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The Case of the Missing Productivity Growth, or Does Information Technology Explain Why Productivity Accelerated in the United States but Not in the United Kingdom?

1. *Introduction*

After the mid-1990s, labor and total factor productivity (TFP) accelerated in the United States but not in most other major economies. A growing body of research has explored the robustness of the U.S. acceleration, generally concluding that the acceleration reflects an underlying technology acceleration. This research, along with considerable anecdotal and microeconomic evidence, suggests a substantial role for information and communications technology (ICT).[1]

In this paper, we seek fresh insights into the nature of the U.S. experience in an international comparative perspective. First, we focus narrowly but more deeply on the relative productivity performance of the United States and the United Kingdom. Second, to understand

*This work was undertaken while the author was at the Bank of England.

1. See Jorgenson (2001) or Jorgenson, Ho, and Stiroh (2002) for reviews of the empirical literature on the productivity acceleration and the role of information technology. We discuss this literature in greater detail later.

comparative productivity performance better, we do detailed growth accounting at an industry level for both countries. Third, we focus on the role of ICT, which many see as being at the heart of the productivity acceleration.

Why do we take this approach? First, the U.K. experience provides an intriguing counterpoint to both the U.S. and continental European experiences. In particular, overall macroeconomic performance looks similar to that of the United States, but productivity performance looks similar to that of the rest of Europe.

In terms of late 1990s macro performance, output growth in both the United States and the United Kingdom rose, investment surged, inflation moderated, and unemployment rates fell to levels that seemed implausible just a few years earlier. In the U.S. case, many commentators attributed this strong macroeconomic performance to the strong productivity growth. But in the U.K. case, both labor and total factor productivity growth *de*celerated rather than *ac*celerated. Hence, understanding the U.K. experience may provide insights into the U.S. experience.

In terms of cross-country productivity evidence, van Ark et al. (2002) and Gust and Marquez (2002), among others, document that TFP and labor productivity growth decelerated in the European Union overall and in Japan.[2] To the extent that one expects ideas—especially when embedded in easily traded physical capital—to diffuse easily across borders, the lack of a strong response abroad surprised many observers. Hence, understanding the lack of a productivity acceleration in the United Kingdom may provide insight into the anemic productivity performance elsewhere.

Second, we build up from industry data in order to understand the aggregate picture. Because of data limitations, most cross-country comparisons have used aggregate data. But many hypotheses about relative productivity growth—e.g., about the role of ICT—are observationally equivalent in aggregate data. To implement this bottom-up approach, we construct a new industry-level dataset for the United Kingdom that includes industry use of information technology. This approach allows us to isolate the sources of U.S. and U.K. productivity growth at an industry level.

Third, we seek to understand better the myriad roles of ICT in both countries. Much discussion has focused on the distinction between the use and production of ICT. In standard neoclassical growth accounting,

2. Gust and Marquez look at 13 industrialized countries. Compared with the 1980–1995 period, their data show a positive TFP acceleration in 1995–2000 for the United States, Finland, Sweden, Australia, and Canada.

the use of ICT leads to capital deepening, which boosts labor productivity. TFP growth in producing ICT goods shows up directly in the economy's measured TFP.

This standard growth accounting framework leads to the first question we ask of the data, for both the United States and the United Kingdom: were the 1990s a time of rising total factor productivity growth outside the production of ICT? Although existing work often seems to consider this an open question, our industry data strongly support the view that most of the TFP acceleration reflects an acceleration *outside* the production of ICT goods and software.[3] Even when we focus on arguably well-measured sectors (Griliches, 1994; Nordhaus, 2002), we find a substantial TFP acceleration outside ICT production.

The productivity acceleration in sectors that use ICT raises a deeper question: does ICT itself explain some or all of the measured acceleration in TFP in sectors using it? This question is at the heart of the debate over whether computers are a new general-purpose technology. Helpman and Trajtenberg (1998), for example, argue yes; Gordon (2003), rejects this notion. The main feature of a general-purpose technology (GPT) is that it leads to fundamental changes in the production process of those using the new invention. Chandler (1977) discusses several examples, such as how railroads allowed nationwide catalog sales, which in turn transformed retailing. David and Wright (1999) also discuss historical examples.

Indeed, the availability of cheap ICT capital is likely to effect truly major changes only if firms can, as a result, deploy their other inputs in radically different and productivity-enhancing ways. That is, if cheap computers and telecommunications equipment stimulates an ever-growing series of complementary inventions in industries using ICT, thereby continually shifting out the demand curve for ICT capital, then innovations in the production of ICT can have substantial long-run effects before diminishing returns set in.

Why do we focus so intently on relatively subtle arguments about the role of ICT? An important reason is that other explanations for the U.K. experience fall short. In particular, in this case of the missing productivity growth, we round up and interrogate the plausible suspects. Some are routine and can be dismissed quickly; others require deeper investigation, as the paper discusses. The suspects include the following:

3. In our view, more studies than not find a widespread acceleration in technology. See, for example, Basu, Fernald, and Shapiro (2001); Baily and Lawrence (2001); Bosworth and Triplett (2002); Council of Economic Advisers (2003); Jorgenson, Ho, and Stiroh (2002); Nordhaus (2002); Oliner and Sichel (2000); and Stiroh (2002a, 2002b). Gordon (2003) remains a skeptic.

1. Cyclical mismeasurement of inputs. Productivity is generally procyclical, rising sharply in the early phase of a business cycle upswing. Basu, Fernald, and Shapiro (2001) and the Council of Economic Advisers (2003), using different methods, conclude that the level of unobserved labor effort and capital utilization probably fell in the United States after the mid-1990s. For example, both capacity utilization and hours per worker fell over the second half of the 1990s. In the U.K. case, macro performance was stronger in the second half of the 1990s than in the first, making it unlikely that business-cycle considerations held down measured productivity.
2. Differences in national accounts methodology. The United States employs hedonic methods for some crucial ICT price indices (e.g., for computers), while the United Kingdom and many other countries do not. Also, the United Kingdom has only recently included software as a form of investment in gross domestic product (GDP). Is it possible that part of the difference between U.S. and U.K. performance is a statistical illusion? The dataset we use for the United Kingdom addresses this issue by using U.S. methodologies.[4]
3. Differences in regulation of product and labor markets. Many people suggest that inflexible labor and product markets prevent European countries from benefiting from new technologies and innovations. Gust and Marquez (2002), for example, find that countries with a more burdensome regulatory environment—particularly regulations affecting labor market practices—tended to adopt information technologies more slowly and also had slower total factor productivity growth. Gust and Marquez suggest that economies with more flexible labor and product markets should benefit first, and to a larger extent, than less flexible economies.

   But many of the institutional features—such as the extent of the labor and product market rigidities emphasized by Gust and Marquez—are similar in the United Kingdom and the United States. Thus, this suspect seems completely absent from the scene.
4. U.K. unemployment fell sharply. When unemployment falls, low-skilled workers are often the ones drawn disproportionately into the labor force, reducing measured labor and total factor productivity. We control for labor quality, but the productivity puzzle remains.
5. Differences in the size of the high-TFP-growth ICT-producing sectors. A larger ICT sector in the United States could explain at least some of the aggregate gap in productivity growth. But relative to GDP, the ICT-producing sectors are about the same size in the two countries (Oulton, 2001b). And even when outside ICT production, the U.S. data still

4. A detailed description of the sources and methods used to construct the U.K. dataset is available at www.nber.org/data (see the *Bank of England Industry Dataset*).

show a sharp productivity acceleration, whereas the U.K. data show an even sharper deceleration.

6. Intensity of competition. Although measures of regulation look similar across sectors, some commentators think that many sectors of the U.K. economy have less competitive pressure, and that this feature retards pressure for innovation. See Nickell, 1996, Lovegrove et al., 1998.[5]
7. Disruption costs associated with investment. Investment accelerated in both the U.S. and the U.K. data in the second half of the 1990s. Much of the literature suggests that because of various adjustment costs, measured output and productivity are lower in the period in which the investment takes place. Basu, Fernald, and Shapiro (2001) argue that in the second half of the 1990s, considerations of adjustment costs raise the magnitude of the U.S. acceleration in "true" technology relative to measured productivity; a similar calibration reduces the magnitude of the slowdown in U.K. productivity growth. But such calibrations don't resolve the puzzle, in part because they increase the acceleration in U.S. productivity at the same time.
8. The GPT nature of ICT capital. Benefiting from ICT requires substantial complementary investments in learning, reorganization, and the like, so that the payoff in terms of measured output may be long delayed. This is our main hypothesis. As it turns out, the evidence is much stronger for the United States than for the United Kingdom, where the evidence remains mixed. Much of the evidence for this hypothesis is circumstantial—the suspect's fingerprints are all over the crime scene.

What is the evidence for the GPT hypothesis? To begin, once we have confirmed that measured U.S. TFP accelerated strongly in non-ICT-producing industries during the late 1990s, we assess whether the acceleration in measured TFP is related to the use of ICT. We find that the U.S. results are quite supportive of 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, because these complementary investments are unmeasured, they can help explain the cross-industry and aggregate TFP growth experience of the United States in the 1990s. Specifically, we find that industries that had high ICT capital growth rates in the 1980s or early 1990s (weighted by ICT revenue shares, as suggested by theory) also had high TFP growth rates in the late 1990s. If we control for lagged capital growth, however, ICT capital growth in the late 1990s

5. A long literature has, of course, explored how competition affects innovation. Aghion et al. (2002) provide recent theoretical and empirical work and suggest that over some range, greater competition raises innovation.

was *negatively* correlated with contemporaneous TFP growth. These results are consistent with—indeed, predicted by—a simple model of unmeasured complementary capital investment.

Bolstered by these encouraging results for the United States, we ask whether complementary capital accumulation can explain the missing TFP growth in the United Kingdom in the second half of the 1990s. The aggregate data are encouraging: the United Kingdom had a huge ICT investment boom in the late 1990s—by some measures, a larger boom than the one labeled historic in the United States over the same period. The United Kingdom had had much lower ICT investment in the early 1990s due to a severe recession. And the U.S. results say that current TFP growth is positively correlated with lagged investment but negatively correlated with current investment—and on both counts measured U.K. TFP growth should have been low in the late 1990s.

However, results using industry-level U.K. data are more mixed. TFP growth does not appear correlated with lagged ICT capital growth, which could mean that lagged ICT capital growth is a poor proxy for unobserved U.K. complementary capital accumulation. Contemporaneously, rising ICT capital growth is positively, not negatively, correlated with the industry's TFP acceleration, although ICT *investment* growth (as the proxy for unobserved complementary investment) is negatively correlated. If the lags between ICT investment and unobserved complementary investment are shorter in the United Kingdom, then this finding, too, is consistent with the GPT story. However, the magnitude of the negative investment effect is too small to explain the pervasive TFP slowdown in U.K. industries. On the other hand, our results do suggest, albeit tentatively, that the United Kingdom could see an acceleration in TFP growth over the next decade.

In sum, we search for suspects in this case of the missing U.K. productivity growth. The crime is of particular interest because the most obvious suspect—differences in labor and product market regulations—appears to be absent from the scene. In our search for clues, we ask which sectors account for the productivity acceleration in the U.S. data, and explore whether those same sectors show an acceleration in the United Kingdom. We explore the role of ICT in the United States and the United Kingdom.

Although our tentative and incomplete answer to the puzzle emphasizes explanation 8—the GPT nature of ICT capital, and the different timing of U.S. and U.K. investment in ICT—more than one of the suspects may have conspired in the crime. For example, our explanation takes as given U.K. complementary investment and leaves open the question of why the timing differs. Other suspects may bear greater responsibility for that situation.

The organization of the paper is as follows. Section 2 compares recent U.S. and U.K. macroeconomic experience and makes some broader observations on the U.S. versus European experiences. Section 3 presents data and basic TFP results and also discusses some augmented growth accounting. Section 4 focuses more specifically on the potential role of information technology as a GPT. Section 5 provides empirical evidence on the importance of ICT in the United States and the United Kingdom, and provides some preliminary empirical results suggesting that the GPT story fits at least some of the facts. Section 6 concludes.

2. *Comparative U.S., U.K., and Continental European Macroeconomic Performance*

2.1 THE UNITED STATES AND THE UNITED KINGDOM

The U.S. economy performed admirably in many dimensions in the late 1990s. As Table 1 shows, output growth rose, investment surged, inflation moderated, and unemployment rates fell to levels that seemed implausible just a few years earlier. Many commentators attributed this macroeconomic strength to rapid productivity growth—linked particularly to information technology—which rose at a rate nearly double that of the preceding years. For example, the Council of Economic Advisers (2001, page. 245) stated that:

The economy this expansion has created is not just greater in sheer size but "new" in its structure and performance. It is dramatically more information intensive and more technology driven, more productive and more innovative. Today's economy utilizes new, more efficient business practices and has redefined many traditional relationships between suppliers, manufacturers, investors, and customers to achieve ever-greater efficiency. The cumulative result of these trends and their interactions is a New Economy, one that is currently providing Americans of all walks of life the benefits of high growth, low inflation, high productivity, rising incomes, and low unemployment.

As Table 1 shows, however, the United Kingdom shared many of these desirable macroeconomic features. Output rose more quickly than in the preceding period, investment boomed, unemployment rates fell sharply, inflation moderated. But in the United Kingdom, productivity growth does not appear to be the explanation for this strong macroeconomic

Table 1 MACRO PERFORMANCE: UNITED STATES VERSUS UNITED KINGDOM (ANNUAL PERCENTAGE CHANGE)[1]

United States									
		Whole economy						*Private nonfarm business*	
		GDP	*Bus. Fixed Inv.*	*Equip. and Soft. Inv.*	*Hours*	*Unemploy-ment*	*PCE[2] Inflation*	*Output/hour*	*TFP*
1980–1995		2.9	5.7	3.3	1.7	7.1	3.8	1.5	0.5
	1980–1985	3.1	6.8	4.5	1.4	8.3	5.0	1.8	0.5
	1985–1990	3.2	4.1	1.1	2.1	5.7	3.7	1.4	0.5
	1990–1995	2.3	6.2	4.3	1.7	6.7	2.7	1.5	0.6
1995–2000		4.0	10.5	8.4	2.5	5.4	1.9	2.5	1.1

United Kingdom									
		Whole economy						*Private nonfarm business*	
		GDP	*Bus. Fixed Inv.*	*Equip. and Soft. Inv.*	*Hours*	*Unemploy-ment*	*RPIX Inflation*	*Output/hour*	*TFP*
1980–1995		2.5	3.1	3.7	0.0	9.9	5.4	3.4	1.2
	1980–1985	2.1	3.2	3.9	–0.3	11.1	7.1	3.5	1.4
	1985–1990	3.1	7.0	6.5	2.0	9.0	5.2	2.6	0.6
	1990–1995	1.8	–0.8	1.1	–1.5	9.5	3.9	3.9	1.7
1995–2000		2.8	6.4	10.0	0.8	6.7	2.5	2.9	0.8

Sources: For the United States, GDP, business fixed investment, equipment and software investment, and PCE inflation are from the Bureau of Economic Analysis and (except for business fixed investment) refer to whole-economy averages. Unemployment rates are from the Bureau of Labor Statistics and are averages over the respective periods. Hours, output per hour, and TFP are from the Bureau of Labor Statistics multifactor productivity dataset, and cover the private nonfarm business sector. TFP incorporates an adjustment for labor quality.

1. For the United Kingdom, output, business fixed investment, hours, unemployment, and inflation are from the Office of National Statistics and (except for business fixed investment) refer to whole-economy averages. Equipment and software investment is from the Office of National Statistics and Oulton and Srinivasan (2003a). Output per hour and TFP are derived from the U.K. dataset constructed for this paper and cover the private nonfarm business sector. While the hours data match the aggregate, the output data differ from the national accounts because of adjustments to ICT investment in each industry and the output of the financial services industry. TFP incorporates an adjustment for labor quality.
2. PCE = personal consumption expenditure and RPIX = retail prices index excluding mortgage interest payments.

performance. Both labor and total factor productivity grew more slowly in the second half of the 1990s than in the first half.

2.2 BROADER REFLECTIONS ON EUROPEAN CONVERGENCE AND DIVERGENCE

Van Ark et al. (2002) provide a fairly comprehensive comparison of the European Union (E.U.) and the United States, using aggregate national accounts data. Their results cover 12 of the 15 E.U. countries, comprising 95 percent of E.U. gross domestic product (GDP) in 2000 (Belgium, Luxembourg, and Greece are excluded), for 1980–2000. They find that labor and total factor productivity grew much faster in the European Union than in the United States in the 1980s and the first half of the 1990s. Labor productivity rose by nearly 2½% per year, about 1¼ percentage points faster than in the United States. But in the second half of the 1990s, productivity decelerated in Europe, while the opposite occurred in the United States. As a result, in 1995–2000, labor productivity grew about ¾ percentage point per year faster in the United States than in the European Union.

With more detailed growth accounting, van Ark et al. find that some of this U.S. advantage reflected the higher contribution to labor productivity from ICT use, and some reflected a larger contribution of ICT production to TFP growth. But another important factor was that TFP growth in the non-ICT part of the economy fell sharply in Europe but rose in the United States. As we shall see, our consideration of the United Kingdom and the United States shows the same picture.

The recent divergence reflects a reversal in convergence forces. Until the 1990s, labor productivity generally grew more rapidly in Europe than in the United States. The reason seemed clear: the European productivity *level* was lower, so the Europeans were catching up. Table 2 shows that, in 1999, the level of labor productivity in the market sector of the United Kingdom lagged France and Germany as well as the United States. In particular, the United States led the United Kingdom by 39 percent, France by 22 percent, and Germany by 19 percent.

Intuitively, it is easier to grow when all you have to do is copy a successful example. And the neoclassical growth model predicts that countries with a lower level of capital will grow faster along the transition path. From this perspective, it was a surprise when the productivity gap between the United States and Europe started to widen again starting in about 1995.

Many popular accounts stress the U.S. strength in basic science and technological innovation. In addition, a vibrant venture capital industry is always eager to commercialize the results of the latest research. Hence,

Table 2 LABOR PRODUCTIVITY IN THE MARKET SECTOR, 1999 (UNITED KINGDOM = 100)[1]

Country	
United States	139
France	122
Germany	119
United Kingdom	100

1. Market sector is GDP, excluding public administration and defense, health, housing, and education, per hour worked, measured at purchasing power parities.
Source: O'Mahony and de Boer (2002, Table 7).

one popular interpretation of the productivity acceleration is that the United States benefited from rapid leading-edge creation of knowledge in producing high-tech goods; other industries then benefited from the presumed relatively cost-free adoption of these new technologies, i.e., by capital deepening.

Such an account is not altogether compelling. First, some of the basic technological innovations were, in fact, European in origin. For example, if any one person can be said to have invented the World Wide Web, that person was an Englishman, Tim Berners-Lee (not Al Gore). In the 1980s, Berners-Lee created the essential elements of the Web—URLs, HTML, HTTP, and Web browser and Web server programs—while employed at CERN, the European center for research in particle physics.[6]

Second, if the difference were just science and basic innovation, with technology adoption by other sectors, one could reasonably expect the revival to diffuse relatively quickly—e.g., personal computers (PCs) and other new technologies developed in the United States could be quickly installed in Europe as well. In other words, if the issue were simply that the ideas were initially developed and implemented in the United States, then the European failure to experience a comparable revival would be particularly puzzling.

Third, as we discuss in Section 3, much of the measured productivity acceleration reflects an acceleration in TFP in sectors *other* than those producing ICT. So the U.S. story goes beyond simple capital deepening, which in principle could be easily replicated elsewhere.

6. See Berners-Lee (1999). Of course, the Web relies on the Internet, which provides the physical infrastructure and low-level software protocols like TCP/IP. In the 1970s, the U.S. Defense Department funded the Internet, and initially its commercial use was banned. But the government did not claim ownership of the intellectual property, and it permitted key personnel to quit and set up companies to exploit the new technology (Abbade, 1999).

If the U.S. advantage is not simply its capability in basic science and technological innovation, then what is it? As we discuss later, many stories of the benefits of ICT emphasize that adopting new technologies requires substantial complementary investments (such as reorganizations) and co-inventions. Gust and Marquez (2002), following Greenspan (2000) and Feldstein (2001), promote essentially this story in arguing that labor and product market regulations prevent many countries in Europe from benefiting fully from new technologies because the regulations inhibit necessary reorganizations.

2.3 STRUCTURAL REFORM IN THE UNITED KINGDOM

If the United Kingdom has not yet benefited from ICT to the same extent the United States has, it is not because of inflexible labor markets, burdensome regulation, or the dead hand of government control of industry—all those factors summed up under the label "Eurosclerosis." The United Kingdom now ranks highly on measures of competitiveness, labor market flexibility, ease of starting a business, and freedom from burdensome regulations; in all these areas, Card and Freeman (2001) argue that the United Kingdom's rank is similar, and sometimes superior, to that of the United States.

Why does the United Kingdom appear to have a more flexible economy than does continental Europe? The rise of Margaret Thatcher to power in 1979 set in motion an extensive program of structural reform. This program continued under her Conservative successor, John Major, prime minister from 1990 to 1997. The elements of reform most relevant in the present context were fivefold. First, the government abandoned the attempt to control inflation through wage and price controls; these methods had been employed in increasingly restrictive form since the 1950s but had become particularly important in the aftermath of the first oil shock in 1973. Second, it reduced the legal privileges of the trade unions (e.g., secondary picketing was banned), while also increasing the rights of individual members vis-à-vis their own union (e.g., requiring ballots before strikes could be called). Third, it began privatizing the "commanding heights" of the British economy—steel and telecommunications, and later the utilities (gas, electricity, and the water supply), coal mining, and the railways. Where elements of natural monopoly existed, as in telecommunications and the utilities, independent regulators were set up. Fourth, it announced that it would cease to "bale out lame ducks": no company was now "too important to fail." This new policy was largely adhered to and was cemented by selling off commercial companies that had for various reasons fallen into government ownership (e.g., Rolls Royce, British Aerospace, British Airways, and the United Kingdom's national champion in the car industry, then known as British Leyland). Fifth, financial markets were deregulated and almost all exchange controls were abolished.

The Labour government that came to power in 1997 announced in advance that it did not intend to reverse the reforms of the Thatcher-Major period. It has continued the process of privatization. For example, air traffic control services are now supplied by a private company, not a government agency as in the United States. Immediately after it came to power, the new government gave the Bank of England operational independence in monetary policy. A Monetary Policy Committee was established at the Bank with the remit of meeting a target for inflation set by the chancellor of the exchequer: this target was (and has continued to be) 2.5% per annum as measured by the Retail Prices Index excluding mortgage interest payments (RPIX). The new government also announced a framework of rules for fiscal policy.

Apart from law and order, defense, health, and education, the government owns or directly controls little of the economy. In 1999, less than 30% of the labor force were members of a trade union, down from 50% in 1980; collective-bargaining agreements now cover fewer than 36% of the labor force, down from 68%, over the same period (Nickell and Quintini, 2001). The bulk of union members work in the public sector; as in the United States, private sector union membership is now quite low. The kind of regulation found in some European countries, which makes it costly to close plants, does not exist in the United Kingdom.

In sum, as Card and Freeman (2001) argue, the United Kingdom's reform program has reversed the process of relative economic decline that became apparent in the 1960s and 1970s.[7] Nor does weak U.K. productivity performance reflect a failure of macroeconomic policy. Inflation peaked at an annual rate of about 9½% in late 1990 but then declined steadily toward what became the target rate of 2.5% in mid-1997; since then, inflation has fluctuated in a narrow range. The unemployment rate (the internationally comparable International Labour Organization definition) peaked in early 1993 at 10.7% and has been reduced by half since.

Lest this should seem too rosy a picture, one long-standing weakness continues to hamper the U.K. economy: a low level of skills (see Table 3). In 1999, the share of the U.K. labor force with a college degree or higher was little more than half the U.S. share. Although the U.K. share was sim-

7. The underlying weaknesses of the U.K. economy and the extent to which these have been alleviated by policy are discussed in Bean and Crafts (1996), Oulton (1995), and Crafts and O'Mahony (2001). O'Mahony and de Boer (2002) compare productivity levels and growth rates across countries.

ilar to France and Germany, the U.K. proportion with vocational qualifications was also much lower.

Other aspects of policy may also be relevant. For example, some have argued that U.K. town and country planning laws limit the expansion of new forms of retailing (Lovegrove et al., 1998). More generally, Nickell (1996) argues that competition promotes productivity growth. But historically, U.K. law has been much more lenient toward uncompetitive behavior than has been the case in the United States. (This situation may now be changing with the coming into force in 2000 of the 1998 Competition Act.)

3. *Data and Preliminary Empirical Results*

We begin with results from standard growth accounting to establish some stylized facts. Doing so will help us dismiss a few potential explanations for the productivity divergence and hence help motivate our later focus on the general-purpose nature of ICT.

We focus on disaggregated, industry-level results for total factor productivity. Even if one is interested in aggregate outcomes, such a disaggregated approach is helpful. Any number of stories can be told to explain a single time series like GDP or GDP per worker. It is often difficult to reject a particular hypothesis using just aggregate data. Here sectoral and industry data can help. In addition, if one wishes to explore the differences between the ICT-producing and ICT-using sectors, then it is natural to disaggregate.

In this section, first we describe briefly our datasets; then we discuss results. Finally, we consider and reject several sources of measurement error as explanations for our results.

3.1 U.S. DATA

We use a 51-industry dataset that updates one used in Bosworth and Triplett (2002) and Basu, Fernald, and Shapiro (2001). For industry gross

Table 3 LABOR FORCE SKILLS, 1999

Percentages at different levels	*Higher: college degree level or higher*	*Intermediate: post–high school vocational qualifications*	*Low: high school only or below*
United States	27.7	18.6	53.7
France	16.4	51.2	32.4
Germany	15.0	65.0	20.0
United Kingdom	15.4	27.7	56.9

Source: O'Mahony and de Boer (2002, Table 5).

output and intermediate-input use, we use industry-level national accounts data from the Bureau of Economic Analysis (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 two-digit industry. Gross output is not available before 1977, and for some industries is not available before 1987.[8,9]

Several issues should be kept in mind. First, we do not have industry measures of labor quality, only raw hours. We do incorporate an aggregate adjustment for labor quality in our top-line numbers, using an index calculated by Aaronson and Sullivan (2001). (Their index is relatively close to that produced by the BLS.) Second, the BEA industry data come from the income-side of the national accounts, which accelerated faster than the expenditure side in the late 1990s, as is well known. It is not clear which side of the national accounts is more reliable; the Council of Economic Advisers, for example, takes an agnostic view and uses a geometric average for growth accounting. This approach is not possible with industry-level data.

The detailed industry definitions differ a bit from those in the United Kingdom. To simplify comparisons in summary tables, we aggregate to approximately a one-digit level, where definitions are reasonably close.

3.2 U.K. DATA

We use a new industry dataset, developed at the Bank of England, containing data for 34 industries spanning the whole U.K. economy and running from 1979 to 2000.[10] For each industry, we have gross output

8. We thank Jack Triplett for sending us the industry dataset that merged the BEA and BLS data. We updated the BEA data to incorporate November 2002 national income and product account (NIPA) industry revisions and also removed owner-occupied housing. The BEA labor compensation data do not include proprietors or the self-employed, so we follow Bosworth and Triplett in using BLS data that correct for these omissions. We thank Larry Rosenblum at the BLS for sending us unpublished industry hours data, which makes adjustments for estimated hours worked by nonproduction and supervisory employees as well as the self-employed. We updated the BLS capital data from http://www.bls.gov/web/prod3.supp.toc.htm (accessed December 2002). We follow Bosworth and Triplett and exclude several service sectors where consistent input or output data are unavailable: holding and other investment offices, social services, membership organizations, and other services. We *do* include those industries in the ICT capital-by-industry data reported later in the paper.
9. Jorgenson, Ho, and Stiroh (2002) use different industry data sources; unfortunately, their dataset was not publicly available as of November 2003. The Brookings Institution (2002) discusses key differences across datasets.
10. Outton and Srinivasan (2003b) describes the industry input, output, and ICT capital data and is available on request.

and inputs of capital services, labor services, and intermediates, in both nominal and real terms. Capital services cover three types of ICT and four types of non-ICT capital. The non-ICT assets are structures, plant and machinery (equipment), vehicles, and intangibles. The three ICT assets are computers, software, and communications equipment. The real capital input index is a rental-price weighted average of the growth rates of these asset stocks. The real intermediate index is a weighted average of purchases from all the other industries and from imports.

Labor services are measured as hours worked and are built up in several steps. First, we estimate total usual hours for each industry. Second, we apply two aggregate adjustments. The first is to constrain the growth of total hours to conform with the official index of aggregate hours worked. This method allows for cyclical variability in hours, though at the same rate in all industries. The second aggregate adjustment is to apply a correction for changes in labor quality, mainly due to rising levels of educational attainment (quality change is discussed below).

Prior to several adjustments described below, the dataset is reasonably consistent with the official U.K. national accounts in both real and nominal terms, which is important because otherwise any story based on industry data will not be convincing as an explanation of what is happening at the macro level.

For making comparisons with the United States, we need to use the same methodology to derive ICT capital services in both countries. Therefore we assume that computers and software depreciate geometrically at rates similar to those used in studies of the United States (e.g., Jorgenson and Stiroh, 2000), which are in turn based on those used by the Bureau of Economic Analysis. We also employ U.S. price indices, converted to sterling terms, to deflate investment in current prices. U.S. ICT price indices generally fall faster than those in the United Kingdom, which means that our ICT capital and investment measures will grow more rapidly. The United Kingdom is also an ICT producer, so we have made corresponding adjustments to the growth rates of output of the ICT industries.

In addition, we have made a large adjustment to the official nominal level of software investment, multiplying it by a factor of 3, for reasons discussed by Oulton (2001b) and (2002). Compared with the United States, official software investment is very low relative to computer investment, and a much lower proportion of the sales of the computer services industry is classified as investment. The "times 3" adjustment can be justified as putting the two countries on the same footing methodologically.

3.3 EXONERATING TWO OF THE SUSPECTS

We briefly expand on two broad data issues related to the challenge of cross-country data comparability. First, the official U.K. statistics do not control for hedonics in the same way or to the same degree that the U.S. national accounts do. Second, the United Kingdom had an even larger decline in unemployment than the United States did, which could reduce overall productivity if those pulled into the labor force have lower-than-average skills and productivity. Neither story explains the divergent performance of U.K. and U.S. productivity because, as noted above, our U.K. industry data incorporate adjustments for these two issues.

First, what difference do the computer hedonics make? National accounts in Europe (including the United Kingdom), have, so far, lagged in introducing satisfactory methods for measuring ICT, leading to implausibly large variation across countries in computer price indices (Schreyer, 2002). Indeed, the main weakness of U.S. methods of measuring ICT is that they don't go far enough. For example, there is no true price index for investment in custom and own account software (two-thirds of the total), only for prepackaged software (Parker and Grimm, 2000). And within telecommunications, hedonic methods are only just starting to be introduced (Grimm, Moulton, and Wasshausen, 2002).

A related issue is that, although measured GDP in both Europe and the United States now includes software investment, different methodologies lead to substantial differences in estimated levels (Lequiller, 2001). Hence, cross-country comparisons again need to use a comparable methodology.

Most researchers have dealt with these issues by applying as far as possible U.S. methods to other countries. However, this approach does not necessarily transform European productivity performance because inputs as well as output grow faster (see again Schreyer, 2002). Oulton (2001b) finds that U.S. methodology raises the growth rate of U.K. GDP by about one-third of a percentage point per annum in the last half of the 1990s. Despite this, aggregate labor productivity still slowed down over this period.[11]

Second, why isn't declining labor quality quantitatively important in explaining the divergence? We apply an index of U.K. labor quality (con-

11. Gust and Marquez (2000) and van Ark et al. (2002) also find that differences in national accounts methodology cannot explain the productivity growth gap between the United States and Europe.

structed by Burriel-Llombart and Jones, 2004). As is standard, we define labor quality as the growth of quality-adjusted labor input minus the growth of unweighted total hours.[12] The unemployed do tend to have below-average skills or qualifications and falling unemployment indeed contributed to a lower growth rate of labor quality from the first to the second half of the 1990s. But other factors affected U.K. labor quality, such as increasing female participation; declining participation by older, unskilled men; and (of particular importance) the retirement or death of older, less qualified people and their replacement by younger, better qualified workers. In both countries, we find that labor quality growth was positive throughout the 1990s, though in both the rate of growth also decelerated.[13]

3.4 RESULT FROM TRADITIONAL GROWTH ACCOUNTING

Tables 4 and 5 provide standard estimates of TFP for various aggregates, including the one-digit industry level. The first three columns show TFP in gross-output terms. 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 final column shows the sector's nominal value-added share.[14]

We start by discussing the U.S. results in Table 4, focusing on the value-added measures. The top line shows the sizable acceleration in TFP growth, from about 0.6% per year to about 1.9%.[15] These calculations incorporate labor quality adjustments from Aaronson and Sullivan (2001), shown in the second line. Labor quality growth grew more slowly in the second half of the 1990s, when the booming economy drew lower skilled workers into employment. Hence, adjusting for

12. Quality-adjusted hours is a Törnqvist index of hours worked by 40 groups, where each group's hours are weighted by its share of the aggregate wage bill. The groups consist of four qualifications groups (degree, A level, O level, and "other") and five age groups (covering ages 16–65), for each gender.

13. See the second line in both Tables 4 and 5. It is labeled "(adjusted for labor quality)."

14. With Törnqvist aggregation, 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 total more than 1. In continuous time, this is equivalent to first converting gross-output residuals to value-added terms by dividing by (1 minus the intermediate share), and then using shares in nominal value added. (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 (2001a).

15. As noted earlier, the acceleration exceeds that in the product-side BLS data shown in Table 1.

Table 4 UNITED STATES: TOTAL FACTOR PRODUCTIVITY (TFP) GROWTH BY INDUSTRY IN PRIVATE NONFARM BUSINESS, 1990–2000 (Percentage change, annual rate)

	Productivity (gross output terms)[2]			*Productivity (value-added terms)*[3]			*Share of nominal value added (2000)*
	Pre-1995	*Post-1995*	*Acceleration*	*Pre-1995*	*Post-1995*	*Acceleration*	
Private nonfarm economy (adjusted for labor quality)[1]	0.30	0.98	0.68	0.59	1.92	1.32	100.0
Contribution of labor quality	*0.16*	*0.09*	*−0.08*	*0.32*	*0.16*		
Private nonfarm economy (*not* adjusted for labor quality)	0.47	1.06	0.60	0.91	2.08	1.17	
Mining	1.61	−1.16	−2.77	3.08	−2.15	−5.23	1.6
Manufacturing	0.86	0.97	0.11	2.40	2.76	0.36	20.6
Nondurables	0.34	−0.39	−0.73	1.02	−1.20	−2.22	8.7
Durables	1.34	2.08	0.74	3.47	5.61	2.14	12.0
Construction	0.22	−0.58	−0.80	0.39	−0.98	−1.38	6.1
Transportation	0.83	0.77	−0.06	1.69	1.53	−0.16	4.2
Communication	1.47	0.01	−1.46	2.31	0.15	−2.16	3.7
Electric/gas/sanitary	0.27	0.11	−0.16	0.42	0.17	−0.25	2.9
Wholesale trade	1.08	3.39	2.32	1.66	5.37	3.71	9.2
Retail trade	0.49	3.23	2.74	0.83	5.33	4.50	11.8

Finance and insurance	0.24	1.95	1.72	0.44	3.39	2.96	10.7
Finance	0.86	2.96	2.10	1.31	4.90	3.59	7.5
Insurance	−0.81	0.05	0.86	−1.49	−0.06	1.44	3.2
Business services and real estate	0.68	0.24	−0.45	1.12	0.40	−0.72	13.9
Business services	0.41	−0.89	−1.30	0.60	−1.40	−2.00	7.1
Real estate	0.87	1.27	0.40	1.55	2.34	0.79	6.8
Other services	−1.19	0.05	1.24	−1.89	0.08	1.97	15.2
ICT-producing[4]	2.41	4.43	2.02	5.52	11.02	5.50	5.3
Non-ICT-producing	0.32	0.80	0.48	0.61	1.54	0.93	94.7
Well-measured ind.[5]	0.82	1.44	0.62	1.80	3.17	1.37	54.2
Well-measured (excluding ICT-producing)	0.62	1.04	0.42	1.35	2.24	0.88	48.9

1. For productivity purposes, our definition of private nonfarm business excludes holding and other investment offices, along with miscellaneous services, because consistent input and output data are unavailable for these industries.
2. A sector's gross output TFP growth is calculated as a weighted average of the industry-level gross output TFP growth rates; the weight for each industry is the ratio of its Domar weight to the sum of the Domar weights for that sector.
3. Value-added TFP growth is defined as (gross output TFP growth)/(1 − share of intermediate inputs). Implicitly, this uses the Törnqvist index of value added for a sector.
4. For the United States: ICT-producing includes industrial machinery and electronic and other electrical equipment sectors.
5. For the United States and the United Kingdom: Well-measured industries include mining, manufacturing, transportation, communication, electric/gas/sanitary, and wholesale and retail trade.

Table 5 UNITED KINGDOM: TOTAL FACTOR PRODUCTIVITY (TFP) GROWTH BY INDUSTRY IN PRIVATE NONFARM BUSINESS, 1990–2000 (Percentage change, annual rate)

	Productivity (gross output terms)[1]			*Productivity (value-added terms)*[2]			*Share of nominal value added (2000)*
	1990–1995	*1995–2000*	*Acceleration*	*1990–1995*	*1995–2000*	*Acceleration*	
Private nonfarm economy with quality adjusted labor input	0.79	0.35	−0.44	1.72	0.78	−0.94	100.0
Labor quality adjustment	*0.39*	*0.21*	*−0.18*	*0.84*	*0.48*	*−0.37*	
Private nonfarm economy with nonquality adjusted labor input	1.18	0.56	−0.62	2.56	1.25	−1.31	100.0
Mining	5.69	0.89	−4.79	9.20	1.34	−7.86	3.8
Manufacturing	1.11	0.51	−0.59	3.03	1.42	−1.61	23.2
Nondurables	1.04	−0.03	−1.07	2.81	−0.07	−2.89	15.7
Durables	1.26	1.57	0.31	3.52	4.57	1.05	7.5
Construction	0.67	−0.31	−0.98	1.77	−0.84	−2.61	6.6
Transportation	1.62	0.50	−1.12	3.46	1.18	−2.28	6.5
Communication	3.26	2.61	−0.65	4.83	4.77	−0.06	3.9
Electric/gas/sanitary	1.22	0.99	−0.24	3.11	2.61	−0.50	3.1
Wholesale trade	2.22	2.13	−0.09	3.44	3.71	0.28	6.8
Retail trade	0.38	−0.58	−0.96	0.73	−1.17	−1.90	13.0

Finance and insurance	0.90	1.56	0.66	1.89	3.87	1.98	6.2
Finance							
Insurance							
Business services and real estate	0.64	0.53	–0.11	1.13	0.99	–0.14	21.0
Business services							
Real estate							
Other services	1.06	0.10	–0.96	2.05	0.19	–1.86	5.7
ICT-producing[3]	1.45	3.75	2.30	3.82	10.46	6.64	3.3
Non-ICT-producing	1.16	0.41	–0.75	2.52	0.93	–1.59	96.7
Well-measured ind.[4]	1.38	0.59	–0.79	3.10	1.37	–1.73	60.5
Well-measured (excluding ICT-producing)	1.37	0.37	–1.00	3.90	0.45	–3.45	57.2

1. A sector's gross output TFP growth is calculated as a weighted average of the industry-level gross output TFP growth rates; the weight for each industry is the ratio of its Domar weight to the sum of the Domar weights for that sector.
2. Value-added productivity growth equals (gross output productivity growth)/(1 – share of intermediate inputs).
3. For the United Kingdom: ICT-producing comprises electrical engineering and electronics (SIC92 30–33).
4. For the United Kingdom: well-measured industries comprise mining, manufacturing, transportation, communication, electricity, water and gas supply, wholesale, retail trade, and waste treatment.

labor quality growth heightens the magnitude of the TFP acceleration calculated with raw hours (shown in the third line, calculated as the appropriate weighted average of the industry TFP growth rates shown in the table).

The remainder of the table shows various subaggregates (none of which incorporate a labor quality adjustment), including the one-digit SIC level. Our dataset shows clearly that acceleration was not limited to the ICT-producing sectors. First, if we focus on the non-ICT producing sectors (third line from the bottom), they show an acceleration of nearly one percentage point. In an accounting sense, these sectors contribute about 0.9 percentage points of the 1.2 percentage point total (non-quality-adjusted) acceleration. Major non-ICT sectors contributing to the acceleration include wholesale trade, retail trade, finance, and insurance.

Second, Griliches (1994) and Nordhaus (2002) argue that real output in many service industries is poorly measured—e.g., it is often difficult even conceptually to decide on the real output of a bank or a lawyer; as another example, in health care, the hedonic issues are notoriously difficult. Nordhaus argues for focusing on what one hopes are the well-measured (or at least, better measured) sectors of the economy. The acceleration in TFP in well-measured industries is even larger than the overall acceleration; the acceleration is sizable even when we exclude ICT-producing sectors.

Table 5 shows the comparable table for the U.K. economy. Between the first and second halves of the 1990s, productivity growth fell in the U.K. private nonfarm economy by about one percentage point, even after adjusting for the much slower growth in labor quality in the second half of the 1990s. Looking at major industries, TFP growth (unadjusted for labor quality) rose substantially in finance/insurance and manufacturing durables, but it was flat or it declined in most other major sectors.

By contrast, aggregate productivity growth rose in the United States by 1.3 percentage points per annum (Table 4), so the difference in acceleration was about 2.3 percentage points. Given this broad difference, there are some similarities in the sectoral pattern across the two countries. For example, the productivity acceleration was much faster in durables than in nondurables; finance and insurance surged.

A closer look at the sectoral data shows a major difference between the United States and the United Kingdom in the trade sectors, especially retail. U.S. retail value-added TFP growth *rose* by 4.5 percentage points per year; U.K. TFP growth *fell* by about 1.7 percentage points.

Nevertheless, they are not the entire story. Even excluding them, the U.S. data still show an acceleration, whereas the U.K. data still show a deceleration.[16]

The fact that the U.S. productivity acceleration was broadbased is consistent with a growing body of recent work. For example, the Council of Economic Advisers (2003) reports that between 1973–1995 to 1995–2002, non-ICT TFP accelerated sharply, with its contribution to U.S. growth rising from 0.18 percentage points per year to 1.25 percentage points, roughly in line with the figures here.[17] Bosworth and Triplett (2002) focus on the performance of service industries and find a widespread acceleration. Jorgenson, Ho, and Stiroh (2002) also find that TFP accelerated outside ICT production, although by a smaller amount.

3.5 AUGMENTED GROWTH-ACCOUNTING CONSIDERATIONS

Some researchers have investigated whether the results cited here are robust to deviations from the standard assumptions of growth accounting, generally concluding that they are. Using different methodologies, Basu, Fernald, and Shapiro (2001); the Council of Economic Advisers (various years); and Baily and Lawrence (2001) find that cyclical mismeasurement of inputs plays little if any role in the U.S. acceleration of the late 1990s. Basu, Fernald, and Shapiro (2001) also find little role in the productivity acceleration for deviations from constant returns and perfect competition.

Basu, Fernald, and Shapiro (2001) do find a noticeable role for traditional adjustment costs associated with investment. Because 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. In other words, if adjusting the capital stock incurs costs and faster growth leads to higher costs, then true technological progress was faster than measured. These considerations strengthen the conclusion that the technology acceleration was broadbased because

16. Wholesale and retail trade account for about three-quarters of the U.S. acceleration (Domar weighted industry TFP growth) and one-third of the U.K. deceleration. The McKinsey Global Institute (2001) provides anecdotal as well as quantitative evidence on the transformation of wholesale and retail trade; Foster, Haltiwanger, and Krizan (2002) link the retail industry data to firm-level developments. Note that Jorgenson, Ho, and Stiroh (2002), who use output data from the BLS Office of Employment Projections, do not find as important a contribution from the trade sectors.

17. The CEA methodology is very similar to that of Oliner and Sichel (2002), who report *no* TFP acceleration outside ICT production. But Oliner and Sichel discount their finding on this score because their method takes non-ICT TFP as a residual. Because the Oliner and Sichel endpoint is a recession year, 2001, they point out that any cyclical effects on productivity are forced to show up in non-ICT TFP. In addition, the CEA measure of labor productivity is a geometric average of income- and product-side measures of output per hour.

service and trade industries invested heavily in the late 1990s and hence paid a lot of investment adjustment costs.

The United Kingdom had even more sharply rising investment than did the United States, so conceivably adjustment costs might be masking an underlying improvement in U.K. productivity growth. From 1990–1995, aggregate investment in the U.K. private nonfarm economy fell at 0.45% per year; over 1995–2000, it rose at 8.60% per year.[18] So how much of the decline in U.K. productivity growth might be attributable to adjustment costs? Following Basu, Fernald and Shapiro (2001), we calibrate these costs as a parameter ϕ times the growth rate of investment; following Shapiro (1986), they take ϕ to be 0.035.[19] This calibration implies that investment adjustment costs held down measured TFP growth by about 0.30 percentage points per year over 1995–2000, but boosted it by 0.02 percentage points over 1990–1995. Hence, the slowdown in true productivity growth was about 0.63, not 0.95, percentage points per annum, and adjustment costs might account for about one-third of the observed productivity deceleration.

Of course, the same correction would raise the U.S. technology acceleration by a bit under 0.2 percentage point.[20] Hence, although this correction makes a larger difference to the U.K. data, it doesn't reverse the U.K. decline or even noticeably narrow the gap with the United States.

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

The U.S. productivity acceleration coincided with accelerated price declines for computers and semiconductors but, as we just saw, most of the TFP acceleration appears to have taken place outside 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 (GPT) and then present a simple model to clarify the issues and empirical implications.

18. This estimate uses the same data employed to estimate capital services in the United Kingdom at the industry level.

19. Shapiro does not estimate different values of ϕ for IT and non-IT capital; one could imagine that the values differ. We hope to estimate these values in future work.

20. These numbers are qualitatively the same but smaller than those reported in Basu, Fernald, and Shapiro (2001) for three reasons. First, we have added an extra year of data (2000) in which investment growth was weak. Second, data revisions have reduced the growth rate of investment in the second half of the 1990s. Third, Jason Cummins and John Roberts pointed out a mistake in our conversion from Shapiro (1986)'s framework to ours. This led us to reduce our estimate of ϕ from 0.048 in Basu, Fernald, and Shapiro (2001) to 0.035 in this work.

4.1 GENERAL-PURPOSE TECHNOLOGIES: "SPOOKY ACTION AT A DISTANCE"

Standard neoclassical growth accountants identify several effects of ICT on aggregate labor and total factor productivity growth. Faster TFP growth in *producing* ICT contributes directly to aggregate TFP. In addition, the *use* of ICT contributes directly to labor productivity through capital deepening: by reducing the user cost of capital, falling ICT prices induce firms to increase their desired capital stock.[21]

Standard growth accounting does not presume that the use of ICT has any particular effect on TFP. By contrast, many microeconomic, firm-level, and anecdotal studies suggest that there are important—but often indirect and hard to foresee—potential roles for ICT to affect measured production and productivity in sectors using ICT. Conceptually, one can separate these potential links into two categories: purposeful co-invention, which we interpret as the accumulation of complementary capital, which in turn leads to mismeasurement of true technology; and externalities of one sort or another.

These indirect effects arising from general-purpose technologies such as ICT are akin to what Einstein, in the context of particle physics, called "spooky action at a distance": quantum physics predicts that, in some circumstances, actions performed on a particle in one location instantaneously influence another particle that is arbitrarily far away. In terms of the effects of ICT, an innovation in one sector, ICT, often causes unexpected ripples of co-invention and co-investment in sectors that seem almost arbitrarily far away. Many of the GPT stories (e.g., Bresnahan and Trajtenberg, 1995; Helpman and Trajtenberg, 1998) fall in the "spooky action" camp. (Of course, Einstein's spooky action was instantaneous; the effects of GPTs are not.)

First, firm-level studies suggest that benefiting from ICT investments requires substantial and costly co-investments in complementary capital.[22] For example, firms that use computers more intensively may reorganize production, thereby creating intangible capital in the form of organizational knowledge. These investments may include resources diverted to learning; they may involve purposeful innovation arising from research and development (R&D). As Bresnahan (undated) argues,

21. Tevlin and Whelan (2000) and Bakhshi et al. (2003) provide econometric evidence for the United States and the United Kingdom, respectively, that falling relative prices of ICT equipment fueled the ICT investment boom.

22. 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. David and Wright (1999) provide a historical reflection on general-purpose technologies.

"[A]dvances in ICT shift the innovation possibility frontier of the economy rather than directly shifting the production frontier;" that is, ICT *induces* co-innovation and co-investment by firms using the technology, with long and variable lags.

The resulting organizational capital is analogous to physical capital because companies accumulate it in a purposeful way. Conceptually, we can think of this complementary capital as an additional input into a standard neoclassical production function; it differs from ordinary capital and labor because it is not directly observed but must somehow be inferred.[23]

Second, the GPT literature suggests the likelihood of sizable 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 is often 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 the mistakes made by others.[24] Indeed, firms that *don't* use computers more intensively may also benefit from spillovers of intangible capital. For example, if there are sizable 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.

These GPT 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.

Note that the spooky action nature of the co-inventions and externalities suggests that we should not expect the benefits of ICT to diffuse quickly across borders. First, if large complementary investments and innovations are necessary, diffusion will inevitably take time. Second, Bresnahan and Trajtenberg (1995) note that co-invention often requires

23. 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 Yorokoglu (1997), Hornstein and Krusell (1996), Hall (2001), and Laitner and Stolyarov (2001).

24. Bresnahan (undated) discusses the channels for externalities to operate. Bresnahan and Trajtenberg (1995) highlight both vertical externalities (between general-purpose technology producers and each application sector) and horizontal externalities (across application sectors).

"coordination between agents located far from each other along the time and technology dimension" (p. 3), so that institutional arrangements and market structure—which affect the ability to contract successfully in an environment with asymmetric information and uncertain property rights—are likely to matter; these factors are likely to differ across countries. Third, adoption costs may differ across countries, just as they seem to differ across firms, so that low adjustment/adoption cost countries may adopt new technologies first. These differences in cost may reflect the presence or absence of complementary factors—business school–trained managers, for example—or the vintage structure of the existing capital stock.[25] Finally, spillover effects may be stronger at closer distances (e.g., within Silicon Valley).

In looking at the United States versus the United Kingdom, this discussion makes clear the difficulty of the task at hand: we need to find a way to infer unobserved complementary investments. That is, the United States could be benefiting from past intangible investments in knowledge and reorganization, leading to high measured TFP growth; the United Kingdom might have begun heavy intangible complementary investment only more recently, diverting resources from production of market output and appearing to have low TFP growth. We now turn to a formal model that suggests variables that might act as proxies for these unobservables.

4.2 INDUSTRY-LEVEL IMPLICATIONS OF ICT AS A NEW GPT: A SIMPLE MODEL

The last ten years, and especially the last five, have seen an explosion in papers modeling the effects of general-purpose technologies (GPTs) and interpreting the ICT revolution as the advent of such technology.[26] But it is quite 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;

25. Chandler (1977), for example, highlights the rise of professional managerial skills. In addition, new technologies may be somewhat specific to a country's particular cultural and institutional arrangements—society's general organization, infrastructure, social capital, and the like. In other words, appropriate technology may matter even in comparisons of U.S. versus U.K. companies. This is related to the literature on factors that affect the costs of adopting a new GPT. Helpman and Trajtenberg (1998), for example, have some interesting examples of which industries adopted semiconductors first—e.g., hearing aids and computers, where the existing technology was inadequate—and which adapted late, notably telecom and automotives, with a large body of vintage capital.

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

and even for observed variables, measurement conventions often depart from those used in national accounting.[27]

On the other hand, conventional industry-level growth-accounting studies of the sort reviewed and extended in Section 3 are typically hard to interpret in terms of GPT considerations because they generally lack a conceptual, general equilibrium 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 not know if they had, in fact, found it.

Finally, as discussed above, a large empirical literature, often using firm-level data or case studies, stresses the importance and costly nature of organizational change accompanying ICT investment. This literature, while important and insightful, rarely makes contact with economywide productivity research.[28] In many ways, our empirical work below is a tentative attempt to make just 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. Our 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 its use to be truly beneficial. For empirical implementation, we focus on industries that use the GPT.

Value added in industries that use, but do not produce, IT is given by[29]:

$$Q_{it} \equiv Y_{it} + A_{it} = F(Z_t G(K_{it}^{IT}, C_{it}), K_{it}^{IT}, L_{it}) \qquad (1)$$

where, $i = 1 \ldots N$, and F and G are homogeneous of degree 1 in their arguments. Z is a technology term that each industry takes as exogenous. We discuss the distinction between A and Y shortly. For simplicity, we ignore materials input (although we add it back in our empirical work), imperfect competition, increasing returns, and capital adjustment costs. All could be added, at the cost of considerable notation.

27. 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 measuring (attempting to measure) capital input in efficiency units. Howitt (1998) attempts to bridge the two conventions.

28. An exception is Brynjolfsson and Yang (2001).

29. With constant returns and competition, one can speak of firms and industries interchangeably. "An industry does x" is our shorthand for "all firms in an industry do x."

Each industry rents ICT capital K^{IT} and non-ICT capital K^{NT} in competitive, economywide markets. The aggregate stocks of the two types of capital evolve as:

$$K_t^{JT} = I_t^{JT} + (1 - \delta^{JT}) K_{t-1}^{JT} \tag{2}$$

where

$J = I, N$

Industries must, however, individually accumulate their stocks of complementary capital, C. We think of this capital as business and organizational models or training in the use of IT, and the investment flow A as the time and resource cost of training and creating new business structures.[30] Industries forego producing market output Y to accumulate this capital:

$$C_{it} = A_{it} + (1 - \delta_C) C_{it-1} \tag{3}$$

We assume that investment in all three kinds of capital is irreversible. Because 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 the ICT capital stock. The difference from the point of view of measurement is that Y is measured in the national income accounts, but A is not.[31]

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 Inadalike conditions such 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 accumulate C is also very strong.

Note that conceptually and as traditionally construed, innovation 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, for example, the component of organizational change that spills over from the sector of origin—for example, the idea of using individual

30. Chandler (1977) discusses innovations in inventory management made possible by railroads. Wal-Mart's inventory management system provides an example of innovations made possible by ITC.

31. 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).

electric motors at each workstation in a factory rather than relying on the single drive train of a steam engine.

4.3 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:

$$\Delta q = \frac{F_{K^{IT}} K^{IT}}{Q} \Delta k^{IT} + \frac{F_C C}{Q} \Delta c + \frac{F_{K^{NT}} K^{NT}}{Q} \Delta k^{NT} + \frac{F_L L}{Q} \Delta l + s_G \Delta z \tag{4}$$

Because we have made Solow's assumptions of constant returns to scale and perfect competition, we have

$$\frac{F_{K^{IT}} K^{IT}}{Q} + \frac{F_C C}{Q} + \frac{F_{K^{NT}} K^{NT}}{Q} + \frac{F_L L}{Q} = 1 \tag{5}$$

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^{NT}. Rewrite equation (6) as:

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

Because Q/Y^{NT} 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 conventional Solow residual:

$$\begin{aligned}\Delta y^{NT} - \frac{P_{K^{IT}} K^{IT}}{PY^{NT}} \Delta k^{IT} - \frac{P_{K^{NT}} K^{NT}}{PY^{NT}} \Delta k^{NT} - \frac{F_L L}{Q} \Delta l \equiv \Delta TFP = \\ \frac{F_C C}{Y^{NT}} \Delta c - \frac{A}{Y^{NT}} \Delta a + s_G \Delta z\end{aligned} \tag{7}$$

We see that omitting complementary inputs can cause us either to overestimate or to underestimate TFP growth. 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 a steady state, of course, the accumulation equation implies that $\Delta c = \Delta a$, which in turn implies that the steady-state mismeasurement is

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

where r^* is the steady-state real interest rate. In a dynamically efficient economy, the mismeasurement is necessarily positive: true steady-state TFP growth is *lower* than measured, not higher.

This point is a simple one, but it is a quantitatively important correction to statements in the existing literature (e.g., Bessen, 2003).[32] Of course, if one corrects only output mismeasurement (Δa), then ICT will appear fantastically productive, far beyond what is ordinarily measured. But firms choose to divert resources to unobserved investment Δa to create an intangible capital stock that 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. In light of the firm-level evidence, observed growth in ICT capital provides a reasonable proxy. Suppose G takes a CES form:

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

We consider the optimization subproblem of producing G at minimum cost, which firms solve every period. The solution of the subproblem is:

$$\Delta c_t = \Delta k_t^{IT} + \sigma \Delta p_t^{IT} \tag{8}$$

where Δp_t^{IT} is the change in the relative rental rate of ICT capital to C capital. This equation implies a direct link between growth in complementary capital and growth of observed ICT capital.

32. Laitner and Stolyarov (2001) also stress the importance of including complementary capital in a growth accounting exercise.

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

$$\Delta TFP = \left[\frac{F_C C}{Y^{NT}} - \frac{C}{Y^{NT}}\right]\left[\Delta k_t^{IT} + \sigma \Delta p_t^{IT}\right] + \left[\frac{C}{Y^{NT}}\frac{(1-\delta_C)}{(1+g)}\right]\left[\Delta k_{t-1}^{IT} + \sigma \Delta p_{t-1}^{IT}\right] + s_G \Delta z \tag{9}$$

The first term is proportional to $(r^* + \delta - 1)$, so under reasonable circumstances it is negative. The second term, on the other hand, is clearly positive. Hence, our GPT-type framework implies that firms or industries that invest substantially in GPTs have lower current measured output but higher future measured output; that is, other things being equal, industries that are making large IT investments today will have low measured TFP growth, but those that made such investments in the *past* will have high measured TFP growth. (This discussion is independent of any externalities, which may also be important.)

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

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

or

$$\frac{C}{Y^{NT}} = \frac{PC}{P_K K^{IT}}\frac{P_K K^{IT}}{PY^{NT}} = \left[\left(\frac{1-\alpha}{\alpha}\right)^{\sigma}\right]\left(\frac{P_K}{P}\right)^{1-\sigma} s_{K^{IT}}$$

In the convenient Cobb-Douglas case, the C/Y^{NT} ratio is proportional to the observed ICT share; other things being equal, the mismeasurement of complementary capital is more important in those industries where ICT capital is used to a greater extent—a reasonable conclusion.

$$\Delta TFP = \left[F_C - 1\right]\beta \tilde{k}_t + \left[\frac{(1-\delta_C)}{(1+g)}\right]\beta \tilde{k}_{t-1} + s_G \Delta z \tag{10}$$

where $\tilde{k}_t = \left(\frac{P_K}{P}\right)^{1-\sigma} s_{K^{ICT}}\left[\Delta k_t^{ICT} + \sigma \Delta p_t^{ICT}\right]$

$$\beta = \left(\frac{1-\alpha}{\alpha}\right)^{\sigma}$$

As an alternative way of implementing equation (7), can we take ICT investment as a direct proxy for unobserved complementary capital investment? Combining the accumulation equations for complementary capital and ICT capital implies:

$$\frac{A_{it}}{C_{it}} = \frac{I_{it}}{K_{it-1}} + \left(\delta_C - \delta_{ICT}\right) + \sigma \Delta p^{ICT}$$

If $\delta_C = \delta_{ICT}$ and $\sigma = 0$, then $\Delta a = \Delta i^{ICT}$, which implies:

$$\begin{aligned} \Delta TFP_{it} &= F_C \tilde{k}_{it} - \left(\frac{PA}{P_I I}\right)\left(\frac{P_I I}{PY}\right) \Delta i_{it}^{ICT} + s_G \Delta z_{it} \\ &= F_C \tilde{k}_{it} - b\tilde{i}_{it} + s_G dz_{it} \end{aligned} \tag{11}$$

where $\tilde{i}_{it} = s_{it}^I \, \Delta i_{it}^{ICT}$

Note that the capital and investment terms incorporate the income share of complementary capital and the share of complementary investment in output, which are likely to differ greatly across industries. So we are assuming that the complementary shares are correlated across industries with the ICT shares.

When is equation (10) preferable to equation (11)? The key issue is the lag between ICT investment and complementary investment. For example, suppose a company invested heavily in an expensive enterprise resource management system in the mid-1980s and then spent the next decade learning how best to reorganize and thus benefit from the improved information availability. Then equation (10)—with long lags—should work well. By contrast, if the reorganization were contemporaneous with the ICT investment, then equation (11) should work well (assuming the other conditions involved in deriving it are not too unreasonable) and there might not be long lags.

Our method of using cost-minimization conditions to act as proxies for unobserved variables from observables is common in the literature on cyclical productivity with unobserved factor input (utilization).[33] As in that literature, the method can imply a fairly elaborate proxy, which may not be easy to estimate. Given that fact, should we try to follow Hall (2001) and several other authors, who measure the importance of organizational capital from the gap between firms' stock market valuations and the replacement values of their physical capital?[34]

We do not do so, for two reasons. First, given the importance of the issue, it is interesting to investigate a different approach to estimation and see if we get roughly the same answer. Second, given the recent large swings in equity markets, we are wary of any attempt to impute the real

33. See, for example, Basu and Kimball (1997).

34. See Brynjolfsson and Yang (2001) for an example of this alternative approach.

service flow of the stock of organizational capital from stock-market valuations. Setting aside the usual concerns about stock-market bubbles, suppose the recent fall in equity prices is due to the realization that much of the current ecapital will become obsolete sooner than previously expected. This information will appropriately lead to a lower market value of the capital, but it does not imply that its current real service flow into production must be lower.[35]

4.4 EXTENSIONS TO THE BASIC FRAMEWORK

Clearly, the implications of a new GPT for measured productivity growth are subtle and may be hard to distinguish from alternatives. But the theory does suggest that one needs lags of ICT capital growth in the TFP equation, in addition to the current growth rate.[36]

One complication is that the externality captured in Δz can be a function of industry C_i as well as aggregate C. In that plausible case, one can no longer tell whether the capital growth terms in equation (9) represent accumulation of a private stock, or externalities that are internalized within the industry. Similarly, if we find that lagged Δk^{IT} 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.

In addition, a free parameter is the length of a period, a point on which the theory gives us no guidance. The lagged Δk^{IT} may be last year's ITC 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.

One additional concern is whether other variables should enter the production function for A, which we do not account for here. Our framework implicitly assumes the same production function for A and Y. But it is possible, as many have recognized, that the production of complementary

35. Formally, capital aggregation theory shows that the service flow of capital is proportional to the value of the stock only if depreciation occurs at a constant, exponential rate. A large, one-time capital loss is an excellent example of a nonconstant depreciation rate. Jovanovic and Rousseau (2003) make exactly the same argument about changes in stock-market valuation when a GPT is introduced. But given the false starts and dead ends that often accompany a recently introduced GPT, their logic should apply equally to episodes after the GPT is introduced but before it has become a mature technology. (Think, for example, of DC power generation in the United States.)

36. Hence one needs to generalize the approach followed by, e.g., Stiroh (2002b), who argues against a spillovers/GPT story by regressing TFP growth on only the current-year growth rate of IT capital. Brynjolfsson and Hitt (2002) also find significant lags in firm-level data, which dovetails our more aggregative evidence.

capital is particularly intensive in skilled (i.e., college-educated) labor.[37] This hypothesis is particularly interesting given the noticeable difference between the United States and the United Kingdom in the fraction of skilled workers that we documented in Table 3. If true, the hypothesis implies that the relative price of accumulating complementary capital may differ significantly between the two countries (and perhaps among industries within a country) in ways that we may not be able to capture.

5. *Evidence for the GPT Hypothesis*

5.1 EMPIRICAL EVIDENCE ON THE ROLE OF ICT

We concluded earlier that much of the U.S. acceleration in measured TFP reflects an acceleration outside the production of ICT products. TFP can move around for many reasons unrelated to ICT. For example, it could be that the United States experienced broadbased managerial innovations that raised TFP growth throughout the economy. Nevertheless, the previous section suggests that the acceleration—and managerial innovations—could be associated with the use of ICT.

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; Wolff, 2002). But given the GPT nature of ICT, the contemporaneous correlation need not be positive—even if ICT is, in fact, an important contributor to measured TFP.

Wolff does find that U.S. industries investing heavily in ICT have greater changes in their occupational mix and the composition of intermediate inputs, consistent with substantial reorganization. Gust and Marquez (2002) find that, in a sample of industrial countries, those with a more burdensome regulatory environment—particularly regulations affecting labor market practices—adopted ICT more slowly and also had slower TFP growth. Those findings are consistent with the notion that the uptake of ICT could affect measured TFP in the sectors using the ICT.[38]

37. In a different framework, Krueger and Kumar (2003) 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 (2002).

38. In terms of standard growth-accounting, van Ark et al. (2002) compare the United States and the European Union by applying U.S. deflators for ICT and equipment. Earlier comparisons by Daveri (2002) and Schreyer (2000), using private sector sources for ICT investment and stocks, and Colecchia and Schreyer (2002), using national accounts data, find results broadly consistent with those of van Ark et al. who find that the European Union and the United States had similar ICT growth rates over 1980–2000. But the European Union had a lower *level* of ICT investment. Consequently, the income share of ICT is much lower in the European Union. As a result, van Ark et al. (2002) find a smaller direct ICT contribution via capital deepening in the European Union.

As discussed in Section 2, the Gust-Marquez regulatory variables look similar in the United States and the United Kingdom. But an open question is whether, for other reasons, U.S. society was better able to undertake the disruptions associated with reorganization than was the United Kingdom (or other countries).

5.2 THE CROSS-INDUSTRY PATTERN OF ICT USE IN THE UNITED STATES AND THE UNITED KINGDOM

A small number of U.S. and U.K. industries account for a large share of ICT use. For example, the finance/insurance and business services/real estate sectors have a disproportionate share of computers and software; communications uses a majority of communications equipment. Manufacturing, which accounts for about one-fifth of GDP in both countries, has only 14 to 16% of computers and software in the two countries.

Tables 6 and 7 show one measure of the importance of ICT capital—the ICT income share, i.e., the ratio of profits attributable to ICT capital to value added. Between 1990 and 2000, the income share of ICT in the United Kingdom increased by almost 50%, rising from 4.30% to 6.26%. The biggest rises occurred in communication (+10.1%), wholesaling (+3.5%), and nondurables (+2.66%). The overall share is now above the corresponding figure for the United States, 5.50%, which rose by much less in the 1990s. In short, on this measure, the United Kingdom has caught up.

These income shares are central for growth accounting because the contribution of ICT capital to output growth uses these shares as weights on growth in ICT capital services. These shares are now similar, which means that we expect a given growth in ICT capital to have the same impact on output growth. In addition, the GPT model above suggests that unobserved complementary capital should be closely related to observed share-weighted ICT capital growth (perhaps with an adjustment for the relative price of ICT).

5.3 CROSS-INDUSTRY EVIDENCE ON THE ROLE OF COMPLEMENTARY INVESTMENT

We now present some preliminary cross-sectional industry evidence for the United States and the United Kingdom that is, broadly speaking, consistent with the hypothesis that complementary investment associated with ICT has macroeconomic consequences. In particular, we explore the correlations between productivity growth (or the productivity acceleration) in the second half of the 1990s and various measures of ICT growth.

Such regressions are, of course, fraught with the potential for misspecification, given the uncertainty about how long it takes to build complementary capital and how long it takes for any spillovers to occur. In addition, given the difficulty of identifying valid instruments, all of our regression results are ordinary least squares (OLS); they capture any correlation between true non-ICT-related industry productivity growth and the accumulation of ICT capital, regardless of the direction of causation (if there is any causation at all). It follows that all our regressions need to be interpreted with a high degree of caution, and they should be interpreted in the spirit of data exploration. Nevertheless, the results suggest that the GPT model does help illuminate the effects of ICT on productivity.

We begin by estimating equation (10). One important difficulty in implementing this equation is that we don't know the length of time over which it should operate. The time lags depend on factors such as the time it takes to learn, innovate, and reorganize, which depends in large part 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 be detected in conventional national accounts data for more than 20 years.

To capture these notions in a loose way, we consider the following:

$$\Delta p_i^{1995-2000} = c_i + a\tilde{k}_i^{1995-2000} + b\tilde{k}_i^{1990-1995} + c\tilde{k}_i^{1980-1990} + \varepsilon_i$$

In this regression, $\tilde{k}^{1995\text{-}2000}$, for example, represents the average value of $\tilde{k}$ for computers and software over the period 1995 to 2000.[39] Thus, we regress average industry TFP growth over the 1995–2000 period on average share-weighted computer and software capital growth in the 1980s, early 1990s, and late 1990s. (We ignore the relative price terms in these regressions.)

We take this equation for each industry as a cross-sectional observation. This approach imposes an identical constant term on each industry, so that any industry-specific fixed effects show up in the error term.[40] Thus, this regression will tell us, simply as a matter of data description, whether we can relate productivity growth to relatively current as well as lagged ICT investment in the cross section. Because we are running an OLS regression, we cannot, of course, infer causation from the results. But this regression tells us whether productivity growth from 1995–2000 was larger in industries that had rapid share-weighted ICT growth in the late or early 1990s, the 1980s, or none of the above. (With minimal restrictions on the timing and stability; these are likely to differ across industries.) In the results that follow, we omit ICT-producing industries to focus on links between ICT *use* and TFP. (Including ICT producers generally has little

39. The regressions including communications equipment as part of ICT gave results that were less significant—arguably because of lack of sufficient adjustment for quality change in communications equipment.

40. We find similar results for a specification that removes these fixed effects by making the dependent variable the *change* in TFP growth from 1990–1995 to 1995–2000.

Table 6 UNITED STATES COMPUTER, SOFTWARE, AND COMMUNICATION SHARES OF VALUE-ADDED REVENUE (Percentage)

	1990				*2000*			
	Computer	*Software*	*Communication*	*Total ICT*	*Computer*	*Software*	*Communication*	*Total ICT*
Private nonfarm economy	1.35	1.24	1.70	4.29	1.60	2.31	1.59	5.50
Mining	0.18	0.15	0.32	0.65	0.27	0.36	0.13	0.77
Manufacturing	1.09	0.94	0.56	2.59	1.32	1.81	0.61	3.74
Nondurables	0.76	0.66	0.31	1.73	1.00	1.37	0.53	2.89
Durables	1.48	1.26	0.84	3.58	1.74	2.32	0.71	4.77
Construction	0.42	0.37	0.12	0.91	2.89	4.01	1.19	8.09
Transportation	0.16	0.14	1.52	1.82	0.64	0.87	2.44	3.95
Communication	1.23	1.09	30.51	32.83	1.70	2.51	24.81	29.01
Electric/gas/sanitary	1.33	1.14	3.18	5.65	1.25	1.66	3.10	6.01
Wholesale trade	2.78	2.48	0.87	6.12	4.37	5.34	1.19	10.91
Retail trade	1.03	0.85	0.20	2.08	1.04	1.35	0.31	2.69

Finance and insurance	3.35	3.56	1.16	8.06	2.60	5.22	0.87	8.69
Finance[1]	3.90	4.16	1.38	9.44	3.01	6.09	0.98	10.08
Insurance	1.97	2.06	0.59	4.62	1.55	2.99	0.61	5.15
Business services and real estate	1.98	1.86	0.64	4.48	1.87	2.08	0.47	4.43
Business services	4.75	4.48	0.95	10.17	3.44	3.82	0.70	7.96
Real estate	0.05	0.04	0.42	0.50	0.13	0.14	0.23	0.49
Other services	0.69	0.62	0.25	1.56	0.67	1.23	0.27	2.16
ICT-producing[2]	1.84	1.57	1.39	4.80	2.49	3.29	0.83	6.60
Non-ICT-producing	1.32	1.23	1.73	4.28	1.56	2.27	1.64	5.47
Well-measured ind.[3]	1.15	0.99	2.39	4.53	1.58	2.06	2.41	6.06
Well-measured (excluding ICT-producing)	1.08	0.94	2.53	4.55	1.51	1.96	2.59	6.06

1. "Holding and other investment offices" data were included in finance, and other services contains more services than had been previously defined for our calculations of productivity.
2. For the United States: ICT-producing includes industrial machinery and electronic and other electrical equipment sectors.
3. For the United States and the United Kingdom: Well-measured industries include mining, manufacturing, transportation, communication, electric/gas/sanitary and wholesale and retail trade.

Source: Authors' calculations using payments to ICT capital from the Bureau of Labor Statistics and nominal value added from the Bureau of Economic Analysis.

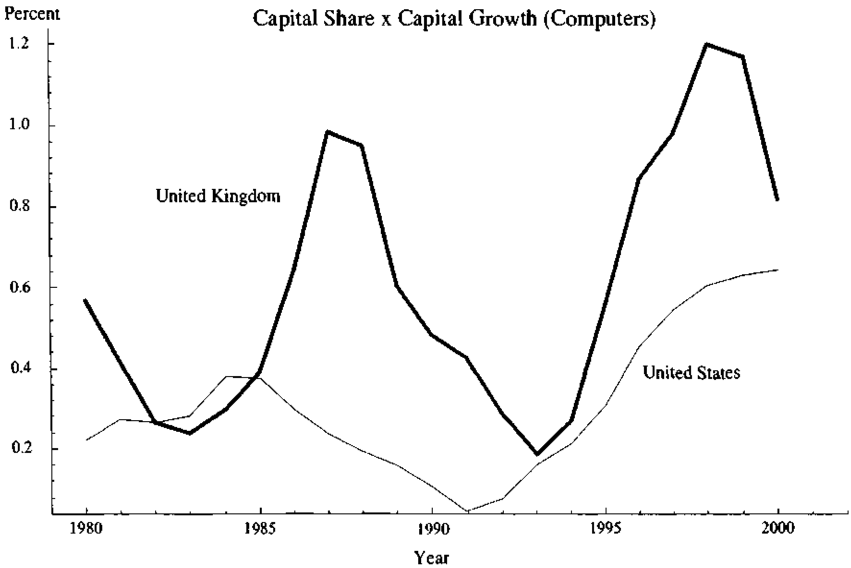
Table 7 UNITED KINGDOM: COMPUTER, SOFTWARE, AND COMMUNICATION SHARES OF VALUE-ADDED REVENUE (Percentage)

	1990				*2000*			
	Computer	*Software*	*Communication*	*Total ICT*	*Computer*	*Software*	*Communication*	*Total ICT*
Private nonfarm economy	1.97	1.58	0.75	4.30	2.82	2.59	0.85	6.26
Mining	0.04	0.11	0.22	0.37	0.02	0.22	0.11	0.35
Manufacturing	0.68	1.08	0.29	2.05	1.74	1.25	0.29	3.28
Nondurables	0.53	0.97	0.47	1.98	2.41	1.55	0.68	4.64
Durables	0.75	1.13	0.20	2.08	1.41	1.11	0.11	2.62
Construction	0.31	2.85	0.49	3.65	0.41	3.11	0.26	3.78
Transportation	0.35	0.35	0.02	0.73	1.10	1.32	0.02	2.44
Communication	1.12	0.22	6.85	8.19	5.51	2.03	10.72	18.26
Electric/gas/sanitary	0.78	0.65	0.83	2.25	1.34	1.10	0.86	3.30
Wholesale trade	2.99	1.55	0.89	5.43	4.74	4.12	0.55	9.40
Retail trade	1.03	0.95	1.28	3.26	1.21	1.46	0.55	3.22

Finance and insurance	5.51	5.90	0.05	11.46	4.75	8.53	0.09	13.37
Finance								
Insurance								
Business services and real estate	6.13	1.84	0.39	8.37	5.70	3.74	0.58	10.02
Business services								
Real estate								
Other services	1.55	1.20	1.37	4.12	1.58	1.88	1.16	4.61
ICT-producing[1]	0.81	1.87	1.21	3.88	2.79	2.61	0.83	6.23
Non-ICT-producing	1.49	1.25	0.60	3.34	2.74	2.57	0.82	6.13
Well-measured ind.[2]	0.91	0.90	0.90	2.71	2.00	1.59	1.05	4.64
Well-measured (excluding ICT-producing)	0.92	0.84	0.88	2.64	1.90	1.55	1.03	4.48

1. For the United Kingdom: ICT-producing comprises electrical engineering and electronics (SIC92 30-33)
2. For the United Kingdom: well-measured industries comprise mining, manufacturing, transportation, communication, electricity, water and gas supply, wholesale, retail trade, and waste treatment.

Figure 1 CAPITAL SHARE × CAPITAL GROWTH



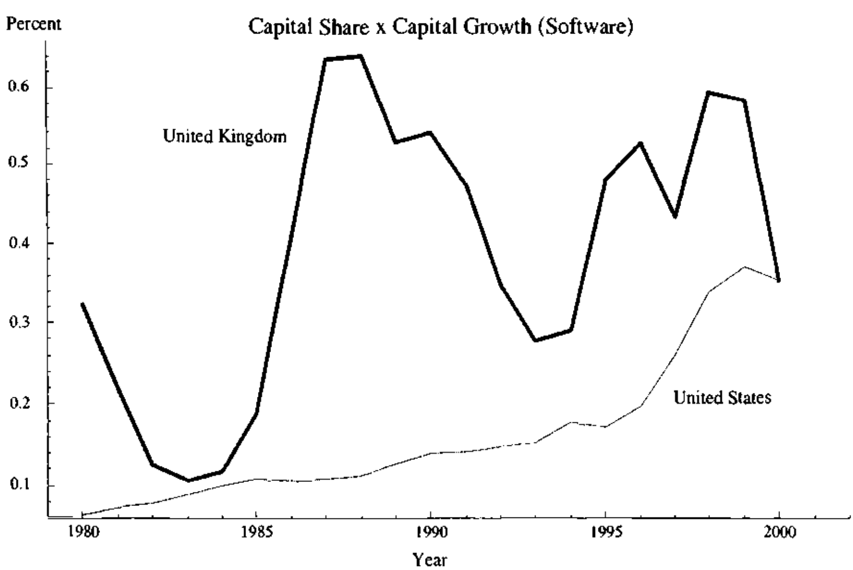


Table 8 ICT REGRESSIONS WITH CURRENT AND LAGGED ICT CAPITAL GROWTH[1]

	United States	*United Kingdom*
C	−0.001	−0.09
	(0.003)	(0.48)
$\tilde{k}_{1980-1990}$	4.1	1.39
	(7.2)	(3.56)
$\tilde{k}_{1990-1995}$	17.4	0.65
	(5.7)	(2.80)
$\tilde{k}_{1995-2000}$	−8.9	0.65
	(4.8)	(1.48)
Poorly*C	0.011	−0.18
	(0.0058)	(0.48)
Poorly* $\tilde{k}_{1980-1990}$	15.3	2.77
	(7.7)	(3.56)
Poorly* $\tilde{k}_{1990-1995}$	−8.1	−1.60
	(6.6)	(2.80)
Poorly* $\tilde{k}_{1995-2000}$	−10.1	−2.60
	(5.8)	(1.48)
R^2	0.38	0.10
Observations	49	28

1. Using $\tilde{k} = S_K \Delta \ln k$ as right-hand regressor, with computers and software as measure of capital. Robust standard errors in parentheses. We omit ICT-producing industries (this omission has relatively little effect on coefficients).

effect on coefficients.) We report results for only the measures of $\tilde{k}$ described above—i.e., for share weighted computer-and-software capital growth.

Figure 1 plots the individual components (computers and software capital) of this measure in the United Kingdom and the United States. The figure shows substantial fluctuations over time for $\tilde{k}$ in the United Kingdom and a more stable pattern for the United States, especially since 1990. This measure of $\tilde{k}$ drops the relative price terms from the alternatives discussed; regression results below appeared more stable with this measure than with the alternatives, although qualitative results were generally similar.

The first column of Table 8 shows that, for the United States, the data are reasonably consistent with the predictions of the theory section that, with long lags, ICT capital growth should be positively associated with TFP growth and that, controlling for past investments, contemporaneous ICT capital growth should be negatively associated with TFP growth. The data definitely want different coefficients across the well-measured and poorly measured groups, which we have addressed by interacting a poorly measured dummy with all right-hand-side variables.[41]

41. The point estimates give a reasonable summary of what happens when we estimate regressions for the two groups separately.

We find that, for both groups, ICT capital investments in the 1980s are positively correlated with the TFP acceleration in the late 1990s. For the poorly measured industries, ICT capital investments from the early 1990s were also positively associated with the TFP acceleration. In the late 1990s, by contrast, share-weighted capital growth is negatively correlated with the TFP acceleration, statistically significantly so for the poorly measured industries. The results for the poorly measured industries are consistent with the firm-level evidence in Bryjolfsson and Hitt (2002) and also suggest a lag length of about five years for U.S. firms.

These results are not driven by outliers. For example, two influential observations (based on the Belsley, Kuh, and Welsch hat matrix test)[42] are wholesale and retail trade. Because of the importance of those two industries in accounting for TFP growth, we experimented with omitting them. Doing so makes 1980s growth less important but 1990s growth more important—1990–1995 is more positive and 1995–2000 is more negative. These results could reflect that wholesale and retail trade have particularly long lags because of the importance of complementary capital. They may also be industries where endogeneity is particularly important. (For reasons unrelated to GPT arguments, ICT grew a lot in the late 1990s, just when the scale of complementary investment was waning.[43])

For the United Kingdom the same regression shows little.[44] Almost nothing is statistically significant, and the signs are reversed from what theory suggested. The lack of significance could reflect mismeasurement—the industry ICT capital stock data for the 1980s are not that reliable. But taken at face value, these results suggest that either the slowdown in U.K. TFP growth was not driven by complementary capital investment or that our ICT-based proxy for such investment works particularly poorly in the United Kingdom (perhaps because our specification is too simple). Another possibility is that the timing assumptions embedded in the estimating equation (on lags between observed ICT investment and unobserved complementary investments) do not match the U.K. experience.

42. 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 $2k/n$.

43. Using the Belsley, Kuh, and Welsch hat matrix test, influential observations include telephone and telegraph, wholesale and retail trade, depository and nondepository institutions, securities brokers, real estate, and business services. When those observations (which account for about one-third of GDP) are omitted, there is no evidence that poorly measured and well-measured industries look different—including the dummy variables would have only minor effects on coefficients or even standard errors. When these outliers are omitted, the data suggest that lagged growth of share-weighted computers and software are positively correlated with late 1990s TFP growth, whereas contemporaneous growth is negatively correlated with TFP.

44. Due to concerns about the data, we drop rail transport, leaving 29 industries.

Table 9 shows results from our second specification, equation (11), which we term the investment accelerator specification. As noted in the theory discussion, this equation may perform better if the complementary investment were closely correlated in time with the ICT investment. We can estimate this equation as a cross section for different time periods. When we do so, we find the right-hand side variables are insignificant. This finding is not surprising because the constant term in the specification differs across industries and may well be correlated with the explanatory variables. But a cross-section regression imposes a common constant. Hence we prefer to take first differences of both sides, thus eliminating the fixed effects. Our dependent variable is now the *acceleration* of TFP growth; i.e., average TFP growth in 1995–2000 minus average TFP growth in 1990–1995. The ICT and investment-deepening terms are defined analogously as changes in weighted growth rates. The estimating equation thus becomes:

$$\left(\Delta TFP_{i,1995-2000} - \Delta TFP_{i,1990-1995}\right) = c_i + a\left(\tilde{k}_{i,1995-2000} - \tilde{k}_{i,1990-1995}\right) - b\left(\tilde{i}_{i,1995-2000} - \tilde{i}_{i,1990-1995}\right) + \varepsilon_i$$

Table 9 shows these results. For the United States, this equation shows little, basically reflecting the point made above, that the U.S. data want long lags.

By contrast, in the United Kingdom, the coefficients have the expected signs and are statistically significant. As expected, ICT capital deepening enters with a positive sign and is significant. Also as expected, investment deepening has a negative sign; we find that it too is significant. Three industries are influential according to the hat matrix, but dropping them has little effect on the results.

This result is highly suggestive, but there is an important qualification. Multiplying these means by their respective coefficients, we find that capital deepening would have raised TFP growth by 0.93% per annum on average, while investment deepening would have lowered it by 0.47% per

Table 9 INVESTMENT-ACCELERATION FORM OF ICT REGRESSION[1]

	United States	*United Kingdom*
$\left(\tilde{k}_{i,1995-2000} - \tilde{k}_{i,1990-1995}\right)$	0.21	4.41
	(2.27)	(1.02)
$\left(\tilde{i}_{i,1995-2000} - \tilde{i}_{i,1990-1995}\right)$	−0.04	−1.63
	(0.75)	(0.41)
R^2	0.01	0.41
Observations	49	28

1. Robust standard errors in parentheses. Constant term not shown. We omit ICT-producing industries (this omission has relatively little effect on coefficients).

annum, for a net positive effect of 0.46% per annum. So although investment deepening did serve to retard measured TFP growth, it cannot be said to account for the absolute fall in TFP growth.

On the other hand, one would expect endogeneity considerations to be particularly important in this equation, in a way that works against finding results consistent with the GPT hypothesis, even if true. In this specification, we regress the TFP acceleration on the contemporaneous investment acceleration. Because investment is endogenous, a positive industry-specific technology shock could lead to higher investment as well as higher TFP, thereby biasing the coefficient on investment upward. Hence, the true investment coefficient may be more negative than we find in our OLS regression.

In sum, the U.S. evidence is consistent with the notion that ICT investments affect measured productivity growth with a long (but variable) lag. Contemporaneously, they are correlated with a lot of diverted resources toward unmeasured complementary investment, and hence they are negatively correlated with output—once one controls for lagged growth rates. It appears that, in the United Kingdom, the rapid growth of ICT investment after 1995—which was higher than the growth of the ICT capital stock—appreciably retarded the measured growth of productivity. Comparing the second half with the first half of the 1990s, the change in TFP growth is positively and significantly related to the change in ICT capital deepening. But it appears significantly and negatively associated with ICT *investment* growth. In the long run, of course, ICT capital and investment must grow at the same rate. This finding suggests one reason that TFP growth in the United Kingdom will eventually recover, at least somewhat. The U.K. data suggest that the lags are much shorter—and that complementary investment was going on in the late 1990s. Although this effect is present, it is not large enough to explain the TFP slowdown in the United Kingdom in the late 1990s.

5.4 EXPLAINING THE U.K. EXPERIENCE

The basic story that we wish to tell based on our simple model of complementary capital investment is one where *measured* output growth is contemporaneously low when complementary investment is high, and it is high in periods after such investment has taken place and the stock of complementary capital is high. The theory also suggests that complementary capital investment will generally be high when observed investment in ICT capital times the share of such capital is high.

Apart from the evidence presented in Table 9, another reason we took this approach is that the aggregate data appear consistent with this story. Look at Figure 1 and the summary statistics by subsample for the United States and the United Kingdom given in Table 1. The regressions used the industry-level versions of the variable plotted in the top panel of Figure 1, the computer share times the growth rate of the computer stock, but we also plot the analogous series for software in the lower panel. We conclude that the United Kingdom had far larger swings in this key variable than did the United States, especially in the period before 1995. As we discussed before, the regressions with U.S. data support the hypothesis that the positive effects of IT investment and—we assume—complementary capital investment show up in measured output with a lag of about five years. (Two important industries in the United States, wholesale and retail trade, prefer longer lags, but these industries are not as important for explaining the U.K. experience as they are for explaining the U.S. experience.)

If investments become productive with roughly a five-year lag, Figure 1 shows that the broad outlines of the macro experience in the United Kingdom are consistent with the story that we are telling. Note that the United Kingdom had extremely high levels of $\tilde{k}$ for both computers and software in the 1985–1990 period, and both dropped sharply in the 1990–1995 period as the United Kingdom fell into a deep recession. Our story suggests that measured TFP growth in 1985–1990 should have been low, and measured growth in 1990–1995 should have been high. This is the pattern one finds in Table 1, where TFP growth in 1985–1990 was 1.2%, and growth in 1990–1995 was 1.6%. Note that this difference is almost certainly understated because the TFP numbers have not been corrected for cyclical mismeasurement coming from changes in utilization. The period of the late 1980s was a time of strong output and fixed investment growth (3.1 and 7%, respectively), while the corresponding figures for the early 1990s are 1.8 and −0.8%. It is amazing that a period with a deep recession should show an increase in measured TFP growth at all, and such a development indicates to us that the effects of IT and complementary capital investment may be quantitatively important.

If one accepts this story, then it should be unsurprising that the next five years were bad for measured TFP growth in the United Kingdom. The reason is twofold. First, the level of IT investment in the previous five years was low, so the contribution of complementary capital was presumably low. Second, the United Kingdom also had a steep increase in computer and software investment in the second half of the 1990s—in many ways a stronger surge than the one labeled historic in the United States. According to our story, this should also have been a time of high unmeasured investment in complementary capital. Both considerations have the effect of reducing measured TFP growth.

Some evidence is consistent with the idea that the United Kingdom was experiencing a surge of supply-driven growth in the period 1995–2000. Note that during this period the United Kingdom was going from a deep slump to a boom. The average growth rate of output was 1 percentage point, and that of investment was 7.2 percentage points, while unemployment fell a full 2.8 percentage points—to 6.7%, a level not seen for decades. And in the midst of this boom, the inflation rate also fell, by 1.4 percentage points—to 2.5%. Admittedly, it is not clear that embedding our story in a short-run macro model must lead to this result because we claim that TFP growth was higher than recorded, in turn because output growth was also higher than recorded, which should put extra upward pressure on prices. But it is suggestive in part because it is difficult to see how else one might reconcile the full set of facts.

Having said all this, it remains true that, although regression results for U.K. industries are somewhat consistent with this GPT story, the point estimates do not allow us to explain the recent growth and TFP experience based on investment in unmeasured complementary capital. That is, the regression suggests that the net effect of ICT is to raise, not lower, TFP growth when comparing the first and second halves of the 1990s.

But as we have already discussed, the form of the equation that appears to work better for the United Kingdom is also subject to larger endogeneity concerns, with a bias against finding support for the GPT view; this provides a potential, but so far only speculative, reconciliation. A second possibility is that the accumulation of complementary capital requires large inputs of skilled labor. This possibility suggests that our proxy for complementary investment may be too simple; we may also need to allow for cross-industry variations in skill intensity. Indeed, it could be that, even if complementary investment explains the divergent TFP performance, it is not, in fact, as closely linked to ICT capital accumulation in the United Kingdom as it is in the United States.

6. *Conclusion*

The "crime" or puzzle we investigated in this paper was the slowdown in U.K. productivity growth, both TFP and labor, in the second half of the 1990s, which coincided with rising U.S. productivity growth. We found that for the private nonfarm economy, the slowdown was nearly one percentage point. The slowdown was particularly marked in industries like wholesale and retail trade, that were among the major contributors to the U.S. improvement.

Many proposed explanations for the weak U.K. productivity performance seem insufficient. For example, the differences do not reflect differences in the importance of ICT production or a failure to account for falling labor quality. Nor do the genuine differences in national accounts methodology explain the differences: the U.K. slowdown persists even when the same methodology is applied to both countries.

Earlier work for the United States suggested that the disruption cost associated with investment might play a role because, in periods when investment is rising, such costs may reduce measured productivity growth. Investment accelerated even more sharply in the United Kingdom than in the United States in the second half of the 1990s, so this suspect has some explaining to do. We found that disruption costs could account for at most about one-third of the measured slowdown.

The most obvious suspects for the U.K. performance seem to have alibis, so we take an alternative path.[45] In particular, we believe that understanding why the United Kingdom has not yet seen a TFP acceleration requires that we understand why, in fact, the United States *did*. Our answer emphasizes ICT and the role of complementary investments and innovations induced by it. To many observers, ICT seems to be the major locus of innovation in recent decades, but at the same time, we find that most of the measured TFP acceleration took place outside the production of ICT goods. These two observations are consistent with the predictions of models of ICT as a general-purpose technology.

In particular, a pervasive theme of the microeconomic literature on ICT is the need for organizational change if full advantage is to be taken of the new technology. We modeled organizational change as the accumulation of intangible complementary capital, which means that the typical firm is also producing a stream of intangible output that constitutes gross investment in complementary capital. Some of this output, such as the production of own-account software, is now explicitly measured in the national accounts, but arguably much is not. To the extent that there is unmeasured output and unmeasured capital, conventional TFP growth will be a biased measure of true technical change. Growth in the complementary capital stock tends to raise measured TFP growth, but growth of complementary investment tends to reduce it by diverting resources from normal production. During the transition to a new steady state, the net bias can go either way, but the more that the growth rate of complementary investment (unmeasured output) exceeds that of complementary capital (unmeasured input), the more likely it is that measured TFP will be below the true rate of technical change. This GPT view also suggests that current productivity growth

45. In keeping with the mystery theme of this paper, now seems an appropriate time to quote Sherlock Holmes: "[W]hen you have excluded the impossible, whatever remains, however improbable, must be the truth." We are dumbfounded anew by Holmes's genius because we have never managed to exclude enough impossibles to reduce the improbable-but-true set to a singleton!

may be influenced by the accumulation of complementary capital in earlier periods.

A fundamental difficulty, of course, is that complementary investment and capital are unmeasured. Theory suggests, however, that observed ICT capital and investment 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 growth with long (and perhaps variable) lags of five to 15 years. Indeed, if we control for past growth in ICT capital, contemporaneous growth in ICT capital is negatively associated with TFP growth in the late 1990s. We find this result encouraging because, to our knowledge, no other empirical exercise has connected aggregate and industry-level U.S. TFP performance in the late 1990s either to the persuasive macro models of general-purpose technologies or to the stimulating micro empirical work that supports the GPT hypothesis.

The results for the United Kingdom are weaker. But we do find that, in the United Kingdom, the rapid growth of ICT investment after 1995, which was higher than the growth of ICT capital, appreciably retarded the measured growth of productivity. Comparing the second with the first half of the 1990s, the change in TFP growth is positively and significantly related to the change in ICT capital deepening. But it is significantly and negatively associated with ICT *investment* growth (the latter weighted by the investment-output ratio). These results are consistent with the notion that U.K. firms were accumulating complementary capital intensively in the late 1990s, in contrast with the U.S. accumulation much earlier. Hence, in this view, the U.K. economy most likely experienced strong underlying TFP growth despite the poor measured figures. But the point estimates suggest that, as a whole, ICT investment raised, not lowered, overall TFP growth in the United Kingdom in the late 1990s—i.e., they do not explain the pervasive TFP slowdown.

The results in this paper are suggestive, but it is too early to indict complementary capital as the sole perpetrator of the crime. Of course, it is always a challenge to provide incontrovertible proof of a hypothesis that implies that both inputs and output are unobserved! Nevertheless, several puzzles remain. In particular, if our hypothesis is correct, why did the United Kingdom invest later in complementary capital than did the United States? Even if they did invest later, why are the coefficients on contemporaneous ICT investment so low?

One hypothesis that we are considering in current research is that there may have been a shortage of skilled, college-educated managers to implement the necessary reorganizations earlier. This hypothesis would suggest that our model (and our empirical specification) is too simple: we need a third factor, skilled labor, to make complementary capital productive or else its accumulation cheaper. Certainly, the evidence that the skills premium has widened in the United Kingdom (as it did earlier in the United States) is potentially consistent with this view. This hypothesis also suggests that, on its own, ICT might be an inadequate proxy to capture fully the complementary investments we think are happening.

In addition, although labor and product market regulation generally appear similar, differences in competitive intensity could still play a role. A major contrast between the United States and the United Kingdom is in wholesale and retail trade. As we have seen, productivity rose sharply in these industries in the United States after 1995, but it fell in the United Kingdom. Some (e.g., Lovegrove et al., 1998) have blamed restrictive planning laws in the United Kingdom, which may have hampered the growth of so called big box retailing.[46] But it is not immediately clear why the major U.K. retailers (who also perform the wholesale function) should invest less in ICT for this reason alone: why would a comparatively low store size in a chain of supermarkets inhibit the retail firm from investing in computerized inventory control systems? However, if planning laws reduce competitive intensity by blocking entry, then they may inhibit investment too. In any event, the role of competitive intensity also seems a fruitful topic for future research.

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46. This is the term used to label very large retailers, typically selling from windowless, rectangular buildings surrounded by parking lots.

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Comment

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This is a very ambitious, very careful, very honest paper. Unfortunately, ambition, care, and honesty are only necessary conditions for success. A bit of luck is also needed and, in this case, luck was not there. The case of U.K. missing productivity growth is not solved. But much is learned, and, building on the paper, more will be learned in the future. Let me first briefly summarize the three major points of the paper.

1. The Divergent Paths of TFP Growth in the United States and the United Kingdom

The basic facts laid out in Tables 4 and 5 of the paper, and reduced to their essence in Table 1 here, are striking. TFP growth in the IT-using sector increased substantially in the second half of the 1990s in the United States but decreased substantially in the United Kingdom. Given that the cyclical behavior of the two economies was largely similar over the decade, this suggests the need to look for structural rather than cyclical factors behind this divergence.

2. IT and Organization Capital

A preeminent role is given to IT for the performance of the U.S. economy in the second half of the 1990s, so this is a logical place to start looking. The authors point out the complex dynamic relation between IT investment, organization investment, and measured TFP.

Table 1 TFP GROWTH IN THE UNITED STATES AND THE UNITED KINGDOM IN THE 1990s (Percentage)

	1990–1995	*1995–2000*	Δ	*Share in VA*
United States				
Overall	0.9	2.1	1.2	
IT-producing	5.5	11.0	5.5	0.05
IT-using	0.6	1.5	**0.9**	0.95
United Kingdom				
Overall	2.6	1.3	−1.3	
IT-producing	3.9	10.8	6.9	0.03
IT-using	2.6	1.0	**−1.6**	0.97

Here again, it may be worth giving a bare-bones version of the more elaborate model in the paper. Suppose output depends only on organizational capital, C, and labor, N, and is used either for final goods, Y, or for investment in organizational capital, A. Organizational capital depreciates at rate δ:

$$Y = F(C, N) - A$$
$$C = A + (1 - \delta)C(-1)$$

True TFP growth is zero by construction. Measured TFP growth is given by:

$$g \equiv \left(\frac{CF_C}{Y}\right)\frac{\Delta C}{C} - \left(\frac{A}{Y}\right)\frac{\Delta A}{A}$$

Growth of unmeasured organization capital leads to an upward bias in measured TFP growth, and growth of unmeasured organization investment leads to a downward bias.

What is therefore the net effect of organization capital accumulation? Around the steady state, g can be rewritten as:

$$g \equiv \left(\frac{rC}{Y}\right)\frac{\Delta C}{C} - \left(\delta\frac{C}{Y}\right)\left(\frac{\Delta C}{C} - \frac{\Delta A}{A}\right)$$

In steady state $\Delta C/C = \Delta A/A$, so only the first term remains: measured TFP growth exceeds true TFP growth. Out of steady state, the net effect depends on the relation of the growth of capital to the growth of investment. A period of increasing investment is likely to lead to undermeasurement of true TFP growth. This can be seen more clearly by manipulating the previous equation to get:

$$g \equiv \left(r\frac{C}{Y}\right)\frac{\Delta C}{C} - \frac{C}{Y}(1 - \delta)\left[\sum_{0}^{\infty}(1 - \delta)^i\frac{\Delta^2 A}{A}(-i)\right]$$

Measured TFP growth depends positively on the growth rate of organization capital, negatively on the **change** in the growth rate of organization investment. I would have liked the authors to try a specification closer to the spirit of this specification, allowing for the rate of change of organization capital (or the proxy used for it), and a distributed lag in the rate of change of organization investment, constrained to have a sum of coefficients equal to zero. It would have made the results and the estimated dynamic structure perhaps easier to interpret.

3. Different IT Accumulation Paths in the United States and the United Kingdom?

The basic implication of the model is that a boom in organization investment leads initially to a decrease in measured TFP, and only later to the promised increase. This suggests a potential explanation for the United Kingdom/United States difference: the boom in IT investment, and thus the boom in induced organization investment, happened earlier in the United States than in the United Kingdom. In the second half of the 1990s, the United States was already reaping the positive effects of high organization capital, and so measured TFP growth was high. The United Kingdom, on the other hand, was still paying the cost of high organization investment, and measured TFP growth was accordingly low. Under this interpretation, the effects will turn positive, and the future may be brighter.

The authors take this hypothesis to the sectoral data, looking at the dynamic relation between TFP growth and proxies for organization capital. This is where the data do not cooperate. The dynamic story appears to work decently for the United States. But it works extremely poorly for the United Kingdom. There is no evidence for a lag structure from IT to productivity growth along the lines suggested by the theory. The authors put a good face on the results, but one cannot conclude that the case has been solved. Let me take each of these points in turn, first focusing on the general line of arguments, then returning to the United States/United Kingdom comparison.

4. On the General Story

4.1 HOW WELL ESTABLISHED ARE THE BASIC TFP FACTS?

The first issue is a standard one. Even if one takes TFP growth numbers at face value, the question is, How much can be read in differences in sample means over periods as short as five years? TFP growth varies a lot from year to year. Using the series constructed in the paper, the sample standard deviation of TFP growth over the last 20 years in the United Kingdom is 1.8%, implying a standard deviation for a five-year mean of about 0.8%. A difference of 1.4%, the number in the table for the difference between U.S. and U.K. productivity growth in the IT-using sector for 1995 to 2000, is not that significant. One could probably ask for more time to pass before feeling that there was a puzzle to be explained.

The second issue is that there are many decisions to be made in constructing TFP growth (income or expenditure side, quality weighting of labor, and so on), and so different studies give different results. The authors of this paper conclude that TFP growth in the IT-using sector increased by 0.9% in the United States from 1990–1995 to 1995–2000 (and overall TFP growth, that is, TFP growth for the whole private nonfarm economy, increased over the same period by 1.2%). This appears to be at the high end of the range of available estimates.

At the low end is Robert Gordon (2000, Table 2), who concludes that there was roughly no increase in underlying TFP growth in the IT-using sector from 1992–1995 to 1995–1999, and a small (0.3%) increase for the whole private nonfarm economy. Next are Oliner and Sichel (2002, Table 4), with an increase of 0.3% in the IT-using sector, and an overall increase of 0.7%. Slightly higher is Jorgenson and Stiroh (2000), with an increase of 0.4% for the IT-using sector (1991–1995 to 1995–1998), and an overall increase of 0.6%. At the high end is the work reported in the *Economic Report of the President* (Council of Economic Advisers, 2001), with an increase of 1% for the IT-using sector, and an increase of 1.2% overall.

All the estimates are (weakly) positive; this is good news. But the magnitudes vary, and one wonders whether plausible variations on hedonic pricing of the IT-producing sector, and thus in the price of IT goods, could not change the allocation of TFP growth between IT-producing and IT-using sectors by a magnitude that would dominate the numbers reported in the previous paragraph and substantially affect the conclusions. This may not affect much the comparison of the United States and the United Kingdom. But it would affect the interpretation of the results: if there was no strong evidence of an increase in TFP growth in the IT-using sector, explanations based on unmeasured organization investment and capital lose a lot of their appeal.

4.2 WHAT ARE THE OUTPUT COSTS OF REORGANIZATION?

It is essential for the authors' thesis that high investment in organizational capital have substantial adverse effects on measured output, and therefore on measured TFP. A study by Lichtenberg and Siegel (1987) on the effects of mergers on TFP is relevant here. Not very surprisingly, they find that TFP in the merged firms goes from 3.9% below the conditional sectoral mean to 1.2% below after seven years. More relevant to the issue at hand, however, is their finding that the improvement is a steady one: there is no evidence of a temporary decrease in measured TFP before reorganization starts paying off.

This evidence is not totally conclusive. Reorganization after mergers may be very different from the types of changes triggered by new IT possibilities. But it makes one want to see more micro evidence that the accumulation of organization capital can have major adverse effects on measured output. This takes me to the next point.

4.3 RETAIL TRADE, THE McKINSEY STUDY, AND WAL-MART

As the authors point out, fully one-third of the increase in TFP growth from the first to the second half of the 1990s in the United States came from the retail trade sector. For this reason, the general merchandising segment, which represents 20% of sales in the sector, was one of the sectors examined in a McKinsey study (McKinsey Global Institute, 2001) aimed at understanding the factors behind U.S. TFP growth in the 1990s.

The study confirmed that there was indeed a large increase in productivity growth, with the growth rate of sales per hour increasing from 3.4% during 1987–1995 to 6.7% from 1995–1999, and it reached two main conclusions: first that more than two-thirds of the increase could indeed be traced to reorganization; second, that much of this reorganization came from the use of IT.

The study also provided a sense of what reorganization means in practice. Improvements in productivity were the result of "more extensive use of cross docking and better flows of goods/palleting; the use of better forecasting tools to better align staffing levels with demand; redefining store responsibilities and cross training of employees; improvements in productivity measurements and utilization rates at check-out." It also showed that, while innovations were first implemented by Wal-Mart, competitors were forced to follow suit, leading to a steady diffusion of these innovations across firms in the second half of the 1990s.

How does the story fit the authors' thesis? In some ways, very well: reorganization, linked with IT investment, clearly played a central role in the increase in TFP growth in the retail sector in the 1990s. But in other and more important ways, the evidence goes against the basic thesis of the paper: the major increase in IT capital took place in the second half of the 1990s. During that period, productivity growth and profits steadily increased. There is no discernible evidence of the adverse effects of organization investment on output, productivity, or profits.

5. *Back to the United States and the United Kingdom*

5.1 THE RELATIVE EVOLUTION OF IT SPENDING

Having stated their hypothesis, the authors proceed to test it using sectoral data. But a natural first step is just to look at the timing of IT investment in both the United States and the United Kingdom and see whether it fits the basic hypothesis.

The authors actually do it, but only in passing, in Figure 1. And what they show does not give strong support to the hypothesis. The figure plots the growth contribution of IT capital in the IT-using sector—constructed as the product of the share times the rate of growth of IT capital. If their hypothesis were right, one would expect to see high IT investment in the United States early on, and high IT investment in the United Kingdom only at the end of the sample. Actual evolutions are quite different. The United Kingdom appears to have two periods of high IT capital contributions: one in the late 1980s, the other in the late 1990s. It does not seem to be lagging the United States in any obvious way.

This impression is largely confirmed in work by others. Table 2 below is constructed from data in Colecchia and Schreyer (2002, Table 1). It also gives the contribution of IT spending to growth, measured as the product of the share times the rate of growth of IT capital for four subperiods, from 1980 to 2000. The numbers yield two conclusions.

First, the growth contribution of IT appears substantially lower in Europe than in the United States, a conclusion at odds with Figure 1 in the paper, which puts the IT contribution to growth in the United Kingdom, both in computers and software, above that in the United States. Much of the difference appears attributable to the multiplication by 3 by the authors of investment in software, and so the larger share of software in their data, relative to Colecchia and Schreyer. The adjustment may well be justified, but it is obviously rough and is a reminder of the many assumptions behind the data we are looking at.

Second, and more directly relevant here, the acceleration in IT appears to have been stronger at the end of the 1990s in the United States than in the three European countries. The contribution to growth roughly doubled in the last five years from an already high level. It also roughly doubled in the United Kingdom and France, but from a lower level. It increased, but far from doubled, in Germany. If these numbers are correct, and if investment in organization is indeed closely related to investment in IT, it is measured TFP growth in the United States that should have suffered the most from unmeasured investment in the late 1990s, not TFP growth in the United Kingdom.

5.2 WHOLESALE AND RETAIL TRADE AGAIN

The sectoral data in the paper give what looks like a promising lead for solving the case of missing productivity. Table 3, constructed from

Table 2 CONTRIBUTION OF IT TO GROWTH FOR FOUR COUNTRIES, 1980 TO 2000

	1980–1985	*1985–1990*	*1990–1995*	*1995–2000*
United States	0.44	0.43	0.43	0.87
United Kingdom	0.18	0.29	0.27	0.48
France	0.18	0.22	0.18	0.33
Germany	0.20	0.27	0.30	0.38

Tables 4 and 5 in the paper, summarizes the relevant information. The first and second columns report TFP growth in 1990–1995 and 1995–2000. The third shows the change in TFP growth. The fourth shows the share of the two sectors in value added. The last column shows the product of change and share, and shows therefore the contribution of the two trade sectors to the change in TFP growth in the two countries. In the United States, the contribution is 0.8%; in the United Kingdom, the contribution is −1.0%. From an accounting point of view, the evolution of TFP growth in just the trade sector accounts for close to half of the difference between the overall evolution of U.S. and U.K. TFP growth from the first to the second half of the 1990s.

This suggests looking at trade more closely. Indeed, the absolute numbers for U.K. TFP growth in both wholesale and retail for the second half of the 1990s are puzzling. Can it be that TFP growth was actually negative in the United Kingdom during that period? I checked the evolution of labor productivity, using OECD data from the STAN project. For wholesale and retail trade together, that source gives a growth rate of real value added of 3.2% a year, a growth rate for employment of 1.0%, so a rate of labor productivity growth of 2.2%. If the numbers are consistent with those used by the authors, this suggests an unusually high rate of capital accumulation during the period, capital that was not used very productively. This raises the question, Why was it used more productively in the United States?

Unfortunately, I do not know enough about the retail sector in the United Kingdom to give the answer or even help direct the search. In a related McKinsey project (McKinsey Global Institute, 2002) in which I participated, we looked at the evolution of labor productivity in the retail sector in the 1990s in Germany and France. Labor productivity was 1.1% for Germany, 1.5% for France, and 2% for the United States. For the first two countries, regulations affecting the rate at which various retail formats could grow seemed relevant. Such regulations appear much less relevant, however, for the United Kingdom in the 1990s.

Table 3 GROWTH CONTRIBUTIONS OF WHOLESALE AND RETAIL TRADE IN THE UNITED STATES AND THE UNITED KINGDOM

	TFP growth				
	1990–1995	*1995–2000*	*Change*	*Share*	*Contribution*
U.S. wholesale	1.7	5.4	3.7	9.2	0.3
U.S. retail	0.8	5.3	4.5	11.8	0.5
U.K. wholesale	3.3	3.2	−0.1	6.8	−0.0
U.K. retail	0.5	−1.2	−1.7	13.0	−0.2

5.3 CONVERGENCE?

An alternative way of looking at the United Kingdom/United States evolutions in the aggregate is that, for most of the postwar period, European TFP growth was high due to convergence. All Europe had to do was copy, not innovate. And this has largely come to an end.

The problem, as the authors mention, is that, in many countries, convergence has not been fully achieved. While several countries indeed have a level of output per worker close or even higher than the United States, this is not the case for the United Kingdom. According to Table 2 in the paper, U.K. output per worker stands at roughly 70% of the U.S. level.

Theory, however, predicts conditional convergence, not absolute convergence. A country with bad institutions (whatever this exactly means) will not achieve the same level of productivity as one with better institutions. I mention this not because it is a new insight, but because this seems to be happening in Europe. Several countries that were much poorer and had been converging for the past few decades seem now to be growing only at the European average, no longer catching up. Portugal and Greece come to mind, but the United Kingdom, in a less obvious way because the gap is much smaller and thus less visible, may be in the same predicament.

So, was it problems in the use of capital in the trade sector, or was it simply the end of convergence? We still do not know. But, thanks to the paper, we have a better sense of what to look for, and we have a number of lids to open. I wish the authors good luck in solving the case in the future.

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Comment

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1. Introduction

The exceptional productivity performance of the U.S. economy in the period 1995–2000 is well documented (see, for example, Jorgenson 2001): relative to the previous five years, total factor productivity (TFP) growth accelerated by 0.7% (and labor productivity growth by 1%) per year in 1995–2000. What are the sources of this sharp acceleration? Should we expect this higher TFP growth to be a long-term trend for the future, as some argue, or is it just a transitory phenomenon? Basu, Fernald, Oulton, and Srinivasan offer a comparative macroeconomics perspective to these important questions. They bring into the picture the experience of another country, the United Kingdom, which in many dimensions is similar to the United States.

From a long-run perspective, the U.S. and the U.K. economies stand at the same stage of development and share—unlike many other European countries—a similar institutional framework of labor and product markets. From a short-run perspective, the business cycle in the two economies in the 1990s was remarkably akin. I'd like to add that the United States and the United Kingdom were the only two among the developed economies that experienced a substantial rise in earnings inequality in the past 30 years, with analogous characteristics (e.g., both within and between skill groups).

Given these short-run and more structural affinities, one would expect a similar evolution of TFP growth in the 1990s for the U.K. economy. Instead, U.K. TFP growth decelerated by 0.5% (and labor productivity growth by 1%) per year from 1990–1995 to 1995–2000.

How do we explain the missing productivity growth in the United Kingdom (or the exceedingly high productivity growth in the United States)? Basu et al. build a convincing argument on two assumptions. First, because of unmeasured organizational capital that is complementary with information technology (IT) capital in production, TFP growth is mismeasured. Periods of strong investment in IT (and in the complementary organizational capital) are times where mostly output is unmeasured, so true TFP growth is underestimated, whereas periods where the economy has large stocks of IT and complementary capital are times where inputs are grossly undermeasured, and true TFP growth is overestimated. Second, IT investment boomed with a lag of 5 to 10 years in the

U.K. economy, relative to the U.S. economy. Thus, in 1995–2000, TFP growth was underestimated in the United Kingdom and overestimated in the United States, which explains, at least qualitatively, the gap.

This comment is organized into three parts: (1) an exploration of the role of convergence between the United Kingdom and the United States within a Solow-growth model; (2) a deeper look into the retail sector, where the TFP acceleration gap between the two countries is particularly striking; and (3) a quantitative exercise based on the model developed by Basu et al. in Section 4 of their paper.

2. *Convergence*

If one extends the comparison for the two countries back to the early 1980s (see Basu et al., Table 1), it emerges clearly that labor productivity growth was considerably faster in the United Kingdom until the mid-1990s. Basu et al. put it in plain words: "[T]he Europeans were catching up." The authors somewhat downplay the role of transition in their analysis, so here I try to assess if the fact that the United Kingdom was catching up is relevant in explaining the productivity acceleration gap. Intuitively, the transitional dynamics of the United Kingdom would naturally lead to a reduction in labor productivity growth as the economy approaches its steady state.

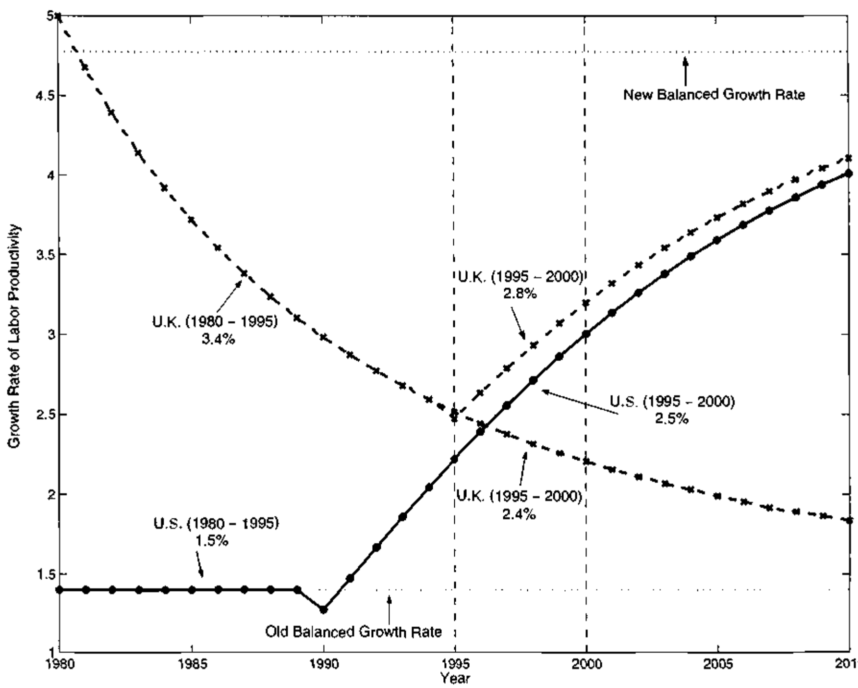
Think of the two countries (indexed by i) in terms of Solow-model economies with capital-embodied technical change: at time t the new investment goods $x_i(t)$ embody a productivity factor $A_i(t) = e^{\gamma_i t}$. The model can be summarized as:

$$x_i(t) = sy_i(t) = sk_i(t)^{\alpha}$$

$$k_i(t) = A_i(t)x_i(t) - (\delta + n)k_i(t)$$

where $k_i(t)$ is capital per worker, s is the savings rate, α is the income share of capital, δ is the depreciation rate, and n is the growth rate of the labor force. The thought experiment is as follows: start the two economies in 1980 with the same parameter vector (s, α, δ, ν, γ) but assume that the United States is already on its balanced-growth path, while the United Kingdom is endowed with lower capital per worker, so it has a faster growth rate of labor productivity and slowly converges toward the U.S. level. In 1990 a technological breakthrough raises permanently capital-embodied productivity growth to γ' in the U.S. economy. From this simple exercise, one can learn the implied labor productivity growth in the United Kingdom in the period 1995–2000 under two scenarios: (1) the acceleration in technological change does not spill over to the United

Figure 1 CONVERGENCE BETWEEN THE UNITED KINGDOM AND THE UNITED STATES IN A SOLOW MODEL ECONOMY



Kingdom and (2) the acceleration occurs with a lag of 5 years in the United Kingdom.[1]

To calibrate the model, I set $\gamma = 1.7\%$ and $\gamma' = 5.7\%$ to match the data on average labor productivity in the United States in the period 1980–1995 and 1995–2000, respectively. I chose the initial level of capital in the United Kingdom so that along the transition in the period 1980–1995, average yearly productivity growth is 3.4%, as documented in Table 1 by the authors.[2]

What can we conclude from this simple exercise on the role of catch-up and transitional dynamics? Figure 1 shows that, under the first scenario, the U.K. rate of labor productivity growth implied by the transitional dynamics in 1995–2000 is 2.4%, which is well below 2.9%, the actual data from Table 1. In the absence of a rapid technological spillover to the

1. The first scenario corresponds to a lag of 10 years or more, assuming that we are interested in the period until 2000.
2. The other parameters are set as follows: $s = 15\%$, $\alpha = 0.45$, $\delta = 5\%$, and $n = 1.5\%$. The somewhat high value of the capital share reflects the presence of human capital.

United Kingdom, pure convergence forces push the implied labor productivity too low compared to the data. Under the second scenario, labor productivity grows at an average yearly rate of 2.8%, thus the combination of the authors' view that the U.K. "implementation lag" is around 5 years together with catch-up forces explains the deceleration in full (in fact, it just overexplains it).[3]

An obvious question arises: Why did the United Kingdom adopt this more productive technology later? A satisfactory answer would require a full investigation. Here, I will limit myself to a brief speculation. In Table 3, Basu et al. document the educational characteristics of the labor force in the two countries. The difference with the United Kingdom does not lie so much in the average numbers of years of schooling, but rather in the fact that the United Kingdom has a much larger fraction of workers with specific skills associated with vocational training. At least since Nelson and Phelps (1966), numerous researchers argued that general education is a key force in technology adoption. In a recent mimeo, Krueger and Kumar (2003) embed the Nelson and Phelps mechanism into an equilibrium model and show that an acceleration in the growth rate of the frontier technology will increase the TFP growth gap between an economy with abundant general skills (like the United States) and an economy mostly endowed with specific skills (like the United Kingdom and most of the other European countries).

The careful reader will have noticed that the predictions of this exercise are relevant to explain the *labor productivity* acceleration gap between the two countries, but not the TFP growth differential. However, this is true only if all inputs are correctly measured. Suppose that the productivity improvements in investment goods captured by the factor $A(t)$ are completely missed by statisticians. In this case, measured total factor productivity $z(t)$ is obtained residually from the production relationship $y(t) = z(t)\hat{k}(t)^{\alpha}$, with $\hat{k}(t) = x(t) - (\delta + n)\hat{k}(t)$. In other words, $z(t)$ is an average of all past values of $A(t)$ weighted by the investment flow in each year.

What are the predictions of our simple calibrated model for TFP? Simulations under the same exact parametrization show that the model generates an acceleration in TFP growth for the United States of 1.5% and an acceleration in TFP growth for the United Kingdom of 0.3% under the first scenario and of 0.7% under the second scenario. Although the model produces larger accelerations in absolute value in the two economies (in particular, it does not generate a TFP deceleration for the United

3. Obviously, if all inputs are correctly measured, the predictions of this exercise are relevant only to explain the labor productivity acceleration gap between the two countries. TFP is constant over time.

Kingdom), it predicts a gap of roughly 1% between the two countries, in line with the data of Table 1.

3. *Institutions in the Retail Sector*

A comparison between Table 4 and Table 5 documenting the size of the TFP acceleration from 1990–1995 to 1995–2000 by industry in the two countries shows a relatively similar sectoral performance with one important exception: in the retail trade sector, TFP growth accelerated by 4.5% per year in the United States, whereas it decelerated by 1.9% per year in the United Kingdom. The authors note this puzzling divergence, but they do not search for its specific causes. It is clear, however, that an argument based on the dynamics of unmeasurable organizational capital is unlikely to account for the TFP acceleration gap in the retail industry. Tables 6 and 7 show that the share of IT investments in value added did not change much between 1990 and 2000 in either country in this sector.

A report of the McKinsey Global Institute (1998) sheds some light on the puzzle: between 1993 and 1996, fearing a massive "high-street flight" of retail stores toward the periphery of towns and cities, the U.K. government voted a series of planning restrictions establishing that local planning authorities should promote the development of small retail stores in town centers and restrict the concession of planning permissions for new stores or for the extension of existing stores outside town centers. By contrast, land regulations in the United States put no significant restrictions on retailers' location decisions.

As a result of these stringent planning guidelines, a large fraction of retail stores in the United Kingdom have suboptimal size and are not located optimally on the territory. McKinsey estimates the productivity loss associated with these strict regulations to be roughly 10% at the sectoral level, so the entire TFP deceleration in the U.K. retail sector (– 1.9% per year compounded over 5 years) could be explained through this channel. Retail trade is a large industry, accounting for about 12% of aggregate value added in both economies, thus these institutional restrictions alone can potentially explain over 60% of the differential TFP acceleration between the two countries.[4]

4. *Complementary Capital*

The equilibrium model of Section 4 allows Basu et al. to obtain the structural equation in equation (9) that relates the bias in TFP growth to the

4. Regulatory restrictions that have a significant impact on store size and productivity are not uncommon in other parts of the world. For example, in Japan, until 2000, the large-scale retail law limited greatly the entry of stores larger than 1,000 square meters.

change in the stock of complementary capital. Consider a special case of the model where $g = r$ (the growth rate of the economy equals the interest rate) and $\sigma = 1$ (a unitary elasticity between IT capital and the complementary organizational capital is necessary to have a balanced growth path in the model), then one can rewrite equation (9) as:

$$\Delta TFP_t^* - \Delta TFP_t = \frac{C}{Y^{NT}} \left(1 - r - \delta_c\right) \left[\Delta C_t - \Delta C_{t-1}\right] \tag{1}$$

where ΔTFP_t^* is true TFP growth in year t, C/Y^{NT} is the long-run (or steady-state) ratio of the stock of complementary capital to output produced in the non-IT industries, and δ_c is the depreciation rate of complementary capital. Given the assumptions made on the substitutability between IT capital and C capital in production, the growth rate of complementary capital at time t can be written also as:

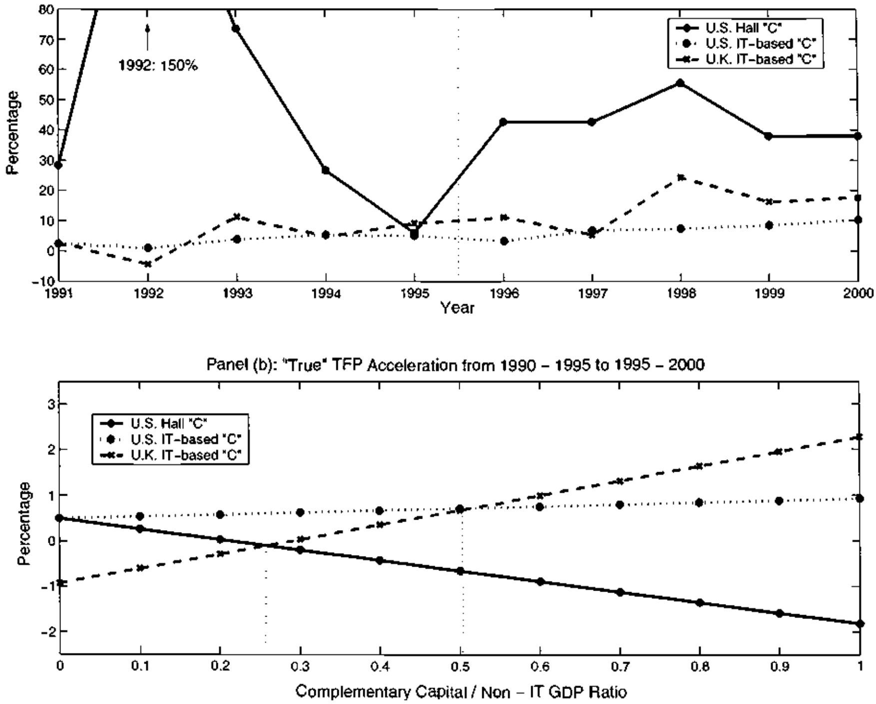
$$\Delta C_t = \Delta K_t^{IT} + \Delta p_t \tag{2}$$

where ΔK_t^{IT} is the growth rate of IT capital, and Δp_t is the change in the price of new IT investment relative to non-IT output.

The authors use equations (1) and (2) as their statistical model in a series of cross-sectional regressions where different rates of IT investment across industries provide a source of variation to estimate the size of the bias in TFP growth due to the missing C capital. The results are encouraging, but not as sharp as one would hope. The main reason of the weak statistical significance, in my view, lies in the very same point the authors are trying to prove: if IT is truly a general-purpose technology, then we should expect similar investment rates across all industries, which makes the cross-sectional data not very informative. Indeed, Tables 6 and 7 show that, with the exclusion of a few outliers (like mining, real estate, and communications), the variability of investment rates in IT among industries is rather small.

I take a different approach for setting the complementary capital model in action. The spirit of the exercise will be as follows. From the data on IT capital and prices and from equation (2), one can construct growth rates of C capital for the whole decade 1990–2000 for both countries. Together with a common parametrization for the pair (δ_c, r), one can then compute the true TFP growth ΔTFP^* in the two countries for different values of the complementary capital output ratio, which is unobservable. Finally, assuming that the United Kingdom and the United States have the same long-run C/Y^{NT} ratio along their balanced growth (and this will be the case if the two economies differ only in the *timing* of the productivity shock, as in the convergence exercise), one can ask, What is the specific value of

Figure 2 GROWTH RATE OF COMPLEMENTARY CAPITAL



C/Y^{NT} that rationalizes the TFP acceleration differential? In other words, given the scarcity of information contained in the industry-level data, and the fact that C capital is not directly measurable, the best we can do is engage in the art of "reverse engineering." I will express later a subjective judgment on the plausibility of the number obtained.

In the exercise, I will also use another indirect source of measurement of C capital growth constructed from Hall's (2001): the difference between the stock-market valuation of firms and the book value of their physical assets provides an implicit measure of the stock of intangibles in the U.S. economy.[5]

The top panel of Figure 2 plots ΔC_t in the United States measured through both IT-based and Hall's methods, and ΔC_t in the United Kingdom measured with the IT-based approach. The U.K. IT-based estimate of C capital growth is higher in the second half of the sample. The

5. Hall's data are available from http://www.stanford.edu/~rehall/. To my knowledge, there is no similar attempt to obtain an estimate of intangible capital for the U.K. economy.

IT-based measure of C capital growth for the United States is slightly increasing over time, albeit at a slower pace than the U.K. measure; instead Hall's U.S. C capital growth is much higher in the first half of the sample. Taken together, these numbers mean that the correction of the bias in TFP growth will go in the right direction.

The lower panel of Figure 2 plots—for a range of values of the C/Y^{NT} ratio—the true acceleration in TFP between 1990–1995 and 1995–2000 calculated using in equation (1) the three series for ΔC_t just constructed.[6] Note that when this ratio is zero, we obtain the measured ΔTFP of Table 1. The point where the U.S. and the U.K. lines cross corresponds to the value of the long-run C/Y^{NT} ratio that reconciles the measured U.S./U.K. differential in *TFP* acceleration with equal true *TFP* growth.

Using Hall's estimates for the growth in the stock of intangible capital in the United States in the 1990s, this value is 0.26, which corresponds to a true TFP deceleration of 0.1% per year in both countries. However, if the U.S. stock market were overvalued in the 1990s, this source of information on intangibles can be imprecise. The alternative IT-based measure of C capital for the United States proposed by the authors tells us that the long-run C/Y^{NT} ratio that solves the puzzle is around 0.5, which corresponds to a true acceleration of 0.7% per year in both economies.

How reasonable are these two numbers? I argue that they are quite plausible. To understand, it is useful to express them in terms of aggregate output Y (non-IT value-added Y^{NT} accounts for 95% of total output in the United States). Take the mean of these two estimates for C/Y, which is 0.35. Given the assumed depreciation rate, this number would imply that steady-state investment in C capital is less than 6% of output, very close to the current share of IT investment in U.S. data, which is around 7%. A C/Y ratio of 0.35 is a conservative estimate in light of the recent work by McGrattan and Prescott (2002, Table 2), who estimate the stock of intangible capital in the United States to be around 0.65 of aggregate gross domestic product (GDP) and, after reviewing the literature, conclude that a reasonable range for this ratio is between 0.5 and 1.

To conclude, this calculation provides support, from a different angle, to the authors' main argument: theory is *still* ahead of measurement. We have rich models suggesting that organizational capital plays an important role in macroeconomics, especially in phases of technological transformation, but we are lacking reliable direct measurements. However, I have also argued that one should not neglect more traditional explanations of productivity differentials, like convergence forces and institutions.

6. I have assumed that, in both countries, the depreciation rate for C capital δ_c is the same as the depreciation rate for IT used by the authors (16%), and that $r = 4\%$.

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Discussion

Several participants remarked on the role of the wholesale and retail trade in the authors' story. Mark Gertler suggested that the TFP slowdown in the United States appears to be partly associated with a slowdown in these sectors, which in turn implies that there is something important about these particular sectors that economists should try to understand. John Fernald remarked that the wholesale and retail trade contributed to three-fourths of the difference in TFP growth between the two countries. He also remarked that net entry alone—the entry of Wal-Mart and the exit of Kmart—explains the productivity performance of the retail sector. Robert Shimer counseled caution in the use of Wal-Mart as an example of the retail trade. He pointed out that by joining together successes such as Wal-Mart and failures such as Kmart, one would get a more realistic picture of the U.S. retail trade in the 1990s. In response to Olivier Blanchard's discussion, Nick Oulton noted that though planning regulations in the United Kingdom could lower the level of TFP, they should not affect the growth rate of TFP. He contended that the small size of individual stores should not affect the incentives for retail chains to invest in IT.

The theme of the choice of sample countries was raised by several participants. Mark Gertler questioned the authors' identification assumption that there are many macroeconomic similarities between the United Kingdom and the United States. He pointed out that according to the authors' Table 1, there was moderate growth in output and strong growth in investment in the United States between 1990 and 1995, but there was low output growth and no net investment in IT in the United Kingdom.

Athanasios Orphanides suggested that the authors expand their sample of two countries to include Australia. It was his view that this approach would help to deal with the identification issue pointed out by Mark Gertler because Australia experienced measured productivity growth even larger than that in the United States but was similar to the United Kingdom in terms of initial conditions and catching up in the 1990s. Kjetil Storesletten suggested that Germany and Sweden would be another interesting pair of countries to compare. He observed that there was a rapid acceleration of TFP growth in the 1990s in Germany, but little growth in IT investment. In the 1990s, Sweden, like the United States, saw sharply falling unemployment and an acceleration in TFP, along with widespread use of IT.

Several participants had concerns about data issues. Robert Shimer contended that the authors were wrong to dismiss the role of declining unemployment in explaining the differential behavior of TFP growth in the United States and the United Kingdom. He maintained that the bigger decline in unemployment in the United Kingdom, resulting in the long-term unemployed being drawn into employment, might contribute more than the authors estimated to the slow growth of TFP. Nick Oulton responded that the authors had controlled for the education characteristics as well as the gender and age of the labor force in the United Kingdom, so composition effects are unlikely to explain the differential TFP performance between the two countries. In response to Gianluca Violante's discussion of the aggregation of different qualities of labor, Susanto Basu agreed that big deviations from Cobb-Douglas do matter. He contended that the authors' aggregation procedure is not subject to this problem because they use a Törnqvist average of shares over time, rather than a pure Cobb-Douglas, to aggregate.

Mark Gertler was curious about whether there are any observable indicators of investment in complementary capital. In response to this question, Susanto Basu drew the attention of the audience to several firm-level studies associated with Brynjolfsson and co-authors from the pre-bubble period in the United States. These studies document that a \$1.00 increase in IT investment is associated with a \$5.00 increase in the stock-market value of a firm, suggesting the order of magnitude of complementary capital investments. The studies also indicate that returns to investments in IT are typically normal or low initially, but large with a five-year lag. He noted that this finding was consistent with the story of the paper.

Daron Acemoglu pointed out that the authors' lag story has additional first-order testable implications. He wondered whether investment in IT would have made sense with lags of the length necessary for the authors' story given that firms could have invested at the risk-free rate. Second, he asked whether a production function with decreasing returns to scale in factors other than the unobservable complementary capital would fit other features of the data.

Eva Nagypal commented that the authors do not discuss the distribution of TFP between newly created and existing firms. She suggested that differences in the composition of firms between the United States and the United Kingdom could explain the contrasting behavior of TFP in the two countries. While creation and destruction of establishments is similar in the two countries, growth in new establishments is much higher in the United States, and a large fraction of TFP growth is attributable to them.

Finally, the authors responded to some concerns of the discussants about data. Nick Oulton noted that differences between national accounts methodology in the United States and the United Kingdom make cross-country comparisons difficult. In particular, in the United Kingdom, software investment is misclassified as the purchase of an intermediate input, resulting in a substantial understatement of information and communications technology (ICT) investment as a whole. With an appropriate adjustment for this misclassification, the growth accounting contribution of ICT is similar in the United Kingdom and in the United States, even though stocks are smaller in the United Kingdom. In response to Olivier Blanchard's discussion, John Fernald pointed out that estimates of the acceleration in non-ICT production depend on whether the data used is product data or industry data. He commented that taking account of investment adjustment costs would strengthen the story that TFP growth took place mainly in non-ICT-producing sectors because sectors that were using IT, not producing it, experienced a surge in complementary investment that diverted resources.