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ARE ICT SPILLOVERS DRIVING THE NEW ECONOMY?

BY KEVIN J. STIROH
Federal Reserve Bank of New York

Some observers have raised the possibility that production spillovers and network effects associated with information and communications technology (ICT) are an important part of the "New Economy." Across U.S. manufacturing industries, however, ICT capital appears correlated with the acceleration of average labor productivity (ALP) growth as predicted by a standard production model, but not with total factor productivity (TFP) growth as these New Economy forces imply. Once one allows for productivity differences across industries, measured TFP growth is uncorrelated with all capital inputs, including ICT capital. This provides little evidence for a New Economy story of ICT-related spillovers or network effects driving TFP growth throughout U.S. manufacturing.

I. INTRODUCTION

The resurgence of U.S. average labor productivity (ALP) growth in the late 1990s has generated considerable attention with many studies reporting a substantial impact from both the production and the use of information and communications technology (ICT).[1] The ALP revival is also a key piece of evidence for those touting a "New Economy" in the U.S.[2] Strong ALP growth, however, easily fits within a traditional "Old Economy" framework that includes technological progress, price-induced input substitution, and capital deepening, and thus does not necessarily imply fundamentally new economic forces.

The U.S. economy also enjoyed a resurgence of measured total factor productivity (TFP) growth, however, which has received considerably less attention and is much more in the spirit of the New Economy. While some of the TFP acceleration reflects technological progress in ICT-producing industries, TFP gains appear widespread. This TFP revival opens the possibility that New Economy forces like ICT-related spillovers or network effects are contributing to economy-wide TFP growth. This would imply that standard measurement tools are failing to capture a substantial portion of the economic impact of ICT-use.

This paper examines TFP growth in U.S. manufacturing industries to address one specific question: Are measured TFP gains linked to ICT-use? Neoclassical theory predicts that ICT-use should not cause TFP growth. The rapid

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[1]For example, Bureau of Labor Statistics (BLS, 2000), the Council of Economic Advisors (CEA, 2001), Jorgenson and Stiroh (2000), and Oliner and Sichel (2000). Gordon (2000) concludes that the productivity revival primarily reflects gains in ICT-production and cyclical forces. I define ICT capital to include computer hardware, computer software, and telecommunications equipment.

[2]Stiroh (1999, 2001b) reviews the new economy literature.

decline in quality-adjusted ICT prices leads to traditional effects of investment, input substitution, and capital deepening. This "pecuniary externality" contributes directly to output and ALP growth, but not TFP growth, which is the residual output growth after one accounts for the contribution of inputs like capital and labor. ICT-related production spillovers or network effects, however, could also yield a "non-pecuniary externality" that pushes the growth contribution of ICT beyond the neoclassical baseline.[3] In this case, ICT investment would also lead to TFP growth. This paper provides a first step in the search for these types of non-traditional effects.

I begin by reviewing the U.S. productivity revival in terms of both ALP and TFP growth. I then outline the neoclassical framework and discuss five channels—production spillovers and network externalities, input measurement error, omitted variables, reverse causality, and increasing returns—that could lead to an observed correlation between ICT capital and measured TFP growth. While these factors are not always conceptually distinct, they allow for the possibility that the neoclassical framework employed in earlier studies is inappropriate for measuring the economic impact of ICT.

To search for these effects, I compare ICT capital to output, ALP, and TFP growth. If ICT capital is approximately described as a neoclassical input where returns are well measured and accrue to the investing firm, there will be a positive link with output and ALP growth, but no link with measured TFP growth. If there is something special about ICT, then one would also expect a link with measured TFP growth. To test this, I use productivity data for U.S. manufacturing industries from 1973 to 1999 to look for correlations between ICT capital intensity and TFP growth.

The data show a link between ICT capital deepening and ALP growth—U.S. manufacturing industries that invested heavily in ICT in the late 1980s and early 1990s show stronger ALP gains in the late 1990s. In terms of TFP growth, however, the relationship is weaker. After dropping the ICT-producing industries, the acceleration of TFP growth for ICT-intensive industries is larger, but not significantly different from other industries. This suggests the primary impact of ICT is through traditional capital deepening channels and provides little evidence that ICT investment also generates measured TFP growth.

A second set of results compares output and measured TFP growth to the growth in all production inputs and leads to three conclusions. First, there is substantial variation in the productive impact of different types of ICT capital. Telecommunications equipment, for example, consistently shows a *negative* coefficient in the output and TFP regressions. This could reflect large adjustment costs associated with implementing this type of capital or possibly mismeasurement of the output produced by that type of capital. Second, it is critical to account for heterogeneity across industries when analyzing ICT and productivity linkages. In particular, the two industries that produce ICT hardware and equipment show much faster productivity growth than other industries and one can draw incorrect inferences if these differences are ignored. Finally, once one

[3]OECD (2000a, 2000b), Schreyer (2000), and van Ark (2000) raise the possibility of this channel. See Griliches (1992) for a discussion of pecuniary and non-pecuniary externalities.

TABLE 1

AVERAGE PRODUCTIVITY GROWTH RATES, 1987–99

	Productivity Growth		
	1987–95	1995–99	Change
Economy aggregates			
	Average Labor Productivity		
Business sector	1.40	2.59	1.19
Nonfarm business sector	1.35	2.39	1.04
	Total Factor Productivity		
Business sector	0.56	1.26	0.70
Nonfarm business sector	0.49	1.09	0.60
Broad sectors			
	Average Labor Productivity		
Agriculture, forestry, and fishing	0.58	–0.67	–1.25
Mining	3.14	2. 50	–0.64
Construction	–0.87	–0.76	0.11
Durable goods manufacturing	3.97	6.47	2.50
Nondurable goods manufacturing	1.48	3.31	1.84
Transportation and public utilities	2.27	2.38	0.11
Wholesale trade	3.23	4.22	0.98
Retail trade	0.97	3.03	2.06
Finance, insurance, and real estate	2.33	2.88	0.54
Services	0.39	1.24	0.85

Notes: Productivity estimates for economy aggregates are from BLS (2001) and broad sectors are from Stiroh (2001a). All figures are average annual growth rates.

accounts for this heterogeneity, TFP growth appears uncorrelated with input growth, suggesting that the neoclassical view of exogenous TFP growth is approximately correct for these manufacturing industries.

These results provide little obvious evidence for a "New Economy" view of large ICT-related production spillovers or network effects that generate TFP growth. Of course, this lack of evidence does not eliminate the possibility that non-traditional ICT effects exist. Integration of computing and communications equipment is still relatively new and manufacturing industries are not the most intensive users of ICT, for example, so these effects may be found elsewhere. More evidence is needed, however, before the New Economy view of production spillovers and network effects replaces the neoclassical view of input substitution and capital deepening.

II. PRODUCTIVITY: TRENDS, DEFINITIONS, AND DATA

A. U.S. Productivity Trends

The late 1990s was a period of strong productivity growth in the U.S. economy. After a sluggish period through the 1970s, 1980s, and early 1990s, both ALP and TFP accelerated sharply in the mid-1990s. Table 1 reports average growth rates of ALP and TFP growth for 1987–95 and 1995–99 for two measures of the aggregate U.S. economy, the private business sector and the nonfarm business sector. Both show an acceleration of ALP growth slightly more than 1 percentage point and TFP growth near two-thirds of a percentage point.[4]

These aggregate data show the well-known U.S. productivity revival after 1995, but they may also hide important variation in the productivity gains across industries and sectors. For example, CEA (2001), Nordhaus (2000), and Stiroh (2001a) all report a broad productivity acceleration, but with wide variation across major sectors and industries. BLS, however, does not report productivity growth for all detailed non-manufacturing industries or sectors, so Table 1 presents estimates of ALP growth for ten broad sectors as estimated by Stiroh (2001a). This breakdown shows that eight out of ten sectors experienced accelerating labor productivity growth after 1995. There is also considerable variation across sectors, with the change in productivity growth ranging from –1.25 percentage points in Agriculture to 2.50 percentage points in Durable Goods Manufacturing.[5]

B. BLS Multifactor Productivity Database

The preceding sectoral breakdown is still quite coarse and is only available for ALP not TFP, so I turn to the BLS multifactor productivity database. The latest data are from BLS (2001) and methodological details are in BLS (1997). These data contain information on gross output, primary inputs (capital and labor), and intermediate inputs (purchased materials, energy, and business services), and are available for all private industries as a whole, manufacturing as a whole, durable manufacturing, nondurable manufacturing, and most two-digit manufacturing industries from 1948 to 1999.[6] BLS does not routinely estimate TFP growth for non-manufacturing industries or sectors.

The limited availability of detailed industry TFP estimates to manufacturing has advantages and disadvantages. Most of ICT investment is in non-manufacturing industries, particularly services, FIRE, and trade, so the biggest impact from ICT may be missed when focusing on manufacturing industries. It is generally thought that output and productivity are better measured in manufacturing, however, so output mismeasurement problems should be less of a concern with this data.

The remainder of this paper focuses on the BLS estimates of ALP and TFP growth for two-digit manufacturing industries. For these industries, ALP growth is defined as:

$$d \ln ALP = d \ln Y - d \ln H \tag{1}$$

and TFP growth is defined in the standard growth accounting fashion as:

$$d \ln Z = d \ln Y - \alpha_K d \ln K - \alpha_H d \ln H - \alpha_M d \ln M \tag{2}$$

where Z is total factor productivity, Y is output, K is capital input, H is hours worked, M is intermediate inputs, and α is the nominal input share of the

[4]The data are from BLS (2001).

[5]The data used in Stiroh (2001a) are available for all sectors only to 1987 and define ALP as real gross output per full-time equivalent employee.

[6]TFP estimates are not published by BLS for tobacco (SIC #21) and leather (SIC #31) because of the small industry size and data limitations, so I do not include them here.

subscripted variable. The modeling assumptions behind this definition are discussed in Section III.

TFP growth is often interpreted as a measure of technological progress, i.e. the ability to produce more output from the same inputs, but in reality it reflects a number of additional factors like omitted variables, increasing returns to scale, and resource reallocation. For example, the impact of any input that contributes to output growth but is not measured ends up in the TFP residual because TFP is calculated as the output growth not explained by input growth. I return to this issue in the next section.

BLS uses a gross output concept for Y for manufacturing industries that excludes transactions within the specific industry, e.g. from one textile mill to another. Output is measured in real, chain-weighted dollars.

H is simply the number of hours worked and is used in both the ALP and TFP calculation, although many economists prefer a measure of labor input in the estimation of TFP growth. Labor input growth differs from hours growth due to labor quality or compositional effects, e.g. if high-skilled workers are growing more rapidly than low-skilled workers labor input increases faster than hours. For the two-digit manufacturing industries, however, the only measure of labor input available from BLS is hours worked, so there are no labor quality/composition effects. This implies that in industries with labor quality growth, measured TFP growth will be biased upward.[7]

BLS measures capital input, K, as the flow of capital services, which is estimated as follows. For individual assets, real productive capital stocks are estimated using a perpetual inventory method with hyperbolic age/efficiency profiles for each asset. These individual productive capital stocks are aggregated into a measure of real capital input using a traditional user cost formula that accounts for price deflators, depreciation rates, and tax parameters. The value of capital income reflects the user cost and the productive capital stock.

BLS now provides details on capital services for various "information capital" assets. In particular, data on real capital input and the value of capital income are available for computer hardware, computer software, telecommunications equipment, and other office and accounting equipment, as well as an aggregate of the four components. In this paper, I define ICT to include computer hardware, computer software, and telecommunications equipment and create an index called "ICT Capital Input" using a standard Tornqvist index. All other assets, including land and inventories, are combined into "Other Capital Input." I also combine computer hardware and computer software into a single index of "Computer Capital Input." Note that this level of ICT aggregation reflects the most detailed data available from BLS.

C. Productivity Growth in U.S. Manufacturing Industries

Table 2 shows summary statistics on the size of the industry and ICT intensity of these manufacturing industries. Gross output is measured in current dollars

[7]Aggregate estimates by Jorgenson and Stiroh (2000) and Oliner and Sichel (2000) put the growth contribution of labor quality at about 0.3 percentage points per year during the late 1990s. It is not possible from this data, however, to know how that varies across industries or is correlated with ICT capital.

TABLE 2

INDUSTRY SIZE AND ICT INTENSITY FOR U.S. MANUFACTURING INDUSTRIES

Industry	SIC	Gross Output ($B)		ICT Capital Share (%)		ICT Intensive
		1984	1999	1984	1999	
Lumber and wood products	24	41.7	83.0	1.9	4.7	0
Furniture and fixtures	25	30.7	70.0	3.4	9.1	1
Stone, clay, and glass products	32	47.0	85.2	7.9	7.2	1
Primary metal industries	33	89.8	125.6	2.2	6.6	1
Fabricated metal products	34	128.9	225.2	2.8	7.3	0
Industrial machinery and equipment	35	183.5	348.2	16.1	32.4	1
Electronic and other electric equipment	36	141.4	295.3	15.3	16.6	1
Motor vehicles and equipment	37	228.3	497.5	5.0	9.6	1
Instruments and related products	38	89.6	155.6	14.7	29.3	1
Miscellaneous manufacturing industries	39	27.7	48.6	2.4	6.8	0
Food and kindred products	20	241.9	408.3	2.3	5.0	0
Tobacco products	21	na	na	2.7	4.8	0
Textile mill products	22	40.2	57.3	2.7	12.6	0
Apparel and other textile products	23	53.0	75.8	4.0	9.1	1
Paper and allied products	26	71.3	128.6	2.2	6.0	0
Printing and publishing	27	96.4	191.6	5.5	31.3	1
Chemicals and allied products	28	149.1	305.2	2.7	7.4	1
Petroleum and coal products	29	181.5	166.0	2.3	2.6	0
Rubber and miscellaneous plastics products	30	69.6	159.3	2.9	10.4	0
Leather and leather products	31	na	na	3.7	6.2	0
Mean of 20 manufacturing industries				5.1	11.3	
Median of 20 manufacturing industries				2.9	7.4	

Notes: Gross output is total value of shipments, measured in billions of current dollars and adjusted for inter-industry sales. ICT capital share is current dollar capital services for computer hardware, software, and telecommunications equipment as a percent of total capital services. ICT-intensive industries (ICT intensive = 1) are defined as those with a 1993 ICT capital share above the median for the 20 manufacturing industries. Data are from BLS.

and shows a range from $49 billion for Miscellaneous Manufacturing to $498 billion for Motor Vehicle and Equipment in 1999. In terms of ICT intensity, measured as the nominal ICT share of total capital services, manufacturing is less ICT-intensive than the economy as a whole, e.g. the average share is 11.3 percent compared to 16.5 percent for the nonfarm business sector. This reflects the rapid ICT investment in services, trade, and finance industries. The ICT capital shares also vary widely ranging from only 2.6 percent for Petroleum and Coal Products to 32.4 percent in Industrial Machinery and Equipment in 1999.

Table 3 reports average ALP and TFP growth rates for the manufacturing industries for two periods—1984–93 and 1993–99. These periods are the main comparison periods and were chosen for the following reason. Productivity is pro-cyclical and rises after recessions, so 1984 was chosen to avoid the productivity slowdown and cyclical recovery that accompanied the recessions of 1980 and 1981–82. 1993 was chosen because econometric tests point to a structural

TABLE 3

INDUSTRY CHANGES IN PRODUCTIVITY GROWTH

	ALP Growth			TFP Growth		
Industry	1984–93	1993–99	Change	1984–93	1993–99	Change
Lumber and wood products	0.15	0.15	0.00	0.24	–0.68	–0.93
Furniture and fixtures	1.54	3.13	1.59	0.33	0.68	0.36
Stone, clay, and glass products	1.54	2.42	0.88	1.27	1.13	–0.14
Primary metal industries	2.47	2.02	–0.45	1.32	0.73	–0.60
Fabricated metal products	1.34	2.06	0.72	0.20	0.59	0.40
Industrial machinery and equipment	5.23	9.62	4.39	3.13	6.10	2.96
Electronic and other electric equipment	6.38	13.57	7.20	3.52	8.08	4.56
Motor vehicles and equipment	2.57	4.58	2.01	–0.37	1.02	1.39
Instruments and related products	3.99	3.16	–0.83	1.00	0.75	–0.26
Miscellaneous manufacturing industries	0.97	1.90	0.93	–0.24	1.17	1.41
Food and kindred products	1.59	1.14	–0.44	–0.05	0.08	0.14
Tobacco products	na	na	na	na	na	na
Textile mill products	3.01	3.56	0.55	1.73	1.73	–0.01
Apparel and other textile products	2.58	6.76	4.18	–0.01	1.80	1.82
Paper and allied products	1.68	1.81	0.13	0.51	0.05	–0.46
Printing and publishing	–0.42	0.63	1.05	–1.36	–0.72	0.64
Chemicals and allied products	2.14	3.17	1.04	0.22	1.28	1.06
Petroleum and coal products	3.96	3.14	–0.82	0.52	0.49	–0.03
Rubber and miscellaneous plastics products	3.08	3.06	–0.02	1.32	1.23	–0.09
Leather and leather products	na	na	na	na	na	na
Mean of 18 manufacturing industries	2.43	3.66	1.23	0.74	1.42	0.68
Median of 18 manufacturing industries	2.30	3.10	0.80	0.42	0.88	0.25

Notes: All figures are annual average growth rates. Means and medians are of period averages. Data are from BLS.

break in the manufacturing ALP series in the third quarter of 1993.[8] For some econometric tests, I also report estimates using data that begin in 1973, the conventional starting point of the aggregate U.S. productivity slowdown.

These data show a substantial pickup in both ALP and TFP growth when 1984–93 is compared to 1993–99 that was not limited to a few industries, e.g. the median change was 0.80 percent for ALP growth and 0.25 percent for TFP growth. There is also considerable variation with several industries showing a slowdown in both ALP and TFP growth (Primary Metal Industries, and Instruments and Related Products) and others showing large pickups (Industrial Machinery and Equipment, and Electronic and Other Electric Equipment).

As a final point, it is useful to identify the two manufacturing industries that actually produce ICT equipment, Industrial Machinery and Equipment (SIC #35) and Electronic and Other Electric Equipment (SIC #36). SIC #35 includes production of computer hardware, as well as various machine tools, construction equipment, and special industry machines, while SIC #36 includes production of

[8]See Stiroh (2001a) for details.

telecommunications equipment and semiconductors, as well as electric motors, household appliances, and lighting equipment. Since the production of ICT has benefited substantially from fundamental technological gains and shows extraordinary measured productivity growth, the econometric work will be careful to see if these two industries are driving the results.

III. Productivity Effects of ICT Capital

This section describes the basic neoclassical model of production and how it has been used to quantify the impact of information and communications technology (ICT) in a traditional neoclassical framework. I then discuss alternative channels beyond the neoclassical model. ICT capital, for example, could generate a production spillover that increases productivity in another firm. Alternatively, analysts could mismeasure ICT capital or ICT capital could be correlated with omitted inputs. In any of these cases, there would be a positive correlation between ICT capital accumulation and measured TFP growth that is not predicted by the neoclassical model.[9]

A. ICT in a Neoclassical Model

The standard neoclassical model is well known and has been used extensively to evaluate the link between ICT and productivity. BLS (2000), CEA (2001), Jorgenson and Stiroh (1999, 2000), and Oliner and Sichel (2000) employ it at the macro level; Berndt and Morrison (1995), Brynjolfsson and Hitt (1995), Gera, Gu and Lee (1999), Lichtenberg (1995), Lehr and Lichtenberg (1999), McGuckin and Stiroh (2001, 2002), Steindel (1992), and Stiroh (1998, 2001a) provide results from an industry or firm perspective.

For industry analysis, I begin with a gross output production function that relates output to primary inputs (capital and labor), intermediate inputs (goods and services purchased from other industries), and TFP as:

$$Y_i = Z_i f_i(K_{i,ICT}, K_{i,O}, H_i, M_i) \tag{3}$$

where Y is real gross output, K_{ICT} is ICT-related capital, K_O is other forms of capital, H is hours worked, M is intermediate inputs, and Z is a Hicks-neutral total factor productivity index that shifts the production function, all for industry i. Time subscripts have been suppressed.[10]

Taking logs of all variables and differentiating equation (3) with respect to time gives:

$$d\ln Y = \varepsilon_{ICT} d\ln K_{ICT} + \varepsilon_O d\ln K_O + \varepsilon_H d\ln H + \varepsilon_M d\ln M + d\ln Z^T \tag{4}$$

where ε represents the output elasticity of each input and $d\ln Z^T$ is *true* TFP growth. Note that constant returns to scale is not imposed here.

Solow (1957) showed how the neoclassical assumptions of competitive input markets (each input is paid its marginal product) and input exhaustion (all

[9]A negative correlation is also possible, perhaps due to adjustment costs as suggested by Kiley (1990, 2000).

[10]This simple representation ignores utilization issues, adjustment costs, and labor quality effects. Basu *et al.* (2000) present a more developed production function.

revenue is paid to factors) lead to the equilibrium condition that an input's factor share (α) equals its output elasticity (ε).[11] For example, for ICT capital:

$$\varepsilon_{ICT} \equiv \frac{\partial Y}{\partial K_{ICT}} \frac{K_{ICT}}{Y} = \frac{P_{K,ICT} K_{ICT}}{Y} \equiv \alpha_{ICT} \tag{5}$$

where $P_{K,ICT}$ is the rental price of ICT capital and output prices have been normalized to one.

In the case of ICT, particularly computer hardware, rapid technological progress in ICT-production gives rise to a "pecuniary externality" in the form of rapidly falling ICT prices. This provides strong incentives for firms to invest in ICT. In addition, ICT rental prices are dominated by rapid depreciation and capital losses, which raise the rental cost of ICT relative to other assets and raises the ICT input share. Thus, ICT capital must have large marginal products to cover the high rental prices.[12]

An important point about this framework is that there is no special role for ICT capital. Economists have long recognized that technological advance differs across industries, which can lead to relative price changes, and that firms substitute between production inputs in response to these changes. Rapid accumulation of ICT equipment can be explained as the profit-maximizing response to falling prices and high marginal products for ICT equipment.

The neoclassical assumptions in equation (5) hold for all inputs and justify the well-known growth accounting approach.[13] The key insight there is that an input's elasticity is not directly observable, but the neoclassical assumptions allow one to use factor shares as proxies. While it is not always easy to estimate factor shares, particularly for capital, TFP growth can be estimated by approximating equation (4) as:

$$d\ln Y = \alpha_{ICT} d\ln K_{ICT} + \alpha_O d\ln K_O + \alpha_H d\ln H + \alpha_M d\ln M + d\ln Z^M \tag{6}$$

where the α's represent observed factor shares of the subscripted input, the neoclassical assumptions imply $\alpha_{ICT} + \alpha_O + \alpha_H + \alpha_M = 1$, and $d\ln Z^M$ is *measured* TFP growth and calculated under the neoclassical assumptions as a residual.[14]

Under the same assumptions, one can rewrite equation (6) in terms of per hour variables:

$$d\ln ALP = d\ln y = \alpha_{ICT} d\ln k_{ICT} + \alpha_O d\ln k_O + \alpha_M d\ln m + d\ln Z^M \tag{7}$$

where lower-case variables are per hour worked.[15]

Equations (6) and (7) can be implemented either as a growth accounting equation (where $d\ln Z^M$ is calculated as a residual to satisfy the equality) or as an estimating equation (where $d\ln Z^M$ is estimated econometrically) which shows

[11] These two assumptions essentially impose constant returns to scale and no profits.

[12] See Jorgenson and Stiroh (1999) for a discussion.

[13] See CEA (2001), Jorgenson and Stiroh (2000), and Oliner and Sichel (2000) for recent examples.

[14] See Diewert (2000) for a broad survey of the difficulties involved in estimating TFP growth this way.

[15] This ignores the labor quality/composition effects described in Jorgenson and Stiroh (2000). This is done here for simplicity and because the BLS data do not include compositional effects at the industry level.

the direct link between ICT capital and output or labor productivity growth. Firms or industries that invest heavily in ICT capital will see ICT capital growing faster than labor hours ($d\ln k_{ICT} > 0$). This leads directly to a link with ALP growth that is proportional to ICT's observed input share; this is often called the "ALP contribution of ICT capital."

In this framework, there is no direct impact on TFP growth from ICT capital deepening. TFP growth, by definition, is the output growth that is *not* explained by input growth, so any output contribution associated with ICT investment is attributed to ICT capital deepening and not TFP. As pointed out by Baily and Gordon (1988, p. 382) "there is no shift in the user firm's production function" and thus no TFP growth from the use of ICT.[16]

B. Non-Traditional Effects of ICT

This section considers the relationship between ICT capital and TFP growth in a world where the neoclassical assumptions do not hold. If the neoclassical assumptions fail, then equations (6) and (7) may be poor approximations to the true productivity relationships.[17] This failure could reflect production spillovers, omitted variables, embodied technological progress, measurement error or reverse causality, all of which could lead to a positive link between TFP growth and ICT intensity.

Without getting into potential explanations for now, consider what happens if the elasticity of ICT exceeds ICT's measured input share, $\varepsilon_{ICT} > \alpha_{ICT}$. In this case, measured TFP growth (equation (6)) will be a biased estimate of true TFP growth (equation (4)). If this is the only error, it implies a direct relationship between ICT capital and measured TFP growth. For example, if $\varepsilon_{ICT} = \alpha_{ICT} + w$, where w is a wedge between the unobserved elasticity and the observed factor share:

(8) $$d\ln Z^M = d\ln Z^T + wd\ln K_{ICT}$$

Equation (8) shows that if the elasticity exceeds the factor share for ICT, then conventionally measured TFP growth will be positively correlated with ICT capital. Thus, failures of the neoclassical framework provide a potential link between ICT capital deepening and measured TFP growth. I now consider various explanations for this type of link.

Production Spillovers and Network Externalities

The idea that investment might generate external productivity effects goes back at least to the "learning-by-doing" model of Arrow (1962), which includes productivity-enhancing experience as a function of the cumulative capital stock. Similarly, DeLong and Summers (1991, 1992, 1993) conclude the social return to equipment exceeds the private return, implying productivity externalities, perhaps

[16]See Stiroh (1998), Jorgenson and Stiroh (1999), and Bosworth and Triplett (2000) for more on this point.

[17]Hall (1988, 1990), for example, argued that imperfect competition was a better description of U.S. industries and relaxed these assumptions. More recently, Basu and Fernald (1995, 1997) have shown how the presence of imperfect competition generates misleading inferences about returns to scale.

through production process efficiency gains, reverse engineering, or organization learning accompanying investment in new equipment.[18] Wolff (1991) reports a statistical link between growth in the capital/labor ratio and TFP growth for seven countries from 1870 to 1979, which he attributes to embodied technical progress, investment-led organizational change, learning-by-doing, technology-induced capital accumulation, and positive feedback effects.[19]

In the specific context of ICT, OECD (2000a, 2000b) discuss potential production spillovers and network effects. For example, OECD (2000a) argues that the emergence of the Internet in the mid-1990s greatly expanded the effectiveness of ICT and may lead to TFP growth. Similarly, OECD (2000b) suggests that improved business-to-business communications, facilitated by ICT, reflect new organizations of production and sales. At a more micro level, Gandal (1994) found evidence that computer spreadsheet users benefit from network externalities as firms gain from the ability to transfer information between users. Similarly, Brynjolfsson and Kemerer (1996) reported potential network effects in software, where the value to a user may rise due to network externalities from a community of users. Thus, one firm's ICT investment could increase the productivity of others, a classic spillover effect that would raise measured TFP growth. Alternatively, the marginal product of capital could exceed the marginal cost as firms receive benefits beyond what the market forces them to pay. van Ark (2000) raises this possibility in the context of ICT.

These types of "non-pecuniary externalities" in the form of production spillovers and network effects could lead the elasticity of ICT to exceed its measured input share and thus generate a correlation between ICT and measured TFP growth. Evidence, however, has been mixed. Griliches and Siegel (1991) find a correlation between computer investment and TFP growth for four-digit U.S. manufacturing industries, while Stiroh (1998) reports no evidence of a correlation between growth in computer hardware and TFP in U.S. industries. In a cross-section of U.S. firms, Brynjolfsson and Hitt (2000a) find that the computers' contribution equals its share in short differences but greatly exceeds it in longer differences. Schreyer (2000) reports little obvious evidence for a link between ICT capital and TFP growth for the G7 countries, although his data end in 1996 and he does not present a rigorous statistical analysis. OECD (2000b) concludes that the available data do not allow clear tests for spillover effects in ICT-using sectors.

Measurement Errors

An alternative explanation is that ICT capital is simply not well measured. At least since Jorgenson and Griliches (1967), economists have known that mismeasured inputs lead directly to mismeasured TFP growth; if input growth is

[18]The DeLong and Summers results have received scrutiny, e.g. Abel (1992), Auerbach *et al.* (1994), and Mankiw (1995) discuss the results.

[19]It is not clear, however, that this is the type of production spillover that the New Economy proponents have in mind. In the learning-by-doing case, aggregate investment raises the productivity of all firms as the stock of knowledge increases, while the DeLong and Summers result are about production externalities where returns to investment spillover to others. Nonetheless, one could argue that there are spillovers between firms within the same industry, so that one might expect a correlation between industry ICT investment and TFP growth.

understated (overstated), measured TFP growth is overstated (understated). This insight has led to considerable effort to correctly measure production inputs and yield better estimates of TFP growth.

In the case of ICT capital, these measurement problems may be particularly difficult, although the direction of the bias is not clear. ICT capital has experienced enormous quality improvements over time, which are accounted for by quality-adjusted price indexes that translate better quality into more quality-adjusted units. The U.S. statistical agencies have expended considerable resources on getting these prices right, but the possibility of systematic error remains. For example, only a small part of software and telecommunication equipment is currently deflated with constant-quality deflators, which suggests a potential understatement of ICT capital and overstatement of TFP growth. Alternatively, the rapid increase in computing power implied by the hedonic deflators may overstate the amount of computing power actually used, e.g. the large increases in measured capacity could be largely unutilized. Thus, ICT hardware could be overstated and TFP understated.

Potential measurement error also clouds the interpretation of production spillovers. In the context of research and development spillovers, Griliches (1995, p. 66) cautions that much of claimed production spillovers in the research and development literature are "not real knowledge spillovers. They are just consequences of conventional measurement problems." The same caveat applies to ICT spillovers, and it seems very difficult to disentangle production spillovers from measurement error.

Finally, there are also potential output measurement problems because the most intensive users of ICT in the U.S. are the services and finance, insurance, and real estate industries (Stiroh, 1998; Triplett, 1999) where output is very hard to measure. For example, the increased convenience and greater accessibility of banking services due to ICT-driven ATM networks might not be fully captured in the output statistics. This type of measurement problem could obscure the contribution from ICT. Dean (1999) provides a detailed discussion of output measurement problems and Diewert and Fox (1999) discus issues related to ICT.

Omitted Variables

A third potential failure of the neoclassical model is omitted variables, which is a specific type of measurement error. In the standard methodology for estimating TFP growth, the productive impact of any excluded input ends up in the measured TFP residual and moves it further from true TFP growth. In the context of ICT, anything that raises productivity, is correlated with ICT-use, and is not measured by the analyst leads to a correlation between measured TFP growth and ICT.

Brynjolfsson and Hitt (2000b, p. 33) conclude that firm-level studies typically find ICT elasticities above input shares because "they neglect the role of unmeasured complementary investments." The excess returns to ICT that were found in some studies, e.g. Brynjolfsson and Hitt (1995), Lichtenberg (1995), and Lehr and Lichtenberg (1999), could reflect returns to omitted inputs.

Examples of this type of omitted variable include organizational change, workplace practices, human capital accumulation and labor quality effects, or research and development efforts. As examples of organizational change, Brynjolfsson and Hitt (2000b) discuss the impact of reduced communications costs, more flexible jobs, outsourcing, concurrent reengineering, and just-in-time inventory control. Bresnahan, Brynjolfsson, and Hitt (1999) point to skill upgrades, education, and increased worker autonomy as factors that interact to raise the value of ICT. In a survey of U.S. establishments, Black and Lynch (2001) find productivity gains associated with a host of workplace practices such as profit-sharing plans and employee voice in decision-making.[20]

If these factors are correlated with ICT investment but unmeasured in the industry-level data, then one could find a correlation between ICT and measured TFP growth. For example, the BLS data used here do not capture labor quality effects. If these labor composition effects are correlated with ICT investment, this would lead to a link between ICT and measured TFP growth.

Reverse Causality

The standard neoclassical model assumes that TFP growth is an exogenous force that shifts the production function. Hulten (1979), however, has pointed out that much of observed capital accumulation is induced by TFP growth, while real business cycle models routinely allow productivity shocks to affect input accumulation. A similar point has been made in the econometrics literature where the endogeneity of input choices is well known. That is, firms respond to productivity shocks by increasing inputs when marginal products rise. This reverse causality story could lead to a correlation between input accumulation and TFP growth.[21] In principle, one can correct for this problem with instrumental variable techniques or by comparing TFP growth to lagged ICT intensity. While it is difficult to obtain valid instruments, this is a practical, not a conceptual concern. Moreover, a link from TFP growth to ICT capital does not seem to be what the New Economy believers have in mind regarding potential links. Rather, the discussions of ICT spillovers argue that the causality runs from ICT capital to measured TFP growth.

Increasing Returns and Imperfect Competition

Finally, measured TFP growth is typically estimated under the maintained assumptions of constant returns to scale and perfect competition. Building on the work of Hall (1988, 1990), Basu and Fernald (1995, 1997) have shown that allowing for non-constant returns and mark-ups (as in the case of imperfect competition) is important. For example, if mark-ups exist so price exceeds marginal cost, elasticities will typically exceed revenue shares so measured TFP growth will be too high because the estimated contribution of inputs is too low. In principle, this could lead to a correlation between ICT and measured TFP growth, but this is not necessarily an ICT issue and would affect all inputs.

[20]One can debate whether things like organizational change or skill upgrading should be measured as inputs or left in the TFP residual. I take the view that if something is measurable and earns a return, e.g. consulting fees for firm reengineering or higher wages for skills, then it is best viewed as an input and not TFP.

[21]See Griliches and Mairesse (1998) for an econometric discussion.

C. Discussion of the Competing Views

There is evidence for some type of failure of the neoclassical model, e.g. papers surveyed by Brynjolfsson and Hitt (2000b) find excess returns, omitted variables, or a correlation between TFP and ICT growth at the firm level. The next issue is whether the potential explanations discussed above are indeed fundamentally different from each other, and whether they can be sorted out empirically. It seems that both practical and conceptual arguments point to broadly defined measurement error—including mismeasured inputs and omitted variables—as the most likely explanation.

ICT capital goods are experiencing enormous quality improvements, which makes it quite difficult to measure them on an accurate and consistent basis. While the U.S. statistical agencies have incorporated hedonic, matched model, and other statistical methods to capture these quality changes, it remains unclear how accurate these are. In addition, many of the micro factors that have been found to be important, e.g. organizational change or workplace practices, are quite difficult to measure at the industry-level and thus may introduce an omitted variable bias. Finally, the most intensive users of ICT are in services and finance-related industries, where output is notoriously hard to measure.

Moreover, it is unclear conceptually what production spillovers really are. Of the five factors discussed by Wolff (1991) to explain the aggregate capital deepening/TFP link, only learning-by-doing and positive feedback effects seem to be true production spillovers. Investment-led organizational changes suggest an omitted input; technology-induced capital accumulation explains the correlation but has the causality reversed; and embodied technical change can be thought of as a type of measurement error.[22] As Griliches (1992, 1995) argued in the context of R&D spillovers, it is very difficult to differentiate measurement errors from true productivity spillovers. Sorting out these explanations is an important task, but this paper only takes the first step and searches for empirical links between ICT capital accumulation and output growth or measured TFP growth.

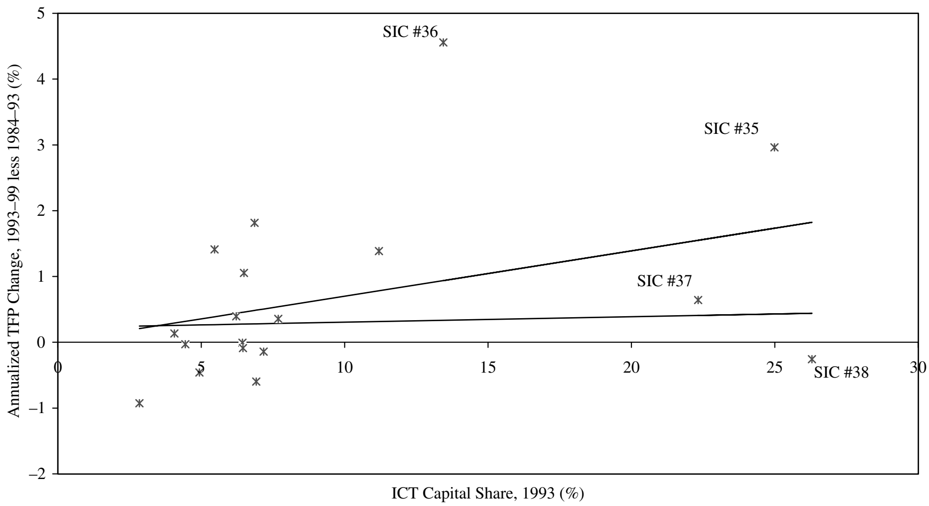
IV. Empirical Results

The econometric work consists of two approaches. The first uses a difference in difference estimator to compare the relative ALP and TFP gains for ICT-intensive industries to other industries. This follows McGuckin and Stiroh (1998, 2001) and Stiroh (2001a). The second estimates a standard production function that compares input growth to output growth and similar equations that use measured TFP as the dependent variable. A correlation between ICT capital and TFP growth would be consistent with the existence of New Economy forces like spillovers or network effects, but it is obviously not sufficient due to other potential explanations discussed above.

A. Difference in Difference Results

Before moving to the difference in difference results, it is useful to examine a plot of TFP acceleration and ICT intensity. Figure 1 compares the acceleration

[22] If hedonic deflators accurately captured all characteristics of an investment good, all vintages would be measured in equivalent, constant-quality efficiency units and embodiment would not exist.



Note: Steep line is fitted values from an OLS regression using all 18 industries. Flat line is fitted values from an OLS regression excluding SIC #35 and #36. See Footnote #24 in text for details.

Figure 1. TFP Acceleration vs. ICT Intensity for U.S. Manufacturing Industries

of TFP growth from 1984–93 to 1993–99 to 1993 ICT capital intensity, measured as the nominal share of ICT capital income in total capital income. Using all industries, there is a strong positive relationship (the steep line). The two ICT-producing industries (SIC #35 and #36) are productivity outliers and when they are excluded, there is no relationship (the flat line). If the two industries with high ICT capital shares but little TFP acceleration, Instruments (SIC #38) and Printing and Publishing (SIC #37), are also excluded, there is some positive relationship. Overall, this does not suggest a robust and pervasive link.[23]

A more formal way to get at this is with a difference in difference regression:

$$X_{i,t} = \alpha + \beta D + \gamma I + \delta D \cdot I + \varepsilon_{i,t},$$
$$\text{(9)} \qquad \text{D} = 1 \text{ if } t \geq 1994,\ D = 0 \text{ otherwise}$$
$$I = 1 \text{ if } ICT - \text{intensive},\ C = 0 \text{ otherwise}$$

where α is the mean growth rate for non ICT-intensive industries in the period prior to 1994, $\alpha + \gamma$ is the mean growth rate for ICT-intensive industries prior to 1994, β is the acceleration for non-ICT intensive industries, $\beta + \delta$ is the acceleration for ICT-intensive industries, and δ is the differential acceleration of ICT-intensive industries relative to others.[24] $X_{i,t}$, the dependent variable, is the annual growth rate of either ALP or TFP.

[23]The lines are fitted values from an OLS regression of TFP acceleration on 1993 ICT intensity and a constant. The slope is 0.069 (p-value = 0.13, $R^2 = 0.13$) when all 18 industries are used and the slope is 0.008 (p-value = 0.80, $R^2 = 0.01$) when SIC #35 and #36 are excluded. When the two other outlier industries, Printing and Publishing and Instruments, are also excluded the slope is 0.212 (p-value = 0.063, $R^2 = 0.26$).

[24]It is important to look at relative TFP growth in order to control for common shocks that affect measured TFP growth for all industries, i.e. it is well known that both ALP and TFP are procyclical, so one must worry about business cycle effects.

The regression in equation (9) addresses a specific question: do ICT-intensive industries, on average, show a larger ALP and TFP acceleration than other industries? In a traditional neoclassical world, one would expect ICT to contribute to ALP growth, but not necessarily to TFP growth. If the neoclassical model fails for any of the reasons described above, however, then there may also be a correlation with TFP growth. Comparing the results from the ALP and TFP regressions gives some insight on the importance of these alternative effects.

I define an ICT-intensive industry as one with an above median value share of ICT capital services in total capital services in 1993 for the 20 manufacturing industries; Table 1 identifies these industries. It is important to define the ICT indicator prior to the acceleration period in order to reduce simultaneity bias from demand or productivity shocks that could induce ICT investment. That is, by defining ICT intensity in 1993 and looking at the acceleration of TFP growth after 1993, one can minimize the possible reverse causality arguments that TFP shocks induced ICT investment. If industries were expecting future demand increases and productivity gains, however, this timing convention will be an imperfect control.

Table 4 reports results; the top panel for the period 1984–99 and the bottom panel for 1973–99.[25] The first column reports results for the ALP regression with all 18 industries and shows that the productivity acceleration was 2.0 percentage points faster for ICT-intensive industries when 1993–99 is compared to 1984–93 and 2.4 percentage points when 1993–99 is compared to 1973–93.

As shown in Figure 1, the ICT-producing industries (SIC #35 and SIC #36) are quite different and the second column drops these two industries. The results still show a sizable differential in ALP accelerations of 1.1 and 1.3 percentage points that are significant at the 10 percent level. This result is weaker statistically, but increased ALP growth of over 1 percentage point is economically large.

The next two columns report estimates of similar regressions, but now with measured TFP growth as the dependent variable. If ICT spillovers, network effects, or measurement error are important, one would expect to see a positive estimate of δ in equation (9). When all manufacturing industries are included, the data show a large and significant difference in the acceleration of TFP growth for the ICT-intensive industries, 1.1 percentage point in the top panel and 1.4 in the bottom. Once the ICT-producing industries are dropped, however, the size of the coefficient drops substantially and it is no longer statistically significant. Combining the time dummy coefficient and the interaction term shows that the ICT-intensive industries do show a significant acceleration of TFP growth, but it is not significantly different from the other industries.

These results indicate a relatively large acceleration in ALP growth for the ICT-intensive industries, but there is less evidence of relative gains in TFP growth. There does seem to have been a difference in the acceleration of TFP for the ICT-intensive industries in the late 1990s, but the data cannot reject the null hypothesis that the ICT intensive industries show the same TFP gains as other industries. While this is a relatively tough test that asks a lot of the available data, the

[25]Standard errors are corrected for heteroskedasticity and are corrected to allow correlations of residuals over time for each industry. This clustering correction increases the standard errors.

TABLE 4

DIFFERENCE IN DIFFERENCE ESTIMATES OF ALP AND TFP GROWTH

	ALP Growth		TFP Growth	
	All Industries	Exclude ICT-Producing	All Industries	Exclude ICT-Producing
1984–93 vs. 1993–99				
Constant	1.970***	1.970***	0.528**	0.528**
	(0.433)	(0.435)	(0.232)	(0.232)
ICT dummy	0.832	0.081	0.377	–0.228
	(0.745)	(0.614)	(0.523)	(0.390)
Time dummy	0.133	0.133	0.054	0.054
	(0.201)	(0.202)	(0.232)	(0.233)
Time dummy *ICT dummy	1.972**	1.051*	1.124*	0.479
	(0.791)	(0.568)	(0.548)	(0.373)
Time dummy + time dummy *ICT dummy	2.105**	1.184**	1.178**	0.532*
	(0.764)	(0.530)	(0.496)	(0.292)
R^2	0.10	0.03	0.06	0.01
No. of obs.	270	240	270	240
1973–93 vs. 1993–99				
Constant	1.969***	1.969***	0.495	0.495
	(0.309)	(0.310)	(0.297)	(0.299)
ICT dummy	0.450	–0.126	0.077	–0.348
	(0.588)	(0.509)	(0.454)	(0.389)
Time dummy	0.134	0.134	0.087	0.087
	(0.363)	(0.365)	(0.327)	(0.328)
Time dummy *ICT dummy	2.354**	1.258*	1.425**	0.598
	(0.933)	(0.645)	(0.670)	(0.409)
Time dummy + time dummy *ICT dummy	2.488**	1.392**	1.511**	0.685**
	(0.860)	(0.532)	(0.585)	(0.244)
R^2	0.06	0.02	0.04	0.00
No. of obs.	468	416	468	416

Notes: All estimates are ordinary least squares. Robust standard errors in parentheses are corrected to allow for correlation in residuals over time for each industry. ICT dummy = 1 if 1993 ICT capital share is above the median; ICT dummy = 0 otherwise. Industries breakdown is shown in Table 2. Time dummy = 1 if year > 1993; Time dummy = 0 otherwise. ICT-producing industries are SIC #35 and #36.

results seem broadly consistent with the neoclassical model. Two caveats deserve mention, however. First, this specification is relatively restrictive and puts all of the explanatory burden on a single ICT capital share; the next section addresses this issue. Second, due to data limitations, this analysis is restricted to manufacturing industries, which are not as ICT-intensive as many services, trade, and finance industries. Nonetheless, these results provide little obvious evidence that ICT capital intensity is correlated with TFP gains.

B. Production Function Style Regressions

This section extends the earlier results by examining the link between output and ICT capital and between TFP and ICT capital. I begin with a production function regression that decomposes capital into ICT and other capital and then further decomposes ICT into computers (hardware and software) and telecommunications equipment components.[26] As above, I then use the same explanatory variables in a regression with TFP as the dependent variable to search for evidence of non-traditional effects.

As is standard, I begin with a Cobb–Douglas form for equation (3):

$$Y_{i,t} = A_i e^{f(t)} K_{ICT,i,t}^{\beta_{ICT}} K_{N,i,t}^{\beta_N} H_{i,t}^{\beta_H} M_{i,t}^{\beta_M} e^{\varepsilon_{i,t}} \tag{10}$$

where A_i is an industry-specific productivity level effect that grows according to a common path $f(t)$, β is the elasticity of the subscripted variable, and $\varepsilon_{i,t}$ are serially uncorrelated random errors for each industry.

This implies a standard form for a production function regression:

$$\begin{aligned} \ln Y_{i,t} = {} & \beta_{ICT} \ln K_{ICT,i,t} + \beta_N \ln K_{N,i,t} \\ & + \beta_H \ln H_{i,t} + \beta_M \ln M_{i,t} + f(t) + \mu_i + \varepsilon_{i,t} \end{aligned} \tag{11}$$

where μ_i are a set of industry-specific effects.

To remove the industry-specific effect, first-difference equation (11) and estimate the following regression:

$$\begin{aligned} d\ln Y_{i,t} = {} & \beta_{ICT} d\ln K_{ICT,i,t} \\ & + \beta_N d\ln K_{N,i,t} + \beta_H d\ln H_{i,t} + \beta_M d\ln M_{i,t} + \lambda_t + \nu_{i,t} \end{aligned} \tag{12}$$

where λ_t are year dummy variables to capture common shocks and $\nu_{i,t}$ is the differenced residual.

If one believes that input choices are made prior to the realization of the productivity shocks, then equation (12) can be estimated by ordinary least squares (OLS). It is more reasonable, however, to assume that input choices are correlated with productivity shocks so that one would want to use an instrumental variable (IV) approach. Since IV estimates can be quite dependent on the instrument set, I report both OLS and IV estimates, where the instrument set includes one and two period lags of all independent variables and time dummy variables.[27]

The top panel of Table 5 reports estimates of equation (12) for a panel of 18 industries for 1984–99. The OLS and IV results in Columns 1 and 3 show a surprising result that ICT capital has a negative and significant coefficient. Hours and intermediate inputs are near their factor shares in the OLS regression, as implied by the production function model, and the other capital coefficient is perhaps too large. The data cannot reject constant returns to scale, i.e. sum of coefficients equals one.

Taken literally, the negative ICT coefficient implies that ICT capital is unproductive, which is quite surprising and warrants further attention. Moreover, these results counter other recent studies that typically found a positive link, e.g. the

[26]Computer hardware is not broken out from software because they are very highly correlated across industries.

[27]See Griliches and Mairesse (1998) for details on this identification issue. An alternative instrument set that consisted of demand variables from Basu *et al.* (2000) produced unreliable estimates and are not reported. An alternative approach based on Arellano and Bond (1991) gave results similar to those reported, although they were quite sensitive to the choice of instrument lag structure and are thus not reported.

TABLE 5

PRODUCTION FUNCTION AND TFP REGRESSIONS, 1984–99

	OLS		IV		ICT-Producing Dummy	Fixed Effects
Output as dependent variable						
ICT capital	–0.070**		–0.086*			
	(0.033)		(0.041)			
Computer capital		–0.022		–0.071**	–0.002	–0.003
		(0.018)		(0.029)	(0.024)	(0.012)
Telecomm capital		–0.204***		–0.242***	–0.059	–0.036
		(0.041)		(0.065)	(0.038)	(0.040)
Other capital	0.518***	0.531***	0.582**	0.918***	0.269***	0.149***
	(0.179)	(0.112)	(0.207)	(0.184)	(0.066)	(0.053)
Hours	0.196**	0.297***	–0.055	0.339	0.273***	0.303***
	(0.074)	(0.065)	(0.168)	(0.237)	(0.054)	(0.074)
Intermediate inputs	0.481***	0.431***	0.758***	0.191	0.420***	0.354***
	(0.073)	(0.062)	(0.240)	(0.377)	(0.057)	(0.056)
ICT-producing dummy					3.610***	
					(0.368)	
Sum of coefficients	1.125	1.032	1.198	1.135	0.902	0.767
	(0.167)	(0.107)	(0.232)	(0.142)	(0.081)	(0.081)
TFP as dependent variable						
ICT capital	–0.070*		–0.086*			
	(0.038)		(0.043)			
Computer capital		–0.018		–0.067*	0.003	–0.007
		(0.020)		(0.036)	(0.025)	(0.019)
Telecomm capital		–0.216***		–0.271***	–0.064	–0.033
		(0.042)		(0.077)	(0.040)	(0.036)
Other capital	0.405**	0.415***	0.470**	0.836***	0.141*	0.058
	(0.182)	(0.108)	(0.210)	(0.216)	(0.075)	(0.093)
Hours	–0.130	–0.024	–0.344	0.098	–0.048	–0.011
	(0.087)	(0.075)	(0.207)	(0.322)	(0.063)	(0.056)
Intermediate inputs	–0.051	–0.104	0.187	–0.441	–0.116	–0.201***
	(0.088)	(0.075)	(0.278)	(0.466)	(0.068)	
ICT-producing dummy					3.789***	
					(0.459)	

Notes: All regressions include 270 observations (15 years for 18 industries), use first differences of log-levels, and include year dummy variables. Robust standard errors in parentheses are corrected to allow for correlation in residuals over time for each industry. OLS is ordinary least squares. IV are instrumental variable estimates using 1-period and 2-period lags of the independent variables and year dummy variables as the instruments. ICT-producing dummy equals 1 for SIC #35 and #36; and zero otherwise. Regressions with ICT-producing dummy are estimated with OLS. Fixed effects includes industry-specific dummy variables.

papers surveyed by Brynjolfsson and Hitt (2000b), and results in Lehr and Lictenberg (1999), Licht and Moch (1999), McGuckin and Stiroh (2002), and Stiroh (2001a). This could reflect the focus on manufacturing industries or this broader definition of ICT that includes software and telecommunications equipment, which were typically not included in earlier studies. Alternatively, this could reflect some type of adjustment cost that temporarily limits the effectiveness of ICT capital, as in Kiley (1999, 2000).

One way to better understand this surprising result is to further decompose ICT capital into computers (hardware and software) and telecommunications equipment components. This regression is reported in columns 2 (OLS) and 4 (IV), and shows a large negative coefficient on telecommunications equipment and a smaller, insignificant coefficient on computers. Large variation in the effect of different types of ICT is consistent with the results in Lehr and Lichtenberg

(1999) and Licht and Moch (1999). Thus, it appears telecommunications capital is the largest drag, which may explain the difference from earlier studies that typically focused on computer hardware.

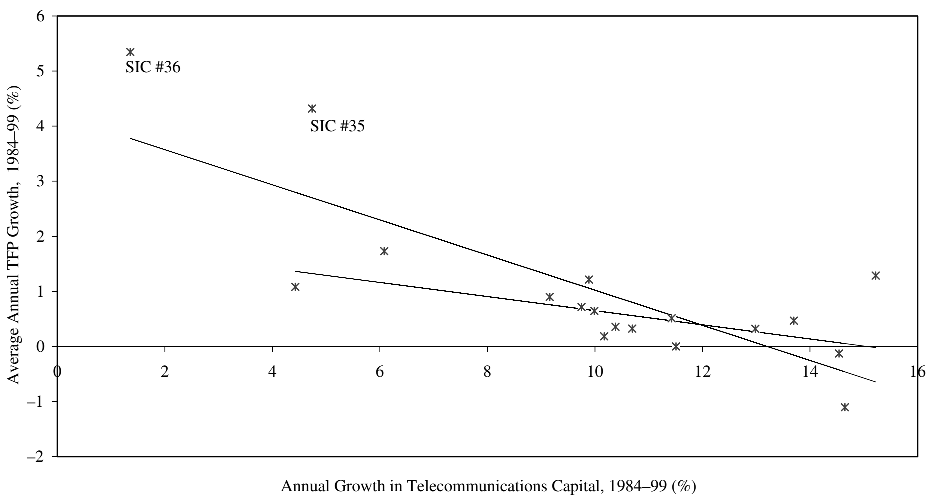
The bottom panel employs the same regression specification, but now uses TFP as the dependent variable as:

$$d \ln Z^M_{i,t} = \beta_{ICT} d \ln K_{ICT,i,t} + \beta_N d \ln K_{N,i,t} + \beta_H d \ln H_{i,t} + \beta_M d \ln M_{i,t} + \lambda_t + \nu_{i,t} \tag{13}$$

where Z^M is measured TFP growth estimated by BLS.

The results again yield a negative coefficient on ICT capital, particularly telecommunications capital, columns 1 through 4. Hours and intermediate inputs are insignificantly different from zero, as one would expect in a neoclassical world of exogenous TFP growth and no reverse causality. Other capital, however, has a strong positive coefficient in both the OLS and IV regressions; this implies that other capital has a bigger productive impact than the neoclassical model suggests. This is consistent with a recent study by Joel Popkin and Company (Association for Manufacturing Technology, 2000), which reports that improved machine tools have made major contributions to the improved performance of manufacturing, e.g. computer numerically controlled devices are more accurate, more flexible, and involve less set-up costs. If these productive characteristics are not accounted for in the conventional capital estimates, then the productivity gains would show up in the measured TFP residual. More work on the appropriate measurement of these tools is needed

The large negative coefficient on telecommunications equipment is still puzzling and a second picture helps. Figure 2 plots the average growth rate of TFP growth for 1984–99 across industries against the average growth rate of telecommunications capital for 1984–99. While this is only a partial relationship



Note: Steep line is fitted values from an OLS regression using all 18 industries. Flat line is fitted values from an OLS regression excluding SIC #35 and #36. See Footnote #29 in text for details.

Figure 2. TFP Growth vs. Telecommunications Capital Growth for U.S. Manufacturing Industries

and endogeneity concerns present any type of structural interpretation, the raw data clearly show a strong negative relationship between TFP growth and telecommunications capital that is driven largely by the ICT-producing industries. These industries account for a large part of this relationship (the steep line), although the relationship remains negative and significant when they are excluded (the flat line).[28]

This can be formalized by including a dummy variable that is set equal to 1 for the two ICT-producing industries (SIC #35 and #36) and set equal to 0 otherwise. These results, column 5 in Table 5, appear somewhat more reasonable. In the output regressions, the ICT coefficients are negative, but they are smaller and not significant, implying that the ICT impact is not well identified here. The other coefficients are reasonable in size, particularly other capital, and are largely significant. While returns to scale falls, the data still do not reject constant returns. In the TFP regressions, only other capital is positive and marginally significant.

One could take the idea that productivity shocks vary across industries even further and allow an industry-specific component in the growth-rate regressions. That is, equation (10) could be relaxed to allow TFP to vary across industries as:

$$Y_{i,t} = A_i e^{f_i(t)} K_{ICT,i,t,}^{\beta_{ICT}} K_{N,i,t}^{B_N} H_{i,t}^{\beta_H} M_{i,t}^{\beta m} e^{\varepsilon_{i,t}} \tag{14}$$

where $f_i(t)$ is the industry-specific time path of A_i.

For ease of exposition, assume that TFP growth in each industry differs only by a constant so that $df_i(t) = \alpha_i + \lambda_t$. Taking logs and first differencing equation (14) yields

$$\begin{aligned} d\ln Y_i = \beta_{ICT} d\ln K_{ICT,i} + \beta_N d\ln K_{N,i} \\ + \beta_H d\ln H_i + \beta_M d\ln M_i + \alpha_i + \lambda_i + v_{i,t} \end{aligned} \tag{15}$$

where equation (15) differs from (12) in which fixed effect remains in the *first-difference* regression.

The final column of Table 5 reports estimates of equation (15) for the output and TFP regression. In general, the results are similar to column 4, suggesting that the ICT-producing industries are the primary source of industry heterogeneity. In terms of output growth, the hours and other capital coefficients are well estimated and reasonable, but the material coefficient and returns to scale appear small.[29] Computers and telecommunications are negative, although neither is significant. In terms of TFP, only the intermediate input variable enters with a negative and significant coefficient.

Overall, these results are somewhat mixed. On the positive side, the coefficients on other capital, hours, and intermediate inputs in the output regression are mostly reasonable and indicate roughly constant returns to scale. In the TFP regressions, most of the inputs appear insignificant as expected, with other capital

[28]The lines are fitted values from an OLS regression of TFP growth (annual average for 1984–99) on telecommunications growth (annual average for 1984–99) and a constant. The slope is −0.319 (p-value = 0.00, R^2 = 0.63) when all 18 industries are used and −0.13 (p-value = 0.02, R^2 = 0.33) when SIC #35 and #36 are excluded.

[29]The low and insignificant capital coefficient and low estimates of returns to scale is a common outcome from fixed effects regressions. See Griliches and Mairesse (1998).

being the exception. On the negative side, ICT capital in general and telecommunications in particular seems to have a negative impact on both output and TFP growth. Others have argued for this type of negative effect from ICT due to large adjustment costs or learning lags, e.g. Kiley (1999, 2000), but these results suggest that industry heterogeneity is a large part of the explanation. Taken as a whole, there is little evidence that broadly defined ICT capital contributes to measured TFP growth.

IV. Conclusions

This paper searches for an empirical link between ICT capital accumulation and measured TFP growth across U.S. manufacturing industries and yields three primary conclusions. First, there is little evidence that ICT capital is associated with measured TFP growth, which is what one would expect in a world with large production spillovers, network effects, or other failures of the neoclassical model. This implies that the benefits of ICT investment are consistent with the costs and accrue to those firms and industries that either produce ICT or restructure their operations to implement ICT.

Second, there is considerable variation in the productive impact of computers relative to telecommunications equipment. This suggests some caution when specifying a production function and it may not be appropriate to analyze the productive effects of a single measure of ICT capital.

Third, it is critical to allow for heterogeneity in productivity shocks across industries. In particular, the two ICT-producing industries have enjoyed quite different productivity experiences in recent years and failure to account for these differences can yield a very misleading picture of the recent productivity experience in U.S. manufacturing.

These findings are a first step in the search for non-traditional productivity effects from ICT capital. While the results provide little evidence that these effects are large, several caveats are warranted. This analysis examines only U.S. manufacturing industries, which are not the most ICT-intensive industries. It is possible that different ICT effects are present in other more intensive users of ICT, so work on other industries or countries is needed to corroborate these findings. In addition, some have argued that it is the combination of computing power and communications ability that will eventually transform how business operates. The widespread commercialization of the Internet is still a fairly recent phenomenon, however, so it is possible that these types of spillover and network gains will eventually be realized after a period of adjustment passes. Given the evidence to date, however, there appears to be no compelling reason to drop the neoclassical framework of technological progress, input substitution, capital deepening in favor of a New Economy explanation of production spillovers and network externalities associated with ICT investment.

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