PRODUCTIVITY GROWTH: CURRENT RECOVERY AND LONGER-TERM TRENDS[†]

Information Technology and Growth

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The rapid diffusion of information technology (IT) is a direct consequence of the swift decline in the price of computer-related equipment, which has led to a vast and continuing substitution of IT equipment for other forms of capital and labor. This substitution generates substantial returns for the economic agents who undertake IT investments and restructure their activities in order to increase the role of IT. There is little evidence, however, that substitution is accompanied by technical change as this term is used by economists. While this appears highly paradoxical to technologists, who think of substitution of a more IT-intensive mode of production for a less IT-intensive mode as a change in technology, it is entirely consistent with the economic framework developed by Robert M. Solow (1957).

What do economists mean by ''technical change'' and how could this exclude the substitution of a more IT-intensive production process for one that is less IT-intensive? Substitution represents movement along a given production function, while technical change corresponds to a shift in the production function. Substitution takes place if the introduction of computer-intensive equipment produces benefits that are fully captured or internalized by the users of IT and their suppliers. Technical change occurs only if more output is produced from the same inputs (e.g., if some of the benefits spill over to third parties not involved in the transaction). This fundamental distinction between substitution and technical change goes back at least to Solow's seminal work and offers a simple solution to the ''Solow productivity paradox'' of rapid IT investment and slow productivity growth. (Erik Brynjolfsson and Shinkyu Yang [1996] summarize the empirical literature on the Solow paradox and Jack Triplett [1998] reviews common explanations.)

Why do economists persist in using this counterintuitive and even paradoxical terminology in describing the impact of information technology? The reasons are very transparent, at least to an economist. Substitution does not require intervention in markets, since the appropriate incentives for investment are provided by the price signals that accompany the balance between demand and supply for IT equipment. Technical change, by contrast, requires intervention, since markets fail to provide adequate incentives to undertake IT investments. Some portion of the returns spill over to the fortunate third parties who benefit from the deployment of IT without undertaking investments in IT equipment or restructuring their own economic activities.

The goal of this paper is to provide new evidence on the substitution of IT for other types of capital and labor inputs in the U.S. economy. For this purpose we extend the pioneering analysis of Stephen Oliner and Daniel Sichel (1994) and our own earlier work, reported in Jorgenson and Stiroh (1995). We focus on the massive substitution toward computers in both business and household sectors as the price of computers fell dramatically in the 1980's and 1990's. We show that, in response, profit-maximizing

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firms and utility-maximizing consumers substituted IT for other goods and services, replacing other types of equipment and economizing on the use of labor effort.

From 1990 to 1996 the acquisition price of IT equipment for investment fell 16.6 percent annually, while the price of computers for consumption fell even faster, at 24.2 percent per year. This rapid price decline cuts two ways in determining the cost of deploying IT equipment. First, a fall in prices reduces the acquisition cost of IT equipment; second, the rate of decline itself adds to the cost of using this equipment. At first blush this appears to be another paradox. How can a rapid decline in the price of a computer make it cheaper to acquire a computer, but more expensive to use it? The resolution of this apparent paradox is that the cost of using a computer is different from the cost of acquiring it. The cost of using a computer is the annualized cost over the lifetime of the equipment, while the acquisition cost is the present value of these annualized costs. The annualized cost includes the forgone opportunity of waiting for an even cheaper computer.

The large decline in the annualized cost or rental price of computers has induced both firms and households to alter their spending patterns and accumulate increasingly less expensive computers. During the 1990's, computer services to firms and households grew by 20 percent per year, exceeding the growth of other inputs by a factor of ten! These results provide persuasive evidence that firms and households respond to relative price changes by substituting IT equipment for other goods and services.

The question that remains is whether the massive substitution of IT equipment for other inputs has been accompanied by technical change in the economic sense. For this purpose, it is necessary to use the tool devised by Solow (1957), namely, the residual in economic growth, to quantify spillovers. Solow showed that these spillovers appear as residual economic growth after the growth of all other inputs, including inputs of IT equipment, are taken into account. The Solow paradox arises from the fact that this residual has slowed considerably since 1973, precisely when IT investment has risen to new heights. This has generated a kind of Computer Cargo Cult among economists and economic historians, patiently awaiting a deluge of spillovers like those that supposedly accompanied earlier technological revolutions.

To address this issue, we summarize recent evidence on technical change, using this term in its precise, if counterintuitive, economic meaning. Technical change also goes by the name of the growth of total factor productivity (TFP) or output per unit of factor input. There is little evidence for a revival of TFP growth in the 1990's. After accounting for both the quantity and the quality of capital and labor inputs, aggregate TFP growth was only 0.23 percent per year for 1990–1996. This is slightly less than the annual average for 1973–1990 of 0.34 percent. A flood of spillovers accompanying the massive deployment of IT equipment would be accompanied by an increase in TFP growth, not a decline.

We conclude that the story of the computer revolution is one of relatively swift price declines, huge investment in IT equipment, and rapid substitution of this equipment for other inputs. Perhaps surprisingly, this technological revolution has not been accompanied by technical change in the economic sense of the term, since the returns have been captured by computer producers and their customers.

I. Measuring the Sources of Growth

Our analysis of the sources of economic growth employs the Laurits Christensen and Jorgenson (1973) framework to distinguish between output of investment and consumption goods and inputs of capital and labor services. The novel contribution of our paper is to quantify the importance of IT equipment as both an input into production by firms and as a form of consumption by households. This enables us to quantify the substitution of the services of IT equipment for other inputs and to measure the growth of TFP over the period 1948–1996, beginning before the commercialization of computers and continuing through the present.

The aggregate production function describes how inputs of capital services K, consumers' durable services D, labor input L, and technology T, are used to create outputs of investment goods I, consumption goods and services C, and a flow of services from consumers' durable goods S:

$$(1) \qquad g(I, C, S) = f(K, D, L, T).$$

In this framework, consumers' durables are treated symmetrically with investment goods, since the accumulated stock of investment goods provides a flow of capital services into production, while the accumulated stock of consumers' durables provides a flow of capital services into consumption. These services appear as both an input into the aggregate production function D and an output of production S.

To isolate the impact of computers we decompose equation (1) as

$$(2) \qquad g(I_c, I_n, C_c, C_n, S_c, S_n) = f(K_c, K_n, D_c, D_n, L, T)$$

where a ''c'' subscript refers to the computer portion and a ''n'' subscript refers to the noncomputer portion. Equation (2) can be rewritten in terms of weighted averages of growth rates of inputs and outputs to obtain a growth-accounting equation. Our analysis is limited to the private, domestic economy, and we do not explicitly examine the role of computers in the government or rest-of-the-world sectors.

A. *Capital Services*

We employ the model of capital as a factor of production as summarized in Jorgenson (1996). Capital services are proportional to the stocks of assets, including computers, but aggregation requires weighting the stocks by rental prices rather than acquisition prices for assets. The rental price for each asset incorporates the rate of return, the depreciation rate, and the rate of decline in the acquisition price. The rental prices employed in our analysis of economic growth also depend on features of the tax structure for capital income that enter into the annualized cost of deploying capital. The rental price equals the marginal product of capital for a profit-maximizing firm, so that firms substitute among inputs in response to changes in rental prices. Given the large decline in the rental price of computers, the substitution of IT equipment for other inputs is an immediate implication of the model of capital as a factor of production.

The Bureau of Economic Analysis (BEA, 1998) provides detailed investment data for 35 types of producers' durable goods, 22 types of nonresidential structures, and 48 types of residential assets. The investment data include a breakdown of computer equipment into mainframe computers, personal computers, direct-access storage devices, printers, terminals, tape drives, and storage devices beginning in 1958, when computers first appear as separate entity in the National Income and Product Accounts. We combine these six components into a single ''computer'' series, which serves as our data on the output of computers as investment goods. A central feature of BEA's estimates is that price indexes for computers and peripheral equipment hold the quality of this equipment constant (see Nadia Sadee [1996] for details).

For each asset, including computers, we calculate capital stock by the perpetual-inventory method, using depreciation rates from Barbara Fraumeni (1997). This is a departure from our previous paper, where we utilized the cohort- and asset-specific retirement patterns developed by Oliner (1993) which were subsequently incorporated into the official capital stock estimates by BEA. We found little difference between a detailed approach based on Oliner (1993) and a simplified approach that uses a geometric approximation like that employed for other assets by BEA. We therefore selected a geometric depreciation rate of 31.5 percent, which is the best geometric approximation to the Oliner-based retirement profiles reported in BEA (1998). We use a similar approach in estimating rental prices for all assets that comprise our aggregate of capital services K.

B. *Services of Consumers' Durables*

Consumers purchase nondurable consumption goods and services for consumption but acquire consumers' durables in order to provide a flow of services. The treatment of consumers' durables by Christensen and Jorgenson (1973) is exactly parallel to that of capital goods. We impute the value of the services of consumers' durables on the basis of the rental-price concept employed in our estimates of the services of investment goods. Consumers maximize utility by substituting among consumption goods and services in response to price changes. The decline in rental prices of IT equipment has resulted in a massive substitution of the services of this equipment for other goods and services by households.

BEA (1998) provides data on purchases of 13 types of consumer durable goods through 1996, including ''computing equipment,'' which made its first appearance in 1979. This series serves as the measure of computer purchases in our consumption accounts. As before, we estimate stocks of IT equipment in the household sector using the perpetual-inventory method and depreciation rates from Fraumeni (1997). We employ BEA's constant-quality price index for computing equipment. The flows of consumption services from consumers' durable goods, including IT equipment, are aggregated to form an index of consumption services, D and S, using our estimates of rental prices for all types of durables.

II. Substitution Toward Computers

Production costs are minimized when marginal rates of substitution between inputs in production are equal to input price ratios. Similarly, utility is maximized when marginal rates of substitution in consumption equal price ratios of consumer goods and services. Under standard assumptions of diminishing marginal products and decreasing marginal utility, a fall in the price of an input or a consumption good will lead to substitution toward the relatively cheap input or consumption good. In adapting this framework to deal with IT equipment it is important to emphasize the fact that the appropriate prices for computer services are rental prices, which reflect the annualized cost of using the equipment.

As a consequence of the pioneering work of BEA, it is well known that the acquisition price of computers, holding quality constant, has fallen rapidly. In Table 1 we show that the price of computer investment fell 16.6 percent per year from 1990 to 1996, and the price of IT equipment to households fell 24.2 percent annually. These dramatic decreases in the acquisition prices resulted in corresponding declines in the rental prices of the services of computer capital deployed by firms (14.9 percent per year) and in the rental prices of computer services to households (23.4 percent per year) during the 1990's. By contrast the price of labor input increased 2.3 percent per year, while the price of the services of noncomputer capital to firms rose by 3.6 percent annually, and the price of noncomputer consumers' durables services to households rose at the annual rate of 2.3 percent.

TABLE 1—ANNUAL GROWTH RATES, 1990–1996

Category	Prices	Quantities
Outputs:		
Total output	2.33	2.36
Noncomputers	2.60	2.01
Computers	−18.69	30.37
Investment goods (I_c)	−16.55	28.32
Consumption goods (C_c)	−24.23	37.32
Consumers' durables services (S_c)	−23.41	31.92
Inputs:		
Capital services (K)	3.24	1.82
Noncomputers (K_n)	3.59	1.50
Computers (K_c)	−14.94	18.71
Consumers' durables services (D)	1.95	2.87
Noncomputers (D_n)	2.28	2.49
Computers (D_c)	−23.41	31.92
Labor input (L)	2.25	2.19

Note: All values are average annual percentages.

In response to the rapid changes in relative prices, firms and households substituted the services of IT equipment for other goods and services. This required substantial investment in computers, as well as restructuring of both production and consumption activities to absorb the new equipment. Investment in computers rose by 28.3 percent per year, while household purchases of computers increased even faster, at 37.3 percent per year. By 1996, U.S. businesses spent over $160 billion (in 1992 dollars) on new computers, and consumers spent an additional $52.7 billion! The rapid accumulation of IT equipment resulted in increases in flows of computer services of 18.7 percent and 31.9 percent per year in the business and household sectors, respectively.

The data we have presented in Table 1 provide persuasive evidence of massive substitution toward computers in both business and household sectors. While computer services were expanding dramatically from 1990 to 1996, the output of the U.S. economy grew at only 2.4 percent per year, and labor input increased 2.2 percent, bringing labor-productivity growth almost to a standstill. Meanwhile, the growth in computer inputs exceeded the growth in other inputs by a factor of ten! Note that we have substantially understated the impact of IT equipment, since we have focused specifically on computers and do not include closely related high-technology products. For example, much telecommunications gear is indistinguishable from IT equipment. Also, computers and semiconductors are now routinely embedded in automobiles and machinery, but we exclude these intermediate inputs from the aggregate production function.

Stiroh (1998) has extended the sectoral model of production of Jorgenson et al. (1987) to encompass computers. At the sectoral level, gross output rather than value added is the appropriate measure of output, and intermediate goods are treated symmetrically with primary inputs. It is crucial to price intermediate inputs correctly in order to measure sectoral productivity growth. Triplett (1996) shows that this is a critical issue in measuring the growth of productivity in the computer and semiconductor sectors. (See Stiroh [1998] for sectoral estimates of productivity and Robert McGuckin and Stiroh [1998] for further discussion.)

TABLE 2—SOURCES OF U.S. ECONOMIC GROWTH, 1948–1996

Source	Growth rate 1948–1973	1973–1990	1990–1996
Outputs:			
Total output	4.020	2.857	2.363
Noncomputer outputs	3.978	2.650	1.980
Computer outputs	0.042	0.207	0.384
Investment goods (I_c)	0.042	0.171	0.258
Consumption goods (C_c)	0.000	0.024	0.086
Consumers' durables services (S_c)	0.000	0.012	0.040
Inputs:			
Capital services (K)	1.073	0.954	0.632
Noncomputers (K_n)	1.049	0.845	0.510
Computers (K_c)	0.025	0.109	0.123
Consumers' durables services (D)	0.550	0.426	0.282
Noncomputers (D_n)	0.550	0.414	0.242
Computers (D_c)	0.000	0.012	0.040
Labor input (L)	1.006	1.145	1.219
Aggregate total factor productivity	1.391	0.335	0.231

Notes: Contribution of inputs and outputs are real growth rates weighted by average, nominal shares. All values are average annual percentages.

III. The Sources of U.S. Growth

In equation (2) we have combined data on investment goods, consumption goods, capital services, services of consumers' durables, and labor services in order to analyze the sources of economic growth. Growth in output is a share-weighted average of growth rates of various types of output or, equivalently, the sum of a share-weighted average of growth rates of inputs and the TFP residual. Table 2 reports estimates of the sources of growth for the U.S. private domestic economy for 1948–1996, broken into three subperiods: 1948–1973, 1973–1990, and 1990–1996. For the entire period (1948–1996), output grew 3.4 percent per year. Capital and consumers' durables services were the most important source of growth, accounting for 43 percent of the total, while labor accounted for 32 percent, and the TFP residual accounted for the remaining 25 percent. The growth of output and TFP slowed sharply after 1973, and there has been another, smaller, decline since 1990.

The growth rate of output for 1990–1996 was 2.4 percent per year, almost half a percentage point less than the average for 1973–1990 of 2.9 percent annually. By contrast, the growth rate for 1948–1973 of 4.0 percent per year was a percentage point greater. This contrast between growth rates before and after 1973 has generated a voluminous literature. The literature on the computer revolution, postulating an increase in growth rates of output and TFP that is yet to be observed, is still expanding rapidly and has not been measurably slowed by the inconsistency between the basic thesis and the facts we have presented in Table 2.

Although the TFP residual decelerated slightly in the 1990's, the picture for TFP growth is subtly different from the growth of output. Most of the slowdown in output growth after 1973 can be attributed to a collapse in TFP growth, but the smaller decline of half a percent per year in output growth after 1990 is primarily due to a decline in the growth of capital inputs. The contribution of labor-input growth actually increased, while the contributions of capital services growth in the business and household sectors fell, even with rapidly rising contributions from IT equipment services. After accounting for the quality and quantity of labor and capital inputs, only 10 percent of aggregate growth remains unexplained by substitution among inputs and must be attributed to the residual. (These TFP estimates are consistent with the estimates of the Bureau of Labor Statistics [1998], which reports that TFP growth fell from 2.1 percent per year for 1948–1973 to 0.3 percent for 1973–1990, and 0.3 percent for 1990–1996.)

We can break out the contribution of the three types of computer outputs (investment, consumption purchases, and consumers' durable services) and combine all other outputs into a single index of ''noncomputer outputs.'' The data show that computers are most important as an investment good, contributing 0.26 percentage points to growth for 1990–1996. Purchases of computing equipment by households and the service flow from this equipment contributed an additional 0.13 percentage points to growth, about half as much. Although computers contributed virtually nothing to growth prior to 1973, nearly one-sixth of the 2.4-percent output growth for 1990–1996 can be attributed to computer outputs.

Alternatively, we can express output growth as the sum of the contributions of the growth of capital services, consumers' durable services, labor inputs, and the TFP residual. The contributions of capital and consumers' durables can be decomposed into computer and noncomputer components. In the 1990's computers were responsible for nearly 20 percent of the contribution of capital inputs to growth and 14 percent of the contribution of consumers' durables services. Taken together, computer inputs contributed 0.16 percentage points to output growth of 2.4 percent per year for 1990–1996. These sources of growth are a direct consequence of substitution toward relatively cheap computers.

The resolution of the Solow paradox is that computer-related gains, large returns to the production and use of computers, and network effects are fundamentally changing the U.S. economy. However, they are not ushering in a period of faster growth of output and total factor productivity. Rather, returns to investment in IT equipment have been successfully internalized by computer producers and computer users. These economic agents are reaping extraordinary rewards for mobilizing investment resources and restructuring economic activities. The rewards are large because of the swift pace of technical change in the production of computers and the rapid deployment of IT equipment through substitution, not because of spillovers to third parties standing on the sidelines of the computer revolution.

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