The acceleration in U.S. total factor productivity after 1995: The role of information technology

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Introduction and summary

After the mid-1990s, labor and total factor productivity (TFP) accelerated in the United States. A growing body of research has explored the robustness of the U.S. acceleration, generally concluding that it 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 article, we briefly discuss the results of so-called growth accounting at the aggregate level. We then look more closely at the experience since the mid-1990s, when TFP accelerated. We look at data on which industries account for the TFP acceleration: Were the 1990s a time of rising total factor productivity growth outside of the production of ICT? Our industry data strongly support the view that a majority of the TFP acceleration reflects an acceleration *outside* of the production of ICT goods and software.[2] Even when we focus on arguably "well-measured" sectors (Griliches 1994; Nordhaus 2002), we find a substantial TFP acceleration outside of ICT production.

In particular, wholesale and retail trade show a substantial acceleration in TFP after the mid-1990s. This observation leads us, in the final part of the article, to discuss anecdotal evidence on the kinds of changes that have taken place in trade industries that might show up in measured TFP. Retailers implemented numerous organizational innovations, many of which required substantial industry, firm, and establishment reorganization; many of these innovations themselves relied centrally on innovations in ICT. Thus, ICT appears to play a nuanced role in the post-1995 pickup in productivity growth. In particular, the benefits of ICT may be subtle, affecting measured TFP in sectors that use ICT, as firms reorganize production in order to take advantage of the new technologies.

Before discussing numbers, why do we care about TFP growth? First, TFP growth allows us to increase the amount of output we produce—and, hence, how much we have available to consume today or invest for the future—without having to increase the resources (mainly capital and labor) used. Equivalently, we can produce the same output with fewer resources. This efficiency gain is clearly good for society. Second, economists generally argue that in the long run, TFP growth is the only means of getting sustained increases in standards of living, or output per worker. The reason is that tangible capital is generally thought to have a "diminishing marginal product." In other words, for a given number of workers, suppose we increase the quantity of capital. It is reasonable to expect that the marginal contribution of that capital falls, since we have to spread the same workers over more machines and structures. As a result, investment in equipment, software, and structures alone probably cannot lead to sustained increases in standards of living—as the marginal product of capital declines, the extra capital leads to little or no extra output.

A complementary way to look at the benefits of TFP growth is that one can show that TFP growth is identically equal to a weighted average of real wages and real payments to capital. If TFP growth rises, either real wages or real payments to capital rise. Thus, if we want to raise real wages without reducing returns to capital, we need TFP growth.

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Aggregate growth accounting results

If the economy's output increases, then someone must have produced it. In our empirical work, we think of the economy as comprising a large number of firms and industries. But to fix ideas, we start by assuming that the economy has an aggregate production function that relates its overall real output Y to inputs of capital K and labor L. Output also depends on the level of technology, A. Output goes up if the economy's capital or labor input increases or if technology improves. We write this function as:

1) $Y = A \times F(K,L)$.

The relationship in equation 1 is relatively intuitive. For example, the United States produces more output than India each year, even though India has a much larger labor force (and many more employed workers) than the United States. Equation 1 suggests that the United States either has more capital than India or is more efficient at converting inputs into output than India (that is, A is higher in the United States), or (most likely) both.

More closely related to the focus of this article, U.S. nonfarm business output increased more than sixfold between 1948 and 2000; equation 1 says that this reflects increases in capital, labor, or technology. According to Bureau of Labor Statistics (BLS) data, over this same period, total labor input (adjusted for changes in the composition of the labor force) increased two and a half times, while capital input increased about eightfold.

But what was the role of technological innovations, represented by A? With a few assumptions about the production function in equation 1, we can be more precise about the role of technological innovations versus input increases in explaining output growth. We discuss these assumptions further and derive the formal equations in the appendix. Loosely speaking, the key is that economic theory indicates how one can account for the productive contribution of the inputs of capital and labor. Any increase in output not accounted for by increases in inputs is called total factor productivity (also known as the Solow residual, after Solow, 1957, or multifactor productivity).

The BLS produces a widely cited measure of TFP growth, and the data that underlie its calculation, for the U.S. economy. The BLS refers to this measure as "multifactor productivity" or MFP; MFP, TFP, and the Solow residual are three names for the same concept—that is, output growth unexplained by growth in inputs—and we use them interchangeably. As of this writing, the data run through 2001. However, we focus on the period through 2000, since 2001 was a recession year and a large literature discusses the fact that the Solow residual is procyclical (rising in booms and falling in recessions).[3] We wish to abstract from that short-run focus here.

Several comments on the data are useful. In particular, there are, of course, many different types of output and input. For real output, the BLS uses national accounting data from the Bureau of Economic Analysis (BEA); (the BEA output indexes combine the real value of the many different types of goods and services produced). For labor, there are also many different types of workers. These workers have different levels of productivity, reflecting factors such as age, experience, and education. The BLS attempts to control for these differences largely by using relative wage rates: If a college-educated worker earns a higher wage than a high-school dropout, then we expect the main reason for this is that the college-educated worker is more productive. Similarly, capital inputs combine a wide range of tangible goods, such as office buildings, factories, machine presses, and computers. For productivity calculations, one wants a measure of the relative service flow from these different types of capital. The main issue is that a building may last 50 or more years, so it needs a low annual service flow per dollar of capital to cover its costs; a personal computer may last only three or so years, and hence must have a high service flow per dollar of capital since it needs to cover its costs in a very short period. The BLS produces a capital input measure that takes into account the composition of the capital stock across different types of capital. To do so, the BLS estimates the service flow of different types of capital.

Table 1 shows BLS data for the private non-farm economy from 1948 to 2000. The first column shows TFP growth, which was at an annual rate of about 1.2 percent between 1948 and 2000. This rate of increase, compounded for 52 years, implies that the level of TFP approximately doubled over this period.

The next three columns show the growth rates of output and input quantities that underlie that TFP growth in the BLS data. Output growth in the non-farm business sector averaged about 3.7 percent per year; labor input grew somewhat more slowly, about 1.8 percent per year; while capital input grew somewhat more quickly, nearly 4.1 percent per year. The next column shows the average share of labor compensation in total cost. Although it fluctuates somewhat from year to year, this share averaged 0.69 over the full sample period.

TABLE 1

Output, inputs, factor prices, and TFP—Nonfarm business sector (average annual percent change)

	TFP 1	Output 2	Labor input 3	Capital input 4	Average labor share 5	Real wage growth 6	Real rental growth 7
1948–2000	1.18	3.66	1.77	4.06	0.69	1.91	–0.45
1948–1973	1.90	4.10	1.45	3.91	0.69	2.79	–0.14
1973–1995	0.38	2.95	1.98	3.94	0.69	0.76	–0.50
1995–2000	1.13	4.54	2.46	5.37	0.67	2.55	–1.83

Note: Real labor compensation and rental rate of capital are deflated using the output deflator.
Source: Data obtained from the U.S. Department of Labor, Bureau of Labor Statistics website on *Multifactor Productivity*, at www.bls.gov/web/prod3.supp.toc.htm.

The final two columns show that over time, labor has benefited substantially from TFP growth, with real wages rising 1.9 percent per year. Real rental rates, by comparison, have been relatively flat—indeed, declining slightly over time. This finding—that technological progress leads to an increase in real wages but not an increase in real rental rates—is consistent with standard theories of economic growth. When TFP increases, the marginal products of labor and capital also increase; initially, this leads to higher payments to these factors as firms compete to hire (or, in the case of capital, rent) them. But in the case of capital, over time the increased marginal product of capital leads to a substantial increase in investment and the quantity of capital, thereby driving the marginal product of capital back down. (The increase in the capital stock, of course, further raises the marginal product of labor, driving the wage up further.) Hence, over time, TFP increases raise the real wage as well as the real *quantity* of capital.

The remainder of the table summarizes important changes over time in the evolution of these series. Several facts are striking. First, comparing the 1948–73 row with the 1973–95 row shows that TFP growth and output growth slowed markedly after 1973. In terms of factor payments, the slowdown in wage growth was particularly marked. By contrast, there is little evidence that factor *quantity* growth changed in any particularly striking way.

Second, after 1995, TFP growth and output growth surged. In the BLS data, although TFP growth did not quite reach its pre-1973 levels, output growth exceeded its earlier rates. Input growth rates rose—with a particularly notable pace of capital growth (nearly 5.4 percent per year). Real wage growth rose at a pace only slightly below its pre-1973 growth rate of nearly 2.8 percent; but real rental growth turned from a slight negative to a sharp negative.

The post-1995 productivity acceleration is, of course, of more than just historical interest, since many aspects of future U.S. economic performance depend on whether this fast pace of growth continues. For example, faster productivity growth means faster growth in income, which not only raises people's standards of living but also means that future tax receipts will be higher, improving the government's budget balance. An important, and still unresolved, issue is the extent to which this productivity acceleration reflects primarily information technology—the most notable example of new technology in recent years.

Industry growth accounting results

The previous section looked at overall TFP growth for the economy. A striking finding was the pickup in TFP growth after 1995. In this section, we ask the interesting follow-up question: Where did the TFP growth take place in the economy? In particular, was the pickup primarily centered in ICT *producing* or ICT *using* industries?

When we disaggregate the data to an industry level, an important conceptual question arises about how to treat intermediate inputs (purchased goods and services such as raw materials, parts, consultants, advertising, and so forth) and, as a result, how to measure output. For example, suppose the economy produces bread. A farmer grows the wheat and sells it to a miller; the miller produces flour and sells it to a baker; and the baker bakes bread and sells it to a household. At an economy-wide level, we do not want to measure total output by summing the value of the wheat plus the value of the flour plus the value of the bread. We just want to count the value of the final loaves of bread. An alternative way to measure that final output is by summing the so-called value added of the farmer, the miller, and the baker—that is, the value of their sales minus the value of the intermediate inputs they purchased. At an economy-wide level, the inputs used to produce the bread comprise the capital and labor used by the farmer, the miller, and the baker.

We focus, for simplicity, on the value-added approach, even at the industry level. The advantage of this approach is that these estimates are "scaled" to be comparable across industries. The potential disadvantage, of course, is that the measure of output—value added—is rather less natural than the "gross output" of shoes, bread, and so forth. In the words of Domar (1961), value added is "shoes lacking leather, made without power." In our example, it is bread lacking flour. Nevertheless, for standard measures of TFP, the value-added measures are simply rescaled versions of gross-output TFP (with a scaling factor that depends on the ratio of nominal gross output to nominal value added), so no important information is lost.[4]

We use a 51-industry dataset discussed in Basu, Fernald, Oulton, and Srinivasan (2003). These data update that used in Bosworth and Triplett (2002) and Basu, Fernald, and Shapiro (2001). The industry value-added measures (derived from industry gross output and intermediate-input use) come from industry-level national accounts data from the BEA. For capital input—including detailed ICT data—we use BLS capital input data by disaggregated industry. For labor input, we use unpublished BLS data on hours worked by two-digit Standard Industrial Classification (SIC) industry. Real industry output data are not available before 1977 and, for some industries, not before 1987.[5]

Table 2 overleaf provides standard estimates of TFP for various aggregates, including the one-digit industry level. The first three columns show TFP in value-added terms. The final column shows the sector's nominal value-added share.[6]

The top line shows the sizable acceleration in TFP growth, from about 0.6 percent per year to about 1.9 percent.[7] These calculations incorporate a labor composition adjustment from Aaronson and Sullivan (2001), shown in the second line. Labor quality growth increased more slowly in the second half of the 1990s, when the booming economy drew lower skilled workers into employment. Hence, adjusting for improvements in labor "quality" 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).[8]

The remainder of the table shows various sub-aggregates, including the one-digit SIC level (none of which incorporate a labor quality adjustment). It is clear that in our dataset, the acceleration was not limited to the ICT-producing sectors. First, if we focus on the non-ICT producing sectors (third line from bottom), we see an acceleration of nearly 1 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—for example, it is often difficult even conceptually to decide on the "real output" of a bank or a lawyer. 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.

Looking more closely at the sectoral data, the trade sectors, especially retail, emerge as a major contributor to the productivity acceleration. U.S. retail value-added TFP growth *rose* by 4.5 percentage points per year. Together, wholesale and retail trade "account" for about three-quarters of the U.S. acceleration (weighted by output shares). Nevertheless, they are not the entire story. Even excluding these sectors, the U.S. data still show an acceleration.[9]

That the U.S. productivity acceleration was broad-based is consistent with a growing body of recent work. For example, the Council of Economic Advisers (2003) reports that between 1973–95 and 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.[10] 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.[11]

Case study: Anecdotal evidence on production and productivity in retail trade

In the preceding sections of the article, we documented the resurgence in TFP growth after 1995 in both aggregate and industry data. We also documented that the majority of the acceleration occurred in sectors that use, rather than produce, information technology. Within these IT-using sectors, we reported that wholesale and retail trade appeared particularly important in accounting for the TFP resurgence. We now look more closely at these industries, seeking anecdotal evidence on the kinds of changes that have taken place in trade industries that might show up in

TABLE 2

Total factor productivity growth by industry in private non-farm business, 1990–2000 (percent change, annual rate)

	Productivity (value-added terms)[b]			Share of nominal value added
	pre-1995	post-1995	Acceleration	2000
Private non-farm economy (adjusted for labor quality)[a]	0.59	1.92	1.32	100.0
Contribution of labor quality	0.32	0.16		
Private non-farm economy (not adjusted for labor quality)	0.91	2.08	1.17	
Mining	3.08	–2.15	–5.23	1.6
Manufacturing	2.40	2.76	0.36	20.6
Nondurables	1.02	–1.20	–2.22	8.7
Durables	3.47	5.61	2.14	12.0
Construction	0.39	–0.98	–1.38	6.1
Transportation	1.69	1.53	–0.16	4.2
Communication	2.31	0.15	–2.16	3.7
Electric/gas/sanitary	0.42	0.17	–0.25	2.9
Wholesale trade	1.66	5.37	3.71	9.2
Retail trade	0.83	5.33	4.50	11.8
Finance & insurance	0.44	3.39	2.96	10.7
Finance	1.31	4.90	3.59	7.5
Insurance	–1.49	–0.06	1.44	3.2
Business services & real estate	1.12	0.40	–0.72	13.9
Business services	0.60	–1.40	–2.00	7.1
Real estate	1.55	2.34	0.79	6.8
Other services	–1.89	0.08	1.97	15.2
ICT producing[c]	5.52	11.02	5.50	5.3
Non ICT producing	0.61	1.54	0.93	94.7
Well-measured industries[d]	1.80	3.17	1.37	54.2
Well-measured (excluding ICT producing)	1.35	2.24	0.88	48.9

[a]For productivity purposes, our definition of private non-farm business excludes holding and other investment offices along with miscellaneous services, since consistent input and output data are unavailable for these industries.
[b]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.
[c]ICT-producing includes industrial machinery and electronic and other electrical equipment sectors.
[d]Well-measured industries include mining, manufacturing, transportation, communication, electric/gas/sanitary, and wholesale and retail trade.
Sources: Authors' calculations based upon data from Bosworth and Triplett (2003), the Bureau of Economic Analysis, and the Bureau of Labor Statistics.

measured TFP. This anecdotal evidence may provide insights into the underlying sources of TFP growth.[12]

The Bureau of Economic Analysis—the source for our data—defines retail trade as a distribution service of goods to individuals.[13] According to the BEA's gross domestic product-by-industry measure, total output in retail trade is measured by retail sales, *excluding* the value of the actual good sold and taxes collected by individual retail stores. Thus, value added would be these distribution services minus the contribution of the electricity, utilities, cleaning services, and other intermediate inputs.[14]

A difficult issue that national accountants have to struggle with is how to measure real, or inflation-adjusted, output. If there are no changes in the quality of goods sold, then simply recording the value of sales and the prices charged makes it relatively easy to measure real output. However, when there are substantial changes in quality—for example, retailers stock a wider variety of products so you are more likely to find what you want; or the Internet makes it easy to buy goods at home if, in fact, you hate fighting crowds at the mall—it becomes much more difficult to properly measure real output. For example, some people have argued that the substantial use of information technology in retailing has made it increasingly difficult to measure real output accurately.

Nakamura discusses the difficulties in measuring output that resulted from changes in the retail environment between 1978 and 1996. Retailers with advanced technology offered lower prices and replaced retailers with older technology whose goods sold for more. Nakamura (1997) defines this "rapid automation of retail transactions processing" as the "retail revolution." According to Nakamura, the BLS methodology measures this decline in price as a decline in output with a stable price, and misleadingly captures efficiency as inefficiency. He suggests that retail output was understated due to an increase in the quality of service provided to consumers. Nakamura cites a report in the trade publication *Progressive Grocer* that the average items per store grew from 7,800 in 1970 to 19,612 in 1994. He notes that "Americans no longer had to make do with bright yellow mustard, canned peas, and gelatin desserts" (Nakamura, 1997), highlighting increased American living standards reflecting a proliferation in goods provided by retailers.

Leaving this measurement issue aside, what do the BEA data show about the growth rates of real output and real inputs of capital and labor? Real value-added in retail trade averaged 5.4 percent from 1995 to 2000, almost doubling the average growth between 1978 and 1995 of 2.9 percent. From our original production function, we see that increases in value added are explained by either increases in inputs (capital and labor) or improvements in technology. According to BLS data, both capital and labor inputs for retail trade grew more slowly, not more quickly, in the latter half of the 1990s. Capital input grew at 4.7 percent between 1978 and 1995, but only 3.9 percent between 1995 and 2000. Labor hour growth slowed from 1.5 percent to 1.3 percent over these periods.

Since the faster pace of output growth does not reflect faster growth in inputs, TFP growth must have risen. To think about the sources of TFP growth, it is useful to think a bit about how information technology shows up in the retail sector. The direct effect of adding, say, new high-tech scanners and computers is simply capital deepening: Each worker can produce more output using the same level of effort. But this new information technology as such represents more *capital* input, not higher TFP. For example, many large retailers invested in barcode technology with scanning capabilities for identifying goods. Prices then entered into registers automatically, leaving less room for mistakes and, consequently, speeding the entire checkout process. As a result, output increased, given that the number of purchases increased along with overall sales.

This capital-deepening raises labor productivity (output per hour), even if it does not raise TFP. Studies conducted by the BLS find that labor productivity accelerated between 1987 and 1999, partially accounted for by information technology investment (Sieling, Friedman, and Dumas, 2001). These BLS findings show capital deepening indeed existed in retail trade and contributed to higher output.

So how could investments in information technology affect TFP? One reason is that when retailers invested heavily in new information technology, additional organizational changes followed that also enhanced production. Small modifications of this nature often appear in TFP measures, and therefore serve as a useful tool for examining TFP growth. For example, adding coiled wire extensions to barcode scanners made it unnecessary for employees to lift heavy objects in stores that sold large items. This wire is a relatively cheap piece of capital; the innovation is really the *idea* of adding it to the scanner, an idea that may have been thought up and implemented by the retailer rather than the scanner manufacturer. This innovation, in turn, helped speed the checkout line; output increased, with a minimal investment.

In the remainder of this section, we investigate changes that took place in retail trade prior to the late 1990s in the hope of gaining further insight into the industry's exceptional TFP performance. However, one challenge is that organizational changes are often coupled with capital investments, making it difficult sometimes to disentangle the role of the capital itself (an increase in capital per worker) from the increase in TFP that came because the organizational innovation allowed retailers to increase output more than they increased inputs. So we do not try to separate or quantify the effects. Given that capital input grew more slowly in the second half of the 1990s than the first, while output grew more quickly, it is clear that the organizational changes played a key role.

The organizational structure of individual retail firms altered dramatically following the introduction of information technology to the industry. Retailers partnered with manufacturers in place of using wholesale trade as an intermediary. With electronic data interchange systems (EDI), retailers linked to suppliers, which allowed for instant data exchanges. In addition, both retailers and suppliers agreed in advance on how suppliers should react to the sales data gathered. Together, these new practices helped reduce imperfect information. According to the *Economic Report of the President*, "Even where firms in the supply chain remain separate entities, the degree of cooperation may come to resemble what might occur in a vertically integrated firm" (Council of Economic Advisers, 2001). Holmes (2000) illustrates this aspect of supply-chain management using the partnership between retailer Wal-Mart and manufacturer Proctor & Gamble (see also Kumar, 1996). According to Lou Prichett, vice president at Proctor & Gamble, "P&G could monitor Wal-Mart's sales and inventory data, and then use that information to make its own production and shipping plans with a great deal more efficiency" (Walton and Huey, 1992). The *Harvard Business Review* finds IT use in retailing helped reduce both human error and shipment time, which then allowed retailers to trim costs. Cutting costs grew in importance as more discount stores entered the market. Changes also occurred in how retailers organized inventory deliveries. Holmes (2000) finds evidence that investment in IT complemented both increases in inventory deliveries and increases to store size. Retailers benefited from economies of scale by filling trucks to capacity with larger orders and, thus, stores grew in size. Holmes also notes that "Wal-Mart and Home Depot led other retailers in increasing the frequency of deliveries," citing Vance and Scott (1994), who claim that Wal-Mart's daily deliveries set them apart from rival Kmart, whose deliveries came once every five days.

As modifications were taking place within individual firms, the entire marketplace experienced a transformation as well. A new larger design for stores emerged—the "big-box" format—whereby retailers took advantage of their size and offered a wide spectrum of goods at lower prices. Retail trade is typically dominated by small businesses; thus, Foster, Haltiwanger, and Krizan's (2000) finding that large retailers displaced smaller, less efficient retailers implies that the entrance of large chain stores significantly affected the industry. They find that this displacement increased overall productivity in retail trade through entry and exit of firms, with the entrance of efficient firms carrying a larger weight in the productivity boost. Anecdotal evidence shows that large retailers also displaced other large retailers. Kmart surpassed Sears, Roebuck, and Co. to dominate market share of the retail industry, but later fell to Wal-Mart, which currently dominates.[15]

Using new systems under supply-side management, retailers cut costs and offered "everyday low prices," yet remained profitable since sales increased with lower-priced goods. Organizational changes tied to the infiltration of information technology increased efficiency and improved the overall production process. These within-firm changes affected the entire industry by displacing inefficient firms and promoting the spread of effective production procedures. In fact, studies by McKinsey Global Institute suggest retail giant, Wal-Mart, had both an indirect and direct impact on general merchandizing through "managerial innovation that increased competitive intensity and drove the diffusion of best practice" (McKinsey, 2001). Below, we discuss operations initiated by Wal-Mart to add a firm-level perspective to the productivity acceleration in retail trade.

Wal-Mart: Examples of ideas put to work

"How did a peddler of cheap shirts and fishing rods become the mightiest corporation in America?"—*Fortune* magazine posed this question after Wal-Mart topped its Fortune 500 list in 2002, making it the first service sector corporation to reach the top. From its small town start in Arkansas, Wal-Mart has grown into an empire spanning the globe. In fact, Wal-Mart accounted for 6 percent of total U.S. retail sales in the fiscal year ending January 31, 2003.[16]

Wal-Mart differed from other retailers in many of its strategies. Large retailers like Kmart and Sears, Roebuck, and Company targeted urban populations, believing that rural areas were not profitable. Wal-Mart, on the other hand, contended that a market existed in rural America as well. Though the advantage of building in urban areas came from proximity to distributors, Wal-Mart solved this problem by building capacity to install an internal distribution system. Essentially, Wal-Mart took on wholesaling in addition to the retail business (McKinsey, 2001). As discussed earlier, retailers cut costs and saved time by establishing direct contact with manufacturers. Wal-Mart exploited this new practice by establishing direct contact with Proctor & Gamble, and then warehoused merchandise in P&G's distribution centers. By centrally placing large orders, Wal-Mart was able to negotiate reduced prices on goods from manufacturers, helping it later to under-price competitors (McKinsey, 2001; Raff and Temin, 1997).

Wal-Mart also benefited from shrewd managerial tactics, beginning with company founder and CEO, Sam Walton. According to McKinsey Global Institute, managerial innovations "gave Wal-Mart a 44 percent productivity gap relative to the remainder of the market" (McKinsey, 2001). In Walton's book, *Made in America*, he discusses the importance of learning from those who were more successful, which at the time was Kmart. Wal-Mart was not an overnight success—in fact, it spent many years on the sidelines learning while retailers like Kmart dominated the industry. Walton asserts that "During this whole early period, Wal-Mart was too small and insignificant for any of the big boys to notice. … That helped me get access to a lot of information about how they were doing things" (Walton and Huey, 1992). While Wal-Mart remained small, Walton invested in intangible capital by learning the most effective methods of operation. Flying all over the country and noting different ways to run a business, Walton accumulated a wide array of business models to develop his own, using what he believed to be the most successful practices. Described by *Fortune* magazine as "an admirer and student of Kmart," Walton was later named one of *Fortune*'s Top 10 CEOs of All Time. During Wal-Mart's fledgling years, Walton spent time and money learning the trade from his competition. That investment made in intangible capital (knowledge) can be considered similar to an investment in physical capital. With some lag, Walton's knowledge would eventually pay off, adding to Wal-Mart's output production by way of efficiency. This heightened efficiency would then contribute to TFP growth.

Wal-Mart is often cited as a leader in using information technology. Walton discusses how he chose to adopt computerization. He discusses how Wal-Mart maintained inventory through lists that they updated manually. At that time other retailers were moving toward computerization. Walton says "I made up my mind I was going to learn something about IBM computers. So I enrolled in a school for retailers in Poughkeepsie, New York" (Walton and Huey, p. 107). Significantly, Walton used this opportunity to recruit talented individuals to work for Wal-Mart. Additionally, Walton recruited Wal-Mart's team from other successful retailers. Though this would seem to benefit Wal-Mart at the expense of other retailers, the overall advantage came from the increased competition for the entire industry. Outside human capital accumulated by scouting other companies for talented individuals who knew the field and free riding off knowledge learned elsewhere—this contribution of knowledge also appears in TFP measures.

Insights from the case study

The preceding discussion of developments in the trade sector, along with the quantitative evidence on the TFP acceleration, suggests some admittedly speculative insights into the U.S. productivity acceleration. In particular, as many people have noted, the 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 of ICT production, such as in retail trade. How are these two observations related?

First, as the retail discussion suggested, innovation is a challenge for the measurement of real output. Information technology makes it possible for retailers to keep track of a much larger variety of goods and to operate much larger stores. Consumers likely value the greater variety of goods that they get access to; this variety thus suggests that consumers get a higher quality shopping experience. Correcting for this quality improvement suggests that we currently overstate prices and understate real output, as Nakamura (1997, 1998) argues. But as Kay (2003) suggests, some consumers may also be getting a less pleasurable shopping experience—offsetting some of that higher quality shopping experience.

It is worth mentioning, however, that innovation and the ensuing difficulties in disentangling price from quantity are not new. Although most people suspect that information technology has made the measurement problems worse, Triplett (1997) expresses skepticism, noting that these difficulties existed in the past as well. De Long (1998) argues that because of unmeasured improvements in the quality of goods and services, real incomes per work hour plausibly rose thirtyfold over the preceding century, compared with the sixfold increase one would find if one simply looked at the *Historical Statistics of the United States*. DeLong's discussion, in particular, highlights the vast range of new products available late in the twentieth century that were unavailable at any price in the late nineteenth century (and, as he suggests, makes it difficult to capture changes in living standards in a single number). For example, DeLong (2000) writes of the shortcomings of life in the mid-nineteenth century as follows:

> I would want, first, health insurance: the ability to go to the doctor and be treated with late-twentieth-century medicines. Franklin Delano Roosevelt was crippled by polio. Without antibiotic and adrenaline shots I would now be dead of childhood pneumonia. The second thing I would want would be utility hookups—electricity and gas, central heating, and consumer appliances. The third thing I want to buy is access to information—audio and video broadcasts, recorded music, computing power, and access to databases. None of these were available at any price back in 1860.
>
> I could substitute other purchases for some. I could not buy a washing machine, but I could (and would) hire a live-in laundress to do the household's washing. I could not buy airplane tickets; I could make sure that when I did travel by long distance train and boat I could do so first class, so that even though travel churned up enormous

> amounts of time it would be time spent relatively pleasantly. But I could do nothing for medical care. And I could do nothing for access to information, communications, and entertainment technology save to leave the children home with the servants and go to the opera and the theater every other week. How much are the central heating, electric lights, fluoridated toothpaste, electric toaster ovens, clothes-washing machines, dishwashers, synthetic fiber-blend clothes, radios, intercontinental telephones, xerox machines, notebook computers, automobiles, and steel-framed skyscrapers that I have used so far today worth—and it is only 10 A.M.?

Of the products DeLong lists, only notebook computers are clearly associated with the late 1990s.

Second, in retailing, many innovations implemented by retailers were accompanied by capital investment in computers or structures (for example, the big box format). In essence, the innovation often required reorganization at the level of the establishment, firm, or industry—which requires tangible physical changes. This can make it difficult to disentangle anecdotally the role of TFP from the role of capital deepening. But conceptually, innovations in computers per se should not show up as faster technology change in retailing: For a retailer, a new computer represents capital deepening, and growth accountants take account of that. (And, indeed, we found that in retailing, there was a slower pace of capital deepening in the late 1990s than in the 1977–95 period.)

Computer innovations would show up as retailing TFP to the extent that computers have an abnormally large return or to the extent that investments in computers are correlated with other, unobserved innovations by retailers. Indeed, many of the key innovations took place in retailing per se, for example, organizational changes that were made *possible* by information technology but nevertheless required substantial investments of time and resources by retailers to implement.

A growing literature on ICT as a "general purpose technology" (GPT) suggests important—but often indirect and hard to foresee—potential ways for ICT to affect measured production and productivity in sectors using ICT.[17] Conceptually, one can separate these potential links into two categories: purposeful co-invention, which we interpret as the accumulation of "complementary capital," which leads to mismeasurement of true technology; and externalities of one sort or another.

For example, Brynjolfsson and Hitt (2003) find that in a sample of 527 large U.S. firms from 1987 to 1994, the benefits of computers for output and productivity rise over time. The full benefits do not appear to be realized for at least five to seven years. They interpret their results as suggesting the importance of combining computer investments with "large and time-consuming investments in complementary inputs, such as organizational capital."

Basu, Fernald, Oulton, and Srinivasan (2003) suggest that these indirect effects that arise 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 other sectors, such as retail trade. Many of the GPT stories (for example, Bresnahan and Trajtenberg, 1995, or Helpman and Trajtenberg, 1998) fall into this "spooky action" camp. (Of course, Einstein's spooky action was instantaneous; the effects of GPTs are not.)

Basu, Fernald, Oulton, and Srinivasan (2003) discuss the difficulties in measuring the "intangible investment" that firms accumulate in the form of organizational knowledge. The resulting "organizational capital" is, to some extent, analogous to physical capital in that companies accumulate it in a purposeful way. Basu et al. interpret this complementary capital as an additional input into a standard neoclassical production function; it differs from ordinary capital and labor in that it is not directly observed but must, somehow, be inferred.[18] When resources (for example, labor time and effort) are diverted from production to investment in this stock of unobserved complementary knowledge, measured output and TFP fall; over time, the service flow from that unobserved stock of knowledge raises measured output and TFP. This story is reasonably consistent with the experience in retail trade, where inputs grew more quickly in the pre-1995 period, while output grew more quickly in the post-1995 period.

In addition, the GPT literature suggests the likelihood of sizeable externalities to ICT. For example, successful new managerial ideas—such as those implemented in retail trade—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, importantly, the mistakes made by others.[19]

Third, the complementary innovations by ICT users, and any spillovers, take time to show up. Sam

Walton, for example, benefited in the 1980s and 1990s from knowledge he accumulated flying around the country visiting competing discount stores and attending IBM conferences in the 1960s and 1970s. More formally, Basu et al. (2003) find that industries that had high growth rates of ICT capital in the 1980s or early 1990s tended to have faster TFP growth rates in the late 1990s. Importantly, 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.

Conclusion

In this article, we have argued that the acceleration in TFP was relatively broad based, with much of it occurring in industries that used, not merely in industries that produced, information and communications technology. Thus, it appears that ICT users themselves introduced a lot of innovations in the way they did business.

Nevertheless, as the experience of retail trade suggests, many of these innovations took advantage of the opportunities opened up by developments in ICT. We view the experience of retail trade as consistent with stories of ICT as a general purpose technology. GPT stories generally suggest a subtle, nuanced, but potentially far-reaching role for ICT to affect the economy. In particular, ICT induces innovations by ICT-users both in the methods or processes they use to produce and in the products themselves, in ways that are often hard to forecast.

APPENDIX

Framework for traditional growth accounting

If the economy's output increases, then someone must have produced it. In our empirical work, we think of the economy as comprising a large number of firms and industries. But to fix ideas, we start by assuming that the economy has an aggregate production function that relates its overall real output Y to inputs of capital K and labor L. Output also depends on the level of technology, A. Output goes up if the economy's capital or labor input increases or if technology improves. We write this function as:

A1) $Y = A \times F(K,L).$

The relationship in equation A1 is relatively intuitive. For example, the United States produces more output than India each year, even though India has a much larger labor force (and many more employed workers) than the United States. Equation A1 suggests that either the United States has more capital than India, or the United States is more efficient at converting inputs into output (that is, A is higher in the United States), or (most likely) both.

More closely related to the focus of this paper, U.S. nonfarm business output increased more than sixfold between 1948 and 2000; equation A1 says that this reflects increases in capital, labor, or technology. According to BLS data, over this same time period, total labor input (adjusted for changes in the composition of the labor force) increased two and a half times, while capital input increased about eightfold.

But what was the role of technological innovations? With a few assumptions about the production function in equation A1, we can be more precise about the role of technological innovations versus input increases in explaining output growth. To begin, we assume that the production function has constant returns to scale in inputs. This assumption implies that if we change all inputs by a given factor, then output changes by the same proportion; for example, if we increase capital and labor inputs by 10 percent each, then output also rises by 10 percent.

In the U.S. example, of course, inputs did not increase proportionately—capital input grew much faster. So how much should we weight each factor? Suppose labor input, say, rises by a small amount dL, while nothing else changes. The resulting increase in output, which we denote dY, is approximately equal to the following:

$$dY = MPL \times dL.$$

MPL is the marginal product of labor, that is, it tells us how much extra output one gets from a little bit more labor input. (In calculus terms, $MPL \equiv \partial Y/\partial L$.) By dividing through by Y and rearranging, one finds:

$$\frac{dY}{Y} = \left[\frac{MPL \times L}{Y}\right]\left(\frac{dL}{L}\right).$$

The left-hand side, dY/Y, is the percent change in output—that is, the actual change dY divided by the level Y. Similarly, dL/L is the percent change in labor input. In words, if labor input rises by, say, 10 percent ((dL/L) = 10 percent), then output growth equals an elasticity $[MPL \times L/Y]$ times 10 percent.

With some further assumptions about how firms behave, we can gain further insight into this output elasticity. Suppose a firm operates in a competitive market (so it takes its output price as given) and hires one additional worker. The benefit is that the firm gets *MPL* more units of output, which it sells at price *P*; the cost equals the wage, *W*. If the firm seeks to maximize profits, it will hire workers as long as the additional revenue it earns exceeds the wage it must pay. The firm stops hiring when the benefits and costs are just equal at the margin:

$$P \times MPL = W.$$

Rearranging, we find an equation for labor's output elasticity:

$$\frac{MPL \times L}{Y} = \frac{WL}{PY} \equiv s_L.$$

Hence, the output elasticity is equal to labor's share in output, s_L, which in turn equals payments to labor, *WL*, as a share of the total value of output, *PY*.

Similarly, suppose *R* represents the rental cost of capital to a firm; if the firm owns the capital, then this rental cost is the implicit "user cost" or opportunity cost of the capital to the firm. Following the same logic as with labor, the elasticity of output with respect to capital is:

$$\frac{MPK \times K}{Y} = \frac{RK}{PY} \equiv s_K.$$

In practice, wages are generally easier to observe directly than is this rental value, since firms often own the capital and do not make an explicit, observable payment. But suppose we are willing to assume that firms earn zero economic profits. Then, by definition, the value of output equals the cost of production; the cost of production, in turn, equals the value of payments to capital and labor. That is,

A2) $PY = WL + RK.$

If we take equation A2 as an accounting identity, then we can take capital's share of output as a residual:

$$RK/PY = 1 - WL/PY$$
$$\rightarrow s_K = 1 - s_L.$$

We can now return to the question of how output growth is related to input growth and technological improvement. Following the same argument we made earlier, we can again differentiate equation A1, this time allowing all inputs as well as technology to change, we find:

A3) $$\frac{dY}{Y} = (1 - s_L)\left(\frac{dK}{K}\right) + s_L\left(\frac{dL}{L}\right) + \left(\frac{dA}{A}\right).$$

This equation shows that for output to grow, either inputs must increase, or technology must improve. This equation also allows us to "account" for growth, by attributing output growth to increases in particular factors or else to technology. In practice, we observe (or can estimate) output growth and growth in capital and labor; we observe labor's share in output. Although we don't observe technology directly, we can estimate it as a residual:

A4) $$\left(\frac{dA}{A}\right) = \frac{dY}{Y} - (1 - s_L)\left(\frac{dK}{K}\right) - s_L\left(\frac{dL}{L}\right).$$

Suppose inputs don't change. Then output only changes if this so-called "total factor productivity" (TFP) residual, or Solow residual, changes.[1] Although we think of it as a broad measure of the economy's technological possibilities, it will capture all sorts of things. These include pure technological innovations (for example, faster computers); managerial innovations such as workplace reorganization that allows the firm to produce more output from a given quantity of inputs; "cost reductions" that allow a firm to produce the same quantity of output using less input; and any spillovers of knowledge from other firms, for example, on how best to benefit from information technology.

Why do we care about TFP growth? First, TFP growth allows us to increase the amount of output we produce—and hence, how much we have available to consume today or invest for the future—without having to increase the amount we use of any input. This is clearly good for society. Second, economists generally argue that in the long run, TFP growth is the only means of getting sustained increases in standards of living, or output per worker. The reason is that capital is generally thought to have a "diminishing marginal product." In other words, for a given number of workers, suppose we increase the quantity of capital. It is reasonable to expect that the marginal contribution of that capital falls, since we have to spread the same workers over more machines and structures. As a result, investment alone cannot lead to sustained increases in standards of living—as the marginal product of capital declines, the extra capital leads to little or no extra output.

A complementary way to look at this question on standards of living is that one can show that TFP growth is identically equal to a weighted average of real factor prices, *W/P* and *R/P*. Thus, if TFP growth rises, either real wages or real payments to capital rise. Thus, if we want to raise real wages without reducing returns to capital, we need TFP growth.[2]

[1]This derivation follows Solow (1957). Hence, *dA/A* is often referred to as the Solow residual. In addition to TFP or the Solow residual, this measure is sometimes referred to as multifactor productivity.

[2]To show this, consider the accounting identity in equation A2 again, but think of it as applying at an economy-wide level rather than a firm-level; this is just the national accounts identity, which tells us that total income equals total output. Taking the total differential—allowing all prices and quantities to change—yields:

$$PdY + YdP = [WdL + LdW] + [RdK + KdR].$$

With considerable rearrangement, one finds that TFP growth equals a weighted average of real factor prices:

$$\frac{dY}{Y} - (1 - s_L)\left(\frac{dK}{K}\right) - s_L\left(\frac{dL}{L}\right) = s_L\left[\frac{dW}{W} - \frac{dP}{P}\right] + (1 - s_L)\left[\frac{dR}{R} - \frac{dP}{P}\right].$$

NOTES

[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.

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

[3]See, for example, Basu and Fernald (2001).

[4]The productivity literature (for example, Jorgenson, Gollop, and Fraumeni, 1987) tends to prefer to use gross-output residuals, with explicit accounting for intermediate inputs. This literature then uses “Domar weights” (the ratio of industry gross output to aggregate value added) to get aggregate residuals. Apart from approximation error, this is equivalent to estimating industry value-added residuals and then using value-added weights. Thus, our approach of focusing on value added is conceptually equivalent to the standard gross-output approach. If the assumptions of constant returns and perfect competition do not hold, however, then not only does TFP not properly measure technology, but for econometric analysis the use of value added versus gross output may make a difference; for a discussion of this point, see Basu and Fernald (1995, 2001).

[5]We thank Jack Triplett for sending us their industry dataset that merged the BEA and BLS data. Basu, Fernald, Oulton, and Srinivasan (2003) updated the BEA data to incorporate November 2002 NIPA industry revisions and also to remove 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 this. We thank Larry Rosenblum at the BLS for sending us unpublished industry hours data, which make adjustments for estimated hours worked by non-production and supervisory employees as well as the self-employed. We updated the BLS capital data from www.bls.gov/web/prod3.supp.toc.htm (downloaded 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. The dataset, along with further details on its construction, is available on request.

[6]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 sum to more than one. In continuous time, this is equivalent to first converting gross-output residuals to value-added terms by dividing by one minus the intermediate share and then using shares in nominal value added. (In discrete time, using average shares from adjacent periods, they are approximately equivalent.) Basu and Fernald (2001) discuss this aggregation and its extension to the case of imperfect competition; see also Oulton (2001).

[7]As noted earlier, the acceleration exceeds that in product-side BLS data shown in table 1.

[8]The BEA industry data come from the income-side of the national accounts, which, as is well known, accelerated faster than the expenditure side in the late 1990s. See Bosworth and Triplett (2002) for an extensive discussion of the difference between TFP growth calculated with industry data and with the aggregate BLS data.

[9]We would 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.

[10]The CEA methodology is very similar to that of Oliner and Sichel (2002), who report *no* TFP acceleration outside of ICT production. But Oliner and Sichel discount their finding on this score, since their method takes non-ICT TFP as a residual. Since the Oliner-Sichel end-point 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.

[11]Some recent research has looked at whether the results cited here are robust to deviations from the usual growth-accounting assumptions that all industries have constant returns to scale and operate under perfect competition; that firms can quickly and costlessly adjust their levels of inputs; and that we observe all variations in input use—that is, there is no unobserved utilization margin. In terms of variable utilization, Basu, Fernald, and Shapiro (2001), Council of Economic Advisers (various years), and Baily and Lawrence (2001) all argue that variations in utilization, that is, cyclical mismeasurement of inputs, play little if any role in the U.S. acceleration of the late 1990s. Basu, Fernald, and Shapiro also find little role in the productivity acceleration for deviations from constant returns and perfect competition. Basu, Fernald, and Shapiro 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 there are costs of adjusting the capital stock 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 broad-based, since service and trade industries invested heavily in the late 1990s and, hence, paid a lot of investment adjustment

[12]McKinsey (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.

[13]BEA definition can be found in Industry Input-Output Methodologies at www.bea.gov/bea/mp.htm.

[14]Sieling, Friedman, and Dumas (2001) and Foster, Haltiwanger, and Krizan (2000) focus on detailed establishment-level data using Census Bureau data on retail sales as their measure of (gross) output. Hence, one needs to keep in mind that some studies use a different definition of output. Nevertheless, although the Census Bureau and BEA measures differ, they nevertheless share identical definitions of value-added output.

[15]Robert Gordon (2003) discusses the importance of the “big box” format that retailers like Wal-Mart follow. He argues Europe has yet to reap the benefits of scale economies in retailing due to strict regulations against large stores, which may help to explain the productivity gap between Europe and the U.S. On the other hand, John Kay (2003) cautions that it is difficult to control for changes in quality—many small markets in Europe, while they may not stock as many products as Wal-Mart, are in many cases a tourist attraction because of the charm and pleasure associated with visiting them.

[16]Wal-Mart’s market share was calculated as Wal-Mart’s reported total net sales for 2002 over total U.S. retail sales in that year.

[17]See, for example, Brynjolfsson and Hitt (2000) and Bresnahan (2001) for a discussion of the kinds of complementary investments and co-invention that firms undertake in order to benefit from ICT, given its “general purpose” attributes. David and Wright (1999) provide a nice historical reflection on general purpose technologies.

[18]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 (2003).

[19]Bresnahan (2001) provides a nice discussion of 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).

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