Information and Communications Technology as a General Purpose Technology: Evidence from U.S. Industry Data*

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Many people point to information and communications technology (ICT) as the key for understanding the acceleration in productivity in the United States since the mid-1990s. Stories of ICT as a general purpose technology (GPT) suggest that measured total factor productivity (TFP) should rise in ICT-using sectors (reflecting either unobserved accumulation of intangible organizational capital, spillovers, or both), but with a long lag. Contemporaneously, however, investments in ICT may be associated with lower TFP as resources are diverted to reorganization and learning. We find that U.S. industry results are consistent with GPT stories: the acceleration after the mid-1990s was broad-based—located primarily in ICT-using industries rather than ICT-producing industries. Furthermore, industry TFP accelerations in the 2000s are positively correlated with (appropriately weighted) industry ICT capital growth in the 1990s. Indeed, as GPT stories would suggest, after controlling for past ICT investment, industry TFP accelerations are negatively correlated with increases in ICT usage in the 2000s.

1. Introduction

After the mid-1990s, both labor productivity and total factor productivity (TFP) accelerated in the United States. A large body of work has explored the sources and breadth of the U.S. acceleration. Much of this research focuses on the role of information and communications technology (ICT).[1]

In this paper, we undertake two tasks. First, we discuss industry-level TFP growth for data from 1987 to 2004. TFP is a relatively broad measure of productivity which, over time, largely reflects innovation and efficiency. Relative to labor productivity (output per hour worked), TFP also controls for capital deepening (increases in capital available per hour worked). Second, we use these results to show that the simple ICT explanation for the U.S. TFP acceleration is incomplete at best. In standard neoclassical growth theory, the use of ICT throughout the economy leads to capital deepening, which boosts *labor* productivity but not TFP in sectors that only *use* but do not produce ICT. TFP growth in *producing* ICT goods shows up directly in the economy's aggregate TFP growth. From the perspective of neoclassical economics, there is no reason to expect an acceleration in the pace of TFP growth outside of ICT production.

However, consistent with a growing body of literature, we find that the TFP acceleration was, in fact, broad-based—not narrowly located in ICT production. In an early study, Basu, Fernald and Shapiro (2001) found a quantitatively important acceleration outside of manufacturing. Triplett and Bosworth (2006, though the original working paper was from 2002) highlighted the finding that the TFP acceleration in the late-1990s was due, in a proximate sense, to the performance of the service sector.

Since these early studies, there have been several rounds of major data revisions by the Bureau of Economic Anal-

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1. Jorgenson (2001) and Oliner and Sichel (2000) provide early discussions of the role of information technology in the productivity acceleration. We discuss the literature in greater detail later. Since 2004, productivity growth has slowed relative to the preceding decade. In this paper, we do not take up the question of whether this slowdown will persist.

ysis (BEA) that changed the details of the size and timing of the measured acceleration in different sectors but did not affect the overall picture. Oliner and Sichel (2006) use aggregate data (plus data on the relative prices of various high-tech goods) and estimate that, in the 2000–2005 period, the acceleration in TFP is completely explained by non-ICT-producing sectors. Jorgenson, Ho, and Stiroh (2006) undertake a similar exercise and reach a similar conclusion. Indeed, both papers find that TFP growth in ICT production slowed from its rapid pace of the late 1990s. Using industry-level data, Corrado et al. (2006), and Bosworth and Triplett (2007) find that non-ICT-producing sectors saw a sizeable acceleration in TFP in the 2000s, whereas TFP growth slowed in ICT-producing sectors in the 2000s. In the data for the current paper, sectors such as ICT production, finance and insurance, and wholesale and retail trade accelerated after the mid-1990s; TFP growth in those sectors remained relatively strong in the 2000s, even as other sectors finally saw an acceleration.

The broad-based acceleration raises a puzzle. According to standard neoclassical production theory, which underlies almost all the recent discussions of this issue, factor prices do not shift production functions. Thus, if the availability of cheaper ICT capital has increased TFP in industries that use but do not produce ICT equipment, then it has done so via a channel that neoclassical economics does not understand well.

We discuss theories of ICT as a general purpose technology (GPT) in an effort to see if these theories can explain the puzzle of why measured TFP accelerated in ICT-using industries. The main feature of a GPT is that it leads to fundamental changes in the production process of those using the new invention (see, e.g., Helpman and Trajtenberg, 1998). For example, Chandler (1977) discusses how railroads transformed retailing by allowing nationwide catalog sales. David and Wright (2003) also discuss historical examples. Indeed, the availability of cheap ICT capital allows firms to deploy their other inputs in radically different and productivity-enhancing ways. In so doing, cheap computers and telecommunications equipment can foster an ever-expanding sequence of complementary inventions in industries using ICT. These complementary inventions cause the demand curve for ICT to shift further and further out, thereby offsetting the effects of diminishing returns.

As Basu, Fernald, Oulton, and Srinivasan (2003; henceforth BFOS) highlight, ICT itself may be able to explain the measured acceleration in TFP in sectors that are ICT users. In their model, reaping the full benefits of ICT requires firms to accumulate a stock of intangible knowledge capital. For example, faster information processing might allow firms to think of new ways of communicating with suppliers or arranging distribution systems. These intangible investments may include resources diverted from direct production to learning; they may involve purposeful innovation arising from research and development (R&D). The assumption that complementary investments are needed to derive the full benefits of ICT is supported both by GPT theory and by firm-level evidence.[2] Since (intangible) capital accumulation is a slow process, the full benefits of the ICT revolution show up in the ICT-using sectors with significant lags.

Note that the BFOS story hews as closely as possible to neoclassical assumptions while explaining the puzzle of TFP growth in ICT-using industries. From a firm's perspective, the story is essentially one of neoclassical capital accumulation. If growth accounting could include intangible capital as an input to production then it would show no technical change in ICT-using industries. (Of course, measuring intangible capital directly is very difficult at best; see Corrado, Hulten, and Sichel 2006.) But the story can easily be extended to include features that are not neoclassical and that would explain true technical progress in ICT-using industries via other mechanisms, such as spillovers. Indeed, to the extent that much of the intangible capital accumulated by ICT users is knowledge, which is a nonrival good, it would be natural to expect spillovers. For example, the innovations that have made Amazon.com and Wal-Mart market leaders could presumably be imitated, at least in the long run, at a fraction of the cost it took to develop these new ideas in the first place.

We assess whether the acceleration in measured TFP is related to the use of ICT. We develop a simple model to motivate our empirical work. The model predicts that observed investments in ICT are a proxy for unobserved investments in reorganization or other intangible knowledge. In this model, the productivity acceleration should be positively correlated with lagged ICT capital growth but *negatively* correlated with current ICT capital growth (with these growth rates "scaled" by the share of ICT capital in output). Note that the unconditional correlation between the productivity acceleration and either ICT capital growth or the ICT capital share can be positive, negative, or zero.

In the data, we find results that support the joint hypothesis that ICT is a GPT—i.e., that complementary investment is important for realizing the productivity benefits of ICT investment—and that, since these complementary investments are unmeasured, they can help explain the cross-industry and aggregate TFP growth experienced by the United States in the 1990s. Specifically, we find that industries that had high ICT capital growth rates in the 1987–2000 period (weighted by ICT revenue shares, as suggested by theory) also had a faster acceleration in TFP growth in the 2000s. Controlling for lagged capital growth, however, ICT capital growth in the 2000s was *negatively* correlated with contemporaneous TFP

2. For evidence, see Bresnahan, Brynjolfsson, and Hitt (2002).

growth. These results are consistent with—indeed, predicted by—the simple model that we present.

The paper is structured as follows. We present preliminary empirical results from industry-level growth accounting in Section 2 and document the puzzle we note above. We then present a simple model of intangible capital investment in Section 3 and show how measured inputs—especially ICT investment—can be used to derive a proxy for unmeasured investment in intangibles. We test the key empirical implications of the model in Section 4. Conclusions, caveats, and ideas for future research are collected in Section 5.

2. Data and Preliminary Empirical Results

We begin by establishing stylized facts from standard growth accounting. We focus on disaggregated, industry-level results for TFP. We first describe our data set briefly and then discuss results.

Our 40-industry data set updates that used in Basu, Fernald, and Shapiro (2001), Triplett and Bosworth (2006), and BFOS (2003). The data run from 1987 to 2004 on a North American Industry Classification System (NAICS) basis. For industry gross output and intermediate inputs, we use industry-level national accounts data from the BEA. For capital input—including detailed ICT data—we use Bureau of Labor Statistics (BLS) capital input data by disaggregated industry. For labor input, we use unpublished BLS data on hours worked by industry.[3]

Several comments are in order. First, there are potential differences in how the conversion from the earlier Standard Industrial Classification system to NAICS has been implemented across agencies; see Bosworth and Triplett (2006) and Corrado et al. (2006) for a discussion. Second, we do not have industry measures of labor quality, only raw hours, as estimated by the BLS. Third, we aggregate industries beyond what is strictly necessary, in part because of a concern that industry matches across data sources are not as good at lower levels of aggregation. (For example, in some cases, our BLS estimate of capital compensation shares in a sub-industry substantially exceeded the implied BEA figure, whereas in another sub-industry the share fell substantially short; once aggregated, the BLS figure was close to—i.e., only slightly smaller than—the BEA figure, as expected.)

Table 1 provides standard estimates of TFP for various aggregates, including the one-digit industry level. The first three columns show TFP growth, in value-added terms, averaged over different time periods. Since aggregate TFP is a value-added concept, we present industry TFP in value-added terms as well; by controlling for differences in intermediate input intensity, these figures are scaled to be comparable to the aggregate figures. The next two columns show the acceleration, first from 1987–1995 to 1995–2000; and then from 1995–2000 to 2000–2004. The final two columns show the average share of intermediate inputs in gross output and the sector's nominal share of aggregate value-added.[4]

The top line shows an acceleration of about ½ percentage point in the second half of the 1990s, and then a further acceleration of about ¾ percentage point in the 2000s. The other lines show various subaggregates, including the one-digit NAICS level. It is clear that in our data set, the acceleration was broad-based. First, suppose we focus on the non-ICT-producing sectors (fourth line from the bottom). They show a very small acceleration in the late 1990s (from 0.68 to 0.81 percent per year), but then a much larger acceleration in the 2000s (to an average of 1.98 percent per year). In contrast, ICT-producing industries saw a sharp acceleration in TFP in the late 1990s but then some deceleration in the 2000s.

A more detailed analysis of the non-ICT sectors shows more heterogeneity in the timing of the TFP acceleration. For example, trade and finance accelerated in the mid-1990s and growth then remained strong in the 2000s. Nondurable manufacturing, business services, and information slowed in the mid-1990s before accelerating in the 2000s. Nevertheless, by the 2000s, most sectors show an acceleration relative to the pre-1995 period (mining, utilities, and insurance are exceptions).

Griliches (1994) and Nordhaus (2002) argue that real output in many service industries are poorly measured—e.g., there are active debates on how, conceptually, to measure the nominal and "real output" of a bank;[5] in health care, the

3. The BEA data on gross product origination were downloaded from http://bea.gov/bea/dn2/gdpbyind_data.htm on March 15, 2006. The BLS capital data were downloaded from http://www.bls.gov/web/prod3.supp.toc.htm on March 21, 2006. We removed owner-occupied housing from the BEA data for the real estate industry. The BEA labor compensation data do not include proprietors or the self-employed, so we follow Triplett and Bosworth (2006) in using BLS data on total payments to capital that correct for this. We thank Steve Rosenthal at the BLS for sending us unpublished industry hours data, which adjusts for estimated hours worked by nonproduction and supervisory employees as well as the self-employed (received via email on June 27, 2006).

4. Aggregate TFP growth is a weighted average of industry gross-output TFP growth, where the so-called "Domar weights" equal nominal industry gross output divided by aggregate value added; the weights thus sum to more than one. See Hulten (1978) for an extensive discussion. In continuous time, this is equivalent to first converting gross-output residuals to value-added terms by dividing by (one minus the intermediate share) and then using shares in nominal value added. Hence, contributions to aggregate TFP growth are the same, using value-added weighted value-added TFP or using Domar-weighted gross-output TFP. (In discrete time, using average shares from adjacent periods, they are approximately equivalent.) Basu and Fernald (2001) discuss this aggregation and its extension to the case of imperfect competition; see also Oulton (2001).

5. See, for example, Wang, Basu, and Fernald (2004).

TABLE 1
U.S. TOTAL FACTOR PRODUCTIVITY BY INDUSTRY IN PRIVATE NONFARM BUSINESS, 1987–2004
(AVERAGE ANNUAL PERCENT CHANGES, EXCEPT WHERE NOTED)

	Productivity[a]			Acceleration		Intermediate input share of nominal VA	Industry share of nominal VA
	1987–1995	1995–2000	2000–2004	1995–2000	2000–2004	1987–2004	1987–2004
Private nonfarm economy (*not* adjusted for labor quality)	0.96	1.43	2.21	0.47	0.79	49.50	100.00
Mining	3.45	–0.37	–3.13	–3.82	–2.76	49.10	1.50
Manufacturing	2.07	3.81	4.09	1.74	0.28	66.36	19.12
Nondurables	0.70	–0.16	2.17	–0.86	2.33	69.77	7.98
Durables	3.06	6.51	5.50	3.45	–1.01	63.47	11.14
Construction	0.00	–2.89	–1.00	–2.90	1.89	49.31	5.36
Transportation	2.31	1.43	2.82	–0.88	1.39	51.51	3.51
Communication[b]	2.92	–0.47	5.75	–3.39	6.23	46.40	3.26
Utilities	2.04	1.04	1.15	–1.01	0.11	41.86	2.87
Information	1.95	0.60	6.33	–1.35	5.74	48.67	5.34
Wholesale trade	1.87	4.28	4.25	2.41	–0.03	36.75	7.66
Retail trade	2.48	4.52	4.48	2.03	–0.03	37.27	8.71
Finance & insurance	0.50	2.30	2.21	1.81	–0.09	43.64	8.62
Finance	0.27	2.84	3.88	2.57	1.04	39.51	5.78
Insurance	0.88	0.11	–1.63	–0.78	–1.74	50.40	2.83
Business services & real estate	0.42	–1.10	2.17	–1.52	3.27	40.41	12.82
Business services	0.19	–1.28	3.64	–1.47	4.93	34.93	5.12
Real estate	0.98	–0.41	1.05	–1.39	1.46	44.48	7.70
Other services[c]	–0.70	–0.03	0.16	0.67	0.20	40.15	26.29
ICT-producing[d]	6.84	14.85	9.39	8.00	–5.45	61.04	4.25
Non-ICT-producing	0.68	0.81	1.98	0.13	1.17	48.76	95.75
Well-measured industries[e]	2.18	3.51	3.58	1.33	0.07	56.71	43.66
Well-measured industries (excluding ICT-producing)	1.66	2.21	3.08	0.55	0.87	56.12	39.41
Poorly measured industries[f]	–0.07	–0.17	1.31	–0.10	1.48	42.23	56.34

a. Productivity is defined as (gross output TFP growth)/(1–share of intermediate inputs). Implicitly, this uses the Törnqvist index of value added for a sector.
b. Communication includes broadcasting and telecommunications from the information industry aggregate.
c. Other services includes NAICS codes 61–62, 71–72, and 81, as well as the noncommunications elements of "information" (NAICS code 51, excluding 513).
d. ICT-producing industries includes machinery, computer and electronic products, and electrical equipment, appliances, and components.
e. Well-measured industries include mining, manufacturing, transportation, utilities, and wholesale and retail trade.
f. Poorly measured industries include construction, information, finance and insurance, real estate and rental and leasing, professional and business services, etc.

hedonic issues are notoriously difficult. Nordhaus argues for focusing on "well-measured" (or at least, "better measured") sectors of the economy. The acceleration in TFP in well-measured industries (third line from the bottom) took place primarily in the 1990s with little further acceleration in the 2000s; but excluding ICT-producing sectors, the acceleration is spread out over the 1995–2004 period.

In the short term, nontechnological factors can change measured industry TFP. These factors include non-constant returns to scale and variations in factor utilization. Basu, Fernald, and Shapiro (BFS, 2001) argue that cyclical mismeasurement of inputs plays little if any role in the U.S. acceleration of the late 1990s. BFS also find little role in the productivity acceleration for deviations from constant returns and perfect competition.

In the early 2000s, some commentators suggested that, because of uncertainty, firms were hesitant to hire new workers; as a result, one might conjecture that firms might have worked their existing labor force more intensively in order to get more labor input. But typically, one would expect that firms would push their workers to work longer as well as harder; this is the basic intuition underlying the use of hours-per-worker as a utilization proxy in Basu and Kimball (1997), BFS, and Basu, Fernald, and Kimball (2006). In the 2000s, however, when productivity growth was particularly strong, hours per worker remained low.

BFS do find a noticeable role for traditional adjustment costs associated with investment. When investment rose sharply in the late 1990s, firms were, presumably, diverting an increasing amount of worker time to installing the new capital rather

than producing marketable output. This suggests that true technological progress was faster than measured. In contrast, investment generally was weak in the early 2000s, suggesting that there was less disruption associated with capital installation. Nevertheless, the magnitude of this effect appears small, for reasonable calibrations of adjustment costs. Applying the BFS correction would raise the U.S. technology acceleration from 1995 to 2000 by about 0.3 percentage points per year, but would have a negligible effect from 2000 to 2004. Hence, the investment reversal could potentially explain some portion of the second wave of acceleration, but not all of it.[6] These adjustment-cost considerations strengthen the conclusion that the technology acceleration was broad-based, since service and trade industries invested heavily in the late 1990s and, hence, paid a lot of investment adjustment costs.

3. Industry-Level Productivity Implications of ICT as a New GPT

The U.S. productivity acceleration in the late 1990s coincided with accelerated price declines for computers and semiconductors. But, as we just saw, much of the TFP acceleration appears to have taken place in the 2000s, and outside of ICT production. Can ICT somehow *explain* the measured TFP acceleration in industries using ICT? We first discuss broad theoretical considerations of treating ICT as a new general purpose technology and then present a simple model to clarify the issues and empirical implications.

3.1. General Purpose Technologies and Growth Accounting

Standard neoclassical growth theory suggests two direct channels through which ICT can affect aggregate labor and total factor productivity growth. First, faster TFP growth in *producing* ICT contributes directly to aggregate TFP growth. Second, by reducing the user cost of capital, falling ICT prices induce firms to increase their desired capital stock.[7] This *use* of ICT contributes directly to labor productivity through capital deepening.

Growth accounting itself does not take a stand on the deep causes of innovation and TFP. Neoclassical growth theory generally takes technology as exogenous, but this is clearly a modeling shortcut, appropriate for some but not all purposes. Endogenous growth theories, in contrast, generally presume that innovation results from purposeful investments in knowledge or human capital, possibly with externalities.

We interpret ICT's general purpose nature in the spirit of the neoclassical growth model, since the GPT arrives exogenously (i.e., technological progress in ICT production is exogenous). ICT users respond in a neoclassical way: Firms respond to faster, more powerful computers and software by reorganizing and accumulating intangible organizational capital. Measured TFP, which omits this intangible organizational investment as output and the service flow from organizational capital as an input, is also affected.

Our motivation for viewing ICT this way is the many microeconomic, firm-level, and anecdotal studies suggesting an important—but often indirect and hard to foresee—role for ICT to affect measured production and productivity in sectors using ICT. Conceptually, we separate these potential links into two categories: purposeful co-invention, which we interpret as the accumulation of complementary organizational capital and which leads to mismeasurement of true technology, and externalities of one sort or another. For example, Bresnahan and Trajtenberg (1995) and Helpman and Trajtenberg (1998) suggest that innovations in ICT cause unexpected ripples of co-invention and co-investment in sectors that seem almost arbitrarily far away.

First, firm-level studies suggest that benefiting from ICT investments requires substantial and costly co-investments in complementary capital, with long and variable lags.[8] For example, firms that use computers more intensively may reorganize production, thereby creating intangible capital in the form of organizational knowledge. Such investments include resources diverted to learning, or purposeful innovation arising from R&D. As Bresnahan (undated) argues, "advances in ICT shift the innovation possibility frontier of the economy rather than directly shifting the production frontier."

The resulting organizational capital is analogous to physical capital in that companies accumulate it in a purposeful way. Conceptually, we think of this unobserved complementary capital as an additional input into a standard neoclassical production function.[9]

6. These numbers are qualitatively the same but smaller than those reported in BFS (2001) for three reasons. The two main reasons are (a) data revisions have reduced the growth rate of investment in the second half of the 1990s, and (b) Jason Cummins and John Roberts pointed out a mistake in our conversion from Shapiro's (1986) framework to ours. This led us to reduce our estimate of the "disruption cost" per unit of investment growth (the BFS parameter ϕ from 0.048 in BFS to 0.035).

7. Tevlin and Whelan (2003) for the U.S. and Bakhshi, Oulton, and Thompson (2003) for the U.K. provide econometric evidence that falling relative prices of ICT equipment fueled the ICT investment boom.

8. See, for example, Brynjolfsson and Hitt (2000) and Bresnahan (undated) for a discussion of the kinds of complementary investments and co-invention that firms undertake to benefit from ICT, given its general purpose attributes. Bloom, Sadun, and Van Reenen (2005) use data on cross-country mergers to provide additional firm-level evidence for the importance of (partially transferable) intangible capital.

9. Much of Brynjolfsson's work tries to quantify the role of unobserved complementary capital. Macroeconomic studies of the effects of organizational capital include Greenwood and Yorukoglu (1997), Hornstein and Krusell (1996), Hall (2001), and Laitner and Stolyarov (2003).

Second, the GPT literature suggests the likelihood of sizeable externalities to ICT. For example, successful new managerial ideas—including those that take advantage of ICT, such as the use of a new business information system—seem likely to diffuse to other firms. Imitation may be easier and less costly than the initial co-invention of, say, a new organization change, because you learn by watching and analyzing the experimentation, the successes, and, importantly, the mistakes made by others.[10] Indeed, firms that *don't* use computers more intensively might also benefit from spillovers of intangible capital. For example, if there are sizeable spillovers to R&D, and if R&D is more productive with better computers, then even firms that don't use computers intensively may benefit from the knowledge created by computers.

The first set of considerations are completely consistent with the traditional growth accounting *framework* but suggest difficulties in implementation and interpretation. In particular, these considerations suggest that the production function is mismeasured because we don't observe all inputs (the service flow from complementary, intangible capital) or all outputs (the investment in complementary capital). Hence, TFP is mismeasured. The second set of ideas, related to externalities, suggest that ICT might also explain "true" technology.

Empirically, the challenge is to infer unobserved complementary investments. We now turn to a formal model that suggests variables that might proxy for these unobservables. Of course, our interpretation of the results will be clouded by our uncertainty about whether our proxies are capturing only neoclassical investment in unobserved organizational capital or whether the proxies are affecting TFP directly through spillovers.

3.2. Industry-Level Implications of ICT as a New GPT: A Simple Model[11]

Many papers modeling the effects of GPTs are motivated by the ICT revolution.[12] But it is difficult to derive industry-level empirical implications from this literature. For example, it is often unclear how to measure in practice some of the key variables, such as unobserved investment and capital; and even for observed variables, measurement conventions often depart from those used in national accounting.[13]

On the other hand, conventional industry-level growth-accounting studies of the sort reviewed and extended in Section 2 are typically hard to interpret in terms of GPT considerations because they generally lack a conceptual framework to interpret movements in TFP. Although some studies try to look for a "new economy" in which ICT has indirect effects on measured TFP in ICT-using industries, in the absence of clear theoretical guidance, it is not clear that many would know if they had, in fact, found it.

Finally, the empirical literature using firm-level data or case studies stresses the importance and costly nature of organizational change accompanying ICT investment. This literature is insightful but rarely makes contact with economy-wide productivity research. (An exception is Brynjolfsson and Yang 2002.) Our empirical work below is a tentative attempt to make that connection. The model below provides the bare bones of a theoretical framework to capture some of the key issues, focusing on cross-industry empirical implications. The model takes as given the arrival of a particular GPT, which here is taken to be the production of ICT capital at a continuously falling relative price. The distinguishing feature of a GPT is that its effects are general—going well beyond the industry of production—but require complementary investments by firms for them to benefit fully from its use. For empirical implementation, we focus on industries that use the GPT.

Value added, Q_{it}, in industries that use, but do not produce, ICT is given by

$$(1)\quad Q_{it} \equiv Y_{it} + A_{it} = F\left(Z_t G(K_{it}^{IT}, C_{it}), K_{it}^{NT}, L_{it}\right), i = 1, \ldots N,$$

where the production function F and the IT services function G are homogeneous of degree 1 in their arguments. Note that effective IT services depend on both ICT capital K^{IT} as well as complementary organizational capital C. Z is a technology term that each industry takes as exogenous. We discuss the distinction between A and Y shortly. For simplicity, we ignore intermediate inputs (though we incorporate them in our empirical work), imperfect competition, increasing returns, and capital adjustment costs. All could be added, at the cost of considerable notation.

10. Bresnahan (undated) provides a nice discussion of the channels for externalities to operate. Bresnahan and Trajtenberg (1995) highlight both "vertical" externalities (between GPT producers and each application sector) and "horizontal" externalities (across application sectors).

11. This section follows Basu, Fernald, Oulton, and Srinivasan (2003) fairly closely.

12. A very incomplete list is Caselli (1999), Greenwood and Yorukoglu (1997), the collection of papers edited by Helpman (1998), Hobijn and Jovanovic (2001), Jovanovic and Rousseau (2004), and Laitner and Stolyarov (2003).

13. For example, capital is typically measured as foregone consumption, which is sensible for an aggregative model but difficult to relate to industry-level capital accounts that deal with capital heterogeneity and quality change by (attempting to) measure capital input in efficiency units. Howitt (1998) attempts to bridge the two conventions.

Each industry hires labor L and rents ICT capital K^{IT} and non-ICT capital K^{NT} in competitive, economywide markets. The two types of capital depreciate at rates δ^{IT} and δ^{NT}, respectively. For given investment flows I^{IT} and I^{NT}, the aggregate stocks of the two types of capital (indexed by J) evolve as

$$K_t^{JT} = I_t^{IT} = (1 - \delta^{JT})K_{t-1}^{JT}, J = I, N. \tag{2}$$

Industries must individually accumulate complementary capital, C, representing business and organizational models or IT training. The investment flow A is the time and resource cost of training and creating new business structures.[14] Industries forego producing market output Y to accumulate this capital, which then depreciates at rate δ^C:

$$C_{it} = A_{it} + (1 - \delta^C)C_{it-1}. \tag{3}$$

Investment is irreversible. Since both A and NT investment goods cost the same to produce, the economic difference between the two types of capital is that they interact in different ways with ICT capital. The difference in terms of measurement is that Y is observable by national accountants but A is not.[15]

The main economic implication of the separability assumption built into equation (1) is that the marginal productivities of K^{IT} and C are closely tied to one another. We assume that the elasticity of substitution between the two inputs in the production of G is relatively small. We also assume standard conditions to the effect that the marginal productivity of each input is very low if the level of the other is close to zero. Thus, when the GPT arrives and ICT capital starts getting cheap, the incentive to also accumulate C is very strong.

Note that conceptually, "innovation" as traditionally construed can take two forms. First, we lump purposeful innovations into C (indeed, we have assumed that *all* purposeful innovation is closely linked to ICT). Second, we interpret Z as all exogenous increases in technology, including the component of organizational change that spills over as an externality from the sector of origin—for example, the idea of using individual electric motors at each workstation in a factory, rather than relying on the single drive train of a steam engine.

14. Chandler (1977) discusses innovations in inventory management made possible by railroads. The Wal-Mart inventory management system provides an example of innovations made possible by ICT.

15. Some fraction of A is probably measured: for example, consultant services and many forms of software. It is not clear how much of what is measured is properly capitalized, as required by equation (3).

3.3. TFP Measurement with Unobserved Inputs and Output

What are the implications of complementary capital accumulation for the measured TFP of ICT-using industries? Differentiating, we can write the production function in growth rates as

$$\begin{aligned}\Delta q &= \frac{Y}{Q}\Delta y + \frac{A}{Q}\Delta a \\ &= \frac{F_{K^{IT}}K^{IT}}{Q}\Delta k^{IT} + \frac{F_C C}{Q}\Delta c + \frac{F_{K^{NT}}K^{NT}}{Q}\Delta k^{NT} \\ &\quad + \frac{F_L L}{Q}\Delta l + \frac{F_Z Z}{Q}\Delta z.\end{aligned} \tag{4}$$

Lowercase letters are logs of their uppercase counterparts. Suppose P is the output price, W is the wage, and P_K^{IT} and P_K^{NT} are the rental prices for the two types of capital. Since we have assumed constant returns to scale and perfect competition, output elasticities equal factor shares in revenue. Hence,

$$\begin{aligned}&\frac{F_C C}{Q} + \frac{F_{K^{IT}}K^{IT}}{Q} + \frac{F_{K^{NT}}K^{NT}}{Q} + \frac{F_L L}{Q} \\ &= \frac{F_C C}{Q} + \frac{P_K^{IT}K^{IT}}{PQ} + \frac{P_K^{NT}K^{NT}}{PQ} + \frac{WL}{PQ} = 1.\end{aligned} \tag{5}$$

If we observed total output Q and knew the required rates of return to capital, we could back out the elasticity of output with respect to complementary capital, C:

$$\frac{F_C C}{Q} = 1 - \frac{WL}{PQ} - \frac{P_K^{IT}K^{IT}}{PQ} - \frac{P_K^{NT}K^{NT}}{PQ}. \tag{6}$$

Without independent information on the flow of A or the stock of C (perhaps from stock market valuations), one cannot implement this procedure using measured output, Y. We rewrite equation (6) as

$$\frac{F_C C}{Y} = \frac{Q}{Y} - \frac{WL}{PY} - \frac{P_K^{IT}K^{IT}}{PY} - \frac{P_K^{NT}K^{NT}}{PY}.$$

Since Q/Y is not observed, within broad limits we are free to believe that complementary capital is arbitrarily important in production by assuming that an arbitrarily large share of the true output that firms produce is not counted in the national accounts.

Some algebraic manipulations of equation (4) yield an expression for the measured Solow residual, i.e., measured TFP:[16]

16. The observed factor shares do not necessarily sum to one, even with perfect competition, as we assumed in our empirical work. In our experience, however, estimating the user costs rather than taking them as a residual makes little practical difference.

$$(7)\quad \Delta y - \frac{P_K^{IT}K^{IT}}{PY}\Delta k^{IT} - \frac{P_K^{NT}K^{IT}}{PY}\Delta k^{NT} - \frac{WL}{PY}\Delta l \equiv \Delta TFP = \frac{F_C C}{Y}\Delta c - \frac{A}{Y}\Delta a + s_G \Delta z,$$

where $s_G \equiv (F_Z Z/Y)$. Omitting complementary inputs can cause us to either overestimate or underestimate true TFP growth, $s_G\Delta z$. When unmeasured *output* is growing ($\Delta a > 0$), TFP growth is underestimated (the "1974" story) as resources are diverted to investment. When unmeasured *input* is growing ($\Delta c > 0$), TFP growth is overestimated. In the steady state, of course, the accumulation equation implies that $\Delta c = \Delta a \equiv g$. Hence, steady-state mismeasurement depends on r^*, the steady-state real interest rate, and g, the steady-state rate of growth:

$$\left[\frac{F_C C}{Y} - \frac{A}{Y}\right]g = \frac{C}{Y}\left[F_C - \frac{A}{C}\right]g = \frac{C}{Y}\left[(r^* + \delta^C) - \frac{g + \delta^C}{1+g}\right]g.$$

In a dynamically efficient economy the mismeasurement is necessarily positive: True steady-state TFP growth is *lower* than measured, not higher.[17]

This point is simple but important. Of course, if one corrects only output mismeasurement (Δa), then ICT will appear fantastically productive, far beyond what is ordinarily measured. But firms divert resources to unobserved investment Δa in order to create an intangible capital stock, which contributes to future production. The resulting unmeasured flow of capital services implies a bias in the other direction. The net bias may be either positive or negative at a point in time, but it is positive in the steady state.

We now seek an observable proxy for unobserved investment in, and growth in the stock of, complementary capital. Observed growth in ICT capital provides a reasonable proxy. Suppose G takes a constant elasticity of substitution (CES) form:

$$G = \left[\alpha K^{IT\frac{\sigma-1}{\sigma}} + (1-\alpha)C^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}.$$

σ is the elasticity of substitution between the two inputs; α gives their relative importance. Consider the optimization subproblem of producing G at minimum cost each period. Let P_K^{IT}/P_K^C be the relative rental rate of ICT capital to C capital. The solution of the subproblem is

$$(8)\quad \Delta c_t = \Delta k_t^{IT} + \sigma\Delta \ln(P_K^{IT}/P_K^C)_t.$$

This equation links growth in unobserved complementary capital and growth of observed ICT capital.

We can use the accumulation equation to express unobserved investment Δa in terms of current and lagged growth in unobserved capital Δc:

$$\Delta a_t = \frac{C}{A}\left[\Delta c_t - \frac{(1-\delta^C)}{(1+g)}\Delta c_{t-1}\right].$$

Substituting the last equation and equation (8) into (7), we have in principle an equation for TFP growth that indicates the importance of complementary capital accumulation:

$$(9)\quad \Delta TFP = \left[\frac{C}{Y}(F_c - 1)\right]\left[\Delta k_t^{IT} + \sigma\Delta\ln\left(\frac{P_K^{IT}}{P_K^C}\right)_t\right] + \left[\frac{C}{Y}\frac{(1-\delta^C)}{(1+g)}\right]\left[\Delta k_{t-1}^{IT} + \sigma\Delta\ln\left(\frac{P_K^{IT}}{P_K^C}\right)_{t-1}\right] + s_G\Delta z.$$

The first term is proportional to $(r^* + \delta^C - 1)$ where r^* is the steady-state interest rate; hence, under reasonable circumstances it is negative. The second term, on the other hand, is clearly positive. Hence, other things equal, industries that are making large ICT investments today will have low measured TFP growth, but those that made such investments in the *past* will have high measured TFP growth.

As an estimating equation, (9) has the difficulty that industries are likely to differ in their long-run *C/Y* ratios. Using the CES assumption for G, the cost-minimizing first-order condition implies that

$$\frac{C}{K^{IT}} = \left[\left(\frac{1-\alpha}{\alpha}\right)^\sigma\right]\left(\frac{P_K^{IT}}{P_K^C}\right)^\sigma.$$

If we define the observed share of payments to ICT capital in revenue as $s_{K,IT} = P_K^{IT}K^{IT}/PY$, then we can rearrange this condition as

$$(10)\quad \frac{C}{Y} = \left[\left(\frac{P}{P_K^C}\right)\left(\frac{1-\alpha}{\alpha}\right)^\sigma\left(\frac{P_K^{IT}}{P_K^C}\right)^{\sigma-1}\right]\left(\frac{P_K^{IT}K^{IT}}{PY}\right) \equiv \beta s_{K,IT}.$$

β is a composite parameter that depends on various things, including the share parameter α, the elasticity of substitution σ, and relative prices. In the Cobb-Douglas case, where σ equals one, *C/Y* is proportional to the observed ICT share. Hence, other things equal, the mismeasurement of complementary capital is more important in those industries where ICT capital is used to a greater extent. We can now substitute equation (10) into equation (9) to find

$$(11)\quad \Delta TFP = [F_C - 1]\beta\tilde{k}_t + \left[\frac{(1-\delta^C)}{(1+g)}\right]\beta\tilde{k}_{t-1} + s_G\Delta z,$$

17. Dynamic efficiency requires that the output elasticity equal or exceed the investment rate. In our discrete-time economy, one can show that dynamic efficiency requires that the marginal product of capital, which equals $r + \delta$, be greater than or equal to $(g + \delta)/(1 - g)$.

where $\tilde{k}_t = s_{K,IT}\left[\Delta k_t^{IT} + \sigma \Delta \ln\left(P_K^{IT}/P_K^C\right)_t\right]$. $\tilde{k}_t$ is a composite variable that, in essence, captures share-weighted ICT capital growth (with a relative-price adjustment).

This model has several general implications. First, one might find a link between ICT use and measured TFP even if there are no externalities to ICT use. Second, the correct proxy for ICT use involves the interaction of ICT intensity (the ICT share) and the growth rate. Intuitively, if ICT capital grows quickly but its share is small, then there probably isn't much complementary capital to cause mismeasurement. In contrast, if the share is large (implying complementary capital is likely important) but the growth of ICT capital is small, then the mismeasurement of true output and true investment is also small during the period at hand. Third, one needs to control for both current and lagged $\tilde{k}$. Since these values are correlated in the data, if one omits one of them, then the regression has an omitted variable problem. Indeed, the regression coefficient could have either sign, since the correlated omitted variable has a coefficient with the *opposite* sign.[18]

3.4. Extensions to the Basic Framework

The model above is, of course, stylized and imposes a lot of structure on the problem to derive an estimating equation. As a result, there are a number of challenges in implementing this framework empirically. First, it is unclear how long the lags are between ICT investment and complementary investment. In other words, the length of a period is a free parameter, and theory gives little guidance. The lagged $\tilde{k}$ may be last year's ICT capital accumulation, or the last decade's. Furthermore, equation (3) for the accumulation of complementary capital has no adjustment costs, or time-to-build or time-to-plan lags in the accumulation of *C*. But such frictions and lags are likely to be important in practice, making it even harder to uncover the link between ICT and measured TFP.

Second, suppose there are externalities captured in technology growth Δz and that they are a function of industry as well as aggregate *C*. Then one can no longer tell whether the $\tilde{k}$ terms represent accumulation of a private stock or intra-industry externalities that are internalized within the industry. Similarly, if we find that lagged $\tilde{k}$ is important for explaining current productivity growth, we do not know whether that finding supports the theory we have outlined or whether it indicates that the externality is a function of lagged capital.

Third, other variables might enter the production function for *A*, which we have not accounted for. We imposed the same production function for *A* and *Y*. But it is possible, as many have recognized, that the production of complementary capital is particularly intensive in skilled (i.e., college-educated) labor.[19] If true, the hypothesis implies that the relative price of accumulating complementary capital may differ significantly across industries (or across countries) in ways that we have ignored.

Fourth, even with the restrictions we've imposed, we need to make further assumptions about σ as well as the relative user costs for ICT and complementary capital. We made the strong assumption that the price of complementary investment is the same as that of output, so this relative price should largely reflect the trend decline in ICT prices. Nevertheless, that was clearly an assumption of convenience—reflecting our lack of knowledge—rather than something we want to rely on too strongly. In what follows, we ignore the relative price terms, but this needs to be explored further. (Suppose we assume that $\sigma = 0$. There is still a relative price effect which, if omitted, would imply a trend in the estimated coefficient over time; but in the cross-section, this relative price is close to common across firms, so its omission shouldn't matter much.)

Finally, given the difficulty of finding good instruments, we report ordinary least squares (OLS) regressions below. But current ICT capital growth is surely endogenous. Given the correlation between current and lagged share-weighted ICT capital growth, any endogeneity potentially biases both coefficients. The effect on estimates depends on the size of the true coefficient as well as the degree of endogeneity. The endogeneity bias might be positive or negative: Basu, Fernald, and Kimball (2006), for example, find that positive technology innovations tend to reduce inputs on impact. As is standard, one trades off bias against precision; indeed, weak instruments could lead to both bias and imprecision. In any case, one needs to interpret the results with caution.

4. Evidence for the GPT Hypothesis

Several studies explore whether TFP growth across industries is correlated with ICT intensity. In contrast to firm-level studies, these industry studies rarely find much correlation between ICT capital and TFP growth (e.g., Stiroh, 2002b). But as noted, our model implies that the contemporaneous correlation need not be positive—even if ICT is, in fact, an important contributor to measured TFP. BFOS found that the industry productivity acceleration in the second half of the 1990s was positively correlated with lagged ICT use but

18. Hence one needs to generalize the approach followed by, e.g., Stiroh (2002b) who looks for ICT spillovers by regressing TFP growth on only the current-year growth rate of IT capital. See Stiroh (2002a) and Stiroh and Botsch (2007) for related work. Brynjolfsson and Hitt (2003) also find significant lags in firm-level data, which nicely complements our more aggregative evidence.

19. Krueger and Kumar (2001) ask whether the different educational systems in the United States and Europe (especially Germany) may be responsible for their different growth experiences in the 1990s. See also Lynch and Nickell (2001).

TABLE 2
U.S. COMPUTER, SOFTWARE, AND COMMUNICATION SHARES OF VALUE-ADDED REVENUE (%)

	1990				2004			
	Computer	Software	Communication	Total ICT	Computer	Software	Communication	Total ICT
Private nonfarm economy	1.22	1.00	1.29	4.91	1.00	2.18	1.34	5.55
Mining	0.25	0.22	0.29	1.62	0.23	1.15	0.13	2.58
Manufacturing	1.08	0.93	0.44	3.60	0.62	2.73	0.29	4.83
Nondurables	0.88	0.75	0.33	3.70	0.71	2.67	0.32	5.54
Durables	1.23	1.07	0.52	3.52	0.56	2.78	0.27	4.32
Construction	0.06	0.05	0.02	0.20	0.27	1.22	0.55	2.38
Transportation	0.11	0.10	1.13	1.44	0.56	1.39	2.58	4.73
Communication[a]	1.27	1.12	24.03	26.89	2.56	4.56	20.60	28.05
Utilities	1.30	1.13	1.87	6.91	0.77	3.54	0.73	6.61
Information	2.33	2.19	15.62	21.16	1.95	5.24	13.05	20.62
Wholesale trade	1.47	0.44	0.63	4.21	1.39	1.06	1.15	4.20
Retail trade	0.94	0.34	0.36	2.10	0.60	0.56	0.52	1.94
Finance & insurance	3.14	3.14	0.73	8.71	1.89	2.29	0.35	5.07
Finance	4.56	3.74	0.97	11.63	2.31	2.08	0.40	5.44
Insurance	0.51	2.02	0.31	3.35	0.88	2.81	0.24	4.19
Business services & real estate	2.03	1.02	0.68	4.28	1.75	2.06	1.07	5.21
Business services	1.24	2.33	0.85	5.36	1.51	4.25	1.66	7.94
Real estate	2.51	0.20	0.57	3.62	1.92	0.49	0.65	3.25
Other services[b]	0.86	1.18	0.50	5.17	0.64	2.63	0.59	5.93
ICT-producing[c]	1.41	1.29	0.91	4.52	0.61	3.30	0.26	4.87
Non-ICT-producing	1.21	0.99	1.31	4.93	1.01	2.14	1.38	5.57
Well-measured industries[d]	1.02	0.65	0.60	3.38	0.75	1.79	0.72	4.07
Well-measured industries (excluding ICT-producing)	0.98	0.58	0.56	3.25	0.76	1.67	0.75	4.00
Poorly measured industries[e]	1.39	1.30	1.88	6.20	1.16	2.42	1.74	6.49

a. Communication includes broadcasting and telecommunications from the information industry aggregate.
b. Other services includes NAICS codes 61–62, 71–72, and 81, as well as the noncommunications elements of "information" (NAICS code 51, excluding 513).
c. ICT-producing industries includes machinery, computer and electronic products, and electrical equipment, appliances, and components.
d. Well-measured industries includes mining, manufacturing, transportation, utilities, and wholesale and retail trade.
e. Poorly measured industries includes construction, information, finance and insurance, real estate and rental and leasing, professional and business services, etc.

Source: Authors' calculations using payments to ICT capital from BLS and nominal value added from BEA.

negatively correlated with current ICT use.[20] This section updates their analysis.

Table 2 shows ICT shares in value added. For the entire private nonfarm economy, ICT accounts for about 5.6 percent of value added. Communications is a substantial outlier. Business services are ICT intensive. Finance was a substantial outlier in 1990, but returned to near average by 2004.

There is considerable uncertainty about how long it takes to build complementary capital and how long it takes for any spillovers to occur. The time lags depend on factors such as the time it takes to learn, innovate, and reorganize, which depends in turn on the adjustment costs associated with that complementary capital investment. Brynjolfsson and Hitt (2002) find evidence of long lags in firm-level data; Howitt (1998) calibrates a model to U.S. data, and finds that the beneficial effects of a new GPT will not show up in national accounts data for more than 20 years. Thus, our regressions need to be interpreted with a high degree of caution, and should be interpreted in the spirit of data exploration.

To capture the idea behind equation (11) in a loose way, Table 3 considers the following regression:

$$\Delta p_i^{00-04} - \Delta p_i^{90-00} = c + a\tilde{k}_i^{87-00} + b\tilde{k}_i^{00-04} + \varepsilon_i,$$

where Δp is gross-output TFP growth; we report results using $\tilde{k}$ for computers, software, and communications equip-

20. In subsequent work, Oulton and Srinivasan (2005) applied the BFOS framework to later U.K. data.

TABLE 3
ICT REGRESSIONS WITH CURRENT AND LAGGED ICT CAPITAL GROWTH

	All industries	Excluding outliers	Mfg.	Nonmfg.	Well-measured
C	–0.58	–0.60	0.47	–1.53	–0.83
	(0.35)	(0.41)	(0.32)	(0.63)	(0.47)
$\tilde{k}_{1987-2000}$	7.15	8.87	7.42	7.75	9.51
	(2.27)	(2.96)	(4.77)	(2.66)	(2.36)
$\tilde{k}_{2000-2004}$	–5.12	–7.72	–13.10	–3.62	–7.83
	(3.03)	(3.43)	(6.52)	(3.04)	(2.90)
R^2	0.22	0.20	0.34	0.35	0.27
Observations	37	34	15	22	29

Notes: Table shows regressions of $\Delta p_i^{00-04} - \Delta p_i^{90-00} = c + a\tilde{k}_i^{87-00} + b\tilde{k}_i^{00-04} + \varepsilon_i$, where Δp_i is the average industry TFP growth over the period specified and where $\tilde{k} = s_{K,IT}\, dk_{IT}$ uses computers, software, and communications equipment as the measure of ICT capital; $s_{K,IT}$ is the share in gross output. Robust standard errors are in parentheses. We omit ICT-producing industries.

ment (in all cases, the variables are averaged over the period shown):

$$\tilde{k} = s_{K,IT}\Delta \ln k_{K,IT},$$

where $s_{K,IT}$ is the share of computers and software in gross output (using value-added shares instead makes little qualitative difference to the results). This measure of $\tilde{k}$ drops the relative price terms from the alternatives discussed; BFOS found that results appeared more stable with this measure than when the relative price terms appeared, although qualitative results were generally similar.

Thus, we regress the acceleration in the 2000s, relative to the late 1990s, on $\tilde{k}$ for the 1990s, and on $\tilde{k}$ for the 2000s. Using the acceleration partially controls for differences in underlying growth rates across sectors.[21] (Separating out $\tilde{k}$ for the early and late 1990s led to multicollinearity problems—i.e., coefficients on the 1990s regressors were statistically insignificant, although in magnitude they remained similar to the combined coefficient a; the coefficient b was not (much) affected.) A virtue of the specification is that it imposes relatively minimal restrictions on lags and on coefficient stability, since the period averaging smoothes through some of that. Nevertheless, there is no reason to expect that the relationship will work equally well when applied to all time periods, since the link between ICT and unobserved intangible investment that we highlight in the model could easily vary over time and over industries. We also throw out ICT-producing industries, since they are such enormous outliers in the productivity dimension. (When we include the ICT-producing industries, results overall and within manufacturing are qualitatively similar but are very sensitive to outliers. Nonmanufacturing is not, of course, affected.)

Table 3 shows that, with long lags, ICT capital growth is positively associated with the industry TFP acceleration; but after controlling for past values, contemporaneous ICT capital growth is negatively associated with the acceleration. That is, $\tilde{k}_i^{87-00}$ enters positively but $\tilde{k}_i^{00-04}$ enters negatively. Thus, the productivity acceleration in the 2000s is somewhat consistent with the predictions of the theory section.

These results are robust to outliers. We identified influential observations (based on the Belsley-Kuh-Welsch "hat matrix" test).[22] When we omit those industries, in the second column, the standard errors go up, but so do the coefficients. We run the regression separately for manufacturing and nonmanufacturing, and the qualitative conclusions remain. In manufacturing, the current growth rate is particularly negative; in nonmanufacturing, the lagged growth rate is a bit more positive. When we look only at "well-measured" industries (basically, manufacturing plus a subset of nonmanufacturing, as discussed in the appendix), the magnitude and significance of the coefficients remains substantial.

These regression results are certainly preliminary and tentative. But they suggest that we can relate productivity growth to relatively current as well as lagged ICT investment in the cross section. Given that we are running an OLS regression, we cannot, of course, necessarily infer causation from the results. But the results are broadly consistent with the notion that ICT investments affect measured productivity growth with a long (and possibly variable) lag. Contemporaneously, they are correlated with a lot of diverted resources towards unmeasured complementary investment, and hence—once one controls for lagged growth rates—they are negatively correlated with output.

5. Conclusions

Even though ICT seems to be the major locus of innovation in the past decade, the TFP acceleration in the United States since the mid-1990s has been broad-based. We reconcile these observations by emphasizing the role of the complementary investments and innovations that ICT induces

21. A better way to do so would be a panel regression, since the model is inherently driven by time-series considerations. The panel setup would impose, however, that the dynamics were constant over time, which might not be the case. In any case, we have so far done only preliminary explorations in the panel dimension.

22. One standard statistical test is to look at the diagonal of the "hat" matrix, $X'(X'X)^{-1}X'$. For a regression with k coefficients and n observations, Belsley, Kuh, and Welsch (1980) identify influential observations as those where the diagonal element of the hat matrix exceeds $2k/n$.

in firms that use it. We thus link the literature on ICT as a general purpose technology with the literature on intangible capital. To the extent that there is unmeasured intangible output and unmeasured intangible capital, conventional TFP growth is a biased measure of true technical change. This GPT view suggests that productivity slowdowns and speedups might reflect the dynamics associated with complementary investment.

A fundamental difficulty, of course, is that complementary investment and capital are unmeasured. We present a simple theoretical framework in which observed ICT capital intensity and growth should serve as reasonable proxies. In line with this GPT view, the U.S. industry data suggest that ICT capital growth is associated with industry TFP accelerations with long lags of 5 to 15 years. Indeed, controlling for past growth in ICT capital, contemporaneous growth in ICT capital is negatively associated with the recent TFP acceleration across industries. More work remains to be done to explore the robustness of the theoretical framework—for example, allowing for different production functions for intangible investment and for final output—and for extending the empirical work. For example, we have not exploited the panel nature of the theory, nor have we explored the importance of the relative price of intangible capital. But we are encouraged by the preliminary results that link aggregate and industry-level U.S. TFP performance in the 2000s to both the persuasive macro models of GPTs and to the stimulating micro empirical work that supports the GPT hypothesis.

Appendix

Further Description of Industries[23]

The BEA publishes GDP-by-industry data for 61 private industries shown in the first column of the appendix table. To focus on private nonfarm industries, we first remove Farms (NAICS 111–112) and Forestry, Fishing, and Related Activities (NAICS 113–115).

Next, we sum up the BEA data for Motor Vehicles, Bodies and Trailers, and Parts (NAICS 3361–3363) and Other Transportation Equipment (NAICS 3364–3366, 3369) because the BLS capital data that we use has data only on their aggregate.

When we calculated TFP by disaggregated industry, we discovered that many subcategories of larger service industries had quite large fluctuations from year-to-year—with offsetting fluctuations in other, closely related subcategories. This could reflect differences in NAICS industry classifications across our data sources. We chain-aggregated these industries into broader aggregates, as indicated in the table. This 40-industry data set comprises three ICT-producing industries and 37 non-ICT-producing industries.

The table also shows other classifications used in the paper.

23. David Thipphavong contributed to the writing of this appendix.

TABLE A1
INDUSTRY LISTS USED IN SUBAGGREGATES AND REGRESSIONS

Industry name	NAICS 1997 Code	ICT prod.	Non-ICT prod.	Well-measured	Poorly measured	Mfg.	Non-mfg.
Farms	111-112						
Forestry, Fishing, and Related Activities	113-115						
Oil and Gas Extraction	211		X	X			X
Mining, except Oil and Gas	212		X	X			X
Support Activities for Mining	213		X	X			X
Utilities	22		X	X			X
Construction	23		X		X		X
Wood Products	321		X	X		X	
Nonmetallic Mineral Products	327		X	X		X	
Primary Metal Products	331		X	X		X	
Fabricated Metal Products	332		X	X		X	
Machinery	333	X					
Computer and Electronic Products	334	X					
Electrical Equipment, Appliances, and Components	335	X					
Transportation Equipment	336		X	X		X	
Motor Vehicles, Bodies and Trailers, and Parts	*3361-3363*						
Other Transportation Equipment	*3364-3366, 3369*						
Furniture and Related Products	337		X	X		X	
Miscellaneous Manufacturing	339		X	X		X	
Food, Beverage, and Tobacco Products	311-312		X	X		X	
Textile Mills and Textile Product Mills	313-314		X	X		X	
Apparel and Leather and Allied Products	315-316		X	X		X	
Paper Products	322		X	X		X	
Printing and Related Support Activities	323		X	X		X	
Petroleum and Coal Products	324		X	X		X	
Chemical Products	325		X	X		X	
Plastic and Rubber Products	326		X	X		X	
Wholesale Trade	42		X	X			X
Retail Trade	44, 45		X	X			X
Air Transportation	481		X	X			X
Rail Transportation	482		X	X			X
Water Transportation	483		X	X			X
Truck Transportation	484		X	X			X
Transit and Ground Passenger Transportation	485		X	X			X
Pipeline Transportation	486		X	X			X
Other Transportation and Support Activities	487, 488, 492		X	X			X
Warehousing and Storage	493		X	X			X
Information	51		X		X		X
Publishing Industries	*511*						
Motion Picture and Sound Recording Industries	*512*						
Broadcasting and Telecommunications	*513*						
Information and Data Processing Services	*514*						
Finance and Insurance	52		X		X		X
Fed. Res. Banks, Credit Intermed., and Related Activities	*521-522*						
Securities, Commodity Contracts, and Investments	*523*						
Insurance Carriers and Related Activities	*524*						
Funds, Trusts, and Other Financial Vehicles	*525*						
Real Estate and Rental and Leasing	53		X		X		X
Real Estate	*531*						
Rental and Leasing Svcs. and Lessors of Intang. Assets	*532-533*						
Professional and Business Services	54-56		X		X		X
Legal Services	*5411*						
Computer Systems Design and Related Services	*5415*						
Misc. Professional, Scientific, and Technical Services	*5412-5414, 5416-5419*						
Management of Companies and Enterprises	*55*						
Administrative and Support Services	*561*						
Waste Management and Remediation Services	*562*						
Educational Services, Health Care, and Social Assistance	61-62		X		X		X
Educational Services	*61*						
Ambulatory Health Care Services	*621*						
Hospitals and Nursing and Residential Care Facilities	*622-623*						
Social Assistance	*624*						
Arts, Entertainment, Recreation, Accommodation, and Food Services	71-72		X		X		X
Perf. Arts, Spectator Sports, Museums, and Related Activities	*711-712*						
Amusements, Gambling, and Recreation Industries	*713*						
Accommodation	*721*						
Food Services and Drinking Places	*722*						
Other Services, except Government	81		X		X		X

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