86	57.69	1.60	69.11	1.12	70.72	0.94	14.96	2.25
1993	2,377.4	0.85	62.00	1.42	69.32	0.98	80.23	1.02	16.26	1.71
1994	2,719.5	0.94	63.16	1.17	84.14	1.05	89.16	1.09	16.14	1.17
1995	2,833.4	0.94	77.77	1.11	89.18	0.99	101.18	1.17	22.64	1.13
1996	3,144.4	1.00	96.36	1.00	101.46	1.00	92.91	1.00	30.19	1.00
1997	3,466.3	1.05	103.95	0.77	119.80	1.04	100.13	1.00	33.68	0.71
1998	3,464.8	0.99	118.42	0.61	128.32	0.97	103.35	0.94	36.53	0.48

Notes: Values are in billions of current dollars. Service prices are normalized to 1.0 in 1996. Total service flows include reproducible assets, consumers' durable assets (CD), land, and inventories. All price indexes are normalized to 1.0 in 1996.

quantity index in the base-year 1996. Capital stocks were then estimated using the perpetual inventory method in equation (B.1) and a geometric depreciation rate, based on Fraumeni (1997) and reported in table B.1.

Important exceptions are the depreciation rates for computers, software, and autos. BEA (1998a) reports that computer depreciation is based on the work of Oliner (1993, 1994b), is nongeometric, and varies over time. We estimated a best-geometric approximation to the latest depreciation profile for different types of computer assets and used an average geometric depreciation rate of 0.315, which we used for computer investment, software investment, and consumption of computers, peripherals, and software. Similarly, we estimated a best-geometric approximation to the depreciation profile for autos of 0.272.

We also assembled data on investment and land to complete our capital estimates. The inventory data come primarily from NIPA in the form of farm and non-farm inventories. Inventories are assumed to have a depreciation rate of zero and do not face an investment tax credit or capital consumption allowance, so the rental price formula is a simplified version of equation (B.5). Data on land are somewhat more problematic. Through 1995, the Federal Reserve Board published detailed data on land values and quantities in its "Balance Sheets for the U.S. Economy" study (Federal Reserve Board, 1995, 1997), but the underlying data became unreliable and are no longer published. We use the limited land data available in the "Flow of Funds Accounts of the United States" and historical data described in Jorgenson (1990b) to estimate a price and a quantity of private land. As a practical matter, this quantity series varies very little, so its major impact is to slow the growth of capital by assigning a positive weight to the zero growth rate of land. Like inventories, depreciation, the investment tax credit, and capital consumption allowances for land are zero.

A final methodological detail involves negative service prices that sometimes result from the use of asset-specific revaluation terms. As can be seen from the simplified cost of capital formula in Equation (B.5), an estimated service price can be negative if asset inflation is high relative to the interest and depreciation rates. Economically, this is possible, implying capital gains were higher than expected. Negative service prices make aggregation difficult so we made adjustments for several assets. In a small number of cases for reproducible assets and inventories, primarily structures in the 1970s, we used smoothed inflation for surrounding years rather than the current inflation in the cost of capital calculation. For land, which showed large capital gains throughout and has no depreciation, we used the economy-wide rate of asset inflation for all years.

Appendix C: Estimating Labor Input

C.1 Labor Input Methodology

We again begin with some notation for measures of hours worked, labor inputs, and labor quality for worker categories:

$H_{j,t}$ = quantity of hours worked by worker category j at time t

$w_{j,t}$ = price of an hour worked by worker category j at time t

$L_{j,t}$ = quantity of labor services from worker category j at time t

and for economy-wide aggregates:

H_t = quantity of aggregate hours worked at time t

W_t = average wage of hours worked at time t

L_t = quantity index of labor input at time t

$P_{L,t}$ = price index of labor input at time t

$q_{L,t}$ = quality index of labor input at time t.

In general, the methodology for estimating labor input parallels capital services, but the lack of an investment-type variable makes the labor input somewhat more straightforward. For each individual category of workers, we begin by assuming the flow of labor service is proportional to hours worked:

$$L_{j,t} = q_{L,j} H_{j,t} \tag{C.1}$$

where $q_{L,j}$ is the constant of proportionality for worker category j, set equal to unity.

The growth rate of aggregate labor input is defined as the share-weighted aggregate of the components as:

$$\Delta \ln L_t = \sum_i \overline{v}_{j,t} \Delta \ln L_{j,t} \tag{C.2}$$

where weights are value shares of labor income:

$$\overline{v}_{j,t} = \frac{1}{2}\left(\frac{w_{j,t}L_{j,t}}{\sum\limits_j w_{j,t}L_{j,t}} + \frac{w_{j,t-1}L_{j,t-1}}{\sum\limits_j w_{j,t-1}L_{j,t-1}}\right) \tag{C.3}$$

and the price of aggregate labor input is defined as:

$$P_{L,t} = \frac{\sum\limits_j w_{j,t}L_{j,t}}{L_t}. \tag{C.4}$$

We define the "aggregate index of labor quality," $q_{L,t}$, $q_{L,t} = L_t/H_t$, where H_t is the unweighted sum of labor hours:

$$H_t = \sum_j H_{j,t}. \tag{C.5}$$

The growth in labor quality is then defined as:

$$\Delta \ln q_{L,t} = \sum_j \overline{v}_{j,t}\Delta \ln H_{j,t} - \Delta \ln H_t. \tag{C.6}$$

Equation (C.6) defines growth in labor quality as the difference between weighted and unweighted growth in labor hours. As with capital, this reflects substitutions among heterogeneous types of labor with different characteristics and different marginal products. As described by Ho and Jorgenson (1999), one can further decompose labor quality into components associated with different characteristics of labor, such as age, sex, and education.

C.2 Labor Data

Our primary data sources are individual observations from the decennial Censuses of Population for 1970, 1980, and 1990, the NIPA, and the annual Current Population Survey (CPS). The NIPA provide totals for hours worked and the Census and CPS allows us to estimate labor quality growth. Details on the construction of the labor data are in Ho and Jorgenson (1999). Table C.1 reports the primary labor used in this study, including the price, quantity, value, and quality of labor input, as well as employment, weekly hours, hourly compensation, and hours worked.

Briefly, the Censuses of Population provide detailed data on employment, hours, and labor compensation across demographic groups in census years. The CPS data are used to interpolate similar data for

Table C.1
Labor input

	Labor Input				Employment	Weekly Hours	Hourly Compensation	Hours Worked
Year	Price	Quantity	Value	Quality				
1959	0.15	1,866.7	269.8	0.82	58,209	38.0	2.3	115,167
1960	0.15	1,877.5	289.1	0.82	58,853	37.7	2.5	115,403
1961	0.16	1,882.0	297.7	0.83	58,551	37.4	2.6	113,996
1962	0.16	1,970.7	315.3	0.86	59,681	37.5	2.7	116,348
1963	0.16	2,000.2	320.4	0.86	60,166	37.5	2.7	117,413
1964	0.17	2,051.4	346.2	0.87	61,307	37.4	2.9	119,111
1965	0.18	2,134.8	375.1	0.88	63,124	37.4	3.0	122,794
1966	0.19	2,226.9	413.7	0.89	65,480	37.1	3.3	126,465
1967	0.19	2,261.8	429.3	0.90	66,476	36.8	3.4	127,021
1968	0.21	2,318.8	480.8	0.91	68,063	36.5	3.7	129,194
1969	0.22	2,385.1	528.6	0.91	70,076	36.4	4.0	132,553
1970	0.24	2,326.6	555.6	0.90	69,799	35.8	4.3	130,021
1971	0.26	2,318.3	600.2	0.90	69,671	35.8	4.6	129,574
1972	0.28	2,395.5	662.9	0.91	71,802	35.8	5.0	133,554
1973	0.29	2,519.1	736.4	0.91	75,255	35.7	5.3	139,655
1974	0.32	2,522.2	798.8	0.91	76,474	35.0	5.7	139,345
1975	0.35	2,441.8	852.9	0.92	74,575	34.6	6.3	134,324
1976	0.38	2,525.6	964.2	0.92	76,925	34.6	7.0	138,488
1977	0.41	2,627.2	1,084.9	0.92	80,033	34.6	7.5	143,918
1978	0.44	2,783.7	1,232.4	0.93	84,439	34.5	8.1	151,359
1979	0.48	2,899.6	1,377.7	0.93	87,561	34.5	8.8	157,077
1980	0.52	2,880.8	1,498.2	0.94	87,788	34.1	9.6	155,500
1981	0.55	2,913.8	1,603.9	0.94	88,902	33.9	10.2	156,558
1982	0.60	2,853.3	1,701.6	0.94	87,600	33.6	11.1	153,163
1983	0.64	2,904.9	1,849.0	0.94	88,638	33.9	11.9	156,049
1984	0.66	3,095.5	2,040.2	0.95	93,176	34.0	12.4	164,870
1985	0.69	3,174.6	2,183.5	0.95	95,410	33.9	13.0	168,175
1986	0.75	3,192.8	2,407.1	0.95	97,001	33.5	14.2	169,246
1987	0.74	3,317.1	2,464.0	0.96	99,924	33.7	14.1	174,894
1988	0.76	3,417.2	2,579.5	0.96	103,021	33.6	14.3	179,891
1989	0.80	3,524.2	2,827.0	0.96	105,471	33.7	15.3	184,974
1990	0.84	3,560.3	3,001.9	0.97	106,562	33.6	16.1	186,106
1991	0.88	3,500.3	3,081.4	0.97	105,278	33.2	16.9	181,951
1992	0.94	3,553.4	3,337.0	0.98	105,399	33.2	18.3	182,200
1993	0.95	3,697.5	3,524.4	0.99	107,917	33.5	18.8	187,898
1994	0.96	3,806.4	3,654.6	0.99	110,888	33.6	18.9	193,891
1995	0.98	3,937.5	3,841.2	1.00	113,707	33.7	19.3	199,341
1996	1.00	4,016.8	4,016.8	1.00	116,083	33.6	19.8	202,655
1997	1.02	4,167.6	4,235.7	1.01	119,127	33.8	20.3	209,108
1998	1.06	4,283.8	4,545.7	1.01	121,934	33.7	21.3	213,951

Notes: Quantity of labor input is measured in billions of 1996 dollars; value of labor input is measured in billions of current dollars. Employment is thousands of workers, hourly compensation is in dollars, and hours worked is in millions. Price of labor input and index of labor quality are normalized to 1.0 in 1996.

intervening years and the NIPA data provide control totals. The demographic groups include 168 different types of workers, Cross-classified by sex (male, female), class (employee, self-employed or unpaid), age (16–17, 18–24, 25–34, 45–54, 55–4, 65+), and education (0–8 years grade school, 1–3 years high school, 4 years high school, 1–3 years college, 4 years college, 5+ years college).[63] Adjustments to the data include allocations of multiple job-holders, an estimation procedure to recover "top-coded" income data, and bridging to maintain consistent definitions of demographic groups over time.

These detailed data cover 1959 to 1995 and are taken from Ho and Jorgenson (1999). This allows us to estimate the quality of labor input for the private business sector, general government, and government enterprises, where only the private business sector index is used in the aggregate growth accounting results. For the years 1996–1998, we estimate labor quality growth by holding relative wages across labor types constant, and incorporating demographic projections for the labor force. Hours worked by employees are taken from the latest data in the NIPA; hours worked by the self-employed are estimated by Ho and Jorgenson (1999).

Appendix D: Estimating Industry-Level Productivity

Our primary data are annual time series of interindustry transactions in current and constant prices, including final demands by commodity, investment and labor inputs by industry, and output by industry. The first building block is a set of interindustry transactions produced by the Employment Projections Office at the Bureau of Labor Statistics (BLS). These data report intermediate inputs and total value added (the sum of capital and labor inputs and taxes) for 185 industries from 1977 to 1995. A major advantage of this BLS interindustry data is that they provide the necessary interpolations between benchmark years.

We aggregate the data from the "Make" and "Use" tables to generate interindustry transactions for 35 private business industries at approximately the two-digit Standard Industrial Classification (SIC) level. These tables enable us to generate growth rates of industry outputs, growth rates of intermediate inputs, and shares of intermediate inputs as needed in equation (3.29). They also provide control totals for value added in each industry, the sum of the values of capital and labor services and taxes.

Estimation of capital services and labor input follows the procedures described above for each industry. We collected information from three sources to estimate prices and quantities of capital and labor inputs by industry. An industry-level breakdown of the value of capital and labor input is available in the "gross product originating" series described in Lum and Yuskavage (1997) of the BEA. Investments by asset classes and industries are from the BEA Tangible Wealth Survey (BEA, 1998a, described by Katz and Herman, 1997). Labor data across industries are from the decennial Census of Population and the annual Current Population Survey. We use employ the prices and quantities of labor services for each industry constructed by Ho and Jorgenson (1999).

We also generate capital and labor services for a Private Household sector and the Government sector.[64] For Private Households, the value of labor services equals labor income in BLS's private household industry, while capital income reflects the imputed flow of capital services from residential housing, consumers' durables, and household land as described above. For Government, labor income equals labor compensation of general government employees and capital income is an estimate flow of capital services from government capital.[65] Note Government Enterprises are treated as a private business industry and are separate from the General Government.

Appendix E: Extrapolation for 1999

Table 3.2 presents primary growth accounting results through 1998 and preliminary estimates for 1999. The data through 1998 are based on the detailed methodology described in Appendices A-D; the 1999 data are extrapolated based on currently available data and recent trends.

Our approach for extrapolating growth accounting results through 1999 was to estimate 1999 shares and growth rates for major categories like labor, capital, and information technology components, as well as the growth in output. The 1999 labor share was estimated from 1995–1998 data, hours growth are from BLS (2000), and labor quality growth came from the projections described above. The 1999 growth rates of information technology outputs were taken from the NIPA, and shares were estimated from 1995–1998 data. The 1999 growth rates of information technology inputs were estimated from recent investment data and the perpetual inventory method, and shares were estimated from 1995–1998 data. The 1999 growth of other capital were estimates from NIPA investment data for broad categories like equipment and software, non-residential structures, residential structures, as well as consumers' durable purchases; the income share was calculated from the estimated labor share. Output growth was estimated from growth in BLS business output and BEA GDP, with adjustment made for different output concepts. Finally, TFP growth for 1999 was estimated as the difference in the estimated output growth and share-weighted input growth.

Notes

1. Labor productivity growth for the business sector averaged 2.7 percent for 1995–1999, the four fastest annual growth rates in the 1990s, except for a temporary jump of 4.3 percent in 1992 as the economy exited recession (BLS, 2000).

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

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

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

5. BLS (2000) estimates for the business sector show a similar increase from 1.6 percent for 1990–1995 to 2.6 percent for 1995–1998. See CEA (2000, pg. 35) for a comparison of productivity growth at various points in the economic expansions of the 1960s, 1980s, and 1990s.

6. See Gullickson and Harper (1999), Jorgenson and Stiroh (2000a), and section 3.4, below, for industry-level analysis.

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

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

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

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

11. Triplett (1996a) points out that much of decline of computer prices reflects falling semiconductor prices. If all inputs are correctly measured for quality change, therefore, much of the TFP gains in computer production are rightly pushed back to TFP gains in semiconductor production since semiconductors are a major intermediate input in the production of computers. See Flamm (1993) for early estimates on semiconconductor prices. We address this further in section 3.4.

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

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

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

15. Jorgenson (1996) provides a recent discussion of our model of capital as a factor of production. BLS (1983a) describes the version of this model employed in the official productivity statistics. Hulten (2001) provides a review of the specific features of this methodology for measuring capital input and the link to economic theory.

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

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

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

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

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

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

22. By comparison, BLS (2000) reports growth in business hours of 1.2 percent for 1990–1995 and 2.3 percent for 1995–1998. The slight discrepancies reflect our methods for estimating hours worked by the self-employed, as well as minor differences in the scope of our output measure.

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

24. Table 3.2 also presents preliminary results for the more recent period 1995-1999, where the 1999 numbers are based on the estimation procedure described in Appendix E, rather than the detailed model described above. The results for 1995–1998 and 1995–1999 are quite similar; we focus our discussion on the period 1995–1998.

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

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

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

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

29. BLS (2000) shows similar trends for the business sector with hours growth increasing from 1.2 percent for 1990–1995 to 2.3 percent for 1995–1998, while ALP increased from 1.58 percent to 2.63 percent.

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

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

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

33. This calculation shows that the simplified model of Oliner and Sichel (2000) is a special case of the complete Domar weighting scheme used in section 3.4.

34. Relative price changes in the Base Case are taken from the investment prices in table 3.5. Output shares are estimated based on final demand sales available from the BEA website for computers and from Parker and Grimm (2000a) for software. Investment in communications equipment is from the NIPA, and we estimate other final demand components for communications equipment using ratios relative to final demand for computers. This is an approximation necessitated by the lack of complete data of sales to final demand by detailed commodity.

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

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

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

38. Note the growth rates in table 3.6 do not exactly match table 3.2 due to differences in calculating growth rates. All growth rates in table 3.6 follow CBO's convention of

calculating discrete growth rates as $g = [(X_t/X_0)^{1/t} - 1] * 100$, while growth rates in table 3.2 are calculated as $g = [\ln(X_t/X_0)/t] * 100$.

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

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

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

42. These comparisons are from CBO (2000, tables 2–6).

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

44. BLS refers to this concept as multifactor productivity (MFP).

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

46. We are grateful to Mun Ho for his extensive contributions to the construction of the industry data.

47. Appendix D provides details on the component data sources and linking procedures.

48. Our industry classification is too broad to isolate the role of semiconductors.

49. This conclusion rests critically on the input share of semiconductors in the computer industry. Triplett reports Census data estimates of this share at 15 percent for 1978–1994, but states industry sources estimate this share to be closer to 45 percent. This has an important impact on his results. At one end of the spectrum, if no account is made for semiconductor price declines, the relative productivity in computer equipment increases 9.1 percent for 1978–1994. Assuming a 15 percent share for semiconductors causes this to fall to 9 percent; assuming a 45 percent share causes a fall to 1 percent.

50. Dean (1999) summarizes the BLS view on this issue. McGuckin and Stiroh (2000) attempt to quantify the magnitude of the potential mismeasurement effects.

51. See Gullickson and Harper (1999), particularly pp. 55–56, for details.

52. These five industries are Agriculture, Construction, Transportation, FIRE and Services. Note that our estimates for 1977–1996 are not given.

53. These seven other industries that are comparable are Agriculture, Nonmetallic Mining, Construction, Transportation, Communications, Trade, and FIRE.

54. The ten industries with small differences are Food Products, Apparel, Furniture and Fixtures, Paper Products, Printing and Publishing, Chemical Products, Primary Metals, Industrial and Commercial Machinery, Electronic and Electric Machinery, and Miscellaneous Manufacturing. The two industries with slightly larger differences are Rubber and Plastic, and Fabricated Metals.

55. This aggregate impact is smaller than that estimated by Gullickson and Harper (1999), partly because our shares differ due to the inclusion of a Household and Government

industry. Also, as pointed out by Gullickson and Harper, a complete re-estimation would account for the change in intermediate inputs implied by the productivity adjustments.

56. Oliner and Sichel (2000) argue that Gordon's conclusion is weakened by the new NIPA data released in the benchmark revision, which allow a larger role for ALP growth outside of computer production.

57. Gordon (1990), table 12.3, p. 539.

58. See BLS (1997), particularly chapter 14, for details on the quality adjustments incorporated into the producer prices indexes that are used as the primary deflators for the capital stock study. Cole *et al.* (1986) and Triplett (1986, 1989) provide details on the estimation of hedonic regressions for computers.

59. A complication, of course, is that ρ_t is endogenous. We assume the after-tax rate of return to all assets is the same and estimate ρ_t as the return that exhausts the payment of capital across all assets in the corporate sector. In addition, tax considerations vary across ownership classes, e.g., corporate, non-corporate, and household. We account for these differences in our empirical work, but do not go into details here. See Jorgenson and Yun (1991b, chapter 2).

60. See Diewert (1980) and Fisher (1992) for details.

61. Katz and Herman (1997) and Fraumeni (1997) provide details on the BEA methodology and underlying data sources.

62. Note that these price indices have been normalized to equal 1.0 in 1996, so they do not correspond to the components of the capital service formula in equation (B.5).

63. There is also an industry dimension, which we do not exploit in this aggregate framework, but is used in the industry productivity analysis discussed below.

64. The Private Household and Government sectors include only capital and labor as inputs. Output in these sectors is defined via a Tornqvist index of capital and labor inputs, so productivity growth is zero by definition.

65. BEA includes a similar imputation for the flow of government capital services in the national account, but our methodology includes a return to capital, as well as depreciation as estimated by BEA.

4

Why Has the Energy-Output Ratio Fallen in China?

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Between 1978 and 1995 energy use per unit of GDP fell by 55 percent in China. There has been considerable debate about the major factors responsible for this dramatic decline in the energy-output ratio. In this chapter we use the two most recent input-output tables to decompose the reduction in energy use into technical change and various types of structural change, including changes in the quantity and composition of imports and exports. In performing our analysis we are forced to deal with a number of problems with the relevant Chinese data and introduce some simple adjustments to improve the consistency of the input-output tables. Our main conclusion is that between 1987 and 1992, technical change within sectors accounted for most of the fall in the energy-output ratio. Structural change actually increased the use of energy. An increase in the import of some energy-intensive products also contributed to the decline in energy intensity.

4.1 Introduction

In China, between 1978 and 1995 reported energy use per *yuan* of GDP fell by 55 percent. Given the importance of fossil fuel use in the generation of local and regional air pollution and in the emission of the greenhouse gasses linked to climate change, this fall in the energy-output ratio has considerable importance for both China and the global environment. Given China's rapid rate of economic growth during this same period, the decline in the energy-output ratio is even more significant. There has been considerable debate about the major factors causing the decline in the energy-output ratio. In general, the debate centers around the relative roles of technical change within individual sectors and structural change between sectors. Answers to the questions central to this debate are important for the design of both energy and environmental policy.

In this chapter we examine the decline in the energy-GDP ratio over the 1987–1992 period using decomposition analysis based on the two most recent input-output tables for China. However, in performing our analysis we are forced to deal with a number of problems with the relevant Chinese data. In particular, as is common in economies undergoing a rapid transition, the input-output tables become incompatible across time as the organization of production changes. In the case of China, a major cause of this phenomenon is that firms have been becoming increasingly specialized and less vertically integrated. Therefore, we try to address these problems by introducing a method to adjust the input-output tables to reconcile conflicting value, price, and physical quantity data. We also perform sensitivity analysis using alternative estimates of the rate of inflation. Our main conclusion is that between 1987 and 1992, technical change within sectors, at the two-digit level, accounted for most of the fall in the energy-output ratio. Structural change actually increased the use of energy. An increase in the import of some energy-intensive products also contributed to the decline in energy intensity.

In the second part of this chapter we review some recent studies on changes in the energy-output ratio in China and try to clarify the reasons for the apparent disagreements. In the third section, we discuss some problems with the relevant Chinese data. In the fourth section, we describe our methodology for constructing a consistent set of input-output tables. In the fifth section, we describe our decomposition methodology. The results of the decomposition analysis are presented in the sixth section. In the seventh section we discuss the effects of assuming different rates of inflation in our decompositions. Some conclusions are presented in the final section.

4.2 Review of Previous Work on China's Energy-Output Ratio

Figure 4.1 shows the energy-GDP ratio for China for the years 1953 to 1995. The ratio rose after 1953, then shot upward due to the drastic declines in output associated with the "Great Leap Forward" (1958–1961). It returned to its previous trajectory in 1967 and then rose fairly steadily for the next ten years. Starting in 1978 and coinciding with the economic reforms pioneered by Deng Xiaoping, the ratio began to decline. In this section of the chapter we briefly review previous work on the decline in the energy-output ratio after 1977 and point out how

Sources: Department of Industrial Statistics (1990), State Statistical Bureau (1997), and Wu (1993).

Figure 4.1
Energy-GDP ratio, 1953–1995.

some of the controversy over the causes of this decline have been based on an apparent confusion in terminology.

Changes in the energy-output ratio are usually classified into two categories. The first category is technical change, also referred to as physical intensity change or real intensity change. Technical change is the change in the energy required to produce a particular product or the physical output of a particular sector. The second category is structural change, which includes *inter alia* the subcategories of final demand shift and sectoral shift. Structural change in energy use is defined as shifts in the share of total output between sectors which may be more or less energy intensive. The sectors can be broadly defined, such as agriculture, industry, and services, or can include hundreds of narrowly defined products or product groups.[1] In addition, changes in the pattern of imports and exports of goods which embody energy are often included under the category of structural change.

Early discussions of post-1977 changes in China's energy-output ratio tended to attribute most of the decline to structural change. Smil (1990) and Kambara (1992) came to this conclusion based on the observed shifts in output from heavy to light industry during the 1980s. Studies using more rigorous analytical methodologies have placed more weight on technical change. Huang (1993) used a Divisia index for six industrial sectors and three energy inputs. His analysis attributed 73–87 percent of the decline in aggregate energy intensity between 1980 and 1988 to technical change. Sinton and Levine (1994) used a Laspeyres index with a variety of data on industrial output. Their three primary data sets were prepared in multiple aggregations and covered various subperiods between 1980 and 1990. They analyzed changes in total energy use rather than disaggregating the energy inputs. Their analysis attributed 58–85 percent of energy savings to technical change, depending on the data set, period analyzed, and aggregation.

Whereas the previously discussed studies were restricted to analyzing changes in energy use within industry alone, Lin and Polenske (1995) and Lin (1996) used structural decomposition analysis based on the input-output tables for 1981 and 1987 to examine changes across all sectors of the Chinese economy. The input-output tables were aggregated to 18 sectors and the analysis covered four energy inputs. Although Lin and Polenske concentrated more on individual factors within the broad categories of structural change and technical change, they concluded that when the individual components were combined, technical change appeared to be responsible for *all* of the energy savings between 1981 and 1987 (Lin and Polenske 1995, p. 81). In the aggregate, structural changes were actually responsible for a slight increase in energy intensity.

Despite the empirical evidence that technical change was the primary cause of the fall in the energy-output ratio after 1977, the World Bank (1994, p. 3; 1997, p. 47) has asserted that structural change was the major causal factor. The origin of this assertion is an earlier World Bank (1993) report which drew heavily on work by the Energy Research Institute (ERI) of the Chinese State Planning Commission (Wang and Xin, 1989). In the 1993 World Bank report, structural factors were credited for 55–65 percent of total energy savings between 1980 and 1990. Technical change was credited for the remaining 35–45 percent. Although it is not clear what analytical methodology was used to reach their conclusions, the ERI study upon which the World Bank report draws attributes structural change at very fine levels of aggregation (e.g., shifts from low quality to higher quality steel) as the greatest single source of energy savings.

Although the assertions of the World Bank and ERI appear to be at odds with the previously cited empirical research, the explanation clearly rests on the level of aggregation upon which the different studies were based. In general, for a given level of aggregation, any subsectoral reallocation of production cannot be discerned from technical change. The level of aggregation is thus of crucial importance in separating technical and structural factors in changes in the energy-output ratio. Unfortunately, it is usually not possible to assemble a complete data set (i.e., a data set with consecutive input-output tables and sectoral price deflators) at a sectoral aggregation of more than about 30 sectors and so changes below that level are attributed to technical change by default.[2]

4.3 Problems with Official Chinese Data

Before proceeding to describe our methodology for analyzing changes in the energy-output ratio, we need to briefly discuss some problems with the relevant Chinese data. The problems center around the output data and the available price deflators. Table 4.1 presents GVO-GDP ratios for various aggregates.[3] The data are drawn from both Chinese statistical yearbooks and published input-output tables. The first three series are for industry only, while the fourth series includes all sectors of the economy. Although eventually arrested in some series, in general, there is an increasing trend in the GVO-GDP ratios over time. The trend is particularly marked in the second series (industrial GVO to industrial GDP in 1990 prices). In the first series (industrial GVO to industrial GDP

Table 4.1
GVO-GDP ratios, 1980–1995

Year	Industrial GVO/ Industrial GDP (in current prices)	Industrial GVO/ Industrial GDP (in 1990 prices)	Industrial GVO/ Industrial GDP (from I-O Tables in current prices)	Total GVO/ Total GDP (from I-O Tables in current prices)
1980	2.58	2.65		
1985	2.82	2.92		
1987	3.01	3.09	2.92	2.25
1990	3.49	3.49	3.28	2.41
1992	3.60 (3.36)	3.60	3.50	2.57
1995	3.72 (3.33)	4.21	3.49	2.63

Note: Figures in parentheses include the most recently published GVO data series revisions.
Sources: Department of Balances (1991, 1993), Department of National Economic Accounting (1995, 1997), and State Statistical Bureau (1995, 1997).

in current prices), recent revisions to the data, shown in parentheses, seem to have stopped or even reversed the trend.[4] The third series (industrial GVO to industrial GDP from the input-output tables), also shows a halt in the general trend after 1992. However, since we use the 1987 and 1992 input-output tables in our decompositions, we are particularly concerned about the upward tendency exhibited for those years (series three and four in the table).[5]

What is responsible for the observed rise in the GVO-GDP ratios? One possibility is that technical change has been material-biased. If this were the case, a shift in production processes toward the use of more material inputs and less other inputs (i.e., capital or labor) could result in an increase in the GVO-GDP ratio. A second possibility is that there has been an increase in subcontracting and/or a splitting up of previously highly vertically integrated enterprises. This process of "deverticalization" could also result in an increase in the GVO-GDP ratio. For example, an auto manufacturer may spin off a company or companies that make various auto parts. GVO, which counts all of the intermediate products separately, would rise, although the GDP of the sector would not change. A third possibility is that there are errors in the data series. Given that GDP is probably measured with more accuracy, Rawski (1993) and Jefferson, Rawski, and Zheng (1996) cite deverticalization, new product bias, and the outright falsification of statistics as factors contributing to an overstatement of Chinese GVO data. New product bias can result when current costs are assigned to new goods for accounting reasons or when old goods are reclassified as new goods to escape price controls. Finally, outright falsification of statistics is a well known problem in China, especially for non-state enterprises and in rural areas (Korski 1998).

These data problems make analyses that use GVO as a measure of output problematic. Table 4.2 compares energy-output ratios based on GDP and GVO. For industry alone, the energy to GVO ratio overstates the decline in energy intensity by about 24 percent compared to the corresponding industrial energy to GDP ratio. Since GDP measures what people actually consume and does not double count, it seems to be a better metric than GVO anyway.

A second problem with the Chinese data rests with the official price deflators. Two examples that illustrate some combination of understated price deflators and the previously discussed output data problems are provided in table 4.3. In the table, we compare growth in deflated GVO measures for coal and oil with their growth in physical quantities measured in tons over the period 1987 to 1992. Because of differences in

Table 4.2
Energy-output ratios, 1980–1995

Year	Industrial Energy/ Industrial GVO (in 1990 prices)	Industrial Energy/ Industrial GDP (in 1990 prices)	Total Energy/ Total GDP (in 1990 prices)
1980	0.52	1.39	0.79
1985	0.37	1.09	0.60
1990	0.26	0.92	0.53
1995	0.14	0.57	0.39
Change 1980–1995	–73%	–59%	–51%

Note: Here "energy" refers to energy for final use.
Sources: Department of Industrial Statistics (1990), State Statistical Bureau (1996, 1997).

Table 4.3
Comparison of value and physical quantity growth rates, 1987–1992

	1987	1992	Real Growth 1987–1992
Coal:			
GVO from I-O Tables (bil. *yuan*)	27.30	72.57	54%
GVO from Yearbooks (bil. *yuan*)	28.30	69.68	42%
Price Deflator (1987 = 1)	1.00	1.73	
Output Quantity (mil. tons)	928.00	1,116.00	20%
Crude Petroleum:			
GVO from I-O Tables (bil. *yuan*)	26.52	61.00	35%
GVO from Yearbooks (bil. *yuan*)	29.14	61.12	23%
Price Deflator (1987 = 1)	1.00	1.70	
Output Quantity (mil. tons)	134.14	142.10	6%

Note: The "GVO from Yearbooks" figures include the output of independent accounting enterprises at and above the *xiang* level plus the output of village-run enterprises.
Sources: Department of Balances (1991), Department of National Economic Accounting (1995), and State Statistical Bureau (1988, 1993, 1995).

coverage, we make calculations using GVO data from both the input-output tables and the statistical yearbooks. The differences in growth rates between value and physical quantities are striking. Coal output measured in 1987 *yuan* grew between 2 and 2.7 times faster than output measured in tons. For oil, growth in value terms was between 3.8 and 5.8 times faster. Changes in quality, for example the washing of coal to remove impurities which raise the value per ton, probably play some role in what seems to be a major overstatement of GVO growth. However, poor deflators and other inconsistencies in the GVO data likely play a much larger role in creating the discrepancies.[6] It is these types of problems that we try to take into account and adjust for in the next section.

4.4 Constructing a Consistent Data Set

Our main goal in this chapter is to identify the sources of the decline in the energy-output ratio in China. Because of their comprehensive, economy-wide coverage, the best sources of data for performing this analysis are the available input-output tables. However, what appears to be an overstatement of growth in real GVO, as outlined in the previous section, would render the input-output tables inconsistent across time and bias analyses made using sequential tables. In this section, we describe a method for adjusting the input-output tables to minimize the bias caused by the overstatement of GVO. In a later section, we discuss adjustments to take into account the possibility of additional errors in the price deflators.

Let $\mathbf{A}$ denote the input-output matrix (with n sectors), $\mathbf{y}$ the vector of final demand, and $\mathbf{x}$ the vector of GVO (both of length n). The sum of the uses of output (intermediate demand plus final demand) equals the supply of output:

$$\mathbf{Ax} + \mathbf{y} = \mathbf{x}. \tag{4.1}$$

Decomposed into scalars, x_i is the domestic output of good i, y_i is the final demand for good i, and A_{ij} is the amount of input i required to produce one unit of good j.[7] In addition, we can let $Y(\mathbf{y})$ denote total real GDP and $Q(\mathbf{x}) = \sum_j x_j$ denote total real GVO. We write the decomposition of the change in the GVO-GDP ratio, $\Delta \frac{Q}{Y}$, as the sum of three parts: (i) material-biased technical change (ΔA); (ii) deverticalization (ΔV); and (iii) other measurement errors ϵ:

$$\Delta \frac{Q}{Y} = \Delta A + \Delta V + \epsilon. \tag{4.2}$$

However, deverticalization cannot, and need not, be distinguished from other measurement errors (such as errors in the price deflators). We thus rewrite the above as simply:

$$\Delta\frac{Q}{Y} = \Delta A + \epsilon. \tag{4.2$'$}$$

In this framework, an example of material-biased technical change is where there is an increase in the use of "machinery" to produce "machinery." In this case, labor and capital inputs and total deliveries to final demand could remain the same, but the production process would use more intermediate inputs produced by other firms within the machinery sector. To be explicit, let j be the subscript for the machinery sector. In this example, the GVO of sector $j(x_j)$ and the intermediate inputs from the same sector (A_{jj}) increase by the same amount, while the other intermediate inputs $(A_{i\neq j,j})$, the value-added entries for j, and the deliveries to final demand (y_j), are unchanged. Then in this case, Y is unchanged but Q is higher, resulting in a higher Q/Y ratio.[8]

For some industries it would be difficult to tell such a story about increased material use. For example, in the case of crude petroleum, what does it mean to say that more "crude petroleum" is now required to produce "crude petroleum"? However, lacking sufficient *a priori* information on specific sectors, we correct all sectors symmetrically. We thus make a range of simple assumptions about the relative size of measurement error versus material-biased technical change.

4.4.1 Case 1—No Material-Biased Technical Change $(\Delta A = 0)$

One possible scenario is that there was no real change in the Q/Y ratio between 1987 and 1992. Instead it could be that all of the observed change was due to measurement error. That is, we could assume that the real intermediate input to output ratio was actually constant, but that measurement errors increased the observed ratio. Then in this case we can let $m_{j0} = \sum_i A_{ij0}$ be total intermediate inputs in period 0, $p^m_{j0}m_{j0}$ be the value of those inputs, and v_{j0} be the value added in industry j. Then the GVO in sector j is $p^x_{jt}x_{jt} = p^m_{jt}m_{jt} + v_{jt}$. Here we assume that

$$\frac{p^m_{jt}m_{jt}}{p^x_{jt}x_{ij}} \quad \text{and} \quad \frac{v_{jt}}{p^x_{jt}x_{jt}}$$

are constant for all t. Therefore, for given final demand $(\mathbf{y}_t)$ and value-added $(\mathbf{v}_t)$ vectors in period t, we need to find a revised intermediate input matrix $(\mathbf{A}'_t)$ and a revised output vector $(\mathbf{x}'_t)$ such that:

$$m'_{jt} = \sum_i A'_{ijt}, \tag{4.3}$$

where

$$p^x_{jt} x'_{jt} = p_{jt} m m'_{jt} + v_{jt},$$

$$\sum_j A'_{ijt} x'_{jt} + y_{it} = x'_{it}, \tag{4.4}$$

and

$$\frac{p^m_{jt} m'_{jt}}{p^x_{jt} x'_{jt}} = \frac{p^m_{j0} m_{j0}}{p^x_{j0} x_{j0}} \quad \text{for } j = 1, 2, \ldots, n. \tag{4.5}$$

There are $3n$ restrictions on the matrix $\mathbf{A}'$ and $'\mathbf{x}$ vector, allowing $(n^2 + n - 3n)$ degrees of freedom. We solve the problem using methods identical to those used to interpolate input-output matrices from two benchmark tables and time series output data. We therefore minimize the sum of the squares of the weighted difference between elements of the revised matrix $\mathbf{A}'_t$ and corresponding elements of the original matrix $\mathbf{A}_t$:[9]

$$\text{Min} \sum_{ij} \left(\frac{A'_{ij} - A_{ij}}{A_{ij}} \right)^2, \tag{4.6}$$

subject to (3), (4), and (5).

The results of this procedure are given in table 4.4.[10] The figures in the first two columns are the unadjusted values of the intermediate inputs ($\text{INT}_j = p^m_j m_j$) and the GVO ($= p^x_j x_j$) for 1987.[11] The following two columns contain the corresponding values for 1992. The adjusted values for 1992 are in the columns under the heading "$\alpha = 0$".[12] Total adjusted GVO is 6,090 billion *yuan* compared to the original value of 6,829 billion *yuan*, a reduction of almost 11 percent. There are a wide range of adjustments for individual sectors. For example, the public administration sector is unchanged since it delivers only to final demand, while the finance and insurance sector, which appears to have a marked (but unexplained) change in definition, requires the largest adjustment. In general, sectors with smaller changes in the intermediate input to output ratio require smaller adjustments to both total intermediate inputs and GVO. These include the food manufacturing, apparel, and construction sectors.

4.4.2 *Case 2—Material-Biased Technical Change* ($\Delta A > 0$)

Next we consider a more general case where one part of the change in the Q/Y ratio, α, is due to material-biased technical change and the remainder, $1-\alpha$, is due to various errors in the data. We repeat the above calculations after changing constraint (4.5) to:

$$\frac{p^m_{jt} m_{jt}}{p^x_{jt} x'_{jt}} = (1 - \alpha R) \frac{p^m_{j0} m_{j0}}{p^x_{j0} x_{j0}}, \tag{4.7}$$

where

$$R = 1 - \frac{p^m_{jt} m_{jt} / p^x_{jt} x_{jt}}{p^m_{j0} m_{j0} / p^x_{j0} x_{j0}}. \tag{4.8}$$

When $\alpha = 0$, this reduces to Case 1 (100 percent error). Conversely, when $\alpha = 1$, all changes are assumed to be due to material-biased technical change and no adjustments are necessary.

The adjusted values for the case where $\alpha = 0.3$ are reported in the last two columns of table 4.4. When $\alpha = 0.3$, the values of the intermediate inputs and GVO are increased from those in the corresponding 100 percent error ($\alpha = 0$) case by approximately 30 percent of the gap between the original values and the values for the 100 percent error case. For most values, the increase is only approximately 30 percent because we must keep the matrices balanced. For the sectors we looked at in table 4.3 (coal and oil), the growth rates of deflated output calculated using the adjusted GVO are now much closer to the physical quantity growth rates than with the original data. For example, for coal, the implied growth of deflated output between 1987 and 1992 is now 22 percent when we use the adjusted data, compared to 54 percent for the unadjusted output data and 20 percent for the physical quantity in tons.

We have repeated the adjustments for other values of α and report some of the results below. In the following section we concentrate on the case where $\alpha = 0.3$. We choose to focus on this case because the growth in the adjusted value of output is then in rough accordance with the growth in the sectors for which we have some independent check through the available physical quantity data (i.e., the data on tons of coal and crude petroleum reported in table 4.3). Unfortunately, similar data are not available for most other sectors. We should point out that our use of one adjustment factor for all sectors is a strong assumption, but it is necessitated by the lack of obvious individual α's

Table 4.4
Summary figures for adjusted input-output tables (bil. *yuan*)

	1987		1992					
	(unadjusted)		(unadjusted)		($\alpha = 0$)		($\alpha = 0.3$)	
Sector	INT	GVO	INT	GVO	INT	GVO	INT	GVO
1 Agriculture	147.37	467.57	323.20	908.47	269.35	854.62	284.83	870.09
2 Coal mining	10.93	27.30	40.73	72.57	21.28	53.12	25.92	57.76
3 Crude petroleum	6.39	26.52	23.06	61.00	12.05	49.99	14.91	52.85
4 Metal ore mining	4.42	9.15	13.96	23.01	8.47	17.53	9.83	18.88
5 Non-metallic ore	7.99	21.36	35.70	63.92	16.85	45.07	21.22	49.45
6 Food processing	136.12	184.70	301.91	406.33	292.60	397.02	295.35	399.77
7 Textiles	123.62	166.21	301.64	379.90	227.14	305.40	246.23	324.50
8 Apparel	33.20	46.58	119.27	151.37	113.38	145.48	114.84	146.94
9 Lumber	15.12	22.26	38.48	51.73	28.09	41.35	30.74	44.00
10 Paper	44.13	66.41	128.78	176.41	94.35	141.98	103.18	150.81
11 Electric power	16.71	39.43	60.35	117.79	42.24	99.68	47.06	104.50
12 Petrol refining	25.38	42.49	73.44	100.86	40.67	68.09	48.02	75.44
13 Chemicals	122.74	181.61	350.35	485.65	282.10	417.40	300.47	435.77
14 Building materials	47.23	80.03	165.61	253.55	126.64	214.57	137.01	224.95
15 Primary metals	73.55	108.65	227.07	317.37	189.27	279.57	199.63	289.93
16 Metal products	33.11	49.11	110.69	145.84	72.70	107.84	81.84	116.99
17 Machinery	91.52	141.27	273.83	381.91	198.81	306.88	218.03	326.10
18 Transport. equip.	32.45	47.16	121.50	166.40	99.03	143.93	105.11	150.01
19 Electric. mach.	42.42	60.30	117.00	157.01	94.97	134.98	100.90	140.91
20 Electronics	28.77	40.30	79.84	106.64	66.84	93.63	70.39	97.19
21 Instruments	5.81	10.00	15.46	23.21	10.78	18.53	11.97	19.73
22 Other industry	7.08	10.47	59.91	78.60	38.90	57.58	43.92	62.61
23 Construction	173.52	243.06	366.34	520.30	384.15	538.10	378.68	532.64
24 Transp. comm.	31.06	83.47	117.25	266.62	88.53	237.89	96.48	245.84
25 Commerce	68.29	170.84	343.94	634.89	314.50	605.44	323.04	613.99
26 Household services	16.11	61.45	85.20	205.32	46.90	167.02	56.81	176.92
27 Educ, health, etc.	62.34	121.94	105.67	227.30	139.81	261.45	128.54	250.18
28 Finance insurance	2.83	52.01	81.95	171.31	5.66	95.01	20.31	109.67
29 Public admin	13.66	37.88	99.66	190.97	99.66	190.97	99.66	190.97
Total	1423.88	2619.52	4165.32	6829.75	3425.72	6090.15	3614.95	6279.38

Notes: INT is the sum of sectoral output consumed as intermediate inputs. GVO is the gross value of output of the same sector.

Table 4.5
Domestic output of energy sectors

	Primary Energy				Secondary Energy		GDP	
Year	Coal (mil. tons)	Crude Petroleum (mil. tons)	Natural Gas (bil. m^3)	Hydro-electricity (Twh)	Total Electricity (Twh)	Refined Petroleum (mil. tons)	Oil&Gas Index	(bil. 1987 *yuan*)
1987	928.00	134.14	13.89	100.00	497.30	96.03	1.000	1,196
1988	980.00	137.05	14.26	109.20	545.20	100.58	1.022	1,331
1989	1,054.00	137.64	15.05	118.30	584.80	104.80	1.028	1,386
1990	1,080.00	138.31	15.30	126.70	621.20	106.65	1.034	1,439
1991	1,087.00	140.99	16.07	124.70	677.50	113.24	1.054	1,572
1992	1,116.00	142.10	15.79	130.70	753.90	118.86	1.062	1,796
Growth	20.26%	5.93%	13.68%	30.70%	51.60%	23.77%	6.20%	50.17%

Sources: Sinton (1996a), State Statistical Bureau (1997), and author's calculations.

for each of the 29 sectors. However, one degree of flexibility is better than none.

4.4.3 *Final Preparation of the Adjusted Matrices*

The final step in preparing the input-output data set for our energy use calculations is producing the constant price 1992 matrix and making the adjusted matrix consistent with the available data on physical energy output. The physical energy output data that we assume to be correct are reported in table 4.5. Given the problems with the price deflators discussed previously, we use the growth in these physical quantities to determine the increase in real GVO between 1987 and 1992. For example, for the coal mining sector we assume that the real output, x_{2t}, grows at the same rate as the total number of tons of coal mined.[13] For the crude petroleum sector (which includes a small amount of natural gas) we aggregate the quantities of crude petroleum and natural gas produced into a single "Oil&Gas Index." Since we are unable to disaggregate the sector further, the output of the electric power sector is assumed to grow at the same rate as the number of kilowatt-hours generated. The refined petroleum sector is indexed to the total number of tons of the various petroleum products produced. Again, this is not entirely satisfactory, but we believe it to be an improvement over using the unadjusted data. For completeness we also report the real GDP series.

Since we do not have similar *a priori* information for the real output of the non-energy sectors, we must rely on published data for our price deflators.[14] After deflating the adjusted data for the non-energy sectors using the official sectoral output price indices we found that total real final demand was 4 percent less than 1992 real GDP. We then scaled all sectors up by this amount so that total final demand was equal to the official figure for GDP given in the last column of table 4.5. This is equivalent to reducing all price changes between 1987 and 1992 by about 4 percent.

4.5 A Methodology for Decomposing the Change in Energy Intensity

In this section we discuss our methodology for decomposing the overall change in energy intensity into technical change (changes in production techniques as represented by the evolution of the input-output matrix) and structural change (changes in final demand patterns). Our methodology draws on the work of Lin and Polenske (1995) and Lin (1996). Similar to Lin and Polenske, we use sequential input-output tables to decompose changes in energy intensity by energy type. However, instead of using fixed base-period shares, we use variable shares based on a Divisia index.

With time subscripts, equation (4.1) can be rewritten as:

$$\mathbf{A}_t\mathbf{x}_t + \mathbf{y}_t = \mathbf{x}_t. \tag{4.9}$$

The final demand vector ($\mathbf{y}_t$) can be decomposed in each period t as:

$$\mathbf{y}_t = \mathbf{c}_t + \mathbf{v}_t + \mathbf{g}_t + \mathbf{e}_t - \mathbf{i}_t, \tag{4.10}$$

where $\mathbf{c}_t$ is household consumption, $\mathbf{v}_t$ is investment, $\mathbf{g}_t$ is government consumption, $\mathbf{e}_t$ is exports, and $\mathbf{i}_t$ is imports. In addition, we can decompose the use of commodities as domestic production plus imports less exports[15]

$$\mathbf{u}_t = \mathbf{x}_t + \mathbf{i}_t - \mathbf{e}_t. \tag{4.11}$$

We rewrite final demand for good i as a share vector of total demand (Y_t)

$$\mathbf{y}_t = \gamma_t Y_t, \tag{4.12}$$

where

$\gamma_t = (\gamma_{1t}, \ldots, \gamma_{nt})'$.

We can also rewrite equations (4.10) and (4.12) as the difference between the demand for domestically produced goods and imports:

$$\mathbf{y}_t = \mathbf{y}_t^d - \mathbf{i}_t = (\gamma_t^d - \gamma_t^i)Y_t. \tag{4.13}$$

The output vector from equation (4.9) can be rewritten as

$$\mathbf{x}_t = (\mathbf{I} - \mathbf{A}_t)^{-1}\mathbf{y}_t \equiv \mathbf{G}_t\mathbf{y}_t = \mathbf{G}_t\gamma_t Y_t. \tag{4.14}$$

As an example of what this means, consider the coal sector (x_{2t}) in the vector ($\mathbf{x}_t$). Writing out equation (4.14) for this single sector gives us

$$x_{2t} = \sum_j G_{2jt}\gamma_{jt}Y_t. \tag{4.15}$$

Given the large increase in the import of energy and energy-intensive goods, we analyze changes in energy use rather than energy output, which has been the measure more commonly used in previous studies.[16] For the coal sector, differentiating equation (4.11) with respect to time and using (4.15) gives us

$$\begin{aligned} \dot{u}_{2t} &= \sum_j \dot{G}_{2jt}\gamma_{jt}Y_t + \sum_j G_{2jt}(\dot{\gamma}_{jt}^d - \dot{\gamma}_{jt}^i)Y_t \\ &\quad + \sum_j G_{2jt}\gamma_{jt}\dot{Y}_t + \dot{i}_{2t} - \dot{e}_{2t}. \end{aligned} \tag{4.16}$$

Integrating equation (4.16) and using the Tornqvist discrete time approximation we get

$$\begin{aligned} \ln\frac{u_{2T}}{u_{2,0}} &= \sum_j \frac{1}{2}(w_{j0} + w_{jT}) \ln\frac{G_{2jT}}{G_{2j0}} + \sum_j \frac{1}{2}\left(w_{j0}\frac{\gamma_{j0}^d}{\gamma_{j0}} + w_{jT}\frac{\gamma_{jT}^d}{\gamma_{jT}}\right) \ln\frac{\gamma_{jT}^d}{\gamma_{j0}^d} \\ &\quad + \left[-\sum_j \frac{1}{2}\left(w_{j0}\frac{\gamma_{j0}^i}{\gamma_{j0}} + w_{jT}\frac{\gamma_{jT}^i}{\gamma_{j0}^i}\right) \ln\frac{\gamma_{jT}^i}{\gamma_{j0}^i}\right] \\ &\quad + \sum_j \frac{1}{2}(w_{j0} + w_{jT}) \ln\frac{Y_T}{Y_0} + \frac{1}{2}(w_{20}^i + w_{2T}^i)\frac{i_{2T}}{i_{2,0}} \\ &\quad - \frac{1}{2}(w_{2,0}^e + w_{2T}^e)\frac{e_{2T}}{e_{2,0}} + R_u \end{aligned} \tag{4.17}$$

where

$$w_{jT} = \frac{G_{2jT}\gamma_{jT}Y_T}{u_{2T}}, \quad w^i_{2T} = \frac{i_{2T}}{u_{2T}}, \quad \text{and} \quad w^e_{2T} = \frac{e_{2T}}{u_{2T}}, \tag{4.18}$$

and R_u is the approximation residual. Our formulation is similar to that used by Liu, Ang, and Ong (1992), who also discuss other Divisia approximations.

Using (4.15) we can rewrite equation (4.17) so that the change in energy intensity (i.e., the change in coal use per unit of GDP) is on the left-hand side

$$\begin{aligned}\Delta_{uT} &= \ln\frac{u_{2T}}{u_{2,0}} - \frac{1}{2}\left(\frac{x_{2,0}}{u_{2,0}} + \frac{x_{2T}}{u_{2T}}\right)\ln\frac{Y_T}{Y_0} \\ &= \sum_j \frac{1}{2}(w_{j0} + w_{jT})\ln\frac{G_{2jT}}{G_{2j0}} + \sum_j \frac{1}{2}\left(w_{j0}\frac{\gamma^d_{j0}}{\gamma_{j0}} + w_{jT}\frac{\gamma^d_{jT}}{\gamma_{jT}}\right)\ln\frac{\gamma^d_{jT}}{\gamma^d_{j0}} \\ &\quad + \left[-\sum_j \frac{1}{2}\left(w_{j0}\frac{\gamma^i_{jT}}{\gamma_{j0}} + w_{jT}\frac{\gamma^i_{jT}}{\gamma_{jT}}\right)\ln\frac{\gamma^i_{jT}}{\gamma^i_{j0}}\right] \\ &\quad + \frac{1}{2}(w^i_{2,0} + w^i_{2T})\frac{i_{2T}}{i_{2,0}} + \left[-\frac{1}{2}(w^e_{2,0} + w^e_{2T})\frac{e_{2T}}{e_{2,0}}\right] + R_u. \end{aligned} \tag{4.19}$$

It should be noted that in a closed economy equation (4.19) would have simplified to

$$\Delta_{uT} = \ln\frac{u_{2T}}{u_{2,0}} - \ln\frac{Y_T}{Y_0},$$

but here the sum of all use elements is not equal to output.

Equation (4.19) says that changes in the intensity of coal use are due to some combination of five factors: (i) changes in technology as represented by changes in the **G** matrix; (ii) changes in final demand patterns for domestic goods as represented by changes in the share vectors (γ^d); (iii) changes in the pattern of imports (γ^i); (iv) changes in the level of imports of coal; and (v) changes in the level of exports of coal. Given the rapid increase in imports of energy both in raw form (e.g., crude petroleum) and embodied in energy-intensive goods (e.g., fertilizers, chemicals, and transportation services) during this period, the change in γ^i_{jt} is quite important. Finally, the use of discrete time variables results in the decomposition error R_u.

We should highlight what a change in the technology term G_{ijt} might mean.[17] One possibility is that there was a physical change in the quantity of input i used to make a ton of commodity j. A second possibility is that the shares of the sub-commodities that make up sector j have changed. For example, more cars may have been produced relative to bicycles in the transportation equipment sector, even if the energy required to make each car or bicycle remained the same. Finally, there may have been new sub-commodities added to the sector (e.g., computers in the electronics sector). By definition, one cannot separate out these effects without using more disaggregated classifications. It should be noted that this problem will exist at all levels of disaggregation other than for the individual commodities themselves.

We should also point out that our Divisia formula uses the average of the initial and end-point weights, w_0 and w_T. This is in contrast to the approach taken by Lin and Polenske (1995) and Lin (1996) which is equivalent to using only the initial year weights, w_0. Another point to note about our formulas is the relationship between the components of final demand and GDP. In equation (4.12) we write the final demand for good i as $y_{it} = \gamma_{it} Y_t$ (where $\sum_i \gamma_i = 1$). This has a clear meaning in value terms. However, y_{it} is expressed in base year units, i.e., nominal GDP in year t is $P_t Y_t = \sum_i p_{it} y_{it}$ where p_{it} is the price of good i. Since we do not have data on the prices, p_{it}, we are unable to do a consistent aggregation to calculate the γ_{it}'s exactly. The official sources do not explain how real GDP, Y_t, is obtained from the components $\{p_{it}, y_{it}\}$. We therefore use the only available data, which are in values, and define $\gamma_{it} = p_{it} y_{it} / P_t Y_t$. Where real GDP appears in the calculations described above, we use the official estimates.[18] These issues are discussed in greater detail in section 4.7 below.

4.6 Decomposition of the Change in China's Energy Intensity

We can now use the methodology developed in the previous section to decompose changes in the energy-output ratio between 1987 and 1992. We calculate the individual terms in equation (4.19) for each of the major sources of energy: coal, crude petroleum, hydroelectricity, electric power, and refined petroleum.[19] The hydroelectric sector, which is part of the power generation sector in the input-output table, is disaggregated into a separate, artificial sector for this analysis.[20] We do this in order to be able to isolate the contribution of the other primary sources of energy—coal and crude petroleum—used in the production of electricity. Nuclear power provided only a small portion of electricity output during 1987–1992 and we do not separate it in this analysis. Although there is substantial use of biomass energy in China, it is not well documented and does not appear in the input-output tables. While a number of other researchers have added all of the sources of energy together by standard coal equivalents (sce), we do not see this as being a particularly useful measure and in our analysis we treat the sources separately. It should be noted that there is great variation in the per sce ton prices of the different types of energy. In 1992, the average price of an sce ton of raw coal was about 95 *yuan*, of an sce ton of crude oil about 290 *yuan*, and of an sce ton of wholesale electricity about 360 *yuan*.

The results of our decompositions of changes in energy use per *yuan* of GDP, corresponding to equation (4.19), are reported in table 4.6. The decompositions are performed using input-output tables adjusted for different assumptions about errors in the data versus material-biased technical change as described in section 4.4. We report the results for the cases where α, the parameter that describes our assumption about the degree of material-biased technical change, is equal to 0, 0.3, and 0.5. In general, we concentrate on the case where α is equal to 0.3, which is our best guess about the degree of material-biased technical change.

In table 4.6, the first column of numbers is the overall change in the use of each type of energy per *yuan* of GDP between 1987 and 1992. The next six columns of numbers correspond to the terms on the right-hand side of equation (4.19) and break down the change in the energy-output ratio into its component parts and the approximation residual. Except for electric power, there is a fall in the energy-output ratio for each type of energy. This holds true for all values of α. For coal, except in the case where α equals 0.5, technical change accounts for more than 100 percent of the fall in the energy-output ratio.[21] Technical change was partially offset by the change in demand patterns, which actually increased the use of energy per unit of GDP. Changes in import patterns and in the quantity of imports and exports all account for small decreases in the energy-output ratio. For crude petroleum, there is also a substantial fall in the energy-output ratio. A major contributor was again technical change. Changes in import patterns also contributed to the decline, however, this effect was offset by increases in the overall quantity of imports. The unusually large residual term for crude petroleum is due to the poor logarithmic approximation for the large increase in imports, which rose from 2 million tons in 1987 to 11 million tons in 1992. The changes in the use of refined petroleum are similar to those for crude

Table 4.6
Decomposition of change in energy use per unit of GDP

Type of energy	Overall change per *yuan* of GDP (Δ_{uT})	of which: Technical change	Change in demand patterns	Change in import patterns	Change in quantity of imports	Change in quantity of exports	Residual
Case $\alpha = 0.0$:							
Coal	−0.237	−0.270	0.082	−0.021	−0.001	−0.006	−0.021
Crude petroleum	−0.287	−0.143	0.014	−0.121	0.108	0.033	−0.177
Hydroelectricity	−0.140	−0.127	0.066	−0.048	0.000	−0.000	−0.031
Electric power	0.011	0.024	0.066	−0.048	0.006	−0.000	−0.036
Refined petroleum	−0.148	−0.174	0.065	−0.011	0.053	−0.001	−0.080
Case $\alpha = 0.3$:							
Coal	−0.239	−0.247	0.083	−0.023	−0.001	−0.007	−0.044
Crude petroleum	−0.293	−0.137	0.013	−0.135	0.117	0.021	−0.172
Hydroelectricity	−0.140	−0.122	0.066	−0.050	0.000	−0.000	−0.034
Electric power	0.012	0.029	0.066	−0.050	0.007	−0.000	−0.039
Refined petroleum	−0.146	−0.167	0.066	−0.020	0.062	−0.006	−0.080
Case $\alpha = 0.5$:							
Coal	−0.240	−0.231	0.085	−0.026	−0.001	−0.009	−0.059
Crude petroleum	−0.298	−0.133	0.012	−0.147	0.124	0.013	−0.167
Hydroelectricity	−0.140	−0.118	0.066	−0.052	0.000	−0.000	−0.036
Electric power	0.012	0.033	0.066	−0.051	0.007	−0.000	−0.042
Refined petroleum	−0.144	−0.162	0.066	−0.028	0.069	−0.010	−0.079

Note: This decomposition is based on equation (4.19) using the official data for real GDP.

petroleum. However, in the case of refined petroleum, the large amount of technical change is offset by both changes in demand patterns and in the quantity of imports.

For electric power, rather than a decline, there is actually a modest increase in the use of electricity per *yuan* of GDP. This can be decomposed into increases caused by a small component of negative technical change and changes in demand patterns, which are partially offset by changes in import patterns. The latter implies that, *ceteris paribus*, less electricity was used because the imports that replaced domestic goods embodied the use of relatively more electricity. Given the size of the residual compared to the total change, we do not put much weight on these results. Similarly, given its artificial nature, we do not put much weight on the decompositions for the hydroelectric sector. Our results reflect the fact that, as shown in table 4.5, the production of hydroelectricity rose by only 30 percent between 1987 and 1992, while total electricity output increased by 52 percent.

Table 4.7 provides data on the energy intensities of the non-energy sectors in 1987 and 1992. The data are in grams of sce per *yuan* of sectoral output. The data for 1992 are in 1987 prices and are adjusted according to our best guess case where α is equal to 0.3. Since we do not have data on the input prices paid by individual sectors, we assume that all sectors paid the same average price for each energy input.[22] The data are equivalent to the energy rows of the input-output tables, normalized to sces. For coal, major users which see large decreases in coal use per *yuan* of output are lumber, chemicals, building materials, transportation and communications, and household services. There are also several major users of coal (metal ore mining and primary metals) that experience increases in coal use, but these increases are modest. Many sectors experience increases in the use of crude petroleum, but overall, total use by the non-energy sectors is limited. The picture for electricity is different. While a few sectors do see small reductions in electricity use, most are part of the trend toward an increasing electrification of the Chinese economy.[23] Overall, the use of electricity rose from 0.417 kWh per *yuan* of GDP in 1987 to 0.421 kWh per *yuan* in 1992. For refined petroleum, the major users (building materials, primary metals, and transport and communication), all saw significant decreases in intensity. Finally, we should point out that our 1992 data depend not only on our adjustment factor α, but also on our price indices. We discuss some possible problems with, and corrections to, the price indices in the next section.

As shown in table 4.6, in all of our decompositions, changes in demand patterns contributed to an increase in the energy-GDP ratio. For all energy types except electric power, this effect partially offset the decreases in energy intensity resulting from technical change. In order to try to understand the underlying reasons for the changes in demand patterns, we have assembled some data on changes in sectoral GVO and final demand in table 4.8. We have divided the sectors into primary energy, secondary energy, and non-energy sectors. The first two columns of table 4.8 are data on GVO and final demand which are provided to give the reader some idea of the relative magnitude of the individual sectors and the relative importance of final demand in GVO. The later distinction is important because for a number of major users of energy, little or none of their output is consumed as final demand, but rather as intermediate inputs. Examples include chemicals, building materi-

Table 4.7
Sectoral energy intensity, 1987 and 1992

	1987				1992 ($\alpha = 0.3$)			
	Crude		Refined		Crude		Refined	
Sector	Coal	Petrol.	Elec.	Petrol.	Coal	Petrol.	Elec.	Petrol.
1 Agriculture	12	0	6	23	14	0	62	22
4 Metal ore mining	137	0	97	112	194	1	96	84
5 Non-metal ore	154	2	74	126	154	1	90	91
6 Food processing	39	0	6	6	74	0	11	18
7 Textiles	36	0	10	7	95	0	15	14
8 Apparel	12	0	3	5	22	0	2	9
9 Lumber	238	0	31	77	104	0	22	44
10 Paper	127	2	22	21	70	1	24	16
13 Chemicals	285	142	50	80	167	149	54	54
14 Building materials	909	8	95	180	544	23	98	129
15 Primary metals	596	24	73	216	616	52	86	122
16 Metal products	94	5	32	61	43	2	26	27
17 Machinery	72	3	23	54	35	3	22	33
18 Transport equip.	61	1	16	48	34	2	6	28
19 Electric mach.	55	1	16	46	20	1	13	17
20 Electronics	18	1	9	15	16	6	11	13
21 Instruments	51	1	16	31	48	8	5	23
22 Other industry	72	1	20	39	107	16	12	49
23 Construction	26	0	7	77	13	0	1	41
24 Transport & comm.	279	4	14	552	132	11	12	406
25 Commerce	44	0	9	29	48	9	5	48
26 Household services	147	1	20	95	77	6	29	86
27 Educ., health, etc.	103	2	22	44	72	6	26	28
28 Finance & insurance	3	0	0	3	13	1	8	12
29 Public admin.	91	0	7	119	82	17	23	70

Notes: Figures are in grams of sce per yuan of output, in 1987 prices. The conversion rates to sce's are: 1 ton of coal = 0.714 ton of sce; 1 ton of crude oil = 1.429 tons of sce; and 1 kWh = 0.1229 kg sce. The intensities for refined petroleum are estimated from the inputs of crude petroleum. All figures are calculated from value data, not directly from quantity data.
Source: Author's estimates.

als, and primary metals. On the other hand, a number of sectors which do not consume much energy directly do consume other goods which are energy-intensive. Examples include the machinery sector, which consumes a large amount of energy-intensive primary metals and chemicals and the construction sector, which consumes a large amount of energy-intensive building materials. The third column of table 4.8 lists

Table 4.8
Changes in composition of final demand, 1987–1992

	1987				1992			
	GVO	Final demand						
Sector	(bil. *yuan*)		$\frac{V_j^E}{GVO_j}$	γ_j^d	γ_j^i	γ_j^d	γ_j^i	$\frac{\gamma_{j92}^d}{\gamma_{j87}^d}$
Primary Energy Sectors:								
2 Coal mining	27.3	5.0	.0797	.0043	.0002	.0056	.0001	1.30
3 Crude petroleum	26.5	4.3	.0331	.0036	.0000	.0058	.0063	1.61
Hydroelectricity	7.9	0.0	.0000	.0000	.0000	.0000	.0000	0.00
Secondary Energy Sectors:								
11 Electric power	39.4	3.4	.4909	.0031	.0003	.0032	.0005	1.04
12 Petroleum refining	42.5	2.9	.4797	.0034	.0010	.0070	.0055	2.06
Non-Energy Sectors:								
1 Agriculture	467.6	253.0	.0092	.2215	.0099	.1790	.0053	0.81
4 Metal ore mining	9.2	−0.6	.0910	.0005	.0010	.0005	.0021	1.16
5 Non-metallic ore	21.4	0.1	.0802	.0012	.0012	.0023	.0022	1.92
6 Food processing	184.7	125.9	.0066	.1143	.0089	.1037	.0043	0.91
7 Textiles	166.2	61.9	.0090	.0604	.0086	.0624	.0185	1.03
8 Apparel	46.6	35.6	.0035	.0303	.0005	.0528	.0034	1.74
9 Lumber	22.3	4.9	.0458	.0052	.0011	.0079	.0023	1.52
10 Paper	66.4	16.1	.0236	.0189	.0054	.0286	.0069	1.52
13 Chemicals	181.6	12.7	.0784	.0298	.0191	.0414	.0263	1.39
14 Building materials	80.0	1.1	.1364	.0030	.0022	.0127	.0027	4.17
15 Primary metals	108.6	−13.3	.1184	.0037	.0037	−.0055	.0133	−1.48
16 Metal products	49.1	11.9	.0379	.0125	.0025	.0156	.0024	1.25
17 Machinery	141.3	5.3	.0293	.0902	.0357	.0897	.0363	0.99
18 Transport equip.	47.2	23.0	.0226	.0101	.0293	.0361	.0165	1.23
19 Electric machinery	60.2	25.1	.0218	.0267	.0057	.0295	.0084	1.11
20 Electronics	40.3	8.8	.0097	.0241	.0084	.0338	.0156	1.41
21 Instruments	10.0	1.6	.0186	.0049	.0035	.0037	.0022	0.76
22 Other industry	10.5	−0.8	.0237	.0006	.0013	.0046	.0044	7.81
23 Construction	243.1	243.1	.0215	.2033	.0000	.1866	.0000	0.92
24 Transport & comm.	83.5	32.8	.1337	.0347	.0073	.0256	.0001	0.74
25 Commerce	170.8	7.6	.0139	.0785	.0136	.0906	.0087	1.15
26 Household services	61.4	48.3	.0381	.0404	.0000	.0370	.0052	0.93
27 Education, health, etc.	121.9	97.3	.0275	.0818	.0004	.0664	.0002	0.81
28 Finance & insurance	52.0	1.0	.0009	.0041	.0032	.0015	.0000	0.36
29 Public admin.	37.9	37.9	.0327	.0317	.0000	.0717	.0000	2.26
Totals	2619.0	1195.0						

Notes: V_j^E is value of energy goods used by sector j. γ_j^d and γ_j^i are the shares of domestic output and imports, respectively, in total final demand, where $\sum_j(\gamma_j^d - \gamma_j^I) = 1$.

the cost shares of energy goods in GVO by sector. The non-energy sectors for which energy goods are a large share of the costs are mining, chemicals, building materials, primary metals, and transportation and communications. The secondary energy sectors, electric power and refined petroleum, are of course major users of primary energy goods. The effects of the electrification of the Chinese economy should be noted. The increase in the intensity of electricity use in most sectors resulted in a small overall increase in the electricity-GDP ratio. As was discussed previously, the increase in total electricity output was much faster than the increase in output from the hydroelectric sector. With the output of the hydroelectric sector not keeping pace, the increase in electricity output was met through increased coal use. Overall then, between 1987 and 1992, electrification had a "structural change" effect that resulted in an increase in the use of coal.

The next four columns of table 4.8 are the shares of domestic output and imports in final demand for the years 1987 and 1992. Negative entries denote inventory reductions. The last column gives the ratios of the final demand shares for the two years. Even over this short five-year time span, there were some noticeable changes. The major sectors that increased in relative importance can be divided into: (i) energy-intensive goods, including chemicals and building materials; and (ii) nonenergy-intensive goods, which include apparel, paper, metal products, machinery, transportation equipment, and commerce. Similarly, we can use the same breakdown and divide the major sectors that decreased in relative importance into: (i) energy-intensive goods, including transportation and communications; and (ii) non-energy intensive goods, including agriculture, food processing, and a number of the service sectors. The aggregate effects of these changes are seen in the positive signs on the coefficients for changes in demand patterns in table 4.6.

4.7 Effects of Using Alternative Estimates of Inflation

The most important result from the decompositions described in the previous section was the importance of technical change in the fall in China's energy-output ratio. Although we made some adjustments for data problems in section four, we also mentioned that there continues to be some uncertainty about the reliability of the available price deflators. Given this uncertainty, in this section we do sensitivity analysis to see how alternative assumptions about inflation might affect our results.

In table 4.9 we present results for alternative assumptions about inflation. We first present our best guess result from section 4.6 where we

Table 4.9
Decomposition of change in energy use with alternative estimates of inflation

Type of energy	Overall change per *yuan* of GDP (Δ_{uT})	Of which: Technical change	Change in demand patterns	Change in import patterns	Change in quantity of imports	Change in quantity of exports	Residual
Case $\alpha = 0.3$, no inflation adjustment:							
Coal	−.239	−.247	.083	−.023	−.001	−.007	−.044
Crude petroleum	−.293	−.137	.013	−.135	.117	.021	−.172
Hydroelectricity	−.140	−.122	.066	−.050	.000	−.000	−.034
Electric power	.012	.029	.066	−.050	.007	−.000	−.039
Refined petroleum	−.146	−.167	.066	−.020	.062	−.006	−.080
Case $\alpha = 0.3$, inflation adjustment = 0.0:							
Coal	−.199	−.218	.083	−.023	−.001	−.007	−.034
Crude petroleum	−.244	−.098	.013	−.130	.111	.029	−.169
Hydroelectricity	−.102	−.087	.066	−.050	.000	−.000	−.031
Electric power	.050	.064	.066	−.050	.006	−.000	−.036
Refined petroleum	−.108	−.131	.065	−.019	.059	−.004	−.077
Case $\alpha = 0.3$, inflation adjustment = 0.01:							
Coal	−.148	−.180	.083	−.023	−.001	−.006	−.021
Crude petroleum	−.183	−.048	.020	−.128	.103	.039	−.169
Hydroelectricity	−.052	−.042	.070	−.050	.000	−.000	−.031
Electric power	.099	.108	.070	−.050	.006	−.000	−.036
Refined petroleum	−.058	−.085	.072	−.021	.059	−.004	−.079
Case $\alpha = 0.3$, inflation adjustment = 0.02:							
Coal	−.097	−.143	.084	−.023	−.001	−.005	−.009
Crude petroleum	−.122	.001	.027	−.125	.096	.048	−.169
Hydroelectricity	−.003	.003	.075	−.050	.000	−.000	−.031
Electric power	.148	.153	.074	−.050	.006	−.000	−.036
Refined petroleum	−.009	−.039	.079	−.023	.059	−.004	−.080

Notes: This decomposition is based on equation (4.19) with adjustments to the producer price indexes for the commodities. The adjusted prices are not consistent with the official data for real GDP.

assumed α to be 0.3 and where our adjusted matrix was scaled to be consistent with the official real GDP figure. In the second set of figures (labeled: "Case $\alpha = 0.3$," inflation adjustment = 0.0), instead of scaling our adjusted matrix, we used the matrix which results from a strict application of the official producer price indices. In general, the net result is a decrease in the term representing the overall change in the energy-output ratio and a corresponding decrease in the term for technical change. The other components of the decompositions are relatively unchanged.

In the final two sections of table 4.9 we adjust the rate of inflation for all sectors upwards by first 1 percent and then 2 percent per year. For coal, the result of assuming a higher actual rate of inflation is a decrease in the absolute magnitude of the terms for overall change, technical change, and the residual. The other coefficients were almost unchanged. The net result is that the relative contribution of technical change actually increased. A common feature of all of the decompositions performed previously was that the change in demand patterns worked to increase the energy-output ratio. This conclusion is not affected by differing assumptions about the actual rate of inflation.

4.8 Conclusions

The decrease in the energy-output ratio in China since 1977 has been quite dramatic and has drawn considerable interest from researchers. Debate about why the ratio has been falling has centered on the relative roles of technical change within individual sectors and structural change between sectors. In this chapter, we examined this question using decomposition analysis based on the two most recent input-output tables. Our major finding is that between 1987 and 1992, technical change accounted for most of the fall in the energy-GDP ratio. Structural change actually increased the use of energy, while the increased import of some energy-intensive goods had the opposite effect. The results are somewhat different for electric power, where the trend toward increased electrification of the economy resulted in an increase in the electricity-GDP ratio. Our conclusions are robust to a number of adjustments to correct for possible problems with the input-output tables and the available sectoral price deflators, which may understate the actual rate of inflation.

Our conclusions are similar to those reached by Lin and Polenske (1995) and Lin (1996) for the 1981–1987 period. Although not strictly comparable because of differences in methodology and the fact that they examine industry alone, our results are also in keeping with the findings of Huang (1993) and Sinton and Levine (1994). However, as discussed in section 4.2, our methodology does not capture structural change effects below the 2-digit level and therefore may not contradict the World Bank (1993, 1994a, 1997) and others who have asserted that this was the most important factor in the fall in the energy-output ratio. This would be the case if the structural change occurred at finer levels of aggregation than we are able to examine with the available data.

Although not the focus of this chapter, in closing it may be worth briefly discussing some factors that could influence the prospects for further decline in the energy-output ratio in China. First, at the beginning of economic reform the Chinese economy was technologically backward and extremely inefficient in the use of energy. Hence many of the easily available efficiency gains may have already been realized. Second, by 1978 China was already quite industrialized. Between 1978 and 1995, the share of industry in GDP changed only slightly, rising from 48 percent to 49 percent of GDP to 31 percent over the same period, may serve to reduce energy intensity in the future. However, this effect could be reduced if there were a rapid increase in household demand for motor vehicles. Third, during the period we examined, energy prices were still under a considerable degree of government control. Great strides in energy price reform were made during the early 1990s, but they are still uncompleted. Higher prices may continue to drive energy-saving technological change. This effect would be strengthened if the government were to increase environmental taxes, which are already collected in limited measure for some air pollutants, to more fully account for the externalities caused by the use of fossil fuels. On the other hand, low world oil prices would have the opposite effect. The examination of these issues would provide many topics for future research.

Notes

1. In China, "industry" refers to all sectors of the economy with the exception of agriculture and services. Included as part of industry are mining, manufacturing, some public utilities (such as electric power generation), and construction.

2. Although there are published input-output tables with 117 (for 1987) and 118 (for 1992) sectors, the biggest obstacle to doing a more disaggregated analysis for China is the lack of appropriate sectoral price deflators. Using a data set limited to the industrial sectors and the years 1980 and 1985, Sinton and Levine (1994) demonstrate the importance of the level of aggregation in the decomposition of changes in the energy-output ratio. As the number of sectors rises from 11 to 267, the proportion of energy savings attributed to real

intensity change falls from 72 percent to 58 percent. However, the marginal contribution of structural change falls with each successive disaggregation.

3. GVO (gross value of output) includes the value of all domestic output, both that consumed as final demand and for intermediate use.

4. The current price industrial GVO data have been revised a number of times. However, the most recent revisions only cover the years back to 1992.

5. The input-output tables for the years 1987 and 1992 are based on surveys. The tables for the years 1990 and 1995 are RASed versions of the respective previous survey-based tables. Only the survey-based tables are appropriate for analysis of changes in the energy-output ratio.

6. Sinton and Levine (1994) mention some of these problems, but do not attempt to adjust for them.

7. This is discussed in more detail in relation to equation (4.9) below.

8. Another example of material-biased technical change could occur in the production of air transportation services. If we regard the old technology as using workers and airplanes, then the new technology could use workers, airplanes, and computers. Even if the total number of workers remains the same (i.e., the clerical workers saved are exactly the number needed to make the computers) and the amount of transportation services is the same (i.e., the same value added) this technical change would result in higher total GVO, where GVO is the sum of the transportation services and the computers.

9. For general matrices $\mathbf{A}_0$ and $\mathbf{A}$, there is no guarantee that a solution that satisfies eqs. (4.3), (4.4), and (4.5) exists. Given the structure of the Chinese input-output matrices and the very different makeup between the two years, a solution does not exist for two sectors. The simplest case is public administration which has no intermediate buyers, only deliveries to final demand, i.e., $x_{29} = y_{29}$. In this case constraint (4.5) cannot be applied. A similar problem exists for the apparel sector. Therefore, for these two sectors we do not impose (4.5) and merely minimize the difference between the left- and right-hand sides of (4.5).

10. Further details about the $\mathbf{A}'$ matrix are available on request.

11. Our $\mathbf{A}$ matrix and $\mathbf{x}$ vector for 1987 are based on the official input-output table, but have been adjusted to incorporate recent revisions of GDP. The revisions mainly reflect the improved coverage of services that followed a major survey of the service sector for the years 1991–1992 (Nationwide Tertiary Sector Survey Office, 1995).

12. The meaning of the parameter α is discussed in the next section.

13. This ignores the fact that there is some heterogeneity in the types of coal mined and that the value of coal can increase at a faster rate than tonnage because of improvements in quality.

14. The sources of the sectoral output price deflators are State Statistical Bureau (1994, pp. 232-233; 1995, p. 32, 114–115, 233, 246, and 249). It is important to note that the official statistics do not provide a reconciliation between these output price deflators and the implied GDP deflators that are only available at a much cruder level of aggregation.

15. Changes in the use of commodities should include changes in inventories. We ignore inventories here for ease of exposition. Inventories are, however, included in our actual calculations.

16. The analysis here has been repeated for output alone and is available by request from the authors.

17. Sinton and Levine (1994) refer to this as the "real intensity.

18. The distinction between values and quantities is not made explicit in Liu, Ang, and Ong (1992). They do not define clearly what aggregate real output is and hence what the sectoral shares are.

19. The electric power sector also includes a small amount of "steam and hot water production and supply." Unfortunately, we are not able to disaggregate these other outputs from electricity. Similarly, the refined petroleum sector also includes some "coking and the manufacture of gas and coal products."

20. We create the hydroelectricity sector by reallocating part of the value-added column from the power generation sector. Lacking more complete data, the amount shifted is proportional to the share of total kWh produced by hydro-power. The total amount of electricity produced is unchanged by this adjustment.

21. Between 1987 and 1992, the consumption of coal per unit of GDP fell from 0.766 kg per *yuan* to 0.611 kg per *yuan*. In logs this change is -0.226 (= log(0.611/0.766)), which is close to the figure of -0.239 given in the first column of table 4.6 in the case where $\alpha = 0.3$.

22. This assumption is important, because in China some goods are sold at both state-set and market prices (Byrd, 1991). During the years covered by our study there were substantial differences between the two for some sectors (China Price Yearbook, 1997).

23. An example of this move towards increased electrification is in the cement industry, as documented in the detailed case studies by Sinton (1996b).

5

Whatever Happened to Productivity Growth?

Dale W. Jorgenson and Eric Yip

5.1 Introduction

In this chapter we present international comparisons of patterns of economic growth among the G7 countries over the period 1960–1995. Between 1960 and 1973 productivity growth accounted for more than half of growth in output per capita for France, Germany, Italy, Japan, and the United Kingdom and somewhat less than half of output growth in Canada and the United States. The relative importance of productivity declined substantially after 1973, accounting for a predominant share of growth between 1973 and 1989 only for France.

Since 1989 productivity growth has almost disappeared as a source of economic growth in the G7 countries. Between 1989 and 1995 productivity growth was negative for five of the G7 countries, with positive growth only for Japan and the United States. The level of productivity for Canada in 1995 fell almost to the level first achieved in 1973, while declines in Italy and the United Kingdom brought productivity down to the levels of 1974 and 1978, respectively. Since 1989 input per capita has grown more slowly than the average for the period 1960 to 1989, except for Germany.

The United States has retained its lead in output per capita throughout the period 1960–1995. The United States has also led the G7 countries in input per capita, while relinquishing its lead in productivity to France. However, the United States has lagged behind Canada, France, Germany, Italy, and Japan in the growth of output per capita, surpassing only the United Kingdom. Except for Germany and the United Kingdom, the United States has lagged behind all the G7 countries in growth of input per capita, while U.S. productivity growth has exceeded only that of Canada and the United Kingdom.

Japan exhibited considerably higher growth rates in output per capita and productivity than the other G7 countries from 1960 to 1995, but most of these gains took place before 1973. Japan's productivity level, along with the levels of Germany and Italy, remain among the lowest in the G7. Japan's performance in output per capita owes more to high input per capita than to high productivity. The growth of Japanese input per capita greatly exceeded that for other G7 countries, especially prior to 1973.

During the period 1960–1995, economic performance among the G7 countries has became more uniform. The dispersion of levels of output per capita fell sharply before 1970 and has declined modestly since then. The dispersion in productivity levels also fell before 1970 and has remained within a narrow range. The dispersion of levels of input per capita has been stable throughout the period from 1960 to 1995. However, the relative positions of the G7 countries have been altered considerably with the dramatic rise of Japan and the gradual decline of the United Kingdom.

We can rationalize the important changes in economic performance that have taken place among the G7 countries on the basis of the neoclassical theory of economic growth, extended to incorporate persistent differences among countries. Productivity growth is exogenous, while investment is endogenous to the theory. Obviously, the relative importance of exogenous productivity growth has been greatly reduced, while a more prominent role must be assigned to endogenous investment in tangible assets and human capital.

In section 5.2 we describe the methodology for allocating the sources of economic growth between investment and productivity. We introduce constant quality indices of capital and labor inputs that incorporate the impacts of investments in tangible assets and human capital. The constant quality index of labor input combines different types of hours worked by means of relative wage rates. The constant quality index of capital input weights different types of capital stocks by rental rates, rather than the asset prices used for weighting capital stocks.

Differences in wage rates for different types of labor inputs reflect investments in human capital through education and training, so that a constant quality index of labor input is the channel for the impact of these investments on economic performance. The constant quality index of capital input includes a perpetual inventory of investments in tangible assets. The index also incorporates differences in rental prices that capture the differential impacts of these investments.

In section 5.3 we analyze the role of investment and productivity as sources of growth in the G7 countries over the period 1960–1995. We subdivide this period at 1973 to identify changes in performance after the first oil crisis. We employ 1989 as another dividing point to focus on the most recent experience. We decompose growth of output per capita for each country between growth of productivity and growth of input per capita. Finally, we decompose the growth of input per capita into components associated with investments in tangible assets and human capital.

International comparisons reveal important similarities among the G7 countries. Investments in tangible assets and human capital now account for the overwhelming proportion of economic growth in the G7 countries and also explain the predominant share of international differences in output per capita. Heterogeneity in capital and labor inputs and changes in the composition of these inputs over time are essential for identifying persistent international differences and accounting for growth.

In section 5.4 we test the important implication of the neoclassical theory of growth that relative levels of output and input per capita must converge over time. For this purpose we employ the coefficient of variation to measure convergence of levels of output per capita, input per capita, and productivity among the G7 countries over the period 1960–1995. As before, we divide the period at 1973 and 1989. We also analyze the convergence of capital and labor inputs per capita implied by the theory.

In section 5.5 we summarize the conclusions of our study and outline alternative approaches to endogenous growth through broadening the concept of investment. The mechanism for endogenous accumulation of tangible assets captured in Robert Solow's (1956) version of the neoclassical theory provides the most appropriate point of departure. Investments in human capital, especially investment in education, can now be incorporated into the theory. When measures of the output of research and development activities become available, investment in intellectual capital can be made endogenous.

5.2 Investment and Productivity

Ongoing debates over the relative importance of investment and productivity in economic growth coincide with disputes about the appropriate role for the public sector. Productivity can be identified with spillovers of benefits that fail to provide incentives for actors within the private sector. Advocates of a larger role for the public sector advocate the position that these spillovers can be guided into appropriate channels by an all-wise and beneficent government. By contrast proponents of a smaller government search for methods of decentralizing investment decisions among participants in the private sector.

Profound differences in policy implications militate against any simple resolution of the debate on the relative importance of investment and productivity. Proponents of income redistribution will not lightly abandon the search for a "silver bullet" that will generate economic growth without the necessity of providing incentives for investment. Advocates of growth strategies based on capital formation will not readily give credence to claims of spillovers to beneficiaries who are difficult or impossible to identify.

To avoid the semantic confusion that pervades popular discussions of economic growth, it is essential to be precise in defining investment. Investment is the commitment of current resources in the expectation of future returns and can take a multiplicity of forms. The distinctive feature of investment as a source of economic growth is that the returns can be internalized by the investor. The most straightforward application of this definition is to investment in tangible assets that creates property rights, including rights to the incomes that accrue to the owners of the assets.

The mechanism by which tangible investments are translated into economic growth is well understood. For example, an investor in a new industrial facility adds to the supply of these facilities and generates a stream of property income. Investment and income are linked through markets for capital assets and their services. The increase in capital input contributes to output growth in proportion to the marginal product of capital. The stream of property income can be divided between capital input and its marginal product. Identifying this marginal product with the rental price of capital provides the basis for a constant quality index of capital input.

The seminal contributions of Gary Becker (1993), Fritz Machlup (1962), Jacob Mincer (1974), and Theodore Schultz (1961) have given concrete meaning to a notion of wealth including investments that do not create property rights. For example, a student enrolled in school or a worker participating in a training program can be viewed as an investor. Although these investments do not create assets that can be bought or sold, the returns to higher educational qualifications or better skills in the workplace can be internalized by the investor.

An individual who completes a course of education or training adds to the supply of people with higher qualifications or skills. The resulting stream of labor income can be divided between labor input and its marginal product. The increase in labor contributes to output growth in proportion to the marginal product. Identifying this marginal product with the wage rate provides the basis for a constant quality index of labor input. Although there are no asset markets for human capital, investments in human and nonhuman capital have in common that returns to these investments can be internalized.

The defining characteristic of productivity as a source of economic growth is that the incomes generated by higher productivity are external to the economic activities that generate growth. Publicly supported research and development (R&D) programs are a leading illustration of activities that stimulate productivity growth. These programs can be conducted by government laboratories or financed by public subsidies to private laboratories. The resulting benefits are external to the economic units conducting R&D. These benefits must be carefully distinguished from the private benefits of R&D that can be internalized through the creation of intellectual property rights.[1]

The allocation of sources of economic growth between investment and productivity is critical for assessing the explanatory power of growth theory. Only substitution between capital and labor inputs resulting from investment in tangible assets is endogenous in Solow's (1956) neoclassical theory of growth. However, substitution among different types of labor inputs is the consequence of investment in human capital, whereas investment in tangible assets induces substitution among different types of capital inputs. Neither form of substitution is incorporated into Solow's (1957) model of production.

The distinction between substitution and technical change emphasized by Solow (1957) parallels the distinction between investment and productivity as sources of economic growth. However, Solow's definition of investment, like that of Simon Kuznets (1971), was limited to tangible assets. Both specifically excluded investments in human capital by relying on increases in undifferentiated hours of work as a measure of the contribution of labor input.

The contribution of investment in tangible assets to economic growth is proportional to the rental price of capital, which reflects the marginal product of capital. By contrast the asset price of capital reflects the present value of the income from a capital asset over its entire lifetime. Both Kuznets (1971) and Solow (1970) identified the contributions of tangible assets to growth with increases in the stock of capital, weighted by asset prices. By failing to employ the marginal products as weights, Kuznets and Solow misallocated the sources of economic growth between investment in tangible assets and productivity.[2]

Investment can be made endogenous within a neoclassical growth model, while productivity growth is exogenous. If productivity greatly predominates among sources of growth, as indicated by Kuznets (1971) and Solow (1970), most of growth is determined exogenously. Reliance on the "Solow residual" as an explanatory factor is a powerful indictment of the limitations of the neoclassical framework. This viewpoint was expressed by Moses Abramovitz (1956), who famously characterized the Solow residual as "A Measure of Our Ignorance."

Jorgenson and Griliches (1967) introduced constant quality indices of capital and labor inputs and a constant quality measure of investment goods output in allocating the sources of growth between investment and productivity. This greatly broadened the concept of substitution employed by Solow (1957) and altered, irrevocably, the allocation of economic growth between investment and productivity. They showed that eighty-five percent of U.S. economic growth could be attributed to investment, while productivity accounted for only fifteen percent.[3]

The measure of labor input employed by Jorgenson and Griliches combined different types of hours worked, weighted by wage rates, into a constant quality index of labor input, using methodology Griliches (1960) had developed for U.S. agriculture.[4] Their constant quality index of capital input combined different types of capital inputs by means of rental rates, rather than the asset prices appropriate for measuring capital stock. This model of capital as a factor of production was introduced by Jorgenson (1963) and made it possible to incorporate differences in capital consumption and the tax treatment of different types of capital income.[5]

Jorgenson and Griliches identified technology with a production possibility frontier. This extended the aggregate production function—introduced by Paul Douglas (1948) and developed by Jan Tinbergen (1942) and Solow (1957)—to include two outputs, investment and consumption goods. Jorgenson (1966) showed that economic growth could be interpreted, equivalently as "embodied" in investment in the sense of Solow (1960) or "disembodied" in productivity growth. Jorgenson and Griliches removed this indeterminacy by introducing constant quality price indices for investment goods.

Jeremy Greenwood, Zvi Hercowitz, and Per Krussell (1997) have recently revived Solow's (1960) concept of embodied technical change.

Greenwood, Hercowitz, and Krussell have applied constant quality price indices for producers' durable equipment constructed by Robert Gordon (1990) to capital input, but not to the output of investment goods, as Gordon did. Within the framework presented by Jorgenson (1966) both the output of investment goods and the input of capital services must be revised in order to hold the quality of investment goods constant. This approach has been employed by Jorgenson and Kevin Stiroh (1995, 1999) in assessing the impact of investment in information technology. For this purpose they employ constant quality price indices for computers and related equipment from the U.S. National Income and Product Accounts.

Laurits Christensen and Jorgenson (1969, 1970) embedded the measurement of productivity in a complete system of U.S. national accounts. They provided a much more detailed model of capital input based on the framework for the taxation of corporate capital income developed by Hall and Jorgenson (1967, 1969, 1971). Christensen and Jorgenson extended this framework to include noncorporate and household capital incomes. This captured the impact of differences in returns to different types of capital inputs more fully.

Christensen and Jorgenson identified the production account with a production possibility frontier describing technology and the income and expenditure account with a social welfare function describing consumer preferences. Following Kuznets (1961), they divided the *uses* of economic growth between consumption and saving. They linked saving to the wealth account through capital accumulation equations for each type of asset. Prices for different vintages of assets were linked to rental prices of capital inputs through a parallel set of capital asset pricing equations.

In 1973 Christensen and Jorgenson constructed internally consistent income, product, and wealth accounts. Separate product and income accounts are integral parts of both the U.S. Income and Product Accounts[6] and the United Nations (1968) *System of National Accounts* designed by Richard Stone.[7] However, neither system included wealth accounts consistent with the income and product accounts.

Christensen and Jorgenson constructed income, product, and wealth accounts, paralleling the U.S. National Income and Product Accounts for the period 1929–1969. They also implemented a vintage accounting system for the United States on an annual basis. The complete system of vintage accounts gave stocks of assets of each vintage and their prices. The stocks were cumulated to obtain asset quantities, providing the perpetual inventory of assets employed by Raymond Goldsmith (1955–1956, 1962).

The key innovation was the use of asset pricing equations to link the prices used in evaluating capital stocks and the rental prices employed in the constant quality index of capital input.[8] In a prescient paper on the measurement of welfare Paul Samuelson (1961) had suggested that a link between asset and rental prices was essential for the integration of income and wealth accounting.[9] The vintage system of accounts employed the specific form of this relationship developed by Jorgenson (1967).

Christensen, Dianne Cummings, and Jorgenson (1980) presented annual estimates of sources of economic growth for the United States and its major trading partners for the period 1960–1973. These estimates included constant quality indices of capital and labor input for each country. Christensen, Cummings, and Jorgenson (1981) gave relative levels of output, input, and productivity for these same countries for the period 1960–1973, also based on constant quality indices. Our first objective in this paper is to extend these estimates to 1995 for the G7 countries.[10] We have chosen GDP as a measure of output. We include imputations for the services of consumers' durables as well as land, buildings and equipment owned by nonprofit institutions in order to preserve comparability in the treatment of income from different types of capital.

Our constant quality index of capital input is based on a disaggregation of the capital stock among the categories given in table 5.1, classified by asset type and ownership in order to reflect differences in capital consumption and tax treatment among assets. We derive estimates of capital stock and property income for each type of capital input from

Table 5.1
Disaggregation of capital by asset characteristics

Asset Type	Ownership Sector
1. Equipment	1. Corporations and government
2. Nonresidential structures	2. Unincorporated businesses
3. Residential structures	3. Households and nonprofit institutions
4. Nonfarm inventories	4. General government
5. Farm inventories	
6. Consumer durables	
7. Residential land	
8. Nonresidential land	

Table 5.2
Disaggregation of labor by demographic characteristics

Sex
Educational Attainment:

1. 1–8 years grade school
2. 1–3 years secondary school
3. Completed secondary school
4. 1–3 years college
5. 4 or more years of college

Employment Status:

1. Business sector employee
2. Self-employed or unpaid family worker
3. General government employee

national accounting data. Similarly, our constant quality index of labor input is based on a disaggregation of the work force among the categories presented in table 5.2, classified by sex, educational attainment, and employment status. For each country we derive estimates of hours worked and labor compensation for each type of labor input from labor force surveys.

5.3 Sources of Growth

In table 5.3 we present output per capita annually for the G7 countries over the period 1960–1995, expressed relative to the United States in 1985. For completeness we present output and population separately in tables 5.4 and 5.5. We use 1985 purchasing power parities from the OECD (1987) to convert quantities of output per capita from domestic currencies for each country into U.S. dollars. The United States was the leader in per capita output throughout the period, and Canada ranked second for most of the period. Among the remaining five countries the United Kingdom started at the top and Japan at the bottom; by 1995 these roles were interchanged with Japan overtaking all four European countries and the United Kingdom lagging behind France and Germany.

In table 5.3 we present input per capita annually for the G7 countries over the period 1960–1995, relative to U.S. input per capita in 1985. We express quantities of input per capita in U.S. dollars, using purchasing power parities constructed for this study.[11] The United States was the

Table 5.3
Levels of output and input per capita and productivity (U.S. = 100.0 in 1985)

Year	U.S.	Canada	U.K.	France	Germany	Italy	Japan
				Output per capita			
1960	55.6	43.1	37.5	29.2	32.9	22.7	17.3
1973	80.9	65.4	53.6	50.9	53.6	41.4	54.0
1989	109.7	96.7	70.8	70.6	75.6	63.7	83.3
1995	116.3	94.6	72.6	74.6	83.5	69.2	92.8
				Input per capita			
1960	70.2	55.6	53.0	42.5	61.7	44.8	50.1
1973	85.6	69.4	60.1	56.3	72.5	49.7	68.6
1989	108.0	98.8	71.7	63.3	88.5	73.2	96.7
1995	112.5	100.1	77.5	68.7	98.5	80.1	106.7
				Productivity			
1960	79.2	77.5	70.9	68.8	53.4	50.7	34.5
1973	94.5	94.3	89.1	90.5	73.9	83.3	78.7
1989	101.6	97.9	98.8	111.5	85.4	87.0	86.1
1995	103.4	94.5	93.7	108.6	84.8	86.5	87.0

Table 5.4
Growth rate and level in output

Year	U.S.	Canada	U.K.	France	Germany	Italy	Japan
				Growth rate (percentage)			
1960–1973	4.11	4.99	3.28	5.28	4.60	5.29	9.95
1973–1989	2.94	4.79	1.40	2.97	2.67	4.36	3.79
1973–1995	2.83	2.98	2.15	2.28	1.85	2.18	3.31
1989–1995	2.00	0.94	0.78	1.49	2.45	1.32	2.14
1960–1989	3.43	4.26	2.50	3.77	3.25	4.03	6.39
1960–1995	3.18	3.69	2.21	3.38	3.12	3.56	5.66
				Level (billions of 1985 U.S. Dollars)			
1960	1826	140	357	243	332	207	292
1973	3115	268	547	482	603	412	1066
1989	4930	481	738	724	852	666	1863
1995	5560	509	773	791	987	721	2118
				Level (U.S. = 100.0 in 1985)			
1960	42.1	3.2	8.2	5.6	7.7	4.8	6.7
1973	71.9	6.2	12.6	11.1	13.9	9.5	24.6
1989	113.8	11.1	17.0	16.7	19.7	15.4	43.0
1995	128.3	11.7	17.8	18.3	22.8	16.6	48.9

Table 5.5
Growth rate and level in population

Year	U.S.	Canada	U.K.	France	Germany	Italy	Japan
				Growth rate (percentage)			
1960–1973	1.22	1.79	0.54	1.01	0.86	0.67	1.18
1973–1989	1.00	1.22	0.01	0.47	−0.17	0.45	1.07
1973–1995	0.94	1.20	0.20	0.51	0.11	0.22	0.61
1989–1995	1.03	1.31	0.36	0.57	0.79	−0.07	0.33
1960–1989	1.08	1.47	0.31	0.73	0.39	0.47	0.96
1960–1995	1.07	1.44	0.32	0.70	0.46	0.38	0.85
				Level			
1960	180.8	17.9	52.4	45.7	55.4	50.2	93.3
1973	211.9	22.6	56.2	52.1	62.0	54.8	108.7
1989	247.3	27.4	57.4	56.4	62.1	57.5	123.1
1995	263.7	79.6	58.6	58.4	65.1	57.3	125.6
				Level (U.S = 100.0 in 1985)			
1960	75.8	7.5	22.0	19.2	23.2	21.1	39.1
1973	88.9	9.5	23.6	21.9	26.0	23.0	45.6
1989	100.0	10.9	23.8	23.2	25.6	24.0	50.6
1995	110.4	12.4	24.6	24.5	27.3	24.0	52.7

leader in per capita input as well as output throughout the period. Germany started in second place, but lost its position to Canada in 1975 and Japan in 1976. In 1995 Japan ranked next to the United States in input per capita with Canada third. France started at the bottom of the ranking and remained there for most of the period. Canada, France, Italy, and Japan grew relative to the United States, while Germany and the United Kingdom declined.

In table 5.3 we present productivity levels annually for the G7 countries over the period 1960–1995, where productivity is defined as the ratio of output to input. In 1960 the United States was the productivity leader with Canada closely behind. In 1970 Canada became the first country to overtake the United States, remaining slightly above the U.S. level for most of the period ending in 1984. France surpassed the United States in 1979 and became the international productivity leader after 1980. The United Kingdom overtook Canada and nearly overtook the United States in 1987, but fell behind both countries in 1990. Japan surpassed Germany in 1970 and Italy in 1990, and Italy overtook Germany in 1963 and maintained its lead during most of the period ending in 1995.

Table 5.6
Growth in output and input per capita and productivity (percentage)

Year	U.S.	Canada	U.K.	France	Germany	Italy	Japan
				Output per capita			
1960–1973	2.89	3.20	2.74	4.26	3.74	4.62	8.77
1973–1989	1.90	2.45	1.75	2.04	2.15	2.69	2.71
1973–1995	1.65	1.68	1.38	1.74	2.02	2.34	2.46
1989–1995	0.97	−0.37	0.42	0.92	1.66	1.40	1.81
1960–1989	2.34	2.79	2.19	3.04	2.86	3.56	5.43
1960–1995	2.11	2.24	1.89	2.68	2.66	3.19	4.81
				Input per capita			
1960–1973	1.53	1.70	0.98	2.15	1.24	0.79	2.42
1973–1989	1.45	2.21	1.10	0.74	1.25	2.42	2.15
1973–1995	1.24	1.67	1.15	0.91	1.39	2.17	2.01
1989–1995	0.68	0.21	1.30	1.37	1.78	1.49	1.63
1960–1989	1.49	1.98	1.04	1.37	1.25	1.69	2.27
1960–1995	1.35	1.68	1.09	1.37	1.34	1.66	2.16
				Productivity			
1960–1973	1.36	1.51	1.76	2.11	2.50	3.82	6.35
1973–1989	0.45	0.23	0.65	1.31	0.90	0.27	0.56
1973–1995	0.41	0.01	0.23	0.83	0.62	0.17	0.45
1989–1995	0.29	−0.59	−0.88	−0.45	−0.11	−0.10	0.18
1960–1989	0.86	0.80	1.15	1.67	1.62	1.86	3.16
1960–1995	0.76	0.57	0.80	1.30	1.32	1.53	2.65

We summarize growth in output and input per capita and productivity for the G7 countries in table 5.6. For completeness we present growth rates of output and population separately in tables 5.4 and 5.5. We present annual average growth rates for the period 1960–1995 and the subperiods 1960–1973, 1973–1989, and 1989–1995. Japan was the leader in output growth for the period as a whole and before 1973. The United Kingdom grew more slowly than the remaining six countries during the period as a whole and after 1960. Output growth slowed in all the G7 countries after 1989 and Canada's growth rate was negative. Differences in growth rates among the G7 countries declined substantially after 1973.

Japan also led the G7 in growth of input per capita for the period 1960–1995 and before 1973. Italy was the leader during the subperiod 1973–1989 and Germany led during 1989–1995. There is little evidence of a slowdown in input growth after 1973; differences among input growth rates are much less than among output growth rates. Japan led the G7 in productivity growth for the period as a whole and before 1973, while France was the leader from 1973 to 1989. All the G7 countries—with the exception of Japan and the United States—experienced negative productivity growth after 1989. The United States had a slightly higher productivity growth rate than Japan during this period. In table 5.3 we present levels of output and input per capita and productivity relative to the U.S. level in 1985.

Our constant quality index of capital input weights capital stocks for each of the categories given in table 5.1 by rental prices, defined as property compensation per unit of capital. By contrast an index of capital stock weights different types of capital by asset prices rather than the rental prices appropriate for capital input. The ratio of capital input to capital stock measures the average quality of a unit of capital, as reflected in its marginal product. This enables us to assess the magnitude of differences between the constant quality index of capital input and the unweighted index of capital stock employed by Kuznets (1971) and Solow (1970).

In table 5.7 we present capital input per capita annually for the G7 countries over the period 1960–1995, expressed relative to the United States in 1985. The United States was the leader in capital input per capita through 1991, when Canada overtook the United States and emerged as the international leader. All countries grew substantially relative to the United States, but only Canada surpassed the U.S. level. Germany led the remaining five countries throughout the period, and the United Kingdom was the laggard among these countries, except for the period 1962 to 1973, when Japan ranked lower.

The picture for capital stock per capita has some similarities to capital input, but there are important differences. The United States led throughout the period in capital stock, while Canada overtook the United States in capital input. France, Germany, and Italy had similar stock levels throughout the period with Italy leading this group of three countries in 1995. Similarly, Japan and the United Kingdom had similar levels throughout the period; Japan ranked last until 1976, but surpassed the United Kingdom in that year. Capital stock levels do not accurately reflect the substitutions among capital inputs that accompany investments in tangible assets.

Capital quality is the ratio of capital input to capital stock. The behavior of capital quality highlights the differences between the constant

Table 5.7
Levels of capital input and capital stock per capita and capital quality (U.S. = 100.0 in 1985)

Year	U.S.	Canada	U.K.	France	Germany	Italy	Japan
				Capital input per capita			
1960	58.5	41.7	21.0	24.0	26.0	17.1	21.6
1973	79.0	61.9	32.4	46.8	56.6	38.4	31.6
1989	109.4	106.7	52.6	76.4	91.9	80.7	56.4
1995	114.3	119.2	60.4	87.1	108.5	97.3	68.3
				Capital stock per capita			
1960	68.2	43.3	18.8	18.8	20.1	19.6	17.3
1973	85.8	60.3	28.0	38.1	41.3	37.5	25.4
1989	105.3	93.3	42.9	63.4	62.9	65.9	47.8
1995	109.4	98.5	48.2	71.8	74.9	79.6	58.7
				Capital quality			
1960	85.8	96.3	111.8	127.2	129.1	87.6	124.7
1973	92.1	102.7	116.1	122.8	137.1	102.2	124.1
1989	103.9	114.3	122.7	120.6	146.1	122.5	118.0
1995	104.5	121.0	125.2	121.3	144.8	122.2	116.3

quality index of capital input and capital stock. Germany was the international leader in capital quality throughout most of the period 1960–1995, while the United States ranked at the bottom. There are important changes in capital quality over time and persistent differences among countries. Heterogeneity of capital input within each country and between countries must be taken into account in international comparisons of economic performance.

We summarize growth in capital input and capital stock per capita and capita quality for the G7 countries in table 5.8. Italy was the international leader in capital input growth and the United States was the laggard for the period 1960–1995. There was a modest slowdown in capital input growth after 1973 and again after 1989 and similar slowdowns in capital stock growth. Italy was the leader in capital quality growth, and Japan the laggard. In table 5.7 we present levels of capital input and capital stock per capita and capital quality relative to the United States in 1985.

Our constant quality index of labor input weights hours worked for each of the categories given in table 5.2 by wage rates defined in terms of labor compensation per hour. An index of hours worked adds together different types of hours without taking quality differences into account.

Table 5.8
Growth in capital input and capital stock per capita and capital quality (percentage)

Year	U.S.	Canada	U.K.	France	Germany	Italy	Japan
				Capital input per capita			
1960–1973	2.32	3.03	3.34	5.15	6.00	6.20	2.93
1973–1989	2.03	3.40	3.02	3.06	3.02	4.65	3.63
1973–1995	1.68	2.98	2.82	2.82	2.95	4.23	3.51
1989–1995	0.74	1.85	2.29	2.19	2.77	3.12	3.18
1960–1989	2.16	3.24	3.17	4.00	4.36	5.34	3.32
1960–1995	1.92	3.00	3.02	3.69	4.09	4.96	3.29
				Capital stock per capita			
1960–1973	1.77	2.54	3.06	5.42	5.54	5.01	2.97
1973–1989	1.28	2.73	2.68	3.17	2.63	3.52	3.94
1973–1995	1.11	2.23	2.48	2.88	2.71	3.42	3.80
1989–1995	0.64	0.91	1.94	2.08	2.92	3.15	3.42
1960–1989	1.50	2.65	2.85	4.18	3.93	4.18	3.51
1960–1995	1.35	2.35	2.69	3.82	3.76	4.01	3.49
				Capital quality			
1960–1973	0.55	0.49	0.29	−0.27	0.46	1.19	−0.04
1973–1989	0.75	0.67	0.35	−0.11	0.40	1.13	−0.32
1973–1995	0.57	0.75	0.35	−0.05	0.25	0.81	−0.30
1989–1995	0.09	0.95	0.34	0.10	−0.15	−0.03	−0.24
1960–1989	0.66	0.59	0.32	−0.18	0.43	1.16	−0.19
1960–1995	0.56	0.65	0.32	−0.14	0.33	0.95	−0.20

The ratio of labor input to hours worked measures the average quality of an hour of labor, as reflected in its marginal product. This enables us to assess the magnitude of differences between the constant quality index of labor input and the unweighted index of hours worked employed by Kuznets (1971) and Solow (1970).

In table 5.9 we present labor input per capita annually for the G7 countries for the period 1960–1995, relative to the United States in 1985. The United Kingdom led until 1962, but was overtaken by Japan in that year. The United States surpassed the United Kingdom in 1977, but the two countries grew in parallel through 1995 with the United States maintaining a slight lead over most of the period. France ranked at the bottom of the G7 for most of the period, but led Italy from 1963 to 1979. Japan remained the international leader through 1995 with levels

Table 5.9
Levels of labor input and hours worked per capita and labor quality (U.S. = 100.0 in 1985)

Year	U.S.	Canada	U.K.	France	Germany	Italy	Japan
				Capital input per capita			
1960	77.8	69.0	95.5	60.5	98.6	66.6	91.2
1973	89.1	75.4	89.8	63.0	84.3	56.6	117.7
1989	107.0	93.0	89.3	55.2	86.1	68.7	145.0
1995	111.1	87.5	93.7	57.5	90.8	70.2	146.2
				Hours worked per capita			
1960	91.1	80.4	110.2	105.0	120.4	89.2	134.4
1973	95.5	83.7	96.6	97.4	98.7	74.6	143.3
1989	104.5	93.4	92.7	77.8	93.5	85.5	150.2
1995	105.3	84.3	92.6	74.2	95.4	84.2	152.1
				Labor quality			
1960	85.4	85.8	86.7	57.7	81.9	74.7	67.9
1973	93.3	90.1	92.9	64.7	85.4	75.9	81.0
1989	102.4	99.6	96.4	71.0	92.0	80.3	93.9
1995	105.5	103.8	101.3	77.5	95.2	83.4	96.1

of labor input more than one-third of the United States and the United Kingdom and more than double that of France.

The picture for hours worked per capita has some similarities to labor input, but there are important differences. Japan was the international leader in hours worked per capita throughout the period, and Germany led the four European countries for most of the period. The United States overtook France in 1975 and Germany and the United Kingdom in 1977. At the beginning of the period Canada ranked last, but lost this position to Italy in 1965. Italy was the laggard in hours worked until 1983, when France fell to the bottom of the G7, remaining there through 1995. Hours worked do not accurately reflect the substitutions among labor inputs that accompany investments in human capital.

Labor quality is the ratio of the constant quality index of labor input to the unweighted index of hours worked. The behavior of labor quality highlights the differences between labor input and hours worked. Canada, the United States and the United Kingdom were the leaders in labor quality; labor quality in these three countries grew in parallel through 1995. France was the laggard among G7 countries in labor quality throughout most of the period 1960–1995. There are important changes in labor quality over time and persistent differences among countries. Heterogeneity within each country and between countries must be taken into account in international comparisons of economic growth.

We summarize growth in labor input and hours worked per capita and labor quality in table 5.10. Japan led the G7 countries in labor input growth for the period 1960–1995 and before 1973. Canada was the international leader during the subperiod 1973–1989, while Germany was the leader after 1989. The United States led growth in hours worked for the period as a whole and after 1989, and Japan was the leader before 1973 and Italy led between 1973 to 1989. Growth was positive throughout the period for Japan and the United States, mostly negative for the four European countries, and alternately positive and negative for Canada. Growth in labor quality was positive for all seven countries with a modest decline after 1973 and a revival after 1989. In table 5.9 we present labor input and hours worked per capita and labor quality relative to the United States in 1985.

Using data from table 5.6, we can assess the relative importance of investment and productivity in per capita growth for the G7 countries. For Canada, the United Kingdom, and the United States, investments in tangible assets and human capital greatly predominated as sources of growth over the period 1960–1995. We can attribute slightly more than half of Japanese growth to productivity, whereas proportions for the four European countries—France, Germany, Italy, and the United Kingdom—are slightly less than half. After 1973 growth in output and productivity declined for all seven countries; however, growth in input has not declined, so the relative importance of productivity has sharply diminished.

Similarly, using data from table 5.8 we can combine estimates of growth in capital input, capital stock, and capital quality to assess the importance of changes in quality. Capital input growth is positive for all countries for the period 1960–1995 and all three subperiods. Capital quality growth is positive for the period as a whole for all G7 countries, except France and Japan. Although capital stock greatly predominates in capital input growth, capital quality is quantitatively significant, so that the heterogeneity of capital must be taken into account in assessing the role of investment in tangible assets.

Finally, using data from table 5.10 we can combine estimates of growth in labor input, hours worked, and labor quality to assess the importance of hours and quality. Labor input growth is negative for the period 1960–1995 in France and Germany, near zero for the United Kingdom and is

Table 5.10
Growth in labor input and hours worked per capita and labor quality (percentage)

Year	U.S.	Canada	U.K.	France	Germany	Italy	Japan
Labor input per capita							
1960–1973	1.05	0.69	−0.46	0.31	−1.20	−1.25	1.96
1973–1989	1.14	1.31	−0.03	−0.82	0.13	1.21	1.13
1973–1995	1.00	0.68	0.20	−0.41	0.34	0.97	0.98
1989–1995	0.64	−1.01	0.80	0.68	0.90	0.34	0.60
1960–1989	1.10	1.03	−0.23	−0.32	−0.47	0.11	1.50
1960–1995	1.02	0.68	−0.05	−0.14	−0.23	0.15	1.35
Hours worked per capita							
1960–1973	0.37	0.31	−1.01	−0.57	−1.53	−1.38	0.60
1973–1989	0.56	0.69	−0.26	−1.41	−0.34	0.86	0.21
1973–1995	0.44	0.03	−0.20	−1.24	−0.16	0.55	0.21
1989–1995	0.13	−1.70	−0.02	−0.79	0.34	−0.27	0.21
1960–1989	0.47	0.52	−0.60	−1.03	−0.87	−0.15	0.38
1960–1995	0.42	0.14	−0.50	−0.99	−0.67	−0.17	0.35
Labor quality							
1960–1973	0.68	0.38	0.53	0.88	0.32	0.13	1.36
1973–1989	0.58	0.62	0.23	0.58	0.47	0.35	0.92
1973–1995	0.56	0.64	0.39	0.83	0.50	0.42	0.78
1989–1995	0.50	0.70	0.82	1.47	0.56	0.62	0.39
1960–1989	0.62	0.51	0.37	0.72	0.40	0.25	1.12
1960–1995	0.60	0.55	0.44	0.85	0.43	0.31	0.99

slightly positive for Italy. Growth in hours worked is mostly negative for all four countries throughout the period. However, growth in labor quality has helped to offset the decline in hours worked in Europe. For Canada, Japan, and the United States labor quality predominates in the growth of labor input, so that the heterogeneity of labor input is essential in assessing the role of investment in human capital.

5.4 Convergence

The objective of modeling economic growth is to explain the *sources* and *uses* of growth endogenously. National income is the starting point for assessments of the uses of growth through consumption and saving. The concept of a measure of economic welfare, introduced by William Nordhaus and James Tobin (1972), is the key to augmenting national income to broaden the concepts of consumption and saving. Similarly, gross domestic product is the starting point for attributing the sources of economic growth to growth in productivity and investments in tangible assets and human capital.

Denison (1967) compared differences in growth rates for national income per person employed for the period 1950–1962 with differences of levels in 1960 for eight European countries and the United States. However, he overlooked the separate roles for a production account with the national product and inputs of capital and labor services and an income and expenditure account with national income, consumption, and saving. From an economic point of view this ignored the distinction between the sources and uses of economic growth.

Denison compared differences in both growth rates and levels of national income per person employed. The eight European countries as a whole were characterized by more rapid growth and a lower level of national income per capita. Although this association was not monotonic for comparisons between individual countries and the United States, Denison concluded that:[12]

> "Aside from short-term aberrations Europe should be able to report higher growth rates, at least in national income per person employed, for a long time. Americans should expect this and not be disturbed by it."

Kuznets (1971) provided elaborate comparisons of growth rates for the fourteen countries included in his study. Unlike Denison (1967), he did not provide level comparisons. Maddison (1982) filled this gap by comparing levels of national product for sixteen countries[13] on the basis of estimates of purchasing power parities by Irving Kravis, Alan Heston, and Robert Summers (1978).[14] These estimates have been updated by successive versions of the Penn World Table and made it possible to reconsider the issue of convergence of output per capita raised by Denison (1967).[15]

Abramovitz (1986) was the first to take up the challenge of analyzing convergence of output per capita among Maddison's sixteen countries. He found that convergence appeared to characterize output levels in the postwar period, but not the period before 1914 and the interwar period. Baumol (1986) formalized these results by running a regression of growth rate of GDP per hour worked over the period 1870–1979 on the 1870 level of GDP per hour worked.[16] A negative regression coefficient is evidence for beta-convergence of GDP levels.

In a notable paper titled "Crazy Explanations for the Productivity Slowdown," Paul Romer (1987) derived a version of the growth regression from Solow's (1970) growth model with a Cobb-Douglas production function. Romer also extended the data set for growth regressions from Maddison's (1982) group of sixteen advanced countries to the 115 countries included in Penn World Table (Mark-3), presented by Summers and Heston (1984). Romer's key finding was that an indirect estimate of the Cobb-Douglas elasticity of output with respect to capital was close to three-quarters. The share of capital in output implied by Solow's model was less than half as great on average.[17]

Gregory Mankiw, David Romer, and David Weil (1992) undertook a defense of the neoclassical framework of Kuznets (1971) and Solow (1970). The empirical portion of their study is based on data for 98 countries from the Penn World Table (Mark-4), presented by Summers and Heston (1988). Like Paul Romer (1987), Mankiw, David Romer, and Weil derived a growth equation from the Solow (1970) model; however, they also augmented this model by allowing for investment in human capital.

The results of Mankiw, David Romer, and Weil (1992) provided empirical support for the augmented Solow model. There was clear evidence of the convergence predicted by the model, where convergence was conditional on the ratio of investment to GDP and the rate of population growth; both are determinants of steady state output. In addition, the estimated Cobb-Douglas elasticity of output with respect to capital coincided with the share of capital in the value of output. However, the rate of convergence of output per capita was too slow to be consistent with the 1970 version of the Solow model.

Islam (1995) exploited an important feature of the Summers-Heston (1988) data overlooked in previous empirical studies, namely, benchmark comparisons of levels of the national product at five year intervals, beginning in 1960 and ending in 1985. Using econometric methods for panel data, Islam tested an assumption maintained in growth regressions, such as those of Mankiw, David Romer, and Weil. Their study, like that of Paul Romer (1987), assumed identical technologies for all countries included in the Summers-Heston data sets.

Substantial differences in levels of productivity among countries have been documented by Denison (1967), Christensen, Cummings, and Jorgenson (1981), and in section 5.2, above. By introducing panel data techniques, Islam (1995) was able to allow for these differences. He corroborated the finding of Mankiw, David Romer, and Weil (1992) that the elasticity of output with respect to capital input coincided with the share of capital in the value of output.

In addition, Islam (1995) found that the rate of convergence of output per capita among countries in the Summers-Heston (1988) data set was precisely that required to substantiate the *unaugmented* version of the Solow (1970). In short, "crazy explanations" for the productivity slowdown, like those propounded by Paul Romer (1987, 1994), are not required. Moreover, the model did not require augmentation, as suggested by Mankiw, David Romer, and Weil (1992). However, differences in productivity among these countries must be taken into account in modeling differences in growth rates.

The conclusion from Islam's (1995) research is that the Solow model is the appropriate point of departure for modeling the accumulation of tangible assets. For this purpose it is unnecessary to endogenize investment in human capital as well. The rationale for this key empirical finding is that the transition path to balanced growth equilibrium requires decades after changes in policies that affect investment in tangible assets, such as tax policies. By contrast the transition after a change in policies affecting investment in human capital requires as much as a century.

In figure 5.1 we present coefficients of variation for levels of output and input per capita and productivity for the G7 countries annually for the period 1960–1995. The coefficients for output decline by almost a factor of two between 1960 and 1974, but then remain stable throughout the rest of the period. Coefficients for productivity decline by more than a factor of two between 1960 and 1970 and then stabilize. Coefficients for input per capita are nearly unchanged throughout the period. This is evidence for the sigma-convergence of output and input per capita and productivity implied by Solow's neoclassical theory of growth, allowing for differences in productivity of the type identified by Islam.

Figure 5.2 presents coefficients of variation for levels of capital input and capital stock per capita and capital quality for the G7 countries. The coefficients for capital input decline gradually throughout the period. Coefficients for capital stock are slightly larger than those for capital input, but behave in a similar manner. Coefficients for capital quality are stable until 1968 and then decline to a slightly lower level after 1971. This is also evidence of the sigma-convergence implied by Solow's growth

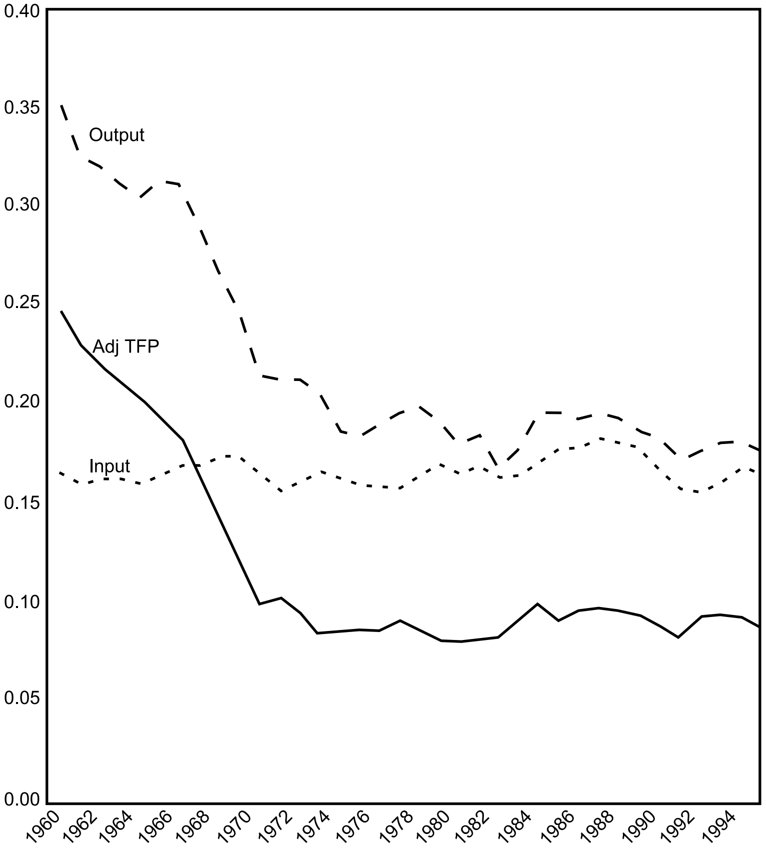


Figure 5.1
Convergence of output and input per capita and productivity.

model with persistent differences in levels of capital quality among countries.

Finally, coefficients of variation for levels of labor input and hours worked per capita and labor quality for the G7 are given in figure 5.3. The coefficients for labor input rise gradually. The coefficients for hours worked rise gradually until 1973 and then stabilize for most of the period. The coefficients for labor quality gradually decline. Again, this is evidence for sigma-convergence with persistent international differences in labor quality.

The evidence of sigma-convergence among the G7 countries presented in figures 5.1, 5.2, and 5.3 is consistent with a new version of

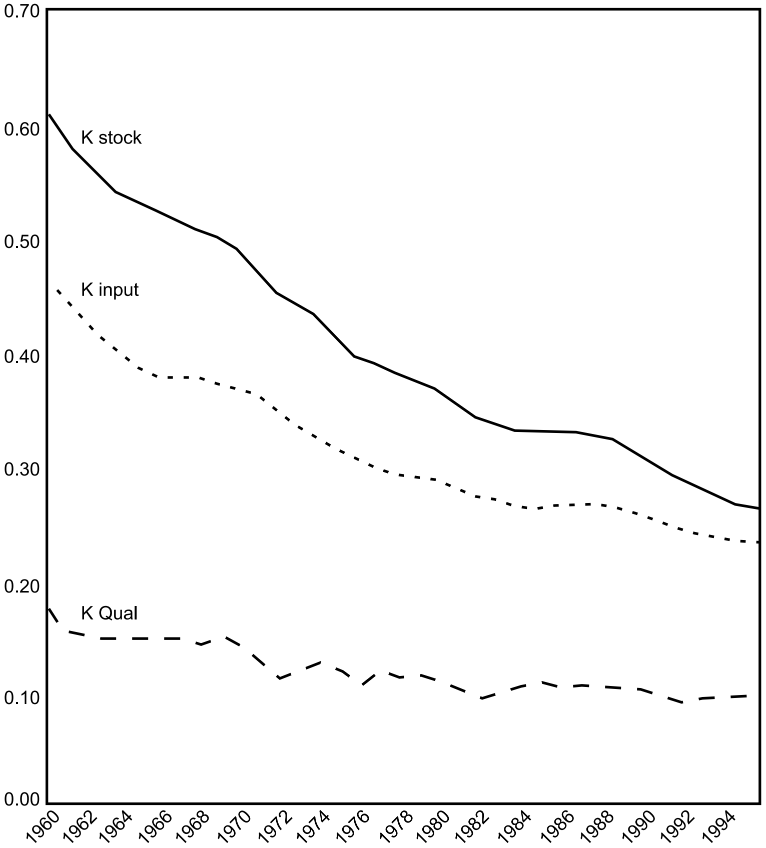


Figure 5.2
Convergence of capital input, capital stock per capita and capital quality.

the neoclassical growth model, characterized by persistent but stable international differences in productivity, capital quality, labor quality, and hours worked per capita. Islam showed that a simpler version of the model with constant differences in productivity among countries successfully rationalizes differences in growth of per capita output among a much broader group of countries over the period 1960–1985.

5.5 Endogenizing Growth

Investment is endogenous in a neoclassical growth model, whereas productivity is exogenous. Solow's (1957) definition of investment was

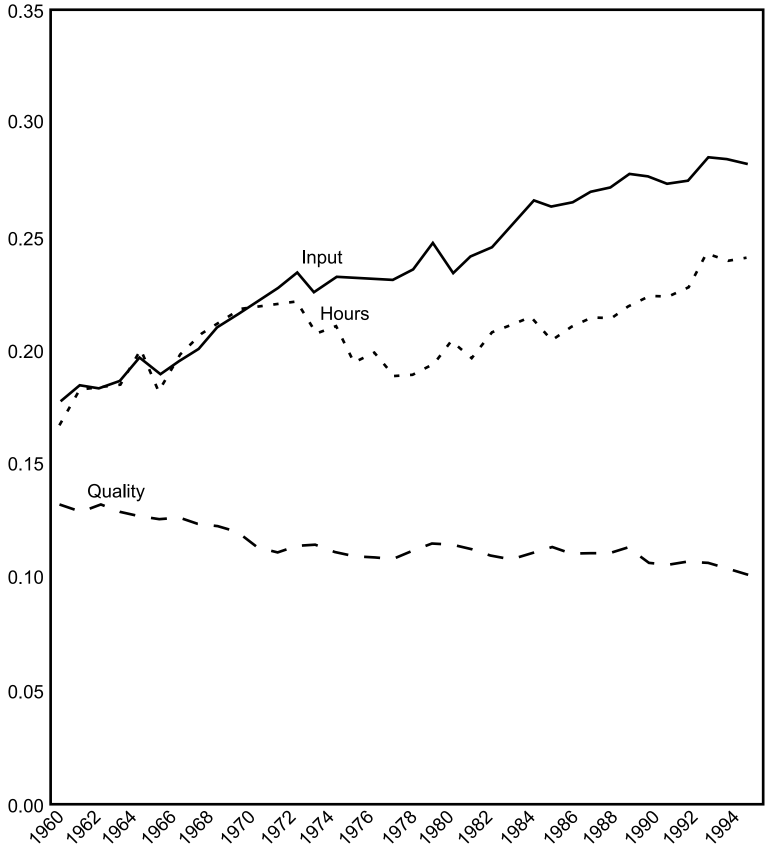


Figure 5.3
Convergence of labor input and hours worked per capita and labor quality.

limited to tangible assets. In order to increase the explanatory power of growth theory, it is necessary to broaden the concept of investment to include human capital. The mechanism by which investments in education and training are translated into economic growth is well understood. An increase in the supply of more highly educated or trained individuals generates a stream of labor income that represents a return to investment in human capital that can be internalized by the investor.

Constant quality indexes of labor input are an essential prerequisite to incorporating human capital into an empirical model of economic growth. The marginal products of workers with different levels of education and training are used to weight the corresponding hours of work.

Jorgenson and Fraumeni (1989) have broadened the vintage accounting system developed by Christensen and Jorgenson (1973) to include investments in human capital. The essential idea is to treat individual members of the U.S. population as human assets with asset prices given by their lifetime labor incomes. Jorgenson and Fraumeni have implemented the vintage accounting system for both human and nonhuman capital for the United States on an annual basis for the period 1948–1984.

In a vintage accounting system for human capital, wage rates correspond to marginal products and can be observed directly from the labor market. Lifetime labor incomes play the role of asset prices in accounting for human wealth. These incomes are derived by applying asset pricing equations to future wage rates, discounting them back to the present. Asset prices for tangible assets can be observed directly in markets for investment goods; asset pricing equations are used to derive rental prices for capital services. These rental prices are the marginal products of tangible capital assets.

Jorgenson and Fraumeni (1992b) have developed a measure of the output of the U.S. education sector. Although education is a service industry, its output is investment in human capital. Investment in education can be measured from the impact of increases in educational attainment on lifetime incomes of individuals enrolled in school. Investment in education, measured in this way, is similar in magnitude to the value of working time for all individuals in the labor force.

Second, Jorgenson and Fraumeni (1992a) have measured the inputs of the education sector, beginning with the purchased inputs by educational institutions. Most of the value of the output of educational institutions accrues to students through increases in their lifetime incomes. Student time is the most important input into the educational process. Given the outlays of educational institutions and the value of student time, the growth of the education sector can be allocated to its sources.

An alternative approach, employed by Schultz (1961), Machlup (1962), Nordhaus and Tobin (1972), and many others, is to apply Goldsmith's (1955–1956) perpetual inventory method to private and public expenditures on educational services. Unfortunately, the approach has foundered on the absence of a satisfactory measure of the output of the educational sector and the lack of an obvious rationale for capital consumption.[18]

Given vintage accounts for human and nonhuman capital, Jorgenson and Fraumeni (1989) constructed a system of income, product, and wealth accounts, paralleling the system Jorgenson had developed with Christensen. In these accounts the value of human wealth was more than ten times the value of nonhuman wealth, while investment in human capital was five times investment in tangible assets. Full investment in the U.S. economy is defined as the sum of these two types of investment. Similarly, the value of nonmarket labor activities is added to personal consumption expenditures to obtain full consumption. The product measure included these new measures of investment and consumption.

Since the complete accounting system included a production account with full measures of capital and labor inputs,[19] Jorgenson and Fraumeni were able to generate a new set of accounts for the *sources* of U.S. economic growth. The system also included an income and expenditure account with income from labor services in both market and non-market activities and an allocation of full income between consumption and saving. This provided the basis for the *uses* of U.S. economic growth and a new measure of economic welfare. The system was completed by a wealth account containing both human wealth and tangible assets.

Jorgenson and Fraumeni aggregated the growth of education and non-education sectors of the U.S. economy to obtain a new measure of U.S. economic growth. Combining this with measures of input growth, they obtained a new set of accounts for the sources of growth. Productivity contributes almost nothing to the growth of the education sector and only a modest proportion to output growth for the economy as a whole, so that productivity accounts for only seventeen percent of growth.

The introduction of endogenous investment in education increases the explanatory power of the theory of economic growth to 83 percent. However, it is important to emphasize that growth is measured differently. The traditional framework for economic measurement of Kuznets (1971) and Solow (1970) excludes nonmarket activities, such as those that characterize the major portion of investment in education. The intuition is familiar to any teacher, including teachers of economics: What the students do is far more important than what the teachers do, even if the subject matter is the theory of economic growth.

A third approximation to the theory of economic growth results from incorporating all forms of investment in human capital, including education, child rearing, and addition of new members to the population.

Fertility could be made endogenous by using the approach of Barro and Becker (1988) and Becker and Barro (1988). Child rearing could be made endogenous by modeling the household as a producing sector along the lines of the model of the educational sector outlined above. The results presented by Jorgenson and Fraumeni (1989) show that this would endogenize 86 percent of U.S. economic growth. This is a significant, but not overwhelming, gain in explanatory power.

In principle, investment in new technology could be made endogenous within a neoclassical growth model by extending the concept of investment to encompass intellectual capital. For example, the Bureau of Economic Analysis (BEA, 1994) has provided a satellite system of accounts for research and development, based on Goldsmith's (1955–1956) perpetual inventory method, applied to private and public expenditures. Unfortunately, this is subject to the same limitations as is the approach to human capital of Schultz (1961) and Machlup (1962). The BEA satellite system has foundered on the absence of a satisfactory measure of the output of R&D and the lack of an appropriate rationale for capital consumption.

The standard model for investment in new technology, formulated by Griliches (1973) is based on a production function incorporating inputs of services from intellectual capital accumulated through R&D investment. Intellectual capital is treated as a factor of production in precisely the same way as tangible assets in section 5.2. Bronwyn Hall (1993) has developed the implications of this model for the pricing of the services of intellectual capital input and the evaluation of intellectual capital assets.

The model of capital as a factor of production first propounded by Jorgenson (1963) has been successfully applied to tangible assets and human capital. However, implementation for intellectual capital would require a system of vintage accounts including not only accumulation equations for stocks of accumulated R&D, but also asset pricing equations. These equations are essential for separating the revaluation of intellectual property due to price changes over time from depreciation of this property due to aging. This is required for measuring the quantity of intellectual capital input and its marginal product.

The disappearance of productivity growth in the G7 countries documented in this chapter is a serious challenge for theories of growth based on externalities, like those of Lucas (1988) and Paul Romer (1986, 1990b). These theories rest on spillovers of benefits that appear as productivity growth within a classification of the sources of economic growth. Externalities have become relatively less important during the period of our study. This has increased, not reduced, the explanatory power of the new version of the neoclassical theory of economic growth that we have outlined.

At this point the identification of the externalities that have contributed to past economic growth in the G7 countries is only a matter for speculation. However, a broader concept of investment is urgently required as a guide for a forward-looking growth strategy. Government policies for channeling externalities must be replaced by assignments of property rights and the design of appropriate price systems for decentralizing investment decisions among participants in the private sector. This strategy will require careful attention to the incentives facing investors in tangible assets, human capital, and intellectual property.

Appendix A: Data Sources

A.1 Canada

Data on nominal and real Canadian GDP, general government output, and subsidies are available in the National Income and Expenditure Accounts (NIEA) from Statistics Canada. Labor hours and employment are available from a number of sources, including the Census, Labor Force Survey, the Input-Output Division and the Labor Force Historical Review. The labor compensation shares by sex and educational attainment are calculated by using data of wage and salary income per employed person for Census years; non-Census years estimates are obtained by interpolation. Capital stock data are available in the NIEA and the Financial Flows Section of National Balance Sheet Accounts.

A.2 France

Data on nominal and real GDP, general government output, indirect taxes, and subsidies are available in De Compte Nationaux, Le Mouvement Economique en France (for 1949–1979), and Compte et Indicateurs Economiques 1996, published by Institut National de la Statistique et des Etudes Economiques (INSEE). Data on employment by sex and educational attainment level are available in the annual Enquete de l'Emploi and Population Active, Emploi et Chomage Depuis 30 Ans, both published by INSEE. Data on average workweeks and weekly hours worked by sex and employment status are again available in Eurostats Labour Force Sample Survey for earlier years and upon special request from Eurostats for 1985 onwards. French Economic Growth by Carre, Dubois and Malinvaud provides data on annual hours worked in the 1960s. As for labor compensation shares, the French Survey of Employment, the Enquete sur la Formation et la Qualification Professionnelle, De Compte Nationaux, Le Mouvement Economique en France contains data on wages and salaries for various categories. French capital stock data can be obtained from INSEE publication Comptes de Patrimoine, De Compte Nationaux, Comptes et Indicateurs Economiques and the OECD National Accounts, volume 2. Consumer durable expenditure can be obtained in a separate account, the INSEE publication La Consommation des Menages.

A.3 Germany

Data on nominal and real GDP, general government output, indirect taxes, and subsidies are available in the Volkswirtschafliche Gesamtrechnungen (VGR) and Statistisches Jahrbuch. Employment data can be obtained from VGR, Beruf, Ausbildung und Arbeitsbedingungen (for some recent years), Wirtschaft und Statistik, and Stand und Entwicklung der Erwerbstätigkeit, which contains the annual results of the German Microcensus, a household survey similar to the U.S. Current Population Survey. Labor income are available through the Luxembourg Income Study (LIS). Most capital stock series can be found in VGR, whereas consumer durable expenditure on various categories are obtained in Einkommen und Verbrauchsstichprobe and the laufende Wirtschaftsrechnungen.

A.4 Italy

Data on nominal and real GDP, general government output, indirect taxes, and subsidies are available in the Annuario di Contabilita Nazionale, the Conti Economici Nazionali. Employment data are available in Statistiche del Lavoro and the Rilevazione delle Forze di Lavoro. Labor hours can also be found in the Rilevazione di Lavoro, which also provides data as well as from the Eurostats. The census publication Censimenti contains employment and hours data in five categories for the years 1961, 1971, 1981 and 1991. Labor compensation data are again obtained by Luxembourg Income Study. Capital stock data are available through the Italian business association, Confindustria, in a study carried out by Alberto Heimler; Gennaro Zezza of the Centro Studi Confindustria supplied estimates of total business inventories in 1985 prices.

A.5 Japan

Data on nominal and real GDP, general government output, indirect taxes, and subsidies are available from the National Economic Accounts, published by the Economic Planning Agency. The sources of data for the number of workers and employees are the Population Census of Japan, Report on the Labor Force Survey, and the Basic Survey on Wage Structures. Masahiro Kuroda of Keio University supplied the capital stock data.

A.6 United Kingdom

Data on nominal and real GDP, general government output, indirect taxes, and subsidies are available in the Blue Book published by the Central Statistical Office (CSO). Employment by sex and employment status are available in the Employment Gazette, Historical Supplement No. 2 and Employment and Earning published by the U.K. Department of Employment, and by special request from Quantime, a subsidiary of SPSS. Data on total general government employment are available in Economic Trends, published by CSO. Data on average workweeks and weekly hours worked by sex and employment status are available in Eurostats Labour Force Sample Survey for earlier years and upon special request from Eurostats for 1985 onwards. General Household Survey provides data in labor income that can be used in calculating labor shares. Capital stock data are available in the Blue Book with the exception of data on land, which is taken from Annual Abstract of Statistics and Inland Revenue Statistics.

A.7 United States

Data on nominal and real GDP, general government output, indirect taxes, and subsidies are available in the U.S. National Income and Product Accounts, published by the Bureau of Economic Analysis. Labor hours and employment are available from the Census of Population and the Current Population Survey, published by the Bureau of the Census. The labor compensation shares by sex and educational attainment are calculated by adding estimates of fringe benefits to data on wage and salary income per employed person from the Census. Capital stock data are available from the Capital Stock Study of the Bureau of Economic Analysis and the National Balance Sheet, published by the Board of Governors of the Federal Reserve System. Further details are given by Jorgenson (1990b).

A.8 Other Data Sources

Data on investment tax credits and average marginal corporate tax rates for Canada, United Kingdom, France, Germany and Italy are available in the data set supplied by Julian Alworth. The Institute for Fiscal Studies also provides estimates of statutory rates, and net present value of allowances for buildings and producer durable equipment for 1979 to 1994 in their recent publication Taxing Profits in a Changing World. The OECD publication Labour Force Statistics, contains data on population from 1976 to 1996. Dougherty (1992) provides further details.

Notes

1. Zvi Griliches (1992, 1995) has provided detailed surveys of spillovers from R&D investment. Griliches (1992) gives a list of survey papers on spillovers.

2. The measurement conventions of Kuznets and Solow remain in common use. See, for example, Robert Hall and Charles Jones (1999) and the references given by Jorgenson (1990b).

3. Jorgenson and Griliches (1967, table 9, p. 272).

4. Constant quality indexes of labor input are discussed in detail by Jorgenson, Frank Gollop, and Barbara Fraumeni (1987), chapters 3 and 8, pp. 69–108 and 261-300; Bureau of Labor Statistics (1993), and Mun-Sing Ho and Jorgenson (1999).

5. Detailed surveys of empirical research on the measurement of capital input are given by Jorgenson (1996) and Jack Triplett (1996b). BLS (1983a) compiled a constant quality index of capital input for its official estimates of productivity, renamed as multifactor productivity. BLS retained hours worked as a measure of labor input until July 11, 1994, when it released a new multifactor productivity measure incorporating a constant quality index of labor input.

6. See Bureau of Economic Analysis (BEA; 1995).

7. The United Nations System of National Accounts (SNA) is summarized by Stone (1992) in his Nobel Prize address. The SNA has been revised by the Inter-Secretariat Working Group on National Accounts (1993).

8. Constant quality price indexes for investment goods of different ages or vintages were developed by Hall (1971). This made it possible for Charles Hulten and Frank Wykoff (1981c) to estimate relative efficiencies by age for all types of tangible assets, putting the measurement of capital consumption required for constant quality index of capital input onto a firm empirical foundation. The BEA (1995) has adopted this approach in the latest benchmark revision of the U.S. National Income and Product Accounts, following methodology described by Fraumeni (1997).

9. See Samuelson (1961), especially p. 309.

10. Dougherty and Jorgenson (1996, 1997) have updated the estimates of Christensen, Cummings, and Jorgenson (1980, 1981) through 1989.

11. Our methodology is described in detail by Dougherty (1992).

12. See Denison (1967), especially chapter 21, "The Sources of Growth and the Contrast between Europe and the United States," pp. 296–348.

13. Maddison added Austria and Finland to Kuznets' list and presented growth rates covering periods beginning as early as 1820 and extending through 1979. Maddison (1991, 1995) has extended these estimates through 1992.

14. For details see Maddison (1982, 159-168). Purchasing power parities were first measured for industrialized countries by Gilbert and Kravis (1954) and Gilbert (1958).

15. A complete list through Mark-5 is given by Summers and Heston (1991), while the results of Mark-6 are summarized by the World Bank in the *World Development Report 1993*.

16. This growth regression has spawned a vast literature, summarized by Ross Levine and David Renelt (1992); Baumol (1994); and Robert Barro and Xavier Sala-i-Martin (1994). Much of this literature has been based on successive versions of the Penn World Table.

17. Unfortunately, this Mark-3 data set did not include capital input. Paul Romer's empirical finding has spawned a substantial theoretical literature, summarized at an early stage by Robert Lucas (1988) and, more recently, by Gene Grossman and Elhanan Helpman (1991, 1994), Paul Romer (1994); Barro and Sala-i-Martin (1994); and Philippe Aghion and Peter Howitt (1998). Romer's own important contributions to this literature have focused on increasing returns to scale, as in Paul Romer (1986), and spillovers from technological change, as in Paul Romer (1990b).

18. For more detailed discussion, see Jorgenson and Fraumeni (1989).

19. Our terminology follows that of Becker's (1965, 1993) theory of time allocation.

6

Tax Reform and the Cost of Capital

Dale W. Jorgenson

6.1 Introduction

Since the early 1980s, the taxation of income from capital in industrialized countries has undergone a surprising series of reversals. The 1980s began with a gradual shift from income to expenditure as the basis for taxation of capital income. At the corporate level the objective was to provide investment incentives, while at the personal level the goal was to stimulate saving. Earlier, three landmark reports in Sweden, the United Kingdom, and the United States had proposed taking these developments to their logical conclusion by substituting expenditure for income as a basis for taxation at both corporate and personal levels.[1]

The initial step in providing tax incentives for investment was to accelerate capital consumption allowances by permitting taxpayers to write off investment outlays against income more quickly. The ultimate manifestation of this approach was to treat investment expenditures symmetrically with outlays on current account by allowing immediate expensing of investment. An alternative approach was to offset tax liabilities by subsidies or grants for investment. In the United States this took the form of an investment tax credit, that is, a credit against tax liabilities in proportion to investment expenditures.

In order to stimulate saving through tax policy, taxpayers were permitted to establish tax-favored or tax-free accounts. These were usually for specific purposes, such as the accumulation of funds to finance a period of retirement. By allowing contributions to these accounts as deductions from income for tax purposes and postponing taxation until funds are withdrawn, the base for the personal income tax was shifted from income toward expenditure. In the United States these accounts took the form of pension funds for corporate and noncorporate businesses and individual retirement accounts (IRAs).

The reversal in tax policies for capital income during the 1980s is best illustrated by the experience of the United States. When the administration of President Ronald Reagan took office in January 1981, there was widespread concern about the slowdown of United States economic growth. Tax reform proposals by the Reagan administration received overwhelming support from Congress with the enactment of the Economic Recovery Tax Act of 1981. The 1981 tax act combined substantial reductions in statutory tax rates for persons and corporations with sizable enhancements in investment incentives.[2]

Beginning with the introduction of accelerated depreciation in 1954 and the investment tax credit in 1962, United States tax policy had incorporated a series of progressively more elaborate tax preferences for specific forms of capital income. The tax act of 1981 brought this development to its highest point with adoption of the accelerated cost recovery system and the introduction of a 10 percent investment tax credit. With these provisions the 1981 tax act totally severed the connection between the economic concept of depreciation and capital cost recovery for tax purposes.

The tax reforms of the early 1980s substantially reduced the burden of taxation on capital income. However, these policy changes also heightened the discrepancies among tax burdens borne by different types of capital. These discrepancies gave rise to concerns in Congress about the impact of tax-induced distortions on the efficiency of capital allocation. In his State of the Union address in January 1984 President Reagan announced that he had requested a plan for further reform from the Department of the Treasury, setting off a lengthy debate that eventuated in the Tax Reform Act of 1986.[3]

The 1986 tax act represented an abrupt change in the direction of United States policy for taxation of income from capital. Statutory tax rates were lowered as in 1981, but the tax base was broadened by wholesale elimination of tax preferences for both persons and corporations. This included sharp cutbacks in tax incentives for investment. The 1986 tax act repealed the 10 percent investment tax credit for property placed in service after December 31, 1985. In addition, accelerated capital consumption allowances were substantially scaled back.

During the 1980s the taxation of income from capital in United Kingdom underwent a similar reversal. In 1981 immediate expensing of 75 percent of investment in industrial buildings and structures was introduced, bringing the tax treatment of these investments more closely into line with 100 percent expensing of manufacturing plant and machinery, previously incorporated into United Kingdom tax law. In 1983 the corporate tax rate was lowered from 52 to 50 percent. Mervyn A. King and Don Fullerton have described these developments as a continuation of a gradual movement toward a tax system based on expenditure rather than income.[4]

The United Kingdom budget of 1984 phased out 100 percent expensing of plant and machinery and 75 percent expensing of industrial buildings and structures in the United Kingdom over a three-year period. This significantly broadened the base for income taxes, especially at the corporate level. The corporate tax rate was reduced to 45 percent in 1984, 40 percent in 1985, and, finally, 35 percent in 1986. In 1988 the top personal tax rate was abruptly reduced from 60 to 40 percent. As in the United States, the United Kingdom reforms employed the revenues generated by base-broadening to reduce corporate and personal tax rates.

The United Kingdom budget for 1984 and the United States Tax Reform Act of 1986 arrested the erosion of the income tax base in the two countries by curtailing investment incentives and broadening the base for income taxes. Capital consumption allowances were brought back into line with economic depreciation, thereby leveling the playing field for income from different assets. The additional revenues generated by base-broadening were used to reduce statutory tax rates at the corporate and personal levels. These rate reductions were intended to reduce distortions in resource allocation.[5]

The provisions for capital cost recovery in the United Kingdom budget of 1984 and the United States Tax Reform Act of 1986 reflected a new conceptual framework for the analysis of capital income taxation. This framework had its origins in two concepts introduced in the 1960s—the effective tax rate, pioneered by Harberger (1962, 1966), and the cost of capital, originated by Jorgenson (1963, 1965). The cost of capital and the effective tax rate were combined in the marginal effective tax rate introduced by Auerbach and Jorgenson (1980).[6]

Widespread applications of the cost of capital and the closely related concept of the marginal effective tax rate are due to the fact that these concepts facilitate the representation of the economically relevant features of highly complex tax statutes in a very succinct form. This has greatly enhanced the transparency of tax rules related to investment incentives. The cost of capital summarizes the information about the future consequences of investment decisions that is essential for current decisions about capital allocation. The marginal effective tax rate characterizes the tax consequences of investment decisions in a way that is particularly suitable for comparisons among alternative tax policies.

Auerbach and Jorgenson used marginal effective tax rates to expose differences in the tax treatment of income from different types of capital in the 1981 tax act. Marginal effective tax rates under the 1981 tax act were presented for all types of assets and all industries by Jorgenson and Sullivan (1981). Subsequently, these effective tax rates helped frame the debate over alternative proposals that led to the Tax Reform Act of 1986. An important objective of tax reform was to level the playing field by equalizing marginal effective tax rates on different forms of capital income.[7]

In this chapter we present an international comparison of tax reforms for capital income over the period 1980–1990. Comparisons are provided among the "Group of Seven" (or "G7") countries—Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States—together with Australia and Sweden, nine countries in all.[8] The empirical framework for these comparisons is provided by marginal effective tax rates for different types of capital income in all nine countries for the years 1980, 1985, and 1990. The measurements of marginal effective tax rates are based on the methodology developed by King and Fullerton (1984).

Previous international comparisons of marginal effective tax rates have been focused on a single point in time. For example, King and Fullerton (1984) have given marginal effective tax rates for four countries—Sweden, the United Kingdom, the United States, and West Germany—for 1980. They present separate measurements of effective tax rates for eighty-one different types of projects within each of the four countries. These projects are classified by type of asset, industry, source of finance, and owner; three categories are distinguished within each of these classifications. However, comparisons are limited to capital income generated within the corporate sector of each country.[9]

More extensive sets of international comparisons of marginal effective tax rates have been given by the Organization for Economic Cooperation and Development (1991) for twenty-four OECD member countries and by the Commission of the European Communities (CEC) (1992) for the European Community member states as of January 1, 1991. The OECD study is limited to the manufacturing sector of each country and classifies investment projects only by type of asset and source of finance. However, this study also provides a very important extension of the conceptual framework of King and Fullerton by incorporating complex provisions for taxation of capital income of nonresidents and taxation of foreign-source income of residents.[10] The study develops effective tax rates for savers in each OECD country with investments in the manufacturing industry of each other OECD country. The CEC report adopts the same methodology used in the OECD study.

We extend the international comparisons of effective tax rates for four countries for 1980 given by King and Fullerton to all nine countries included in our study for all three years—1980, 1985, and 1990. Comparisons among the time periods for each country provide the information needed to analyze successive reforms of tax policy for capital income. For capital income originating in the corporate sector we divide the tax burden between components attributable to corporate and personal income taxes. This important extension of the King-Fullerton framework makes it possible to identify sources of differences in effective tax rates.

For example, the tax base for the corporate income tax depends on provisions for capital cost recovery, while the tax base for the personal income tax depends on the tax treatment of corporate distributions of capital income in the form of dividends, interest, and capital gains or losses. To analyze the impact of changing tax incentives for investment, the corporate income tax is the appropriate focus. To study the effects of alterations in incentives to save, attention must be concentrated on the personal income tax. Of course, consideration of both levels of the tax structure are required to provide an appropriate basis for assessing the economic impact of the corporate income tax.

Whereas King and Fullerton (1984) and the OECD (1991) study limit international comparisons of effective tax rates to income generated in the corporate sector, in this chapter we also present effective tax rates for the noncorporate sector and owner-occupied housing. This information is essential for comparisons of the taxation of income originating in the corporate sector with taxation of noncorporate enterprises and income generated from owner-occupied housing. Since the corporate tax is not levied on noncorporate income or income from owner-occupied housing, this tax leads to underallocation of capital to the corporate sector.

In the appendix to this chapter we review the King-Fullerton framework and its extensions. I define a tax wedge as the difference between the remuneration of capital before taxes, which corresponds to the marginal product of capital, and the compensation after taxes available to holders of financial claims on the firm. The effective tax rate is the ratio of the tax wedge to the marginal product. The cost of capital is the key to measuring the tax wedge. For income originating in the corporate sector this wedge depends on provisions of both corporate and personal income taxes. The cost of capital incorporates statutory tax rates and definitions of the tax bases at both levels of taxation.

I extend the King-Fullerton framework by expressing the tax wedge as the sum of corporate and personal tax wedges. I define a marginal effective corporate tax rate as the ratio of the corporate tax wedge to the marginal product of capital. Similarly, I define a marginal effective personal tax rate as the ratio of the personal tax wedge to the rate of return to capital after the corporate tax. The corporate tax rate reflects differences between rates of remuneration to capital before and after corporate taxes, while the personal tax rate on corporate source income is based on rates of compensation before and after personal taxes.

I also extend the King-Fullerton framework to encompass the taxation of capital income in the noncorporate sector and owner-occupied housing.[11] Capital income of noncorporate enterprises is subject to taxation at the personal level, but not the corporate level. Except in Italy, income from owner-occupied housing is not included in the tax base for either personal or corporate income taxes. However, these two types of income, as well as corporate income, are subject to taxation through property and wealth taxes.

In the section that follows I present a detailed international comparison of marginal effective tax rates for 1980, 1985, and 1990 for all nine countries included in our study. I find that changes in tax policy for capital income in many countries took similar directions to those outlined above for the United Kingdom and the United States. Base-broadening through elimination of investment incentives and rate reductions are nearly universal. This has resulted in a leveling of the playing field for different forms of assets. However, wide gaps among tax rates remain in all countries included in our study, so that many important opportunities remain for further tax reform.

The King-Fullerton approach has been the subject of an extensive critical literature, dealing with the empirical implications of specific assumptions incorporated into the cost of capital. The most important of these assumptions is the adoption of the "new" view of taxation and corporate finance introduced by King (1974a, 1974b, 1977). This can be contrasted with the "traditional" view employed in the literature on corporate finance. The international comparisons presented in this section, like those of King and Fullerton (1984), present results only for the new view of the corporate tax.

I then compare alternative approaches to measurement of the cost of capital and marginal effective tax rates. I first review the empirical evidence on the validity of new and traditional views of the corporate income tax. Jorgenson and Kun-Young Yun (1991b) have provided a detailed alternative to the King-Fullerton framework, based on the traditional view. They have used this framework in analyzing tax reforms in the United States since 1947 by compiling marginal effective tax rates on an annual basis. They have also presented a comparison of marginal effective tax rates under alternative tax reform proposals considered in the debate that preceded the Tax Reform Act of 1986.[12]

Statutory tax rates and definitions of capital income for tax purposes provide only part of the information needed to measure the cost of capital. In addition, estimates of economic depreciation are needed to incorporate the impact of tax provisions for capital cost recovery. This requires extensive empirical research on the relationship of asset prices to the age of assets. Since income tax bases are not insulated from the effects of inflation, the rate of inflation must also be taken into account in measuring the cost of capital. In the discussion of alternative approaches I summarize the empirical literature on the effects of depreciation and inflation on the cost of capital.

In my summary and conclusion I evaluate the cost of capital approach to tax policy analysis. This approach has amply proved its usefulness as a guide to tax reform. For example, while the United States tax policy changes of the early 1980s introduced additional obstacles to efficient capital allocation, the Tax Reform Act of 1986 reduced these obstacles substantially. However, significant discrepancies remain between effective tax rates on income generated by owner-occupied housing and income from corporate and noncorporate enterprises. These discrepancies present the most important opportunities for increasing the efficiency of capital allocation.[13]

The cost of capital has also become an indispensable analytical tool for studies of the economic impact of changes in tax policies for the taxation of capital income. These studies have taken two forms. First, the cost of capital has been incorporated into the investment functions used in standard macroeconometric models. These models are useful in modeling the short-run dynamics of an economy's response to changes in tax policy. More recently, the cost of capital has been incorporated into applied general equilibrium models that focus on the impact of tax policy on the allocation of capital. These models are essential for capturing the long-run effects of tax reforms.

6.2 International Comparisons

In this section I present a detailed international comparison of marginal effective tax rates for 1980, 1985, and 1990 for the nine countries studied in this volume—Australia, Canada, France, Germany, Italy, Japan, Sweden, the United Kingdom, and the United States. These effective tax rates are based on the elaborations of the King-Fullerton methodology outlined in the preceding section. Differences among the nine countries in overall effective tax rates at corporate and personal levels for income originating in the corporate sector are considered. Changes in these tax rates over the period 1980–1990 are also considered as a means of analyzing the consequences of tax reforms in each country.

King and Fullerton (1984) have shown that effective tax rates for the four countries—Sweden, the United Kingdom, the United States, and West Germany—included in their study for 1980 were very sensitive to rates of inflation.[14] The tax bases for corporate and personal income taxes in these four countries were not fully indexed for inflation in 1980. None of the nine countries included in our study for the years 1980, 1985, and 1990 has adopted complete indexation of corporate and personal income tax bases for inflation. To reduce the complexity of international comparisons and the analysis of tax policy changes for individual countries for 1980–1990, our estimates of marginal effective tax rates are based on a rate of inflation of five percent.

Marginal effective corporate tax rates provide the information required for a comparison of incentives to invest in different types of assets and different industries. Differences among these tax rates indicate barriers to efficient allocation of capital among assets and industries, since corporations equalize rates of return *after* corporate taxes. However, efficient allocation of corporate capital requires equal rates of return *before* corporate taxes. Similarly, marginal effective personal tax rates on income originating in the corporate sector are needed to compare incentives for saving through different financial instruments and different forms of ownership. Differences among these tax rates indicate barriers to efficient allocation of capital among financial instruments and different forms of ownership.

The next step is to compare marginal effective tax rates for income originating in the corporate sector with tax rates for noncorporate enterprises and owner-occupied housing. These comparisons are essential for assessing the economic impact of the corporate income tax. Savers equalize rates of return *after* both corporate and personal taxes, but efficient allocation of capital among corporate enterprises, noncorporate enterprises, and owner-occupied housing requires that rates of return *before* taxes must be equalized among the three sectors.

The final step is to compare marginal effective tax rates by type of asset, industry, source of finance, and form of ownership. I provide these comparisons for effective corporate and personal tax rates on income originating in the corporate sector. For comparisons among tax rates on noncorporate income, only the type of asset, industry, and debt-versus-equity sources of finance are relevant, since noncorporate enterprises are owned by households. Similarly, only debt and equity finance are relevant for comparisons among tax rates for owner-occupied housing.

Table 6.1 gives marginal effective corporate tax rates for 1980, 1985, and 1990 for all nine countries included in our study. In 1980 these tax rates were negative for four of the nine countries—France, Italy, Sweden, and the United Kingdom. Effective corporate tax rates were substantially below statutory rates for all nine countries. For example, the statutory corporate tax rate for the United States was 46 percent, while the effective rate was only 14.4 percent. This reflects investment incentives included in provisions for capital recovery under the corporate income tax. Australia had the highest corporate tax rate at 41.8 percent, while Italy had the lowest at a negative 91.6 percent, so that the gap between tax rates for the two countries was a stunning 133.4 percent!

In 1985 marginal effective corporate tax rates were negative for France, Italy, and Sweden. The most significant change in the taxation of corporate income between 1980 and 1985 was for the United Kingdom, which underwent a sharp reversal in tax policy with the budget of 1984, described by King and Robson (1993). The corporate tax rate in the United Kingdom jumped from a negative 31.4 percent in 1980, lower than for any other country except Italy, to a positive 21.4 percent in 1985, the highest among all nine countries. The gap between the United Kingdom and Italy, the countries with the highest and lowest tax rates in 1985, was 116.8 percent, a modest decrease from 1980. Sweden and Canada instituted increases in corporate tax rates between 1980 and 1985, while tax rates declined for the remaining six countries. The largest decline was from 41.8 percent in 1980 to 17.0 percent in 1985 for Australia. This reflected the substantial enhancement of investment incentives, described by Robert Jones (1993).

In 1990 only France and Italy retained negative marginal effective corporate tax rates. The corporate tax rate for Italy rose from a negative 95.4 percent in 1985 to a negative 72.8 percent in 1990, still the lowest level

Table 6.1
Marginal effective corporate tax rates, nine countries, 1980, 1985, 1990

Item	Australia	Canada	France	Germany	Italy	Japan	Sweden	United Kingdom	United States
					1980				
Asset									
Machinery	28.1	4.3	−42.1	15.2	−101.1	2.6	−54.4	−67.0	−12.0
Buildings	46.4	30.3	−42.2	9.3	−90.5	0.5	−9.3	20.4	19.1
Inventories	55.7	20.6	−5.2	23.9	−79.4	5.7	−5.6	−34.2	28.5
Industry									
Manufacturing	41.4	10.3	−30.3	16.2	−94.4	7.6	−19.7	−53.3	33.8
Other industry	33.3	25.6	−23.1	28.1	−87.8	−8.8	−28.6	−24.2	−13.7
Commerce	44.1	19.2	−36.6	7.6	−88.4	7.0	−25.9	12.7	15.5
Source of finance									
Debt	−22.2	−25.0	−46.9	−46.0	−104.5	−70.6	−59.5	−157.8	−49.2
New share issues	57.0	44.7	−29.6	52.4	−13.9	54.5	−6.5	−61.2	47.1
Retained earnings	57.1	44.7	−13.7	83.0	−82.4	57.0	19.0	2.3	45.6
Owner									
Households	37.0	19.2	−30.3	16.0	−91.5	0.7	−14.1	−45.5	15.8
Tax-exempt institutions	49.4	10.7	−21.9	14.3	0.0	16.0	−34.8	−12.9	9.1
Insurance companies	52.9	−6.9	−17.0	9.7	−104.5	17.0	−15.2	−29.5	26.3
Overall tax rate	41.8	16.9	−28.8	15.2	−91.6	3.1	−22.5	−31.4	14.4
					1985				
Asset									
Machinery	−9.2	8.2	−58.3	11.5	−109.7	1.7	−14.2	−5.4	−18.6
Buildings	26.7	31.6	−37.9	−1.4	−92.1	−2.4	−1.5	43.9	12.2
Inventories	50.3	20.4	−3.1	23.9	−79.2	2.7	0.3	46.8	28.7
Industry									
Manufacturing	13.6	11.2	−35.3	11.1	−100.3	1.0	−0.9	14.7	27.5
Other industry	0.5	28.3	−26.6	21.9	−91.3	0.2	14.7	14.5	−16.7
Commerce	24.8	22.8	−40.1	1.3	−89.4	−0.5	−9.0	38.9	9.2

Table 6.1 (continued)

Item	Australia	Canada	France	Germany	Italy	Japan	Sweden	United Kingdom	United States
					1985 (continued)				
Source of finance									
Debt	−50.1	−20.5	−54.3	−53.6	−130.4	−82.5	−37.7	−36.8	−55.5
New share issues	41.9	45.2	12.5	48.2	−25.1	58.3	9.5	−10.1	43.0
Retained earnings	41.9	45.3	−17.8	80.1	−75.8	62.0	31.7	38.0	42.1
Owner									
Households	4.4	21.2	−34.8	10.6	−96.8	−6.9	1.7	14.9	9.5
Tax-exempt institutions	32.6	13.2	−21.8	8.8	−82.0	10.4	−15.1	30.1	2.4
Insurance companies	36.8	−3.4	−20.1	4.1	−85.8	27.3	1.7	22.2	25.1
Overall tax rate	17.0	19.0	−33.0	9.9	−-95.4	0.5	−5.0	21.4	9.2
					1990				
Asset									
Machinery	9.0	15.5	−48.1	11.5	−86.3	8.8	−11.3	8.0	18.5
Buildings	11.7	35.9	−45.8	1.6	−57.2	2.5	1.3	49.7	25.3
Inventories	27.5	30.7	−18.1	−0.3	−72.9	7.0	12.5	39.8	26.3
Industry									
Manufacturing	15.0	24.5	−37.3	5.2	−78.4	6.7	n.a.	24.8	34.0
Other industry	10.2	29.1	−33.5	19.7	−76.1	5.9	n.a.	21.2	11.7
Commerce	15.1	25.0	−28.7	−2.7	−64.8	5.2	n.a.	37.8	21.8
Source of finance									
Debt	−15.9	−6.3	−40.9	−55.0	−111.3	−74.6	−19.0	−15.9	−14.7
New share issues	−15.9	47.2	9.1	46.7	−14.2	70.9	5.8	4.1	44.1
Retained earnings	48.8	47.3	−30.0	69.4	−51.1	62.8	23.2	40.5	43.7
Owner									
Households	3.3	26.9	−33.9	5.3	−74.3	−1.2	4.8	23.1	23.6
Tax-exempt institutions	25.0	20.2	−29.8	3.7	−59.2	14.3	−4.8	34.5	19.3
Insurance companies	27.4	31.1	−29.1	−0.8	−69.5	30.7	5.0	28.7	40.9
Overall tax rate	14.6	25.9	−33.4	4.6	−72.8	6.1	1.0	28.0	24.0

Source: Data drawn from the chapters in this volume.
n.a.: not available.

among the nine countries included in our study. Canada, Japan, Sweden, the United Kingdom, and the United States also raised corporate tax rates. As in 1985, the United Kingdom had the highest rate at 28.0 percent. The gap between Italy and the United Kingdom was 100.8 percent, a further modest decrease from 1980 and 1985. From 1980 to 1990, increases in corporate tax rates predominated slightly over declines.

The reduction of the corporate tax rate in the 1981 tax act in the United States was reversed by a substantial increase in the Tax Reform Act of 1986. This was the consequence of cutbacks in investment incentives described by Fullerton and Karayannis (1993). Parallel reductions in investment incentives in Canada, described by Daly, Mercier, and Schweitzer (1993), were partly offset by a reduction in the statutory corporate tax rate. Effective corporate tax rates in the United States and Canada rose from 9.2 to 24.0 and 19 to 25.9 percent, respectively, between 1985 and 1990.

Table 6.2 gives marginal effective personal tax rates on corporate source income for all nine countries included in our study. In 1980 France had the highest personal tax rate at 74.1 percent, while Japan had the lowest at 15.6 percent. The gap between the two was 58.5 percent. In 1985 personal tax rates were the highest for the three countries with negative corporate tax rates—France, Italy, and Sweden. Australia lowered the personal tax rate from 23.4 to 18.7 percent, while the United States lowered this rate from 22.5 to 18.7 percent. France retained the highest personal tax rate, raising this rate slightly from 74.1 to 75.2 percent. The gap between France and Japan, the country with the lowest rate at 16.3 percent, was 58.9 percent, almost the same as in 1980.

In 1990 marginal effective personal tax rates were, once again, highest for France and Italy, the only remaining countries with negative effective corporate tax rates. France lowered this rate from 75.2 to 65.4 percent, again retaining the highest rate. Between 1985 and 1990 Sweden reduced the personal tax rate substantially from 37 to 27.8 percent, while the United Kingdom became the country with the lowest rate by reducing this rate from 17.2 to 13.8 percent. The gap between the highest and lowest rates was 51.6 percent, a decline from 1985. Canada, Germany, and Italy slightly reduced the personal tax rate, while Australia, Japan, and the United States increased this rate. Tax reductions predominated over increases from 1985 to 1990.

The next step is to compare marginal effective tax rates for corporate source income with effective tax rates for the noncorporate sector and owner-occupied housing. For this purpose I first combine corporate and personal tax rates into a tax rate on corporate source income in table 6.3. In 1980 Australia and France had the highest tax rates for corporate source income at 55.4 and 66.6 percent, respectively, while the United Kingdom had the lowest rate at 8.9 percent. The result was a difference between the highest and lowest rates of 57.7 percent.

Between 1980 and 1985 France slightly raised the marginal effective tax rate on corporate source income from 66.6 to 67.0 percent, while Australia cut this rate sharply from 55.4 to 32.5 percent. The United Kingdom raised the tax rate on corporate source income from 8.9 to 34.9 percent, whereas Japan reduced this rate from 18.2 to 16.7 percent, in the process replacing the United Kingdom as the country with the lowest tax rate. The gap between the highest and lowest tax rates narrowed modestly from 57.7 to 50.3 percent. Germany and the United States also lowered the tax rate on corporate source income, whereas Canada, Italy, and Sweden raised it. Overall, no trend in tax rates on corporate source income is discernible from the results presented in table 6.3 for 1980 and 1985.

Changes in marginal effective tax rates on corporate source income between 1985 and 1990 also revealed no trend. Despite the adoption of a full imputation scheme for corporate income taxation by Australia, the tax rate actually rose from 32.5 to 38.6 percent. Integration of the corporate and personal income tax was offset by the elimination of investment incentives described by Jones (1993). Canada, Italy, Japan, the United Kingdom, and the United States also raised these rates, while France, Germany, and Sweden lowered them. Australia, Japan, and the United States lowered the rates between 1980 and 1985 and raised them between 1985 and 1990. France and Sweden raised rates between 1980 and 1985 and lowered them between 1985 and 1990. Canada, Italy, and the United Kingdom increased rates in both periods, while Germany lowered rates in both periods. I conclude that reversals of direction predominated over rate increases or decreases.

Table 6.4 gives marginal effective personal tax rates on income from noncorporate enterprises for all nine countries included in our study. In 1980 Germany and Italy had full imputation systems for corporate source income and gaps between effective tax rates on corporate source income and noncorporate income of 3.9 and 13.2 percent, respectively. Canada, France, Japan, Sweden and the United Kingdom had partial imputation systems for corporate source income. Only Canada had a higher tax rate for noncorporate income (36.3 percent) than for corporate income (33.5 percent). The gaps for France, Japan, Sweden, and the

Table 6.2
Marginal effective personal tax rates, nine countries, 1980, 1985, 1990

Item	Australia	Canada	France	Germany	Italy	Japan	Sweden	United Kingdom	United States
					1980				
Asset									
Machinery	20.4	21.4	70.4	32.8	57.3	15.7	34.5	35.9	22.6
Buildings	23.9	18.1	70.4	32.9	58.3	15.8	38.0	23.1	22.6
Inventories	26.9	20.1	82.7	33.0	60.2	15.3	40.9	31.3	22.3
Industry									
Manufacturing	23.4	20.0	73.6	33.0	58.0	15.0	31.8	33.9	21.8
Other industry	21.5	18.4	75.8	29.3	59.2	16.9	56.9	29.8	23.3
Commerce	23.8	21.4	71.9	33.4	59.2	15.2	39.1	24.2	23.8
Source of finance									
Debt	29.3	37.1	61.7	40.1	43.0	22.7	37.5	105.7	26.0
New share issues	51.4	10.4	81.4	19.8	87.5	25.0	70.8	50.7	53.0
Retained earnings	6.1	8.4	86.8	25.4	71.0	8.1	38.2	10.6	18.2
Owner									
Households	30.5	26.1	76.4	43.4	59.1	17.8	64.2	52.5	44.4
Tax-exempt institutions	0.0	0.0	72.7	7.4	0.0	0.9	0.0	0.0	−31.9
Insurance companies	33.9	−22.9	48.7	−9.9	−19.1	7.3	22.9	32.3	−17.2
Overall tax rate	23.4	20.0	74.1	32.9	58.5	15.6	37.9	30.7	22.5
					1985				
Asset									
Machinery	15.9	22.2	68.6	31.5	57.9	16.2	34.2	21.1	18.9
Buildings	18.8	19.1	73.8	31.5	60.1	16.5	37.1	13.9	18.8
Inventories	23.4	21.4	87.3	31.7	61.9	16.1	39.5	13.5	18.4
Industry									
Manufacturing	18.5	21.1	74.5	31.6	58.8	16.2	31.9	18.2	17.7
Other industry	16.9	19.3	77.4	28.4	60.4	16.4	53.2	18.3	19.8
Commerce	19.4	22.3	73.1	32.0	60.7	16.4	37.6	14.6	19.2

Table 6.2 (continued)

Item	Australia	Canada	France	Germany	Italy	Japan	Sweden	United Kingdom	United States
					1985 (continued)				
Source of finance									
Debt	29.3	39.5	61.2	37.9	43.5	23.6	34.6	62.8	23.6
New share issues	38.5	10.4	105.5	16.3	83.1	22.6	68.6	32.3	44.2
Retained earnings	6.3	8.3	89.3	24.9	71.6	9.3	39.5	4.8	14.0
Owner									
Households	26.1	27.3	77.6	41.0	62.5	19.3	62.5	28.4	36.5
Tax-exempt institutions	0.0	0.0	76.8	8.8	66.1	1.1	0.3	0.0	–25.3
Insurance companies	32.2	–22.9	39.0	–7.9	18.9	5.6	23.8	21.4	–13.6
Overall tax rate	18.7	20.9	75.2	31.5	59.7	16.3	37.0	17.2	18.7
					1990				
Asset									
Machinery	27.4	20.6	61.5	28.5	56.1	22.6	27.6	16.3	19.1
Buildings	27.6	17.7	62.1	28.6	61.1	23.4	27.8	11.0	19.1
Inventories	30.0	19.2	70.5	28.6	58.1	22.9	28.0	12.3	19.0
Industry									
Manufacturing	28.2	18.5	64.3	28.6	57.0	22.6	n.a.	14.2	18.8
Other industry	27.5	18.4	65.5	26.4	57.8	23.7	n.a.	14.6	19.4
Commerce	28.2	21.5	66.8	29.0	59.9	23.3	n.a.	12.5	19.2
Source of finance									
Debt	32.4	37.6	53.4	34.6	39.4	38.0	29.4	44.0	20.5
New share issues	40.6	24.9	92.4	7.4	83.7	20.0	42.9	22.3	35.7
Retained earnings	20.0	4.4	75.0	22.4	73.0	9.2	26.2	5.6	17.0
Owner									
Households	32.4	24.5	67.6	36.1	61.0	27.8	44.8	23.5	32.8
Tax-exempt institutions	12.7	0.0	67.4	11.5	69.2	1.0	10.0	0.0	–14.6
Insurance companies	47.7	–6.4	27.0	–5.2	23.5	5.4	24.4	14.5	–7.9
Overall tax rate	28.1	19.3	65.4	28.6	58.2	23.0	27.8	13.8	19.1

Source: Data drawn from the chapters in this volume.
n.a.: not available.

Table 6.3
Marginal effective tax rates on corporate source income, nine countries, 1980, 1985, 1990

Item	Australia	Canada	France	Germany	Italy	Japan	Sweden	United Kingdom	United States
					1980				
Asset									
Machinery	42.8	24.8	57.9	43.0	14.1	17.9	−1.1	−7.0	13.3
Buildings	59.2	42.9	57.9	39.1	20.6	16.2	32.2	38.8	37.4
Inventories	67.6	36.6	81.8	49.0	28.6	20.1	37.6	7.8	44.4
Industry									
Manufacturing	55.1	28.2	65.6	43.9	18.4	21.5	18.4	−1.3	48.2
Other industry	47.6	39.3	70.2	49.2	23.4	9.6	44.6	12.8	12.8
Commerce	57.4	36.5	61.6	38.5	23.1	21.1	23.3	33.8	35.6
Source of finance									
Debt	13.6	21.4	43.7	12.5	−16.6	−31.9	0.3	114.7	−10.4
New share issues	79.1	50.5	75.9	61.8	85.8	65.9	68.9	20.5	75.1
Retained earnings	59.7	49.3	85.0	87.3	47.1	60.5	49.9	12.7	55.5
Owner									
Households	56.2	40.3	69.2	52.5	21.7	18.4	59.2	30.9	53.2
Tax-exempt institutions	49.4	10.7	66.7	20.6	0.0	16.8	−34.8	−12.9	−19.9
Insurance companies	68.9	−31.4	40.0	0.8	−143.6	23.1	11.2	12.3	13.6
Overall tax rate	55.4	33.5	66.6	43.1	20.5	18.2	23.9	8.9	33.7
					1985				
Asset									
Machinery	8.2	28.6	50.3	39.4	11.7	17.6	24.9	16.8	3.8
Buildings	40.5	44.7	63.9	30.5	23.4	14.5	36.2	51.7	28.7
Inventories	61.9	37.4	86.9	48.0	31.7	18.4	39.7	54.0	41.8
Industry									
Manufacturing	29.6	29.9	65.5	39.2	17.5	17.0	31.3	30.2	40.3
Other industry	17.3	42.1	71.4	44.1	24.2	16.6	60.1	30.1	6.4
Commerce	39.4	40.0	62.3	32.9	25.6	16.0	32.0	47.8	26.6

Table 6.3 (continued)

Item	Australia	Canada	France	Germany	Italy	Japan	Sweden	United Kingdom	United States
					1985 (continued)				
Debt	−6.1	27.1	40.1	4.6	−30.2	−39.4	9.9	49.1	−18.8
New share issues	64.3	50.9	104.8	56.6	78.9	67.7	71.6	25.5	68.2
Retained earnings	45.6	49.8	87.4	85.1	50.1	65.5	58.7	41.0	50.2
Owner									
Households	29.4	42.7	69.8	47.3	26.2	13.7	63.1	39.1	42.5
Tax-exempt institutions	32.6	13.2	71.7	16.8	38.3	11.4	−14.8	30.1	−22.3
Insurance companies	57.2	−27.1	26.7	−3.5	−50.7	31.4	25.1	38.8	14.9
Overall tax rate	32.5	35.9	67.0	38.3	21.3	16.7	33.9	34.9	26.2
					1990				
Asset									
Machinery	33.9	32.9	43.0	36.7	18.2	29.4	19.4	23.0	34.1
Buildings	36.1	47.2	44.7	29.7	38.8	25.3	28.7	55.2	39.6
Inventories	49.3	44.0	65.2	28.4	27.6	28.3	37.0	47.2	40.3
Industry									
Manufacturing	39.0	38.5	51.0	32.3	23.3	27.8	n.a.	35.5	46.4
Other industry	34.9	42.1	53.9	40.9	25.7	28.2	n.a.	32.7	28.8
Commerce	39.0	41.1	57.3	27.1	33.9	27.3	n.a.	45.6	36.8
Source of finance									
Debt	21.7	33.7	34.3	−1.4	−28.0	−8.3	16.0	35.1	8.8
New share issues	31.2	60.3	93.1	50.6	81.4	76.7	46.2	25.5	64.1
Retained earnings	59.0	49.6	67.5	76.3	59.2	66.2	43.3	43.8	53.3
Owner									
Households	34.6	44.8	56.6	39.5	32.0	26.9	47.4	41.2	48.7
Tax-exempt institutions	34.5	20.2	57.7	14.8	51.0	15.2	5.7	34.5	7.5
Insurance companies	62.0	26.7	5.8	−6.0	−29.7	34.4	28.2	39.0	36.2
Overall tax rate	38.6	40.2	53.8	31.9	27.8	27.7	28.5	37.9	38.5

Source: Data drawn from the chapters in this volume.
n.a.: not available.

Table 6.4
Marginal effective noncorporate tax rates, nine countries, 1980, 1985, 1990

Item	Australia	Canada	France	Germany	Italy	Japan	Sweden	United Kingdom	United States
					1980				
Asset									
Machinery	31.1	25.8	47.5	36.2	−1.2	15.1	−55.7	0.0	−3.1
Buildings	46.1	47.0	47.7	37.4	8.5	14.6	14.9	19.5	22.6
Inventories	52.7	40.2	75.8	45.7	17.8	15.9	32.5	0.0	25.0
Industry									
Manufacturing	41.7	29.4	56.8	39.5	5.2	15.8	−8.8	n.a.	19.8
Other industry	35.1	41.5	61.9	45.5	10.2	13.6	19.1	n.a.	9.2
Commerce	43.8	42.6	52.3	36.2	9.8	16.0	−0.6	n.a.	23.3
Source of finance									
Debt	21.9	29.2	42.5	9.7	−25.6	1.6	−60.8	6.3	24.6
Equity	46.8	41.1	70.0	69.5	25.8	26.9	62.2	6.7	13.7
Overall tax rate	42.0	36.3	57.9	39.2	7.3	15.2	−2.0	6.5	17.4
					1985				
Asset									
Machinery	7.4	30.3	37.0	36.4	−4.4	15.6	−5.5	19.0	−8.8
Buildings	36.1	48.4	52.3	32.1	9.3	14.2	18.1	17.6	17.2
Inventories	54.6	42.5	78.6	48.3	18.8	15.7	40.0	60.4	22.8
Industry									
Manufacturing	26.4	31.8	54.0	38.4	2.7	14.9	15.7	n.a.	14.6
Other industry	13.7	44.5	61.6	43.4	9.7	16.1	25.7	n.a.	5.9
Commerce	33.7	46.2	49.9	34.2	11.4	14.9	17.2	n.a.	17.7
Source of finance									
Debt	4.8	34.9	40.6	7.3	−33.8	1.1	−42.3	31.4	20.7
Equity	37.0	42.1	68.2	69.4	29.4	27.4	83.6	33.2	8.6
Overall tax rate	28.2	39.2	56.1	37.9	6.6	15.1	17.8	32.3	12.7

Table 6.4 (continued)

Item	Australia	Canada	France	Germany	Italy	Japan	Sweden	United Kingdom	United States
					1990				
Asset									
Machinery	36.4	36.2	36.6	30.4	5.2	26.4	9.5	20.2	18.3
Buildings	38.3	51.9	40.1	26.1	27.7	23.7	27.2	29.8	23.7
Inventories	51.7	51.3	66.9	26.6	15.6	24.7	45.5	49.0	20.5
Industry									
Manufacturing	41.4	42.4	47.4	28.0	11.1	24.5	n.a.	n.a.	21.0
Other industry	37.4	45.7	52.9	35.2	13.2	26.9	n.a.	n.a.	21.6
Commerce	41.3	48.3	42.2	24.4	22.0	25.1	n.a.	n.a.	23.1
Source of finance									
Debt	21.9	43.1	26.7	−0.5	−25.7	18.4	3.9	32.1	29.6
Equity	50.2	46.1	65.6	56.8	39.0	31.0	53.3	33.7	17.7
Overall tax rate	41.0	44.9	48.5	27.7	15.6	25.1	27.6	32.9	21.7

Source: Data drawn from the chapters in this volume.
n.a.: not available.

United Kingdom were 8.7, 3, 25.9, and 2.4 percent, respectively. Australia and the United States had classical systems for corporate source income and gaps of 13.4 and 16.3 percent, respectively. Surprisingly, the integration of corporate and personal taxes for corporate source income was not closely correlated with differences between effective tax rates on corporate and noncorporate income. These differences indicate obstacles to efficient allocation of capital between corporate and noncorporate sectors.

Australia reduced the marginal effective tax rate for noncorporate income from 42.0 to 28.2 percent between 1980 and 1985, and Sweden increased this rate from a negative 2.0 percent to 17.8 percent. More modest declines took place in France, Germany, Italy, Japan, and the United States, while smaller increases occurred in Canada and the United Kingdom. Marginal effective tax rates on noncorporate income rose for seven of the nine countries between 1985 and 1990, with the greatest increase—from 28.2 to 41.0 percent—occurring in Australia.

During the period 1985–1990 Australia adopted the full imputation system for corporate source income described by Jones (1993), but sharply reduced investment incentives, raising the effective corporate tax rate from 32.5 to 38.6 percent, below the tax rate of 41.0 percent on noncorporate income. As pointed out by Tachibanaki and Kikutani (1993), Japan modified its split-rate system for corporate source income with a reduced corporate tax rate for distributed profits and abolished tax-free savings accounts. This increased the effective tax rate from 16.7 to 27.7 percent, still the lowest among the nine countries. Gaps between effective tax rates on corporate source income and noncorporate income narrowed for a substantial number of countries, primarily as a consequence of the elimination of investment incentives from provisions for capital recovery for noncorporate enterprises.

Table 6.5 gives marginal effective tax rates on owner-occupied housing. In 1980 all nine countries had substantial gaps between tax rates on corporate source income and owner-occupied housing. Japan had a negative effective tax rate of 29.9 percent on owner-occupied housing and a positive tax rate on corporate source income of 18.2 percent, resulting in a gap of 48.1 percent. This reflects the highly favorable tax treatment of owner-occupied housing in Japan described by Tachibanaki and Kikutani (1993). However, the largest gaps were for Australia at 53 percent and France at 64 percent, reflecting high tax rates on corporate source income for these countries. Only Italy and Sweden had tax rates for owner-occupied housing that exceeded the tax rates for noncorporate income.

Table 6.5
Marginal effective housing tax rates, nine countries, 1980, 1985, 1990

Item	Australia	Canada	France	Germany	Italy	Japan	Sweden	United Kingdom	United States
1980									
Method of finance									
Debt	31.5	51.2	0.3	29.0	0.7	−0.8	−96.1	0.0	8.5
Equity	0.0	10.7	6.0	−6.0	8.8	−16.2	36.4	0.0	15.0
Overall tax rate	2.4	15.4	2.6	11.5	8.4	−29.9	3.3	0.0	12.8
1985									
Method of finance									
Debt	34.8	56.1	0.5	32.0	0.7	−0.8	−39.2	0.0	6.4
Equity	4.6	12.3	5.0	−3.0	7.0	−16.2	44.2	0.0	14.5
Overall tax rate	7.0	17.4	2.3	14.5	6.6	−29.9	15.0	0.0	11.8
1990									
Method of finance									
Debt	35.5	61.0	0.6	27.0	0.5	0.1	7.0	0.0	5.2
Equity	8.8	18.0	4.5	−8.0	9.2	−29.5	43.9	0.0	14.1
Overall tax rate	11.0	23.0	2.2	9.5	8.4	−34.4	31.0	0.0	11.2

Marginal effective tax rates for owner-occupied housing in Sweden rose from 15.0 percent in 1985 to 31.0 percent in 1991, higher than effective rates on corporate and noncorporate income. This reflects the radical revamping of tax provisions for owner-occupied housing in the Swedish tax reform of 1991 described in detail by Södersten (1993). Smaller increases occurred in Australia, Canada, and Italy, while decreases took place in France, Germany, Japan, and the United States. Large differences remained between effective tax rates on corporate source income and income from owner-occupied housing in all countries except Sweden. These differences present much more formidable obstacles to efficient capital allocation than differences between effective tax rates on corporate and noncorporate income.

Despite the reversals in tax policy for corporate source income that characterized the period 1980–1990, many countries succeeded in narrowing the gap between marginal effective tax rates on corporate and noncorporate income. An effective strategy for equalizing these tax rates, successfully employed by Australia, was to eliminate investment incentives in both sectors while introducing partial or full imputation of corporate tax payments and income to corporate stockholders through the personal income tax. By itself, integration of corporate and personal income taxes was largely ineffective in eliminating differences between tax rates for corporate and noncorporate income. This is an implication of the "new" view of the corporate taxation discussed in more detail later in this chapter under "Alternative Approaches."

Sweden was the only country that succeeded in eliminating the differences between marginal effective tax rates on corporate source income and owner-occupied housing. The most straightforward approach to this problem is to include an imputation for income from owner-occupied housing in the personal income tax base. In practice such an imputation is vulnerable to political pressures from homeowners and is usually reduced far below the value of income generated by housing. As Alworth and Castellucci (1993) point out, only Italy has retained this approach. The Swedish tax reform of 1991 described by Södersten (1993) replaced the imputation of housing income by a nondeductible property tax on housing. In addition, the Swedish value-added tax (VAT) was broadened to include investment expenditures on housing. The reduction in statutory corporate and personal tax rates also helped to eliminate the gap between tax rates on corporate income and housing.

Differences among marginal effective tax rates on corporate source income, noncorporate income, and owner-occupied housing constituted substantial barriers to efficient allocation of capital for the countries included in our study, except for Sweden. Despite the predominance of reversals of changes in tax rates over the period 1980–1990, modest progress was made in reducing these barriers. However, an important limitation of our study is the omission from consideration of special tax treatment of investments in favored regions. Although many of these special provisions were reduced or eliminated during the period 1980–1990, Germany is an important exception. A new system of special tax incentives, described in detail by Leibfritz (1993), was instituted in 1990 for investment in former East Germany.

The third and final step is to compare marginal effective tax rates for different types of investments. We focus on corporate tax rates for different assets and industries, since provisions for capital recovery under the corporate income tax are the most important source of differences in tax rates by type of asset and industry. The tax treatment of corporate distributions under both corporate and personal income taxes is important in analyzing differences among financial instruments and ownership forms. For example, tax deductibility of interest at the corporate level must be weighed against personal taxation of interest payments.

Table 6.1 gives marginal effective corporate tax rates for 1980, 1985, and 1990 by type of asset and industry. In 1980 machinery was the most favorably treated type of asset for Australia, Canada, Italy, Sweden, the United Kingdom., and the United States, while inventories were the least favorably treated for Australia, France, Germany, Italy, Japan, Sweden, and the United States. Five countries—France, Italy, Sweden, the United Kingdom, and the United States—had negative tax rates for machinery. Except for the United States, these countries had negative but higher tax rates for inventories. Effective tax rates for machinery and inventories reflected the predominance of investment incentives for machinery in provisions for capital recovery under the corporate tax and the taxation of inflationary gains on inventories at corporate income tax rates.

To compare barriers to efficient allocation of capital among countries and trace the course of tax reforms, it is useful to consider the difference between marginal effective tax rates for the most and least favorably treated assets. In 1980 the largest gap was for the United Kingdom at 87.4 percent, while the smallest was that for Japan, at only 5.2 percent. For the United States, the gap was near the midpoint of this range, at 40.5 percent. Modest tax reforms in the United Kingdom described by King and Robson (1993), cut the gap to 52.2 percent in 1985, while adoption of tax incentives for investment in Australia outlined by Jones (1993) more than doubled this gap, from 27.6 to 59.5 percent. In addition, France, Germany, Italy, and the United States increased the difference in tax rates between 1980 and 1985 through enhancement of investment incentives, while Canada, Japan, and Sweden reduced this difference. Japan retained its position as the country with the smallest gap, at only 5.1 percent. Australia, France, Italy, Sweden, the United Kingdom, and the United States had negative tax rates for machinery in 1985.

Australia reversed course and reduced the difference between marginal effective tax rates to only 18.5 percent in 1990, a 41 percentage point decline from 1985. This slightly exceeded the decline in the United States from 47.3 to only 7.8 percent. Canada, France, Germany, Italy, and the United Kingdom also narrowed this gap. For France this reversed the enhancements of incentives between 1980 and 1985 described by Alworth and Bourguignon (1993). From 1980 to 1990 only France, Italy, and Japan failed to make substantial progress in narrowing the difference between the most and least favorably treated types of assets. In 1990, as in 1980, the United Kingdom had the largest gap at 41.7 percent, less than half that in 1980, and Japan had the smallest gap at only 6.3 percent, essentially unchanged from 1980 and 1985. Only France, Italy, and Sweden retained negative tax rates for machinery in 1990.

The predominant direction of tax policy changes in 1980–1985 was to increase differences in effective tax rates among types of assets. This tendency was reversed, however, between 1985 and 1990, when tax incentives for investment in machinery were reduced. Machinery was given the most favorable tax treatment in all countries except Germany and Japan in 1990. France, Italy, and Sweden continued to tax machinery at negative rates. Tax reform efforts from 1980 to 1990 resulted in a definite trend toward leveling the playing field by equalizing tax rates among assets. These efforts were especially successful in the United States, where the difference between effective tax rates on machinery and inventories fell to 7.8 percent in 1990. In Japan no reforms were required to maintain the lowest differences in effective tax rates among assets for all nine countries for the years 1980, 1985, and 1990.

In 1980 the largest differences in marginal effective corporate tax rates between industries were 66.0 percent between manufacturing and commerce in the United Kingdom and 47.5 percent between manufacturing and other industry in the United States The smallest differences were 6.6 and 8.9 percent between manufacturing and other industry for Italy and Sweden, respectively. Tax rates were negative for all industries for France, Italy, and Sweden, for manufacturing and other industry in the United Kingdom, and for other industry in the United States. Tax reform narrowed the difference in the United Kingdom to 24.4 percent in 1985. This difference was also reduced in Germany, Japan, and the United States, although the change in Germany was negligible. Tax policy changes increased gaps between the most and least favored industries in Australia, Canada, France, Italy, and Sweden.

Tax reforms between 1985 and 1990 reduced differences among industries in corporate tax rates for Australia, Canada, France, the United Kingdom, and the United States, and increased the differences for Germany, Italy, and Japan. (No information on these differences is available for Sweden.) The changes for Germany and Japan were very small, so that tax policy changes predominantly narrowed the gaps. This represented a substantial reversal from tax policy changes for 1980–1985 for Australia, Canada, and France. From 1980 to 1990 only Germany and Italy failed to reduce differences in tax rates between most and least favored industries. Germany's tax rates for 1980, 1985, and 1990 were essentially unchanged, whereas Italy widened the gap from 6.6 percent in 1980 to 10.9 percent in 1985 and, finally, to 13.6 percent in 1990.

The overall trend in tax policy changes from 1980 to 1990 was to reduce differences in marginal effective corporate tax rates between the most and least favored industries. These efforts achieved the greatest success in the United Kingdom and the United States, where the gaps were reduced by almost 50 percentage points and more than 25 percentage points, respectively. Australia, Canada, France, and Japan succeeded in narrowing the gaps to less than 10 percent. Italy was an exception to this trend, with steadily widening gaps among industries throughout the period.

Differences among marginal effective tax rates by type of asset and industry for noncorporate enterprises presented in table 6.4 largely reflect the differences among these tax rates for corporations given in table 6.1. Tax incentives included in provisions for capital recovery favor investment in machinery for all countries except Japan in 1980, all countries except Japan, Germany, and the United Kingdom in 1985, and all countries except Germany and Japan in 1990. In 1980 and 1985, Italy, Sweden, and the United States had negative tax rates for machinery, but these were eliminated in 1990 for all three countries. Differences in tax rates among industries exceeded 10 percent in 1990 only for France and Italy.

The most important remaining opportunities for gains in the efficiency of capital allocation within the noncorporate sector are through equalizing tax rates for different types of assets. Tax reforms similar to those I have suggested for corporations would be the most effective to achieve these gains.

Marginal effective corporate tax rates for debt finance presented in table 6.1 were negative for 1980, 1985, and 1990 for every country included in our study. These tax rates were also well below the corresponding rates for equity finance for every country except Australia in 1990, where the rates on debt and new share issues were the same. Combining provisions of corporate and personal taxes in table 6.3, one finds that marginal effective tax rates on corporate source income were negative for debt finance only for Italy, Japan, and the United States for 1980. These three countries, together with Australia, had negative tax rates for debt in 1985, but Australia and the United States eliminated negative rates while Germany adopted a negative rate in 1990. With the important exception of the United Kingdom, tax rates for debt finance were below those for equity in all three years.

Differences among marginal effective corporate tax rates by form of ownership presented in table 6.1 were relatively unimportant by comparisons with differences by source of finance. Marginal effective tax rates on corporate source income given in table 6.3 reveal that with few exceptions households had higher tax rates than tax-exempt institutions and insurance companies. Insurance companies in Australia and Japan had higher rates for 1980, 1985, and 1990. Tax-exempt institutions had higher rates in Australia, France, and Italy in 1985 and France and Italy in 1990. In 1990 substantial gaps among tax rates remained for all countries except Japan and the United Kingdom These gaps indicate important opportunities for further gains in efficiency of capital allocation through tax reform.

Marginal effective tax rates by source of finance for noncorporate enterprises largely reflect the differences for corporations given in table 6.3. Tax deductibility of interest under the personal income tax results in lower tax rates for debt than for equity for all countries except the United States in 1980, 1985, and 1990. In 1980 the difference between tax rates on debt and equity is greatest for Sweden at 123.0 percent and least for the United Kingdom at only 0.4 percent. In 1985 this gap was also largest for Sweden, 125.9 percent, and smallest for the United Kingdom, 1.8 percent. Finally, in 1990 the gap was largest for Italy, 64.7 percent and smallest for the United Kingdom, 1.6 percent.

Marginal effective tax rates for debt were higher than those for equity finance for owner-occupied housing in 1980, 1985, and 1990 for Australia, Canada, Germany, and Japan, and higher for equity than debt for France, Italy, Sweden, and the United States. Tax rates for debt were negative for Japan and Sweden in 1980 and 1985 and negative for equity for Japan in 1980, 1985, and 1990. I conclude that debt was favored relative to equity for corporate and noncorporate sectors in almost all countries included in our study. Elimination of tax deductibility of interest in corporate and personal income taxes would provide an obvious remedy. For housing the elimination of tax deductibility of mortgage interest presents a similar opportunity for tax reform in many countries, including the United States.

In conclusion, very significant progress in reducing differences in tax rates among assets, or both has been made by every country except Italy. However, opportunities remain for further gains in efficiency of capital allocation through reducing these differences. This can be done by eliminating the remaining investment incentives from provisions for capital recovery, especially accelerated capital consumption allowances for machinery, and reducing taxation of inflationary gains on inventories by permitting taxpayers to substitute LIFO (last in, first out) for FIFO (first in, first out) inventory accounting. Except for Sweden important opportunities also exist to improve efficiency through the elimination of the tax-favored status of owner-occupied housing.

Another important goal for tax reform in all countries is to reduce the special tax treatment of debt finance and the tax-favored status of tax-exempt institutions and insurance companies. High priority should also be given to the elimination of tax deductibility of mortgage interest for owner-occupied housing. This is an important source of the tax advantages given to investment in housing in many countries, including the United States. Obviously, much remains to be accomplished before the goal of equalizing marginal effective tax rates on all forms of income from capital is achieved.

6.3 Alternative Approaches

Many of the most important issues in the implementation of marginal effective tax rates have been debated for nearly three decades, following the introduction of the cost of capital by Jorgenson (1963, 1965). The first of these issues is the incorporation of inflation in asset prices. This was the focus of a detailed empirical comparison of the effects of alternative measures of the cost of capital on investment expenditures by Jorgenson and Siebert (1968a, 1968b, 1972). The assumption of perfect foresight or rational expectations of inflation emerged as the most appropriate formulation and has been used in almost all measures of marginal effective tax rates, including those in the preceding section of this chapter.

The second empirical issue in the implementation of the cost of capital is the measurement of economic depreciation. Hulten and Wykoff (1981b) developed the econometric methodology appropriate for this purpose. This methodology is based on modeling the acquisition prices of assets as a function of age. The important innovation by Hulten and Wykoff was to take account of the fact that the sample of used-asset prices is "censored" by retirements of assets from service. Hulten and Wykoff have shown that censoring must be taken into account in estimating the rate of depreciation. They have also demonstrated that geometric decline in efficiency of assets provides a satisfactory approximation to the actual decline in efficiency of durable goods.[15]

The empirical research of Hulten and Wykoff rekindled the debate over the decline in efficiency of assets with age.[16] The stability of patterns of decline in efficiency in the face of changes in tax policy and shocks such as the sharp rise in energy prices during the 1970s was carefully documented by Hulten, Robertson, and Wykoff (1989, p. 255). They concluded that "the use of a single number to characterize the process of economic depreciation (of a given type of capital asset) seems justified in light of the results of this chapter." Measures of economic depreciation based on those of Hulten and Wykoff (1981b) have been used in constructing estimates of marginal effective tax rates by Hulten and Wykoff (1981a), Jorgenson and Sullivan (1981), King and Fullerton (1984), Jorgenson and Yun (1986b, 1991b) and the OECD (1991), and in the preceding section of this chapter.

The third empirical issue in the measurement of the cost of capital is the description of complex tax provisions for capital-cost recovery. The cost-of-capital formula originally used by Jorgenson (1963, 1965) allowed for differences between tax and economic depreciation. The modeling of provisions for capital-cost recovery as the present value of reductions in tax liabilities was the crucial innovation in the papers of Hall and Jorgenson (1967, 1969, 1971). This important reformulation of the cost of capital has been adopted in almost all subsequent studies, including those in the preceding section of this chapter.

Initially, the modeling of tax provisions for capital-cost recovery was based on the assumption that taxpayers choose among alternative formulas so as to minimize their tax liabilities. This assumption was used, for example, by Hall and Jorgenson (1967, 1969, 1971) and by Christensen and Jorgenson (1969, 1973). A detailed study of actual practices for calculating capital consumption allowances and the investment tax credit for the United States was carried out by Jorgenson and Sullivan (1981). The resulting description has been used in many subsequent studies, including those of King and Fullerton (1984) and Jorgenson and Yun (1986b, 1991b).

The introduction of the marginal effective tax rate by Auerbach and Jorgenson (1980) was limited to the effective corporate tax rate. The resolution of major issues concerning the appropriate representation of inflation in asset prices, depreciation in the value of assets with age, and tax incentives for investment—such as capital consumption allowances and the investment tax credit—cleared the way for detailed measurement of marginal effective corporate tax rates for the United States by Jorgenson and Sullivan (1981), Hulten and Wykoff (1981a), and many others.[17]

The integration of corporate and personal income tax provisions into the marginal effective tax rate for corporate-source income was initiated by Hall (1981).[18] This tax rate, including both corporate and personal taxes, provided the basis for the detailed studies of taxation of the corporate sector in Canada by Boadway, Bruce, and Mintz (1984), and Germany, Sweden, the United Kingdom, and the United States by King and Fullerton (1984). Fullerton (1987), as well as Fullerton, Gillette, and Mackie (1987), gave comparisons among tax rates for corporate, noncorporate, and housing sectors for the United States.

The marginal effective tax rates we have presented in the preceding section must be carefully distinguished from the average effective tax rates introduced by Harberger (1962, 1966). Marginal and average tax rates differ substantially, since changes in tax laws usually apply only to new assets. Since new and existing assets are perfect substitutes in production in the model of capital as a factor of production, it is marginal rather than average rates that are relevant to measurements of distortions in the allocation of capital. Rosenberg (1969) presented a set of average effective tax rates for the United States for the period 1953–1959 that includes a breakdown by forty-five industry groups. The average effective tax rates given by Harberger (1962) and Rosenberg (1969) include corporate income taxes and property taxes, but do not incorporate individual taxes on distributions from corporate and noncorporate business. Harberger (1966) included taxes on dividends paid by the corporate sector as well as taxes on capital gains realized by holders of corporate equity.[19]

Feldstein and Summers (1979) have presented average effective tax rates for the U.S. corporate sector that incorporate individual as well as corporate income tax liabilities. The estimates of Feldstein and Summers cover 1954–1977 and are given separately for twenty two-digit industries within manufacturing. The estimates for the corporate sector as a whole have been updated and revised to cover the periods 1953–1978 by Feldstein (1982), 1953–1978 by Feldstein, Dicks-Mireaux, and Poterba (1983), and 1953–1984 by Feldstein and Jun (1987).[20]

Since the effect of the personal income tax on the corporate cost of capital depends on the determinants of corporate financial policy, the incorporation of personal taxes into the corporate cost of capital has raised a host of new issues. A number of alternative approaches to taxation and corporate finance have been discussed in the literature.[21] In the new view proposed by King (1974a, 1974b, 1977), the corporation retains earnings sufficient to finance the equity portion of investment and dividends are determined by the residual cash flow.[22] The marginal source of equity funds is retained earnings, so that the rate of return on corporate source income does not depend on the taxation of dividends at the personal level. The tax rate on dividends does not affect the rental price of capital services or the effective tax rate on corporate source income.

Under the new view of corporate finance and taxation, the most attractive investment opportunity available to the corporation is to liquidate its assets and repurchase its outstanding shares. Each dollar of assets liquidated reduces the value of the firm's outstanding shares. However, if repurchasing the firm's outstanding shares is ruled out by assumption, equity is "trapped" in the firm and it makes sense for the firm to continue holding assets. Accordingly, this view of corporate taxation has been characterized as the "trapped equity" approach.[23]

Jorgenson and Yun (1986b, 1991b) have presented an alternative model of the cost of capital in the corporate sector based on a fixed ratio of dividends to corporate income. This is the "traditional" view of corporate finance and taxation employed, for example, by Harberger (1966), Feldstein and Summers (1979), McLure, Jr. (1979), and Poterba and Summers (1983, 1985). In this view the marginal source of funds for the equity portion of the firm's investments is new share issues, since dividends are fixed. An important implication of the traditional view is that an additional dollar of new issues adds precisely one dollar to the value of the firm's assets, so that the value of outstanding financial liabilities of the firm is equal to the value of the firm's assets.

It is important to emphasize the critical role of the assumption that dividends are a fixed proportion of corporate income in the traditional view of taxation and corporate finance. If the firm were to reduce dividend payments by one dollar and retain the earnings in order to finance investment, stockholders would avoid personal taxes on dividend payments. The addition to retained earnings would result in a capital gain taxed at a lower rate, so that shareholders would experience an increase in wealth. Following this line of reasoning, it would always be in the interest of the shareholders for the firm to finance investment from retained earnings rather than new issues of equity, as in the new view.

As Sinn (1991a) has emphasized, both the traditional and the new views of corporate taxation depend critically on assumptions about financial policy of the firm. The traditional view depends on the assumption that dividends are a fixed proportion of corporate income, so that the marginal source of funds for financing investment is new issues of equity. The new view depends on the assumption that new issues of equity (or repurchases) are fixed, so that the marginal source of funds is retained earnings.[24] In fact, firms use both sources of equity finance, sometimes simultaneously. The King-Fullerton framework outlined in the appendix to this chapter is based on the actual distribution of new equity finance from new issues and retained earnings. Since retained earnings greatly predominate over new issues as a source of equity finance, this approach turns out to be empirically equivalent to adopting the new view.[25]

A satisfactory resolution of issues that have been raised in taxation and corporate finance would require the formulation of a theory of corporate finance with endogenous determination of financial structure and dividend policy.[26] A possible avenue for development of such a theory might be to require explicit incorporation of uncertainty about the returns from capital. The incorporation of uncertainty into the cost of capital by means of risk-adjusted rates of return has been discussed by Auerbach (1983a), Bulow and Summers (1984), and Shoven (1990).

An important implication of the new view of taxation and corporate finance is that investment expenditures of the firm are independent of the rate of taxation of dividends at the individual level. Poterba and Summers (1983, 1985) have presented the results of tests of this hypothesis that support the traditional view. Auerbach (1984) has presented evidence that the cost of capital for new issues is higher than that for retained earnings. These findings support the new view.

The second set of issues raised by the introduction of personal taxes into the corporate cost of capital relates to the treatment of debt and equity in the corporate tax structure. Jorgenson and Yun (1986b, 1991b) and King and Fullerton (1984) have assumed that debt-capital ratios are the same for all assets within the corporate sector. Bosworth (1985) and Gordon, Hines, and Summers (1987) have argued that different types of assets should be associated with different debt-equity ratios.[27] Empirical evidence supporting the view that debt-equity ratios are independent of the composition of assets has been provided by Auerbach (1983a) and Gravelle (1987).

The inclusion of personal taxes on corporate distributions to holders of equity also raises more specific issues concerning the impact of inflation in asset prices. A comprehensive treatment of these issues is provided by Feldstein (1983). Since nominal interest expenses are deductible at the corporate level while nominal interest payments are taxable at the individual level, an important issue is the impact of inflation on nominal interest rates. Feldstein and Summers (1979) have assumed that Fisher's Law holds, namely, that a change in inflation is reflected point for point in changes in nominal interest rates. This assumption is used by Jorgenson and Yun (1986b, 1991b). King and Fullerton (1984) have used a modified version of Fisher's Law in which nominal rates of return after tax increase point for point with the rate of inflation. Empirical support for Fisher's Law is provided by Summers (1983).[27]

The second issue in the impact of inflation on the cost of capital is the relationship between accrual and realization of capital gains. As pointed out earlier in this section, capital gains are taxed when they are realized and not when they are accrued. However, capital consumption allowances for used assets reflect the price at which the asset is acquired. This presents opportunities for "churning;" that is, selling assets, realizing capital gains, and acquiring a higher basis for capital consumption allowances. Optimal strategies for churning are analyzed by Gordon, Hines, and Summers (1987) and Gravelle (1987). Sunley (1987) argues that churning is negligible empirically and Gravelle (1987) supports empirical evidence to substantiate this view.

The final set of issues in corporate finance relates to more detailed descriptions of the tax structure for capital income. These issues revolve around multiperiod tax rules. For example, firms experiencing losses may be unable to avail themselves of the tax benefits of deductions for interest, depreciation, and other expenses. However, some of these benefits may be carried forward to periods in which the firms make profits. A general approach to this problem has been developed by Auerbach (1986) and implemented empirically for data on individual firms by Auerbach and Poterba (1987). Ballentine (1987) has argued for the incorporation of these and other tax provisions for specific assets into marginal effective tax-rate calculations. Fullerton, Gillette, and Mackie (1987) have examined the importance of these provisions and have concluded that the impact on marginal effective tax rates for industry groups is relatively modest. Obviously, the importance of this issue is much greater at the level of the individual firm.

An important objective of further research in taxation and corporate finance will be to endogenize the responses of debt-capital and dividend-payout ratios to changes in tax policy at both corporate and personal levels. In addition, more detailed features of the tax structure, such as opportunities for "churning" and, more generally, optimal realization of capital gains, must be encompassed by the theory. Finally, a more finely grained description of tax statutes, including the complexities introduced by provisions for multiperiod treatment of corporate income, tax deductions, and tax credits must be utilized.[28]

6.4 Summary and Conclusion

The purpose of this section is to evaluate the usefulness of the cost of capital as a practical guide to tax reform. The primary focus is U.S. tax reform, since the cost of capital has been used much more extensively in the United States than in the other countries analyzed in this chapter. Auerbach and Jorgenson (1980) introduced the key concept, the *marginal effective tax rate*, early in the debate over the U.S. Economic Recovery Tax Act of 1981. They employed this concept as a means of comparing the tax burdens among different types of assets under the provisions for capital-cost recovery ultimately incorporated into the 1981 Tax Act.

The initial results of applying the cost-of-capital approach to the 1981 tax act had no effect on the final legislation. However, this approach spread very rapidly among the community of tax policy analysts, both inside and outside the U.S. government. The initial impetus for the diffusion of the-cost-of-capital approach was testimony by Jorgenson (1979, 1980b) before the Senate Committee on Finance on October 22, 1979, and the House Committee on Ways and Means House on November 14, 1979.[29]

A milestone in the diffusion of cost-of-capital approach was provided by the Conference on Depreciation, Inflation, and the Taxation of Income from Capital, held at the Urban Institute in Washington, D.C., on December 1, 1980. The participants in this conference included tax analysts from universities, research institutions, the U.S. Department of the Treasury, and the staff of Congress. Key papers in the implementation of the cost-of-capital approach by Bradford and Fullerton, Hall, Hulten and Wykoff, and Jorgenson and Sullivan were presented at the conference. The publication of the conference proceedings in 1981 was followed shortly by presentation of the first official estimates of marginal effective tax rates by the President's Council of Economic Advisers (1982).

The literature on the cost-of-capital approach developed at an explosive pace during the early 1980s, leading up to the presentation of the Treasury proposal, requested by President Reagan, in November 1984.[30] The proposal was accompanied by marginal effective corporate tax rates for different types of assets. A primary objective of the proposal was to "level the playing field" by equalizing marginal effective tax rates on business assets. A second objective was to insulate the definition of capital income from the impact of inflation. However, leveling the playing field between the household and business sectors was not included among the objectives of the Treasury proposal.[31]

The initial application of the cost-of-capital approach to tax policy analysis was based on the inclusion of investment functions incorporating the cost of capital in macroeconometric forecasting models. Investment functions of this type were first proposed for the Brookings quarterly econometric model of the United States by Jorgenson (1965).[32] By the beginning of the debate over the Economic Recovery Tax Act of 1981, the investment equations for all major forecasting models for the U.S. economy had incorporated the cost of capital.[33] Simulations of alternative tax policies by means of these models had become the staple fare of debate over the economic impact of specific tax proposals.[34]

An important issue in this type of application, emphasized by Lucas, Jr. (1976) in his critique of econometric methods for policy evaluation, is the modeling of expectations of future prices of investment goods. This is required in measuring the cost of capital and simulating the impact of changes in tax policy on investment expenditures. The resolution of this issue can be found in the model of capital as a factor of production. The key dynamic relationships are an accumulation equation, which expresses capital stock as a weighted sum of past investments and a capital asset pricing equation, which expresses the price of acquisition of investment goods as the sum of future rental prices of capital services. Both of these relationships must be incorporated into the simulation of the effects of changes in tax policy. Macroeconometric models have incorporated the backward-looking equation for capital stock, but have omitted the forward-looking equation for the price of investment goods.

The reason for the omission of the capital-asset pricing equation from macroeconometric models is that such an equation would have required simulation techniques appropriate for perfect foresight or rational expectations. These techniques were introduced by Lipton, Poterba, Sachs, and Summers (1982) and Fair and Taylor (1983), long after the methodology for constructing and simulating macroeconometric forecasting models had crystallized. In order to evaluate the economic impact of the 1981 tax reforms, Jorgenson and Yun (1986a) constructed a dynamic general-equilibrium model that incorporates both the backward-looking equation for capital stock in terms of past investment and the forward-looking equation for the price of acquisition of investment goods in terms of future prices of capital services.[35]

Shortly after the passage of the Tax Reform Act of 1986, the Office of Tax Analysis of the U.S. Treasury (1987) published a detailed study of the impact of the new legislation on marginal effective tax rates by Fullerton, Gillette, and Mackie (1987). The results were incorporated into an applied general equilibrium model of the U.S. economy by Fullerton, Henderson, and Mackie (1987) and used to estimate the economic impact of the 1986 tax act. Fullerton (1987) presented a closely related study of marginal effective tax rates; Fullerton and Henderson (1989a, 1989b) incorporated the results into an applied general equilibrium model of the U.S. economy and analyzed the impact of the legislation and directions for future tax reform. However, these applied general equilibrium models did not include the capital asset pricing equation and are subject to the "Lucas critique."

Jorgenson and Yun (1990, 1991a) have evaluated the economic impact of the 1986 tax reform, using a new version of their dynamic general equilibrium model of the U.S. economy.[36] In this model equilibrium is characterized by an intertemporal price system that clears the markets for all four commodity groups included in the model—labor services, capital services, consumption goods, and investment goods. Equilibrium at each point of time links the past and the future through markets for investment goods and capital services. Assets are accumulated as a result of past investments, while the prices of assets must be equal to the present values of future capital services. The time path of consumption must satisfy the conditions for intertemporal optimality of the household sector under perfect foresight. Similarly, the time path of investment must satisfy requirements for the accumulation of assets by both business and household sectors.

Jorgenson and Yun (1991b) have summarized the 1986 tax reform in terms of changes in tax rates, the treatment of deductions from income for tax purposes, the availability of tax credits, and provisions for indexing taxable income for inflation. They have also summarized proposals for tax reform that figured prominently in the debate leading up to the 1986 tax act. For this purpose they have used the concepts of marginal effective tax rates and tax wedges, defined in terms of differences in tax burdens imposed on different forms of income. These gaps are indicators of the likely impact of substitutions among different kinds of capital induced by changes in tax policy.

In other studies, Jorgenson and Yun (1990, 1991a) have analyzed the impact of each of the alternative tax policies on U.S. economic growth. They have also evaluated the effects of changes in tax policy on economic efficiency by measuring the corresponding changes in potential economic welfare. The reference level of welfare, which serves as the basis of comparison among alternative tax policies, is the level attainable by the U.S. economy under the tax law in effect prior to the 1986 tax reform. Finally, they have analyzed losses in efficiency associated with tax wedges among different kinds of capital income.

Jorgenson and Yun found that much of the potential gain in welfare from the 1986 tax reform was dissipated through failure to index the income tax base for inflation. At rates of inflation near zero the loss is not substantial. However, at moderate rates of inflation, like those prevailing since the early 1980s, the loss is highly significant. Second, the greatest welfare gains would have resulted from incorporating the income from household assets into the tax base, while reducing tax rates on income from business assets. The potential welfare gains from an income-based tax system, reconstructed along these lines, would have exceeded those from an expenditure-based system.

My conclusion is that the cost-of-capital approach to tax policy analysis has proved its value as a guide to the formulation of proposals to improve the taxation of income from capital in the United States. The initial focus of the cost-of-capital approach originated by Auerbach and Jorgenson was on the allocation of capital within the corporate sector. This focus also characterized the extensions of the cost-of-capital approach by Boadway, Bruce, and Mintz (1984) and Fullerton and King (1984). More recent work has also encompassed allocation between business and household sectors. The tax policy changes of the early 1980s, especially the 1981 tax act, increased barriers to efficient allocation of capital. By contrast, the 1986 tax act reduced these barriers substantially.

It must be emphasized that effective tax rates or tax wedges do not provide a complete analysis of the distortionary effects of capital-income taxation. The distortion of resource allocation depends on substitutability between assets as well as the tax wedges. As an example, consider the allocation of capital between short-lived and long-lived depreciable assets in the corporate sector. Even if the interasset difference in tax treatment is large, the distortion of capital allocation can be small if the services of the two types of assets are not substitutable. Similarly, the distortion in the allocation of resources for consumption over time can be small if intertemporal substitutability in consumption is small.

The analysis of the economic impact of tax policy requires the integration of the cost of capital into macroeconometric models and applied general equilibrium models. The impact of the Tax Reform Act of 1986 has been analyzed by means of models of both types. The Jorgenson-Yun model incorporates long-run dynamics based on the backward-looking accumulation equation for capital stock and the forward-looking asset-pricing equation for the acquisition price of investment goods. Each tax policy is associated with an intertemporal equilibrium based on optimization by producers and consumers. This equilibrium includes markets for different types of capital, including corporate, noncorporate, and household capital, broken down by short-lived and long-lived assets. The detailed disaggregation exposes all the margins for substitution affected by changes in tax policy.

The cost-of-capital approach to tax policy analysis will continue to be a useful guide to tax reform within the framework of the corporate and individual income tax. Income taxation remains the primary basis for taxation in the United States and all of the other countries we have analyzed. The shift toward expenditure and away from income as a basis for taxation in the 1970s has been reversed during the 1980s. The erosion of the income tax base to provide tax incentives for investment and saving has been arrested through vigorous and far-reaching tax-reform efforts in many of the countries included in our study. Investment incentives have been curtailed and efforts have been made to equalize marginal effective tax rates among corporate, noncorporate, and household sectors.

The intellectual impetus for recent tax-reform efforts has been provided by the cost of capital and the closely related concept of the marginal effective tax rate. Effective tax rates at both corporate and personal levels are now available for many countries around the world. In this chapter our objective is to use the results for an international comparison of tax reforms for income from capital. This comparison provides extensive illustrations of the work on the cost of capital that has been accomplished, using data sources of the type that are readily available for most industrialized countries. Our hope is that these illustrations will serve as an inspiration for policy makers who share our goal of making the allocation of capital within a market economy more efficient.

Appendix A: King-Fullerton Framework

The starting point for our presentation of the King-Fullerton framework[37] is the concept of a tax wedge. Presentation of this concept requires the following notation: p is the before-tax rate of return, and s is the after-tax rate of return.

The tax wedge, w, is defined as the difference between before-tax and after-tax rates of return:

$$w = p - s. \tag{A.1}$$

Given the tax wedge (A.1), we can define the effective tax rate, t, as the ratio of the tax wedge to the before-tax rate of return p:

$$t = \frac{w}{p} = \frac{p - s}{p}. \tag{A.2}$$

To express the tax wedge as the sum of components associated with provisions of corporate and personal taxes I introduce the notation q—after-corporate, before-personal tax rate of return.

The corporate tax wedge, w_c, is defined as the difference between the before-tax rate of return and the after-corporate, before-personal tax rate of return:

$$w_c = p - q. \tag{A.3}$$

Similarly, the personal tax wedge, w_p, is defined as the difference between the after-corporate, before-personal tax rate of return and the after-tax rate of return:

$$w_p = q - s. \tag{A.4}$$

The tax wedge (A.1) is the sum of corporate and personal tax wedges (equations A.3 and A.4)

$$w = w_c + w_p,$$

since

$$p - s = (p - q) + (q - s).$$

Given the corporate tax wedge (A.3), one can define the effective corporate tax rate, t_c, as the ratio of corporate tax wedge to the before-tax rate of return:

$$t_c = \frac{w_c}{p} = \frac{p - q}{p}. \tag{A.5}$$

Similarly, given the personal tax wedge (A.4), one can define the effective personal tax rate, t_p, as the ratio of the personal tax wedge to the after-corporate, before-personal tax rate of return:

$$t_p = \frac{w_p}{q} = \frac{q - s}{q}. \tag{A.6}$$

The effective tax rates (equations A.2, A.5, and A.6) satisfy the identity:

$$1 - t = (1 - t_c)(1 - t_p),$$

so that

$$t = t_c + t_p - t_c t_p,$$

since

$$\frac{s}{p} = \frac{q}{p} \cdot \frac{s}{q}.$$

The measurement of effective tax rates depends on statutory tax rates and the definition of taxable income at both corporate and personal levels. This information is summarized by means of the cost of capital. The simplest form of the cost of capital arises in a model of capital as a factor of production.[38] The rental price of capital services is the unit cost of using a capital good for a specified period of time. For example, a building can be leased for a number of months or years, an automobile can be rented for a number of days or weeks, and computer time can be purchased by the second or the minute. The cost of capital transforms the acquisition price of an asset into an appropriate rental price.

The distinguishing feature of capital as a factor of production is that durable goods contribute services to production at different points in time. The technology of this model is described in terms of *relative efficiencies* of capital goods of different ages. The relative efficiency of a capital good depends on the age of the good and not on the time it is acquired. When a capital good is retired, its relative efficiency drops to zero. For simplicity I assume that the relative efficiencies of durable goods of different ages decline geometrically.[39] The rate of decline in efficiency δ, is constant, so that the relative efficiencies take the form

$$1, 1-\delta, (1-\delta)^2 \ldots,$$

where I normalize the relative efficiency of a new durable good at unity.

In the durable goods model of production the rental prices of capital goods of different ages are proportional to the rental price of a new capital good. The constants of proportionality are the relative efficiencies $(1-\delta)^\tau$. The acquisition price of investment goods is the present value of future rental prices of capital services, weighted by the relative efficiencies of capital goods in each future period. The future rental prices are discounted in order to express prices for different time periods in terms of present values. Depreciation is the decline in the acquisition price of a durable good with age. The acquisition price declines geometrically with age, so that the rate of depreciation is constant, where δ is the rate of depreciation.

The before-tax rate of return p can be expressed in terms of the cost of capital, net of depreciation, say $c(q)$:

$$p = c(q) = \frac{1-A}{1-\tau}(q+\delta) - \delta, \tag{A.7}$$

where q is the after-corporate, before-personal tax rate of return, δ is the rate of depreciation, A is the present value of allowances for capital recovery, and τ is the corporate tax rate.

Provisions for recovery of investment expenditures under the corporate income tax can be summarized by means of the present value of allowances for capital recovery.[40]

$$A = f_1 A_d + f_2 \tau + f_3 g, \tag{A.8}$$

where f_1, f_2, f_3 are proportions of an asset subject to "standard" capital-consumption allowances, immediate expensing, and grants or subsidies, respectively; A_d is the present value of capital consumption allowances; and g is the rate of grant or subsidy.

To integrate provisions of the personal income tax into the cost of capital, I consider the tax treatment of corporate distributions in the form of interest, dividends, and capital gains. Under debt finance these distributions take the form of interest payments, so that the rate of return after corporate and personal taxes, s, is

$$s = (1 - m)i - \pi, \tag{A.9}$$

where π is the inflation rate and i is the interest rate, not corrected for inflation, and m is the marginal personal tax rate on interest income.

If interest is deductible from corporate income for tax purposes, the rate of return after corporate, but before personal tax q is

$$q = (1 - \tau)i - \pi, \tag{A.10}$$

where τ is the corporate tax rate.

The tax treatment of dividends and capital gains depends on whether the corporate and personal income taxes are integrated. Under a *classical* corporate income tax like that in the United States, no additional tax is collected or refunded when dividends are paid out.[41] Under a *partial imputation* system, like that in France and the United Kingdom, a personal tax credit is attached to dividends paid out or dividends are subject to lower tax rates at the personal level. Under a *full imputation* system, like that in Australia, Germany, and Italy, dividends are fully deductible from income under the corporate tax in the same way that interest is, so that dividends are taxed at personal rather than corporate tax rates. Various other forms of partial tax relief of shareholders are used in Canada, Japan, and Sweden.

To represent alternative corporate income tax systems King and Fullerton (1984) introduce a variable θ that reflects the degree of discrimination between retentions and distributions in the tax system. This variable is defined as the additional dividends stockholders would receive if an additional unit of earnings after corporate taxes were distributed. For a classical system the variable θ is equal to unity, since the distribution of dividends does not affect corporate tax liabilities. For a partial imputation system this variable is

$$\theta = \frac{1}{1-c},$$

where c is the rate of imputation of corporate income tax to stockholders. For a full imputation system this parameter is

$$\theta = \frac{1}{1-\tau},$$

where τ is the corporate tax rate, since dividends are fully deductible at the corporate level.

I have defined tax wedges for projects that are debt financed. Now these wedges can be considered for projects financed by new share issues and retained earnings. For new share issues the dividend yield after corporate taxes, net of tax credits at the personal level, must be equal to the stockholder's opportunity cost of funds, both after personal taxes. The dividend yield is $(1-m)\theta(q+\pi)$ and the opportunity cost is $(1-m)i$, where m is the marginal personal tax rate on dividends. The rate of return after corporate taxes, but before personal taxes, q, is

$$q = \frac{i}{\theta} - \pi. \tag{A.11}$$

Projects financed through retained earnings enable stockholders to be taxed at the personal level at capital gains rates rather than income tax rates. Since capital gains are taxed upon realization, not as they are accrued, the rate of return after corporate taxes, but before personal taxes q is

$$q = i\frac{(1-m)}{(1-z)} - \pi, \tag{A.12}$$

where z is the proportion of accrued capital gains subject to taxation.

To complete the King-Fullerton framework for income from depreciable assets originating in the corporate sector it is necessary to incorporate property or wealth taxes. If these taxes are not deductible from corporate income for tax purposes, they are subtracted from the rate of return after corporate taxes in determining the after-corporate, before-personal rate of return. If these taxes are deductible, they must be subtracted from the tax base before one calculates the corporate tax liability. For nondepreciable assets, such as inventories, the rate of depreciation δ is equal to zero. The corporate income tax base may be defined in terms of inventories at historical cost, so that inflationary gains on inventories are taxed at the corporate rate. This requires further modification of the corporate rate of return.[42]

King and Fullerton (1984) consider different types of investment projects by corporate enterprises. For each project they consider a fixed rate of return p before corporate and personal income taxes, which they take to be 10 percent. They then calculate an appropriate rate of return s after corporate and personal income taxes. The difference between the two rates of return is the tax wedge equation (A.1), used in calculating the marginal effective tax rate equation (A.2). The international comparisons given also include the rate of return after corporate taxes, but before personal taxes q for each project. The corporate tax wedge and the personal tax wedge (equations A.3 and A.4) are then determined and used in calculating the marginal effective corporate tax rate and the marginal effective personal tax rate (equations A.5 and A.6).[43]

The King-Fullerton framework has been extended by defining effective tax rates for projects undertaken by noncorporate enterprises and owner-occupied housing.[44] For this purpose the noncorporate tax wedge is defined as the difference between noncorporate rates of return before and after personal taxes. This tax wedge is strictly analogous to the corporate tax wedge defined above, but with the marginal personal tax rate on noncorporate income m in place of the corporate tax rate τ. All the tax provisions described for corporate enterprises—capital recovery allowances for depreciable assets, property and wealth taxes, and the treatment of inflationary gains on inventories—must be incorporated into the cost of capital for noncorporate enterprises. For income generated from owner-occupied housing the tax deductibility of mortgage interest and the tax treatment of wealth and property taxes at the personal level must be taken into account.

King and Fullerton (1984) have implemented their framework for hypothetical investment projects in the corporate sector classified into the following categories

- Classes of assets: machinery, buildings, and inventories.
- Industries: manufacturing, other industry, and commerce.
- Sources of finance: debt, new share issues, and retained earnings.
- Forms of ownership: households, tax-exempt institutions, and insurance companies.[45]

To aggregate rates of return over the eighty-one different types of projects resulting from all the possible combinations of assets, industries, sources of finance, and forms of ownership, King and Fullerton (1984) define the average rate of return before taxes, $\overline{p}$, as a weighted average of rates of return before taxes for the individual projects:

$$\overline{p} = \sum_{k=1}^{81} p_k \alpha_k,$$

where p_k is the before-tax rate of return on the k-th project and α_k is the share of the k-th type of project in total capital stock. Similarly, the average rate of return after taxes, $\bar{s}$, is defined as

$$\overline{s} = \sum_{k=1}^{81} s_k \alpha_k,$$

where s_k is the after-tax rate of return on the k-th project.

The average tax wedge, $\overline{w}$, is defined as the difference between average before- and after-tax rates of return:

$$\overline{w} = \overline{p} - \overline{s}. \tag{A.13}$$

This average tax wedge is a weighted average of tax wedges for the individual projects:

$$\overline{w} = \sum_{k=1}^{81} (p_k - s_k)\alpha_k = \sum_{k=1}^{81} w_k \alpha_k,$$

where w_k is the tax wedge on the k-th project.

The average marginal effective tax rate, $\bar{t}$, is defined as the ratio of the average tax wedge $\overline{w}$ to the average rate of return before taxes $\overline{p}$ (A.14)

$$\bar{t} = \frac{\overline{w}}{\overline{p}} = \frac{\sum_{k=1}^{81} (p_k - s_k)\alpha_k}{\sum_{k=1}^{81} p_k \alpha_k}. \tag{A.14}$$

If the rate of return before taxes p is the same for all projects,

$$\bar{t} = \sum_{k=1}^{81} t_k \alpha_k,$$

so that the average effective tax rate is a weighted average of effective tax rates for individual projects.

One can define the average after corporate, before personal tax rate of return, $\overline{q}$, as a weighted average of these rates of return for individual projects:

$$\overline{q} = \sum_{k=1}^{81} q_k \alpha_k.$$

The average corporate tax wedge, w_c, can be defined as a weighted average of corporate tax wedges for individual projects:

$$\overline{w}_c = \sum_{k=1}^{81} (s_k - q_k)\alpha_k. \tag{A.15}$$

Similarly, the average personal tax wedge, w_p, may be defined as a weighted average of personal tax wedges for these projects:

$$\overline{w}_p = \sum_{k=1}^{81} (p_k - q_k)\alpha_k. \tag{A.16}$$

Finally, the average marginal effective corporate and personal tax rates, $\bar{t}_c$ and $\bar{t}_p$, can be defined in terms of the tax wedges (equations A.15 and A.16), as

$$\bar{t}_c = \frac{\overline{w}_c}{\overline{p}}, \quad \bar{t}_p = \frac{\overline{w}_p}{\overline{q}}. \tag{A.17}$$

Notes

1. See Lodin (1978), Meade and others (1978), and United States Department of the Treasury (1977). Hall and Rabushka (1983) and Bradford (1986) have presented proposals for implementation of an expenditure-based tax system in the United States. The income-based approach incorporated into the Tax Reform Act of 1986 was proposed by the United States Department of the Treasury (1984).

2. A detailed description of the Economic Recovery Tax Act of 1981 is given by the Joint Committee on Taxation (1981). Changes in tax policy have been discussed by Gravelle (1982) and Hulten and O'Neill (1982). The impact of the 1981 tax act on United States economic growth is analyzed by Jorgenson and Yun (1986b, esp. pp. 365–370).

3. An illuminating account of the tax reform debate that preceded the 1986 tax act is provided by Birnbaum and Murray (1987). A detailed description of the legislation is given by the Joint Committee on Taxation (1986). The changes in tax policy have been analyzed by Steuerle (1992), in symposiums edited by Aaron (1987) and Slemrod (1982), and the symposium by Bosworth, and Burtless (1992). Henderson (1991) has surveyed studies of the economic impact of these tax policy changes.

4. King and Fullerton (1984).

5. King (1985) provides a detailed comparison between the 1984 tax reform in the United Kingdom and tax reform proposals in the United States.

6. A discussion of alternative notions of the effective tax rate is presented by Fullerton (1984). A summary of the literature on empirical implementation of the cost of capital is given by Harper, Berndt, and Wood (1989).

7. The objectives of the 1986 tax reform are discussed by McLure and Zodrow (1987).

8. Pechman (1988) provides comparisons among tax reform efforts in eleven industrialized countries, as of the end of 1987, including the nine countries covered by this study, Denmark, and The Netherlands. Boskin and McLure (1990) have provided similar comparisons for industrialized and developing countries through the end of 1988.

9. King and Fullerton (1984) also provide estimates for 1960 and 1970 and Bernheim and Shoven (1987) have updated the King-Fullerton study through 1985, replacing Sweden with Japan.

10. This extension of the King-Fullerton framework is presented by the Organization for Cooperation and Development (1991), pp. 207–218. International aspects of taxation are discussed by Alworth (1988), Frenkel, Razin, and Sadka (1991), and in the volume edited by Razin and Slemrod (1990).

11. This extension follows Fullerton (1987) and Fullerton, Gillette, and Mackie (1987).

12. Fullerton (1987) and Fullerton, Gillette and Mackie (1987) have analyzed the Tax Reform Act of 1986 and alternative proposals within the King-Fullerton framework.

13. Jorgenson and Yun (1990, 1991a) provide quantitative estimates of the potential gains in efficiency for the United States.

14. King and Fullerton (1984, especially chapter 7, pp. 268–302).

15. See, especially, Hulten and Wykoff (1981b), p. 387.

16. This debate is summarized by Biorn (1989) and Jorgenson (1989).

17. Effective corporate tax rates are also presented by Bradford and Fullerton (1981) and Hall (1981) and, subsequently, by Gravelle (1982), Auerbach (1983a, 1987), and Hulten and Robertson (1984).

18. Alternative marginal effective tax rate concepts are compared and analyzed by Bradford and Fullerton (1981).

19. Harberger's (1966) estimates were revised and corrected by Shoven (1976).

20. Fullerton (1984) has discussed the distinction between average and marginal effective tax rates and concludes that empirical measures of effective tax rates based on these two different concepts are not closely related. King and Fullerton (1984, table 6.34, p. 265) provide an estimate of the average effective tax rate for the United States in 1978–1980 and the accompanying text provides comparisons with the results of Feldstein, Dicks-Mireaux, and Poterba and the earlier work of Rosenberg.

21. Summaries of the alternative views of taxation and corporate finance are given by Atkinson and Stiglitz (1980, especially pp. 128–159, Auerbach (1983b), and Sinn (1991a).

22. This view is discussed by Auerbach (1979), Bradford (1981), and Sinn (1987).

23. An important issue for the trapped-equity approach is how equity initially enters the firm. A resolution of this issue based on the life cycle of the firm has been proposed by King (1989) and Sinn (1991b).

24. The third view of taxation and corporate finance presented by Stiglitz (1973) drops the assumption that the debt-equity ratio is fixed, so that the cheapest source of finance is debt, which is tax deductible at the corporate level. This provides an interesting rationale for the Modigliani-Miller (1958, 1961) theory of corporate finance in which dividend policy and the financial structure of the firm are independent of tax policy.

25. Sinn (1991a) has suggested choosing new issues and retained earnings so as to minimize the cost of equity finance. The results presented in table 6.3 show that this is also empirically equivalent to the new view for most countries.

26. This has been suggested, for example, by Scott (1987).

27. However, see the exchange between McCallum (1984, 1986) and Summers (1986).

28. An important reformulation of the theory of taxation and corporate finance dealing with many of these issues has been presented by Scholes and Wolfson (1992).

29. These committees have responsibility for all tax legislation emanating from the U.S. Congress.

30. This proposal is described by the U.S. Department of the Treasury (1984).

31. The political reasons for this crucial omission are discussed by McLure (1986).

32. A much more detailed version of this model was constructed by Jorgenson and Stephenson (1967a, 1967b, 1969) and Jorgenson and Handel (1971). A detailed review of the initial studies of investment behavior incorporating the cost of capital is given by Jorgenson (1971a).

33. See, for example, Chirinko and Eisner (1983) and Gravelle (1984).

34. Illustrations of this type of simulation study are provided by Jorgenson (1971b) and Gordon and Jorgenson (1976), using modifications of the DRI quarterly econometric model of the United States.

35. As suggested by Lucas (1976), this model also includes expectations about future changes in tax policy.

36. Henderson (1991) surveys six studies of the economic impact of the 1986 tax act by means of applied general equilibrium models.

37. A more detailed presentation is given by King and Fullerton (1984, pp. 7-30).

38. Capital as a factor of production has been discussed by Jorgenson (1967), Diewert (1980), and Hulten (1990).

39. While the assumption of geometric decline in relative efficiency of capital goods is a convenient simplification, this assumption is inessential to modeling capital as a factor of production. For a more general treatment, see Jorgenson (1973, 1989) and Biorn (1989).

40. This approach to modeling provisions for capital recovery was introduced by Hall and Jorgenson (1967, 1969, 1971).

41. The U.S. Department of Treasury (1984, 1992) has recommended replacing the classical system with a partial imputation system. Integration of corporate and personal taxes in the United States has been discussed in detail by McLure (1979).

42. Details are given by King and Fullerton (1984, pp. 20-21).

43. King and Fullerton (1984) refer to the approach we have outlined as the "fixed-p" approach. They also consider a "fixed-r" approach, based on a fixed real rate of return $r = i - \pi$ of 5 percent. Under the "fixed-p" approach, international comparisons are limited to differences in provisions for taxation of capital income. Poterba (1991) has surveyed a parallel literature on international comparisons of the cost of capital, focusing on differences in the costs of debt and equity finance.

44. Fullerton (1987); Fullerton, Gillette, and Mackie (1987).

45. The OECD (1991) study includes only manufacturing industries and considers ownership by stockholders with different marginal tax rates ranging from zero to the top marginal rate in each OECD country. This study is based on the "fixed-r" approach rather than the "fixed-p" approach employed here.

7

Investment and Growth

Dale W. Jorgenson

7.1 Introduction

The early 1970s marked the emergence of a rare professional consensus on economic growth, articulated in two strikingly dissimilar books. Simon Kuznets, the greatest of twentieth-century empirical economists, summarized his decades of research in *Economic Growth of Nations* (1971). The enormous impact of that research was recognized in the same year by the Royal Swedish Academy of Sciences in awarding the third Bank of Sweden Prize in Economic Science 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" (Lindbeck, 1992, p. 79).

Robert Solow's book *Growth Theory* (1970), modestly subtitled *An Exposition*, contained his 1969 Radcliffe Lectures at the University of Warwick. In those lectures, Solow also summarized decades of research initiated by the theoretical work of Roy Harrod (1939) and Evsey Domar (1946). Solow's seminal role in that 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 Memorial Prize in Economic Science in 1987 "for his contributions to the theory of economic growth" (Maler, 1992, p. 191).

After a quarter of a century, the consensus on economic growth reached during the early 1970s has collapsed under the weight of a massive accumulation of new empirical evidence, followed by a torrent of novel theoretical insights. The purpose of this essay is to initiate the search for a new empirical and theoretical consensus. An attempt at this thoroughly daunting task may be premature, because professional interest in growth currently appears to be waxing rather than waning.

Moreover, the disparity of views among economists, always looming remarkably large for a discipline that aspires to the status of a science, is greater in regard to the topic of growth than for most other topics.

The consensus of the early 1970s emerged from a similar period of fractious contention among competing schools of economic thought, and that alone is reason for cautious optimism. However, I believe that it is critically important to understand the strengths and weaknesses of the earlier consensus and how it dissolved in the face of subsequent theory and evidence. It is also essential to determine whether or not elements have survived that can provide a useful point of departure in the search for a new consensus.

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

With the benefit of hindsight, the most obvious deficiency of the neoclassical framework of Kuznets and Solow was the lack of a clear connection between the theoretical and the empirical components. That 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 at the same geographic location—Cambridge, Massachusetts.

Searching for analogies to describe this remarkable coincidence of views on growth, we can perhaps think of two celestial bodies in 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 that extraordinary event has been burned into the collective memory of economists, even if the details have long been forgotten. The common perspective that emerged remains the guiding star for subsequent conceptual development and empirical observation.

In section 7.2 we shall consider challenges to the traditional framework of Kuznets and Solow arising from new techniques for measuring economic welfare and productivity. The elaboration of production theory and the corresponding econometric techniques led to the successful implementation of constant quality measures of capital and labor inputs and investment-goods output. However, it was not until July 11, 1994, that the Bureau of Labor Statistics (BLS) incorporated those measures into a new official productivity index for the United States.

The recent revival of interest in economic growth by the larger community of economists can be dated from Angus Maddison's (1982) updating of Kuznets's (1971) long-term comparisons of economic growth among industrialized countries. That was followed by successful exploitation of the Penn World Table—created by Irving Kravis, Alan Heston, and Robert Summers—which provided comparisons among more than 100 developed and developing countries. Exploiting the panel-data structure of these comparisons, Nasrul Islam (1995) was able to show that the Solow model is the appropriate point of departure for modeling the endogenous accumulation of tangible assets.

The new developments in economic measurement and modeling summarized in section 7.3 have cleared the way for undertaking the difficult, if unglamorous, task of constructing quantitative models of growth suitable for analysis of economic policies. Models based on the neoclassical framework of Kuznets and Solow determine growth on the basis of exogenous forces, principally spillovers from technological innovations. By contrast, models based on the new framework described in section 7.4 determine the great preponderance of economic growth endogenously through investments in tangible assets and human capital.

Endogenous models of economic growth require the concepts of an aggregate production function and a representative consumer, concepts that can be implemented econometrically. These concepts imply measurements of welfare and productivity that can best be organized by means of a system of national accounts. The accounts must include production, income and expenditure, capital formation, and wealth accounts, as in the United Nations (1993) System of *National Accounts*. Alternative economic policies can then be ranked by means of equivalent variations in wealth, providing the basis for policy recommendations.

In section 7.5 we shall consider quantitative models suitable for the analysis of economic policies. Econometric techniques have provided the missing link between the theoretical and empirical components of the consensus of the early 1970s. The development of those techniques was a major achievement of the 1970s, though successful applications began to emerge only in the 1980s. These techniques were unavailable when Solow (1970) first articulated the objective of constructing econometric models of growth for analysis of economic policies.

The growth of tangible assets is endogenous within a Solow (1956, 1970) neoclassical growth model. Kun-Young Yun and I constructed a complete econometric model for postwar U.S. economic growth with this feature in two papers published in 1986 (Jorgenson and Yun, 1986a,b). We have used this model to analyze the economic impact of fundamental tax reforms. Subsequently, Mun Ho and I extended this model to incorporate endogenous growth in human capital, and we have employed the extended model to analyze the impact of alternative educational policies (Jorgenson and Ho, 2002).

Although endogenous investment in new technology has been a major theme in growth theory for four decades, empirical implementation has foundered on an issue first identified by Zvi Griliches (1973): measuring the output of research-and-development activities. Until this issue has been resolved, a completely endogenous theory of economic growth will remain a chimera, forever tantalizing to the imagination, but far removed from the practical realm of economic policy. Section 7.6 assesses the prospects for endogenizing investment in new technology and concludes this chapter.

7.2 Sources and Uses of Growth

The objective of modeling economic growth is to explain the sources and uses of economic growth endogenously. National income is the starting point for assessment of the uses of economic growth through consumption and saving. The concept of "a measure of economic welfare," introduced by William Nordhaus and James Tobin (1972), is the key to augmenting national income to broaden the concepts of consumption and saving. Similarly, gross national product is the starting point for attributing the sources of economic growth to investments in tangible assets and human capital, but could encompass investments in new technology as well.

The allocation of the sources of economic growth between investment and productivity is critical for assessing the explanatory power of growth theory. Only substitution between capital and labor inputs resulting from investment in tangible assets is endogenous in Solow's neoclassical model of economic growth. However, substitution among different types of labor inputs is the consequence of investment in human capital, and investment in tangible assets also produces substitution among different types of capital inputs. These were not included in Solow's 1957 model of production.

Productivity growth is *labor-augmenting* or equivalent to an increase in population in the simplest version of the neoclassical growth model. If productivity growth greatly predominates among the sources of economic growth, as indicated by Kuznets (1971) and Solow (1957), most of growth is exogenously determined. Reliance on the Solow residual as an explanatory factor is a powerful indictment of the limitations of the neoclassical framework. This viewpoint was expressed by Moses Abramovitz (1956), who famously characterized productivity growth as "a measure of our ignorance."

The appropriate theoretical framework for endogenous growth is the Ramsey model of optimal growth introduced by David Cass (1965) and Tjalling Koopmans (1965). A promising start on the empirical implementation of this model was made in my 1967 paper with Griliches (Jorgenson and Griliches, 1967). It appeared that 85 percent of U.S. economic growth could be made endogenous; determinants of the remaining 15 percent were left for further investigation, but might be attributable to investments in new technology.[1]

The conclusions of that paper (Jorgenson and Griliches, 1967) were corroborated in two subsequent studies (Christensen and Jorgenson, 1969, 1970). Those studies provided a markedly more detailed implementation of the concept of capital as a factor of production. We used a model of the tax structure for corporate capital income that had been developed in a series of papers with Robert Hall (Hall and Jorgenson, 1967, 1969, 197l). Christensen and I extended that model to noncorporate and household capital incomes in order to capture the impact of additional differences in returns to capital due to taxation on substitutions among capital inputs.

In 1973 we incorporated estimates of the sources of economic growth into a complete system of U.S. national accounts in our paper "Measuring Economic Performance in the Private Sector" (Christensen and Jorgenson, 1973).[2] Our main objective was the construction of internally consistent income, product, and wealth accounts. Separate product and income accounts were integral parts of both the U.S. National Income and Product Accounts and the United Nations (1968) *System of National Accounts* designed by Richard Stone.[3] However, neither system included wealth accounts consistent with the income and product accounts.

Christensen and I constructed income, product, and wealth accounts, paralleling the U.S. National Income and Product Accounts for the period 1929–1969. We implemented our vintage accounting system for the United States on an annual basis. The complete system of vintage accounts gave stocks of assets of each vintage and their prices. The stocks were cumulated to obtain asset quantities, providing the perpetual inventory of assets accumulated at different points in time or different vintages employed by Raymond Goldsmith (1955, 1962).

The key innovation in our vintage system of accounts was the use of and the rental prices employed in our constant quality index of capital input. In a prescient paper on the measurement of welfare, Paul Samuelson (1961, p. 309) had suggested that the link between asset and rental prices was essential for the integration of income and wealth accounting proposed by Irving Fisher (1930). Our system of accounts employed the specific form of this relationship developed in my 1967 paper "The Theory of Investment Behavior" (Jorgenson, 1967).

Christensen and I distinguished two approaches to the analysis of economic growth. We identified the production account with a production-possibilities frontier describing technology. The underlying conceptual framework was an extension of the aggregate production function—introduced by Paul Douglas (1948) and developed by Jan Tinbergen (1959) and Solow (1957)—to include two outputs, investment and consumption goods. These two outputs were distinguished in order to incorporate constant quality indices of investment goods.

We used constant quality indices of capital and labor inputs in allocating the sources of economic growth between investment and productivity. Our constant quality index of labor input combined different types of hours worked into a constant quality index of labor input, using the method Griliches (1930) had developed for U.S. agriculture. That considerably broadened the concept of substitution employed by Solow (1957) and altered, irrevocably, the allocation of economic growth between investment and productivity.[4]

Our constant quality index of capital input combined different types of capital inputs into a constant quality index. We identified input prices with rental rates, rather than the asset prices appropriate for the measurement of capital stock. For this purpose we used a model of capital as a factor of production that I had introduced in my 1963 article "Capital Theory and Investment Behavior" (Jorgenson, 1963). That made it possible to incorporate differences in returns due to the tax treatment of different types of capital income.[5]

Our constant quality measure of investment goods generalized Solow's (1960) concept of embodied technical change. My 1966 paper "The Embodiment Hypothesis" showed that economic growth could be interpreted, equivalently, as "embodied" in investment or "disembodied" in productivity growth (Jorgenson, 1966). My 1967 paper with Griliches removed that indeterminacy by introducing constant quality indices for investment goods (Jorgenson and Griliches, 1967).[6] The Bureau of Economic Analysis (1986a) has now incorporated a constant quality price index for investment in computers into the U.S. National Accounts.[7]

Constant quality price indices for investment goods of different ages or vintages were developed by Hall (1971). That important innovation made it possible for Hulten and Wykoff (1982) to estimate relative efficiencies by age for all types of tangible assets included in the national accounts, putting the measurement of capital consumption onto a solid empirical foundation. Estimates of capital inputs presented in my 1987 book with Gollop and Fraumeni were based on the Hulten-Wykoff relative efficiencies (Jorgenson, Gollop, and Fraumeni, 1987). The Bureau of Economic Analysis (1995) has incorporated these relative efficiencies into measures of capital consumption in the latest benchmark revision of the U.S. National Income and Product Accounts.[8]

Christensen and I identified the income and expenditure account with a social-welfare function. The conceptual framework was provided by the representation of intertemporal preferences employed by Ramsey (1928), Samuelson (1961), Cass (1965), Koopmans (1965), and Nordhaus and Tobin (1972). Following Kuznets (1961), we divided the uses of economic growth between current consumption and future consumption through saving. Saving was linked to the asset side of the wealth account through capital-accumulation equations for each type of asset. Prices for different vintages were linked to rental prices of capital inputs through a parallel set of capital-asset pricing equations.

The separation of production and welfare approaches to economic growth had important implications for the theory. The Ramsey model, so beautifully exposited by Solow (1970), had two separate submodels, one based on producer behavior, and the other on consumer behavior. The production account could be linked to the submodel of production, and the income and expenditure account to the submodel of consumption. That made it possible, at least in principle, to proceed from the design stage of the theory of economic growth, emphasized by Solow, to econometric modeling, which he accurately described as "much more difficult and less glamorous."[9]

In summary, the dizzying progress in empirical work on economic growth by 1973 had created an impressive agenda for future research. Christensen and I had established the conceptual foundations for quantitative models of growth suitable for analyzing the impact of policies affecting investment in tangible assets. However, critical tasks, such as construction of constant quality indices of capital and labor inputs and investment-goods output, remained to be accomplished. The final step in this lengthy process was completed only with the benchmark revision of the U.S. National Income and Product Accounts in September 1995.

7.3 The Growth Revival

On October 16, 1973, the Organization of Petroleum Exporting Countries (OPEC), acting as a cartel, initiated sharp increases in world petroleum prices that led to a rapidly deepening recession in industrialized countries, accompanied by a rise in inflation. Because that contradicted one of the fundamental tenets of the reigning Keynesian orthodoxy in macroeconomics, it engendered a shift in the focus of macroeconomic research from economic growth to stagflation. Debates among Keynesians ("old" and "new"), monetarists, and "new classical macroeconomists" took center stage, pushing disputes among the proponents of alternative views on economic growth into the background.

In graduate courses in macroeconomics the theory of economic growth was gradually displaced by newer topics, such as rational expectations and policy ineffectiveness. The elementary skills required for growth analysis—national-income and national-product accounting, index-number theory, the perpetual-inventory method, and intertemporal asset pricing—were no longer essential for beginning researchers and fell into disuse. Even the main points of contention in the rancorous debates over growth in the early 1970s began to fade from the collective memory of economists.

Like a water course that encounters a mountain range, the stream of research on endogenous growth continued to flow unabated and unobserved, gathering momentum for its later reemergence into the light of professional debate. When it did erupt in the early 1980s, the initial impulse threatened to wash away the entire agenda that had been laboriously put into place, following the canonical formulation of the neoclassical framework in the early 1970s. The renewed thrust toward endogenizing economic growth acquired startling but illusory force by channeling most of its energy into a polemical attack on the deficiencies of the "exogenous" theories of growth of Kuznets and Solow.

The flow of new talent into research on economic growth had been interrupted for a decade, sapping the high level of intellectual energy that had fueled the rapid progress of the early 1970s. The arrival of a new generation of growth economists in the early 1980s signaled a feverish period of discovery and rediscovery that is still under way. That has been followed by a revival of the latent interest of many economists in economic growth, after a substantial time lapse. The consequence of that time lapse has been a form of amnesia, familiar to readers who recall Washington Irving's fictional character Rip Van Winkle. To remedy this collective lapse of memory, it is essential to bring our story of the dissolution of the neoclassical framework up-to-date.

We can fix the revival of interest in economic growth among the larger community of economists with some precision at Angus Maddison's (1982) updating and extension of Kuznets's (1971) long-term estimates of the growth of national product for 14 industrialized countries, including the United States. Maddison added Austria and Finland to Kuznets's list and presented growth rates covering periods beginning as early as 1820 and extending through 1979. Maddison (1991, 1995) has extended these estimates through 1992. Attempts to analyze Maddison's data led to the "convergence debate" initiated by Moses Abramovitz (1986) and William Baumol (1986).

Denison (1967) had compared differences in growth rates for national income per capita for the period 1950–1962 with differences in levels in 1960 for eight European countries and the United States. He also compared the sources of these differences in growth rates and levels. The eight European countries as a whole were characterized by considerably more rapid growth and a lower level of national income per capita. However, that association was not monotonic for comparisons between individual countries and the United States. Nonetheless, Denison's conclusion was that "aside from short-term aberrations Europe should be able to report higher growth rates, at least in national income per person employed, for a long time. Americans should expect this and not be disturbed by it" (Denison, 1967, ch. 21).

Kuznets (1971) provided elaborate comparisons of growth rates for the 14 countries included in his study. Unlike Denison (1967), he did not provide comparisons of levels. Maddison (1982) filled that gap by comparing levels of national product for 16 countries. Those comparisons were based on estimates of purchasing-power parities by Irving Kravis, Alan Heston, and Robert Summers (1978).[10] Those estimates have been updated by successive versions of the Penn World Table.[11] These data have made it possible to reconsider the issue of convergence of productivity levels raised by Denison (1967).

Abramovitz (1986) was the first to take up the challenge of analyzing convergence of productivity levels among Maddison's 16 countries. He found that convergence appeared to characterize the postwar period, whereas the period before 1914 and the inter-war period revealed no tendencies for productivity levels to converge. Baumol (1986) formalized those results by running a regression of the growth rate of gross domestic product (GDP) per hour worked over the period 1870–1979 on the 1870 level of GDP per hour worked.[12]

In his notable paper "Crazy Explanations for the Productivity Slowdown," Paul Romer (1987) derived a version of the growth regression from Solow's (1970) growth model with a Cobb-Douglas production function. An important empirical contribution of the paper was to extend the data set for growth regressions from Maddison's (1982) group of 16 advanced countries to the 115 countries included in the Penn World Table (Mark-3), presented by Summers and Heston (1984). Romer's key finding was that an indirect estimate of the Cobb-Douglas elasticity of output with respect to capital was close to three-quarters. The share of capital in the gross national product (GNP) implied by Solow's model was less than half as great on average.[13] Gregory Mankiw, David Romer, and David Weil (1992) provided a defense of the neoclassical framework of Kuznets (1971) and Solow (1970). The empirical portion of their study is based on data for 98 countries from the Penn World Table (Mark-4), presented by Summers and Heston (1988). Like Romer (1987), Mankiw, Romer and Weil (1992) derived a growth equation from the Solow (1970) model; however, they augmented that model by allowing for investment in human capital.

The results of Mankiw, Romer and Weil (1992) produced empirical support for the augmented Solow model. There was clear evidence of the convergence predicted by the model; in addition, the estimated Cobb-Douglas elasticity of output with respect to capital was in line with the share of capital in the value of output. The rate of convergence of productivity was too slow to be consistent with the 1970 version of the Solow model, but was consistent with the augmented version.

Finally, Nasrul Islam (1995) exploited an important feature of the Summers and Heston (1988) data set overlooked in prior empirical studies. That panel-data set contained benchmark comparisons of levels of national product at five-year intervals, beginning in 1960 and ending in 1985. That made it possible for Islam to test an assumption maintained in growth regressions, such as those of Mankiw and associates. Their study, like that of Romer (1987), was based on cross sections of growth rates. Both studies assumed identical technologies for all countries included in the Summers-Heston data sets.

Substantial differences in overall levels of productivity among countries have been documented by Denison (1967), Christensen, Cummings, and Jorgenson (1981), and, more recently, Dougherty and Jorgenson (1996). By introducing econometric methods for panel data, Islam (1995) was able to allow for these differences in technology. He corroborated the finding of Mankiw, Romer and Weil (1992) that the elasticity of output with respect to capital input coincided with the share of capital in the value of output. That further undermined the empirical support for the existence of the increasing returns and spillovers analyzed in the theoretical models of Romer (1986, 1990b).

In addition, Islam (1995) found that the rate of convergence of productivities among countries in the Summers and Heston (1988) data set was precisely that required to substantiate the *unaugmented* version of the Solow model (1970). In short, "crazy explanations" for the productivity slowdown, such as those propounded by Romer (1987, 1994), are not required to explain the complexities of panels of data for advanced and developing countries. Moreover, the model did not require augmentation, as suggested by Mankiw, Romer and Weil (1992). However, differences in technology among these countries must be taken into account in econometric modeling of differences in growth rates.

The conclusion from Islam's (1995) research is that the Solow model is an appropriate point of departure for modeling the endogenous accumulation of tangible assets. For this purpose it is not essential to endogenize human-capital accumulation as well. The rationale for this key-empirical finding is that the transition path to reach balanced growth equilibrium requires decades after a change in policies, such as tax policies, that affect investment in tangible assets. By comparison, the transition after a change in policies affecting investment in human capital requires as much as a century.

Islam's conclusions have been strongly reinforced in two important papers by Charles Jones (1995a,b) testing alternative models of economic growth based on endogenous investment in new technology. Jones (1995a) tested models proposed by Romer (1990b), Grossman and Helpman (1991), and Aghion and Howitt (1992). The Jones model is based on an endogenous growth rate, proportional to the level of resources devoted to research and development (R&D). Jones (1995a) demonstrated that this implication of the model was contradicted by evidence from the advanced countries that conduct the great bulk of research and development. Although these countries have steadily increased the resources devoted to R&D, growth rates have been stable or declining.

Jones (1995b) also tested models of endogenous investment in new technology proposed by Romer (1986, 1987), Lucas (1988), and Rebello (1991), so-called AK models. These models feature a growth rate that is proportional to investment rate, and Jones (1995b) has shown that there are persistent changes in investment rates for advanced countries, but there are no persistent changes in growth rates. Jones concluded that "both AK-style models and the R&D-based models are clearly rejected by this evidence" (p. 519). Jones (1995a) suggested, as an alternative approach, models that make investment in new technology endogenous, but preserve the feature of the Solow model that long-run growth rates are determined by exogenous forces. We shall consider the remaining obstacles to implementation of this approach in section 7.6.

In summary, the convergence debate has provided an excellent medium for the revival of interest in growth. The starting point for this debate was the revival of Kuznets's program for research on long-term trends in the growth of industrialized countries by Maddison (1982, 1991, 1995). As the debate unfolded, the arrival of successive versions of the Penn World table engaged the interest of the new entrants into the field in cross-sectional variations in patterns of growth. However, a totally novel element appeared in the form of relatively sophisticated econometric techniques. In the work of Islam (1995), those techniques were carefully designed to bring out the substantive importance of cross-sectional differences in technology. That proved to be decisive in resolving the debate.

7.4 Endogenous Growth

Despite substantial progress in endogenizing economic growth over the past two decades, profound differences in policy implications militate against any simple resolution of the debate on the relative importance of investment and productivity. Proponents of income redistribution will not easily abandon the search for a "silver bullet" that could generate economic growth without the necessity of providing incentives for investment in tangible assets and human capital. Advocates of growth strategies based on capital formation will not readily give credence to claims of the importance of external benefits that spill over to beneficiaries that are difficult or impossible to identify.

The proposition that investment is a more important source of economic growth than productivity is just as controversial today as it was in 1973. The distinction between substitution and technical change emphasized by Solow (1957) parallels the distinction between investment and productivity as sources of economic growth. However, Solow's definition of investment, like that of Kuznets (1971), was limited to tangible assets. Both specifically excluded investments in human capital by relying on undifferentiated hours of work as a measure of labor input.

Kuznets (1971) and Solow (1957) identified the contribution of tangible assets with increases in the stock, which does not adequately capture substitution among different types of capital inputs. Constant quality indices of both capital and labor inputs and investment-goods output are essential for successful implementation of the production approach to economic growth. By failing to adopt these measurement conventions, Kuznets and Solow attributed almost all of U.S. economic growth to the Solow residual.[14]

To avoid the semantic confusion that pervades popular discussions of economic growth it is essential to be precise in distinguishing between investment and productivity. Investment is the commitment of current resources in the expectation of future returns, and it can take a multiplicity of forms. This is the definition introduced by Fisher (1906) and discussed by Samuelson (1961). The distinctive feature of investment as a source of economic growth is that the returns can be internalized by the investor. The most straightforward application of this definition is to investments that create property rights, including rights to transfer the resulting assets and benefit from incomes that accrue to the owners.[15]

Investment in tangible assets provides the most transparent illustration of investment as a source of economic growth. This form of investment creates transferable property rights with returns that can be internalized. However, investment in intangible assets through R&D also creates intellectual property rights that can be transferred through out-right sale or royalty arrangements and returns that can be internalized. Private returns to this form of investment—returns that have been internalized—have been studied intensively in the literature surveyed by Griliches (1994, 1995) and Bronwyn Hall (1996).

The seminal contributions of Gary Becker (1993), Fritz Machlup (1962), Jacob Mincer (1974), and Theodore Schultz (1961) have given concrete meaning to the concept of "wealth in its more general sense" employed by Fisher (1906). This notion of wealth includes investments that do not create property rights. For example, a student enrolled in school or a worker participating in a training program can be viewed as an investor. Although these investments do not create assets that can be bought or sold, the returns to higher educational qualifications or better skills in the workplace can be internalized. The contribution of investments in education and training to economic growth can be identified in the same way as for tangible assets.

The mechanism by which tangible investments are translated into economic growth is well understood. For example, an investor in a new industrial facility adds to the supply of assets and generates a stream of rental income. The investment and the income are linked through markets for capital assets and capital services. The income stream can be divided between the increase in capital input and the marginal product of capital or rental price. The increase in capital contributes to output growth in proportion to the marginal product. This is the basis for construction of a constant quality index of capital input.

Griliches (1973, 1979, 1995) has shown how investments in new technology can be translated into economic growth. An investor in a new product design or process of production adds to the supply of intellectual assets and generates a stream of profits or royalties. The increase in intellectual capital contributes to output growth in proportion to its marginal product in the same way as the acquisition of a tangible asset. However, investments in R&D, unlike those in tangible assets, frequently are internal to the firm, so that separation of the private return between the input of intellectual capital and the marginal product or rental price of this capital is highly problematical. The BLS (1994) and Griliches have provided estimates of the contributions of these investments to economic growth.

Finally, an individual who completes a course of education or training adds to the supply of people with higher qualifications or skills. The resulting income stream can be decomposed into a rise in labor input and the marginal product of labor or wage rate. The increase in labor contributes to output growth in proportion to the marginal product. This provides the basis for constructing a constant quality index of labor input. Although there are no asset markets for human capital, investments in human capital and nonhuman capital have the common feature, pointed out by Fisher (1906), that returns are internalized by the investor.

The defining characteristic of productivity as a source of economic growth is that the incomes generated by higher productivity are external to the economic activities that generate growth. These benefits spill over to income recipients not involved in these activities, severing the connection between the creation of growth and the incomes that result. Because the benefits of policies to create externalities cannot be appropriated, these policies typically involve government programs or activities supported through public subsidies. Griliches (1992, 1995) has provided detailed surveys of spillovers from investment in R&D.[16]

Publicly supported R&D programs are leading illustrations of policies to stimulate productivity growth. These programs can be conducted by government laboratories or financed by public subsidies to private laboratories. The justification for public financing is most persuasive for aspects of technology that cannot be fully appropriated, such as basic science and generic technology. The benefits of the resulting innovations are external to the economic units conducting the R&D, and these must be carefully distinguished from the private benefits of R&D that can be internalized through the creation of intellectual property rights.

An important obstacle to resolution of the debate over the relative importance of investment and productivity is that it coincides with ongoing disputes about the appropriate role for the public sector. Productivity can be identified with spillovers of benefits that do not provide incentives for actors within the private sector. Advocates of a larger role for the public sector advance the view that these spillovers can be guided into appropriate channels only by an all-wise and beneficent government sector. By contrast, proponents of a smaller government will search for means to privatize decisions about investments by decentralizing investment decisions among participants in the private sector of the economy.

Kevin Stiroh and I have shown that investments in tangible assets have been the most important sources of postwar U.S. economic growth (Jorgenson and Stiroh, 1995). These investments appear on the balance sheets of firms, industries, and the nation as a whole as buildings, equipment, and inventories. The benefits appear on the income statements of these same economic units as profits, rents, and royalties. The BLS (1983b) compiled an official constant quality index of capital input for its initial estimates of total factor productivity, renamed as multifactor productivity.

The BLS retained hours worked as a measure of labor input until July 11, 1994, when it released a new multifactor productivity measure incorporating a constant quality index of labor input as well as the BEA's (1986) constant quality index for investment in computers. The final step in empirically implementing a constant quality index of the services of tangible assets was incorporation of the Hulten and Wykoff (1982) relative efficiencies into the U.S. National Income and Product Accounts by the BEA (1995). Four decades of empirical research, initiated by Goldsmith's (1955–1956) monumental treatise *A Study of Saving*, have provided a sound empirical foundation for endogenizing investment in tangible assets.

Stiroh and I have shown that the growth of labor input is second in importance only to capital input as a source of economic growth. Increases in labor incomes have made it possible to measure investments in human capital and to assess their contributions to economic growth (Jorgenson and Stiroh, 1995). Jorgenson and Fraumeni (1989) extended the vintage accounting system developed by Christensen and Jorgenson (1973) to incorporate these investments. Our essential idea was to treat individual members of the U.S. population as human assets, with "asset prices" given by their lifetime labor incomes. Constant quality indices of labor input are an essential first step in incorporating investments in human capital into empirical studies of economic growth. We implemented our vintage accounting system for both human capital and non-human capital for the United States on an annual basis for the period 1948–1984.

Asset prices for tangible assets can be observed directly from market transactions in investment goods; intertemporal capital-asset pricing equations are used to derive rental prices for capital services. For human capital, wage rates correspond to rental prices and can be observed directly from transactions in the labor market. Lifetime labor incomes are derived by applying asset pricing equations to these wage rates. These incomes are analogous to the asset prices used in accounting for tangible assets in the system of vintage accounts developed by Christensen and Jorgenson (1973).

Fraumeni and I have developed a measure of the output of the U.S. education sector (Jorgenson and Fraumeni, 1992b). Our point of departure was that whereas education is a service industry, its output is investment in human capital. We estimated investment in education from the impact of increases in educational attainment on the lifetime incomes of all individuals enrolled in school. We found that investment in education, measured in this way, is similar in magnitude to the value of working time for all individuals in the labor force. Furthermore, the growth of investment in education during the postwar period exceeded the growth of market labor activities.

Second, we have measured the inputs of the education sector, beginning with the purchased inputs recorded in the outlays of educational institutions (Jorgenson and Fraumeni, 1992a). A major part of the value of the output of educational institutions accrues to students in the form of increases in their lifetime incomes. Treating these increases as compensation for student time, we evaluated that time as an input into the educational process. Given the outlays of educational institutions and the value of student time, we allocated the growth of the education sector to its sources.

An alternative approach, employed by Schultz (1961), Machlup (1962), Nordhaus and Tobin (1972), and many others, is to apply the Goldsmith (1955–1956) perpetual-inventory method to private and public expenditures on educational services. Unfortunately, this approach has foundered on the absence of a satisfactory measure of the output of the educational sector and the lack of an obvious rationale for capital consumption. The approach fails to satisfy the conditions for integration of income and wealth accounts established by Fisher (1906) and Samuelson (1961).[17]

Given vintage accounts for human capital and nonhuman capital, we (Jorgenson and Fraumeni, 1989) have constructed a system of income, product, and wealth accounts, paralleling the system I had developed with Christensen. In these accounts, the value of human wealth was more than 10 times the value of nonhuman wealth, and investment in human capital was 5 times the investment in tangible assets. We defined "full" investment in the U.S. economy as the sum of these two types of investments. Similarly, we added the value of nonmarket labor activities to personal-consumption expenditures to obtain "full" consumption. Our product measure included these new measures of investment and consumption.

Because our complete accounting system included a production account with "full" measures of capital and labor inputs, we were able to generate a new set of accounts for the sources of U.S. economic growth. Our system also included an income and expenditure account, with income from labor services in both market and nonmarket activities. We combined this with income from capital services and allocated "full" income between consumption and saving.[18] This provided the basis for a new "measure of economic welfare" and a set of accounts for the uses of U.S. economic growth. Our system was completed by a wealth account containing both human wealth and tangible assets.

We aggregated the growth of education and noneducation sectors of the U.S. economy to obtain a new measure of U.S. economic growth. Combining this with measures of input growth, we obtained a new set of accounts for the sources of growth of the U.S. economy. Productivity contributes almost nothing to the growth of the education sector and only a modest proportion to output growth for the economy as a whole. We also obtained a second approximation to the proportion of U.S. economic growth that can be made endogenous. Within a Ramsey model with separate education and noneducation sectors we find that exogenous productivity growth accounts for only 17 percent of growth.

The introduction of endogenous investment in education increases the explanatory power of the Ramsey model of economic growth to 83 percent. However, it is important to emphasize that growth without endogenous investment in education is measured differently. The traditional framework for economic measurement of Kuznets (1971) and Solow (1970) excludes nonmarket activities, such as those that characterize the major portion of investment in education. The intuition is familiar to any teacher, including teachers of economics: What the students do is far more important than what the teachers do, even if the subject matter is the theory of economic growth.

A third approximation to the proportion of growth that could be attributed to investment within an extended Ramsey model results from incorporation of all forms of investment in human capital. This would include education, child-rearing, and addition of new members to the population. Fertility could be made endogenous by using the approach of Barro and Becker (1988) and Becker and Barro (1988). Child-rearing could be made endogenous by modeling the household as a producing sector along the lines of the model of the educational sector outlined earlier. The results presented by Jorgenson and Fraumeni (1989) show that this would endogenize 86 percent of U.S. economic growth. This is a significant, but not overwhelming, gain in explanatory power for the Ramsey model.

In summary, endogenizing U.S. economic growth at the aggregate level requires a distinction between investment and productivity as sources of growth. There are two important obstacles to empirical implementation of this distinction. First, the distinctive feature of investment as a source of growth is that the returns can be internalized. Decisions can be successfully decentralized to the level of individual investors in human capital and tangible assets. Productivity growth is generated by spillovers that cannot be captured by private investors. Activities generating these spillovers cannot be decentralized and require collective decision-making through the public sector. Successive approximations to the Ramsey model of economic growth increase the proportion of growth than can be attributed to investment, rather than productivity.

7.5 Econometric Modeling

We are prepared, at last, for the most difficult and least glamorous part of the task of endogenizing economic growth—constructing quantitative models for the analysis of economic policies. The Ramsey growth model of Cass (1965) and Koopmans (1965) requires empirical implementation of two highly problematical theoretical constructs, namely, a model of producer behavior based on an aggregate production function and a model of a representative consumer. Each of these abstracts from important aspects of economic reality, but both have important advantages in modeling long-term trends in economic growth.

My 1980 paper "Accounting for Capital" presented a method for aggregating over sectors, the existence of an aggregate production function imposes very stringent conditions on production patterns at the industry level. In addition to value-added functions for each sector, an aggregate production function posits that these functions must be identical. Furthermore, the functions relating sectoral capital and labor inputs to these components must be identical, and each component must receive the same price in all sectors.[19]

Although the assumptions required for the existence of an aggregate production function appear to be highly restrictive, Fraumeni and I estimated that errors of aggregation could account for less than 9 percent of aggregate productivity growth (Fraumeni and Jorgenson, 1980, table 2.38, lines 4 and 11). In 1987 we published updated data on sectoral and aggregate production accounts in our book *Productivity and U.S. Economic Growth* (Jorgenson *et al.*, 1987). We generated the data for sectoral production accounts in a way that avoids the highly restrictive assumptions of the aggregate production function. These data were then compared with those from the aggregate production account to test for the existence of an aggregate production function. We demonstrated that this hypothesis is inconsistent with empirical evidence. However, our revised and updated estimate of errors arising from aggregation over industrial sectors explained less than 3 percent of aggregate productivity growth over the period of our study, 1948–1979 (Jorgenson, Gollop, and Fraumeni, 1987, table 9.5, lines 6 and 11).

Jorgenson, Gollop, and Fraumeni (1987) presented statistical tests of the much weaker hypothesis that a value-added function exists for each industrial sector, but that hypothesis was also rejected.[20] The conclusion of our research on production at the sectoral level was that specifications of technology such as the aggregate production function and sectoral valued-added functions result in substantial oversimplifications of the empirical evidence. However, these specifications are useful for particular but limited purposes. For example, sectoral value-added functions are indispensable for aggregating over sectors, and the aggregate production function is a useful simplification for modeling aggregate long-run growth, as originally proposed by Tinbergen (1942).

Sectoral value-added functions were employed by Hall (1988, 1990a) in modeling production at the sectoral level. In measuring capital and labor inputs, he adhered to the traditional framework of Kuznets (1971) and Solow (1970) by identifying labor input with hours worked, and capital input with capital stock. He found large apparent increasing returns to scale in the production of value added.[21] Producer equilibrium under increasing returns requires imperfect competition. However, Susanto Basu and John Femald (1997) have pointed out that the value-added data employed by Hall were constructed on the basis of assumptions of constant returns to scale and perfect competition.

Basu and Femald (1997) employed the strategy for sectoral modeling of production recommended by Jorgenson, Gollop, and Fraumeni (1987), treating capital, labor, and intermediate inputs symmetrically. They estimated returns to scale for the sectoral output and input data of Jorgenson (1990b) to be constant. Those data included constant quality measures of capital, labor, and intermediate input. Basu and Femald (1997) also showed that returns to scale in the production of value added are constant, when value added is defined in the same way as by Jorgenson, Gollop, and Fraumeni (1987) and constant quality measures of capital and labor inputs are employed.

Data for individual firms provide additional support for value-added production functions with constant or even decreasing returns to scale. Estimates incorporating intellectual capital have been surveyed by Griliches (1994, 1995) and Hall (1996). These estimates are now available for many different time periods and several countries. Almost all existing studies have employed value-added data for individual firms and have provided evidence for constant or decreasing returns to scale. This evidence is further corroborated by an extensive study of plant-level data by Baily, Hulten, and Campbell (1992) providing evidence of constant returns at the level of individual manufacturing plants.

Turning to the task of endogenizing investments in tangible assets and education, we first review the endogenous accumulation of tangible assets. An important objective of the Christensen and Jorgenson (1973) accounting system was to provide the data for econometric modeling of aggregate producer and consumer behavior. In 1973 we introduced an econometric model of producer behavior (Christensen, Jorgenson, and Lau, 1973). We modeled joint production of consumption and investment goods from inputs of capital and labor services, using data on these outputs and inputs from the aggregate production account.

In 1975 we constructed an econometric model of representative consumer behavior (Christensen, Jorgenson, and Lau, 1975). We estimated this model on the basis of data from the aggregate income and expenditure account of the Christensen and Jorgenson (1973) accounting system. We tested and rejected the implications of a model of a representative consumer. Subsequently we constructed a model of consumer behavior based on exact aggregation over individual consumers that specializes to the representative-consumer model for a fixed distribution of total expenditure over the population of consumers[22] (Jorgenson, Lau, and Stoker, 1982).

Yun and I constructed an econometric model for postwar U.S. economic growth with endogenous accumulation of tangible assets (Jorgenson and Yun, 1986a,b). Our model of consumer behavior involved endogenous labor-leisure choice, following Tinbergen's (1942) neoclassical econometric model of economic growth. Labor-leisure choice is exogenous in Solow's (1956) neoclassical model. In addition, we employed the Ramsey (1928) representation of intertemporal preferences to model saving-consumption behavior, following Cass (1965) and Koopmans (1965). In Solow's model the saving ratio is exogenous.

Econometric application of Ramsey's model of optimal saving was initiated by Robert Hall (1978), removing the final remaining gap between theoretical and empirical perspectives on economic growth.[23] That occurred only eight years after Solow's (1970) classic exposition of the neoclassical theory of growth! The key to Hall's achievement in 1978 was the introduction of an econometrically tractable concept of "rational expectations" that he combined with Ramsey's theoretical model. Building on Hall's framework, Hansen and Singleton (1982, 1983) have tested and rejected the underlying model of a representative consumer.

Yun and I have revised and updated our econometric model of U.S. economic growth and analyzed the consequences of the Tax Reform Act of 1986 for U.S. economic growth (Jorgenson and Yun, 1990). We have also considered alternative proposals for fundamental tax reform, including proposals now under consideration by the U.S. Congress, such as consumption-based and income-based value-added taxes. We found that the 1986 act resulted in a substantial increase in social welfare. However, we also discovered that several of the alternative proposals would have produced substantially higher gains.

Our econometric model of U.S. economic growth (Jorgenson and Yun, 1990, 1991a,b) provided the starting point for our endogenous growth model for the U.S. economy (Jorgenson and Ho, 2002). While my model with Yun endogenized capital input, the endogenous growth model also endogenizes investment in human capital. This model includes all of the elements of our Ramsey model of U.S. economic growth. However, the new model also includes a highly schematic model of production for the U.S. educational system.

Our production model includes a production-possibilities frontier for the noneducation sector that is analogous to the frontier in my papers with Yun (Jorgenson and Yun, 1990, 1991a). The model also includes a production function for the education sector, with investment in education as the output. The inputs include capital and labor services as well as purchases of goods and services from the noneducation sector. For both submodels we allow for exogenous growth of productivity; however, we have shown that this is negligible for the education sector (Jorgenson and Fraumeni, 1992a).

Ho and I have evaluated alternative educational policies through the equivalent variation in wealth associated with each policy (Jorgenson and Ho, 2002). As an alternative case we consider an educational policy that would raise the participation rates and policies, keeping taxes and expenditures constant. Presumably, this would result in a lower level of "quality." We also consider an alternative case that would retain the base-case participation rates, but raise "quality" by increasing expenditures on consumption goods and capital and labor services in the education sector and the corresponding taxes. Hanushek (1994) has shown that the second of these alternative policies, substantial improvement in educational quality through increased expenditure, is closely comparable to the actual educational policy pursued during the 1980s.

Jorgenson and Ho (2002) have shown that increasing participation rates without altering expenditure would produce substantial gains in social welfare. In this sense the quality level of the existing educational system is too high to be cost-effective. On the other hand, increasing the quality with no change in participation rates would result in a sizable loss in social welfare. These results are consistent with the literature on educational production functions surveyed by Hanushek (1986, 1989).[24]

With endogenous accumulation of tangible capital, as in the model of Jorgenson and Yun (1986a), almost three-quarters growth is endogenous. By contrast, the model with endogenous investment in education (Jorgenson and Ho, 2002) accounts for 83 percent of growth. By endogenizing fertility behavior and child-rearing it would be possible, at least in principle, to add an incremental three percentage points to the explanatory power of the Ramsey model of economic growth. Modeling population growth endogenously is clearly feasible. However, the construction of an econometric model with this feature would require considerable new data development and is best left as an opportunity for future research.

In summary, our endogenous models of growth (Jorgenson and Yun, 1986a,b; Jorgenson and Ho, 2002) require the econometric implementation of concepts of an aggregate production function and a representative consumer. While each of these concepts has important limitations, both are useful in modeling long-run economic trends. Furthermore, these concepts lead, naturally, to a substantial increase in the level of sophistication in data generation, integrating investment and capital into a complete system of national accounts.

7.6 Conclusion

The key innovation in economic measurement required for endogenizing growth is a wealth account that can be integrated with production and income and expenditure accounts. This encompasses the system of vintage accounts for tangible assets implemented by Christensen and Jorgenson (1973) as well as the vintage accounts for human capital developed by Jorgenson and Fraumeni (1989). These incorporate accumulation equations for tangible assets and human capital, together with asset pricing equations. Both are essential in constructing endogenous models of growth to replace the exogenous models that emerged from the professional consensus of the early 1970s.

The framework for economic measurement developed by Christensen and Jorgenson (1973) and Jorgenson and Fraumeni (1989) incorporates the principal features of the United Nations (1993) *System of National Accounts*. This provides a production account for allocating the sources of economic growth between investment and growth in productivity. It also includes an income-and-expenditure account for analyzing the uses of economic growth through consumption and saving. Alternative policies are ranked by means of equivalent variations in wealth for the representative consumer.

In principle, investment in new technology could be made endogenous by extending the accounting framework to incorporate investment in new technology. The BEA (1994) has provided a satellite system of accounts for R&D based on Goldsmith's (1955–1956) perpetual-inventory method, applied to private and public expenditures. Unfortunately, this is subject to the same limitations as the approach to human capital of Schultz (1961) and Machlup (1962). The BEA satellite system has foundered on the absence of a satisfactory measure of the output of R&D and the lack of an appropriate rationale for capital consumption.

The standard model for investment in new technology, formulated by Griliches (1973), is based on a production function incorporating inputs of services from intellectual capital accumulated through investment in R&D. Intellectual capital is treated as a factor of production in precisely the same way as tangible assets are treated by Christensen and Jorgenson (1973). Hall (1990) has developed the implications of this model for the pricing of the services of intellectual-capital input and the evaluation of intellectual-capital assets.[25]

Griliches (1973) represented the process of R&D by means of a production function that included the services of the previous R&D. That captures the notion of "standing on the shoulders of giants," originated by Jacob Schmookler (1966) and elaborated by Caballero and Jaffe (1993) and Jones and Williams (1996). Under constant returns to scale this representation also captures the "congestion externality" modeled by Jones and Williams (1996) and Stokey (1995). R&D, leading to investment in intellectual capital, is conducted jointly with production of marketable output, and this poses a formidable obstacle to measuring the output of new intellectual capital.

The model of capital as a factor of production that I first proposed in 1963 has been applied to tangible assets and human capital. However, implementation of this model for intellectual capital would require a system of vintage accounts including not only accumulation equations for stocks of accumulated R&D, but also asset pricing equations. These equations are essential for separating the revaluation of intellectual property due to price changes over time from depreciation of this property due to aging. This is required for measuring the quantity of intellectual-capital input and its marginal product.

Pricing of intellectual capital is the key issue remaining before investment in new technology can be endogenized in quantitative models for the analysis of alternative economic policies. Hall (1990) has constructed prices for stocks of accumulated intellectual capital from stockmarket valuations of the assets of individual firms. However, she points out that the high degree of persistence in expenditures on R&D at the firm level has made it virtually impossible to separate the effects of the aging of assets from changes in the value of these assets over time. Her evaluation of intellectual capital is conditional upon a pattern of relative efficiencies imposed on past investments in new technology.

Nonetheless, Hall's pioneering research on pricing of intellectual assets has yielded interesting and valuable insights. For example, the gross rate of return in the computer and electronics industry, including depreciation and revaluation of these assets, greatly exceeds that in other industries. This can be rationalized by the fact that revaluation in this industry, as measured by Hall, is large and negative, mirroring the rapid decline in the price of the industry's output. This is evidence for the empirical significance of the process of creative destruction described by Schumpeter (1942) and modeled by Aghion and Howitt (1992), Stokey (1995), and Jones and Williams (1996). Because revaluation enters negatively into the gross rate of return, this rate of return exceeds that for industries with positive revaluations.

Another important result that emerges for Hall's (1996) survey of gross rates of return to R&D is the repeated finding that investment funded by the federal government has zero private return. Even private firms conducting this research under government contract have been unable to internalize the returns. This has the very important policy implication that public investments in new technology can be justified only by comparisons of the costs and benefits to the government. Measurement of these benefits requires careful case studies like those of civilian space technology by Henry Hertzfeld (1985) and commercial aircraft by David Mowery (1985). Grandiose visions of spillovers from public R&D have been exposed as rapidly fleeting mirages.

The final issue that must be resolved in order to complete the endogenization of economic growth is modeling of spillovers. Griliches (1995) has provided a detailed survey of alternative methods and results, based on the model he originated in 1979. The essential idea is to include aggregate input of intellectual capital, together with the inputs of individual producers, as determinants of output. Unfortunately, this requires precisely the same separation of marginal product and capital input for intellectual capital needed for the identification of returns that can be internalized by the individual producer.

Caballero and Lyons (1990, 1992) have attempted to circumvent the problem of measuring intellectual capital by including aggregate output as a determinant of sectoral productivity. However, Basu and Femald (1995) have shown that the positive results of Caballero and Lyons depend on the same value-added data employed by Hall (1988, 1990a). Treating capital, labor, and intermediate inputs symmetrically, as in their research on economies of scale, Basu and Femald have shown that the evidence for spillovers evaporates. This leaves open the question of the importance of spillovers from investment in new technology, which must await satisfactory measures of the output of R&D.

An elegant and impressive application of the Griliches (1979) framework for modeling spillovers across international boundaries has been presented by Coe and Helpman (1995). The key idea is to trace the impact of those spillovers through trade in intermediate goods. For each country the stock of accumulated R&D of its trading partners is weighted by bilateral import shares. However, Keller (1998) has shown that the evidence of spillovers is even more impressive if the bilateral trade shares are assigned randomly, rather than matched with the countries conducting the R&D. Another vision of spillovers can be assigned to the lengthening roll of unproven theoretical hypotheses.

In summary, a great deal has been accomplished, but much remains to be done to complete the endogenization of economic growth. An important feature of recent research has been the linking of theoretical and empirical investigations, as in the seminal papers of Romer (1986, 1987, 1990b). This integration need no longer be left to the remarkable coincidence of empirical and theoretical perspectives that led Kuznets (1971) and Solow (1970) to the neoclassical framework. In the absence of a clear and compelling link between the theoretical model and the data-generation process, the breakdown of this framework had left economists without a guide to long-run economic policy for two decades.

Fortunately, a new empirical and theoretical consensus on economic growth would require only a relatively modest reinterpretation of the neoclassical framework established by Solow (1956, 1970, 1988), Cass (1965), and Koopmans (1965). However, the traditional framework of economic measurement established by Kuznets (1961, 1971) and embedded in the U.S. National Income and Product Accounts will have to be augmented considerably. The most important change is a reinterpretation of the concepts of investment and capital to encompass Fisher's (1906) notion of "wealth in its more general sense."

In closing I must emphasize that my goal has been to provide a new starting point in the search for a consensus on economic growth, rather than to arrive at final conclusions. The new framework I have outlined is intended to be open-ended, permitting a variety of different approaches to investment—in tangible assets, human capital, and new technology. There is also ample, if carefully delimited, space within this framework for endogenizing spillovers by using the Lindahl-Samuelson theory of public goods. New entrants to the field will continue to find a plethora of opportunities for modeling economic growth.

Notes

1. 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 Edward Denison (1974, p. 56) pointed out. For additional details, see Jorgenson, Gollop, and Fraumeni (1987, pp. 179–181).

2. This paper was presented at the 37th meeting of the Conference on Research in Income and Wealth, held at Princeton, New Jersey, in 1971.

3. The United Nations *System of National Accounts* (SNA) is summarized by Stone (1992) in his Nobel Prize address. The SNA has been revised (United Nations, 1993).

4. Constant quality indices of labor input are discussed in detail by Jorgenson, Gollop and Fraumeni (1987, chapters 3 and 8, pp. 69–108, 261–300) and Jorgenson, Ho, and Fraumeni (1994).

5. A detailed survey of empirical research on the measurement of capital input is given in my 1996 paper "Empirical Studies of Depreciation" (Jorgenson, 1996a) and Jack Triplett's (1996b) paper, "Measuring the Capital Stock: A Review of Concepts and Data Needs," both presented a meeting of the Conference on Research in Income and Wealth, held at Washington, D.C., in May 1992.

6. A detailed history of constant quality price indices is given by Ernst Berndt (1991). Triplett's (1990) contribution to the jubilee of the Conference on Research in Income and Wealth discusses obstacles to the introduction of these indices into government statistical

programs. Robert Gordon (1990) constructed constant quality indices for all types of producers' durable equipment in the national accounts, and Paul Pieper (1989, 1990) gave constant quality indices for all types of structures.

7. Cole *et al.* (1986) reported the results of a joint project conducted by the Bureau of Economic Analysis (BEA) and IBM to construct a constant quality index for computers. Triplett (1986) discussed the economic interpretation of constant quality price indices in an accompanying article. Dulberger (1989) presented a more detailed report, while Triplett (1989) gave an extensive survey of empirical research on constant quality price indices for computers. Allan Young (1989) answered Denison's (1989) objections and reiterated the BEA's rationale for introducing a constant quality price index for computers.

8. The method is described by Fraumeni (1997).

9. See Solow (1970, p. 10.5). He went on to remark, "But it may be what God made graduate students for. Presumably he had something in mind."

10. For details, see Maddison (1982, pp. 159-168). Purchasing-power parities were first measured for industrialized countries by Gilbert and Kravis (1954) and Gilbert *et al.* (1958).

11. A complete list through Mark-5 is given by Summers and Heston (1991), and the results for Mark-6 are summarized in the *World Development Report 1993* (World Bank, 1994b).

12. This "growth regression" has spawned a vast literature, summarized by Levine and Renelt (1992), Baumol (1994), and Barro and Sala-i-Martin (1994). Much of this literature has been based on successive versions of the Penn World Table.

13. Unfortunately, this Mark-3 data set did not include capital input. Romer's empirical finding has spawned a substantial theoretical literature, summarized at an early stage by Lucas (1988) and, more recently, by Grossman and Helpman (1991, 1994), Romer (1994), and Barro and Sala-i-Martin (1994). Romer's own important contributions to this literature have focused on increasing returns to scale (Romer, 1986) and spillovers from technological change (Romer, 1990b).

14. The measurement conventions of Kuznets and Solow remain in common use. See, for example, the references given in my article "Productivity and Economic Growth" (Jorgenson, 1990b), presented at the jubilee of the Conference on Research in Income and Wealth, held in Washington, D.C., in 1988. For recent examples, see Baily and Gordon (1988), Englander and Mittelstadt (1988), Blanchard and Fischer (1989, pp. 2–5), Baily and Schultz (1990), Gordon (1990), Englander and Gurney (1994), and Lau (1996).

15. Fisher (1906, ch. 2, pp. 18–40) discussed property rights.

16. Griliches (1992) also provided a list of survey papers on spillovers. Griliches (1979, 1995) has shown how to incorporate spillovers into a growth accounting.

17. For more detailed discussion, see Jorgenson and Fraumeni (1989).

18. Our terminology follows that of the Becker (1965, 1993) theory of time allocation.

19. A detailed survey of econometric modeling of production is included in my paper "Econometric Modeling of Producer Behavior" (Jorgenson, 1986). This is also the focus of Solow's 1967 survey article "Some Recent Developments in the Theory of Production." The conceptual basis for the existence of an aggregate production function was provided by Robert Hall (1970).

20. Jorgenson, Gollop, and Fraumeni (1987, table 7.2, pp. 239–241). The existence of an aggregate production function requires identical value-added functions for all sectors.

21. Hall (1990a) reported the median degree of returns to scale in value added for two-digit U.S. manufacturing industries of 2.2!

22. A survey of empirical approaches to aggregation was given by Stoker (1993).

23. Hall's 1978 paper and his subsequent papers on this topic have been reprinted in his book The *Rational Consumer* (1990b). Hall (1990b) and Deaton (1992) have presented surveys of the literature on econometric modeling of consumer behavior within the Ramsey framework.

24. Note that the meaning of "production function" in this context is different from the meaning of this term in our model of the education sector. In Hanushek's terminology the output of the education sector is measured in terms of measures of educational performance, such as graduation rates or test scores. Our terminology is closer to the Hanushek (1994) concept of "value added" by the educational system. The output of the education system is the addition to the lifetime incomes of all individuals enrolled in school.

25. These implications of the model are also discussed by Jones and Williams (1996).

8

Policies to Stimulate Economic Growth

Mun S. Ho and
Dale W. Jorgenson

8.1 Introduction

This chapter examines policies that affect human capital accumulation and hence the rate of economic growth. The influential theoretical work since the 1980s that extended growth models to include human capital and scale economies has renewed empirical research into the economic growth of nations. Among these are Paul Romer (1990b), Robert Barro (1991), Gregory N. Mankiw, David Romer and David Weil (1992), Ross Levine and David Renelt (1992), and Nazrul Islam (1995). While this research is far from being conclusive, they suggest an important role for human capital.

These empirical studies use data from a panel of countries to test various models of growth. Typically this has consisted of putting post-war 2 GDP growth on the left-hand side of regressions. Paul Romer (1990), finding implausible savings coefficients, rejects the standard Solow model and suggests that production externalities be considered. Barro (1991) and Barro and Xavier Sala-i-Martin (1991) using a different approach found that economic growth rates across states and countries are converging, albeit at a slow rate of some two percent per year. This is regarded by some as evidence for the Solow model and a rejection of models that imply nonconvergence.

Mankiw, David Romer and Weil (1992) find that while the standard Solow model fitted the data poorly, the Solow framework extended to include human capital provided a good explanation of post-1960 world growth rates.[1] They rejected Paul Romer's (1990) attribution of growth to externalities in the accumulation of physical capital and concluded that a model without externalities, but with savings expanded to include investment in human capital, provides "the best framework" to analyze growth. They point out that countries with similar exogenous parameters should converge in income per capita but at a rate slower than that predicted by the standard Solow model without human capital.

Further evidence of convergence comes from Levine and Renelt (1992). They examined carefully the sensitivity of these cross-country regressions and found a "robust" negative correlation between initial income and post-1960 growth rates.[2] With different data sets they estimated that investment share, secondary school enrollment, population growth and initial income explain about half of the variance in growth rates. They also find that indicators of fiscal and trade policies are not robustly correlated with growth. Islam (1995), using panel data methods that permit unobservable country-specific differences in the growth regressions, also finds convergence in growth rates.

The research cited above uses regressions of reduced form equations. While they provide convenient summary correlations and may have the power to reject particular theories of growth, they do not give an exact accounting of the sources of growth, nor do they provide a model to give a structural explanation of how the production of human capital affects growth over time. There is, however, another strand of research that has extended the "growth accounting" method to include human capital. Jorgenson and Fraumeni (1989), using data on wages and educational attainment, calculated the stock of physical and human capital. By their definitions, the stock of human capital is 13 times that of tangible private capital. Similarly, less than 20 percent of the extended definition of national savings is in physical capital; the rest is savings in human capital.

Jorgenson and Fraumeni (1992a) then calculate the contribution of the various factors to U.S. economic growth. They find that technical progress (the "Solow residual") contribute only 1.02 percent of the postwar average annual growth rate of 3.29 percent. The growth of physical capital accounted for 1.31 percent, while changes in labor input contributed 0.96 percent. One-quarter of this 0.96 percent is due to changes in composition of the labor force as educational attainment rises and the age profile becomes older; i.e., due to changes in the quality of human capital.

Given the important role of human capital in these growth accounts, Jorgenson and Fraumeni (1992b) produce a further set of calculations that treat the education sector explicitly and separately. (In the empirical studies cited above, human capital is often proxied by some measure of formal schooling of the population). Most previous work (John

Kendrick, 1976; Robert Eisner, 1989) define the output of the education industry as equal to the sum of the inputs, since there are no market prices for much of the industry that is run by state and local governments. Jorgenson and Fraumeni's contribution is to calculate an independent measure of output. This is measured as increases to the stock of human capital due to rising educational attainment, where human capital is defined as lifetime income. The education industry's output defined in this way is almost as large as the traditional measure of GNP.

In this chapter we employ the human capital approach of Jorgenson and Fraumeni in a growth model to examine how the education sector, as producers of human capital, affect economic growth. Given the strong empirical support for convergence models, as opposed to models with externalities that allow for perpetual endogenous growth as in Robert Lucas (1988) or Paul Romer (1990b), we use an extended Cass-Koopmans model that includes both physical and human capital. This model, however, does share an important feature with the Lucas-type models—resources must be diverted from current consumption and physical investment to have more future human capital.[3]

Our model has infinite-life households, in contrast to other numerical models that use overlapping generations, e.g., John Laitner (1993), James Davies and John Whalley (1991), and James Heckman, Lance Lochner and Christopher Taber (1998).[4] Both Laitner and our models, however, use production functions that are characterized by constant returns to scale and does not have perpetual growth outside of exogenous technical progress. Davies and Whalley's model has myopic expectations unlike this and the other two models which have perfect foresight.

Our aim is to show how different levels of inputs into the education sector—teachers, schools and student time—would affect both the transition path and the steady state of the economy. Spending more on education means more taxes, sending more students to school means a smaller current supply of labor. These effects are captured in a dynamic general equilibrium model with a savings rate for human capital investment much like the savings rate for physical investment in the standard Solow model.

We find that current spending on education may be excessive. Welfare over the life of the economy may be improved by reducing expenditures on formal education and lowering taxes. On the other hand, higher rates of enrollment, and the associated higher expenses, will raise welfare.

Our model is estimated over U.S. data from the entire postwar period. This is in contrast to the usual calibrated models as, for example, in

Davies and Whalley (1991). The functional forms employed allow for subsitution among inputs, e.g., teachers for equipment.

In the next section we describe the U.S. education sector in some detail, and in section 8.3 the main features of the model are laid out. The simulation results of the model are given in sections 8.5 and 8.6.

8.2 The Education Sector and Human Capital

The link between education and human capital goes back at least to Gary Becker (1964) and Jacob Mincer (1974). They have emphasized how the education sector, by raising the level of skills of workers, i.e., producing more human capital, raises total economic output. Early attempts to quantify the education sector and how it contributes to growth usually involve running wage regressions with educational attainment on the right-hand side. A good example is Eugene Kroch and Kriss Sjoblom (1986).

In this chapter we use the more direct approach of Dale W. Jorgenson and Barbara Fraumeni (1992a,b) [hereafter JF] to calculate investment in human capital based on education data. They define the human capital of a person in a given sex, age, and education category as the discounted stream of his "full income." Full income is labor income plus imputations to leisure time, where the price of leisure is the after-tax wage. Each category has its own wage rate and number of hours worked. People in different categories thus have different amounts of human capital. This approach provides quite a bit more detail than calculations using estimates from wage regressions. It is also different from most other work, e.g., Kendrick (1976), which use only labor income in the definition of human capital.

Denoting the value, or price, of the human capital of a person of sex s, age a, and education attainment e, by P^H_{sae} we have

$$P^H_{saet} = P^{Hm}_{saet} + P^{Hn}_{saet} \tag{8.1}$$

where the superscript m denotes the component due to participation in the labor market and n denotes the one due to nonmarket leisure activities (24 hours minus labor time, school time and 10 hours for personal maintenance). The time subscript t will be suppressed unless necessary. Each of the two components of human capital is the discounted stream of lifetime income. This is defined recursively as follows.

A person at age 75 or older is assumed to command a zero wage and therefore have zero P^H's. At other ages the value of human capital per capita at a particular age is the annual income at that age, plus the discounted human capital of a person a year older. The capital of "a year older" is the average of those that went for another year of schooling and those who did not

$$P^{Hm}_{saet} = y^m_{sae} + [e_{sae}s_{s,a+1}P^{Hm}_{s,a+1,e+1,t+1} + (1 - e_{sae})s_{s,a+1}P^{Hm}_{s,a+1,e,t+1}]\frac{1}{1+d}, \tag{8.2}$$

where y^m_{sae} is the market labor income for one period, $s_{s,a+1}$ is the survival probability of a person at age a making it to age $a+1$ and e_{sae} is the school enrollment rate. The first term in the brackets is for those who reached a higher level of education attainment by the next period, while the second term is for those who stopped going to school. The rate of discount between t and $t+1$ is denoted by d.

The equation as written contains P^H_{t+1}, and cannot be used since future wages are not known. To make it operational, it is assumed that wages grow at a constant rate μ. That is, a person of age a today will get at time $t+1$ a wage equal to that of a person at age $a+1$ today times $1+\mu$. Thus

$$P^{Hm}_{saet} = y^m_{sae} + [e_{sae}s_{s,a+1}P^{Hm}_{s,a+1,e+1,t} + (1 - e_{sae})s_{s,a+1}P^{Hm}_{s,a+1,e,t}]\frac{1+\mu}{1+d}. \tag{8.3}$$

An identical equation holds for the nonmarket component, P^{Hn}_{sae}, with a corresponding flow of nonmarket income y^n_{sae}. (The economy total market labor income, y^m, was some $2520 billion in 1987 while y^n was $6536 billion. These estimates, and others below, are from the accounts described in JF and updated.)

Multiplying this human capital per capita by the number of people in each sae category, N_{sae}, and aggregating over all 2700 categories, we obtain the economy's stock of human capital and its price

$$P^H_t, H_t \leftarrow \text{Divisia aggregate } (P^H_{sae}, N_{sae}) \quad s = 1, 2;\ a = 0, 1, \ldots, 75;\ e = 1, \ldots, 18. \tag{8.4}$$

The stock of human capital in the United States as defined above is estimated by JF to be $268.6 trillion in 1986. The stock of physical capital (in the private sector), in contrast, was only $16.1 trillion.[5]

To complete a growth model we need both stocks and flows of capital. The stock of human capital is changed by investment, depreciation due to aging, births and immigration of new residents, and deaths. The annual gross investment in human capital per capita is the increment to lifetime income due to an extra year of formal education

$$P^{IH}_{sae} = e_{sae}(P^{H}_{s,a,e+1} - P^{H}_{s,a,e}). \tag{8.5}$$

Aggregating these P^{IH}_{sae}'s over all the *sae* groups gives the annual economy investment in human capital,

$$P^{IH}_{t}, I^{H}_{t} \leftarrow \text{Divisia aggregate of } (P^{IH}_{sae}, N_{sae})$$
$$s = 1, 2;\ a = 0, 1, \ldots, 75;\ e = 1, \ldots, 18. \tag{8.6}$$

We consider this aggregate investment in human capital I^{H}_{t}, to be the output of the education sector. This is a measure of output that is independent of the inputs. The total gross investment in I^{H} was \$3780 billion in 1986. This should be contrasted with the GNP in that year of \$4230 billion. If the education sector is estimated from the amounts paid to the *inputs*, as in other studies, the figure for 1986 would be only \$277 billion.[6]

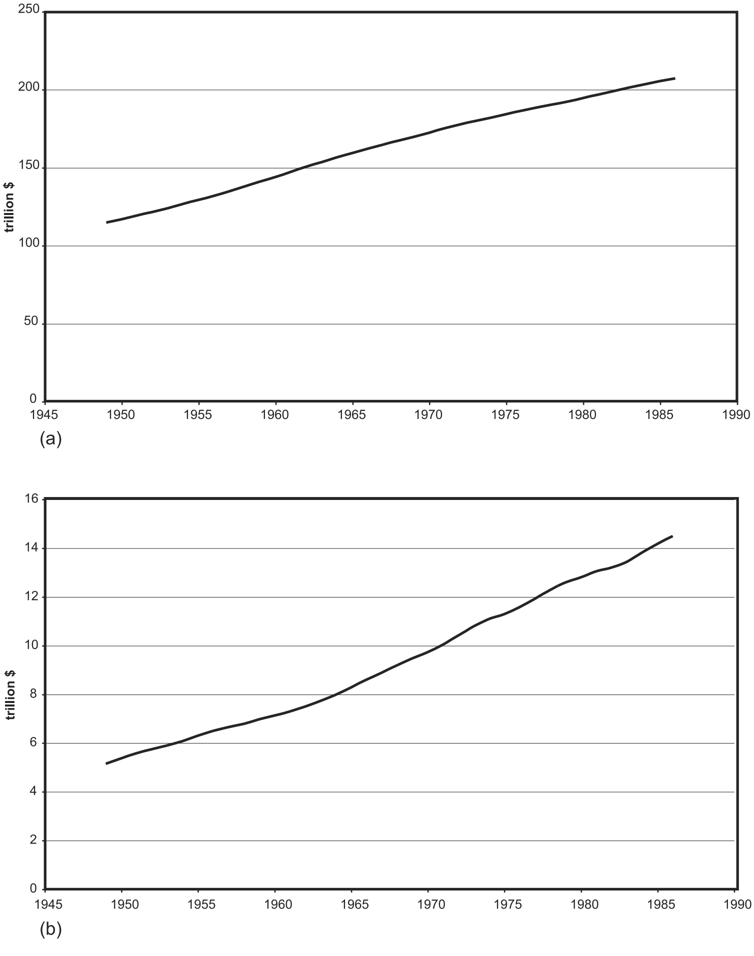
The second flow item affecting the stock of human capital is the change due to aging. Holding sex and education attainment fixed, the wage-age profile first rises and then falls. On average it falls with age. In addition, a fraction of each age group dies every period. In parallel with the terminology for physical capital, we label these changes "depreciation." Denoting the rate of depreciation by δ^{H}, the annual loss is

$$\delta^{H} H_{t-1} = -\sum_{sae}(P^{H}_{sa+1et} - P^{H}_{saet})N_{saet-1}. \tag{8.7}$$

The aggregate accumulation equation can now be written as

$$H_t = \Delta N_t + (1 - \delta^{H})H_{t-1} + I^{H}_{t}, \tag{8.8}$$

where ΔN are the exogenous changes in the stock of human capital due to births, deaths and net immigration. Figure 8.1 graphs the postwar path of U.S. human capital. For comparison, the stock of physical capital, K_t (defined below) is also given. In this period H_t has been growing at an average of some 0.70 percent per year while K_t grew at 1.22 percent.

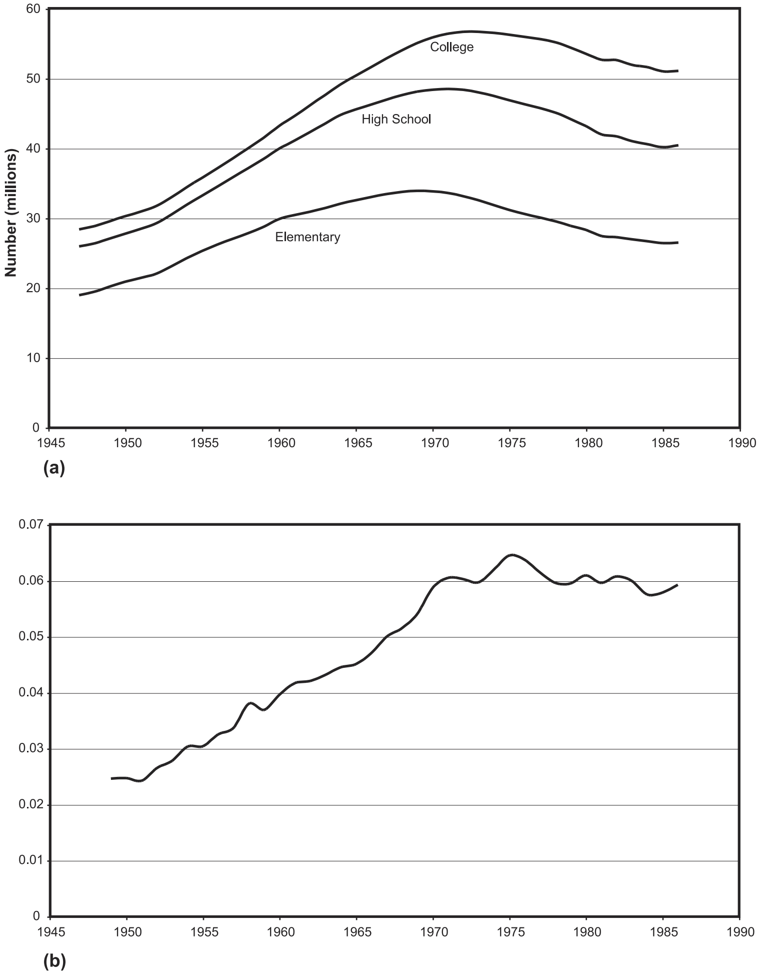


Note: Data are in 1982 dollars.

Figure 8.1
(a) Human capital of the United States and (b) capital of the United States.

8.2.1 Modeling the Production of Human Capital

The formal education sector in the United States consists of state and local government-run public schools and a smaller subsector of privately-run institutions. Public schools and universities employed some 7.6 million workers in 1989 while the private sector (for profit and non-profit) had 1.7 million. These constituted about 8.2 percent of the employed



Note: This is the tangible costs of education (teacher salaries, books, schools) divided by GDP.

Figure 8.2
(a) Student enrollment and (b) education cost as share of GDP.

work force in 1989. In terms of expenditures the public sector share is about 78 percent of the total. In what follows, the sum of these two subsectors is our education sector. The postwar school enrollments are graphed in the top panel of figure 8.2. In 1986 there were a total of 51.1 million students.

As noted in section 8.1, the important feature of this, and other growth models, is that resources are required today to produce human capital for use in the future. To model the education sector we characterize the output as being produced by four inputs—capital (schools and equipment), labor (teachers), intermediate goods (books and other nondurables) and student time

$$I_t^H = f(K^{Hd}, L^{Hd}, C^{Hd}, L^{ST}, t), \tag{8.9}$$

where K^{Hd} is the demand for capital, L^{Hd} is demand for labor, and C^{Hd} is the use of nondurables. L^{ST} is an index of aggregate student time. The time argument is to capture technical progress.

The use of function (8.9) for modeling the production of human capital requires further discussion. In computing human capital we have defined gross investment as the increment to lifetime income due to an extra year of education (equation (8.5)). This ignores factors like level of education expenditures, teacher-student ratios, SAT scores, etc. It would be extremely difficult to separate the effects of cohort and these quality of education factors that have been gradually changing over time.[7]

On the other hand, we wish to capture the point at which resources other than student time are required for the production of human capital. There is evidence that the quantity of inputs, e.g., teachers, matter to lifetime income, i.e., human capital. David Card and Alan Krueger (1992) found a significant relation between wages and quality indicators like teacher-student ratios, teacher salaries and term length.[8] The simplest way to implement this in a Solow model is to have a function with students and education inputs as arguments, and imposing constant returns to scale. Hence equation (8.9).

The education sector is unique in that it is mostly run by public or non-profit organizations. Furthermore, laws require that minors attend school while attendance at colleges are voluntary. We find it useful to characterize this sector as being populated by competitive cost-minimizing firms with the difference that they are given an exogenous number of students as one of the inputs. The choice of the other inputs are made endogenously, given prices and quantity of students.

JF reports estimates of all five time series in equation (8.9) for the sample period 1948–1986. The tangible cost items, K^{Hd}, L^{Hd}, and C^{Hd}, constitute only about 7.5 percent of the value of output. The value of student input is the residual imposing a zero-profit condition on the education sector

$$P^{LST} L^{ST} = P^{IH} I^H - P^{Kd} K^{Hd} - P^L L^{Hd} - P^C C^{Hd}. \tag{8.10}$$

The price of student time P^{LST} is *not* the familiar opportunity cost of forgone wages of going to school. It is the increment to lifetime income due to another year of education, less the tangible costs of schooling. In other words, it is the amount the average student should be willing to pay for an extra year of education (assuming our rate of discount and ignoring the risk aversion to the uncertainty of survival).

The quantity of student input is the aggregate of all students weighted by prices that are consistent with zero-profit identities like the one above for each education subsector—elementary schools, secondary schools and higher education. (See JF for details.)

In the numerical implementation of the model, the production function (equation 8.9) is written in a way that allows the elasticity of substitution to be freely estimated (unlike the common Cobb-Douglas form). We use the price dual function

$$P^{IH} = \tilde{f}(P^{Kd}, P^{Ld}, P^{C}, P^{LST}, t). \tag{8.11}$$

The precise form and parameter estimates are given in table 8.2. Constant returns to scale is imposed on this function.

In our general equilibrium growth model the household is required to buy the output of the education sector (in the same spirit that students are required to go to school). At the same time, we have the government giving an "education subsidy" to the household to match the actual situation where students do not pay fees directly to public schools and out-of-pocket costs are only a small fraction of total costs. The amount of the implied subsidy is set to mimic the actual public educational expenses.

To pin down the size of the education sector in the model (recall that student time is fixed but the other inputs are endogenously determined), we further specify that the government fix the level of tangible education expenditures. This is done by setting exogenously the fraction of national income to be devoted for such expenses (everything except the value of student time). This is described algebraically below.

This approach is in contrast to other models (e.g., Lucas, 1988) where the student time is endogenously determined. We shall comment on this further in the concluding section. We would note here that this model is more realistic in that resources other than student time are required to produce human capital.

Our exclusion of human capital stock as an argument of this production function is unlike many models including Heckman, Lochner, and

Taber's (1998) but is similar to Davies and Whalley (1991). Models that use human capital to produce human capital may generate endogenous growth. Our approach deliberately avoids this.

8.3 A Dynamic Model with Human Capital

Our model extends the one in Jorgenson and Yun (1986b) to include the education sector described in section 8.2. Jorgenson and Yun's model is a Cass-Koopmans type model with perfect foresight and endogenous saving rates. Our extension here to a government-determined rate of savings in human capital makes it a hybrid "Cass-Koopmans-Solow" model. We shall give only a brief description of the main features of the model here and focus instead on the human capital sector. The details are in Ho and Jorgenson (1994). The input-output structure of the model is given in table 8.1.

There are three agents in the model—consumer, producer, and government. The aggregate consumer owns the initial capital stock and maximizes a discounted sum of future consumption. The consumer is also endowed with human capital which gives time that can be allocated to work, leisure or schooling. The economy produces two types of output—goods and human capital. Goods are used for private and public consumption, and for augmenting the physical capital stock. The public sector imposes taxes on capital, labor and goods on one hand, and buys goods and labor on the other. This is a closed economy model and the external trade sector is characterized exogenously.

In this economy with perfect foresight, constant returns to scale, no adjustment costs and no externalities, the decentralized market outcome

Table 8.1
Input-output structure of model

	Industry			Final Demands			
	Goods	Educ.	Enterp.	C	I	G	X
Goods		C^H	0	C	I^d	$C^G + I^G$	$C^R + I^R$
Educ.	0		0	I^H	0	0	0
Enterp.	0	0		C^E	0	0	0
Capital	K^d	K^{Hd}	0	0	0	0	0
Labor	L^d	L^{Hd}	L^E	0	0	L^G	L^R
Student	0	L^{ST}	0	0	0	0	0

is the same as the planning solution. If the problem is seen from a planner's point of view then it should be characterized as choosing a path of consumption, investment, and sectoral allocation of factors to maximize the consumer's discounted utility. It should be emphasized that the solution is not the global optimum, certain variables are set exogenously, in particular the government-determined level of educational expenditures.

To give an *economic* interpretation to the variables, we view the economy as a decentralized one where the consumer maximizes utility, given the time path of prices (including wages and interest rates), and the value of his claim on the physical capital stock. On the other side, the producer rents capital and hires labor to maximize profits given current prices. The producer does not need to know future prices in this model that has neither adjustment costs nor "learning-by-doing."

8.3.1 The Consumer

The consumer lives infinitely and maximizes a discounted stream of consumption. He also owns the physical and human capital stocks. As noted, the accumulation of human capital is essentially in the hands of the government. We begin by considering the capitalist aspect of the household. As owner of the capital stock, he has to decide on the use and rate of accumulation of capital, given a time path of prices and interest rates.

There are two users of physical capital, the goods producing sector and the education sector. They pay the annual rental price of $P^{Kd}$for one unit of capital. Investment goods for new capital sells at a price P^I. The capitalist problem is thus

$$\text{Max} \sum_{t=1}^{\infty} \frac{(1-t^K)P_t^{Kd}K_{t-1} - P_t^I I_t^d}{\prod_{s=1}^{s=t}(1+r_s)} \quad s.t.\ K_t = (1-\delta)K_{t-1} + I_t^d, \tag{8.12}$$

where K is the capital stock, I^d is the demand for investment goods, t^K is the tax rate on capital income, r is the interest rate, and δ is the rate of depreciation of capital.

The Euler equation from solving (8.12) is

$$(1-t^K)P_t^{Kd} = (r_t - \pi_t + (1+\pi_t)\delta)P_{t-1}^I, \tag{8.13}$$

where π is the capital gains on the capital stock. In this model without adjustment costs, the price of investment goods is equal to the stock price of capital.

Consumers maximize a discounted stream of consumption, we represent aggregate utility by

$$\frac{1}{1-s}\sum_{t=0}^{\infty}\frac{N_t U_t^{1-s}}{(1+\rho)^t}. \tag{8.14}$$

This is an utilitarian function, where the utility per person, U_t, is multiplied by the number of people, N_t. The intertemporal elasticity of substitution is given by $1/s$, and ρ is the rate of time preference. The atemporal utility depends on the per capita "full consumption," F_t, which is measured in efficiency units

$$U_t = F_t(1+\mu)^t. \tag{8.15}$$

The exogenous rate of Harrod-neutral productivity growth is μ, and the term $(1+\mu)^t$ converts the population from natural units to efficiency units. Full consumption is the aggregate of goods and leisure. The term *full* is used to distinguish the variable from the more familiar tangible component. The term *consumption* will be used to refer to the consumption of goods only.

Equation (8.14) is maximized subject to the intertemporal budget constraint

$$W_0 = \sum_{t=0}^{\infty}\frac{N_t(1+\mu)^t P_t^F F_t}{\prod_{s=0}^{t} 1 + r_s}, \tag{8.16}$$

where W_0 is the full wealth at time 0. The RHS is the present value of full consumption over the entire future of the economy, discounted at the nominal private rate of return r_s. P^F is the price of full consumption. Full wealth is the present value of all income; it is to be distinguished from tangible wealth which includes only labor and capital income, not imputations to leisure. Wealth includes other minor items like government transfers and financial assets.

The welfare function is additively separable in U_t. We can, therefore, describe the consumer problem as a two-stage process. In the first stage, full wealth is allocated across time, i.e., the choice between current consumption ($P_t^F F_t$) and savings. In the second stage, full consumption is allocated between goods and leisure. We express this second stage problem as

$$\text{Max}\, U(C_t, LJ_t) \;\; s.t.\; P_t^F F_t \geq P_t^C C_t + P_t^{LJ} LJ_t \tag{8.17}$$

where C and LJ denote consumption of goods and leisure, P^C denotes the price of consumption goods, and P^{LJ} denotes the opportunity cost of leisure, the after-tax wage rate.

Maximizing objective (8.14) subject to constraint (8.16) gives the Euler equation

$$\frac{F_t}{F_{t-1}} = \left[\frac{P_{t-1}^F}{P_t^F} \frac{1+r_t}{(1+\rho)(1+\mu)^s} \right]^{1/s} \tag{8.18}$$

which must be obeyed along the optimal time path.

The second stage problem (8.17) is represented by a translog indirect utility function which is homothetic and has an elasticity of subsitution between goods and leisure different from unity (see table 8.2). With this functional form the inequality in (8.17) of course becomes

$$P^F F = P^C C + P^{LJ} LJ. \tag{8.19}$$

At any time t, the aggregate household has a stock of human capital which is translated to a pool of time, $\overline{L}_t$, which is to be used for work or leisure. Study time has been exogenously excluded. Labor supply at t, L_t^s, is given by the effective time available less leisure

$$L_t^s = \overline{L}_t - LJ_t. \tag{8.20}$$

The household's available time (i.e., excluding study time) changes with the population size and composition, and the amount of human capital per person. Let H_t denote the stock of human capital for the whole economy at the end of period t. The effective time available for work and leisure is given as

$$\xi^L H_{t-1} = \overline{L}_t, \tag{8.21}$$

where ξ^L is an aggregation coefficient that translates capital to time.[9] The accumulation equation for H_t is equation (8.8).

Finally, the disposable income in any period is Y_t = capital income + labor income + govt. transfer + financial asset income.

Table 8.2
(top) Estimates of the parameters of model; (bottom) estimates of coefficients of production and consumption functions

Parameters	Value
t^K	0.1
t^P	0.012
t^L	0.13
t^{Lm}	0.318
t^C	0.049
t^I	0.049
ρ	0.0213
$\sigma = 1/s$	0.593
μ	0.017
δ	0.049
δ^h	0.0178*
γ	0.06
α^E	0.78
K_{1987}	\$14,8 trillion
H_{1987}	\$207,2 trillion

* Value in steady state, varied by year. Dollar figures are in 1982 equivalents.

Consumption function:

$$\ln P^F = [0.2710.729] \ln p + 1/2 \ln p' \begin{bmatrix} 0.133 & 0.133 \\ -0.133 & 0.133 \end{bmatrix} \ln p$$

$$\ln p \equiv (\ln P^C, \ln P^{LJ})'$$

Goods production function:

$$\ln P^{Ld} = [1.396\ 1.394\ 1.790] \ln p + 1/2 \ln p' \begin{bmatrix} 0.552 & 0.649 & 0.097 \\ -0.649 & 0.277 & 0.372 \\ 0.097 & 0.372 & 0.469 \end{bmatrix} \ln p$$

$$\ln p \equiv (\ln P^{Cs}, \ln P^{Is}, \ln P^{Kd})'$$

Human capital production:

$$\ln P^{IH} = [0.058.052.017.989] \ln p$$

$$+ 1/2 \ln p' \begin{bmatrix} 0.0226 & 0.0016 & 0.0022 & 0.0188 \\ 0.0016 & 0.0178 & 0.0015 & 0.0209 \\ 0.0022 & 0.0015 & 0.0011 & 0.0048 \\ 0.0188 & -0.0209 & -0.0048 & 0.0069 \end{bmatrix} \ln p$$

$$\ln p \equiv (\ln P^{Khd}, \ln P^{Lhd}, \ln P^{Chd}, \ln P^{LST})'$$

8.3.2 The Producers

To have a model that gives as close a characterization of the aggregate data as possible we have divided the domestic producers of goods and services into the private sector and the government. These are represented by the first three columns in the input-output matrix. We shall use the term "goods" to refer to the sum of goods and services as defined in the National Accounts.

We divide final output into three types—consumption goods, investment goods for physical capital, and investment in human capital. The supply of these goods are denoted by C, I and I^H, while their (supply) prices are P^{Cs}, P^{Is}, and P^{IH}. The private producers are divided into two industries, the education industry described in section 8.2 and an industry supplying consumption and physical investment goods, C^s and I^s.

The private goods industry is characterized as using capital and labor to produce consumption and investment goods jointly

$$(C^s, I^s) = f(K^d, L^d, t). \tag{8.22}$$

The superscript d denotes the demand for factors. The production technology exhibit constant returns to scale and improves over time in a Harrod-neutral fashion at rate μ.

Given current prices the producer chooses the unit input demands. The producer in this model does not need to know future prices unlike models with investment adjustment costs or "learning."

Like the education production function, equation (8.22) is represented in the dual form as a translog function of the prices. To have a well-defined steady state the rate of Harrod-neutral technical progress of the education sector is constrained to be the same as that of the goods sector, i.e. μ. (The coefficients estimated over the sample period are not equal at standard significance levels. All multisector models, like Ho and Jorgenson (1994), that estimate the production and consumption functions have to confront this short-run apparent inconsistency. We say apparent because we have ignored issues such as new goods and discrete changes in production functions.) The estimates of the functions are summarized in table 8.2.

In the National Accounts a small portion of "Personal Consumption Expenditures" is spent on goods and services provided by government-run enterprises. To be consistent with the data, we have a simple government production sector which produces output using only labor

$$C^E = f(L^E, t), \tag{8.23}$$

where C^E is the quantity of goods supplied by the government enterprises and L^E is the labor used.

8.3.3 The Government

The government imposes taxes on factor incomes, on sales of goods, and estate taxes on wealth. It purchases goods and labor, transfers income, and pays interest on the public debt. The difference between expenditures and revenue is made up by borrowing from the household. In this model the public deficit is set exogenously. The stock of government debt held by the household is thus fixed and play no important role.

The total revenue collected by the government is

$$\begin{aligned}\text{REV} = {} & t^C P^{Cs} C^s + t^I P^{Is} I^s + t^L P^{Ld} L^s + t^K P^{Kd} K^d \\ & + t^P P^K_{t-1} K_{t-1} + t^W W^t_{t-1}\end{aligned} \tag{8.24}$$

where t^C and t^I are sales taxes, t^P is the property tax rate and t^W is the estate tax on wealth, t^K is the tax on capital income, and t^L is the average tax rate on labor income. This is to be distinguished from the marginal labor tax rate that enters into the calculation for the opportunity cost of leisure

$$P^{LJ} = (1 - t^{Lm}) P^{Ld}. \tag{8.25}$$

On the other side of the ledger, the government buys goods and labor services, (C^G, I^G, L^G). L^G does not include workers in the education sector which is accounted for separately. It also pays interest on the public debt (E^I), subsidizes education (E^E), and transfers income directly to the household sector (E^L). We have

$$\text{EXPEND} = P^C C^G + P^I I^G + P^L L^G + E^I + E^E + E^L. \tag{8.26}$$

The individual components of this total public expenditure other than E^E, are set as exogenous shares of government spending other than education, GOV. That is, $P^C C^G = \alpha^{GC}\text{GOV}$, etc. The level of GOV is determined by the endogenous revenue and an exogenous deficit.

As noted in section 8.2, the government decrees the level of tangible expenditures on education (i.e., those excluding the imputed value of student time). This policy choice is represented by γ, the fraction of GNP devoted to such expenses. This is set equal to the shares in the recent data. Thus

$$P^{Khd}K^{Hd} + P^{Lhd}L^{Hd} + P^{Chd}C^{Hd} = \gamma\text{GNP}. \tag{8.27}$$

8.3.4 *The Foreign Sector*

Ours is a one-country model without an endogenous function for exports and imports. To be consistent with the actual non-zero trade balances in the data we specify a simple closure. The current account deficit is set exogenously, which implies a given time path for the stock of foreign assets/debts held by U.S. residents. This deficit is allocated exogenously to net trade balances in consumption goods (C^R) and investment goods (I^R) in such a way to mimic recent patterns. (The superscript R denotes Rest-of-the-world.)

8.3.5 *The Markets*

There are two markets for outputs and two for the factors. For consumption and investment goods, the supply-demand clearing conditions are

$$C^s + C^E = C + C^{Hd} + C^G + C^R \tag{8.28}$$

$$I^s = I^d + I^G + I^R.$$

C^R and I^R are net exports which may be positive or negative.

The market balance for physical capital (K) and human capital (H) are given by

$$\xi^k K_{t-1} = K_t^s = K_t^d + K^{Hd} \tag{8.29}$$

$$L_t^s = L_t^d + L_t^{Hd} + L_t^E + L_t^G + L_t^R,$$

where K^s denotes supply of capital services, which is derived from the stock of capital available at the end of the previous period, K_{t-1}. Labor supply L^s, is determined in the leisure demand equation (8.20). ξ^k is an aggregation coefficient like ξ^L in eq. (8.21) above.

8.3.6 *The Steady State, Static, and Dynamic Equilibria*

The model as described is a simple extension of the standard Cass-Koopmans growth model. It exhibits saddle path stability with one state variable (capital, K) and one costate variable. Although there are other stock variables that accumulate over time (human capital, public debt, foreign assets), these are not chosen by the household and hence have no interesting endogenous costate variables.

At any period t, whether in or out of dynamic equilibrium, the economy begins with inherited stocks of physical and human capital (K_{t-1}, H_{t-1}). Given a savings decision (which is equivalent to a given investment decision in this model) from the intertemporal optimization process, there is a set of prices that will enable the economy to reach a *static* equilibrium where all the markets in equations (8.28)–(8.29) clear. This static equilibrium will have, in particular, quantities of physical and human investment (I, I^H). These will determine the stocks of productive factors for the next period.

The *dynamic* equilibrium is reached when adjacent static equilibria satisfy the Euler equations (8.13) and (8.18). Since the functional forms for consumption and production conform to the standard Cass-Koopmans model (there are no scale economies or externalities), the dynamic equilibrium path converges to a well-defined steady state.

The steady state is characterized by constant relative prices and real interest rates, and constant quantities measured in efficiency units. We have allowed the economy to have an exogenous Harrod-neutral rate of productivity growth at rate μ. All quantities—consumption, capital stock, human capital, etc.—grow at rate μ when measured in natural units. The steady state is defined by all the equations determining the static equilibrium and three further equations derived from the Euler conditions (8.18), (8.12), (8.8):

$$1 + r_{ss} = (1+\rho)(1+\mu)^s$$

$$I_{ss} = \delta K_{ss} + \mu K_{ss}$$

$$\Delta N_{ss} + I^H_{ss} = \delta^H H_{ss} + \mu H_{ss} \tag{8.30}$$

where the subscript ss denotes the steady state, and recall that $1/s$ is the intertemporal elasticity of substitution. Investment in the steady state covers depreciation and maintains the capital-effective labor ratio. For the case of human capital there is an additional factor, ΔN_{ss}, for births and immigration.

8.3.7 *Welfare Analysis*

To evaluate the effects of different educational spending policies we have to calculate the different levels of utility attained as defined in equation (8.14).

$$V = \frac{1}{1-s} \sum_{t=0}^{\infty} \frac{N_t U_t^{1-s}}{(1+\rho)^t}. \tag{8.31}$$

To express this in monetary terms we calculate the intertemporal counterpart of Hicks' equivalent variation of moving from equilibrium 0 to equilibrium 1:

$$\Delta W = W(P_0^F, D_0, V_1) - W(P_0^F, D_0, V_0) \tag{8.32}$$

where

$$W(P_0^F, D_0, V) = P_0^F \left[\frac{(1-s)V}{D_0^s} \right]^{1/1-s}.$$

P_0^F is the price of full consumption in the first period, and D_0 is a term involving the whole path of interest rates. Both variables denote values from the reference case 0.[10]

8.4 Data and Parameter Estimates

The data corresponding to the variables used in the model described above are calculated from various U.S. sources for the period 1948–1986. The methodology is described in Jorgenson and Yun (1986b). These data are used to estimate the consumption functions (8.17)–(8.18), the production function (8.22), and the education production function (8.9).

These functions (and associated cost-minimizing first-order conditions) are estimated simultaneously using nonlinear, three stage least-squares.[11] Constant returns and curvature restrictions are imposed on these functions to ensure that the resulting parameter estimates give meaningful objective functions. As explained in section 8.3, the rates of technical change in both goods and education sector are constrained to be equal. The results are reported in table 8.2 (bottom).

The rate of Harrod-neutral technical progress is estimated to be 1.7 percent per year. In the household sector, the rate of time preference, ρ, is 0.0213, while the intertemporal elasticity, μ is 0.593.

Study time, L^{ST}, is set exogenously according to the population demographics at time t. In the sample period this is set to the index of student time calculated in Jorgenson and Fraumeni (1992a). This index is the number of enrolled students weighted by the value of their human capital, excluding the tangible costs of schooling. For periods after the sample, we project the population according to the model used by the Social Security Administration [12] and use the formulas in JF to calculate the student time index. The population projections are also used to calculate the elements of the human capital accumulation equation (8.8). Births and the rate of depreciation of human capital both depend on the demographic structure at time t. The formulas for these are also given in JF. The sample period value for δ^h is about 2 percent per year.

The "education subsidy" E^E, is the portion of the tangible expenses of the education industry borne by the government. This is calculated from the data on public expenditures on education and total national education expenditures.[13] For the postwar period this share, α^E, is about 80 percent. As a share of GNP, education expenses are about 6 percent in the recent years, this is plotted in figure 8.2b. The share is much lower in the earlier years, partly in line with the lower college enrollments.

8.5 The Effect of Increased Expenditures on Education

We now turn to the question of whether current levels of expenditures on formal schooling in the United States are optimal. This is answered within the framework of the assumptions built into the model, i.e., that formal education is mandated by the government, which also determines the level of tangible expenditures (those excluding the opportunity cost of student time). We examine how welfare, measured as a discounted stream, will be changed if expenditures on education are raised, together with the necessary taxes. Specifically, we change the tax rate on labor income to adjust to different levels of education expenses.

To do this the model is first simulated using the initial stocks of capital and base case parameters given in table 8.2. The solution consist of finding the level of initial consumption that will bring the economy to the steady state along the perfect foresight path described in section 8.3.6. (The solution algorithm for the dynamic equilibria that we use is described in Jorgenson and Yun, 1986b). The base case welfare is calculated from the path of full consumption (8.31).

As described in section 8.3.3, the government deficit is set exogenously, thus given tax rates, the endogenous level of economic activity will produce an endogenous level of government expenditures. It should be noted that government output does not enter into the consumer's utility function in this model. To preserve comparability across simulations, the level of public expenditures (excluding education) from the base case is recorded and thereafter kept fixed for all counterfactual experiments.

In the next step the share of GNP devoted to the formal education sector (γ) is changed from the base case 6 percent to 7 percent, and the new dynamic path calculated. The base case government deficit and expenditures are maintained by adjusting both average and marginal tax rates on labor income (t^L, t^{LM}) every period. The new level of welfare is again calculated using the new path of full consumption. These levels of welfare are expressed in monetary terms using (8.32). The results are summarized in table 8.3. The percentage change in the time paths of consumption and capital between the counterfactual and base case are given in figure 8.3.

Table 8.3
Effects of higher expenditures on education

	Base Case	Counterfactual
γ	0.06	0.07
Welfare (bil. 82$)	243760	242066
At $t = 1$		
F	7181	7146
L^J	7075	7086
C	2284	2242
t^L	0.13	0.146
At $t = \infty$		
F	10499	10427
L^J	10679	10753
K	18347	18019
H	304470	305621
r^K	0.0507	0.0507
r^H	0.0447	0.0417
t^L	0.13	0.153

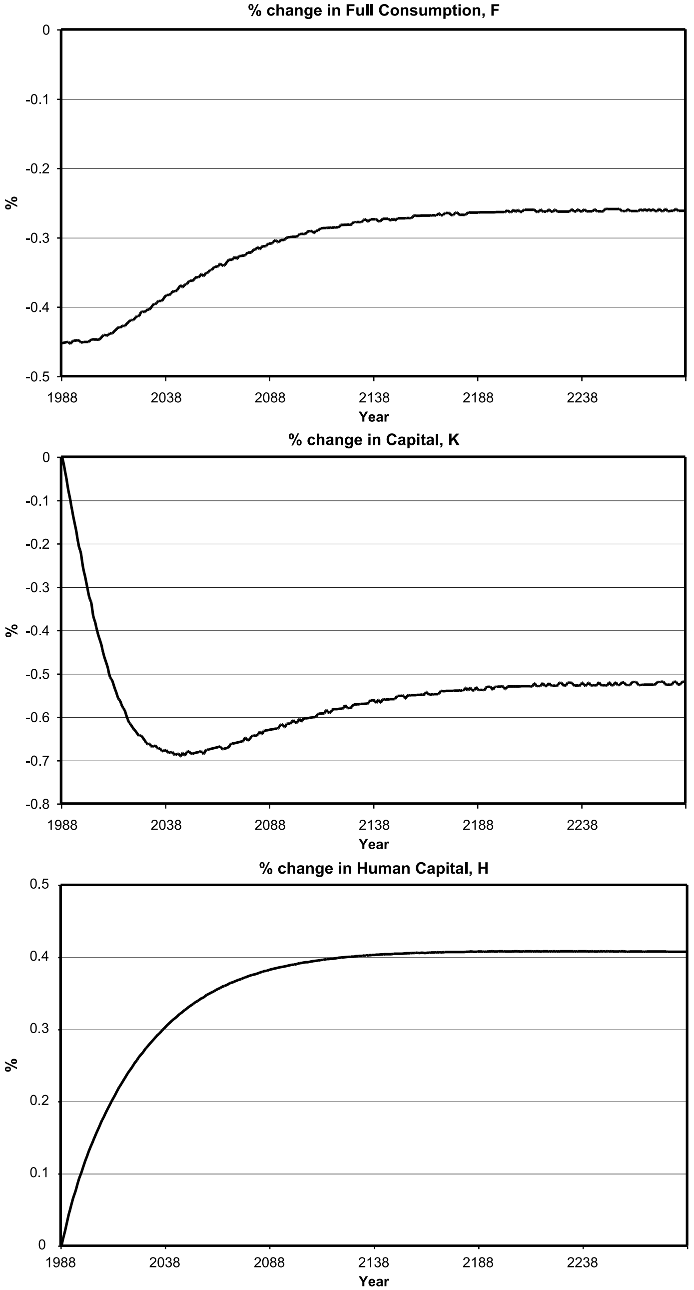


Figure 8.3
Effects of increasing expenditures on education (percentage change from base case).

With a higher level of tangible expenditures on the education sector resources are initially taken from goods production to produce more human capital. Initially, consumption of goods and investment in physical capital are both lower. The higher taxes on labor lower the price of leisure and more leisure is consumed. The net effect on full consumption is a slight decrease; F in the first period is about 0.5 percent lower than the base case.

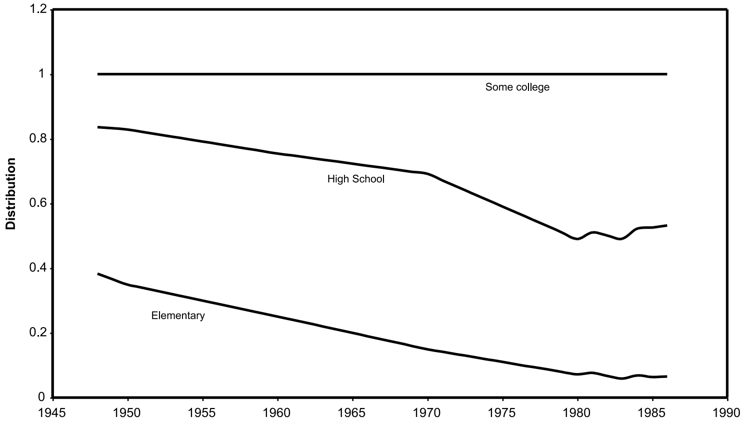
Over time this combination of higher investment in human capital and lower investment in physical capital give the time paths drawn in the bottom two panels of figure 8.3. The stock of human capital is eventually 0.35 percent higher while the capital stock is 1.8 percent lower. The higher expenditures on education require a higher steady state tax rate on labor income, 0.153, up from 0.130. The effect on steady state full consumption is to lower it by 0.7 percent compared to the base case. This is the combination of a 0.7 percent higher level of leisure (due to the lower net wages) and a 3.0 percent lower level of goods consumption. The counterfactual steady state thus has a slightly higher output of human investment, but a bigger reduction in the production of goods for consumption and investment. Adding up over the entire time path the level of welfare is 0.7 percent, or some $1.69 trillion, lower.

As a check, a symmetrical counterfactual experiment was conducted where the expenditures are *lowered* to 5 percent of GNP. In this case welfare is 0.6 percent higher than the base case. The results are parallel to the other experiment; lower education expenditures lowers the stock of human capital but the reduced taxes give rise to higher output and a higher stock of physical capital.

8.6 The Effects of Increased Enrollment

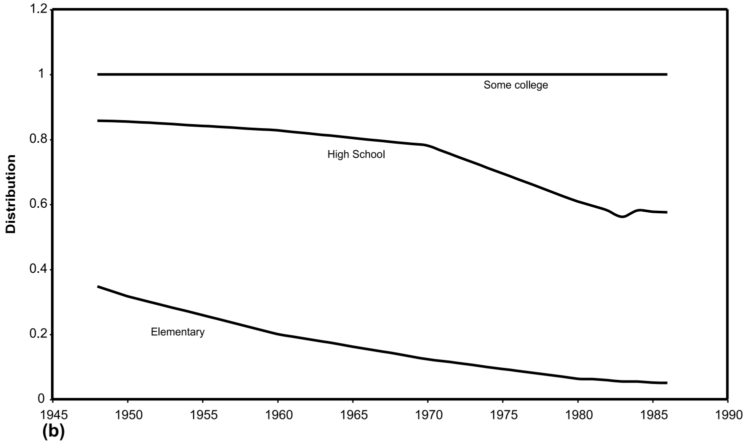
The educational attainment of the U.S. population has risen substantially in the postwar period. This change is illustrated in figure 8.4 which gives the highest level of formal education achieved by 34-year olds. In 1950 only 17 percent of 34-year old men have some college; by the 1980s this has risen to about 50 percent. However, this also means that around 50 percent of males and 57 percent of females in the United States today do not have any post-secondary education. Therefore, there is quite a bit of room to raise educational attainment.

In this section we examine the effects of higher mandatory enrollment accompanied by the associated higher expenses (and taxes). The counterfactual experiment consists of raising college enrollment gradually by 20 percent. In the first year the number of college freshmen is in-



(a)

Note: This gives the educational distribution of all males aged 34 in a particular year, adding up to 100%. For example in 1986, 6% have elementary schooling or less, 53% had some high school, and the remaining 41% had some college.



(b)

Note: This gives the educational distribution of all females aged 34 in a particular year, adding up to 100%. For example in 1986, 5% have elementary schooling or less, 58% had some high school, and the remaining 37% had some college.

Figure 8.4
(a) Educational attainment of males, age 34 and (b) females, age 34.

creased by 20 percent, and in the second year the number of freshmen and sophomores are 20 percent higher than in the base case. By the fifth year there are 20 percent more students with 1,2,3,4 or 5 years of college education. A new index of student input, L^{ST}, is computed from these higher enrollments. The new index is ultimately 8.9 percent higher than the base projections. (Recall that the student index includes elementary, secondary, and college students.)

Table 8.4
Effects of higher enrollment

	Base Case	Counterfactual
Welfare (bil. 82$)	243760	246247
At $t = 1$		
F	7181	7165
L^J	7075	7052
C	2284	2283
t^L	0.13	0.131
At $t = \infty$		
F	10499	11029
L^J	10679	11172
K	18347	19589
H	304470	319545
r^K	0.0507	0.0507
r^H	0.0447	0.0438
t^L	0.13	0.122

As in the previous case, the counterfactual simulation is run and the results compared to the base case dynamic path. This is run with the new student input index, while again maintaining government expenditures and deficits at base case levels. Here also we use changes in the tax rate on labor income to adjust government revenue to meet these targets. The results are given in table 8.4 and figure 8.5.

Welfare measured as a discounted stream of consumption is higher by 1.31 percent (3202 billions of 1982 dollars). The interesting feature is the time path of full consumption, F_t. Initially, F falls due to a 0.3 percent fall in leisure and an essentially similar level of consumption of goods. It then rises over time, and in the steady state F is 5.0 percent higher. With a higher enrollment of mostly 19- or 20-year olds, there is an initial reduction in the supply of workers. With the higher expenditures on education, there is an increase in the demand for labor (teachers). The outcome is a higher price of labor and lower level of leisure consumption despite an increase in the labor tax. For all periods in the base case, the labor tax rate, t^L, was 0.130, but in the higher enrollment case it is 0.131 in the first year, and by the fifth year, it has risen to 0.137.

The stock of physical capital is also lower in the initial periods. Resources are drawn from the goods-producing sector into the education

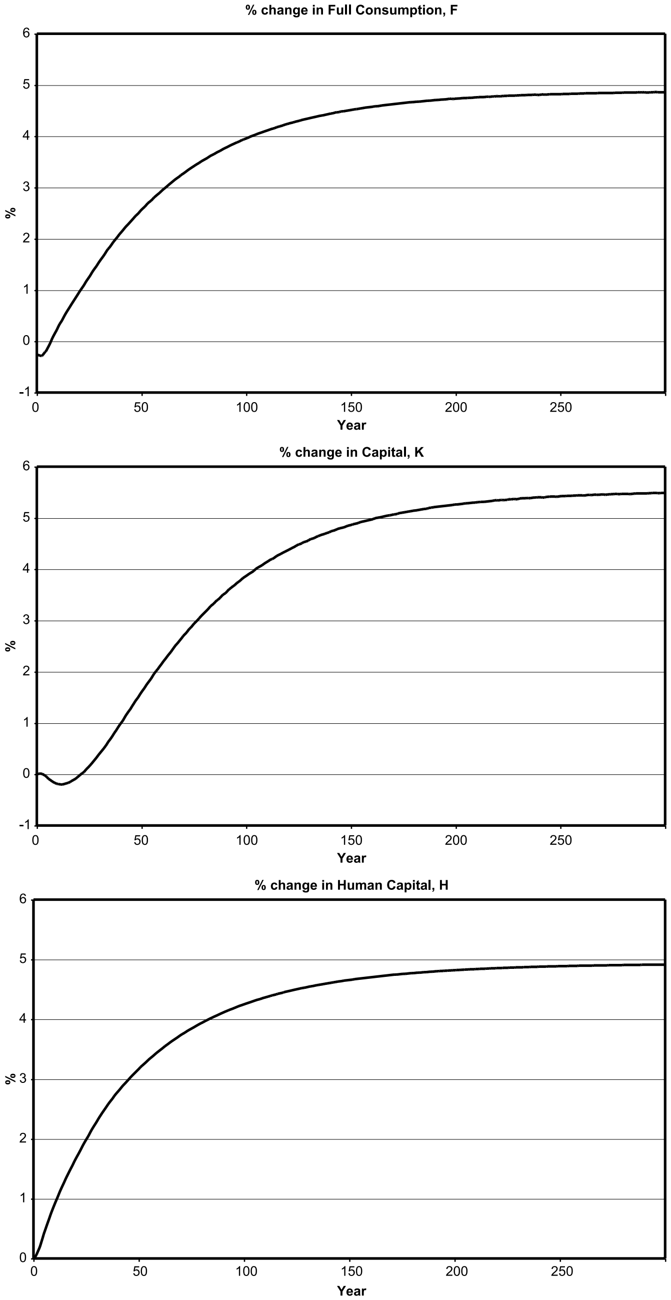


Figure 8.5
Effects of increasing college enrollment by 20 percent (percentage change from base case).

sector, producing less investment, I_t. Another way to look at this is that the government is mandating a higher level of savings in the form of human capital. The perfectly foresighted consumer reacts by saving less in the form of tangible capital. This smaller K_t is temporary, eventually it catches up and overtakes the capital path of the base case. In the steady state the capital stock is 6.8 percent higher.

The compulsory increase in school enrollment gives rise to a higher time path of H_t. This increase is due mostly to the higher student input and partly to higher inputs of schools and teachers. This accounts for the major difference between this experiment and the one in section 8.5 where the increase in H is due only to higher tangible expenditures. The tax distortion here is much smaller in comparison to the increase in human capital.

The initial increase in investment in human capital comes from a reduction in leisure and a reduced rate of investment in K_t. Over time, the higher H_t allows higher output and higher leisure consumption. This additional output is divided between more investment and more consumption. By the 25th year the stock of K_t has caught up with the base case value. In that period H_t is some 1.9 percent higher than the base case.

Over time, the increase in factor supplies raises output by so much that the tax distortion is reversed. The tax rate on labor income eventually becomes lower than that in the base case, in the steady state, t^L is 0.122 compared to 0.130 in the base case, and 0.139 at the peak of the counterfactual path. Tax rates rise initially with the steady increase in enrollments in the first five years, but over time fall as output, and hence revenue, rises. The price effect of this reduction in tax distortion is offset by the income effect of higher output resulting in a level of leisure consumption in the steady state that is 4.6 percent higher. Consumption of goods is 5.8 percent higher than the base case.

The steady state is thus characterized by higher stocks of factors ($K + 6.8\%$, $H + 5.0\%$), higher output of all goods, higher consumption of all goods and lower taxes. That is, a 20 percent increase in post-secondary enrollment (equivalent to an 8.9 percent increase in the student index) leads eventually to a 5.0 percent higher full-consumption. Present value welfare for the infinite-lived household is 1.3 percent higher.

8.6.1 Sensitivity Analysis

To give an idea of the sensitivity of these results to the parameters of the education production function we repeated the base case and counterfactual simulations for another set of values. The parameters (reported in table 8.1) show elasticities of substitution less than one. The results of using a Cobb-Douglas function (i.e., with the *B* coefficients set to zero) are very similar to the ones reported in figure 8.5 and table 8.4. The adjustment, as expected, is marginally quicker. In the steady state the stock of human capital and the level of full consumption are both 5.2 percent higher instead of 5.0 percent.

8.7 Conclusion

While we do not focus here on tax reform our results might be compared to those found by Davies and Whalley (1991) and Heckman, Lochner and Taber (1998), which examine the role of taxes and human capital. Using an OLG model without leisure and with myopic expectations, Davies and Whalley find that while a change in the tax system that lowers capital taxes and raises labor taxes reduces the stock of human capital, there are offsetting increases in the stock of physical capital (a point ignored in partial equilibrium analysis). Heckman *et al.*, also using an OLG model without leisure, but with foresight, finds that a flattening of the income tax which raises the return to human capital will produce more human capital in the steady state but lower physical capital. The effect on welfare is rather small. Our simulations with exogenous study time show that an effort to increase human capital with more spending and more taxes will result in less physical capital and a similarly small reduction in welfare.[14]

Our 3-sector model, despite its relative simplicity, gives a quantitative characterization of the major economic variables of the effects of changes in education policy. The model is forward-looking and our results are for both the short and long run. We should point out here some special features of the model and results.

We have defined investment in human capital as the increase to lifetime income due to an extra year of formal schooling. Schools and colleges are certainly not the sole sources of human capital. Training within the family and on-the-job learning may be important determinants of work skills (ability to produce tangible output that is measured in the GNP accounts). We have regarded formal education as the producer of human capital for two basic reasons. One is the common believe, which we share, that formal education contributes substantially to productive skills, notwithstanding the signalling issue raised by Spence (1974).[15] The other reason is that data on the formal education sector is available and usable, whereas measures of work experience of the total work force are still being constructed.

We have assumed that all workers in a given sex, age, and education category are the same. While the number of categories are large (2700), there are many people in each cell and they may be heterogenous. The experiment in section 8.6 consists of raising enrollments of college-aged students. To the extent that these new students are different from existing ones, our results have to be modified. If the marginal student is less able than the average one then the marginal productivity of educational inputs would be lower, and hence the benefits of increased enrollments would be lower than estimated.[16]

The model used is an infinite-lived representative agent one. Such a framework cannot be used to analyze distributional issues. A scheme which raises spending on today's young students by taxing the current generation of mature workers obviously has distributional consequences. However, one can imagine an alternative financing system that taxes the beneficiaries of higher output of human capital.

Finally, in this model the accumulation of physical capital is done in a perfect foresight manner. The initial level of consumption is chosen such that the economy is on the saddle path where the Euler equation linking the price of capital between adjacent periods is satisfied. The accumulation of human capital, on the other hand, is governed by an exogenous savings rate. An obvious extension of the current model is to also have human capital accumulated in a perfect foresight way. In the current simulations, the rate of return to human capital is different from the return to physical capital. In a model where both stocks are under the control of the household, these rates of return would be equalized.

Notes

1. Rate of investment in human capital is proxied by data on enrollment in secondary schools.

2. Right-hand side variables are said to be robust if their coefficients remain significant and of the same sign when different variables are added to the regression.

3. A model with externalities but income convergence is Tamura (1991). This model does not have physical capital, and there is decreasing returns to human capital in the production of human capital.

4. Other work include Glomm and Ravikumar (1992) which features endogenous growth. Our model is somewhat similar to Caballe and Santos (1993) with the important exception that human capital appears as an argument in their human capital production function.

5. See Jorgenson and Fraumeni (1989, table 5.33). This is different from the Bureau of Economic Analysis's figure because of different definitions of capital and different accumulation and aggregation methods. In particular our definition includes consumer durables.

6. This includes teacher salaries and imputations to rental value of school capital. It is the total of both private and public education as defined in the National Accounts.

7. Consider two persons of the same sex, age, and level of educational attainment at two different years, t and t'. From the data we know that they have different time profiles of wages. It is difficult to distinguish whether this difference in wages is due to the fact that they are born into different cohorts or to the fact that the "quality of education" they received was different.

8. The divisia indices of capital and labor input that we use take into account such factors as movements in relative teacher salaries.

9. See Ho and Jorgenson (1994) for details.

10. Details are in Ho and Jorgenson (1994). The formulas involve summing over t from 0 to infinity. In the simulation exercises the steady state is assumed to be reached by $T = 500$. The values for $t = T + 1, T + 2, \ldots$ are set at the ones for T and added up analytically. The difference between the values at $t = T$ and the separately calculated steady state is miniscule.

11. See Jorgenson (1984) for a description of estimating translog price functions.

12. The population model of the SSA projects the population by individual year of age, sex and race. It contains details on mortality, fertility and immigration. This is an updated version of the model described in Anderson (1985).

13. These correspond to the lines "Educational Services" and "State and Local Government; Education" in table 6.2 of the National Income and Product Accounts Tables in the *Survey of Current Business*. The NIPA data on compensation of employees is combined with imputations on the capital stock of the public education sector that we separately estimated. Intermediate goods are estimated from Input-Output and Personal Consumption Expenditures data.

14. We thank an anonymous referee for pointing this out.

15. An example of research that shows a positive contribution of education is Chamberlain and Griliches (1994). Using sibling data, they suggest that the link between education and labor market outcomems would not be overturned by unobserved attributes.

16. This may not be very significant. As Murray and Herrnstein (1992) point out, the Scholastic Aptitude Test (SAT) scores were stable in the 1950s and early 1960s when there was the surge of college-bound test takers. It may be argued that SAT scores are not related to effective human capital, but student input is a key input in this model and SAT scores are certainly not irrelevant in this regard.

9

Did We Lose the War on Poverty?

Dale W. Jorgenson

Was the War on Poverty a failure or a success? Official U.S. poverty statistics based on household income imply that the War on Poverty ended in failure. According to the Bureau of the Census the proportion of the U.S. population below the *poverty level of income* reached a minimum of 11.1 percent in 1973. This ratio rebounded to 15.2 percent in 1983 and has fluctuated within a narrow range since then, giving rise to the widespread impression that the elimination of poverty is difficult or even impossible.[1] However, poverty estimates based on household consumption imply that the War on Poverty was a success. Dale W. Jorgenson and Daniel T. Slesnick (1989) showed that the proportion of the U.S. population below the *poverty level of consumption* fell to 10.9 percent in 1973, only slightly below the incidence as measured by income in that year; the poverty ratio for consumption declined further, reaching 6.8 percent in 1983.

Slesnick (1993) presents estimates of poverty ratios incorporating consumption data from the Consumer Expenditure Survey (CEX), conducted by the Bureau of Labor Statistics. The poverty rate for consumption fell to 9.7 percent in 1973 and reached a low of 8.7 percent in 1978 before rising to 12.0 percent in 1980. The consumption-based poverty rate declined to a new low of 8.3 percent in 1986, ending at 8.4 percent in 1989. Calibrating consumption to levels reported in the U.S. National Income and Product Accounts, Slesnick (1993) obtained a poverty rate of 4.1 percent in 1978 and a postwar low in 1989 of only 2.2 percent.[2]

Measures of poverty based on consumption imply that anti-poverty programs should not be lightly abandoned, as advocated by some conservatives.[3] At the same time, liberal concern about the alleged persistence of poverty may be misplaced. While poverty has not been eradicated, as envisioned by poverty warriors in the 1960s, the combined impact of economic growth and expansion of income support programs has reduced the incidence of poverty to modest proportions.

The purpose of this chapter is to consider the implications of replacing household income with consumption in the measurement of poverty. The next section reviews the methods used in the official measures published by the Bureau of the Census. I then discuss the estimation of poverty rates based on consumption. This requires setting living standards for different types of households and adjusting these standards for price changes. The following section discusses integration of the measurement of poverty with redistributional policy, based on society's willingness to pay to reduce inequality and poverty. In the final section I recommend improvements in official programs for measuring poverty and inequality, as well as the cost and standard of living.

9.1 The Official Poverty Line

The original government poverty threshold, established for the year 1963 by Mollie Orshansky (1965, 1966) of the Social Security Administration was based on consumption rather than income.[4] Her starting point was a Low Cost Food Plan for meeting food consumption standards established by nutrition experts from the U.S. Department of Agriculture. She multiplied food cost by a factor of three, reflecting the proportion of food in the cost of total household consumption, to derive the cost of a poverty level of consumption. To compare poverty levels for different years, Orshansky inflated the poverty line by the Consumer Price Index for All Urban Consumers (CPI-U) of the Bureau of Labor Statistics (BLS). She adjusted the total cost of consumption to reflect the nutritional requirements of households that differ in family size, age and sex of household head, and farm versus nonfarm residence. These adjustments were based on food cost rather than the cost of total consumption. Differences in households by sex of head and farm versus nonfarm residence were dropped in 1981. Otherwise, the official poverty thresholds have been unaltered since they were first published by the Office of Economic Opportunity for the year 1964.[5]

Although Orshansky's poverty thresholds were based on the cost of a poverty level of consumption, the infrequency of surveys of household spending posed a barrier to the measurement of poverty. Until 1980 the BLS conducted the Consumer Expenditure Survey (CES) at roughly ten-year intervals to provide weights for the Consumer Price Index. To estimate the incidence of poverty, Orshansky (1965) employed data on income from the Census Bureau's Current Population Survey. This intuitive leap made it possible to estimate the proportion of the population living in poverty by enumerating the individuals with household incomes below a poverty threshold based on consumption.

Since 1980 the Bureau of Labor Statistics has conducted the Consumer Expenditure Survey on a quarterly basis. Despite this fact the official statistics have retained income rather than consumption as a measure of poverty. Given the sensitivity of poverty estimates to Orshansky's choice of income rather than consumption as a measure of family resources, an examination of the feasibility and desirability of replacing the official measure of poverty by a consumption-based measure is long overdue.[6]

Whatever standard of living is selected as the poverty level, an appropriate measure of household resources must be chosen, this measure must be adjusted to reflect price changes, and living standards must be compared among different types of households. The official poverty estimates employ Orshansky's poverty line, use income rather than consumption as a measure of household resources, employ the CPI-U to adjust for inflation, and utilize food cost rather than the cost of total household consumption to capture differences in standards of living among households. In the following sections I describe an approach to poverty measurement originated by Jorgenson and Slesnick (1989) that retains Orshansky's poverty line. However, this approach uses consumption as a measure of household resources, employs cost-of-living indexes specific to each household to adjust for price changes, and utilizes total consumption rather than food consumption to compare standards of living among different types of households. The theory of a utility-maximizing consumer provides a unifying framework for considering these issues.

9.2 Measuring the Household Standard of Living

To represent consumer preferences in a form suitable for measuring household standards of living, I assume that expenditures on commodities are allocated to maximize a household welfare function. As a consequence, the household behaves in the same way as an individual maximizing a utility function, even though a household typically includes a number of individuals.[7] To provide money measures of the cost and standard of living, we represent preferences by means of a household expenditure function, giving the minimum cost of a consumption bundle required to achieve a particular standard of living. These concepts are illustrated in Figure 9.1.

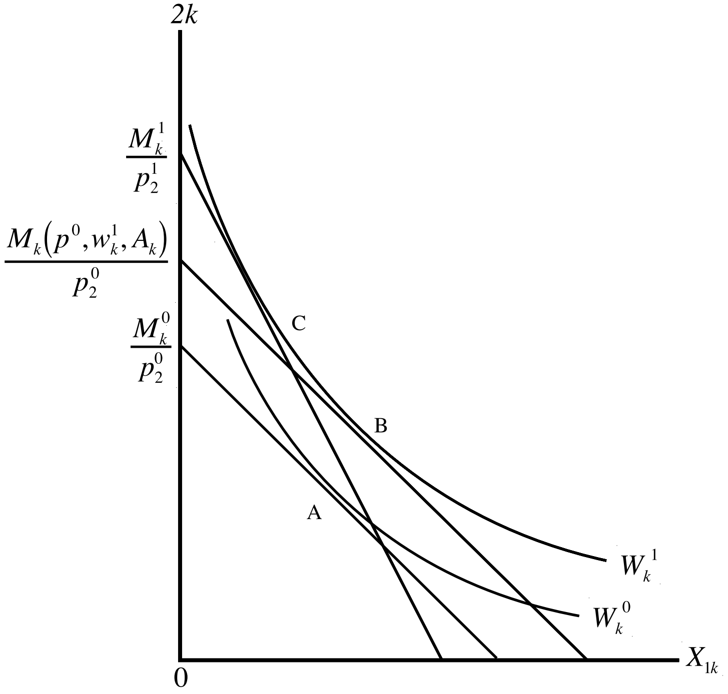


Figure 9.1
Household standard and cost of living.

Figure 9.1 represents the indifference map for the k-th household with expenditure function $M_k(p, W_k, A_k)$, where M_k is the cost of household consumption, p is the vector of prices faced by the household, W_k is household welfare or the standard of living, and A_k is the vector of attributes of the household that determine preferences. For simplicity we consider only two commodities. Indifference curves represent different standards of living. Household equilibrium in the base period is represented by the point A, while equilibrium in the current period is at the point C.

To measure the cost and standard of living we translate the current standard of living W_k^1 into the cost of household consumption at the prices of the base period. The resulting level of expenditure $M_k(p^1, W_k^1, A_k)$ corresponds to equilibrium at point B. The ratio between the cost of consumption at B and the cost at A is a quantity index of the standard of living. This reflects the difference between the costs of the two indifference curves, holding relative prices constant. The ratio between the cost of consumption at *C* and the cost at *B* is a price index of the cost of living. This measures the relative costs of remaining on the same indifference curve at two different sets of prices.

Estimates of poverty depend critically on the choice between income and consumption as a measure of household resources. Milton Friedman's (1957) permanent income hypothesis provides the intuition helpful for understanding the implications of this choice. The permanent income hypothesis focuses on wealth as a measure of household resources; however, important components of wealth, such as the present value of earnings from labor services, are unobservable. Permanent income, the yield on wealth, could provide a valid indicator of family resources but is also unobservable. While measured income is correlated with household resources, the substantial transitory component is uncorrelated with permanent income. The transitory component of income is relatively low for households with low measured income and relatively high for households with high measured income. Fortunately, measured consumption is an excellent proxy for household resources, since permanent consumption is proportional to permanent income and the transitory component of consumption is relatively small.

Under the permanent income hypothesis, the proportion of measured consumption to measured income falls as income increases over a cross section of individual households. For households at the poverty level the proportion of consumption to income is relatively high, while for affluent households this proportion is relatively low. For any fixed level of income, such as the poverty level, the proportion of consumption to income rises with the growth of average income, as revealed by the divergence of measures of poverty based on consumption and income over time.

9.3 Comparing Standards of Living among Households

The official poverty estimates published by the Bureau of the Census incorporate comparisons of living standards among households based on the costs of food consumption. Jorgenson and Slesnick (1989) utilize comparisons based on the costs of total household consumption. These comparisons are derived from an econometric model of aggregate consumer behavior for the United States constructed by Jorgenson and

Slesnick (1987). This model combines aggregate time series data on personal consumption expenditures with cross-section data for individual households.

Our model determines the allocation of total household spending among five commodity groups by households classified by five demographic characteristics. We have divided personal consumption expenditures among energy, food, other consumer goods, capital services, and other services. We have divided the population of U.S. households by family size (1, 2, ..., 7 or more persons), age of household head (16–24, 25–34, ..., 65 and over), region of residence (Northeast, North Central, South, and West), race (white or nonwhite), and urban vs. rural residence.

We obtain cross-section data on expenditures on each of the five commodity groups by each household from the Survey of Consumer Expenditures for 1973. The survey also contains information on the demographic characteristics of each household. We obtain annual time series data on aggregate personal consumption expenditures for each commodity group from the U.S. National Income and Product Accounts for the period 1947–1982. We complete our time series data set by constructing shares of each demographic group in aggregate consumption.

We have pooled aggregate time series data with cross-section data for individual households, using methodology originated by Jorgenson, Lau, and Stoker (1982). Time series data provide information on the impact of prices on the allocation of household budgets. Cross-section data enable us to capture the effects of the demographic characteristics of individual households on spending. Both types of data are useful in modeling the impact of total spending on consumption patterns.

Finally, we have derived equivalence scales suitable for making standard of living comparisons among households from our econometric model. An equivalence scale for two households with different attributes A_k is the ratio of the costs required for these households to achieve the same standard of living at a given set of prices. This can be interpreted as the ratio of the equivalent number of members of the two households.

We present equivalence scales for households classified by size, age of head, and region of residence in table 9.1. These equivalence scales are independent of the standard of living at which comparisons among households take place. This has the important advantage that the comparisons require only the attributes of the households being compared.[8] Household equivalence scales are analogous to the cost-of-living

Table 9.1
Jorgenson-Slesnick household equivalence scales (Reference: Size 4, age 35–44, northeast, urban, white)

Household Size:		Region of Residence:	
1	0.30	Northeast	1.00
2	0.58	North Central	1.01
3	0.75	South	1.15
4	1.00	West	0.79
5	1.07		
6	1.48	Type of Residence:	
7+	1.99	Urban	1.00
		Rural	1.94
Age of Head:		Race of Head:	
16–24	0.43	White	1.00
25–34	64	Nonwhite	0.94
35–44	1.00		
45–54	1.08		
55–64	1.08		
65+	0.89		

Source: Jorgenson and Slesnick (1987), tables 1, 2, and 3, pp. 227–228.

indexes presented in figure 9.1, but a cost-of-living index is independent of the standard of living only if the relative shares of commodity groups in total spending are independent of the spending level.

The Bureau of the Census follows Orshansky (1965, 1966) in constructing the official poverty line on the basis of household equivalence scales for food consumption rather than total household consumption. The official equivalence scales are presented in table 9.2. Slesnick (1993) shows that the official scales impart a substantial *downward* bias to poverty measures based on consumption. However, these measures decline much less rapidly during the 1970s and 1980s than do measures that incorporate the equivalence scales presented in table 9.1.

9.4 Measuring the Household Cost of Living

Jorgenson and Slesnick (1990a) have derived cost-of-living indexes for individual households like those illustrated in figure 9.1 from our econometric model of aggregate consumer behavior. Cost-of-living indexes

Table 9.2
Census equivalence scales (Reference: Size 4, nonfarm, male)

	Nonfarm		Farm	
	Male	Female	Male	Female
Size 1, age < 65	0.53	0.49	0.37	0.34
Size 1, age > 65	0.47	0.47	0.33	0.33
Size 2, age < 65	0.66	0.63	0.46	0.43
Size 2, age > 65	0.59	0.59	0.42	0.41
Size 3	0.78	0.75	0.55	0.53
Size 4	1.00	0.99	0.70	0.69
Size 5	1.18	1.17	0.83	0.83
Size 6	1.32	1.32	0.93	0.96
Size 7	1.63	1.60	1.14	1.09

Source: Slesnick (1993) table 2, part B, p. 13.

for households with different attributes are nearly identical for the twenty-year period 1958–1978. Jorgenson and Slesnick (1999) have compared cost-of-living indexes for individual households through 1995. Again, indexes for households with different attributes are very similar.

The empirical implementation of price index numbers, such as the CPI-U, has proved to be highly problematical. Slesnick (1991b) has estimated that the CPI-U incorporated an upward bias of about ten percent during the period 1964–1983, due to deficiencies in the treatment of costs of owner-occupied housing.[9] Similarly, sample rotation procedures adopted in 1978 led to a "formula bias" of 0.49 percent per year that was not addressed by BLS until 1995 (Advisory Commission, Reinsdorf, 1997).

A rental equivalent measure of housing costs was incorporated into the CPI-U in 1983, but the index was not revised backward and includes a permanent upward bias. Slesnick (1993) showed that this results in a substantial *upward* bias in the official poverty estimates. The Census Bureau has recently introduced an alternative set of poverty ratios based on the 81-X-1, an "experimental" price index compiled by BLS that employs a rental equivalent measure of housing costs.

9.5 Estimates of the Poverty Rate

Jorgenson and Slesnick (1989) enumerated the individuals with household consumption below a poverty level based on the official threshold constructed by Orshansky (1965, 1966) for the period 1947–1985. We estimated levels of household consumption for the year 1973 from the Survey of Consumer Expenditures for that year. We extrapolated the 1973 level backward and forward on the basis of estimated relationships between consumption and income for 1973, using income data from the current Population Survey. Finally, we calibrated levels of consumption to estimates of aggregate personal consumption expenditures from the U.S. National Income and Product Accounts. Slesnick (1993) constructed estimates of poverty rates based on consumption for the period 1947–1989. Slesnick's estimates incorporated data on household consumption from the Surveys of Consumer Expenditure for 1960–1961, 1972–1973, and 1980–1989. He obtained estimates for other years by extrapolation and interpolation on the basis of income data from the Current Population Survey. In addition, Slesnick (1993) provided estimates with levels of consumption calibrated to aggregate consumption data from the U.S. National Income and Product Accounts. Both sets of estimates are given in figure 9.2, with the official income-based poverty rates published by the Bureau of the Census, beginning in 1959.

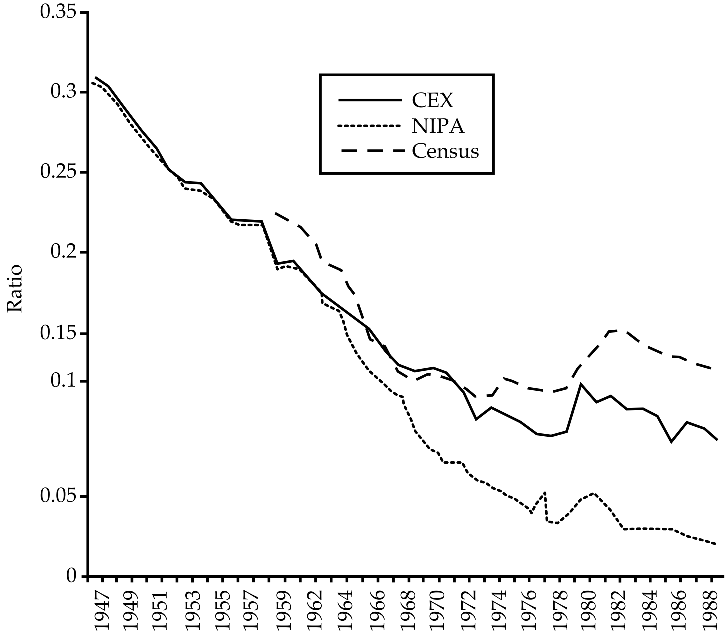


Figure 9.2
U.S. poverty ratios.

Slesnick's (1993) consumption-based estimates of poverty rates show that 30.9 percent of the U.S. population fell below the poverty level in 1947, 19.3 percent in 1959, and 9.7 percent in 1973. The consumption-based poverty rate continued to fall, reaching 8.7 percent in 1978, rising to 11.2 percent in 1982, declining to 8.3 percent in 1986, and ending at 8.4 percent in 1989. Poverty rates calibrated to data on aggregate personal consumption from the U.S. National Income and Product Accounts decreased from 30.9 percent in 1947 to 4.1 percent in 1978, declining further to postwar minimum of 2.2 percent in 1989.[10]

Official estimates of poverty rates based on income published by the Bureau of the Census show that 22.4 percent of the U.S. population fell below a poverty line based on income in 1959. The official poverty rate reached a minimum of 11.1 percent in 1973, rebounded to 15.2 percent in 1983, and then fluctuated within a narrow range, ending at 12.8 percent in 1989. Slesnick (1993) attributed this to several factors: the use of income rather than consumption as a measure of household resources; the construction of equivalence scales from food budgets rather than household budgets for all items, and the use of the CPI-U to adjust for changes in the cost of living. The official estimates have given rise to the common impression that poverty has been difficult or impossible to eradicate.

In summary, the measurement of poverty is based on the preferences of households, as revealed by their consumption choices. An econometric approach is essential for summarizing the necessary information on the cost and standard of living and making comparisons among households. While all of these conceptual elements are present in the official poverty statistics, serious flaws in implementation can be traced to the pioneering work of Orshansky (1965, 1966). When these flaws are corrected, poverty trends diverge markedly from those suggested by official poverty rates. The War on Poverty was a success, not a failure.

9.6 Poverty and Redistributional Policy

The official statistics on poverty published by the Bureau of the Census are one component of a comprehensive program for measuring the standard of living for the U.S. population as a whole and inequality in the distribution of household standards of living. Similar issues arise in measuring poverty, inequality, and the standard of living. The resolution of these issues requires replacing all three programs by an econometric approach.

In the econometric approach to normative economics the concept of individual welfare is derived from the theory of the utility-maximizing household. Individual welfare is transformed into a money metric by defining an individual expenditure function as the minimum cost of attaining a given standard of living. This is standard apparatus in the theory of consumer behavior, but it is important to note that the individual units are households, which are social entities, rather than biological individuals. Measures of individual welfare recovered from an econometric model of aggregate consumer behavior can be combined into an indicator of social welfare.[11] The measure of inequality implied by this formulation reflects society's willingness to pay for the redistribution of individual welfare. A similar measure of poverty reflects society's willingness to pay for redistributions that bring all individuals to the minimum level of well-being represented by a poverty line. We illustrate these concepts geometrically in figure 9.3.

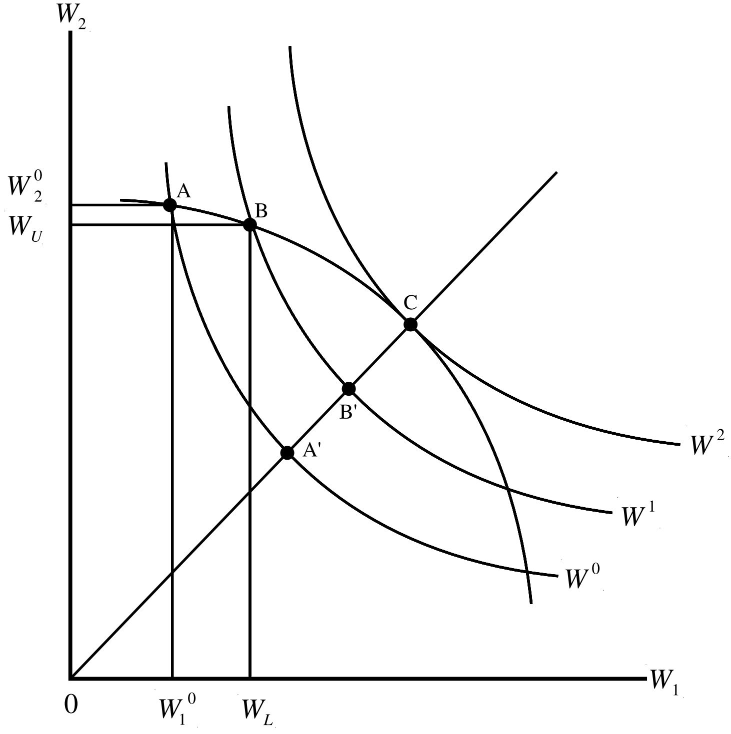


Figure 9.3
Poverty and inequality.

For simplicity we consider a society consisting of two identical individuals, one poor (W_1) and the other rich (W_2). We represent the contours of a concave social welfare function in figure 9.3. The 45° line through the origin represents perfectly egalitarian distributions of individual welfare ($W_1 = W_2$). The actual distribution of welfare corresponds to the point A with social welfare level W^0. Next, we consider the locus of individual welfare levels that result from lump sum redistributions of aggregate spending ($M = M_1 + M_2$). We refer to this as the *redistribution locus*.

If the poverty threshold is set at W_L, the level of social welfare that results from the elimination of poverty, say W^1, corresponds to the point B. This is obtained by moving along the redistribution locus until the welfare of the poor attains this threshold. We refer to the resulting level of welfare of the rich as the *threshold of affluence*. To represent the level of welfare corresponding to the elimination of inequality, we continue along the redistribution locus to the point C with level of social welfare W^2 equal to the maximum that can be attained through lump sum redistributions. In figure 9.3 the point A' represents perfect equality at the same level of social welfare W^0 as at point A. Similarly, the point B' represents perfect equality at the same level of welfare W^1 as at point B.

Finally, we decompose the measures of inequality illustrated in figure 9.3 into the sum of measures of poverty and the remaining inequality. The level of social welfare that results from the elimination of poverty W^1 is intermediate between the actual level W^0 and the potential level W^2. Measures of poverty and the remaining inequality sum to the measure of inequality illustrated in figure 9.3, while relative measure of poverty and the remaining inequality sum to the corresponding relative measure of inequality.[12]

9.7 From Individual to Social Welfare

The first step in measuring inequality is to derive individual welfare functions for all households. The second step is to evaluate the social welfare function.[13] The third step is to transform social welfare into a money metric by means of a social expenditure function, defined as the minimum aggregate spending on consumption required to attain a given level of social welfare. While the social expenditure function is a much less familiar concept than the individual expenditure function, the application of these concepts is precisely chosen.[14]

We define a measure of the loss of welfare due to failure to eliminate poverty as the difference between the values of the social expenditure function at W^1 and W^0. Expressing both values in terms of base period prices, this corresponds to the difference between aggregate expenditures at B and A, namely, $M(p^0, W^1)$ and $M(p^0, W^0)$. This represents a society's willingness to pay to eliminate poverty. The ratio between this difference and aggregate expenditure is a relative measure of poverty. This is the willingness to pay to eliminate poverty expressed as a proportion of aggregate consumer spending.

Similarly, we define a measure of the inequality remaining after poverty is eliminated as the difference between the values of the social expenditure functions at C and B, namely, $M(p^0, W^2)$ and $M(p^0, W^1)$. The ratio between this difference and aggregate expenditure is a relative measure of the remaining inequality. The relative measures of poverty and the remaining inequality sum to the relative measure of inequality. These measures represent a society's willingness to pay to eliminate poverty and the remaining inequality as a proportion of aggregate consumer spending.

Jorgenson and Slesnick (1989) presented consumption-based measures of relative poverty and inequality like those illustrated in figure 9.3 for the period 1947–1985. As before, we have employed the poverty threshold constructed by Orshansky (1965, 1966). Consumption is the measure of household resources, cost-of-living indexes for individual households are employed to adjust for price changes, and household equivalence scales based on total consumption are used to compare standards of living for different households. The results are presented in figure 9.4. Our measures show that American society's willingness to pay to eliminate inequality has declined as a proportion of aggregate consumer spending over the period 1947–1985 and that willingness to pay to eliminate poverty has been a sharply declining proportion of inequality. However, the decline in inequality occurred only during 1958–1978 and 1983–1985.

Slesnick (1994) presented consumption-based measures of inequality for the period 1947–1991 that reveal little change in inequality since the early 1970s. Slesnick also assessed the sensitivity of inequality measures to several factors: the choice of income rather than consumption as a concept of household resources, omission of adjustments for changes in the cost of living, and the selection of different household equivalence

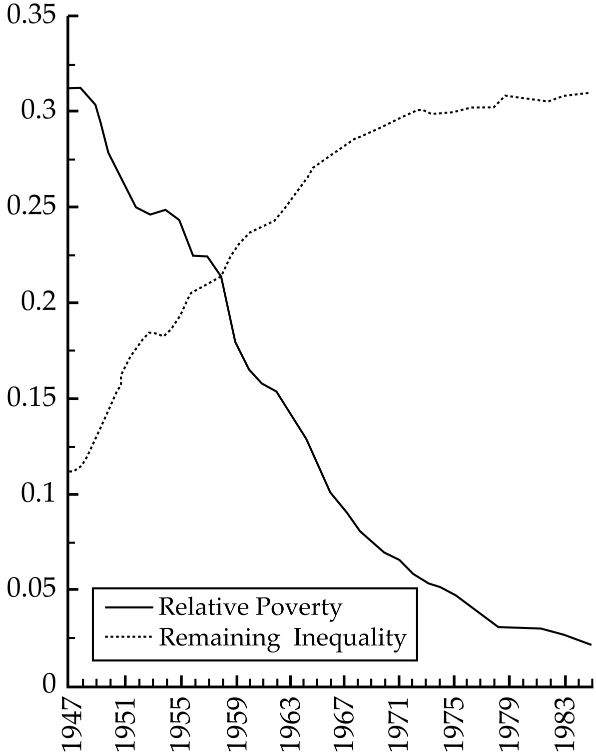


Figure 9.4
Relative poverty and remaining inequality.

scales. Consumption-based inequality measures differ drastically from those based on income. These measures are insensitive to the omission of price changes, but depend critically on the choice of appropriate household equivalence scales.

The Bureau of the Census publishes a measure of inequality for family income (based on a Gini coefficient), which shows a widely reported U-turn with decreases in inequality until 1973 and rising since then. By contrast the measure of inequality presented in figure 9.4 shows a steady decline throughout the period 1958–1985. However, the Census uses income rather than consumption as a concept of household resources, omits adjustments for price changes, and does not incorporate household equivalence scales like those employed in the official poverty estimates.

9.8 Poverty and Inequality within and between Groups

Jorgenson and Slesnick (1984) decomposed a social welfare function by defining group welfare functions for a set of mutually exclusive and exhaustive groups, for example, age groups. We define a welfare function between groups on the group welfare functions in the same way a social welfare function is defined on individual welfare functions. Using these concepts and the corresponding group and social expenditure functions, we decompose relative inequality into the sum of between- and within-group components.

Focusing on groups defined in terms of age of the head of household, we first consider relative inequality for each group. These measures of inequality have declined over the period 1958–1978, but much of the decline is concentrated in the early part of the period. The great predominance of inequality for United States is within rather than between age groups. Overall, inequality within groups falls steadily from 1958 to 1970 and then remains almost unchanged through the remainder of the period. Inequality between groups falls after 1958 and then rises to a peak in 1969, falling gradually through 1978.

Jorgenson and Slesnick (1989) exploited the decomposition of social welfare into within- and between-group components to decompose our measures of poverty. We define poverty within groups in terms of welfare gains due to redistribution within the group so as to eliminate poverty. We then define poverty between groups in terms of additional gains in welfare that result from redistribution between groups. The results reveal substantial gains from redistribution within age groups, while gains from redistribution between groups are negligible.

Slesnick (1994) has analyzed the decomposition of inequality among groups in considerably greater detail. Inequality between age groups is a relatively small proportion of overall inequality and changes relatively little over the period 1947–1991. The decline in overall inequality through the 1970s is largely within age groups. Inequality between groups classified by size of household is about half of total inequality, but there is little change during the period. A fall in inequality within size groups accounts for the decline in overall inequality.

Inequality between regions falls sharply over the period 1947–1980, reflecting the rise in the standard of living of the South. However, most of the fall in overall inequality can be attributed to a reduction in inequality within regions. Inequality between farm and nonfarm groups of the population is a very small part of overall inequality and nearly vanishes over the period 1947–1991. Inequality between racial groups is a very modest proportion of total inequality and has not changed over this period.

9.9 Measuring the Standard of Living

The standard of living appears at first glance to be one of the most straightforward ideas in the conceptual toolkit of the normative economist. A measure of household resources is divided by a cost-of-living index to obtain an index of the standard of living. The first issue is selection of an appropriate measure of household resources. A second issue is how to allow for changes in distributional equity. A satisfactory resolution of this issue requires combining measures of individual welfare into an overall indicator of social welfare.

Jorgenson and Slesnick (1990b) presented a consumption-based measure of the U.S. standard of living for the period 1947–1985. As before, we choose consumption as the measure of household resources, adjust for price changes on the basis of cost-of-living indexes for individual households, and compare standards of living by means of the household equivalence scales constructed by Jorgenson and Slesnick (1987). The standard of living grows forty percent faster than real expenditure per capita, defined as the ratio of aggregate personal consumption expenditures per capita to the CPI-U. Important biases in the real expenditure measure arise from the use of the CPI-U, to adjust for price changes, utilization of the head-count definition of the population in place of the number of household equivalent members, and the omission of equity considerations.

The U.S. Bureau of the Census constructs a measure of the standard of living based on median real family income. According to this measure, the U.S. standard of living has been stagnant for the past two decades. The fundamental difficulty with this income-based approach is that the standard of living should be defined in terms of consumption rather than income. Consumption-based measures of the standard of living do not exhibit the stagnation reported by the Census. Slesnick (1991b) traced important biases in the Census measure to biases in the CPI, the definition of the population, and the omission of equity considerations.

In summary, the econometric approach to normative economics unifies the treatment of inequality and poverty, as well as the cost and standard of living. However, this approach brings to light some very significant flaws in statistical programs that cover these important areas. The stagnation of the U.S. standard of living and the U-turns in inequality and poverty have been revealed as statistical artifacts. The most important deficiency in the Census programs that generate the official statistics is the use of income rather than consumption as a measure of household resources. Serious deficiencies also arise from biases in the CPI and the use of household equivalence scales based on food consumption.

9.10 Recommendations and Conclusions

For some practitioners of normative economics, the application of an econometric model to the measurement of poverty is a highly innovative but also unfamiliar and even disturbing idea. Multi-million dollar budgets are involved in statistical reporting of price index numbers and millions more are spent on measures of poverty, inequality, and the standard of living. Unfortunately, these well-established programs give highly misleading results and require a total overhaul.

The key to revision of existing programs for measuring poverty and inequality and the cost and standard of living is the exploitation of surveys of household consumption. The Consumer Expenditure Survey provides the information required for consumption-based measures. However, the value of this survey could be greatly enhanced by increasing the sample size. Additional resources will be required to reconcile estimates of personal consumption expenditures from the Consumer Expenditure Survey with the U.S. National Income and Product Accounts and to add information in in-kind transfers.

Census programs for measuring poverty, inequality, and the standard of living should be put onto a consistent basis. All three programs should employ a common framework for measuring household standards of living. Consumption should be used as a measure of household resources. Cost-of-living indexes should be employed in place of the current Consumer Price Index. This requires consistency in the treatment of components of the index, such as housing services, over time. It also requires elimination of the biases that have been identified by the Advisory Commission to Study the Consumer Price Index (1996). A cost-of-living index could be implemented on an annual basis, using information from the Survey and Consumer Expenditures.[15] Comparison among households should be based on the cost of total household consumption, rather than the cost of food alone. The resulting measures would provide a far more accurate guide to the impact of economic growth and income support program in the level and distribution of household well-being.

Notes

1. The persistence of poverty, as reflected in the official statistics, is discussed by Sawhill (1988).

2. Slesnick (1993) presented a detailed decomposition of the differences between estimates of poverty rates based on consumption and the *official* estimates based on income. Neither measures of consumption from the Consumer Expenditure Survey nor measures of income used by the Bureau of the Census include in-kind transfers. Slesnick (1996) discussed the effects of these transfers on *measures* of poverty.

3. The classic attack on anti-poverty programs is Charles Murray's (1984) *Losing Ground: American Social Policy, 1950–1980*.

4. Fisher (1992a, 1992b) gives a detailed history of official poverty measurement.

5. Additional details about the official poverty line are provided by Slesnick (1993), Revallion (1994), and the Panel on Poverty and Family Assistance (1995). The Panel on Poverty and Family Assistance advocated replacing the official poverty measure by an entirely new approach based on income. The *key* feature of this proposal is a shift from an *absolute* measure of poverty, based on a fixed poverty threshold, to a *relative* measure with a threshold that changes with the standard of living. This paper focuses on an absolute measure of poverty based on consumption rather than income.

6. The feasibility of constructing consumption-based measures of powerty on the basis of *existing* primary data sources is discussed by the General Accounting Office (1996b).

7. This is demonstrated by Paul Samuelson (1956). The resulting model of household behavior is employed by Gary Becker (1981). A critique of this model is presented by Shelby Lundberg and Robert Pollak (1996).

8. Conditions for independence of the standard of living are given by Lewbel (1989). The literature on equivalence scales is surveyed by Browning (1992).

9. The treatment of housing costs in the CPI is discussed by Robert Gillingham and Walter Lane (1982).

10. Slesnick (1992) shows that aggregate consumption expenditures in the U.S. National Income and Product Accounts exceeded the expenditures in the BLS Survey of Consumer Expenditures by $1224 billion in 1989 and that these measures have diverged over time.

11. A detailed exposition of the econometric approach to normative economics is presented by Jorgenson (1990a).

12. Sen (1976) presented an alternative approach to measuring poverty that also captures the intensity of deprivation of households in poverty.

13. Since the pioneering work of Atkinson (1970) and Kolm (1969), the measurement of social welfare has been based on explicit social welfare functions. However, the social welfare functions introduced by Atkinson and Kolm are defined on the distribution of income rather than the distribution of individual welfare.

14. The social expenditure function was originated by Pollak (1981).

15. Further details on implementation of a cost-of-living index are given by Jorgenson and Slesnick (1999).

10

Indexing Government Programs for Changes in the Cost of Living

Dale W. Jorgenson and
Daniel T. Slesnick

This chapter presents social-cost-of-living indexes constructed from an econometric model of aggregate consumer behavior. The econometric price index has the same average inflation rate as a Tornqvist price index over the period 1947–1995, but rises less rapidly after 1973. Group cost-of-living indexes are presented for white and nonwhite, male- and female-headed, and elderly and nonelderly households. Elderly households have experienced a slightly higher rate of inflation than the nonelderly since 1980. We recommend indexing government programs, such as Social Security, by social and group cost-of-living indexes, rather that the Consumer Price Index.

The first and most important recommendation of the Advisory Commission to Study the Consumer Price Index, appointed by the Senate Finance Committee, is

> 1. The BLS (Bureau of Labor Statistics) should establish a cost-of-living index as its objective in measuring consumer prices. All of our specific recommendations are aimed toward this goal (Boskin, Dulberger, Gordon, Griliches, and Jorgenson, 1996, p. 77).

The purpose of this chapter is to present an econometric methodology for constructing consumer price indexes for indexing government programs for changes in the cost of living.

The economic theory of cost-of-living measurement is customarily formulated for an individual household, whereas price indexes are constructed for groups of households. For example, BLS publishes monthly indexes for all urban consumers (CPI-U), who make up 87 percent of the U.S. population, and urban wage earners and clerical workers (CPI-W), who compose 32 percent. These indexes combine data on prices with averages of expenditure patterns for the households in each group. BLS also employs this approach in the experimental price indexes for the smaller groups of elderly and poor households described by Moulton and Stewart (1999). Diewert (1981) and Pollak (1989) presented detailed surveys of cost-of-living measurement for individual households, and Pollak (1981) discussed group cost-of-living indexes.

In section 10.1, we review the theory of cost-of-living measurement for individual households as well as for groups of households. At the micro-level, a cost-of-living index measures the amount total expenditure must change in response to price variation in order to maintain the household's standard of living. A social cost-of-living index is the amount aggregate expenditure must change in order to maintain a constant level of social welfare as prices change. Implementation of a social cost-of-living index requires the recovery of household welfare functions from observed demand patterns and aggregation of these welfare functions to obtain an indicator of social welfare.

The most common method for cost-of-living measurement is to combine data on prices with observations on the average expenditure patterns of groups of households. This is the *index-number method* employed by BLS in compiling the Consumer Price Indexes (CPI's). Prices are collected monthly by very detailed surveys of providers of goods and services. Average expenditure patterns for the groups of interest (urban households in the CPI-U or wage workers in the CPI-W) are surveyed on a quarterly basis in the Consumer Expenditure Survey (CEX). More details on the construction of the CPI are given by BLS (1992), Boskin, Dulberger, Gordon, Griliches, and Jorgenson (1996, sec. III), Shapiro and Wilcox (1996), and Moulton and Stewart (1999). The problem with this approach is that it relies on the existence of a representative consumer for each group. Social welfare, moreover, is represented by the utility of this mythical consumer and may be inconsistent with even the most basic principles of social choice, as pointed out by Kirman (1992, pp. 124–125).

An alternative approach to cost-of-living measurement involves building an econometric model of consumer behavior. Demand functions are estimated and used to infer the underlying welfare functions of consumers. These welfare functions are used as arguments of an explicit social welfare function that has a well-defined social-choice-theoretic interpretation. This social welfare function facilitates the estimation of an aggregate cost of living as the change in aggregate expenditure necessary to maintain the level of social welfare as prices change. This is the *econometric method* for cost-of-living measurement.

The econometric approach to cost-of-living measurement encompasses all of the information employed in the index-number approach, but preserves important features of the data that are suppressed in constructing index numbers. This method, for example, captures changes in the allocation of household spending in response to changes in prices and the level of total expenditure. In addition, it incorporates the effects of changes in demographic structure on aggregate spending patterns. In Jorgenson and Slesnick (1990a) we have presented cost-of-living measurements for individual households and groups of households based on an econometric model, and Balk (1990) and Kokoski (1987) have given cost-of-living measurements for individual households based on econometric models.

In section 10.2 we compare index-number methods with the econometric method for measuring the cost of living. We find that, over the entire sample period, the stimated inflation rates are identical. The two indexes, however, do not track each other perfectly. Over the first half of the sample period, the econometric index increases slightly faster than the index-number approach; the reverse is true in the second half of the sample.

The econometric method provides a unified framework for generating cost-of-living measures for society as a whole and for groups defined by demographic characteristics. Cost-of-living measures for subgroups of the population reflect the distinctive features of group expenditure patterns as well as the level of total expenditure and the demographic structure of the group. Index-number measures of the group cost of living, such as the CPI-U and CPI-W, incorporate group expenditure patterns, but exclude other important information captured by the econometric approach.

Jorgenson and Slesnick (1990b) defined group welfare functions for a set of mutually exclusive and exhaustive groups of households, for example, age groups. We defined a social welfare function between groups on the group welfare functions in the same way a social welfare function is defined on individual welfare functions. Using the group welfare functions and the corresponding group expenditure functions, measures of the cost of living for groups can be defined by analogy with the social cost of living. Slesnick (1991b) used group welfare functions to measure growth rates of the standard of living across demographic groups, and Slesnick (1994) has employed them in measuring levels of inequality between groups differentiated by age, race, gender and region of residence.

In section 10.3 we compare econometric measures of the cost-of-living for different demographic groups of the U.S. population. We find that group cost-of-living indexes for nonelderly households, as well as white and nonwhite households and female- and male-headed households, are essentially the same as the social cost-of-living index. This corroborates and extends our previous findings, reported by Jorgenson and Slesnick (1990a), that cost-of-living indexes for the United States as a whole and for subgroups of the population are very similar. We find, however, that the elderly have experienced a slightly higher rate of inflation since the late 1970s.

Measures of the cost of living are designed to compare the costs of maintaining a given standard of living in two different price situations. For example, how does the cost compare between 1996 and 1997 for households with two elderly adults, one a Social Security beneficiary, residing in the New York metropolitan area? The answer to this question is very important for policy because government programs are adjusted for cost-of-living changes to protect program participants from losses in purchasing power. The econometric approach is particularly suited to address this question; data limitations make it difficult to use the index-number method for this purpose.

Social Security is by far the most important of the federal outlays that are indexed by the CPI. Supplementary Security Income, Military Retirement, and Civil Service Retirement are similarly indexed. Other federal retirement programs, Railroad Retirement, veterans' compensation and pensions, and the Federal Employees' Compensation Act also contain provisions for indexing. The Economic Recovery Tax Act of 1981 indexes individual income-tax brackets and the personal exemption to the CPI.

In section 10.4 we conclude that it is feasible to implement a cost-of-living index, as recommended by the Advisory Commission (Boskin, Dulberger, Gordon, Griliches, and Jorgenson, 1996). We recommend, more specifically, that the CPI be replaced by a social cost-of-living index based on an econometric model of aggregate consumer behavior. This index would use information on prices and household expenditures from BLS surveys and would be suitable for indexing many government programs. For example, the compensation of federal government employees, as well as features of the personal income tax, could be indexed in this way.

Since the elderly have experienced somewhat higher inflation rates than the nonelderly, we conclude that a group cost-of-living index is essential for indexing programs for the elderly. We recommend that such an index be constructed for the elderly from an econometric model and used for indexing federal government retirement programs and Social Security benefits. Indexing these programs by a cost-of-living index for the United States as a whole could fail to preserve the purchasing power of elderly beneficiaries.

10.1 Measuring the Cost of Living

Our first objective in this section is to review the theory of the cost of living for an individual household. We employ the individual expenditure function, giving the minimum level of spending required to achieve a given standard of living for the household. We then outline a theory of the cost of living for groups of households. For this purpose we employ a social expenditure function, giving the minimum level of aggregate spending required to maintain a given standard of living for society as a whole.

In the economic theory of cost-of-living measurement, the standard of living is identified with individual welfare. It is important to note, however, that observations of consumer expenditures are for households, which are social entities, rather than biological individuals. The standard of living for an individual household is transformed into a money metric by means of the household expenditure function.

To describe the price indexes used in measuring the household cost of living, we employ the following notation:

p_n—price of the n-th commodity, assumed to be the same for all households ($n = 1, 2, \dots, N$).

$p = (p_1, p_2, \dots, p_N)$—vector of prices of all commodities.

x_nk—quantity of the n-th commodity consumed by the k-th household ($n = 1, 2, \dots, N; k = 1, 2, \dots, K$).

$x_k = (x_1k, x_{2k}, \dots, x_{Nk})$—vector of quantities of all commodities consumed by the k-th household ($k = 1, 2, \dots, K$).

$M_k = \sum_{n=1}^{N} p_n x_{nk}$—total expenditure of the k-th household ($k = 1, 2, \dots, K$).

A_k—vector of attributes of the k-th household ($k = 1, 2, \dots, K$).

The analytical framework for cost-of-living measurement is based on the assumption that a household is trying to achieve the highest possible standard of living, while staying within its budget. Another way to state this is to say that a household is trying to maximize its welfare, say W_k, subject to the budget constraint

$$M_k = \sum_{n=1}^{N} p_n x_{nk}.$$

Cost-of-living measurements compare the levels of spending required to maintain a given standard of living for different price situations. A concise way to summarize the necessary information is to express the minimum total expenditure M_k required for the k-th household to achieve a given standard of living W_k, given the prices p faced by the household and the household's attributes A_k

$$M_k(p, W_k, A_k) = \min \left\{ M_k = \sum_{n=1}^{N} p_n x_{nk} : W_k(x_k, A_k) \geq W_k \right\}.$$

This is the *individual expenditure function* introduced by McKenzie (1957).

We consider two different time periods, the base period denoted by 0 and the current period denoted by 1. The ratio between the levels of spending required to achieve the same level of welfare in the two periods is the *household cost-of-living index*, say P_k, introduced by Konyus (1939):

$$P_k(p^1, p^0, W_k) = \frac{M_k(p^1, W_k, A_k)}{M_k(p^0, W_k, A_k)},$$

where M_k is the expenditure function for household k, p^1 is the vector of prices in the current period, p^0 the base period prices, and W_k is the reference level of individual welfare.

The analytical framework for cost-of-living measurement proposed by Konyus (1939) is appropriate for a single household. Cost-of-living measures for indexing government programs refer to groups, however, such as all federal employees, all Social Security beneficiaries, or all taxpayers. We extend the framework to groups by specifying a social welfare function and defining the social cost-of-living index as the cost of maintaining a given level of social welfare as prices change.

The first step in defining a social cost-of-living index is to identify the standard of living for society as a whole with social welfare. Social welfare is transformed into a money metric by means of the social expenditure function, defined as the minimum level of aggregate expenditure required to maintain a given standard of living for society. Although the social expenditure function is a much less familiar concept than the individual expenditure function, the application of these concepts is precisely analogous.

To describe cost-of-living measures for groups of households, including society as a whole, we require this additional notation:

x—matrix with N by K elements $\{x_{nk}\}$ describing the quantities of all commodities consumed by all households.

$u = (W_1, W_2, \ldots, W_K)$—vector of individual welfare functions of all N households.

Let $W(u, x)$ be a social welfare function defined over the distribution of household welfare functions. Aggregation of the household welfare functions into a social welfare function requires normative assumptions related to their measurability and comparability. Jorgenson (1990a, 1997a) and Slesnick (1998) discussed these issues in more detail. Cost-of-living measurements for society as a whole compare the levels of aggregate spending required to maintain a given standard of living for different price situations. To summarize the necessary information, we express the minimum level of aggregate expenditure, $M = \sum_{k=1}^{K} M_k$, required to attain a given level of social welfare W through lump-sum redistributions among households, given the prices p faced by all households

$$M(p, W) = \min \left\{ M = \sum_{k=1}^{K} M_k : W(u, x) \geq W \right\}.$$

This is the *social expenditure function* introduced by Pollak (1981).

As before, we consider two different time periods, the base period and the current period. The ratio between the level of aggregate spending required to achieve the reference level of welfare in the current period to the level of spending required in the base period is the *social cost-of-living index*, say P, introduced by Pollak (1981):

$$P(p^1, p^0, W) = \frac{M(p^1, W)}{M(p^0, W)},$$

where M is the social expenditure function and W is the reference level of social welfare.

Prais (1959) has presented an alternative to Pollak's social cost-of-living index by defining a "plutocratic" index as a weighted average of household cost-of-living indexes with weights given by the shares of households in aggregate expenditure. This can be derived from a social expenditure function defined as the sum of individual expenditure functions. Prais has also defined a "democratic" social cost-of-living index as an unweighted average of individual cost of living indexes. Neither the plutocratic nor the democratic index provide the additional expenditure required to maintain the level of social welfare as prices change.

The econometric approach to the measurement of the cost of living uses household expenditure patterns to identify the welfare levels of the population of households. The welfare functions serve as arguments of an explicit social welfare function that is the basis for the measurement of the social cost of living. The index-number approach assumes that aggregate spending by households is consistent with the behavior of a hypothetical representative consumer. Although this assumption is excessively restrictive and obscures the interpretation of the cost-of-living index, it is of practical interest to determine whether the two methods give fundamentally different estimates of the cost of living in the United States.

10.2 Implementing Cost-of-Living Indexes

We turn next to methods for implementing measures of the cost of living. An important issue for all methods is that commodities included in the index must be constant in quality. We first consider the index-number method employed by the BLS in constructing the CPI. We compare the two different implementations the CPI methodology, the CPI-U for all urban consumers and the CPIX1, an index for the same group of consumers that holds the quality of services of owner-occupied residential housing constant.

The Consumer Price Index (CPI), say P^L, is a "modified" Laspeyres price index, because the quantities consumed x_{nk} are for a reference period that is not necessarily the same as the base period for price comparisons. This index is defined as the ratio of the expenditure required to purchase the reference quantities consumed x_{nk} at current prices p^1 to the expenditure needed to purchase these quantities at base period prices p^0:

$$P^L(p^1, p^0, x) = \frac{\sum_{n=1}^{N} \sum_{k=1}^{K} p_n^1 x_{nk}}{\sum_{n=1}^{N} \sum_{k=1}^{K} p_n^0 x_{nk}}.$$

As relative prices change, the composition of spending also changes through substitution away from commodity groups that have become more expensive. The Laspeyres price index holds the quantities fixed, producing a "substitution" bias that results from ignoring changes in composition. An important assumption in cost-of-living measurement is that commodities are constant in quality. Constant quality measures of prices and quantities were discussed in more detail by Gordon and Griliches (1997) and Moulton and Moses (1997). On February 25, 1983, BLS altered the CPI-U to treat housing costs for homeowners on a rental equivalent basis. Housing costs for preceding years employed a "homeownership measure . . . based on house prices, mortgage interest rates, property taxes and insurance, and maintenance costs" (Gillingham and Lane, 1982).

A sharp rise in interest rates during the 1970s resulted in overestimate of the rate of inflation. The rental-equivalent treatment of housing was introduced into the CPI-U without revising the index backward, so that a permanent upward bias was incorporated into the price level. To assess the importance of this bias, we compare the CPI-U with the CPIX1, an experimental index that treats homeownership costs consistently on a rental-equivalent basis.

We present the CPI-U and CPIX1 price indexes in figure 10.1 and table 10.1. Levels of the two indexes and estimated inflation rates are presented in the figure. Both series show the same pattern of movements in prices. Price increases accelerated in the 1970s due, largely, to the oil price shocks of 1973–1974 and 1979–1980. The inflationary surge receded after 1980. Over the entire postwar period, the CPI-U increased at a rate of 4.0 percent per year compared to 3.8 percent for the CPIX1.

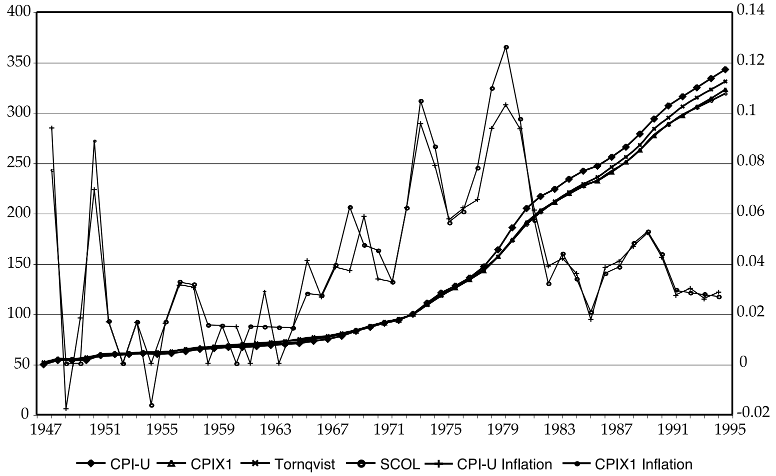


Figure 10.1
CPI-U and CPIX1 price indexes.

Table 10.1
Group cost-of-living indexes

	Aggregate cost-of-living indexes			
Year	CPI-U	CP1X1	Tornqvist	SCOL
1947	50	51	52	50
1948	54	56	55	54
1949	54	55	55	54
1950	54	56	57	56
1951	59	60	59	58
1952	60	61	60	59
1953	60	61	61	60
1954	61	62	62	61
1955	60	62	62	62
1956	61	63	63	63
1957	63	65	65	65
1958	65	67	66	66
1959	66	67	68	68
1960	67	68	69	69
1961	67	69	70	69
1962	68	69	71	70
1963	69	71	72	71
1964	70	71	73	73
1965	71	72	75	74
1966	73	75	77	76
1967	75	77	78	78
1968	78	80	81	81
1969	83	83	84	84
1970	87	88	88	88
1971	91	91	92	92
1972	94	94	95	95
1973	100	100	100	100
1974	111	110	109	110
1975	121	119	118	119
1976	128	126	126	126
1977	136	134	135	135
1978	147	143	144	145
1979	164	157	157	157
1980	186	174	173	173
1981	205	191	190	189
1982	217	203	202	201
1983	224	211	212	211
1984	234	220	221	219
1985	242	228	229	227
1986	247	232	236	233
1987	256	241	246	242
1988	266	251	256	251
1989	279	263	268	263
1990	294	277	284	278
1991	307	289	295	288
1992	316	297	306	298
1993	325	306	315	305
1994	334	314	323	312
1995	343	323	331	319

Table 10.2
Unit-root tests; null hypothesis: unit root

	Levels		First differences	
Inflation rate	*t* statistic	*p* value	*t* statistic	*p* value
CP1U	−0.92	0.95	−5.84	0.00004
CPIX1	−0.98	0.94	−5.46	0.00009
Tornqvist	−1.54	0.83	−5.76	0.00004
TCOLI	−1.57	0.82	−5.58	0.00006
White	−1.58	0.82	−5.53	0.00007
Nonwhite	−1.48	0.85	−6.15	0.00002
Male	−1.57	0.82	−5.60	0.00006
Female	−1.63	0.80	−5.27	0.00014
Elderly	−1.61	0.81	−5.26	0.00015
Nonelderly	−1.56	0.82	−5.63	0.00006

The housing bias did not manifest itself until the late 1960s when CPI-U and CPIX1 indexes began to diverge. Between 1977 and 1982, the CPI-U increased at an average rate of 9.3 percent per year while the CPIX1 rose at 8.3 percent per year. Between 1979 and 1980, the CPI-U increased 12.7 percent while the inflation rate measured by the CPIX1 was only 10.6 percent. Over the fifteen-year period between 1967 and 1983, the treatment of costs of homeownership cumulated into a substantial bias of 6.3 percent in the CPI-U relative to the CPIX1. This illustrates the importance of maintaining constant quality for each commodity group included in a cost-of-living index.

A natural question is whether the different treatments of housing resulted in persistent differences in the stochastic trends of the two indexes. Despite the presence of an important housing bias in the CPI-U, relative to the CPIX1, the two series have almost identical stochastic trends. In table 10.2 we present augmented Dickey-Fuller unit-root tests for inflation rates and first differences of the inflation rates, showing that the levels of both series are integrated of order two. Lag lengths are selected on the basis of the Schwartz-Bayes information criterion, and *p* values are computed on the basis of tables presented by MacKinnon (1991). The levels regressions include a constant term and linear trend, while the first-difference regressions include only a constant term.

In table 10.3 we present tests of the null hypothesis of no cointegration for pairs of inflation rates. These tests are based on Dickey-Fuller *t* ratios.

Table 10.3
Cointegration tests; null hypothesis: no cointegration

Inflation rate	t statistics	p value	Sample mean	Standard error
CPI-U-CPIX1	−3.54	−0.01100	0.0017	0.00093
Tornqvist-TCOLI	−3.32	0.01900	0.00013	0.00046
White-nonwhite	−5.85	0.00003	0.000036	0.00026
Male-female	−5.75	0.00004	0.000087	0.00019
Elderly-nonelderly	−6.20	0.00001	0.00066	0.00015

Means and standard errors robust to serial correlation are reported in the last two columns of table 10.3. Augmented Dickey-Fuller tests were unnecessary because the disturbances do not appear to be serially correlated. Durbin-Watson ratios for the five regressions are 1.68, 1.99, 1.97, 1.98, and 1.81. As before the p values are based on the tables presented by MacKinnon (1991).

Although widely used and simple to calculate, the CPI has several problems that limit its ability to measure the cost of living. It assumes that the quantities consumed remain fixed even though, in general, households will adjust their expenditure patterns as relative prices change. Moreover, it can be used as a cost-of-living index only if demands are consistent with a representative consumer with Leontief preferences. Alternative index-number methods have been proposed that retain the assumption of a representative consumer but relax the condition of fixed coefficient preferences to accommodate substitution by households.

Diewert (1981) developed a theory of exact index numbers that provide cost-of-living indexes for a broader class of preferences relative to the Laspeyres index used by the BLS. Consider, for example, the Tornqvist (1936) price index,

$$\ln P^T(p^1, p^0, x^1, x^0) = \frac{1}{2}\sum_{n=1}^{N}(w_n^0 + w_n^1) \ln \frac{p_n^1}{p_n^0},$$

where w_n^0 is the expenditure share of the n-th commodity in the base period and w_n^1 is the corresponding share in the current period. This index eliminates the substitution bias in the Laspeyres index P^L. Diewert showed that the Tornqvist index can be interpreted as a cost-of-living index if preferences are of the translog form and the reference welfare level is a geometric average over the two periods.

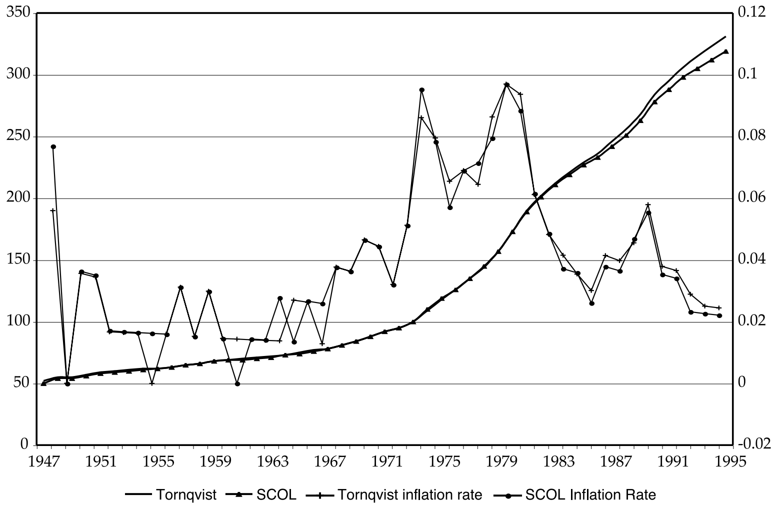


Figure 10.2
Tornqvist and social cost-of-living indexes.

The econometric approach to the measurement of the cost of living relaxes the assumption of a representative consumer and enables us to develop cost-of-living measures with meaningful welfare-theoretic interpretations. We present the econometric social cost-of-living index P and the Tornqvist indes P_T in figure 10.2. To describe our method, we require the following additional notation:

$\ln p = (\ln p_1, \ln p_2, \ldots, \ln p_N)$—vector of prices.

$w_n = \frac{\sum_{k=1}^{K} p_n x_{nk}}{M}$ —aggregate expenditure share of the n-th commodity $(n = 1, 2, \ldots, N)$.

$w = (w_1, w_2, \ldots, w_N)$—vector of aggregate expenditure shares.

Jorgenson and Slesnick (1987) estimated the unknown parameters—α_p, B_{pp}, B_{pA}—of the translog model of aggregate consumer behavior:

$$w = \frac{1}{D(p)}\left(\alpha_p + B_{pp}\ln p + B_{pp}i\frac{\sum_{k=1}^{K} M_k \ln M_k}{M} + B_{pA}\frac{\sum_{k=1}^{K} M_k A_k}{M}\right),$$

where $D(p) = -1 + i' B_{pp} \ln p$.

For this purpose we have pooled aggregate time series data on prices for the U.S. National Income and Product Accounts with individual cross-section data on consumer spending from the 1973 Consumer

Expenditure Survey. We employ econometric methodology originated by Jorgenson, Lau, and Stoker (1982) and discussed in detail by Jorgenson and Stoker (1986) and Jorgenson (1997a). Demand functions of this type are consistent with household welfare functions of the form

$$W_k = \ln p'\alpha_p + \ln p' B_{pp} \ln p - D(p) \ln[M_k/m_0(p, A_k)].$$

Jorgenson and Slesnick (1990a) used the household welfare functions as arguments of a social welfare function that incorporates principles of horizontal and vertical equity. We have defined the social cost-of-living index, say P, as

$$\ln P(p^1, p^0, W) = \frac{1}{D(p^1)}[\ln p^1(\alpha_p + B_{pp} \ln p^1) - W] + \ln\left[\sum_{k=1}^{K^1} m_0(p^1, A_k)\right] - \ln M^0.$$

10.3 Group Cost-of-Living Indexes

In this section we present price indexes for groups of households, classified by demographic characteristics. Cost-of-living indexes may differ across groups of households if there are important differences in spending patterns and large variations in relative prices. For example, if the price of health care increases, elderly households that use more health care will experience a rise in their cost of living relative to the cost of living of nonelderly households. Similarly, an increase in the price of food or energy will have a larger impact on poor households, which spend more of their resources on these necessities.

The CPI-U, the Tornqvist price index, and the econometric social cost-of-living index summarize price changes at the aggregate level. Price information is obviously crucial for cost-of-living measurement, but attributes of households are important too, since households may differ in their spending patterns and this must be reflected in cost-of-living measurements. The attributes of a household are demographic characteristics like the place of residence (New York metropolitan area), family size (two adults), age (elderly), and program participation (Social Security beneficiary).

Figure 10.3 and table 10.4 give prices of energy, food, consumer goods, capital services, and consumer services between 1947 and 1995. The

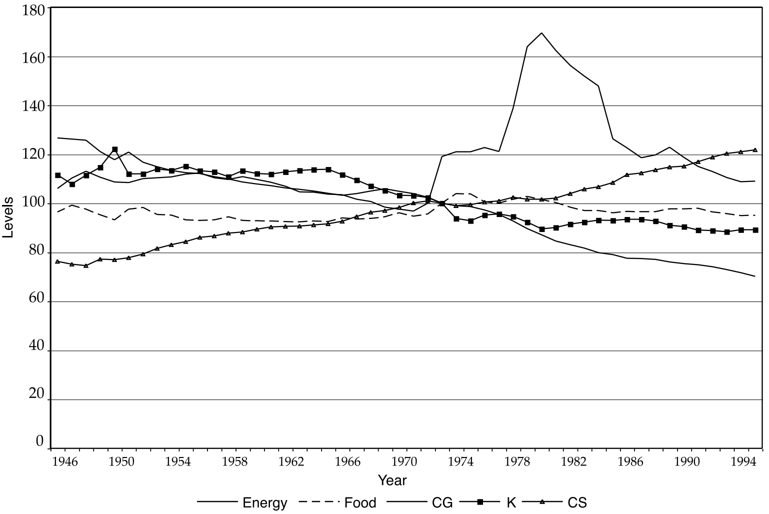


Figure 10.3
Relative prices.

price for each commodity group is deflated by the PCE price index. The relative price of consumer services has increased steadily, reflecting the sharp rise in health care prices. The relative price of consumer goods has exhibited an equally precipitous decline from 1.27 in 1947 to 0.70 in 1995. The price of food has remained stable, and the price of capital services, including housing and consumers' durables, has fallen slightly. Most conspicuous is the dramatic increase in the relative price of energy from 1973 to 1981.

The variations in relative prices illustrated in figure 10.3 suggest the possibility of substantial differences in measures of the cost of living for different groups; however, the importance of these differences for the cost of living is an empirical issue. Using Laspeyres index numbers, Michael (1979) and Hagemann (1982) have found substantial differences among households. Boskin and Hurd (1985), employing similar methodology, estimated price indexes for the elderly and nonelderly groups and reported only modest differences.

Moulton and Stewart (1999) discussed BLS experimental price indexes for the elderly and the poor. The index for the elderly grows at 0.23 percent per year more rapidly than the CPI-U for the period December 1992 to December 1997. Various price indexes for the poor grow at rates that are similar to the CPI-U for the same period. BLS plans to

Table 10.4
Relative prices

Year	Energy	Food	CG	K	CS
1946	105.99	96.46	126.66	111.59	76.33
1947	110.30	99.26	126.21	107.91	75.18
1948	113.04	97.58	125.71	111.48	74.59
1949	110.57	95.34	121.15	114.62	77.16
1950	108.67	93.20	117.81	122.10	76.99
1951	108.46	97.59	120.86	112.06	77.75
1952	110.10	98.24	116.71	112.01	79.25
1953	110.39	95.47	114.84	113.98	81.61
1954	110.80	95.20	113.36	113.39	83.10
1955	111.88	93.20	112.44	115.14	84.37
1956	112.39	93.00	112.07	113.28	86.05
1957	110.45	93.23	110.85	112.85	86.63
1958	109.66	94.53	109.89	110.90	87.78
1959	110.84	93.00	108.62	113.29	88.26
1960	109.71	92.85	107.89	112.18	89.42
1961	108.61	92.82	107.19	111.84	90.34
1962	106.99	92.50	106.21	112.83	90.56
1963	104.64	92.47	105.70	113.42	90.73
1964	104.55	92.72	105.01	113.69	91.15
1965	103.69	92.56	104.03	113.88	91.63
1966	103.54	94.01	103.26	111.71	92.67
1967	101.62	93.53	103.99	109.49	94.60
1968	100.69	93.81	104.97	107.00	96.36
1969	98.36	94.49	105.88	105.20	97.03
1970	97.63	96.13	104.87	103.25	98.28
1971	96.75	94.72	103.90	103.17	100.11
1972	100.00	95.68	102.44	102.34	100.91
1973	119.01	100.00	100.00	100.00	100.00
1974	121.01	103.89	98.95	93.76	98.98
1975	121.01	103.88	98.69	92.87	99.48
1976	122.68	100.63	97.21	95.22	100.46
1977	121.12	100.08	95.47	95.66	100.94
1978	138.76	101.62	92.71	94.56	102.41
1979	163.87	102.75	89.65	92.35	101.65
1980	169.57	101.50	87.16	89.56	101.59
1981	162.39	100.24	84.62	90.16	102.10
1982	156.26	98.43	83.11	91.48	103.97
1983	151.91	97.05	81.65	92.34	105.78
1984	147.88	97.05	79.89	93.12	106.66
1985	126.25	96.06	79.00	92.97	108.40
1986	122.56	96.70	77.57	93.44	111.64
1987	118.55	96.54	77.41	93.41	112.38
1988	119.75	96.61	77.12	92.71	113.65
1989	122.84	97.72	76.04	91.02	114.83
1990	118.68	97.73	75.34	90.50	115.16
1991	114.97	97.93	74.89	89.12	116.99
1992	112.95	96.40	74.05	88.86	118.85
1993	110.48	95.74	72.89	88.43	120.34
1994	108.75	95.00	71.68	89.17	121.00
1995	109.00	95.10	70.21	89.23	121.83

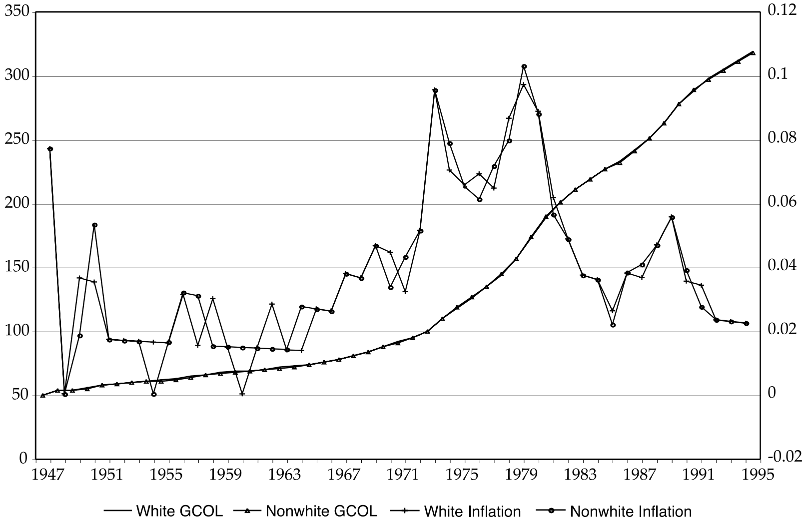


Figure 10.4
White and nonwhite cost-of-living indexes.

update the index for the elderly periodically, but has no plans to update the indexes for the poor.

We present econometric group cost-of-living indexes for households distinguished by age, race and gender of the head of the household in figures 10.4, 10.5, and 10.6 and table 10.5.

The figures give the level and rate of inflation of the indexes. The group cost-of-living index for each demographic group is analogous to the social cost-of-living index presented by Jorgenson and Slesnick (1990a). Potential social welfare is replaced by potential group welfare as the reference level of welfare *W*, and the number of household equivalent members in the society as a whole is replaced by the number of household equivalent members in the group.

Figure 10.4 shows that group cost-of-living indexes for white and nonwhite groups essentially coincide throughout the period. Similarly, group cost of living index for male- and female-headed households largely coincide, as shown in figure 10.5. Price indexes for the nonelderly and elderly presented in figure 10.6 coincide through 1978, as shown by Jorgenson and Slesnick (1990a). The two indexes begin to diverge around 1978 and the cumulative difference amounts to 1.7 percent by the end of the period.

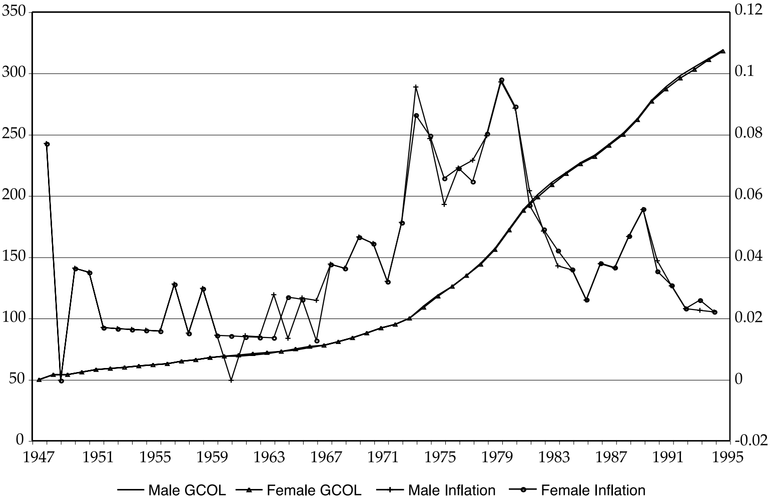


Figure 10.5
Male- and female-head cost-of-living indexes.

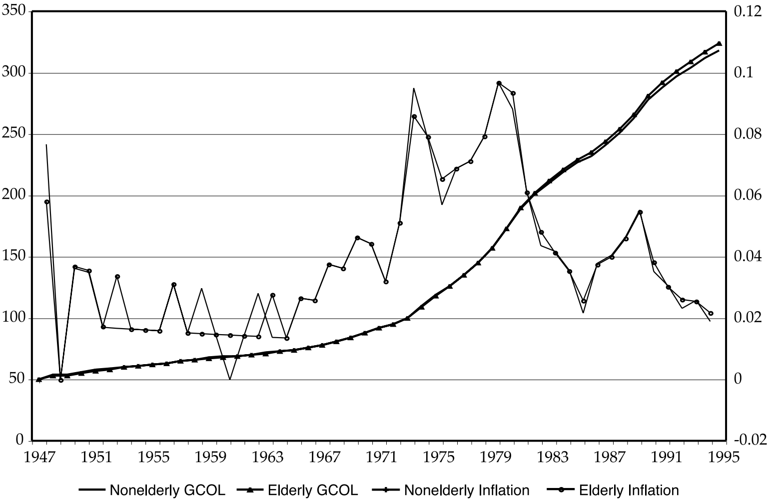


Figure 10.6
Nonelderly and elderly cost-of-living indexes.

Table 10.5
Group cost-of-living indexes

Year	White	Nonwhite	Male	Female	Nonelderly	Elderly
1947	50	50	50	50	50	50
1948	54	54	54	54	54	53
1949	54	54	54	54	54	53
1950	56	55	56	56	56	55
1951	58	58	58	58	58	57
1952	59	59	59	59	59	58
1953	60	60	60	60	60	60
1954	61	61	61	61	61	61
1955	62	61	62	62	62	62
1956	63	62	63	63	63	63
1957	65	64	65	65	65	65
1958	66	66	66	66	66	66
1959	68	67	68	68	68	67
1960	69	68	69	69	69	68
1961	69	69	69	70	69	69
1962	70	70	70	71	70	70
1963	72	71	71	72	72	71
1964	73	72	73	73	73	73
1965	74	74	74	75	74	74
1966	76	76	76	77	76	76
1967	78	78	78	78	78	78
1968	81	81	81	81	81	81
1969	84	84	84	84	84	84
1970	88	88	88	88	88	88
1971	92	91	92	92	92	92
1972	95	95	95	95	95	95
1973	100	100	100	100	100	100
1974	110	110	110	109	110	109
1975	118	119	119	118	119	118
1976	126	127	126	126	126	126
1977	135	135	135	135	135	135
1978	144	145	145	144	145	145
1979	157	157	157	156	157	157
1980	173	174	173	172	173	173
1981	189	190	189	188	189	190
1982	201	201	201	199	201	202
1983	211	211	211	209	210	212
1984	219	219	219	218	219	221
1985	227	227	227	226	227	229
1986	233	232	233	232	232	235
1987	242	241	242	241	241	244
1988	251	251	251	250	251	254
1989	263	263	263	262	263	266
1990	278	278	278	277	278	281
1991	288	289	289	287	288	292
1992	298	297	298	296	297	301
1993	305	304	305	303	304	309
1994	312	311	312	311	312	317
1995	319	318	319	318	318	324

Table 10.6
Tornqvist cost-of-living indexes

Year	White	Nonwhite	Male	Female	Nonelderly	Elderly
1980	175.28	174.35	175.03	176.42	175.40	173.80
1981	191.84	192.00	191.77	192.73	192.11	190.62
1982	203.26	204.27	203.33	204.12	203.53	202.73
1983	213.24	214.25	213.32	214.03	213.52	212.69
1984	221.94	223.47	222.08	222.74	222.21	221.78
1985	229.39	230.96	229.59	229.81	229.69	229.19
1986	235.12	236.46	234.42	234.72	234.50	234.19
1987	242.88	245.33	243.24	243.15	243.27	243.01
1988	252.47	255.39	252.89	252.94	252.96	252.60
1989	264.32	267.09	264.77	264.40	264.77	264.44
1990	279.24	282.39	279.76	279.32	279.80	279.17
1991	289.40	292.52	289.84	290.04	289.97	289.26
1992	298.99	302.63	299.63	299.07	299.65	299.07
1993	306.56	310.75	307.26	306.72	307.26	306.82
1994	314.67	319.40	315.46	315.11	315.46	315.16
1995	321.83	326.67	322.53	322.65	322.64	322.12

For completeness we present Tornqvist cost-of-living indexes for households distinguished by age, race, and gender of the head of the household in table 10.6. Like the econometric group cost-of-living indexes for each group given in table 10.5, these indexes have a fixed base of 1973. The average expenditure shares for each group are calculated from the CEX. Although the indexes for nonelderly, white, nonwhite, male- and female-headed households largely coincide, the index for the elderly shows slightly higher inflation rates over the period 1980–1995.

Despite the slight divergence between group cost-of-living indexes for the elderly and nonelderly, the two indexes have identical stochastic trends. Augmented Dickey-Fuller unit root tests for rates of inflation and first differences in inflation rates presented in table 10.2 show that levels of these indexes are integrated of order two. Tests of the null hypothesis of no cointegration are given in table 10.3 for the inflation rates in these indexes as well as for the indexes for male- and female-headed households and white and nonwhite households. These results show that each of these pairs of indexes is cointegrated, based on *p* values tabulated by MacKinnon (1991).

The index for the nonelderly, who comprise most of the U.S. population, coincides with the social cost-of-living index, so that this index would be suitable for indexing federal programs for changes in the purchasing power of the nonelderly. This would include compensation of federal employees and features of the personal income tax, such as the tax brackets and personal exemptions. Indexing Social Security benefits by a social cost-of-living index could fail to preserve the purchasing power of elderly beneficiaries.

We conclude that a group cost-of-living index for the elderly should be used to index federal retirement programs and Social Security benefits. The group cost-of-living index for the elderly nearly coincides with CPIX1 over the period as a whole. The CPI-W is used to index Social Security benefits, however, and the correction for owner-occupied housing was not incorporated into the CPI-W until 1985. As a consequence, Social Security benefits have been overindexed, as demonstrated by Duggan, Gillingham, and Greenlees (1997).

10.4 Recommendations and Conclusions

The Consumer Price Index published by the Bureau of Labor Statistics is one component of a comprehensive federal program for measuring the standard of living for the population as a whole and inequality in the distribution of household welfare. Similar issues arise in measuring poverty, inequality, and the cost and standard of living. Resolution of these issues requires replacing these programs by an econometric approach. Slesnick (1998) provided a comprehensive survey of econometric methods for welfare measurement and their applications. The econometric approach to measuring inequality and poverty was presented by Jorgenson (1998) and Slesnick (1993, 1994), whereas Slesnick (1991a) used an econometric approach to measure the standard of living.

For practitioners of normative economics, the application of an econometric model to the measurement of the standard and cost of living is a highly innovative but also unfamiliar and even disturbing idea. Multimillion dollar budgets are involved in statistical reporting of price index numbers and millions more are spent on measures of poverty, inequality, and the standard of living. Fortunately, the data collected for these programs, such as consumer prices and household expenditure patterns, are precisely those required for implementation of the econometric approach to cost-of-living measurement outlined in this chapter.

The index-number methodology employed in the construction of the CPI is unsatisfactory as a basis for cost-of-living measurement. We recommend that the CPI-U, widely employed as an aggregate measure of consumer price inflation, be replaced by a social cost-of-living index constructed from an econometric model of aggregate consumer behavior. Such an index would capture the impact of the reallocation of household budgets due to price changes as well as changes in the standard of living and the demographic structure of the population. The social cost-of-living index is suitable for indexing federal programs for the nonelderly, such as the compensation of federal employees, and features of the personal income tax, such as tax brackets and personal exemptions.

Households with different demographic characteristics have different patterns of household expenditures. This results in a modest divergence between group cost-of-living indexes for the elderly and nonelderly. We recommend that a group cost-of-living index for the elderly be constructed from an econometric model. The group cost-of-living index for the elderly is appropriate for indexing federal retirement programs and the benefits of the Social Security System. Indexing these programs by the social cost-of-living index could fail to preserve the purchasing power of the elderly beneficiaries.

Finally, both the social cost-of-living index and the group cost-of-living index for the elderly should be based on constant quality price indexes for individual commodities. Failure to hold quality constant for the services of owner-occupied housing has resulted in substantial overindexing of Social Security benefits. The existing adjustments for quality change, described by Moulton and Moses (1997), should be augmented by the measures of quality change presented by the Advisory Commission (Boskin et al., 1996). Detailed recommendations are presented in section V of that report (especially table 2, pp. 61–62).

11

Controlling Carbon Emissions in China

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In this chapter we examine the use of carbon taxes to reduce emissions of CO_2 in China. To do so, we develop a dynamic computable general equilibrium (CGE) model of the Chinese economy. In addition to accounting for the effects of population growth, capital accumulation, technological change, and changing patterns of demand, we also incorporate into our model elements of the dual nature of the Chinese economy where both plan and market institutions exist side by side.

After specifying the time paths of the exogenous variables used in the model, we run a "business as usual" baseline simulation that gives us estimates of GDP, carbon emissions, and other endogenous variables for the 40 years starting from the 1992 base year. Most analyses for developed countries look at the effects of stabilizing or reducing emissions below some target, such as 1990 levels. However, China and other developing countries have raised strenuous objections to attempts to get them to agree to these types of targets. Therefore, we instead simulate the effects of uniform emissions reductions of 5, 10, and 15 percent from our baseline. To do this we use the model to calculate a carbon tax rate that will hold carbon emissions to a given percentage of the baseline level. The imposition of the carbon tax raises additional revenue for the government. In order to keep the emissions reduction simulations revenue neutral, we reduce all other taxes proportionately.

We then compare the outcomes of the carbon reduction simulations with the baseline solution. Increasing the percentage reduction in emissions requires a more than proportionate increase in the per unit tax rate on a ton of carbon. In the case of a 15 percent reduction in carbon emissions, the imposition of sectoral carbon taxes on coal and oil results in an increase of 21 percent in the price of coal and a 3 percent increase in the price of oil in the 1st year. The imposition of the carbon taxes increases energy prices in general and this in turn increases the prices of other goods that use energy. Increases in prices result in a decline in the real wage and a fall in real household income. However, given our assumption that the labor supply in China is inelastic, the decline in the real wage does not have a distortionary effect on hours worked. At the same time, because of the reduction in taxes on enterprises, enterprise retained earnings are increased and this increase in retained earnings is transferred into an increase in investment. Over time, the increase in investment results in an increase in total output and, with a short lag, this is reflected in increases in consumption.

In all of the alternative scenarios, there is a very small decline in GDP in the 1st year of the simulation. However, in each case, GDP is increased in every year thereafter. In the 15 percent emissions reduction case, by the 30th year of the simulation, the level of GDP is increased by almost one percent over the baseline. Although subject to a number of caveats, we find potential for what is in some sense a "double dividend," a decrease in emissions of CO_2 and a long-run increase in GDP and consumption.

11.1 Introduction

China's rapid growth since the beginning of economic reform in late 1978 has been accompanied by a rapid increase in the use of fossil fuels. Over this period, the rate of increase in the use of primary energy has been about 4 percent per year. While this is only about half the rate of increase in real national output, given the sheer size of the Chinese economy, this has led to emissions, in 1995, of some 870 million tons of carbon in the form of carbon dioxide, the main anthropogenic greenhouse gas. In the same year, by comparison, the world's largest emitter, the United States, generated an estimated 1.4 billion tons of carbon, while the world total was about 6.4 billion tons.[1]

Although there exist a wide range of plausible forecasts of future Chinese emissions, they are unanimous in predicting that China will become the world's largest emitter of CO_2 sometime within the next several decades. Our previous baseline projection, for example, puts China's annual carbon emissions at about 1.8 billion tons by the year 2020 (Ho, Jorgenson, and Perkins 1998). Given the current interest in controlling global greenhouse gases, it is crucial to understand the workings of China's economy and its relationship to carbon emissions. In addition, there is great concern about the costs of any attempt at controlling these emissions. Is there a large tradeoff between environmental objectives and economic development? This question must be a central concern of policy makers in China.

In this chapter, we discuss how carbon taxes might be used to reduce carbon emissions and the effect of such taxes on both total output and the output of individual sectors. Our goal is not only to examine the link between current fossil fuel use, carbon emissions reduction strategies, and costs in forgone output, but also to study the effects on economic growth and hence future emissions and costs. In previous work (Garbaccio, Ho, and Jorgenson 1999a) we examined the effects of economic liberalization on fossil fuel use. In this paper, we study the effects of carbon taxes on the choice of energy inputs, given a level of economic activity, and the effects of these policies over time on economic growth.

For this purpose we develop a dynamic economy-energy environment model for China. While the model abstracts from many aspects of this complex economy, it does contain a number of features we believe are essential for capturing the policy impacts we wish to assess. Previous studies have used numerical models to examine some of these issues (e.g., World Bank (1994); Xie (1995); Rose et al. (1996), and Zhang (1998a, 1998b)). Like Ho, Jorgenson, and Perkins (1998), the study by the World Bank (1994a) employs exogenous forecasts of technology and demand patterns to provide a range of plausible forecasts of future greenhouse gas emissions. Neither of these studies, however, attempts to estimate the effects of specific policies, such as carbon taxes, to control these emissions. Xie (1995) uses a CGE model to examine the effects of emissions taxes on pollution, including particulates, but excluding CO_2. However, while Xie's model has detailed pollution control cost functions, they are specified within a static framework. Rose *et al.* (1996) use a linear programming model to examine the output cost of reducing carbon emissions. In their simulations, they compare two economies that are optimized at each level of carbon targets. They do not, however, have an explicit role for prices and ignore the "nonoptimizing" features of the Chinese economy, such as the residual elements of the planned economy and credit controls. Zhang's (1998a, 1998b) work is the closest to our own, using a 10-sector dynamic CGE model to assess the effects of various policies designed to reduce the growth of CO_2 emissions. However, Zhang also assumes a completely marketized economy.

In the model described here we emphasize two features of the economy. First, our model is dynamic and tries to take into account the effects of population growth, capital accumulation, technology change, and changing patterns of demand. Second, we attempt to model the dual nature of the Chinese economy, whereby both plan and market institutions exist side by side. Although the scope of the plan has been drastically reduced for most commodities, it still exists for some important energy goods, such as coal and oil.[2] In addition, capital markets are still largely under government control, either directly through the state budget or indirectly through the state-owned banking system.

In our simulations, we find that to reduce emissions by 5 percent, a unit carbon tax of about 9 *yuan* per ton (in 1992 *yuan*) would be required. This is equivalent to approximately a 7 percent tax on the price of coal. If a tighter emissions target is imposed, higher tax rates are required. For a 10 percent reduction in every period, a unit carbon tax of 18 to 20 *yuan* per ton is required. The effect of the imposition of the carbon tax, after the extra revenue raised is offset by a reduction in all other taxes, is to reduce household income and raise enterprise retained earnings. If there is no other offsetting government intervention, spending is shifted from consumption to investment. The higher level of investment leads in turn to higher future output. Although subject to a number of caveats which we discuss later, in some sense there is a "double dividend," a decrease in emissions of CO_2 and an increase in GDP and consumption.

In the second section of this chapter we briefly describe the modeling approach we have employed in this study. The third section gives a short description of the construction of the data base and the exogenous variables used in the model. Section four discusses the results of simulations where total emissions from fossil fuels are reduced through the imposition of carbon taxes. Some conclusions are given in section five. The model is presented in more detail in an appendix.

11.2 A Dynamic Economy-Energy-Environment Model for China

Large-scale numerical models have been used to study the use of carbon taxes to attain given emissions targets for many countries. Some examples for the United States are the Jorgenson and Wilcoxen (1992) and Goulder (1995a) models. Hoeller, Dean, and Hayafuji (1992) give a summary of the results of simulating carbon reductions using a number of models, including multi-regional models. However, with the exception of some of the work cited in the previous section, the potential costs of carbon reductions for China have not been as carefully studied as for developed country economies.[3]

Our model of the Chinese economy is somewhat similar in structure and scope to the Jorgenson and Wilcoxen model for the United States, but we have tried to incorporate a number of special features of the Chinese economy. In contrast to models that use fixed coefficients and often produce high welfare costs when reducing emissions, our current model allows for substitution among the inputs (e.g., capital for energy, or oil for coal). Our model is formulated as a Solov growth model with exogenous savings rates. The growth of the economy is traced over time, taking into account population growth, capital accumulation, and technical change.

The agents in the model are: (i) Households which supply labor inelastically, own part of the capital stock, and purchase goods and services; (ii) enterprises which produce commodities using inputs that are partly allocated through the plan and partly purchased in the market; (iii) the government which buys goods and services, imposes taxes, redistributes income, and sets down a central plan; and (iv) the foreign sector which purchases exports and supplies imports and foreign investment. The flow of payments among the various actors in the economy is summarized in the social accounting matrix (SAM) given in table 11.1. (The SAM is described more fully in section 11.3.)

The economy is divided into the 29 sectors listed in table 11.2. Our plan-market formulation follows the theoretical work of Byrd (1989) and Sicular (1988) and the static CGE implementation of Garbaccio (1994, 1995). For those commodities and factors of production with both a market and plan component, there is a division between the two tracks. A fixed amount of total output is sold at the plan price, while the remainder is sold on the market. The market price equates demand and supply for all commodities. Marginal decisions are made on the basis of the market prices while changes in plan prices and quantities are infra-marginal. In a single period, for those sectors in which both tracks exist, the net effect of the plan allocations is to create lump sum transfers between producers and consumers. However, over time, the plan allocations do affect sectoral retained earnings and investment.

The factors of production in the model are capital, labor, land, energy, and other intermediates. Given the unavailability of sectoral time-series data, we use Cobb-Douglas production functions, with the coefficients changing over time so that there is both technical progress (more output with the same inputs) and biased technical change (changes in input demands unrelated to prices). This exogenous technical change is

Table 11.1

Summary social accounting matrix for China, 1992 (billion *yuan*)

	Expenditures:											
	1	2	3	4	5	6	7	8	9	10	11	12
Receipts:	Commodity	Activity	Value Added	Households	Enterprises	Government Subsidies	Public Sector Self-Finance	Government	Foreign Trade Margins	Capital Account	Rest of World	Totals
1 Commodity		4,182		1,246	79		106	228	0	967	518	7,326
2 Activity	6,846											6,846
3 Value Added		2,464										2,464
4 Households			1,205		446			15			4	1,670
5 Enterprises			1,259					4				1,263
6 Government Subsidies		−45		−32	−27			103				0
7 Pub. Sect. Self-Finance		1		7	89							106
8 Government	21	245		3	124					61		454
9 Foreign Trade Margins	0											0
10 Capital Account				436	552			102			−62	1,028
11 Rest of World	458							2				460
12 Totals	7,326	6,846	2,464	1,670	1,263	0	106	454	0	1,028	460	

Sources: Development Research Center Social Accounting Matrix for 1992 and World Bank (1996).

Table 11.2
Sectoral characteristics for China, 1992

	Sector	Gross Value of Output (bil. *yuan)*	Estimated Capital Stock (bil. *yuan)*	Energy Use (mil. tn. coal equivalent)	Output Tax Rate (Net of Subsidies, percentage)
1	Agriculture	909	407	50	1.22
2	Coal Mining	76	109	44	−0.89
3	Crude Petroleum	69	142	22	0.43
4	Metal Ore Mining	24	25	6	1.26
5	Other Non-metallic Ore Mining	66	54	13	3.29
6	Food Manufacturing	408	171	36	9.09
7	Textiles	380	166	33	3.54
8	Apparel & Leather Products	149	62	5	2.63
9	Lumber & Furniture Manufacturing	50	23	20	3.81
10	Paper, Cultural, & Educational Articles	176	112	19	2.77
11	Electric Power	115	398	49	9.57
12	Petroleum Refining	108	60	32	7.92
13	Chemicals	473	268	138	4.70
14	Building Material	254	186	109	4.11
15	Primary Metals	321	229	119	6.28
16	Metal Products	141	56	23	3.25
17	Machinery	390	183	34	3.16
18	Transport Equipment	163	80	5	3.17
19	Electric Machinery & Instruments	155	57	9	3.59
20	Electronic & Communication Equipment	107	52	2	2.04
21	Instruments and Meters	24	13	1	3.34
22	Other Industry	75	37	7	3.28
23	Construction	520	175	14	1.10
24	Transportation & Communications	267	516	51	2.89
25	Commerce	635	352	14	−0.45
26	Public Utilities	205	829	17	1.54
27	Culture, Education, Health, & Research	227	388	19	−0.75
28	Finance & Insurance	171	74	1	4.40
29	Public Administration	191	256	7	0.44
	Totals	6,846	5,477	900	

Sources: Development Research Center Social Accounting Matrix for 1992; State Statistical Bureau (1994); and author's estimates.

projected such that the Chinese input demands resemble the U.S. 1992 structure in forty years.

The use of energy in China in recent years is discussed in Garbaccio, Ho, and Jorgenson (1999b). Using the 1987 and 1992 input-output tables, we show that recent declines in the energy-GDP ratio have been due mostly to a fall in the use of energy per unit of output at the sectoral (roughly 2-digit) level. By contrast, very little of the change in the energy-GDP ratio has been due to changes in the composition of output. This fall in energy use cannot be plausibly explained by changes in relative prices alone and should be largely attributed to technical change (or change in sectoral composition below the 2-digit level). Our projections of biased technical change allow for this trend to continue in the simulations.

The capital input for each industry consists of a plan component that is not mobile across sectors and a market component that is rented from a common capital stock. The capital stock evolves over time with new investment and depreciation. The labor input is mobile across sectors with the total supply projected using a population model. For two industries, agriculture and crude petroleum, "land" is an input and its supply is fixed exogenously.

Consumers derive income from wages, dividends, and transfers. They make purchases at both plan and market prices. The pattern of consumption demands changes over time (due to effects other than just changes in relative prices) and this is again projected using 1992 U.S. data. Household savings are set as an exogenous share of income and form part of national savings together with enterprise retained earnings and (net) foreign investment. Savings are used for investment in domestic capital and to finance the government budget deficit.

The government imposes taxes on enterprise capital income, sales, and imports. On the expenditure side, the government buys goods, provides subsidies and investment grants, pays interest on government bonds, and makes transfer payments. The deficit is covered by domestic and foreign borrowing. The modeling of imports and exports follows the standard one-country treatment and the trade and current account deficits are set exogenously. The evolution of the stocks of domestic and foreign debts and interest payments are treated consistently.

11.3 Data and Exogenous Variables

The primary data set for the model is built around the official Chinese input-output tables for 1992.[4] The input-output tables have in turn been used to construct the SAM for the same year (table 11.1). The SAM provides a tabular snapshot of the economy for a single year. For each economic agent, there is a row that records incomes and a column that records expenditures. Our SAM allows for a distinction between commodities and activities (industries). Each activity can produce more than one commodity so that we can incorporate both the official USE (commodity by activity) and MAKE (activity by commodity) matrices.[5]

The SAM includes accounts for the household, enterprises, and the government. The capital account collects savings from households, enterprises, the government, and the rest of the world and uses those funds for investment and the financing of the government budget deficit (corresponding to equation (A.34) in the appendix). As an example, the bottom of the second column of the SAM shows that the total value of domestic gross output of the 29 industries is 6,846 billion *yuan*, of which 4,182 billion goes to the suppliers of intermediate goods, 200 billion to indirect taxes (net of 45 billion *yuan* of subsidies), and 2,464 billion *yuan* to workers and the owners of capital. Of this, the owners of capital (enterprises, row and column 5) receive 1,259 billion *yuan*, of which they keep 552 billion as retained earnings (including depreciation allowances). Households receive 1,205 billion *yuan* as labor income and 446 billion from enterprises as dividends and payments in kind. Of total household income of 1,670 billion *yuan*, 436 billion *yuan* is saved.

Where applicable, each cell in the commodity row is divided into a plan and market component. The original plan data are from a Chinese Academy of Social Sciences (CASS) survey of 769 state-owned enterprises which covered the years 1980 to 1989, but have been updated to 1992. The sectors with the highest plan share are coal, oil, and electric power. The relative size of the sectors together with capital stocks and energy use data are given in table 11.2. The biggest end users of energy are the chemicals, building materials, and primary metals sectors.

Because the official input-output table includes only a single column of net exports, export and import data are assembled from Chinese customs statistics. Differences between the customs statistics data, which are in world prices, and the input-output table net exports, which are in domestic producer prices, are assumed to be the trade margins (both positive and negative) of Chinese foreign trade corporations.

Turning to the exogenous variables, the sectoral labor force data were put together from various Chinese sources. Projections of the future labor force are calculated from World Bank (1990) as described in Ho, Jorgenson, and Perkins (1999b). The initial sectoral capital stock data are estimated using the depreciation allowances given in the input-output tables. The government deficit is set initially to current levels, but declines gradually to zero. The current account balance is set at a deficit initially, but declines to zero in 20 years. World prices of Chinese imports are projected to be the same as in the base period, except for world oil prices which are taken from projections by the U.S. Department of Energy. Base exports grow initially at a rate of 8 percent, but the growth rate is projected to gradually slow over the next forty years. This growth rate is used for all goods except for oil exports which are set to zero growth. The productivity growth parameter (μ_j in the $g(t)$ function in equation (A.3)) is set such that the initial growth rate is three percent per annum, the rate estimated for the aggregate economy (see Ho, Jorgenson, and Perkins 1999b). Given the lack of industry level estimates, this rate is used for all sectors.

11.4 Carbon Taxes and Emissions

In this section we describe our simulations of the use of carbon taxes (taxes on fuels based on their carbon content) to control carbon emissions in China. Although China does not currently impose carbon taxes and is unlikely to do so in the near future, it should be noted that China does have some history of using emissions charges in attempting to control the emissions of a number of pollutants, including air pollutants (NEPA 1992, World Bank 1997).[6] For the developed countries (i.e., Annex I countries under the UN Framework Convention on Climate Change), most studies of carbon emissions reduction policies have looked at a goal of stabilizing emissions at some target, such as 1990 emissions levels (Intergovernmental Panel on Climate Change, 1996). However, for China and other developing countries, which have considerably lower per capita emissions, there are strenuous objections to establishing these types of targets. Therefore, instead of focusing on stabilization, we look at the effects of reductions from a "business as usual" baseline level of carbon emissions.

To provide a useful picture of the economic impact of carbon taxes, we have chosen to simulate a range of uniform reductions. To do this we first run a base case with no emissions targets and no carbon taxes. In the base case, total carbon emissions in each period may be written as

$$CAR_{\text{base}}(t) = \sum_i \theta_i (QI_{it} - X_{it} + M_{it}), \qquad (11.1)$$

where QI_{it}, X_{it}, and M_{it} are industry output, exports, and imports, respectively, of coal and oil and θ_i is the emissions coefficient by fuel type.[7]

After establishing the base case, we then run alternative simulations where emissions of carbon dioxide are constrained to be a fraction (γ) of the base case in every period:

$$CAR_{\text{alt}}(t) = \gamma CAR_{\text{base}}(t), \quad t = 1, 2, \ldots, T. \tag{11.2}$$

All other exogenous variables and parameters are held constant. To achieve the carbon emissions target, we let the carbon tax be an endogenous variable which has the effect of raising the prices of coal and oil.[8] The imposition of the carbon tax raises additional revenue for the government. In order to keep the alternative simulations revenue neutral, we reduce all other taxes proportionately. With government deficits held constant, this means that we are keeping government spending the same as in the base case. To scale the original tax rates, we introduce an additional endogenous variable λ_t, into the alternative system such that:

$$t_t^k = \lambda_t t_0^k, \qquad t_{it}^t = \lambda_t t_{io}^t, \text{ etc.} \tag{11.3}$$

where t_t^k is the capital income tax rate and t_{it}^t is the indirect tax rate for sector i. The sectoral indirect tax rates (net of subsidies) are provided in the last column of table 11.2. The government expenditure neutrality constraint is then set so that

$$GG_{\text{alt}}(t) = GG_{\text{base}}(t), \tag{11.4}$$

where GG is the quantity index of government purchases (equation (A.15) in the appendix). This keeps aggregate spending constant. The quantity of specific commodities purchased will, of course, change. To summarize, in the alternative simulations there are two additional equations, (11.2) and (11.4), and two additional endogenous variables, the tax rate per ton of carbon and λ. GG, an endogenous variable in the base case is made an exogenous variable in the alternative solutions. Tax rates on capital income, sales, and tariffs are made endogenous in the alternative cases.

We then compare the outcome of the alternative simulations with the base case solution. Although our base case may be of independent interest, we do not focus on it in this chapter. The base case levels of output, emissions, etc., are driven by the assumptions about the exogenous variables, such as the rates of population growth and technological change.

In Ho, Jorgenson, and Perkins (1998), we examined a number of plausible assumptions about the exogenous variables and produced a wide range of forecasts of the levels of output and emissions. Our assumptions about the exogenous variables in the current chapter lead to fairly high average growth rates. In the base case, GDP rises at an average of 5.7 percent per year over the first thirty years. The growth rate is higher in the beginning but gradually declines as both population and productivity growth slow in the later years. The high rate of GDP growth leads to a high rate of growth of carbon emissions, averaging 3.8 percent per year over the first thirty years.

We ran three alternative scenarios: 5 percent, 10 percent, and 15 percent reductions in carbon emissions (i.e., $\gamma = 0.95$, 0.90, and 0.85). The impacts of these carbon reductions on some important variables are presented in tables 11.3, 11.4, and 11.5 and graphed in figures 11.1 through 11.6. The base case levels of total carbon emissions and the levels for the 5 percent, 10 percent, and 15 percent reduction cases are shown in figure 11.1.[9] For each of the reduction scenarios, the percentage change in GDP relative to the base case is shown in figure 11.2. In all of the alternative scenarios, there is a very small decline in GDP in the 1st year. However, in each case, there is an increase in the level of GDP in every year thereafter. In the 15 percent carbon reduction case, by the 30th year of the simulation, the level of GDP has increased by almost 1 percent over the baseline.

The unit carbon tax rates calculated for the three emissions reductions cases are shown in figure 11.3. For the 5 percent emissions reduction case, a tax of about 9 *yuan* per ton of carbon is required in the 1st year of the simulation.[10] Increasing the percentage reduction in emissions requires a more than proportionate increase in the unit carbon tax. Offsetting the new revenue from the carbon tax is the reduction in all other taxes by the factor λ. The value for λ in each period is graphed in figure 11.4. Each of the other tax rates is reduced by about 1 percent in the simulation period for the 5 percent carbon reduction case and by approximately 3 to 4 percent in the 15 percent case.

The imposition of the carbon tax increases energy prices and this in turn leads to increases in the prices of other goods (relative to the numeraire, the nominal wage rate). A decline in the real wage results in a fall in household income and, in the first few years of the simulations, a decline in aggregate consumption. This is shown in figure 11.5. However, given our assumption that the labor supply in China is inelastic, the decline in the real wage does not have a distortionary effect on hours

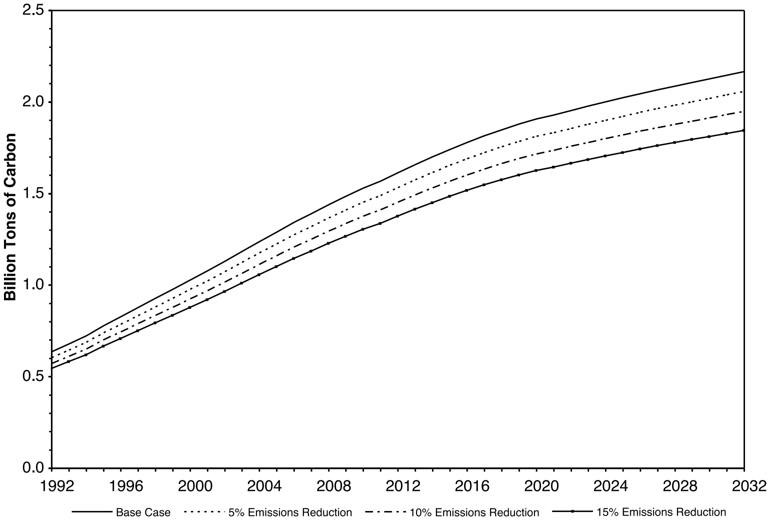

Figure 11.1
Carbon emissions.

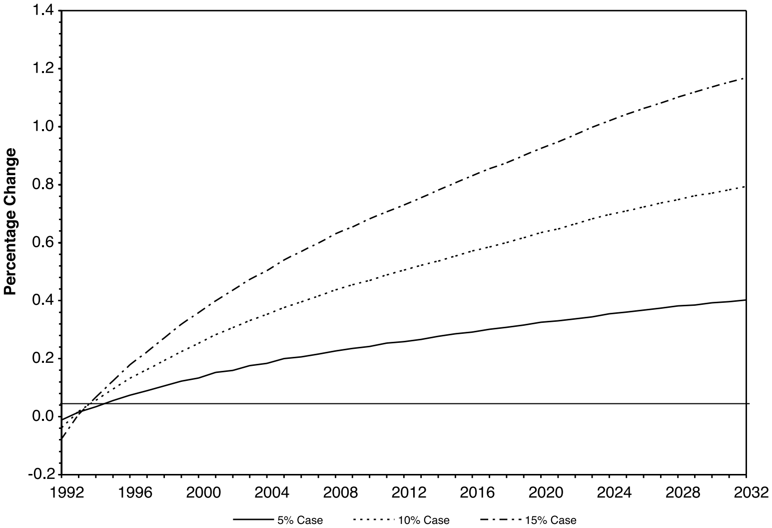

Figure 11.2
Percentage change in GDP relative to base case.

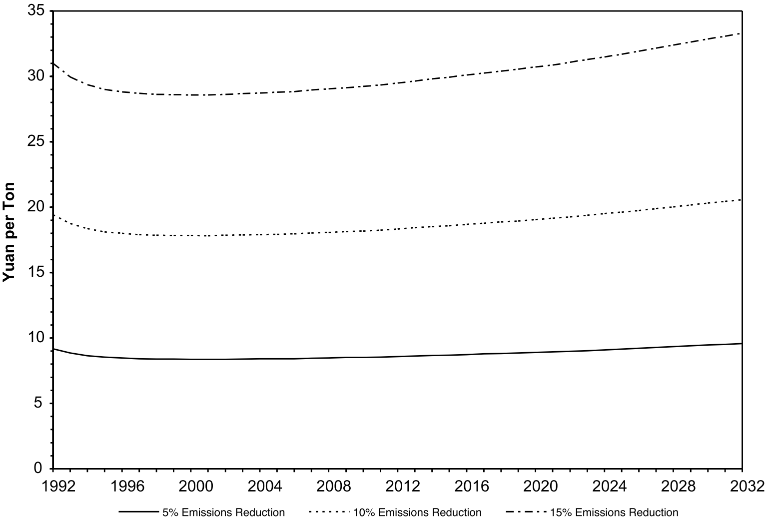

Figure 11.3
Carbon taxes required to attain a given reduction in emissions.

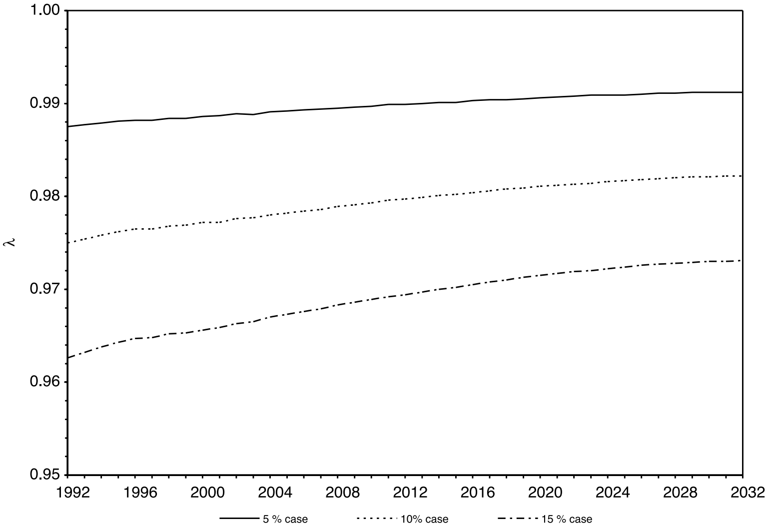

Figure 11.4
Reduction in other taxes to offset carbon tax revenues.

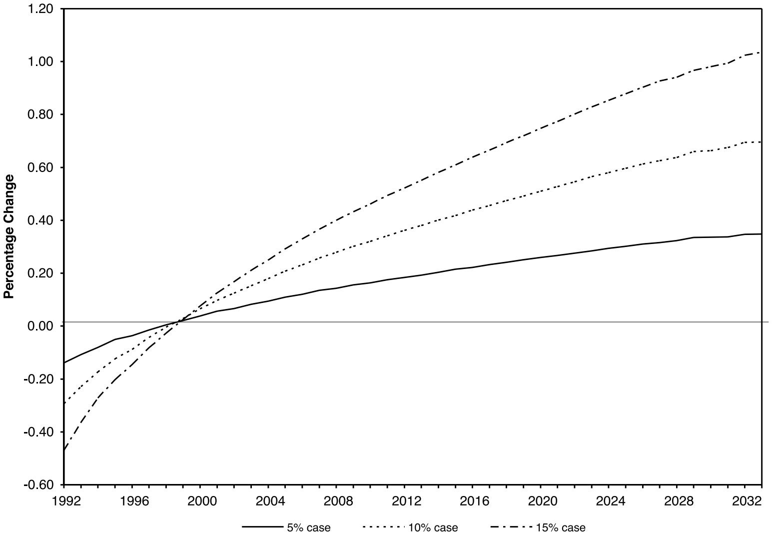

Figure 11.5
Percentage change in consumption relative to base case.

worked. At the same time, because of the offsetting reductions in enterprise taxes, enterprise retained earnings are increased. Households do not receive a similar benefit from the reduction in the taxes on labor income because these taxes are negligible in the base year. As shown in figure 11.6, the increase in retained earnings is transferred into an increase in investment. Over time, this increased investment results in an increase in total output. This shows up within a few years in an increase in consumption over the baseline in all of the carbon tax simulations.

We can now look at the effects on the individual primary energy sectors (see tables 11.3, 11.4, and 11.5). After the imposition of the sectoral carbon tax on coal, in the 1st year of the 5 percent reduction simulation the purchaser's (market) price of coal increases by 6.1 percent. Because of its lower carbon content, the imposition of the sectoral carbon tax on oil causes the purchaser's price of oil to rise by only 1.0 percent. The increase in the price of coal results in a 6.0 percent reduction in coal output. In the 1st year, oil sector output falls by 0.8 percent while imports of oil and refined petroleum both fall by about 2 percent. Overall, these changes lead to a fall in total primary energy use of 4.7 percent, slightly less than the 5 percent decline in total carbon emissions.[11]

Increasing the percentage reduction in carbon emissions requires a more than proportionate increase in sectoral carbon tax rates. For coal,

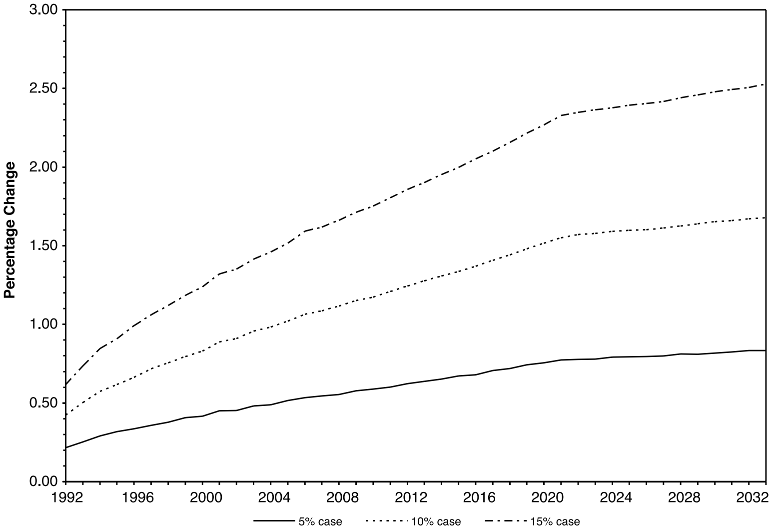

Figure 11.6
Percentage change in investment relative to base case.

the 5 percent, 10 percent, and 15 percent reductions in carbon emissions require, respectively, 6.1, 12.9, and 20.7 percent increases in coal prices in the 1st year. Similar disproportionate increases in prices are required for oil. As shown in table 11.3, this holds true for coal and oil in both the 1st and 30th years of the simulations.

The effects on other sectors are predictable. Changes in purchaser's (market) prices for the 1st year are given in table 11.4. Because of the rise in primary energy prices, sectors that use energy intensively experience proportionate price increases. For example in the 5 percent reduction scenarios, the price of electricity increases by 0.8 percent, building materials by 0.3 percent, and primary metals by 0.3 percent. Figures for changes in sectoral output are given in table 11.5. There are reductions in the output of electricity and refined petroleum. Agricultural output falls slightly because of the decline in demand due to the drop in real household income. At the same time, sectors that sell investment goods (transport equipment and construction) experience increases in demand and output.

Over time, as the GDP and capital stock rise relative to the base case, higher demand for energy requires that the carbon tax rates be increased in order to continue to achieve the same proportionate reduction in

Table 11.3
Effects of a carbon tax on selected variables (percentage change from base case)

	Effect in 1st Year with:			Effect in 30th Year with:		
Variable	5% Emissions Reduction	10% Emissions Reduction	15% Emissions Reduction	5% Emissions Reduction	10% Emissions Reduction	15% Emissions Reduction
GDP	−0.01	−0.04	−0.08	0.34	0.66	0.97
Consumption	−0.14	−0.29	−0.47	0.28	0.55	0.80
Investment	0.22	0.42	0.62	0.78	1.57	2.35
Primary Energy	−4.71	−9.44	−14.17	−4.60	−9.21	−13.83
Market Price of Coal	6.05	12.88	20.63	6.69	14.32	23.09
Market Price of Oil	1.02	2.16	3.43	0.62	1.35	2.21
Coal Output	−5.97	−11.91	−17.82	−6.50	−12.95	−19.36
Oil Output	−0.83	−1.75	−2.78	−0.48	−1.07	−1.78

Source: Author's estimates.

emissions. In the 5 percent carbon reduction case, this results in a 6.7 percent increase in the market price of coal in the 30th year compared to the 6.1 percent increase during the first year of the simulation (see table 11.3). The effect is reversed for oil because of the assumed availability of oil imports at the projected world price. The assumption that government spending is fixed in real terms, coupled with an increasing tax base, results in the revenue from the carbon tax falling as a share of total revenue over time. In the 5 percent carbon reduction case, the share of revenue from the carbon tax falls from 1.2 percent in the first year to 0.6 percent in the 30th year. In the 15 percent reduction case, the share falls from 3.6 to 1.9 percent.

Two comments are in order on the pattern of carbon taxes over time in our model. The first concerns our assumptions about capital mobility. In the initial years of our simulations, the plan portion of capital dominates the total. The plan portion of capital is assumed to be immobile. Compared to models with completely mobile capital, this results in a much slower rate of substitution of capital for energy. Over time, the stock of mobile *market* capital rises in each industry and this results in more flexibility in later years. The second comment concerns the specification for the crude oil sector. The crude oil sector is one of two industries in the model with "land" (oil reserves) as an input and the quantity of domestic reserves is assumed fixed. The domestic price of oil therefore rises

Table 11.4
Effects of a carbon tax on first year sectoral prices (percentage change from base case)

	Sector	5% Emissions Reduction	10% Emissions Reduction	15% Emissions Reduction
1	Agriculture	0.08	0.16	0.25
2	Coal Mining	6.05	12.88	20.63
3	Crude Petroleum	1.02	2.16	3.43
4	Metal Ore Mining	0.20	0.41	0.64
5	Other Non-metallic Ore Mining	0.17	0.35	0.53
6	Food Manufacturing	0.05	0.10	0.16
7	Textiles	0.09	0.19	0.29
8	Apparel & Leather Products	0.08	0.16	0.25
9	Lumber & Furniture Manufacturing	0.15	0.32	0.50
10	Paper, Cultural, & Educational Articles	0.11	0.24	0.37
11	Electric Power	0.80	1.67	2.61
12	Petroleum Refining	0.74	1.56	2.46
13	Chemicals	0.19	0.39	0.62
14	Building Material	0.33	0.69	1.06
15	Primary Metals	0.27	0.56	0.87
16	Metal Products	0.17	0.34	0.54
17	Machinery	0.13	0.26	0.41
18	Transport Equipment	0.14	0.28	0.43
19	Electric Machinery & Instruments	0.12	0.25	0.38
20	Electronic & Communication Equipment	0.10	0.21	0.33
21	Instruments and Meters	0.11	0.23	0.36
22	Other Industry	0.13	0.28	0.44
23	Construction	0.17	0.37	0.56
24	Transportation & Communications	0.18	0.39	0.59
25	Commerce	0.10	0.19	0.30
26	Public Utilities	0.13	0.28	0.43
27	Culture, Education, Health, & Research	0.11	0.23	0.35
28	Finance & Insurance	0.07	0.15	0.22
29	Public Administration	0.13	0.26	0.41

Source: Author’s estimates.

Table 11.5
Effects of a carbon tax on first year sectoral output (percentage change from base case).

	Sector	5% Emissions Reduction	10% Emissions Reduction	15% Emissions Reduction
1	Agriculture	−0.00	−0.00	−0.01
2	Coal Mining	−5.97	−11.91	−17.82
3	Crude Petroleum	−0.83	−1.75	−2.78
4	Metal Ore Mining	−0.08	−0.17	−0.27
5	Other Non-metallic Ore Mining	−0.17	−0.36	−0.56
6	Food Manufacturing	0.03	0.05	0.06
7	Textiles	0.01	0.02	0.01
8	Apparel & Leather Products	−0.01	−0.03	−0.06
9	Lumber & Furniture Manufacturing	−0.01	−0.03	−0.08
10	Paper, Cultural, & Educational Articles	−0.01	−0.04	−0.07
11	Electric Power	−0.99	−2.03	−3.13
12	Petroleum Refining	−0.63	−1.31	−2.04
13	Chemicals	−0.10	−0.23	−0.37
14	Building Material	−0.16	−0.35	−0.56
15	Primary Metals	−0.18	−0.40	−0.63
16	Metal Products	−0.08	−0.18	−0.29
17	Machinery	−0.01	−0.02	−0.05
18	Transport Equipment	0.07	0.12	0.16
19	Electric Machinery & Instruments	−0.06	−0.13	−0.22
20	Electronic & Communication Equipment	0.01	0.01	-0.01
21	Instruments and Meters	−0.05	−0.11	−0.18
22	Other Industry	−0.13	−0.26	−0.41
23	Construction	0.18	0.36	0.52
24	Transportation & Communications	−0.12	−0.25	−0.40
25	Commerce	−0.00	−0.01	−0.03
26	Public Utilities	−0.08	−0.17	−0.27
27	Culture, Education, Health, & Research	−0.04	−0.09	−0.15
28	Finance & Insurance	−0.02	−0.06	−0.09
29	Public Administration	−0.01	−0.02	−0.04

Source: Author’s estimates.

relative to most other prices and imports of oil rise faster in the carbon tax simulations than in the base case. Alternative specifications, such as including exploration costs into our model or different assumptions about future world oil prices, could alter our results.

Finally, we should emphasize what our assumptions about the production functions and technical change imply. As discussed previously, the share coefficients are projected exogenously. This affects the level of energy use and has a major influence on the "business as usual" baseline solution. However, the percentage change in energy use induced by the imposition of carbon taxes is determined by the elasticity of substitution between the various inputs. These elasticities are constant in our production functions and are therefore identical in both the base case and carbon tax simulations. The percentage change in input demands is not determined by the value of the share coefficients.[12]

11.5 Conclusions

Our results paint a rather optimistic picture of the use of carbon taxes to induce a reduction in CO_2 emissions in China. Although the imposition of a carbon tax results in a fall in consumption in the first few years of our simulations, in all of the emissions reduction scenarios analyzed, GDP rises above the baseline level after the first year. Within a few years, increases in investment also lead to increases in consumption above the baseline. Since we do not use an intertemporal utility function, we do not calculate discounted consumption. However, it would take an extremely high discount rate to produce a loss in the aggregate.

Recent work using analytical and computable general equilibrium models by Bovenberg and de Mooij (1994), Goulder (1995a), Parry (1995), Bovenberg and Goulder (1996), Rutherford, Bohringer, and Pahlke (1999) and others have cast doubt on the likelihood of a "double dividend" from environmental taxation. A review of this evolving literature is beyond the scope of this chapter.[13] However, it is possible to point out a number of reasons why our results differ and in fact do not contradict those obtained in these studies. First, we should emphasize that our main result comes about because of the shift from consumption to investment brought about indirectly through the imposition of the carbon tax. Although GDP increases in every year after the first year, it drops below the baseline in the first year of all of our carbon tax simulations. Second, the most important element driving our results is our assumption that the labor supply in China is inelastic. With this specification, the fall in the real wage brought about by increases in goods prices has no distortionary effect on hours worked. The assumption of a positive labor supply elasticity is one of the key assumptions that leads to the rejection of the "double dividend" hypothesis for developed country economies, but seems inappropriate in the context of China's transition economy.[14] Third, the fact that in China, taxes on labor are negligible means that households receive almost no benefit from the revenue neutral reduction in tax rates. This effect serves to further shift the burden of the carbon tax onto households. Fourth, most of the dynamic CGE models for developed economies have endogenously determined savings rates with perfect foresight, while the private savings rate in our model is exogenous (although not constant). Enterprise savings are affected by the revenue neutral reduction in the enterprise income tax, but there is no price effect on retained earnings. Hence the passive rise in investment. Finally, other distortions, like the two-tier price system and highly differentiated net output tax rates on intermediate and final goods, leave open the possibility for many welfare enhancing reforms, which may relate only coincidentally to environmental objectives.[15] Given that carbon taxes have the effect of reducing subsidies and raising prices for energy goods, our results are consistent with calls by the World Bank and others for China to increase efficiency by liberalizing energy markets.

Our results contrast with those of Zhang (1998a, 1998b) who found large decreases in output in his carbon tax simulations for China. Although Zhang also assumes an inelastic labor supply and an exogenous savings rate, there are a number of differences between the models which may account for the differing results. First, Zhang's model is based on data for 1987, while ours is based on data for 1992. As an example of the difference in base year data, Chinese imports of crude oil were negligible in 1987, but by 1992 had risen to 14 percent of the value of domestic oil consumption. Second, the economy in Zhang's model is completely marketized, while we incorporate a number of features that reflect the mixture of plan and market that still exists in China. Third, Zhang's model has 10 sectors while ours has 29. The more refined classification in our model allows for a greater degree of substitution and hence reduces the losses from the imposition of carbon taxes.[16] Fourth, Zhang recycles only part of the carbon tax revenue while our simulations are revenue neutral. In addition, Zhang reduces only the indirect taxes, while we reduce all tax rates. These and other differences make a one-to-one comparison of the two models difficult if not impossible.[17]

While we believe that our model helps to point out how certain features of the Chinese economy may serve to ameliorate what might otherwise be negative consequences of the imposition of carbon taxes, a number of caveats are in order. First, the nature of the experiment is somewhat extreme. Consumers are not compensated while enterprises reap the full benefit of the revenue neutral reductions in tax rates. Also, given the underdevelopment of capital markets in China, one could certainly ask if the marginal efficiency of additional investment would be as high as is implied in our carbon tax simulations. Second, the cost of reducing emissions depends on the ability to substitute to alternative fuels or technologies. Our simple production functions are abstractions of much more complex current and future technologies. Although included implicitly in the production function for the electricity sector, a more detailed model might explicitly include hydro, nuclear, wind, and other non-carbon energy sources. In particular, our modeling of the electric power sector, as in most similar models, is very aggregated and may over or understate the degree of substitution possible. Finally, we do not take into account the very substantial environmental benefits, aside from the decrease in greenhouse gas emissions, that would likely accompany reductions in CO_2 emissions in China. We hope to deal with these and other issues in future work.

Appendix A: Description of the Model

The main features of the dynamic economy-energy-environment model for China are discussed in this appendix. Further details are given in Garbaccio, Ho, and Jorgenson (1997). We describe the modeling of each of the main agents in the model in turn. Table A.1 lists a number of parameters and variables which are referred to with some frequency. In general, a bar above a symbol indicates that it is a plan parameter or variable. A tilde indicates that a symbol refers to a market variable. Symbols without markings are, in general, total quantities or average prices. To reduce unnecessary notation, whenever possible, we drop the time subscript, t, from our equations.

A.1 Production

Each of the 29 industries is assumed to produce its output using a constant returns to scale technology. For each sector j this can be expressed as:

Table A.1
Selected parameters and variables in the China model parameters

Parameters	
s_i^e	export subsidy rate on good *i*
t_i^c	carbon tax rate on good *i*
t^k	tax rate on capital income
t^L	tax rate on labor income
t_i^r	net import tariff rate on good *i*
t_i^t	net indirect tax (output tax less subsidy) rate on good *i*
t^x	unit tax per ton of carbon
Endogenous Variables	
G_I	interest on government bonds paid to households
G_INV	investment through the government budget
G_IR	interest on government bonds paid to the rest of the world
*G*_transfer	government transfer payments to households
P_I^{KD}	rental price of market capital by sector
PE_i^*	export price in foreign currency for good *i*
PI_i	producer price of good *i*
PI_i^t	purchaser price of good *i* including taxes
PL	average wage
PL_i	wage in sector *i*
PM_i	import price in domestic currency for good *i*
PM_i^*	import price in foreign currency for good *i*
PS_i	supply price of good *i*
PT_i	rental price of land of type *i*
QI_i	total output for sector *i*
QS_i	total supply for sector *i*
$r(B^*)$	payments by enterprises to the rest of the world
*R*_transfer	transfers to households from the rest of the world

$$QI_j = f(KD_j, LD_j, TD_j, A_{1j}, \ldots, A_{nj}, t), \tag{A.1}$$

where KD_j, LD_j, TD_j, and A_{ij} are capital, labor, land, and intermediate inputs, respectively.[18] In sectors for which both plan and market allocation exists, output is made up of two components, the plan quota output ($\bar{Q}I_j$) and the output sold on the market ($\tilde{Q}I_j$). The plan quota output is sold at the state-set price ($\bar{P}I_j$) while the output in excess of the quota is sold at the market price ($\tilde{P}I_j$).

A more detailed discussion of how this plan-market formulation is different from standard market economy models is given in Garbaccio, Ho, and Jorgenson (1999a). In summary, if the constraints are not binding, then the "two-tier plan/market" economy operates at the margin as a market economy with lump sum transfers between agents. The return to the owners of fixed capital in sector j is:

$$\begin{aligned}\text{profit}_j = \bar{P}I_j\bar{Q}I_j + \tilde{P}I_j\tilde{Q}I_j - \tilde{P}_j^{KD}\tilde{K}D_j - PL_jLD_j - PT_jTD_j \\ - \sum_i \bar{P}S_I\bar{A}_{ij} - \sum_i \tilde{P}S_I\tilde{A}_{ij}.\end{aligned} \tag{A.2}$$

For each industry, given the capital stock $\bar{K}_j$ and prices, the first-order conditions from maximizing equation (A.2), subject to equation (A.1), determine the market and total input demands.

Given the lack of a consistent time-series data set, in this version of the model, we use Cobb-Douglas production functions. Equation (A.1) for the output of industry j at time t then becomes:

$$QI_{jt} = g(t)KD_{jt}^{\alpha_{Kj}}LD_{jt}^{\alpha_{Lj}}TD_{jt}^{\alpha_{Tj}}E_{jt}^{\alpha_{Ej}}M_{jt}^{\alpha_{Mj}}, \tag{A.3}$$

where

$$\log E_{jt} = \sum_k \alpha_{kj}^E \log A_{kjt}$$

and k = coal, oil, electricity, and refined petroleum,

$$\log M_{jt} = \sum_k \alpha_{kj}^M \log A_{kjt}$$

and k = nonenergy intermediate goods .

Here α_{Ej} is the cost share of aggregate energy inputs in the production process and α_{kj}^E is the share of energy of type k within the aggregate energy input. Similarly, α_{Mj} is the cost share of aggregate nonenergy intermediate inputs and α_{kj}^M is the share of intermediate nonenergy input of type k within the aggregate nonenergy intermediate input.

To allow for biased technical change, the α_{Ej} coefficients are indexed by time and are updated exogenously. We set α_{Ej} to fall gradually over the next 40 years while the labor coefficient, α_{Lj}, rises correspondingly. The composition of the aggregate energy input (i.e., the coefficients α_{kj}^E) are also allowed to change over time. These coefficients are adjusted gradually so that they come close to resembling the U.S. use patterns of 1992. The exception is that the Chinese coefficients for coal for most industries will not vanish as they have in the United States.[19] The coefficient $g(t)$ in equation (A.3) represents technical progress and the change in $g(t)$ is determined through an exponential function ($\dot{g}_j(t) = A_j \exp(-\mu_{jt})$. This implies technical change that is rapid initially, but gradually declines toward zero. The price to buyers of this output includes the indirect tax on output and the carbon tax:

$$PI_i^t = (1 + t_i^t)PI_i + t_i^c. \tag{A.4}$$

A.2 Households

The household sector derives utility from the consumption of commodities, is assumed to supply labor inelastically, and owns a share of the capital stock. It also receives income transfers and interest on its holdings of public debt. Private income after taxes and the payment of various non-tax fees (FEE), Y^p, can then be written as

$$Y^p = YL + DIV + G\_I + G\_\text{transfer} + R\_\text{transfer} - FEE, \tag{A.5}$$

where YL denotes labor income from supplying LS units of effective labor, less income taxes. YL is equal to

$$YL = (1 - t^L)PLLS. \tag{A.6}$$

The relationship between labor demand and supply is given in equation (A.31) below. LS is a function of the working age population, average annual hours, and an index of labor quality

$$LS_t = POP_t^w hr_t q_t^L. \tag{A.7}$$

Household income is allocated between consumption (VCC_t) and savings. In this version of the model we use a simple Solow growth model formulation with an exogenous savings rate (s_t) to determine private savings (S_t^p).

$$S_t^p = s_t Y_t^p = Y_t^p - VCC_t. \tag{A.8}$$

Household utility is a function of the consumption of goods such that

$$U_t = U(C_{1t}, \ldots, C_{nt}) = \sum_i \alpha_{it}^c \log C_{it}. \tag{A.9}$$

Assuming that the plan constraints are not binding, then as in the producer problem above, given market prices and total expenditures, the first-order conditions derived from equation (A.9) determine household demand for commodities, C_i, where $C_i = \bar{C}_i + \tilde{C}_i$. Here $\bar{C}_i$ and $\tilde{C}_i$ are household purchases of commodities at state-set and market prices. The household budget can be written as

$$VCC = \sum_i (\tilde{P}S_i\tilde{C}_i + \tilde{P}S_i\tilde{C}_i). \tag{A.10}$$

We use a Cobb-Douglas utility function because we currently lack the disaggregated data to estimate an income elastic functional form. However, one would expect demand patterns to change with rising incomes and this is implemented by allowing the α_{it}^C coefficients to change over time. These future demand patterns are projected using the U.S. use patterns of 1992.

A.3 Government and Taxes

In the model, the government has two major roles. First, it sets plan prices and output quotas and allocates investment funds. Second, it imposes taxes, purchases commodities, and redistributes resources. Public revenue comes from direct taxes on capital and labor, indirect taxes on output, tariffs on imports, the carbon tax, and other nontax receipts

$$\begin{aligned}\text{Rev} = {} & \sum_j t^k(P_j^{KD}KD_j - D_j) + t^L \sum_j PL_jLD_j + \sum_j t_j^t PI_jQI_j \\ & + \sum_i t_i^r PM_i^* M_i + \sum_i t_i^c(QI_i - X_i + M_i) + FEE,\end{aligned} \tag{A.11}$$

where D_j is the depreciation allowance and X_i and M_i are the exports and imports of good i. The carbon tax per unit of fuel i is

$$t_i^c = t^x\theta_i, \tag{A.12}$$

where t^x is the unit carbon tax calculated per ton of carbon and θ_i is the emissions coefficient for each fuel type i.

Total government expenditure is the sum of commodity purchases and other payments

$$\begin{aligned}\text{Expend} = {} & VGG + G\_INV \\ & + \sum s_i^e PI_iX_i + G\_I + G\_IR + G\_\text{transfer}.\end{aligned} \tag{A.13}$$

Government purchases of specific commodities are allocated as shares of the total value of government expenditures, VGG. For good I

$$PS_i G_i = \alpha_i^G VGG. \tag{A.14}$$

We construct a price index for government purchases as $\log PGG = \sum_i \alpha_i^G \log PS_i$. The real quantity of government purchases is then

$$GG = \frac{VGG}{PGG}. \tag{A.15}$$

The difference between revenue and expenditure is the deficit, ΔG, which is covered by increases in the public debt, both domestic (B) and foreign (B^{G*})

$$\Delta G_t = \text{Expend}_t - \text{Rev}_t, \tag{A.16}$$

$$B_t + B_t^{G*} = B_{t-1} + B_{t-1}^{G*} + \Delta G_t. \tag{A.17}$$

The deficit and interest payments are set exogenously and equation (A.16) is satisfied by making the level of total government expenditure on goods, VGG, endogenous.

A.4 Capital, Investment, and the Financial System

We model the structure of investment in a fairly simple manner. In the Chinese economy, some state-owned enterprises receive investment funds directly from the state budget and are allocated credit on favorable terms through the state-owned banking system. Non-state enterprises get a negligible share of state investment funds and must borrow at what are close to competitive interest rates. There is also a small but growing stock market that provides an alternative channel for private savings. We abstract from these features and define the capital stock in each sector j as the sum of two parts, which we call plan and market capital

$$K_{jt} = \bar{K}_{jt} + \tilde{K}_{jt}. \tag{A.18}$$

The plan portion evolves with plan investment and depreciation

$$\bar{K}_{jt} = (1-\delta)\bar{K}_{jt-1} + \bar{I}_{jt}, \quad t = 1, 2, \ldots, T. \tag{A.19}$$

In this formulation, $\bar{K}_{j0}$ is the capital stock in sector j at the beginning of the simulation. This portion is assumed to be immobile across sectors. Over time, with depreciation and limited government investment, it will decline in importance. Each sector may also "rent" capital from the total stock of market capital, $\tilde{K}_t$

$$\tilde{K}_t = \sum_j \tilde{K}_{jt}, \tag{A.20}$$

where $\tilde{K}_{ji} > 0$.

The allocation of market capital to individual sectors, $\tilde{K}_{jt}$, is based on sectoral rates of return. As in equation (A.2), the rental price of market capital by sector is $\tilde{P}_j^{KD}$. The supply of $\tilde{K}_{jt}$, subject to equation (A.20), is written as a translog function of all of the market capital rental prices, $\tilde{K}_{jt} = K_j(\tilde{P}_1^{KD}, \ldots, \tilde{P}_n^{KD})$.

In two sectors, agriculture and crude petroleum, "land" is a factor of production. We have assumed that agricultural land and oil fields are supplied inelastically, abstracting from the complex property rights issues regarding land in China. After taxes, income derived from plan capital, market capital, and land is either kept as retained earnings by the enterprises, distributed as dividends, or paid to foreign owners

$$\begin{aligned}\sum_j \text{profits}_j + \sum_j \tilde{P}_j^{KD}\tilde{K}_j + \sum_j PT_jT_j \\ = \text{tax}(k) + RE + DIV + r(B*),\end{aligned} \tag{A.21}$$

where tax(k) is total direct taxes on capital (the first term on the right-hand side of equation (A.11)).[20]

As discussed below, total investment in the model is determined by savings. This total, VII, is then distributed to the individual investment goods sectors through fixed shares, α_{it}^I

$$PS_{it}I_{it} = \alpha_{it}^I VII_t. \tag{A.22}$$

Like the α_{it}^C coefficients in the consumption function, the investment coefficients are indexed by time and projected using U.S. patterns for 1992. A portion of sectoral investment, $\bar{I}_t$, is allocated directly by the government, while the remainder, $\tilde{I}_t$, is allocated through other channels.[21] The total, I_t, can be written as

$$I_t = \tilde{I}_t + \bar{I}_t = I_{1t}^{\alpha_1^I} I_{2t}^{\alpha_1^I} \ldots I_{nt}^{\alpha_n^I}. \tag{A.23}$$

As in equation (A.19) for the plan capital stock, the market capital stock, $\tilde{K}_{jt}$, evolves with new market investment

$$\tilde{K}_{jt} = (1 - \delta)\tilde{K}_{jt-1} + \tilde{I}_{jt}. \tag{A.24}$$

A.5 The Foreign Sector

Trade flows are modeled using the method followed in most single-country models. Imports are considered to be imperfect substitutes for domestic commodities and exports face a downward sloping demand curve. We write the total supply of commodity i as a CES function of the domestic (QI_i) and imported good (M_i)

$$QS_i = A_0[\alpha^d QI_i^\rho + \alpha^m M_i^\rho]^{1/\rho}, \tag{A.25}$$

where $PS_i QS_i = PI_i^t QI_i + PM_i M_i$ is the value of total supply. The purchaser's price for domestic goods, PI_i^t, is discussed in the producer section above. The price of imports to buyers is the foreign price plus tariffs (less export subsidies), multiplied by a world relative price, e

$$PM_i = e(1 + t_i^r)PM_i^*. \tag{A.26}$$

Exports are written as a simple function of the domestic price relative to world prices adjusted for export subsidies (s_{it}^e)

$$X_{it} = EX_{it}\left(\frac{\tilde{P}I_{it}}{e_t(1 + s_{it}^e)PE_{it}^*}\right)^{\eta_i}, \tag{A.27}$$

where EX_{it} is base case exports that are projected exogenously.

The current account balance is equal to exports minus imports, less net factor payments, plus transfers

$$CA = \sum_i \frac{PI_i X_i}{1 + s_i^e)} - \sum_i PM_i M_i - r(B^*) - G\_IR + R\_\text{transfer}. \tag{A.28}$$

Like the government deficits, the current account balances are set exogenously and accumulate into stocks of net foreign debt, both private (B_t^*) and public (B_t^{G*})

$$B_t^* + B_t^{G*} = B_{t-1}^* + B_{t-1}^{G*} - CA_t. \tag{A.29}$$

A.6 Markets

The economy is in equilibrium in period t when the market prices clear the markets for the 29 commodities and the two factors. The supply of commodity i must satisfy the total of intermediate and final demands:

$$QS_i = \sum_j A_{ij} + C_i + I_i + G_i + X_i, \qquad i = 1, 2, \ldots, 29. \tag{A.30}$$

For the labor market, we assume that labor is perfectly mobile across sectors so there is one average market wage which balances supply and demand. As is standard in models of this type, we reconcile this wage with the observed spread of sectoral wages using wage distribution coefficients, ψ^L_{jt}. Each industry pays $PL_{jt} = \psi^L_{jt} PL_t$, for a unit of labor. The labor market equilibrium is then given as

$$\sum_j \psi^L_{jt} LD_{jt} = LS_t. \tag{A.31}$$

For the non-plan portion of the capital market, adjustments in the market price of capital, $\tilde{P}^{KD}_j$, clears the market in sector j

$$KD_{jt} = \psi^K_{jt} K_{jt}, \tag{A.32}$$

where ψ^K_{jt} converts the units of capital stock into the units used in the production function. The rental price PT_j adjusts to clear the market for "land"

$$TD_j = T_j, \tag{A.33}$$

where j "agriculture" and "petroleum extraction."

In this model without foresight, investment equals savings. There is no market where the supply of savings is equated to the demand for investment. The sum of savings by households, businesses (as retained earnings), and the government is equal to the total value of investment plus the budget deficit and net foreign investment

$$S^p + RE + G\_INV = VII + \Delta G + CA. \tag{A.34}$$

The budget deficit and current account balance are fixed exogenously in each period. The world relative price (e) adjusts to hold the current account balance at its exogenously determined level.

Notes

1. Carbon Dioxide Information Analysis Center (1997).

2. As of 1996, 79 percent of agricultural products, 93 percent of consumer goods, and 81 percent of industrial production materials were sold at market prices (China Price Yearbook Editorial Committee, 1997). The remainder were sold at state-set or guidance prices (prices allowed to fluctuate within a narrow band).

3. In general, in the multi-regional models the level of detail for China is not as great as that for the developed countries.

4. Details of the data construction and sources are given in Garbaccio, Ho, and Jorgenson (1997). Details of the projections of many of the exogenous variables are also included.

5. For example, the "petroleum refining" activity produces both the "petroleum refining" and "chemical" commodities.

6. As to the effectiveness of emissions charges in China, Wang and Wheeler (1996) note that for water pollutants, while some provinces lag behind, on the whole the current levy system is relatively effective and has been "accompanied by large reductions in water pollution."

7. Net imports of refined petroleum are also calculated and included in the total.

8. See equations (A.4) and (A.12) in the appendix.

9. In the base case, carbon emissions in year 2032 are 2.16 billion tons. This figure is reduced by 5 percent, 10 percent, and 15 percent in the alternative simulations.

10. There are 0.518 tons of carbon emitted per ton of average coal. The average price of coal output in 1992, derived by dividing the value in the input-output table by the quantity of coal mined, is about 68 *yuan* per ton. This implies a tax on coal of about 7 percent.

11. Total primary energy use is calculated as the simple sum of the standard coal equivalents of coal, oil, natural gas, and hydroelectricity.

12. This comment applies to the other exogenous variables in the model as well. A different rate of technical progress, for example, would lead to a different path for the base case. However, the percentage change in variables (like GDP) resulting from the imposition of a carbon tax, would be only marginally affected. Assuming a more rapid rate of liberalization of the plan elements would have income, but not price effects.

13. A good overview of the "double dividend" literature is given in Goulder (1995b).

14. At this time we are aware of no study that has estimated a labor supply elasticity for China. However, we should note that allowing for an elastic labor supply in our model would require the inclusion of leisure in the welfare function. Given the development of labor markets in China and the high rate of unemployment, we do not believe that this would be a useful complication of the model.

15. Some of the sectoral inequality in commodity tax rates was reduced following the taxation system reforms that took place at the beginning of 1994.

16. On the other hand, Zhang's model separates natural gas from the crude petroleum sector, allowing for an additional degree of fuel substitution after the imposition of a carbon tax.

17. Zhang also makes some comparisons between the results of simulations with his China model and the China components of the Global 2100 (Manne, 1992) and GREEN (Oliveira-Martins et al., 1993) multi-country models. Without revenue recycling, for a 20 percent cut in carbon emissions, in year 2010 there is a 1.52 percent decline in GDP in Zhang's model, a 0.98 percent decline in Global 2100, and a 0.25 percent decline in GREEN. With partial revenue recycling, Zhang found a 1.47 percent decline in GDP in the 20th year. Unfortunately, a comparison of the same revenue recycling scenario is not available for the two multi-country models.

18. QI_j denotes the quantity of industry j's output. This is to distinguish it from QC_j, the quantity of commodity j. In the actual model each industry may produce more than one commodity and each commodity may be produced by more than one industry. In the language of the input output tables, we make use of both the USE and MAKE matrices. For ease of exposition we ignore this distinction here.

19. We have chosen to use U.S. patterns in our projections of these exogenous parameters because they seem to be a reasonable anchor. While it is unlikely that China's economy in 2032 will mirror the U.S. economy of 1992, it is also unlikely to closely resemble any other economy. Other projections, such as those by the World Bank (1994a), use the input-output tables of developed countries including the United States. We have considered making extrapolations based on recent Chinese input-output tables, but given the short sample period and magnitude of the changes in recent years, this did not seem sensible.

20. In China, most of the "dividends" are actually income due to agricultural land.

21. It should be noted that the industries in the Chinese accounts include many sectors that would be considered public goods in other countries. Examples include local transit, education, and health.

12

The Economic Impact of Fundamental Tax Reform

Dale W. Jorgenson and
Peter J. Wilcoxen

12.1 Introduction

In this chapter we present a new intertemporal general equilibrium model for analyzing the economic impact of tax policies in the United States. We preserve the key features of more highly aggregated models like that of Jorgenson and Yun (1990, 1991a). One important dimension for disaggregation is to introduce a distinction between industries and commodities to model business responses to tax-induced price changes. We also distinguish among households by level of wealth and demographic characteristics, so that we can model differences in household responses to tax changes. This is also useful in examining the distributional effects of taxes. We present the model in more detail in the following section.

We model demands for different types of capital services in each of thirty-five industrial sectors of the U.S. economy and the household sector (table 12.1). These demands depend on tax policies through measures of the cost of capital presented by Jorgenson and Yun (1991b) that incorporate the characteristic features of U.S. tax law. The cost of capital makes it possible to represent the economically relevant features of highly complex tax statutes in a very succinct form. The cost of capital also summarizes information about the future consequences of investment decisions required for current decisions about capital allocation. We describe the provisions of U.S. tax law that have been incorporated into our model in the third section.

Section four illustrates the application of our new model by simulating the economic impacts of fundamental tax reforms. We consider the effects of substituting a tax on consumption for income taxes at both federal and state and local levels in the United States.[1] The data for each year are divided between a *use* table and a *make* table. The use table shows

Table 12.1
The definitions of industries

Number	Description
1	Agriculture, forestry and fisheries
2	Metal mining
3	Coal mining
4	Crude petroleum and natural gas
5	Nonmetallic mineral mining
6	Construction
7	Food and kindred products
8	Tobacco manufactures
9	Textile mill products
10	Apparel and other textile products
11	Lumber and wood products
12	Furniture and fixtures
13	Paper and allied products
14	Printing and publishing
15	Chemicals and allied products
16	Petroleum refining
17	Rubber and plastic products
18	Leather and leather products
19	Stone, clay and glass products
20	Primary metals
21	Fabricated metal products
22	Machinery, except electrical
23	Electrical machinery
24	Motor vehicles
25	Other transportation equipment
26	Instruments
27	Miscellaneous manufacturing
28	Transportation and warehousing
29	Communication
30	Electric utilities
31	Gas utilities
32	Trade
33	Finance, insurance and real estate
34	Other services
35	Government enterprises

Table 12.2
Make and Use table variables

Category	Variable	Description
Industry-Commodity flows:	USE	Commodities Used by Industries (use table)
	MAKE	Commodities Made by Industries (make table)
Final Demand Columns:	C	Personal Consumption
	I	Gross Private Domestic Investment
	G	Government Spending
	X	Exports
	M	Imports
Value Added Rows:	N	Noncompeting Imports
	K	Capital
	L	Labor
	T	Net Taxes
	R	Rest of the World
Commodity and Industry Output:	O	Commodity Output
	D	Industry Output
Other Variables:	B	Value Added Sold Directly to Final Demand
	V	Total Value Added
	F	Total Final Demand

the quantities of each commodity-intermediate inputs, primary factors of production, and noncompeting imports used by each industry and final demand category.[2] The make table gives the amount of each commodity produced by each industry. In the absence of joint production this would be a diagonal array. The organization of the use and make tables is illustrated in figures 12.1 and 12.2; table 12.2 provides definitions of the variables appearing in these figures.

The econometric method for choosing the parameters of our model stands in sharp contrast to the calibration method used in previous general equilibrium models of tax policies. Calibration involves choosing parameters to replicate the data for a particular year.[3] Almost all general equilibrium models employ the assumption of fixed "input-output" coefficients for intermediate goods, following Johansen (1960). This allows the ratio of the input of each commodity to the output of an industry to

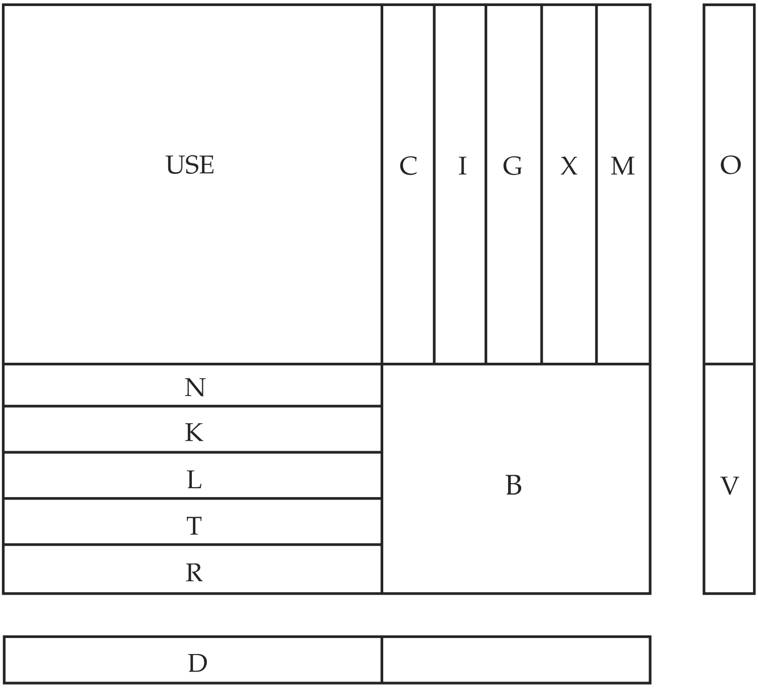

Figure 12.1
Organization of the Use table.

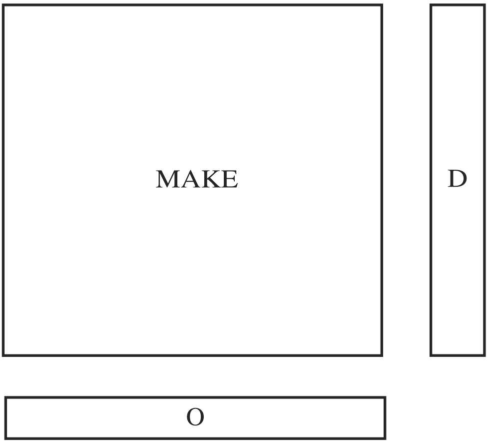

Figure 12.2
Organization of the Make table.

be calculated from a single use table like the one presented in figure 12.1; however, it rules out substitution among intermediate goods, such as energy and materials, by assumption. It also ignores the distinction between industries and commodities and rules out joint production.

The econometric approach to parameterization has several advantages over the calibration approach. First, by using an extensive time series of data rather than a single data point, we can derive the response of production patterns to changes in prices from historical experience. This is particularly important for the analysis of tax policies, since these policies have changed substantially during our sample period and tax rates have varied widely. The extensive time series evidence on behavioral responses to changes in tax policy is ignored in the calibration approach.

A second advantage of the econometric approach is that parameters estimated from time series are much less likely to be affected by the peculiarities of a particular time period. By construction, parameters obtained by calibration are forced to absorb all the random errors present in the data for a single benchmark year. This poses a severe problem when the benchmark year is unusual in some respect. For example, parameters calibrated to the year 1973 would incorporate into the model all the distortions in energy markets that resulted from price controls and the rationing of energy during the first oil crisis. Econometric parameterization greatly mitigates this problem by reducing the influence of disturbances for a particular time period.

Empirical evidence on substitutability among inputs is essential in analyzing the impact of tax policies. If it is easy for industries to substitute among inputs, the effects of these policies will be very different than if substitution were limited. Although calibration avoids the burden of data collection required by econometric estimation, it rules out substitutability among inputs by assumption. This can easily lead to substantial distortions in estimating the impacts of alternative tax policies. By contrast the econometric approach determines the extent of substitutability on the basis of empirical evidence.

12.1.1 Consumer Behavior

The substitution of a consumption tax for an income tax would affect relative prices faced by consumers. However, this substitution would have different impacts on different households. To capture these differences, we have subdivided the household sector into demographic groups that differ by family size, age of head, region of residence, race, and urban versus rural location. We treat each household as a consuming unit, so that the household behaves like an individual maximizing a utility function.

We represent the preferences of each household by means of an econometric model of consumer behavior. Our models of consumer behavior incorporate time series data on personal consumption expenditures from the annual interindustry transactions tables for the U.S. economy represented in figure 12.1. The econometric approach to parameterization enables us to derive from historical experience the response of household expenditure patterns to changes in prices. Empirical evidence on substitutability among goods and services by households is essential in analyzing the impact of alternative tax policies. If it is easy for households to substitute among commodities, the effects of these policies will be very different than if substitution were limited.

The econometric approach to modeling consumer behavior has the same advantages over the calibration approach as those we have described for modeling producer behavior. Our models of consumer behavior incorporate detailed cross-section data on the impact of demographic differences among households and levels of total expenditure on household expenditure patterns. We do not require that consumer demands must be homothetic, so that patterns of individual expenditure change as total expenditure varies, even in the absence of price changes. Consumer demands also depend on the demographic composition of the population. These features of our model capture important characteristics of household expenditure patterns often ignored in general equilibrium modeling.

Finally, we aggregate over individual demand functions to obtain a system of aggregate demand functions. This makes it possible to dispense with the notion of a representative consumer. The system of aggregate demand functions allocates total expenditure to broad groups of consumer goods and services. Given prices and total expenditure, this system allows us to calculate the elements of personal consumption column in the make table of figure 12.1. We employ the model to represent aggregate consumer behavior in simulations of the U.S. economy under alternative tax policies.

To determine the level of total expenditure we embed our model of personal consumption expenditures in a higher-level system that represents consumer preferences between goods and leisure and between saving and consumption. At the highest level each household allocates *full wealth*, defined as the sum of human and nonhuman wealth, across time periods. We formalize this decision by introducing an infinite-lived representative agent who maximizes an additive intertemporal utility function, subject to an intertemporal budget constraint. The allocation of full wealth is determined by the rate of time preference and the intertemporal elasticity of substitution. The representative agent framework requires that intertemporal preferences must be identical for all households.

We model the household allocation decision by assuming that full consumption is an aggregate of goods and leisure. Our model of consumer behavior allocates the value of full consumption between personal consumption expenditures and leisure time. Given aggregate expenditure on goods and services and its distribution among households, this model then allocates personal consumption expenditures among commodity groups, including capital and labor services and noncompeting imports. Finally, the income of the household sector is the sum of incomes from the supply of capital and labor services, interest payments from governments and the rest of the world, all net of taxes, and transfers from the government. Savings are equal to the difference between income and consumption, less personal transfers to foreigners and nontax payments to governments.

12.1.2 Capital Formation

Our investment model, like our model of saving, is based on perfect foresight or rational expectations. Under this assumption the price of investment goods in every time period is based on expectations of future capital service prices and discount rates that are fulfilled by the solution of the model. In particular, we require that the price of new investment goods is always equal to the present value of future capital services.[4] The price of investment goods and the discounted value of future rental prices are brought into equilibrium by adjustments in future prices and rates of return. This incorporates the forward-looking dynamics of asset pricing into our model of intertemporal equilibrium.

In each of the thirty-five industrial sectors and the household sector the demand for capital services is first subdivided between the corporate and noncorporate subsectors. Within each of these subsectors, the demand for capital is further subdivided between short-lived assets or equipment and long-lived assets-structures, inventories, and land. The prices for these different types of capital services reflect provisions of

U.S. tax law for the taxation of capital income in the corporate, noncorporate, and household sectors. These prices also include tax provisions that affect short-lived and long-lived assets differently, such as depreciation allowances and investment tax credits. A detailed description of these tax provisions, based on Jorgenson and Yun (1991b), is given in the following section. In our model the supply of capital in each time period is perfectly inelastic, since the available stock of capital is determined by past investments. An accumulation equation relates capital stock to investments in all past time periods and incorporates the backward-looking dynamics of capital formation into our model. For tractability we assume there is a single capital stock in the economy which is perfectly malleable and mobile among sectors, so that it can be reallocated among industries and final demand categories at zero cost. Under this assumption changes in tax policy can affect the distribution of capital and labor supplies among sectors, even in the short run.

12.1.3 Government and Foreign Trade

The two remaining categories of final demand in our model are the government and rest of the world sectors. We determine government consumption from the income-expenditure identity for the government sector.[5] The first step is to compute total tax revenue by applying exogenous tax rates to all taxable transactions in the economy. We then add the capital income of government enterprises, which is determined endogenously, and nontax receipts, also determined exogenously, to tax receipts to obtain total government revenue.

The key assumption of our submodel of the government sector is that the government budget deficit can be specified exogenously. We add the deficit to total revenue to obtain total government spending. To arrive at government purchases of goods and services, we subtract interest paid to domestic and foreign holders of government bonds together with government transfer payments to domestic and foreign recipients. We allocate the remainder among commodity groups according to fixed shares constructed from historical data. Finally, we determine the quantity of each commodity by dividing the value of government spending on that commodity by its price. Government consumption is not included in our representation of the preferences of the household sector.

Foreign trade has two quite different components—imports and exports. We assume that imports are imperfect substitutes for similar domestic commodities.[6] The goods actually purchased by households and firms reflect substitutions between domestic and imported products. The price responsiveness of these purchases is estimated from historical data taken from the import and export columns of the use table, figure 12.1, in our annual interindustry transactions tables.

Exports, on the other hand, are modeled by a set of explicit foreign demand equations, one for each commodity, that depend on exogenously given foreign income and the foreign price of U.S. exports. Foreign prices are computed from domestic prices by adjusting for subsidies and the exchange rate. The demand elasticities in these equations are estimated from historical data. We assume that U.S. firms are price-takers in foreign markets. The alternative approach of modeling imperfections in international markets would require firm-level data, not only for the U.S., but also for all of its international competitors.

The key assumption of our submodel of the rest of the world sector is that the current account is exogenous and the exchange rate is endogenous. The current account surplus is equal to the value of exports less the value of imports, plus interest received on domestic holdings of foreign bonds, less private and government transfers abroad, and less interest on government bonds paid to foreigners.

12.2 Provisions of U.S. Tax Law

The purpose of this section is to introduce the characteristic features of U.S. tax law into the cost of capital.[7] We distinguish among assets employed in three different legal forms of organization—households and nonprofit institutions, noncorporate businesses, and corporate businesses. Income from capital employed in corporate business is subject to the corporate income tax, while distributions of this income to households are subject to the individual income tax. Income from unincorporated businesses—partnerships and sole proprietorships—is taxed only at the individual level. Income from equity in household assets is not subject to the income tax. Capital utilized in all three forms of organization is subject to property taxation.

Although income from equity in the household sector is not subject to tax, property taxes and interest payments on household debt are deductible from income for tax purposes under the individual income tax. The value of these tax deductions is equivalent to a subsidy to capital employed in the household sector. Interest payments to holders of household debt are taxable to the recipients. Capital gains on household assets are effectively excluded from taxable income at the individual level by generous “roll over” provisions for owner-occupied residential housing. Capital gains on owner-occupied housing are not included in income so long as they are “rolled over” into the same form of investment. In addition, certain gains are excluded altogether.

Income from capital employed in noncorporate businesses is taxed at the level of the individual. Income from noncorporate equity is treated as fully distributed to equity holders, whether or not the income is actually paid out. Interest payments to holders of debts on noncorporate businesses are subject to taxation. Property taxes and interest payments are treated as deductions from revenue in defining income from noncorporate businesses for tax purposes. Revenue is also reduced by deductions for capital consumption allowances. Until 1986 tax liabilities were reduced by an investment tax credit that was proportional to investment expenditures. Capital gains on noncorporate assets are subject to favorable treatment as outlined below. Property taxes and interest payments are treated as deductions from revenue in defining corporate income for tax purposes. Revenue is also reduced by allowances for capital consumption and an investment tax credit has been directly offset against tax liability. At the individual level distributions of corporate income in the form of interest and dividends are subject to taxation as ordinary income. Capital gains realized from the sale of corporate equities are subject to special treatment outlined below. Interest payments to holders of corporate bonds are also taxable.

The special treatment of capital gains arises from three separate features of U.S. tax law. First, capital gains are taxed only when they are realized and not when they are accrued. This feature makes it possible to defer tax liability on capital gains until assets are sold. Second, capital gains have often been given favorable treatment by including only a fraction of these gains in income defined for tax purposes. Finally, capital gains taxes on assets received as part of a bequest are based on their value at the time of the bequest. Capital gains accrued prior to the bequest are not subject to tax.

In this chapter we have described the characteristic features of U.S. tax law in terms of the cost of capital and the rate of return. We have modeled provisions of U.S. tax law on corporate income taxes, individual income taxes, and property taxes. We have also incorporated the effects of the financial structure of the firm on the taxation of capital income. The financial structure determines the form of distributions of capital income to owners of financial claims. We have distinguished between equity, associated with distributions in the form of dividends and capital gains, and debt, associated with distributions in the form of interest payments.

In order to analyze the impact of changes in tax policies, we simulate the growth of the U.S. economy with and without changes in these policies.[8] Our first step is to generate a simulation with no changes in policy that we call the Base Case. The second step is to change the exogenous variables of the model to reflect a proposed policy change. We then produce a simulation that we refer to as the Alternative Case. Finally, we compare the two simulations to assess the effects of the change in policy. Obviously, the assumptions underlying the base case are of considerable importance in interpreting the results of our simulations.

12.3 Fundamental Tax Reform

The debate over fundamental tax reform is both a challenge and an opportunity for economists because economic research has already generated much valuable information about the impacts of tax policy. Provided that the economic debate can be properly focused, economists and policy makers will learn a great deal about the U.S. economy and its potential for achieving a higher level of performance. Substitution of a consumption tax for existing individual and corporate income taxes would be the most drastic change in federal tax policy since the introduction of the income tax in 1913. It should not be surprising that the economic impact could be large.

12.3.1 Issues in Tax Reform

The first issue that will surface in the tax reform debate is progressivity or the use of the federal tax system to redistribute resources. Our recommendation is that this issue be set aside at the outset. Fiscal economists of varying persuasions can agree that progressivity or the lack of it should be used to characterize all of government activity, including both taxes and expenditures. Policies to achieve progressivity could and should be limited to the expenditure side of the government budget. This initial policy stance would immeasurably simplify the debate over the economic impact of fundamental tax reform. We view this radical simplification as essential to intellectual progress, since there is no agreed upon economic methodology for trading off efficiency and equity in tax policy.

The second issue to be debated is fiscal federalism or the role of state and local governments. Since state and local income taxes usually employ the same tax bases as the corresponding federal taxes, it is reasonable to assume that substitution of consumption for income taxes at the federal level would be followed by similar substitutions at the state and local level. For simplicity we propose to consider the economic impact of substitution at all levels simultaneously. Since an important advantage of a fundamental tax reform is the possibility, at least at the outset, of radically simplifying tax rules, it does not make sense to assume that these rules would continue to govern state and local income taxes, if the federal income tax were abolished.

The third issue in the debate will be the economic impact of the federal deficit. Nearly two decades of economic dispute over this issue has failed to produce resolution. No doubt this dispute could continue well into the next century and preoccupy the next generation of fiscal economists, as it has the previous generation. An effective rhetorical device for insulating the discussion of fundamental tax reform from the budget debate is to limit consideration to deficit neutral proposals. This device was critical to the eventual enactment of the Tax Reform Act of 1986 and is, we believe, essential to progress in the debate over fundamental tax reform.

12.3.2 Consumption Taxation

A useful starting point for the definition of consumption is Personal Consumption Expenditures (PCE) in the U.S. national income and product accounts. However, the taxation of services poses important administrative problems reviewed in the U.S. Treasury (1984) monograph on the value added tax. First, PCE includes the rental equivalent value of the services of owner-occupied housing, but does not include the services of consumers durables. Both are substantial in magnitude and could be taxed by the "prepayment method" described by David Bradford (1986). In this approach taxes on the consumption of the services would be prepaid by including the original investment in housing and consumers' durables rather than the corresponding flows of consumption services in the definition of the tax base.

The prepayment of taxes on services of owner-occupied housing would remove an important political obstacle to substitution of a consumption tax for existing income taxes. At the time of the substitution all owner-occupiers would be deemed to have prepaid all future taxes on their dwellings. This is equivalent to excluding not only mortgage interest, but also capital gains, which might be taxed upon the sale of a residence with no corresponding purchase of property of equal or greater value. Of course, taxation of these capital gains is relatively modest under the current law.

Under the prepayment method purchases of consumers' durables would be subject to tax. This would include automobiles, appliances, home furnishings, and so on. In addition, new construction of owner-occupied housing would be subject to tax, as would sales of existing renter-occupied housing to owner-occupiers. These are politically sensitive issues and it is important to be clear about the implications of prepayment as the debate proceeds. Housing and consumers' durables must be included in the tax base in order to reap the substantial economic benefits of putting household and business capital onto the same footing.[9]

Other purchases of services especially problematical under a consumption tax would include services provided by nonprofit institutions, such as schools and colleges, hospitals, and religious and eleemosynary institutions. The traditional, tax-favored status of these forms of consumption would be defended tenaciously by recipients of the services and even more tenaciously by the providers. Elegant and, in some cases, persuasive arguments could be made that schools and colleges provide services that represent investment in human capital rather than consumption. However, consumption of the resulting enhancements in human capital often takes the form of leisure time, which would remain as the principal untaxed form of consumption. Taxes could, however, be prepaid by including educational services in the tax base. Finally, any definition of a consumption tax base will have to distinguish between consumption for personal and business purposes. On-going disputes over home offices, business-provided automobiles, equipment, and clothing, and business-related lodging, entertainment and meals would continue to plague tax officials, the entertainment and hospitality industries, and holders of expense accounts. In short, substitution of a consumption tax for the federal income tax system would not eliminate all the practical issues that arise from distinguishing between business and personal activities in defining consumption. However, these issues are common to the two tax systems.

12.3.3 Implementation

In *Hearings on Replacing the Federal Income Tax* (1996), held by the Committee on Ways and Means in June 1995, testimony focused on alternative methods for implementing a consumption tax. The consumption tax base can be defined in three alternative and equivalent ways. First, subtracting investment from value added produces consumption as a tax base, where value added is the sum of capital and labor incomes. A second definition is the difference between business receipts and all purchases from other businesses, including purchases of investment goods. A third definition of the tax base is retail sales to consumers.

The three principal methods for implementation of a consumption tax correspond to these three definitions of the tax base:

1. *The subtraction method.* Business purchases from other businesses, including investment goods, would be subtracted from business receipts, including proceeds from the sale of assets. This could be implemented within the framework of the existing tax system by integrating individual and corporate income taxes, as proposed by the U.S. Treasury (1992). If no business receipts were excluded and no deductions and tax credits were permitted, the tax return could be reduced to the now familiar postcard size, as in the Flat Tax proposal of Majority Leader Dick Armey and Senator Richard Shelby.[10] Enforcement problems could be reduced by drastically simplifying the tax rules, but the principal method of enforcement, auditing of taxpayer records by the Internal Revenue Service, would remain.

2. *The credit method.* Business purchases would produce a credit against tax liabilities for value added taxes paid on goods and services received. This method is used in Canada and all European countries that impose a value added tax. From the point of view of tax administration the credit method has the advantage that both purchases and sales generate records of all tax credits. The idea of substituting a value added tax for existing income taxes is a novel one. European and Canadian value added taxes were added to pre-existing income taxes. In Canada and many other countries the value added tax replaced an earlier and more complex system of retail and wholesale sales taxes. The credit method would require substantial modification of collection procedures, but decades of experience in Europe have ironed out many of the bugs.

3. *National retail sales tax.* Like existing state sales taxes, a national retail sales tax would be collected by retail establishments, including service providers and real estate developers. An important practical difficulty is that only sales to households would be covered by the tax, while sales to businesses would be excluded. A federal sales tax would require a new system for tax collection; one possibility is to subcontract that collection to existing state agencies. The Internal Revenue Service could be transformed into an agency that would manage the subcontracts. Alternatively, a new agency could be created for this purpose and the IRS abolished. Enforcement procedures would be similar to those used by

the states. The crucial point is that all three methods for implementing a consumption tax could be based on the same definition of the tax base. This greatly simplifies the tax economist's task, since the economic impact would be the same for all three approaches. However, the Armey-Shelby Flat Tax incorporates a system of individual exemptions for labor income that have the effect of setting the marginal tax rates equal to zero up to the exempt amount of income. After that point the marginal tax rate is constant at a flat rate that is also applied to non-labor income. The purpose of these exemptions is to introduce progressivity in the rate structure; although the marginal tax rates are either zero or equal to the Flat Tax rate, the average tax rates decline gradually from zero to the flat rate.

12.3.4 Simulation Results

We have simulated the impact of implementing two different versions of a consumption tax at the beginning of 1996. The first is the Armey-Shelby Flat Tax. The Armey-Shelby proposal levies taxes on the difference between business receipts and the sum of business purchases and business payrolls. Labor income is taxed at the individual level. An important feature of the proposal is the system of personal exemptions at the individual level that we have described. The second proposal we have considered is the National Retail Sales Tax. The tax base is the same as in our simulations of the Flat Tax. However, the method of tax collection is different. The Armey-Shelby Flat Tax preserves the existing structures of the corporate and individual income taxes, but alters the tax base. The National Retail Sales Tax eliminates corporate and individual income taxes; retail establishments would collect the taxes. This would require a broad definition of these establishments to include real estate developers and providers of services, such as medical, legal, and personal services. Most important, no personal exemptions are provided. We have summarized our conclusions in a series of figures. We express all the impacts of alternative tax policies relative to the Base Case of U.S. economic growth under current tax law.

1. Figure 12.3 provides our Base Case projection for the period 1996–2020 of the U.S. gross domestic product (GDP) under current tax law. Gross domestic product is the sum of consumption, investment, government, and net exports, equal to the difference between exports and imports.

2. Figure 12.4 compares the consumption tax rates for revenue-neutral substitution of the Armey-Shelby Flat Tax (FT) and the National Retail

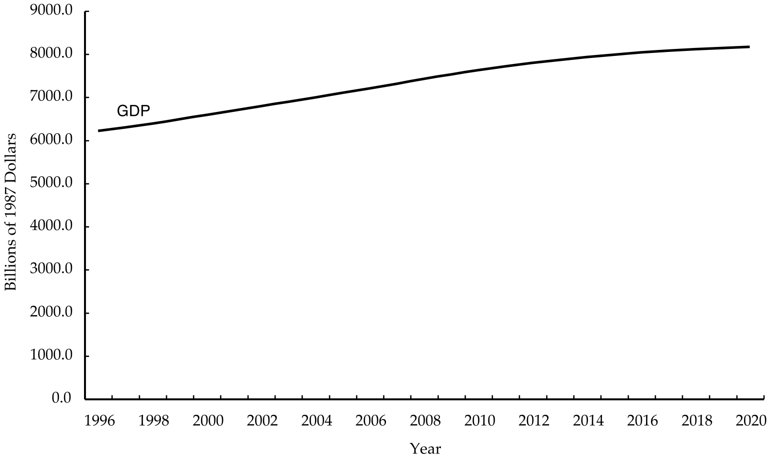

Figure 12.3
Base Case GDP.

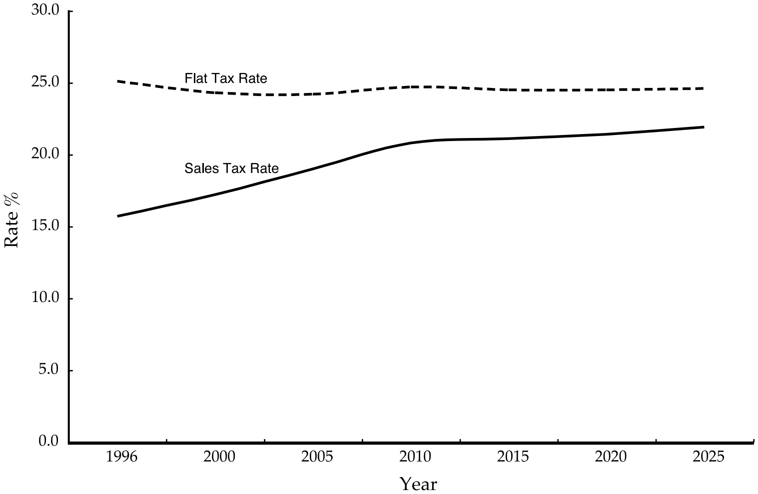

Figure 12.4
Consumption tax rates.

Sales Tax (ST) for existing income taxes. The Flat Tax rate is 25.1 percent in the year 1996 and remains virtually constant through the year 2020. The National Retail Sales Tax rate rises from only 15.7 percent in 1996 to 21.4 percent in the year 2020. Only the Flat Tax includes a system of personal exemptions, so that the tax rate is considerably higher, especially

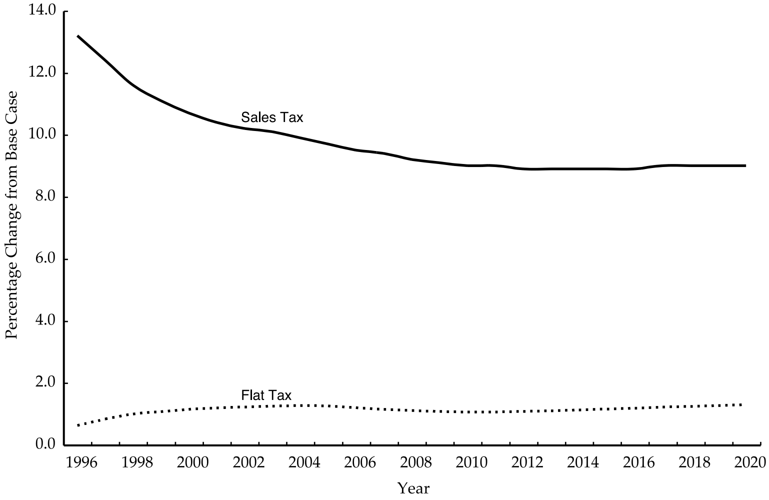

Figure 12.5
GDP.

at the initiation of the tax reform. Second, the consumption tax base for the Flat Tax grows at nearly the same rate as government expenditures, while the tax base for the Sales Tax grows more slowly, reflecting the increased importance of investment.

3. Figure 12.5 compares the impacts of the Flat Tax and the Sales Tax on GDP. Under the Flat Tax the GDP is only 0.6 percent higher than the Base Case in 1996; the impact of this tax reform on GDP gradually rises, reaching 1.3 percent in 2020. Under the Sales Tax the GDP jumps by 13.2 percent in 1996, but the impact gradually diminishes over time, falling to 9.0 percent in the year 2020. The short-run differences between these two tax reforms are due mainly to the impacts on labor supply, while the long-run differences also reflect the impacts on capital accumulation.

4. Figure 12.6 compares the impacts of the two tax reform proposals on consumption. The impact of the Flat Tax in 1996 is to increase consumption by 3.5 percent, relative to the Base Case. This impact gradually diminishes over time, falling to 1.3 percent by 2020. While it may seem paradoxical that consumption increases with a rise in the consumption tax, the marginal tax rate for low-income taxpayers is reduced to zero, stimulating consumption. By contrast the Sales Tax curtails consumption sharply in 1996, resulting in a decline of 5.6 percent, relative to the Base Case. However, the level of consumption overtakes the

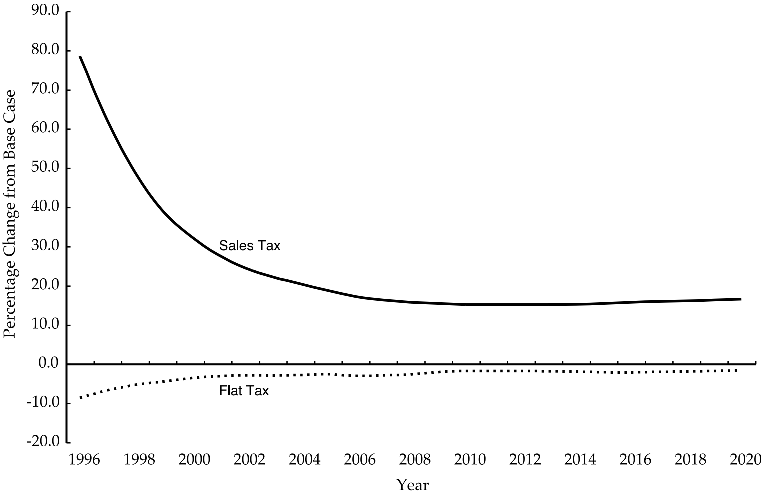

Figure 12.6
Investment.

Base Case level in 1998 and rises to 5.5 percent above the Base Case in 2020.

5. Figure 12.7 compares the impact of the two tax reform proposals on investment. The impact of the Flat Tax in 1996 is to depress investment by 8.6 percent, relative to the Base Case. Investment recovers over time, eventually reaching a level that is only 1.7 percent below the Base Case in the year 2020. Substitution of the Sales Tax for existing income taxes generates a dramatic investment boom. The impact in 1996 is a whopping 78.5 percent increase in the level of investment that gradually gives way by the year 2000 to a substantial increase of 16.5 percent, relative to the Base Case.

6. Figure 12.8 compares the impacts of the tax reforms on exports, while figure 12.9 compares the impacts on imports. It is important to keep in mind that net foreign investment, the difference between exports and imports in nominal terms, is exogenous in our simulations, while the exchange rate is endogenous. The Flat Tax results in a very modest decline in exports of 0.5 percent in 1996, relative to the Base Case, but exports recover rapidly and exceed Base Case levels in 1997, rising eventually to 4.6 percent above these levels in 2020. Imports initially rise by 2.0 percent, relative to the Base Case, in 1996, but this impact declines to only 0.3 percent by 2020. The Sales Tax generates a substantial export

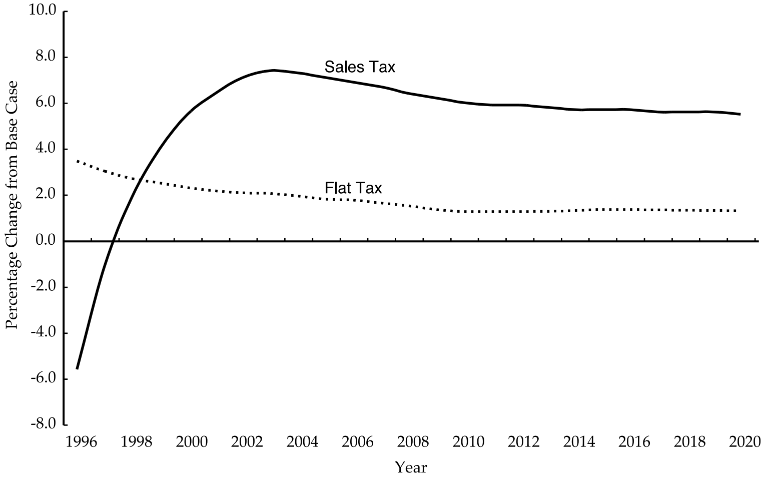

Figure 12.7
Consumption.

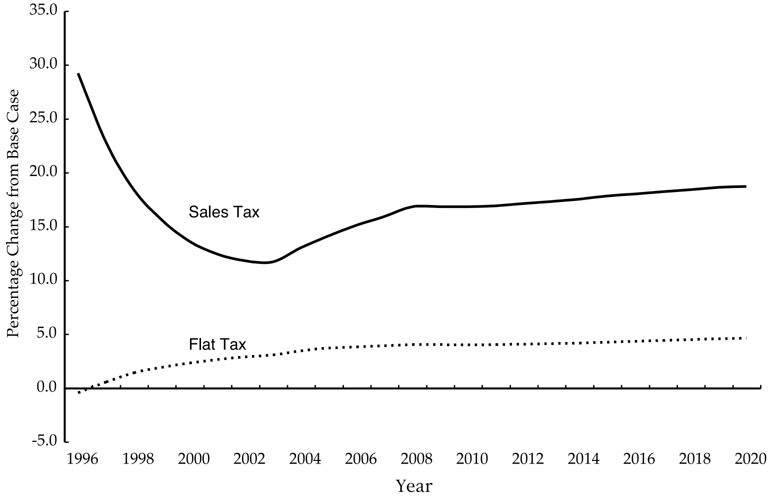

Figure 12.8
Exports.

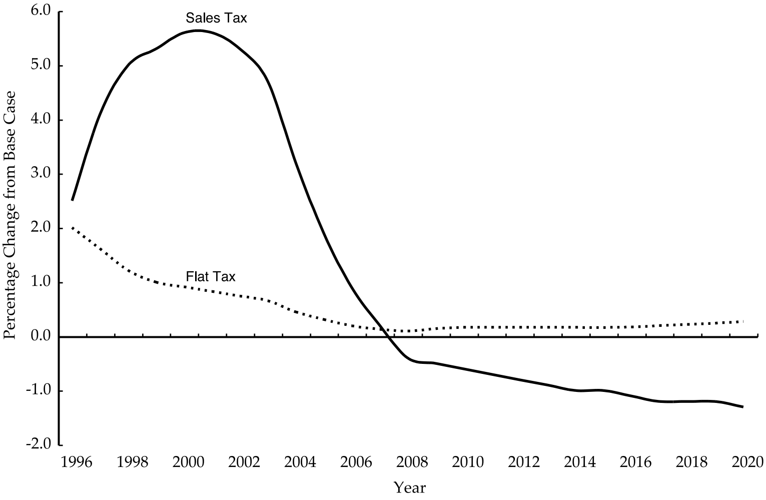

Figure 12.9
Imports.

boom; the level jumps to 29.2 percent about the Base Case level in 1996, but declines by 2020, reaching 18.9 percent of this level. Imports in 1996 exceed the Base Case level by 2.5 percent, but fall to 1.3 percent below this level in 2020.

7. The intertemporal price system provides the mechanism for reallocations of resources in our simulations. Figures 12.10 and 12.11 give the impacts of the tax reforms on the prices of investment goods and consumption goods and services. Under the Flat Tax the price of investment goods drops by more that 6.8 per cent in 1996 and the price decline continues, falling only modestly to a little over six percent by 2020. The Sales Tax produces a reduction in investment goods prices exceeding twenty percent in 1996, rising gradually to between twenty-five and thirty percent over the period 2000–2020. Under the Flat Tax prices of consumption goods and services decline by more than 4.5 percent in 1996, but this price reduction falls over time to around three percent in 2020. The Sales Tax reduces the price of consumption by a little over three percent in 1996, but this price decline increases to more than ten percent by 2020.

8. The implied subsidy to leisure time is equal to the marginal tax rate on labor income and would drop to zero when the individual income tax is abolished. Individuals sharply curtail consumption of both goods

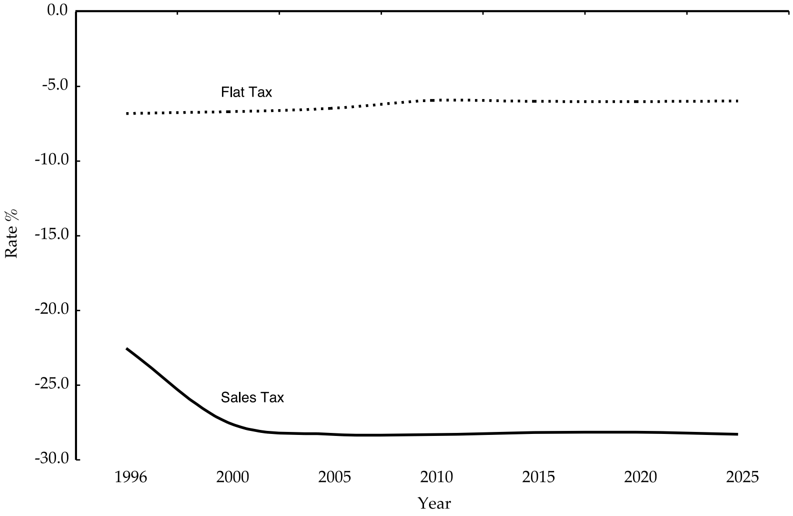

Figure 12.10
Price of investment.

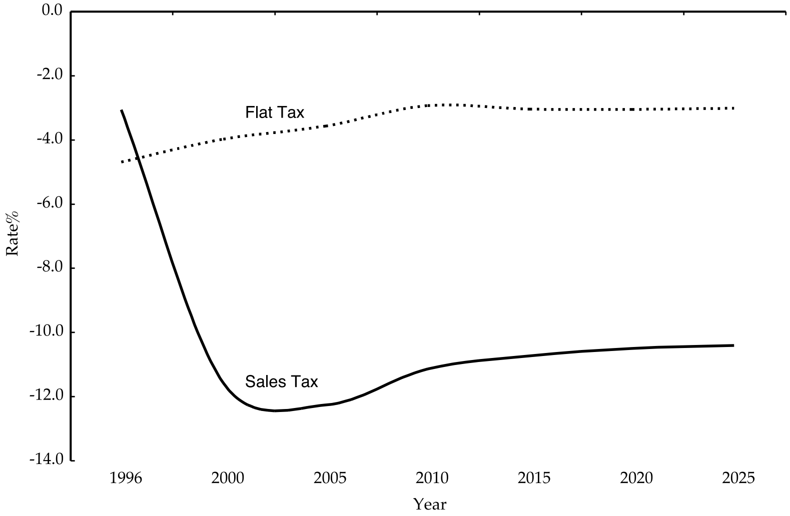

Figure 12.11
Price of consumption.

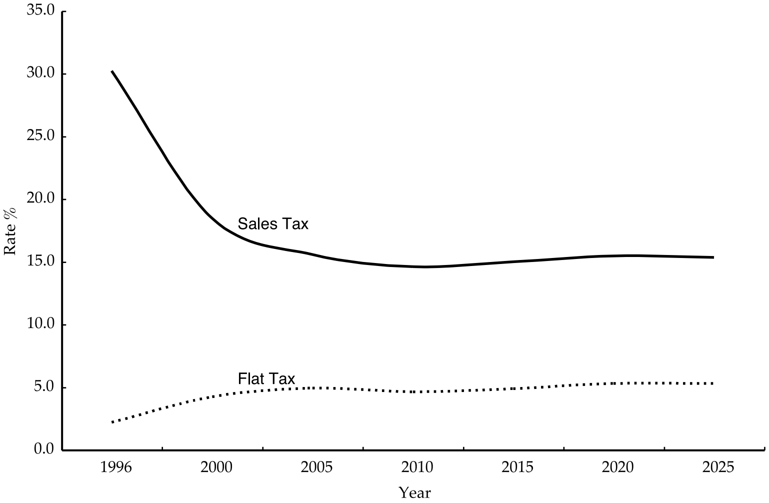

Figure 12.12
Labor supply.

and leisure under the Sales Tax. Figure 12.12 shows that labor supply (and demand) jumps initially by thirty percent in 1996. This labor supply response recedes to a level of around 15 percent by 2020. By contrast the Flat Tax generates an increase in both consumption and labor supply. The labor supply response is only two percent in 1996, but gradually rises to more than five percent by 2020.

9. Since producers capital and workers would no longer pay taxes on profits or other forms of income from no longer pay taxes on wages, prices received by producers under the Sales Tax, shown in figure 12.13, would fall by an average of twenty percent in 1996. Figure 12.14 shows that prices received by producers would fall by an average of twenty-five percent by 2020. The impact of the Flat Tax on prices received by producers is much less dramatic. Prices decline in the range of six to eight percent for most industries in 1996 and five to seven percent by 2020.

10. Figures 12.15 and 12.16 give the simulation results for quantities of output at the industry level for both tax reform proposals. The Sales Tax produces substantial increases in output levels for most industries shown in figure 12.15 for 1996. This reflects the size of the impact for the Sale Tax on overall economic activity. By 2020 the changes in outputs of the individual industries have increased by around fifteen percent,

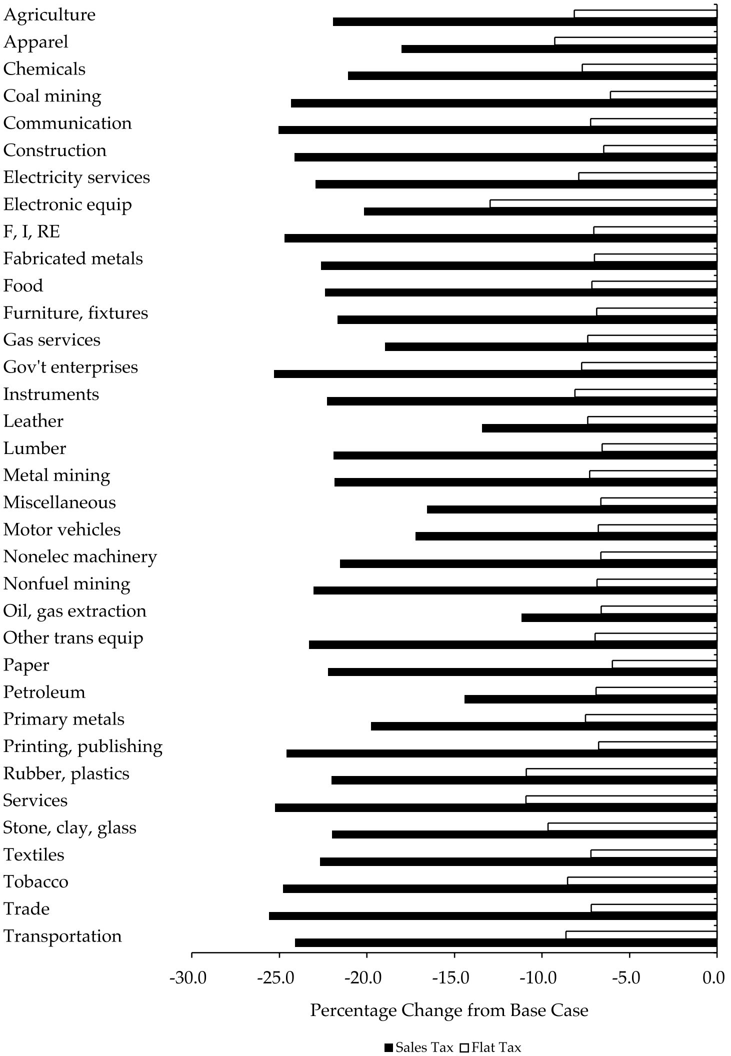

Figure 12.13
Industry prices, 1996.

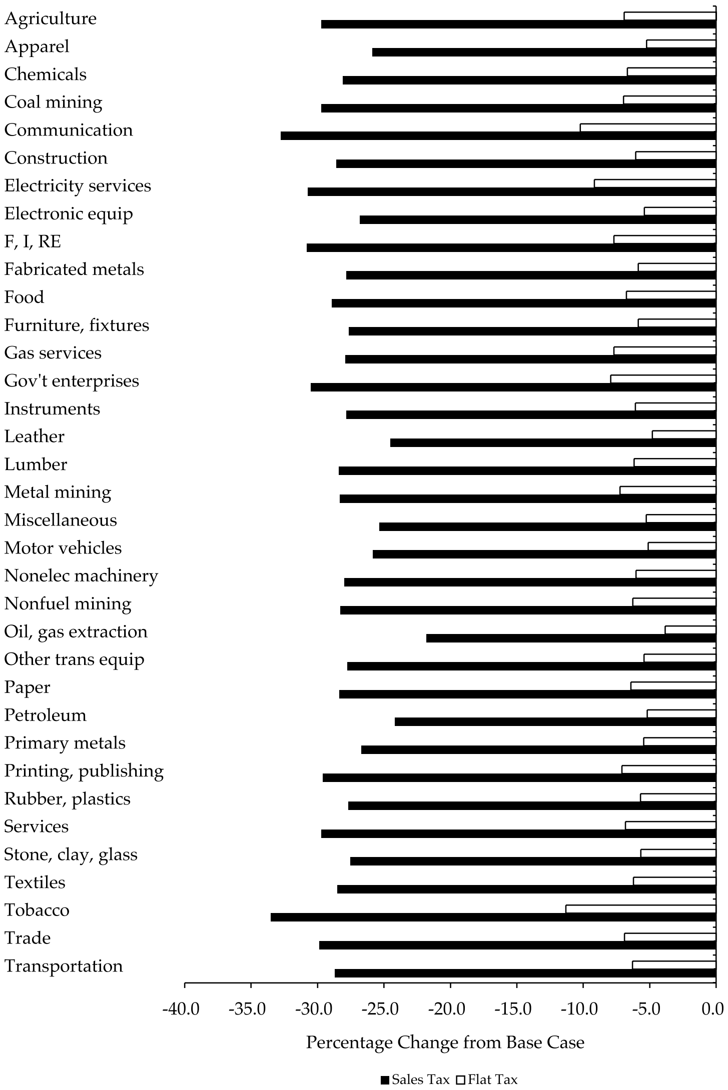

Figure 12.14
Industry prices, 2020.

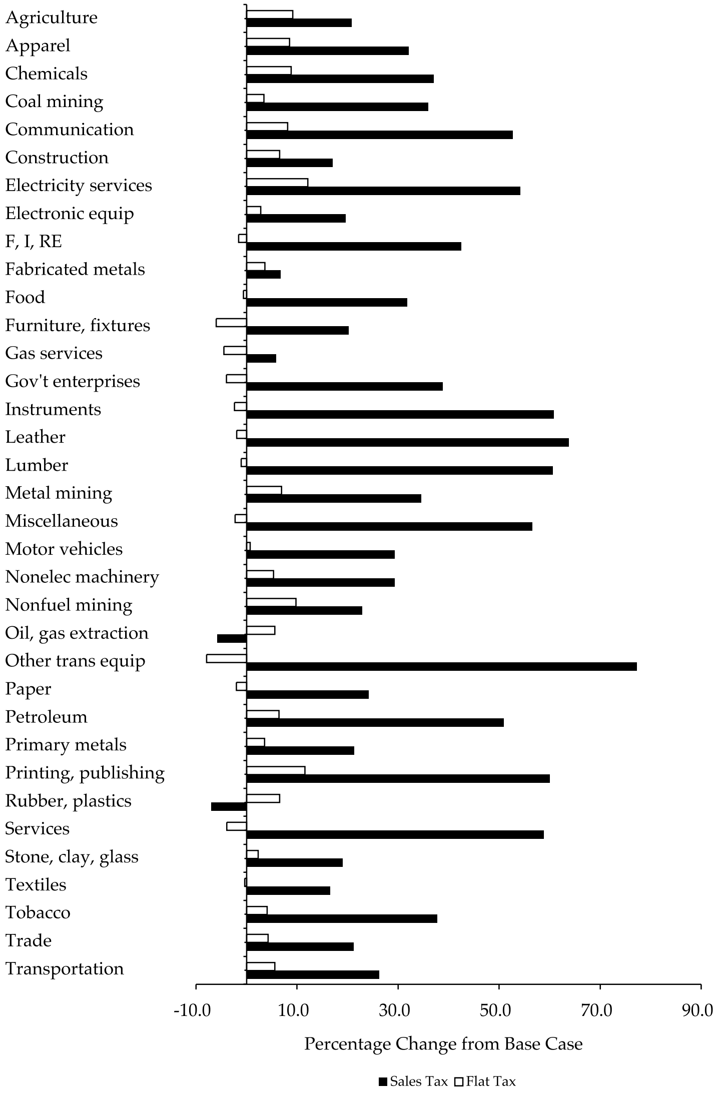

Figure 12.15
Industry outputs, 1996.

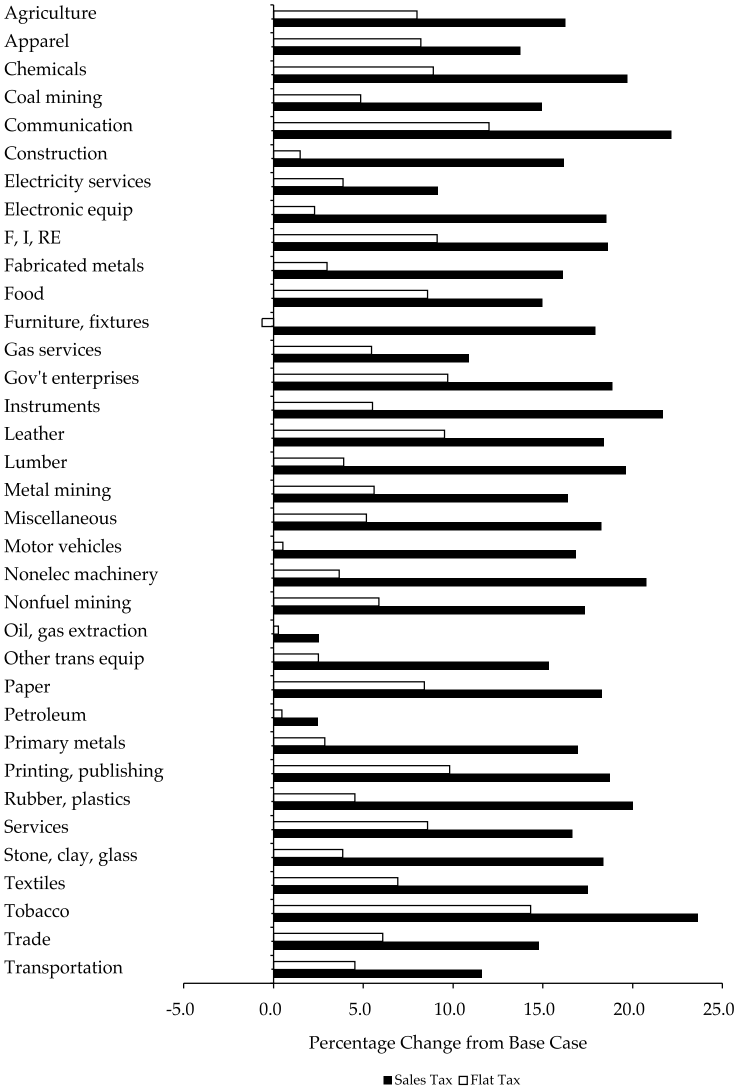

Figure 12.16
Industry outputs, 2020.

again reflecting the impact on aggregate economic activity. The Flat Tax results given in figure 12.15 for 1996 are much more modest; increases in the outputs of industries oriented toward consumption are partially offset by decreases in the outputs of industries contributing to investment. By 2020 the Flat Tax produces modest increases in almost all industrial sectors.

In summary, the Sales Tax generates a substantial acceleration in the rate of economic growth, initially through a sharp rise in labor supply since capital stock is fixed in the short run. In the longer run a higher level of economic activity is generated by a higher rate of capital formation under the Sales Tax. The Sales Tax also produces drastic changes in relative prices with a sharp fall in the price of investment goods and a much smaller decline in the price of consumption goods and services. The Flat Tax generates a very modest rise in the level of economic activity through an increase in labor supply. Under the Flat Tax investment falls initially and remains below Base Case levels.

12.4 Conclusion

We conclude that intertemporal general equilibrium modeling provides a very worthwhile addition to methodologies for analyzing the economic impact of tax reforms. The neoclassical theory of economic growth is essential for understanding the dynamic mechanisms that underlie long-term and intermediate-term impacts. The econometric implementation of this theory is critical for understanding the changes in economic behavior that would result from tax reforms. The wealth of historical experience, interpreted within an intertemporal framework, provides valuable guidance in the formulation of tax policy.

Intertemporal general equilibrium modeling provides a natural framework for economic analysis of the impact of taxes. The organizing mechanism of these models is an intertemporal price system balancing demand and supply for products and factors of production. The intertemporal price system links the prices of assets in every time period to the discounted value of future capital services. This forward-looking feature is combined with backward linkages among investment, capital stock, and capital services in modeling the dynamics of economic growth. Alternative time paths of economic growth depend on taxes through their impact on capital formation. Although the intertemporal general equilibrium approach has proved to be useful in modeling the impact of alternative tax policies, much remains to be done to exploit the full potential of this approach. As an illustration, the model of consumer behavior employed by Jorgenson and Wilcoxen (1990b) successfully dispenses with the notion of a representative consumer. An important feature of this model is that systems of individual demand functions can be recovered from the system of aggregate demand functions. The consumer preferences underlying these individual demand systems can be used to generate measures of individual welfare for evaluating the distributional consequences of changes in tax policy, as described by Jorgenson, Slesnick, and Wilcoxen (1992).

Notes

We are grateful to Richard Goettle for performing the simulations reported in this paper. This research was supported by the Alliance to Save Energy and is reported in more detail in Norland and Ninassi, Price It Right (1998). The authors retain sole responsibility for the views expressed in this paper and any remaining deficiencies.

1. Our data integrate the productivity accounts described by Jorgenson (1990b) with an accounting system based on the United Nations (1993) System of National Accounts.

2. Noncompeting imports are imported commodities that are not produced domestically.

3. Jorgenson (1986) describes the econometric approach, while Mansur and Whalley (1984) present the calibration approach.

4. The relationship between the price of investment goods and the rental price of capital services is discussed in greater detail by Jorgenson (1996).

item Our treatment of government spending differs from the U.S. national accounts in that we have assigned government enterprises to the corresponding industry wherever possible. We include the remaining purchases by the government sector in final demands by governments.

5. This approach was originated by Armington (1969). See Ho and Jorgenson (1994) for further details on our implementation of this approach.

6. The incorporation of provisions of U.S. tax law into the cost of capital is based on Jorgenson and Yun (1991b), Chapter 2. Jorgenson and Yun (1990, 1991a) have employed the results in analyzing the impact of the Tax Reform Act of 1986. The cost of capital in nine countries is compared in a volume edited by Jorgenson and Landau (1993).

7. Methods for solving intertemporal general equilibrium models are surveyed by Wilcoxen (1992).

8. See, for example, Jorgenson and Yun (1990).

9. Economists will recognize the Flat Tax proposal as a variant of the consumption-base value added tax proposed by Robert Hall and Alvin Rabushka (1995).

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Index